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Characteristics of Physical Properties in the Ulleung Basin

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울릉분지 내의 물리적 특성

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A layer of salinity-minimum which characterizes the East Sea Intermediate Water (ESIW) is found at an approximate depth of 200 m in three CTD sections taken in the Ulleung Basin on May 17~21, 1988. Properties at this layer vary in ranges of 1.1℃<T<2.7℃ and 34.02‰<S<34.11‰ except at stations near the east coast of Korea where temperature is as high as 4.39℃ and salinity is as low as 33.992‰. To be distinguished from the ESIW the East Sea Proper Water (ESPW) may be characterized by temperature less than 1℃. Salinity at the salinity-minimum layer and 500db increases southward in general, implying that the cold waters, both ESIW and ESPW, formed in the northern basin of the East Sea are spreading southward below the permanent thermocline in the basin. Hydrography in the Ulleung Basin is very similar to that in the Alboran Sea, suggesting a possibility of an anticyclonic circulation in the Ulleung Basin which is controlled strongly by the shoaling bottom.

동해 중층수의 특성인 염분 최소층이 1988년 5월 17~21일에 울릉분지에서 관측된 CTD 단면의 약 200 m 수심에서 발견되었다. 이 층의 수온은 1.1~2.7℃ 그리고 염분은 34.02~34.11‰의 범위 내에서 변하나, 한국 동해안에 연한 관측점에는 예외적으로 4.39℃의 고온과 33.992‰의 저염이 있다. 동해 고유수는 수온이 1℃ 미만의 특성으로 동해 중층수와 구별된다. 염분 최소층과 500 db의 수심에서 염분은 남쪽으로 증가한다. 이것은 동해 북부 분지에서 형성된 동해 중층수와 동해 고유수가 울릉분지 내에서 수온약층 밑으로 퍼져감을 의미한다. 울릉분지 내의 물리적 성질 분포는 알보란해와 매우 유사하여, 울릉분지 내에 시계방향의 순환이 해저 지형에 의하여 형성될 가능성을 제시한다.

INTRODUCTION

About 86% of the sea water in the East Sea (Sea of Japan) is colder than 1℃ (Yasui, 1967), which has been known as the East Sea Proper Water (ESPW) after Uda (1934). Kim and Chung (1984) recently found a distinct layer of salinity-minimum and dissolved-oxygen maximum between 100 and 300 m above the ESPW in the southwestern region of the East sea. As a similar water south of the polar front in the central part of the East Sea (Kajiura, 1958) was called "another water" in the past, Kim and Chung (1984) named the East Sea Intermediate Water (ESIW) for the water of this layer.

It is certain that the ESIW and ESPW in the

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Ulleung Basin are not formed locally and brought into the basin, since the sea surface temperature does not fall below 8℃ in the area. The cold water in the basin are rich of dissolved oxygen (Kim and Chung, 1984), which indicates that these waters are renewed rapidly. The mean residence time of the bottom water (below 2,000 m approximately) estimated by Gamo and Horibe (1983) is about 300 years, which is smaller than that of the average deep water throughout the world ocean (Broecker and Peng, 1982). We may speculate that the residence time for the cold waters above 2,000 m would be substantially smaller then 300 years.

Despite its abundance and importance in the circulation of the East Sea, however, detailed observations of the cold waters are scarce to understand their formation and subsequent movement. Recent observation of currents flowing southeastward along the east coast of Korea with a mean speed of 3 cm/sec at 620 m and 790 m (Lie *et al.*, 1989) is the first evidence of the movement of the cold waters in the Ulleung Basin. Previously Nanniti, Akamatsu and Yasuoka (1966) observed a southwestward current of 1.5 cm/sec at 800 m over 4 days by tracking a float, deployed about 400 km north of Ulleung-Do.

Most researches on the circulation in the East Sea in the past were primarily concerned with the Tsushima Current which flows in the upper 100 m. Particularly the branching of the Tsushima Current has been the major subject of investigations ever since it was suggested by Uda (1934). In analysis of historical data and numerical models (Kawabe, 1982a and b; Yoon, 1982a, b and c) the branching has been considered as a permanent phenomena. However, Kim and Chung (1984) found the presence of anomalously cold waters off the east coast of Korea in the fall of 1981. Kim and Legeckis (1986) confirmed the absence of the branching in the spring of 1981 also. This unusual phenomena makes clear that the movement of the cold waters should not be neglected in relation to the branching.

