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Oceanographic Studies Related to the Tidal Front in the Mid-Yellow Sea off Korea: Physical Aspects*

YOUNG HO SEUNG, JUNG HO CHUNG AND YONG CHUL PARK
Dept. of Oceanography, Inha University, Incheon 402-751 Korea

황해 중부의 조석전선과 연관된 해양학적 연구 : 물리적 특성*

승영호 · 정정호 · 박용철
인하대 해양학과

Observations by CTD castings, moored current meters and satellite imageries reveal some physical characteristics of the area around the tidal mixing front found in the mid-Yellow Sea off Korea. Tidal mixing is the greatest at the promontory of Taean Peninsula with a front around it. The front appears in April with the start of solar heating, becomes most clear in August and disappears in November with the start of surface cooling. In the north of the front, tidal fluctuations of temperature and salinity induced by tidal currents manifest the existence of the front. Differently from the usual tidal mixing front, the front in Kyunggi Bay is formed by presence of the water discharged from the Han River which meets the offshore water at the front. Near the surface cold center, vertically well-mixed zone extends to about 50 Km offshore from the coast. Further south, this structure is generally retained but with lesser degree of vertical mixing. Within the relatively well-mixed coastal zone, the fresh water discharged from the Kum River makes another salinity front of smaller extent. At some places around this salinity front, an upwelling-like feature is remarked.

CTD, 해류계, 인공위성 영상사진을 이용하여 황해 중부의 조석전선 주변역을 조사한 결과 몇 가지 물리적 특성을 알 수 있었다. 전선은 태안반도 끝 부분을 중심으로하여 4월 중에 태양열에 의한 해표면 가열과 함께 나타나기 시작하여 8월에 가장 뚜렷하며 11월에는 표층냉각과 함께 소멸한다. 전선의 북측에서는 전선을 가로지르는 조류에 의하여 수온 염분의 조석주기 변화가 나타남으로써 전선구조를 보여준다. 경기만에서 나타나는 전선은 통상의 조석전선과 달리 한강에서 유출된 담수와 외양수의 만남에 의하여 형성된다. 표층냉수의 중심에서는 조석혼합역이 연안으로부터 약 50 km 외양까지 분포한다. 전선의 남측에서도 전선의 구조는 비슷하나 전반적으로 혼합 정도가 약하게 나타난다. 이 연안 혼합역의 연안쪽에서는 금강에서 유출된 담수에 의하여 염분전선이 좁은 범위에서 형성된다. 이 염분전선 부근의 일부에서는 용승과 같은 현상이 관측되었다.

INTRODUCTION

In shallow region where tidal currents are strong, vertical mixing occurs and destroys the vertical stratification. In offshore region where tidal current is weak, the vertical stratification is retained. Between the two regions, a tidal front forms. Simpson and Hunter (1974) have performed extensive observations on the tidal front in the Irish Sea and, for the first time, given a physical explanation in terms of energy balance. The increase of potential energy by vertical mixing is the same as the work done by turbulence which again takes energy from tidal current. These authors have proposed the stratification parameter, difined as the water depth divided by

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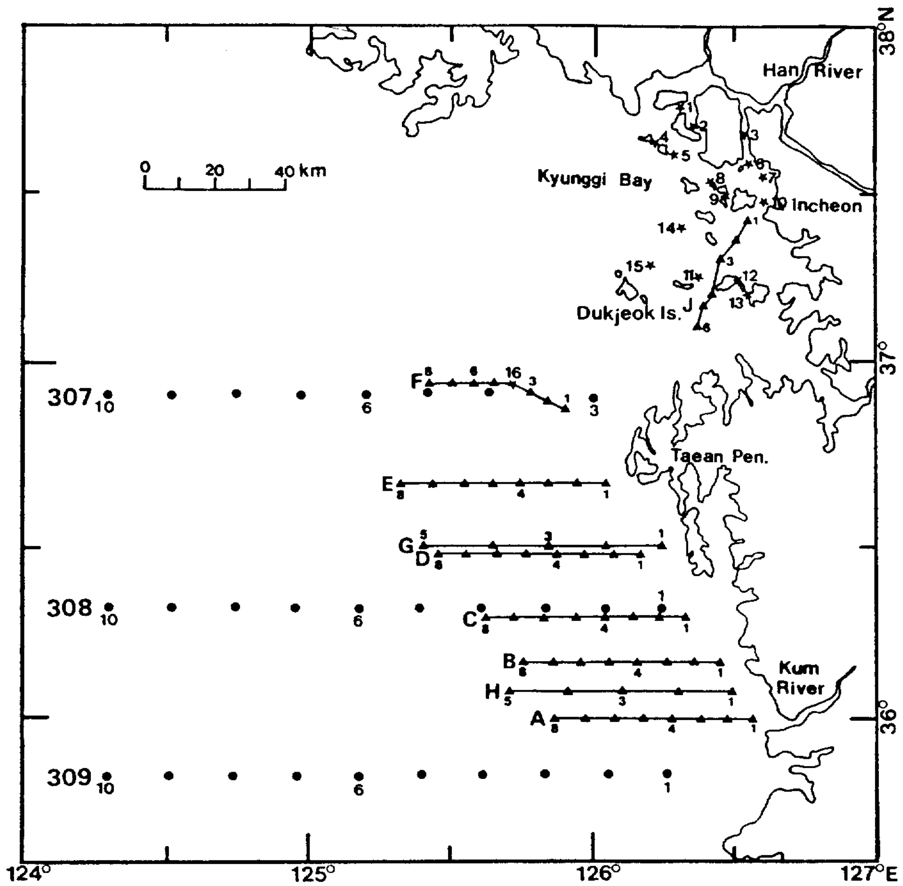

