Journal of Korean Society of
Coastal and Ocean Engineers
Vol. 9, No. 2, pp. 86~96, June 1997

A Shallow Water Front and Water Quality in Chinhae Bay
鎭海灣에 形成되는 淺海前線과 水質分布

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Abstract □ In order to investigate the formation of a shallow water front and its relation to water quality distributions, oceanographic measurements were made, and the numerical computations of the Simpson-Hunter stratification parameter $\log(H/U^3)$ were performed. It is shown from satellite image and hydrographic data that the shallow water front is formed near the northern Kaduk channel, and the stratification parameter $\log(H/U^3)$ near the front is in a range of 2.0~2.5. Measured COD (Chemical Oxygen Demand) concentrations in offshore region of the front and in the western part of the bay are below 2.0 mg/l, whereas the concentrations in Masan Bay located in the northern inside of the frontal zone are as high as 3.0~5.5 mg/l. COD concentrations decrease gradually from Masan Bay toward the offshore due to the dilution by strong water mixing. Anoxic and hypoxic water masses at the bottom layer in summer occur in the western part of Chinhae Bay and in Masan Bay, and DO (Dissolved Oxygen) concentrations become low with increasing the stratification parameter. DO concentrations outside the front are more than about 4.0 mg/l, whereas the concentrations inside the front are low. The shallow water front plays a significant role for material transport from coastal area to oceanic area, and the frontal region seems to be important physical and chemical boundaries.

Keywords : shallow water front, water quality, stratification parameter, hypoxic water mass, material transport

要 旨 : 진해만에서 천해전선의 형성 및 전선과 수질분포와의 관계를 해석하기 위해 해양학적인 조사가 수행되었으며, 또한 Simpson-Hunter의 성층계수 $\log(H/U^3)$을 수치계산하였다. 인공위성 자료와 현지조사결과에 의하면, 진해만의 천해전선은 가덕수로 북쪽해역 부근에서 형성되며, 전선부근에서 성층계수 값은 2.0~2.5이다. 전선이 형성되는 위치를 기준으로 했을 때 만의 외해역과 진해만 서부해역에서는 COD 농도가 2.0 mg/l 이하로 낮으나, 전선역의 북쪽 내해에 위치한 마산만에서는 3.0~5.5 mg/l로써 높다. COD 농도는 마산만에서 외해로 갈수록 강한 해수교환으로 인해 점차 감소한다. 하계 저층 무산소 및 저산소 수괴는 진해만 서부해역과 마산만에서 일어나며, DO 농도는 성층계수가 증감함에 따라 감소한다. DO 농도는 전선이 형성되는 해역을 기준으로 만외에서는 약 4.0 mg/l 이상으로 높으나, 만내에서는 낮다. 천해전선은 연안에서 외해로의 물질수송에 대해 중요한 역할을 하며, 또한 전선의 형성지역은 물리적 및 화학적으로 중요한 경계를 이루는 것 같다.

핵심용어 : 천해전선, 수질, 성층계수, 저산소 수괴, 물질수송

1. INTRODUCTION

Chinhae Bay, located in the southeastern sea of Korea, is a semi-enclosed bay (Fig. 1), and the bay area is 637 km^2. The water exchange of the bay takes place through Kaduk and Kyunnaeryang channels, and 86~90% of the exchange occurs through Kaduk channel (Kim, 1984). The semi-diurnal constituents M_2 and S_2 are dominant, and the mean spring tidal range at Kaduk channel is 1.73 m (KORDI, 1983). The bay is surrounded by three big cities and large industrial complex which has been built since 1960's. Therefore, the bay has been subjected to in-

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creasing environmental stress due to industrial development in recent decades. Chinhae Bay is one of the most polluted coastal bay in Korea, and the productivity has declined significantly. Large amounts of domestic sewage and industrial wastes from land have entered and continue to enter into the bay. The increased loading of contaminants into water bodies has resulted in the degradation of water quality, frequent red tide problem and a decline in the abundance and diversity of fish and habitats. The concentrations of nitrogen and phosphorus which are the main nutrient sources of eutrophication have rapidly increased since 1985 (Kang and Lee, 1992). Many of these problems including bottom-water anoxia, red tide and decline in fisheries are associated with the eutrophication of the bay.

Although extent studies on the physical, chemical and biological aspects of Chinhae Bay (Park and Kim, 1967; Park, 1975; Park, 1982; Hong, 1987; Kim *et al.*, 1989; Kim, 1990; Ministry of Environment, 1991; Lee *et al.*, 1993, Kim *et al.*, 1994; Kim, 1994; NFRDA, 1995) have been made since the past decades, clear countermeasures for environmental improvement have not been suggested. Because the contaminants may exist in both dissolved and particulate forms, their distribution in the water column is mainly affected by the flow field and sediment dynamics. Thus, as a first step to improve the water quality, it is essential to investigate the structure of water mass and the transport characteristics of contaminants. This study is focused on the formation of a shallow water front and its relation to contaminant distributions. In order to understand the mechanism of material transport in Chinhae Bay, oceanographic measurements across the front are very important. Studies on tidal front in the southeastern sea of Korea have been undertaken by Lie (1989) and Cho *et al.* (1995), but no report has been made on the front in coastal bay. Therefore, the present study is to investigate the distribution of physico-chemical factors and the frontal structure in Chinhae Bay, because these features are the key process in the occurence of red tide and anoxic water masses. Additionally a numerical model is used to derive the distributions of the