In 1988 a three-year, multi-disciplinary study was started in order to investigate the characteristics of the cold waters and their circulation in the Ulleung Basin. Movements of deep waters in large ocean basins are usually subjected to topography and it is important to know the detailed bathymetry in and around the Ulleung Basin (Fig. 1). The Ulleung Basin is connected to the Japan Basin to north and it is most likely that the cold waters flow into the Ulleung Basin through the deep channel between Ulleung-Do (Island) and Dok-Do (Island). An indirect evidence of strong bottom current is the incised bottom profile between two island (Chough, 1983; Fig. 5.1). As the deep water below the permanent thermocline is nearly homogeneous which support little vertical shear, the bottom current also implies a significant motion of the deep water column.

A CTD survey was conducted in the Ulleung Basin on May 17-21, 1988. Our survey aimed at a few specific objectives. Firstly, we occupied stations between Ulleung-Do and Dok-Do in order to find any indication of the motions of the cold waters between the two islands. Secondly, we used a high-resolution CTD profiler. The precision and accuracy of CTD data are much better than most hydrographic data collected from bottle casts in the past. The continuous profiles give high resolutions which enable us to look into vertical structures in details. Thirdly, water samples are collected for various biological and chemical analysis including stable isotope ratios such as δO^{18} vs δO^{16} to test a circulation model in the Ulleung Basin. Results of these analysis will be published separately later.

In this paper we present results of the analysis of CTD data and suggest a circulation model which is consistent with the observed hydrographic structure.

DATA

Because of limited ship time it was necessary to predetermine a few sections which may be representative to describe characteristics of waters flowing in and out of the Ulleung Basin. Therefore, 24 CTD stations were completed on May 17-21, 1988 in three sections designated as U1, U2 and U3 as shown in Fig. 2. Stations 1-4 of U1