Fig. 1. The area surveyed. The stars numbered from 1 to 16 denote mooring stations. Hydrographic surveys are made along the lines A through J with stations marked by triangles and lines 307 through 309 with stations marked by circles. The latter lines are those undertaken by Fisheries Research and Development Agency.

the cubic of maximum tidal current speed, which measures the infensity of tidal mixing.

Since then many problems associated with the tidal front have been studied. Among others, van Heijst (1985) has illustrated how the shape of frontal structure is determined and estimated the mean current induced by frontal adjustment. The secondary circulation generated around the front has been estimated numerically by James (1984) and diagnostically by Garrett and Loder (1981). The effect of fresh water discharge on tidal mixing has been discussed by Czitrom *et al.* (1989) based on observations.

Tidal mixing fronts in the Yellow Sea have long been recognized along the Korean coast. Off the southern part of Korea, the frontal structure is documented by Lie (1989). Off the middle part of Korea, it has been observed by some oceanographers (Choi, 1984; Choo and Cho, 1984; Choi, 1987) and later, by Cho and Seung (1989). On the other hand, Seung(1987) applied the same method as that of van Heijst (1985) to estimate the mean current around the tidal front in the Yellow Sea.

To understand better the tidal front occurring in the mid-Yellow Sea off Korea, more observations have been performed during the period of 1987-1989, which include CTD castings and short-term moorings of current meter. The area

Table 1. Summary of observations

Line/Station	Period	Instruments	Measurements
A-E	Aug. 25-27, 1989	AST-3000 (CTD)	T,S
		Niskin sampler	water sampling
F,J	Sept. 2-4, 1987	AST-3000	T,S
G,H	June 24-25, 1988	AST-3000	T,S
	Aug. 10-12, 1988	AST-3000	T,S
307-309	Aug. 5-7, 1988	AST-300	T,S
1,2,10	May-Aug., 1987	DRCM-II	T,S,current
4,5,7,8	May-Sept., 1988	DRCM-II	T,S,current
9,11,12,13			
3,6	Aug., 1989	AST-3000	T,S,current
		DCM-2	
14,15	June, 1988	AST-300	T,S,current
		DCM-2	
16	Sept., 1987	AST-3000	T,S,current
		DCM-2	

covered by the survey extends from the Kyunggi Bay in the north down to the Kum River mouth in the south(Fig. 1). This paper thus describes physical aspects of the observations.

OBSERVATIONS

For convenience, the survey area is divided into two regions:one, the northern half and the other, the southern half with respec to Taean Peninsula where the tidal mixing is presumed to be the strongest(Fig. 1). In the northern half, extensive moorings of current meter, which measures temperature and salinity as well as current, were performed together with CTD castings. In this region, strong tidal currents crossing the tidal front (refer to Hydrographic Office, 1982 for tidal currents) will give rise to the tidal fluctuation of temperature and salinity thus reflecting the cross-frontal structure. In the southern half, the major interest is to understand the longshore variability of the frontal structure. For this purpose, extensive CTD castings were performed near the coast of this region.

Over the whole area, the CTD casting were performed along the cruise lines A through J (except for I) along with the lines 307,308 and 309 taken conventionally by Fisheries Research and Development Agency (Fig. 1). At each casting, the sensors of CTD detect temperature and salinity at every 2 m depth. The salinity values obtained by CTD are later found to be about 1‰ lower than those obtained by chemical titration. This systematic error is not considered serious because we are not interested in the absolute values but in relative difference in space and time. Moorings are performed at 16 stations (numbered from 1 to 16) using either direct reading (DCM-2) or direct recording (DRCM-II) current meters. The former (DCM-2) measures only current at the predetermined depth and the latter (DRCM-II) allows the vertical profiling of temperature, salinity and current by recording signals every two seconds. So, when using the former, the sensors of CTD are lowered at the same time to complement the vertical profiles of temperature and salinity. Both current meters are lowered from a moored vessel with mooring period greater than one semi-diurnal tidal cycle. These observations are summarized in Table 1. Since the individual observations spread over long period (from May to September), some seasonal differences are expected between them. However, we assume here that they represent statistically the summer season.