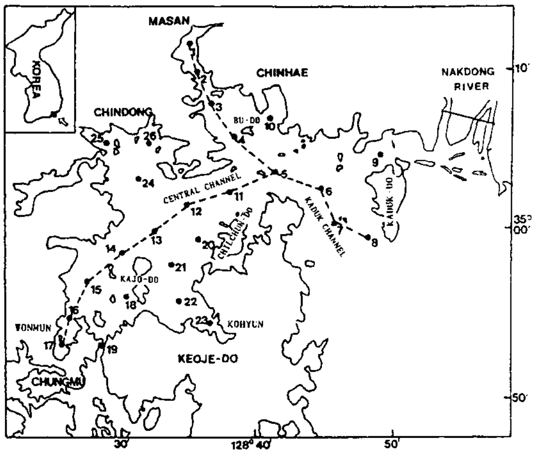

Fig. 1. Observation stations in Chinhae Bay.

Simpson-Hunter stratification parameter $\log(H/U^3)$ in Chinhae Bay, where H is the water depth and U is the amplitude of M_2 tidal current. Positions of predicted front are compared with structures of infrared satellite image and with sea temperature.

2. OBSERVATIONS

Field observations of temperature, salinity, DO (Dissolved Oxygen) and COD (Chemical Oxygen Demand) in Chinhae Bay were carried out from 1990 to 1994, and observation stations are shown in Fig. 1. Measurements of temperature and salinity were performed on August 4 and 16, 1993 and April 25~26 and July 23~24, 1994 using 3 observation ships. The time required for measurements of entire region was about 4 hours. Additionally DO and COD were observed in summer from 1990 to 1994. Temperature and DO profiles at each station were observed at 1.0~2.0 m depth interval using HYDROLAB (Surveyer III, USA). Salinity was measured using HYDROLAB and Inductively Coupled Salinometer (601 MK III, Japan). COD concentration was determined by potassium permanganate method in the laboratory.

3. NUMERICAL TIDAL MODEL

The governing equations used in the mathematical model to derive the Simpson-Hunter parameter are the depth integrated equations of continuity and momentum. The governing differential equations are expressed in an alternating direction implicit (ADI) finite difference form using a space staggered grid scheme. The difference equations and solution techniques are same as the model outlined by Kim *et al.* (1994). The open boundaries at Kaduk and Kyunnaeryang channels are forced with M_2 tidal constituents only using the data (KORDI, 1983). Computational grid size is square being 250 m, the corresponding time step is 30 sec, and the horizontal eddy viscosity is 15.75 m^2/s.

4. RESULTS AND DISCUSSIONS

4.1 Structure of the Front

4.1.1 Horizontal distributions of temperature and salinity

Horizontal distributions of temperature measured at surface on April 25 and July 24, 1994 are shown in Fig. 2. The Temperature in the northern (Sts. 1-3) and western parts (Sts. 15-16) of the bay on April 25 ranged between 15.0 and 16.0°C, and the temperature in the bay entrance (Sts. 7-8) was about 14.0°C. The horizontal temperature gradient between the inner bay (Sts. 1-2, 25-26 and 16-17) and the bay entrance on April 25 was about 1.5°C.

The temperature in the inner bay on July 24, 1994 was 29.5°C, whereas in the bay entrance and the northern part (St. 5) of Keoje-do was 27.5 and 25.0°C, respectively. The lowest temperature of 25.0°C on July 24 was observed around St. 5. Then it increased toward nothern (St. 1) and western parts (Sts. 17 and 25) of the bay, and became as high as 29.5°C. Near St. 5, the onshore-offshore gradient of the temperature became more accentuated. The horizontal temperature gradient between the inner bay and the bay entrance on July 24 was about 4.5°C.

Horizontal distributions of salinity observed at surface on April 25 and July 24, 1994 are shown in Fig. 3. The salinity on April 25 was in a range of 33.4~33.8‰ in Kaduk channel (Sts. 6-8), 31.2~31.6‰ in Masan