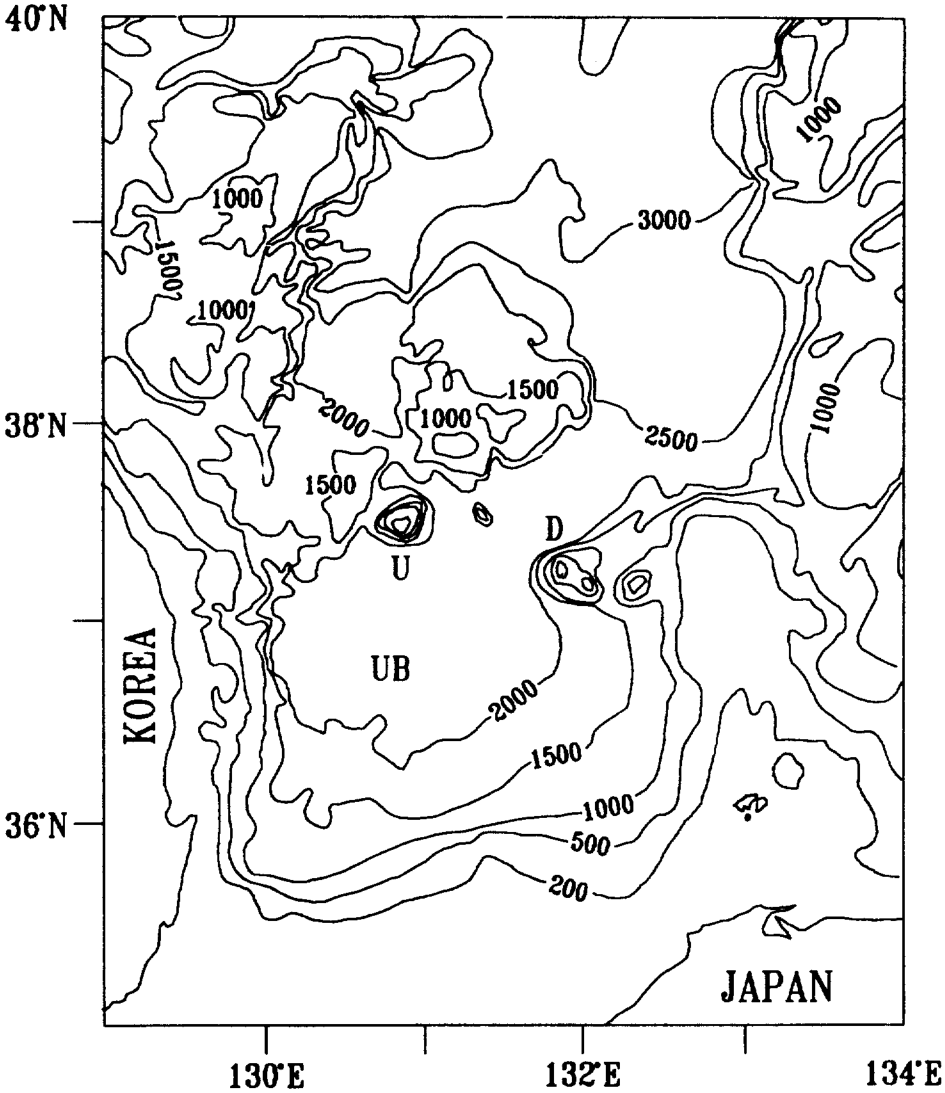


Fig. 1. Bathymetry of the East Sea. U, D and UB denote Ulleung-Do, Dok-Do and the Ulleung Basin. Depths are in meters.

section were taken between Ulleung-Do and Dok-Do, and Stations 7-13 are located west of Ulleung-Do toward the east coast of Korea. U2 section runs north-south across the Ulleung Basin and U3 section may be useful to identify water masses entering the East Sea through the Korea Strait.

At each station Smart CTD of EG&G Marine Instruments was lowered to a nominal depth of 500 m at a speed of 60 m/min approximately, taking five samples of temperature, conductivity and pressure in one second, which give a vertical resolution of about 20 cm. Minor corrections were applied to the data, following post cruise calibration of all sensors performed by the manufacturer. Final data for analysis were obtained by averaging temperature and salinity data over two decibars.

Soon after the completion of the above sections the Korea Oceano Research and Development Institute (KORDI, 1989) took CTD sections around the western part of U1 section. This survey was conducted on May 28-31, 1988 along Line 105 and 104 shown in Fig. 2, which have been