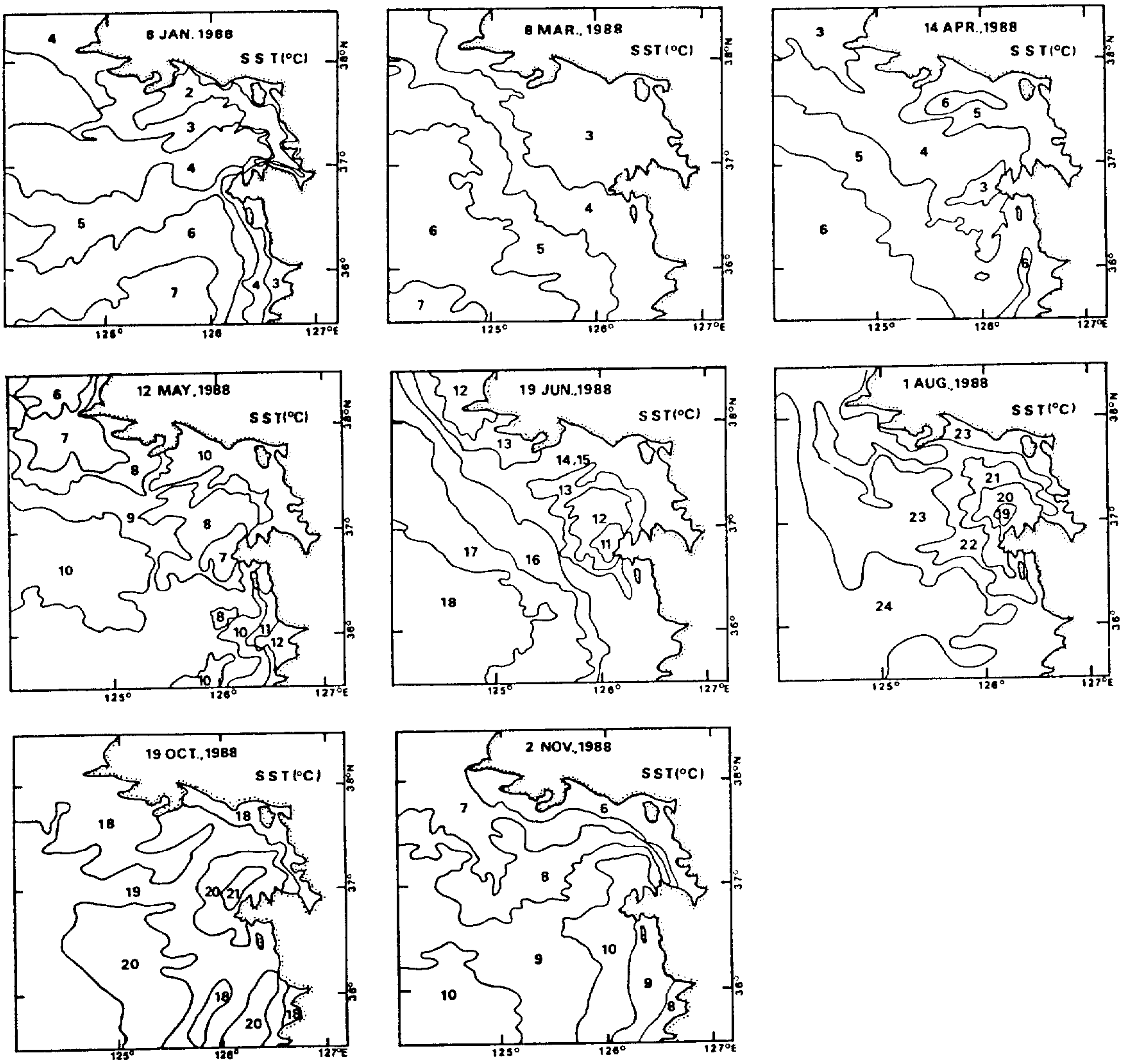

Fig. 2. The SST distributions obtained from the IR images of NOAA 9 and 10. Decimal numbers are supressed in temperature values.

GENERAL DESCRIPTION OF THE FRONT

A general idea of location and temporal change of the tidal front can be obtained by inspecting the SST distributions obtained from satellite imagery (Fig. 2). In January, the SST has a general trend of northward decrease. Superimposed on this, an onshore-offshore gradient is seen in coastal zone of limited width. By the end of winter(early March), the onshore-offshore gradient becomes more accentuated. The surface cold center begins to appear in April around the promontory of Taean Peninsula. It intesifies until August then weakens and finally disappears in November. The cold center coincides with the places of maximum dissipation of tidal kinetic energy (Choi, 1980) and minimum stratification parameter (Cho and Seung, 1989) defined by Simpson and Hunter (1974).

The temperature sections (for salinity refer to Chung, 1990) taken along the lines 307,308 and

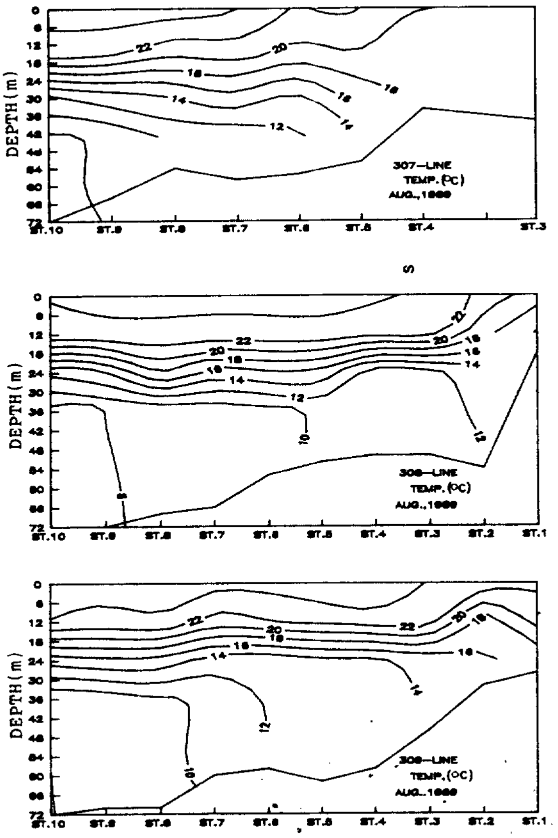

Fig. 3. Temperature sections along the lines 307 through 309.