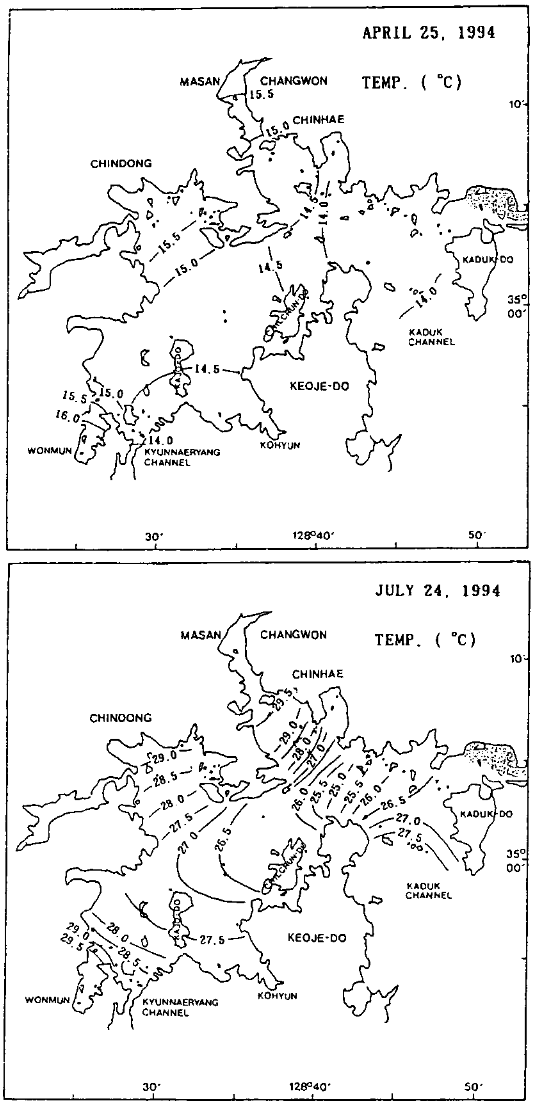

Fig. 2. Horizontal distributions of surface temperature on April 25 and July 24, 1994.

Bay (Sts. 1-2) and 32.2~32.8‰ in the western part of Chinhae Bay. The lowest salinity of 31.2‰ on April 25 was measured in Masan Bay. Then it increased toward the bay entrance, and became as large as 33.8‰. The salinity in Kaduk channel on April 25 was higher than that in the inner bay by 1.0~2.6‰.

The salinity on July 24 was in a range of 31.8~32.2‰ in Kaduk channel, 30.2~31.4‰ in Masan Bay and 32.8~33.4‰ in the western part of Chinhae Bay. The lowest salinity of 30.2‰ on July 24 was also ob-

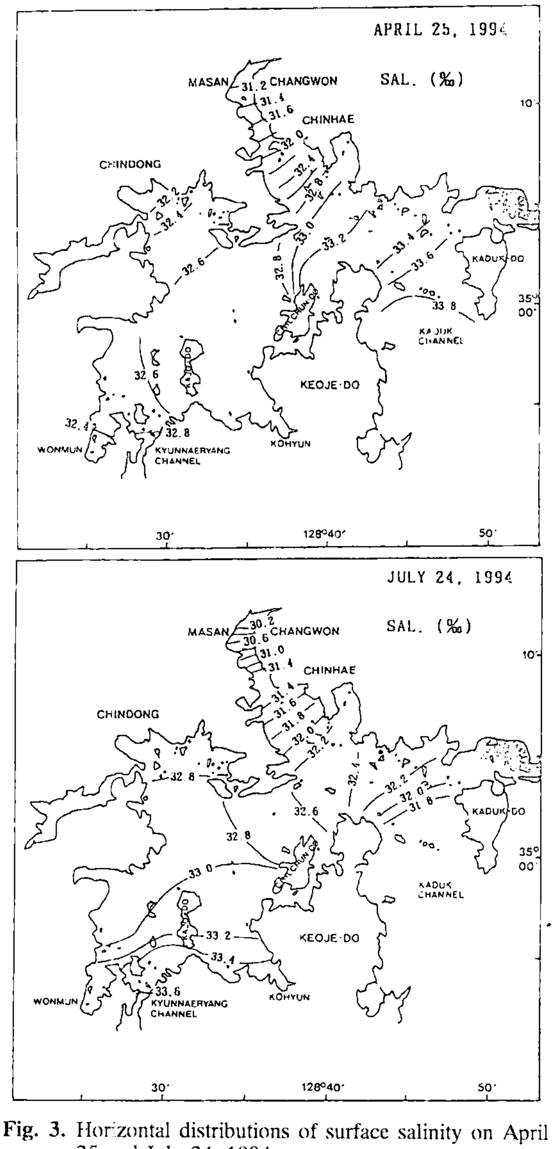

Fig. 3. Horizontal distributions of surface salinity on April 25 and July 24, 1994.

served in Masan Bay, and then it increased toward Chinhae Bay entrance. In both cases the lowest salinity appearsed in Masan Bay, and it is due to the large freshwater inflow from rivers around Masan Bay. Also low salinity in Kaduk channel on July 24 may be due to the effect of large freshwater inflow from Nakdong River. Salinity was higher in April than in July in the northern and eastern parts of the bay, whereas it was higher in July than in April in the western part. It is related to the results of the dilution by the large freshwater inflow from Masan Bay and Nakdong River due to large rainfall from May to July. The horizontal gradient from Masan Bay to Chinhae Bay entrance was large; whereas it was small in the western part of Chinhae Bay. As a result, we can see the fact that the freshwater discharged from rivers around Masan Bay and Nakdong River is rarely extended to the western part of Chinhae Bay.

4.1.2 Vertical distributions of temperature and salinity

Vertical structures of temperature measured on April 25 and July 24, 1994 are shown in Fig. 4. The vertical temperature difference ΔT on April 25, surface minus bottom, ranged from ΔT=3.5~4.0°C in the inner bay (Sts. 16-17 and 1-2) to ΔT=0.0°C in the bay entrance (Sts. 7-8). The range of the temperature difference in Masan Bay (Sts. 1-2) on July 24 was ΔT=8.0°C, whereas the difference in the mouth was ΔT=5.5°C. The well-mixed zone develops from near St. 5 toward the bay entrance, whereas vertical stratification exists from near St. 4 toward Masan Bay (St. 1) and from St. 12 toward the western part (St. 17) of the bay. An interesting point is that, near Station 6 on July 24, there is an uprising of isotherm. It is very probable that this is an upwelling. Vertical gradients of the temperature around Sts. 4-5 and 5-11 are sharp, and thermal stratification was changed abruptly at there. Therefore we can see that a shallow water front is formed around Sts. 4-5 and 5-11.