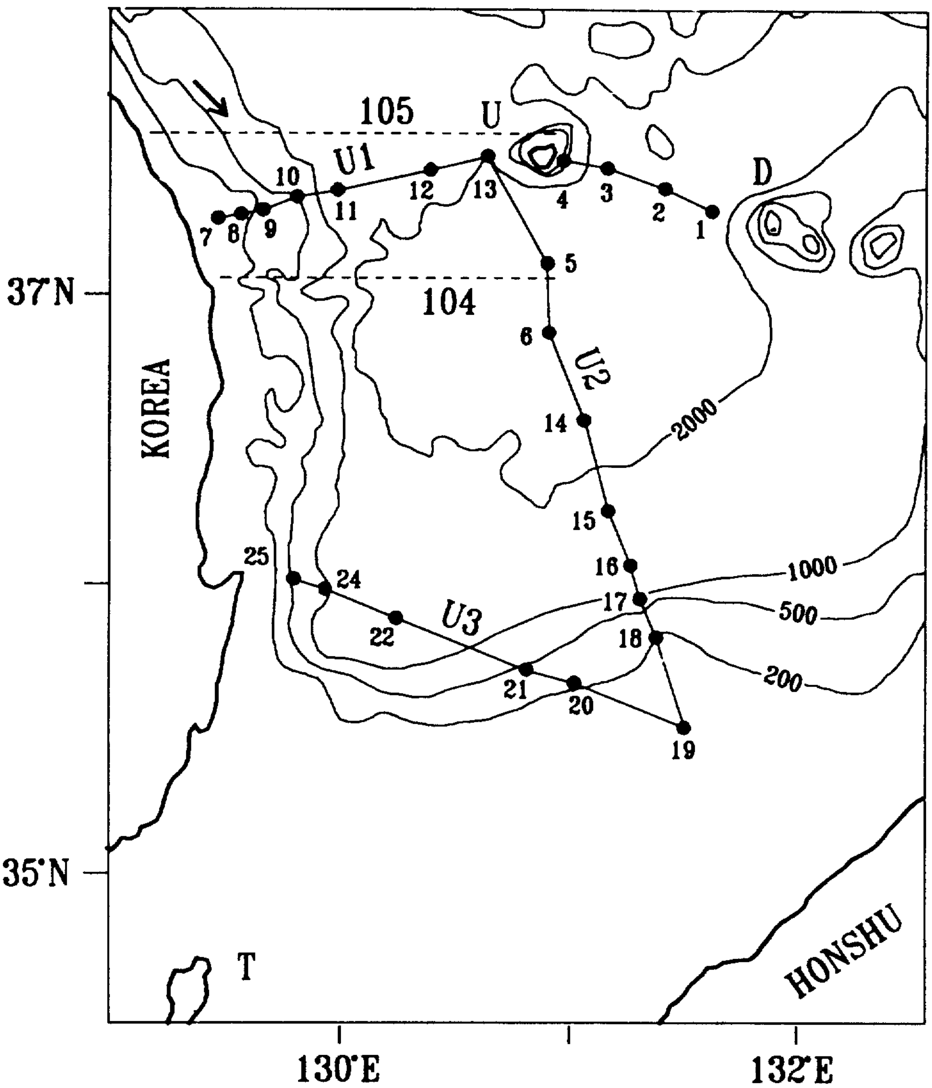


Fig. 2. CTD (U1, U2, U3) sections taken on May 17~21, 1988. Line 105 and 104 were occuppied on May 28~31, 1988 by KORDI (1989). An arrow indicates a mean current of 3 cm/sec measured by Lie *et al.* (1989).

designated by the National Fisheries Research and Development Agency of Korea (NFRDA). Both hydrographic lines were reoccupied later as part of bimonthy routine surveys by the NFRDA (1990) on June 10-11, 1988. This series of surveys over 20 days provide a rare opportunity to examine the hydrographic structure in detail and its temporal evolution.

In order to complement the limited data we also utilize the image of the sea surface temperature (SST), obtained by processing NOAA-9 data at the Research Institute of Oceanography, Seoul National University. The SST was estimated by using a multi-channel analysis method of the IR data from NOAA-9 satellite.

WATER MASSES

The T-S diagram of all CTD data from Sections U1, U2 and U3 (Fig. 3) reveal three distinct water types; the salinity maximum at about 34.5‰, the salinity minimum at 34.01‰ or less and the rela-

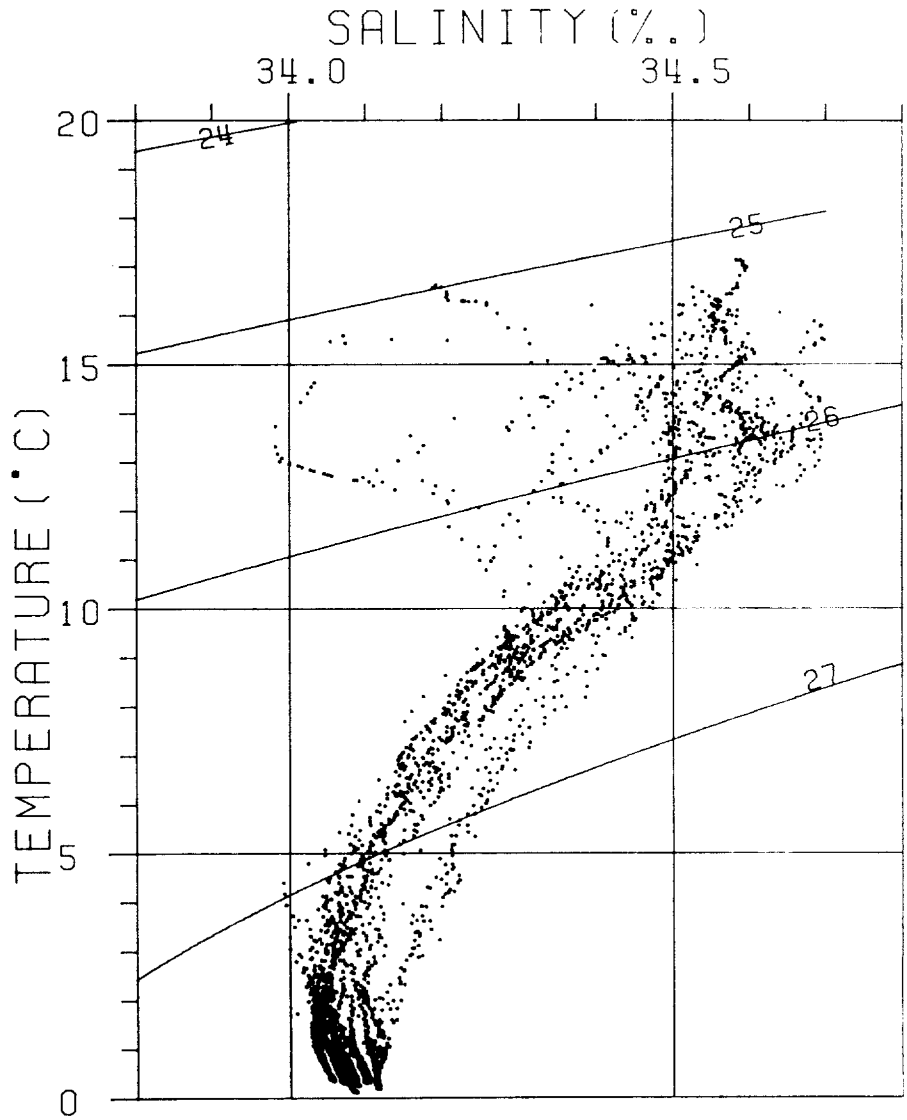


Fig. 3. Temperature-salinity diagram for all CTD data from U1, U2 and U3 Section.

tively high salinity of the coldest water of about 0.5℃. Temperature and density of the salinity-maximum water are T=13~14℃ and σ_t=26.0 respectively. For the salinity-minimum water T=1~3℃ and σ_t=27.2 approximately.