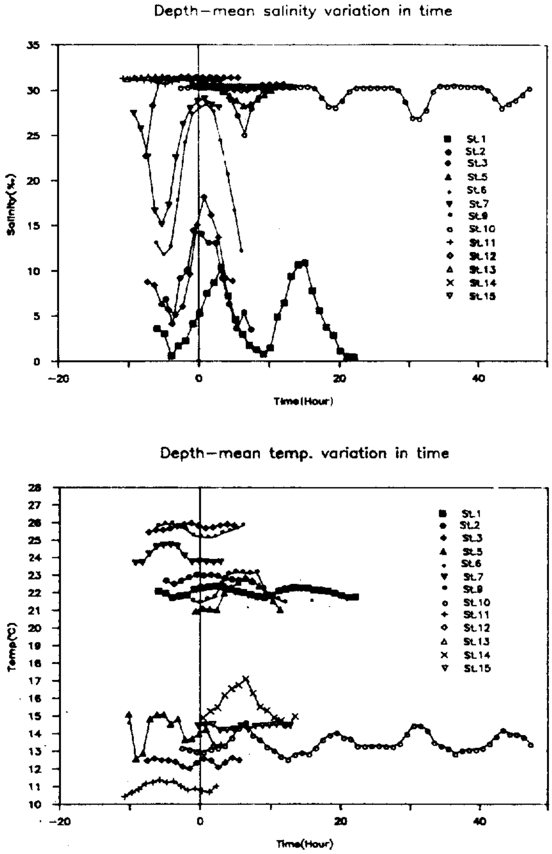

Fig. 4. Time variations of vertically averaged temperature and salinity at mooring stations 1 through 15. Time is measured with respect to high tide at Incheon.

309 in August (Fig. 3) show the general structure of the tidal front. The line 307 passes through the surface cold center. Therefore, the well mixed zone develops extending from the coast to about 50 Km offshore. Further offshore, vertical stratification exists but is weaker than those in the south. To the south (lines 308 and 309), most part of the section is vertically well stratified except near the coast where the stratification becomes weaker, thus making weak fronts there. Though different in strength, the shape of these fronts are similar to those observed elsewhere (Lie, 1989; van Aken *et al.*, 1986 etc.).

NORTHERN HALF

Tidal fluctuations of temperature and salinity are expected in an area where strong tidal current crosses the front. These fluctuations are recorded at mooring stations 1 through 16. Stations 1 through 15 are located on the inshore side of front and station 16, on the offshore side (Fig. 1). For the purpose of comparison, a hydrographic section is made on each side. The section F runs offshore from the edge of front passing through the mooring station 16. The section J runs inshore from the edge of front passing through some of mooring stations (Fig. 1). Descriptions about these moorings are referred to Table 1.

The results abtained from moorings 1 through 15 are summarized in Fig. 4. Temperature and salinity are vertically averaged because st-

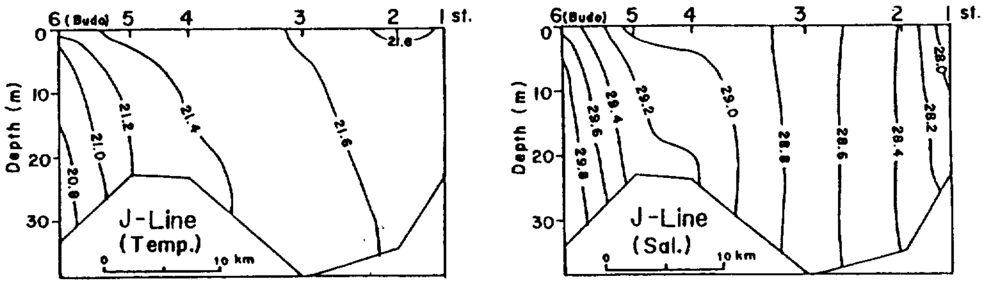

Fig. 5. Temperature(in deg.c.) and salinity(in ppt) sections along the line J.