Vertical structures of salinity measured on August 4 and 16, 1993 are shown in Fig. 5. The vertical salinity difference ΔS, bottom minus surface, on August 4 and 16 was ΔS=10.0‰ and ΔS=13.5‰, respectively. The salinity in Masan Bay and around Chinhae Bay entrance (St. 7) on August 4 was as low as 23‰ and 24‰ respectively, whereas the salinity around St. 5 was higher than 28.0‰. The salinity in Masan Bay (Sts. 1-2) and Kaduk channel (Sts. 6-8) on August 16 was as low as 19~20‰. The partially mixed zone due to the fresh water from Nakdong River and rainfall develops from near St. 5 toward Chinhae Bay entrance, whereas vertical stratification exists from near St. 5 toward Masan

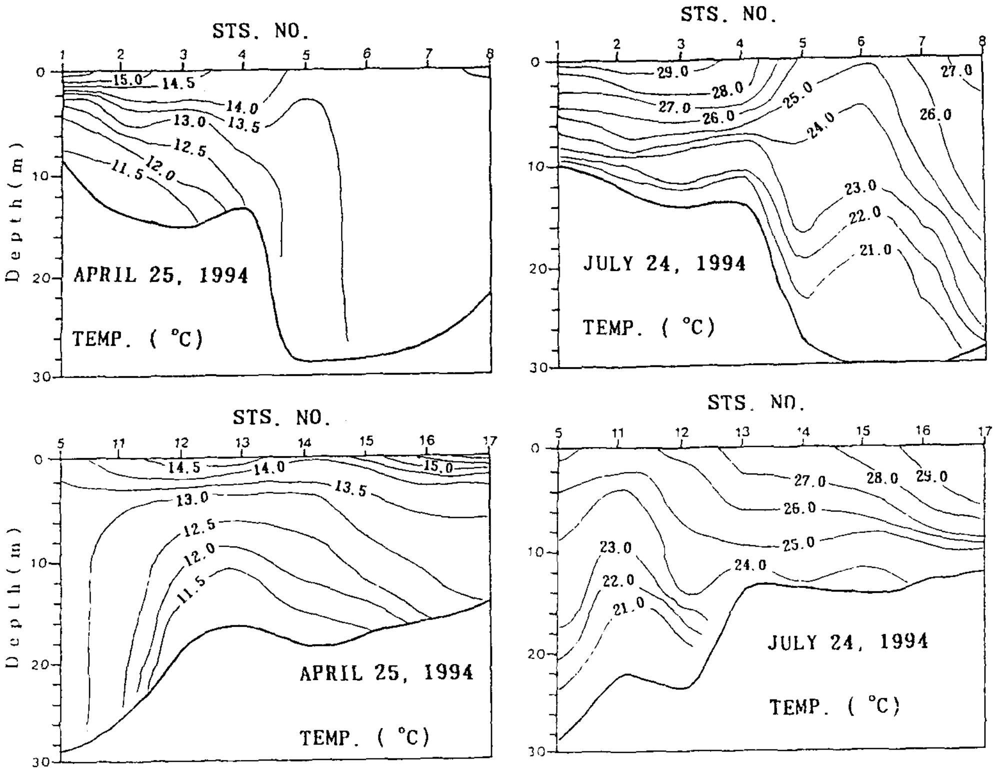

Fig. 4. Vertical structures of temperature on April 25 and July 24, 1994.

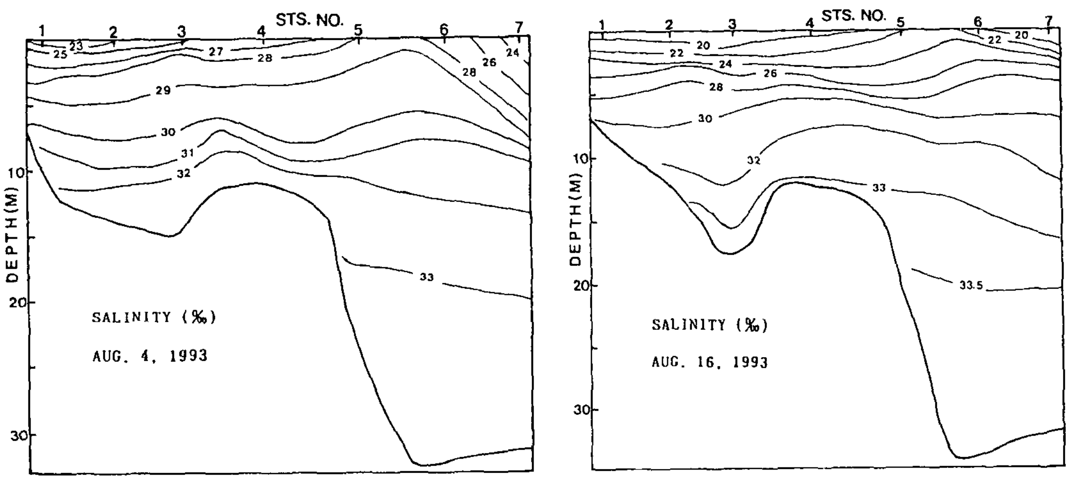

Fig. 5. Vertical structures of salinity on August 4 and 16, 1993.

Bay (St. 1).

From the vertical and horizontal structures of temperature and salinity, it is suggested that the shallow water front is formed in transition zones (Sts. 4-5 and 5-11) between well-mixed and stratified areas. The areas from St. 5 toward the bay entrance have strong currents while the areas from Sts. 4 and 13 toward the inner bay (Sts. 1-2 and 16-17) have relatively weak currents (Kim, 1994; Kim *et al.*, 1994). Unfortunately, author could not measure the vertical distributions of salinity on April 25 and July 24, 1994 because of some trouble of the salinometer.

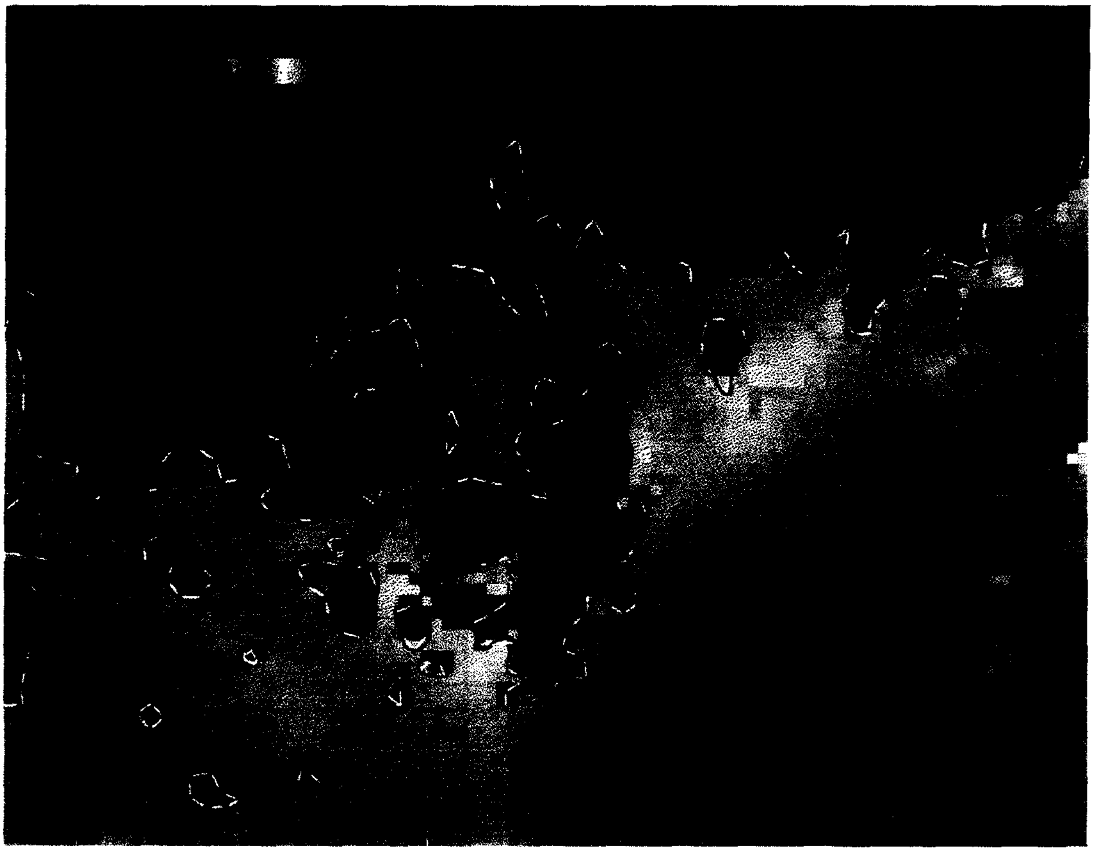

Fig. 6. NOAA-11 infrared image around Chinhae Bay on August 14, 1994.

4.1.3 Infrared image

Fig. 6 shows infrared image of around Chinhae Bay on August 14, 1994. The lighter-shaded portions of the sea indicate lower sea surface temperatures and the darker depicts higher temperatures. The positions (near St. 5) of the front seen in infrared imagery are roughly consistent with observed frontal positions. This front is the surface signature of the transition zone between the stratified waters of the inner Chinhae Bay and the vertically well-mixed waters in Kaduk channel having strong tidal mixing.

4.1.4 Computed log(H/U^3)

Fig. 7 shows the contours of $\log_{10}(H/U^3)$ in the numerical model with forcing by the M2 constituent only. The criterion parameter in the central channel (Sts. 5-11) and northern Kaduk channel (Sts. 4-5) is 2.0~2.5. Therefore we can see that the front in Chinhae Bay is found to be located at log(H/U^3) value of 2.0~2.5.