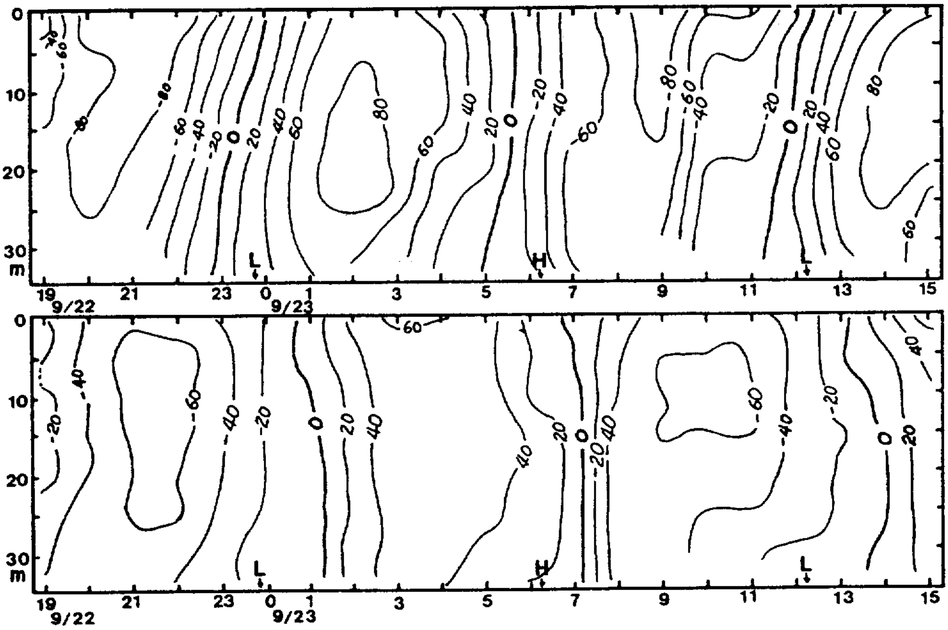

Fig. 6. Time-depth diagrams of eastward(upper panel) and northward(lower panel) components of tidal current (in cm/sec) measured at mooring station 16. H and L mean high and low tides at nearly Dukjeok Is.

rong tidal mixing in this area renders no significant vertical variation (Kim, 1990). Neverthless, the distribution of tidally mean temperature and salinity shows that the waters in this region undergo a transition, namely a front, from cold and saline to warm and fresh as one goes from offshore toward the Han River mouth. A part of this feature is also seen from temprature and salinity distributions along the section J(Fig. 5). As ascertained by Cho and Seung (1989), the front shown here is due to the presence of the water discharged from the Han River which meets the offshore water near the front.

At each mooring station, tidal fluctuation presents. Though there are some exceptions, the fluctuation is such that cold and saline (warm and fresh) water appears near high(low) tide. The tidal fluctuation of temperature and salinity at one place is due to the advection by tidal current of different waters. Tidal currents in this region are generally in the directions of local tidal channels(c.f., Hydrographic Office, 1982). Exceptions to this occur where topography is complicated due to the presence of small islands and shallow areas(Kim, 1990). Apart from these exceptions, flood(ebb) current flows toward

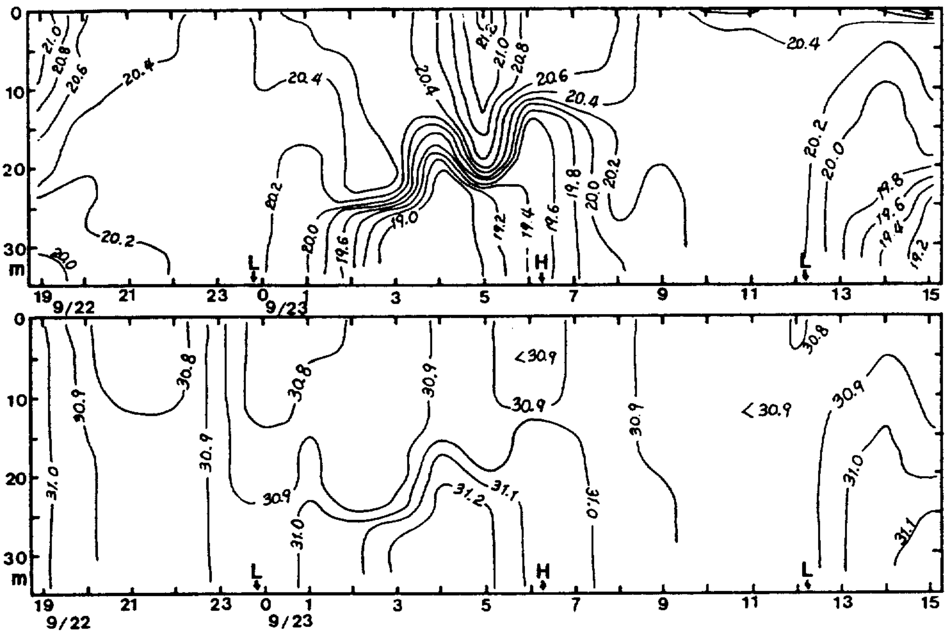

Fig. 7. Time-depth diagrams of temperature(upper panel, in deg.c.) and salinity(lower panel, in ppt) at mooring station 16.

(away from) the Han River mouth from (toward) offshore until high(low) tide approaches (Kim, 1990; Hydrographic Office, 1982), i.e., current and sea level are in quadrature each other.

At mooring station 16, tidal current is slightly oscillatory with major axis oriented in the northeast-southweat(Fig. 6). As in the inshore side of the front, high(how) tide occurs after the end of northeastward(southwestward) flood (ebb) current. Therefore, near the high(low) tide, the stratified(well-mixed) water is advected to its maximum onshore(offshore) position(Fig. 7). This feature is compatible with the temperature and salinity distributions along the line F(Fig. 8). More quantitatively, assume that the tidal current is a simple harmonic function with maximum spped of about 0.7 m/sec (c.f., Fig. 6). Tidal excursion is then about 10 Km. Upon referring to Fig. 8, this distance is enough to create the change in vertical stratification, such as shown in Fig. 7, within a tidal period.

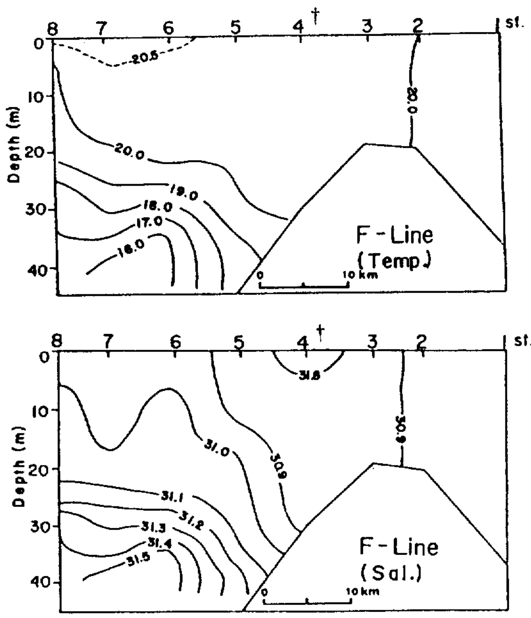

Fig. 8. Temperature(in deg.c.) and salinity(in ppt) sections along the line F. The position marked by † is the mooring point.

SOUTHERN HALF

Fig. 9 presents the results (only for salinity) of

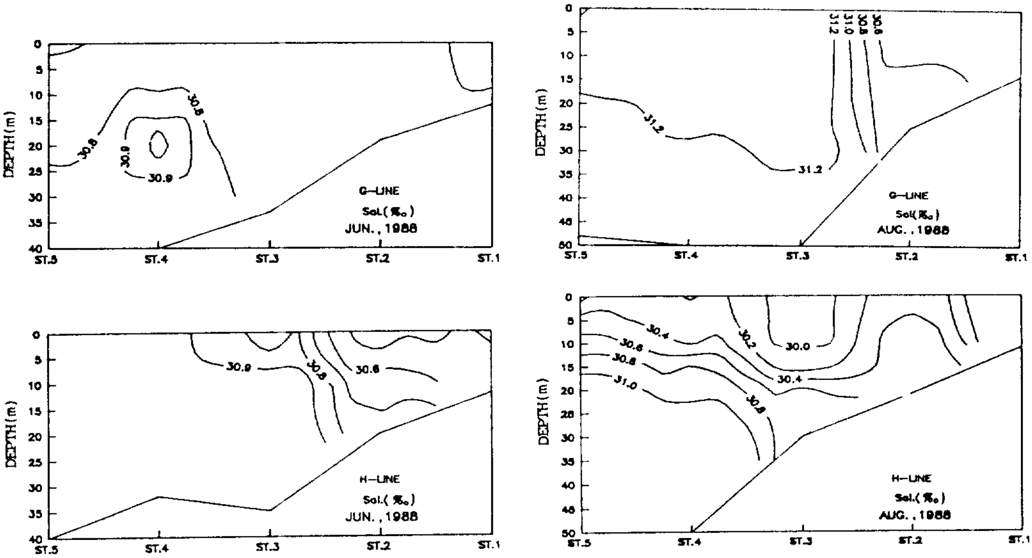

Fig. 9. Salinity sections along the lines G and H obtained in June and August, 1988.

hydrographic surveys made along the lines G and H both in June and August, 1988. The two periods of surveys are separated by the rainy season between them. As a result, effect of fresh water from the Kum River appears more in August than in June near the coast. On the contrary, salinity is higher in August than in June further offshore. It is thought that the offshore area, being not much affected by the coastal fresh water, is under the effect of some oceanic conditions which are not detectable here.

The contrast between fresh and saline waters diminishes as one goes from the south (section H) to the north(section G) away from the Kum River mouth. This may be due to the fact that the fresh water undergoes a vertical mixing while extending northward. The presenc of the salinity front observed in section G in August is a special example in that the vertical mixing is much stronger than horizontal mixing. These observations were made during the spring tide period and hence the vertical mixing seems to have been largely enhanced.

In 1989, this area was surveyed again with more detailed horizontal resolution. The survey period is just after the rainy season and the effect of fresh water is expected large. The horizontal distribution of salinity (Fig. 10) shows that the effect of fresh water can be traced to about 10 Km offshore and 50 Km to the north from the river mouth in upper 10 m. Assuming that the fresh water is from the Kum River and considering the right-hand propagation of the coastal trapped waves induced by the buoyancy input, the fresh water discharged from the river mouth is thought to extend northward. However, we don't know here what happens in the south of the river mouth.