Using a similar parameter, typical values of 2~3 were calculated around Britain: 1.7~2.0 (Simpson and Hunter,

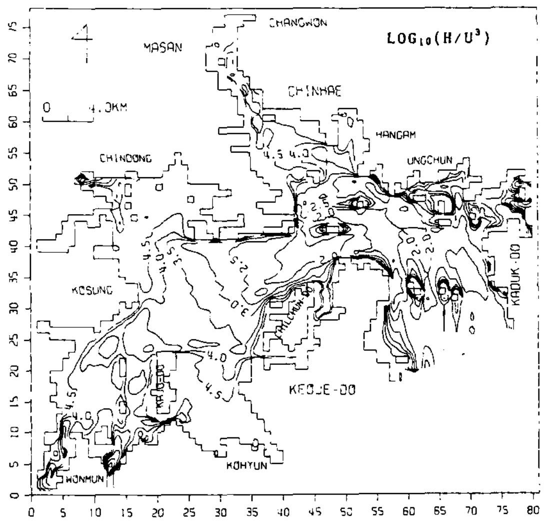

Fig. 7. Distribution of $\log_{10}(H/U^3)$.

1974); 1.5~2.0 (Simpson, 1976); 2.5~3.0 (James, 1977); and 2.0~2.5 (Fearnhead, 1975), while the values in Osaka Bay is 2.5~3.0 (Yanagi and Takahashi, 1988).

Although uncertainties remain such as in the exact transition value of $\log(H/U^3)$, the spatial variability in the predicted range should be useful in choosing locations for observational or biological studies. Furthermore, there are generally insufficient data to fix accurately the position of a frontal boundary which is subject to both the effects of weather and longer-period seasonal variations. The front in the bay is presumably attributed to the freshwater inflow from Nakdong River. To clarify the frontal position and the formation mechanism, the future detailed observations such as the influence of river discharge and tidal range will be needed.

The formation of the tidal front may be attributed to a change in the energy balance between tidally generated mixing and buoyancy input. Simpson and Hunter (1974) reported that tidal fronts appear in the transition zone between the stratified area and the vertically mixed area induced by tidal current. Since then tidal front has been observed in many continental-self seas and coastal seas around the world. Additionally Yanagi and Yoshikawa (1987) reported that tidal front in Osaka Bay is formed in transition zone between stratified area and vertically mixed area. Osaka Bay has the stratified region shoreward and therefore, differs from other regions with the formation of tidal fronts such as those near the British coast (e.g., Simpson and Hunter, 1974). Yanagi *et al.* (1989) reported the frontal structure of Tokyo Bay, and the frontal structure is similar to that of Osaka Bay. Yanagi and Yoshikawa (1987) pointed out that the tidal front in Osaka Bay is caused by the strong tidal current in the central deep region and the front is greatly influenced by freshwater inflow from rivers located at the bay head. Chinhae Bay has the stratified region shoreward too, and therefore the shallow water front appearing in the bay is presumably the tidal front such as that in Osaka Bay. It is found for the first time that the shallow water front exists in Chinhae Bay. The frontal location is known to be related to the variations of tidal range, buoyancy input and current regime (Schumacher *et al.*, 1979; Yuasa and Ueshima, 1992). Therefore, the future detailed measurements will be needed to clarify the dependency on river discharge, or on tidal range from spring tide to neap tide.

4.2 Horizontal Distributions of COD at Surface

Horizontal distributions of COD concentration at surface in summer from 1990 to 1994 are shown in Fig. 8. COD concentrations in the western part of the bay had a range of 1.3~1.8 mg/l in August 1990, 1.5~1.8 mg/l in August 1992, 0.8~1.5 mg/l in April 1994 and 0.4~0.8 mg/l in July 1994. The concentrations in 1994 were very low compared to other years because of small rainfall.

COD concentrations in offshore region of the Chinhae Bay front (around St. 5) were below 1.0~2.0 mg/l, whereas the concentrations in Masan Bay were as high as 3.0~5.5 mg/l, because the discharged contaminants from Masan and Changwon areas were mainly accumulated in Masan Bay due to the weak current. COD concentrations decrease gradually toward the offshore, and the concentrations in the central channel (Sts. 5-11) and northern Kaduk channel (Sts. 4-5) were less than 2.0 mg/l because of the dilution by strong water mixing in the horizontal and vertical directions. The measurements show that COD concentrations outside the shallow water front ($\log(H/U^3)$=2.0~2.5) are very low compared to the northern part of the front. We can see that the shallow water front plays a significant role for material transport from coastal area to oceanic area. Generally, nutrient distributions are determined by the physical mixing process. Additionally, the horizontal distributions of phosphate phosphorus (PO_4-P) and dissolved inorganic nitrogen (DIN) measured by NFRDA (1995) in Chinhae Bay show conspicuous changes of those concentrations around the front.

4.3 Horizontal Distributions of DO at Bottom

Sources of DO (Dissolved Oxygen) include algal photosynthesis and atmospheric reaeration. DO is consumed through algal and heterotrophic respiration, nitrification, and exertion of COD released from the sediments.