The north-south variation of temperature and salinity structures is shown in Fig. 11. The prominent feature is the change of fresh water character as it extends northward along the coast. Just at the river mouth(section A), the discharged fresh water conserves well its property. As noticed earlier, the fresh water loses its character as it mixes with surrounding waters while extending northward. Over the whole area, the stratified and mixed regimes are not quite distinct. Generally, station 5 or 6 may be taken as a transition of the two regimes. Within the area covered by observations, no significant longshore change of structure is remarked ex-

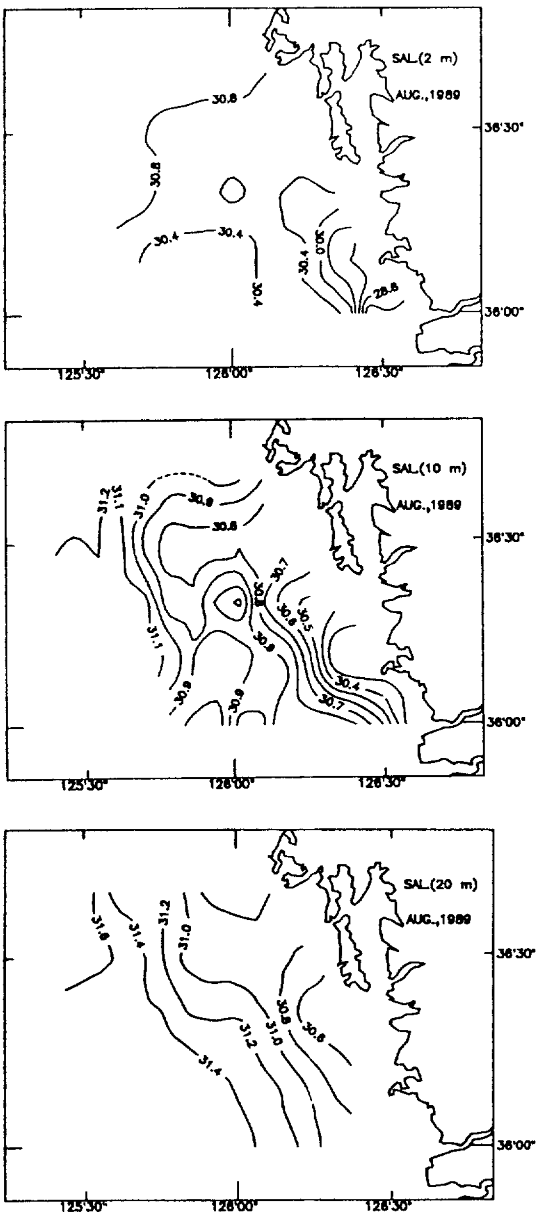

Fig. 10. Horizontal distributions of salinity(in ppt) at depeths 2m, 10m and 20m obtained in August, 1989.

cept for the change due to the presence of fresh water.

An interesting point is that, near stations 4 especially in line B and C, there is an uprising of isotherms and isohalines. To examine this, we used dissolved organic matters having fluorescence character as tracers. The sampled water at each sampling point contains the dissolved organic matters which have their own fluorescence characters. These matters, when excited at a certain wave length, emit fluorescent lights at various emission wave lengths. For each sample, fluorescence intensities are thus measured as functions of both emission wave lengths (from 260 nm 460 nm with interval 20 nm) and excitation wave lengths(from 220 nm to 420 nm with interval 20 nm) using a spectrofluorophotometer. In this way, 85 intensity values are obtained at each sampling point. These values can be compared between two sampling points with one-to-one correspondence at the same wave lengths of both emission and excitation.

Fig. 12 shows the distribution of resulting correlation coefficients in the sections B and C. In this analysis, samples obtained in upper 10 m are excluded because they are easily contaminated by other materials active in fluorescence always present at the surface or by photosynthesis etc. The correlations are measured with respect to the deepest sampling point located at the offshroe edge of each section. The distribution at each section shows an anisotropy. The line joining the local maxima passes through the places where the uprisings of isotherms and isohalines are remarked (Fig. 11). Therefore, it is very probable that this is an upwelling. This upwelling may be caused by the large onshore-offshore gradient of density induced by the presence of fresh water at the coast. Presently, our knowledge about this is quite limited and more efforts are needed to understand it well.

CONCLUDING REMARKS

The major results obtained are summarized as follows:Tidal mixing is the greatest at the promontory of Taean Peninsula with fronts around it. The front appears in April, becomes most clear in August and disappears in November. In the north of the front, tidal fluctuations of temperature and salinity are induced by tidal