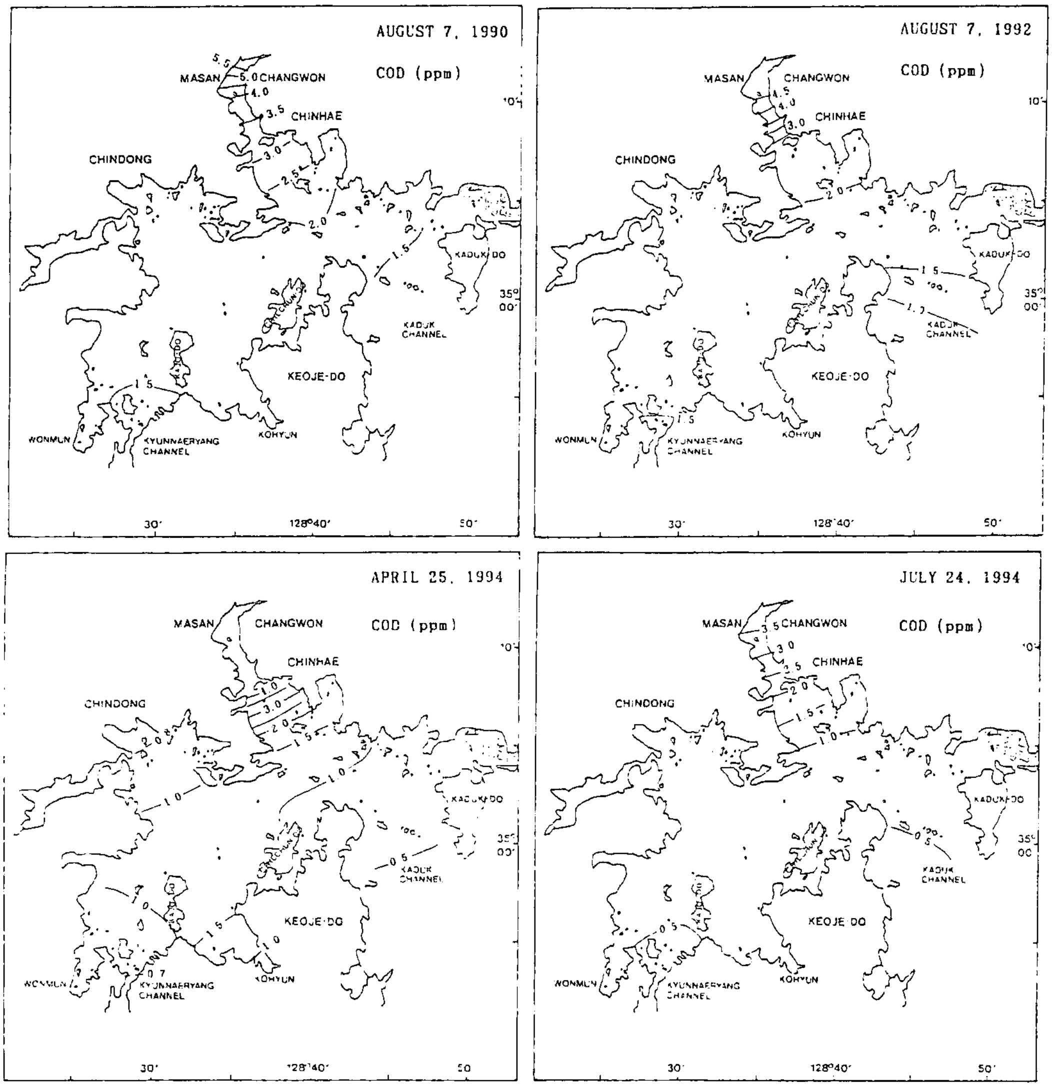

Fig. 8. Horizontal distributions of COD concentration at surface from 1990 to 1994.

Fig. 9 shows the horizontal distributions of lowest DO concentration at bottom during the summer period from 1990 to 1993. Hypoxic water masses (less than 2.0 mg/l) in 1990 were extended to the western central part of Chinhae Bay and around Bu-do, but the concentrations in the central channel, located in the northern part of Chilchun-do and between Sts. 4 and 5 were more than 3.0 mg/l. DO concentrations in the central channel in 1991 were more than 4.0 mg/l, whereas an anoxic water (less than 1.0 mg/l) in the western part of the bay existed. DO distributions in Masan Bay in 1991 were not observed. Though DO concentrations in 1992 were higher than those in other years, and the concentrations in the western part including Kajo-do, Wonmun and Kohyun Bay and in Masan Bay were below 2.0 mg/l. The distributions in 1993 were similar to those in 1991, and the anoxic water appeared in the western part and Masan Bay. The lower DO concentration can be attributed to the existence of strong stratification and the excess loading of organic and inorganic pollutants from the Masan and Changwon areas. DO concentrations in Kaduk channel and the central

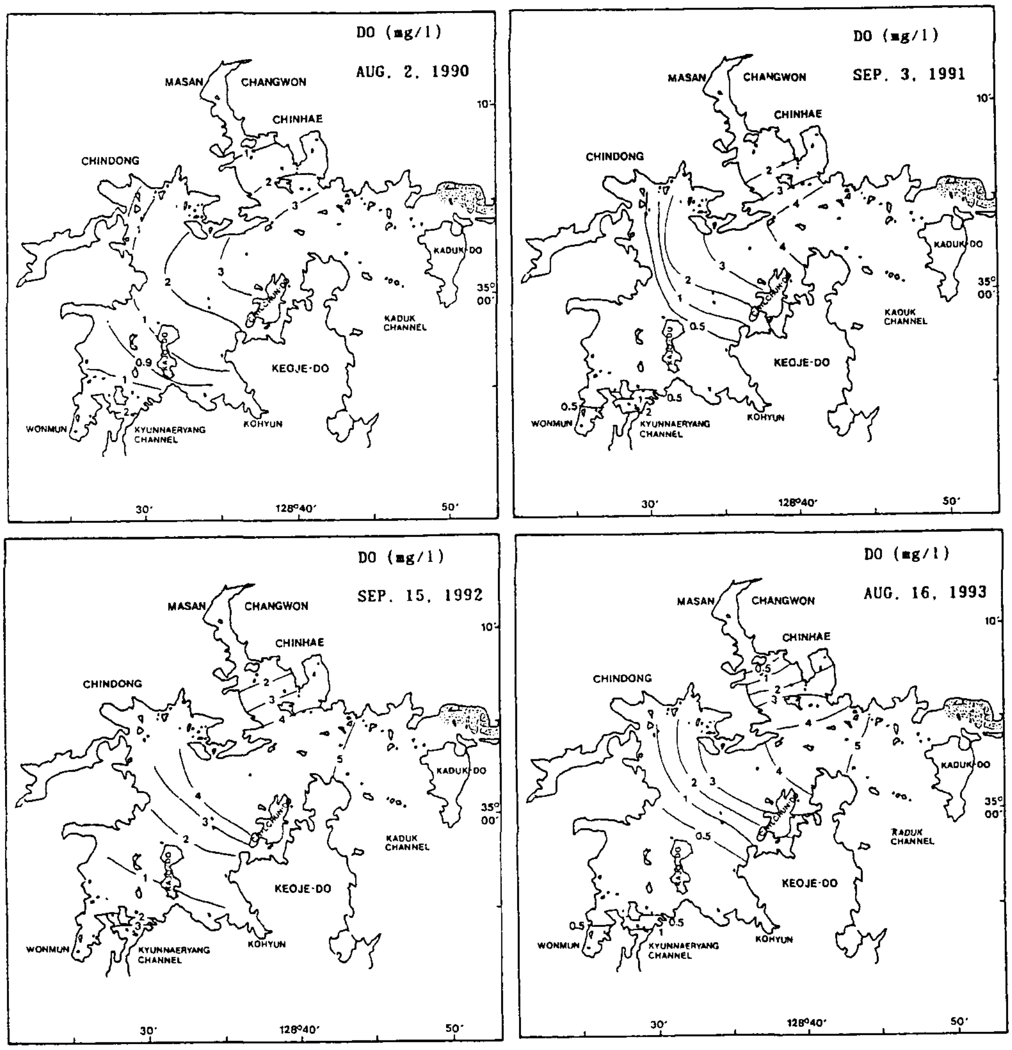

Fig. 9. Horizontal distributions of DO concentration at bottom in summer from 1990 to 1993.

channel of the bay having strong current (Kim *et al.*, 1994; Kim, 1994) and culturing facilities of low density were more than 3.5~4.0 mg/l. Consequently, the anoxic and hypoxic water masses in Masan Bay occur due to large amounts of industrial and domestic wastewater input and weak mixing, and also these water masses frequently occur in the western part of Chinhae Bay due to the weak current regimes and the increment of the oxygen consume in high density of culturing facilities.

The distributions of DO are strongly related to the stratification parameter, and DO concentrations at bottom become low with increasing the parameter. DO concentrations outside the front ($\log(H/U^3)=2.0\sim2.5$) are more than about 4.0 mg/l, whereas the concentrations inside the front are low. The concentrations in the mixed layer is generally higher than those in the strtified regime. The boundaries between stratified and well-mixed zones cause to the conspicuous changes of COD and DO concentrations, and also the distributions of phytoplankton and nutrients are strongly correlated with the frontal structures (Simpson and Hunter, 1974; Yuasa and Ueshima, 1992). To prevent the formation of the anoxia water masses and to reduce the damage of fisheries due to the water masses, the studies on the frontal structures and the effective countmeasures minimizing the water pollution such as the enhancement techniques of the water exchange are required.

5. SUMMARY AND CONCLUSIONS

In order to investigate the formation of a shallow water front and its relation to water quality distributions, field measurements of temperature, salinity, DO and COD in Chinhae Bay were carried out from 1990 to 1994, and the stratification parameter $\log(H/U^3)$ was computed.

It is shown from satellite imagery and hydrographic data that the shallow water front is formed near the northern Kaduk channel, and the parameter $\log(H/U^3)$ near the front is in a range of 2.0~2.5. The positions of the front seen in infrared image are consistent with observed frontal positions, and the observed results suggest a possibility that the front is presumably a tidal front. This report depends on observations in only summer and spring, in the furture detailed observations will be needed to clarify the dependency on river inflow, tidal range and current regime.

Measured COD concentrations in offshore region of the Chinhae Bay front are below 1.0~2.0 mg/l, whereas the concentrations in Masan Bay located in northern inside of the front are as high as 3.0~5.5 mg/l. COD concentrations decrease gradually from Masan Bay toward the offshore due to the dilution by strong water mixing.

Anoxic and hypoxic water masses at the bottom layer in summer occur in the western part of Chinhae Bay and in Masan Bay. The distributions of DO are strongly related to the stratification parameter, and DO concentrations become low with increasing the parameter. DO concentrations outside the front are more than about 4.0 mg/l, whereas the concentrations inside the front are low.

The shallow water front plays a significant role for material transport from coastal area to oceanic area, and the frontal region seems to be important physical and chemical boundaries. The frontal location and water quality distributions can vary with variations of tidal range and river inflow, and also correlate with the magnitude of current.

ACKNOWLEDGEMENTS

The author is grateful to Pil-Yong Lee, Jong-Soo Park and the researchers of NFRDA for their assistance during the field works.

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