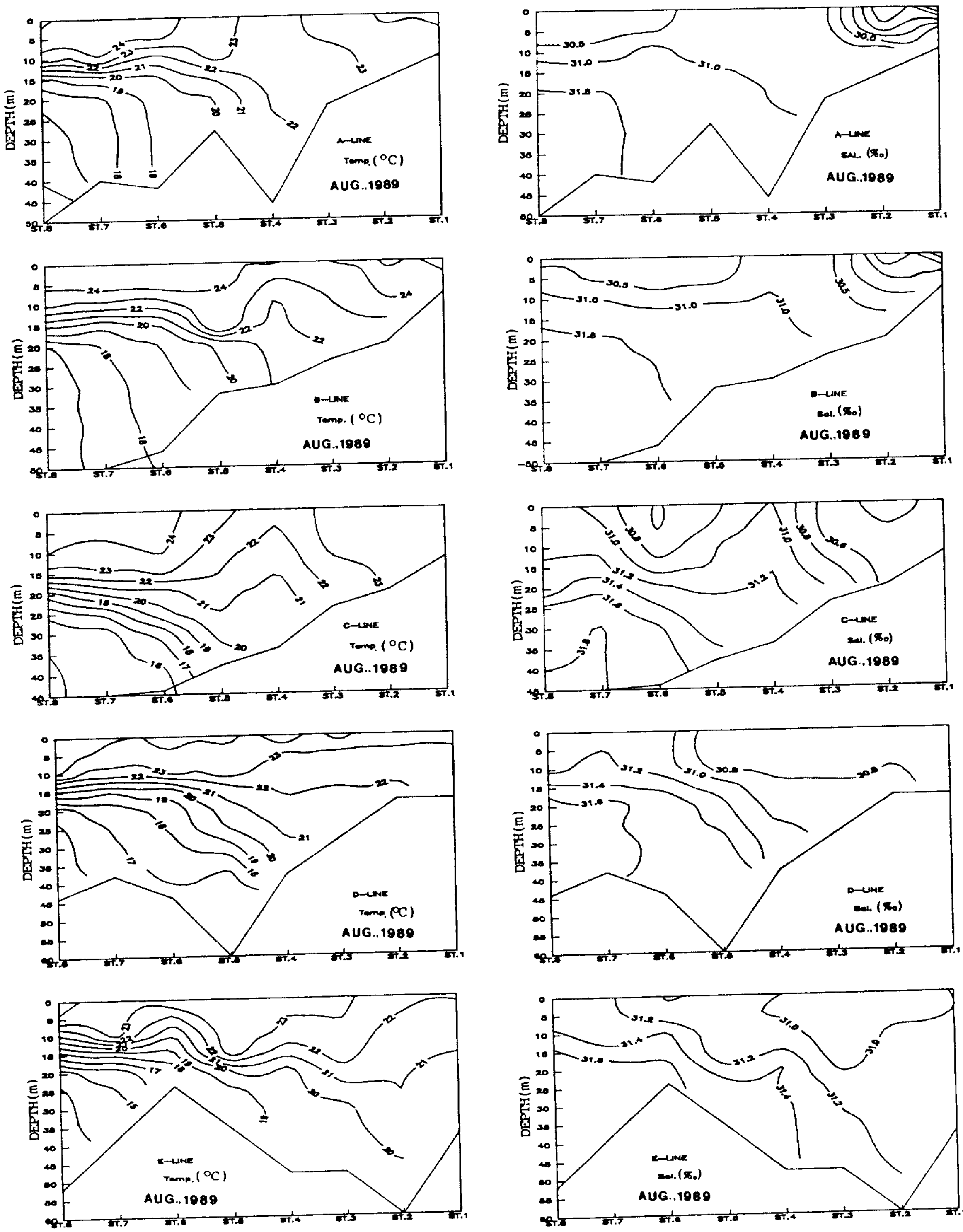

Fig. 11. Temperature and salinity sections along the lines A through E.

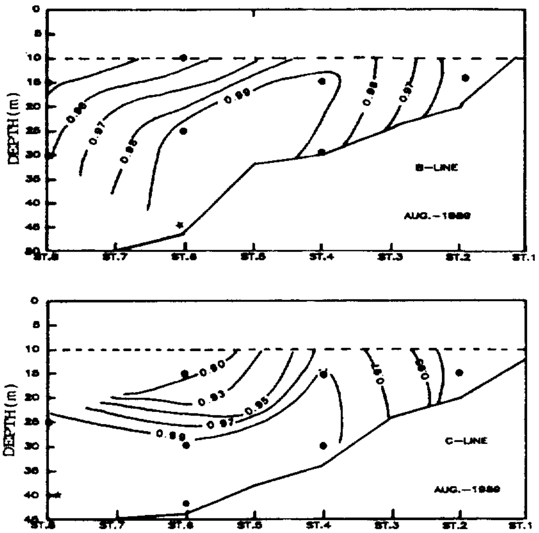

Fig. 12. Contour plots of correlation coefficients of fluorescence intensity among sampling points. In each section, the corelation is measured with respect to the point marked by a star. Dots represent the sampling points; upper 10m is excluded from considerations. Coefficients larger than 0.25 are significant at the 1% level. For more details, see text.

currents. The front in Kyunggi Bay is formed by presence of the water discharged from the Han River which meets the offshore water at the front. Near the surface cold center, vertically well-mixed zone extends to about 50 Km offshore from the coast. Further south, this structure is generally retained but with lasser degree of vertical mixing. Within the relatively well-mixed coastal zone, the fresh water discharged from the Kum River makes another salinity front of smaller extent. At some places around this salinity front, an upwelling-like feature is remarked of which the formation mechanism is not yet well understood.

Several questions arise as to how the longshore scales are determined in this regime of strong tidal mixing. The surface cold center is well localized. Dynamically, any longshore density gradient created at the coast cannot stay there but extends alongshore as a form of propagating internal Kelvin waves(e.g., Ikeda, 1984). The fresh water discharged from the Kum River extends northward but the extension is largely limited too. It may be quite interesting to investigate how the effect of local vertical mixing, probably in combination with bottom friction, restricts the longshore extension of both the surface cold center and the fresh water discharged from the Kum River.

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