It is interesting to compare this T-S relationship with another one found in the southwestern part of the Ulleung Basin in September, 1981 by Kim and Chung (1984). As the previous data were taken right after summer, surface temperature is as high as 25℃ and salinlty is as low as 31.8‰. But the presence of the salinity maximum and minimum are the same as the present data and the extreme salinities are almost the same.

It is well known that the saline water in the upper layer of the East Sea is brought in through Korea Strait (Ichiye, 1982). Frequently, therefore, the Tsushima Current is traced by the subsurface salinity core (Kolpack, 1982). In the Korea Strait the temperature is above 10℃ in winter and increases in time except for the presence of cold waters near the bottom. Therefore, the isotherm of 10℃ serves as a reference temperature for warm waters of the Tsushima Current, corresponding to S=34.3‰ and σ_t=26.5 approximately. It will be seen in vertical sections that isopleths of these particular temperature and salinity indeed make a boundary between the upper and lower (deep) water structures.

Kim and Chung (1984) has pointed out that the salinity minimum would be very useful as a tracer to investigate the subsurface circulation. Since the precision of our salinity data is 0.001‰, the present data confirm that the salinity minimum is real and widespread in the Ulleung Basin. The high precision also makes it possible to examine the variation of the salinity minimum station by station.

VERTICAL STRUCTURE

Sections of temperature and salinity are examined in order of U3, U2 and U1.

U3 Section

The highest temperature of this section(Fig. 4a) was observed at the surface of Station 19, which is the southern-most station located on the continental shelf off Honshu, Japan. In fact this station is warmer than other stations at any depth in the entire water column. Together with a core of the salinity maximum (S>34.6‰) at mid-depth the high temperature indicates that the Tsushima Current passes this station (Fig. 4b). Since the temperature near the bottom is as high as 10℃, it is most likely that the entire column of Station 19 moves with the Tsushima Current. This current may include the upper 50 m of Station 20, as the high salinity core was also found at this depth.

It is interesting to observe another core of the salinity maximum on the Korean side of this section(Fig. 4b). At Stations 24 and 25 the salinity at 40 m is as high as that found at Stations 20 and 19. The core on the Korean side is presumably an indication of the East Korean Warm Current (EKWC), which has been known as a branch of the Tsushima Current. The double cores of salinity seem to indicate occurrence of the branching of the Tsushima Current. An image of the sea surface temperature (SST) from NOAA-9 satellite, which is shown later, is consistent with the branching.

It is worth noticing a shallow halocline near the surface at Station 25. As there is no source of fresh water except for Nakdong River near Pusan, we think that the halocline is a kind of river front which is advected by the EKWC.

Below 100 m it is most important to find a layer of salinity minimum at depths of 150~250 m except Station 19 (Fig. 4b). This layer was first observed near the east coast of Korea by Kim and Kim (1983) and since then its presence was reported further offshore as far east as 130° 40′E in this area (Kim and Chung, 1984; Kim, Lie and Chu, 1990). Present study extends it to 131° E. In August, 1986 Kim *et al.* (1990) found this layer as deep as 160~180 m, but in our survey it is at a deeper depth. Because the surveys were conducted in different years, the difference may represent a long-term variability.

The lowest salinity in Section U3 is found at Station 22, where the minimum layer is the deepest of all stations. Salinity of this layer tends to be higher as the layer rises to both ends of the section. Above the layer of the salinity minimum lies the permanent thermocline which can be defined by isotherms of 3~8℃. Much like the salinity-minimum layer the permanent thermocline is most deep at Station 22 and rises toward the continental slope and shelf.

An interesting question is why the permanent thermocline and isohalines below 100 m are bowl-shaped. Such hydrographic structure immediately implies geostrophic motions. However, any motion in this section is part of the circulation in Ulleung Basin and it is more appropriate to discuss the circulation after an in-depth investigation of all three sections.

U2 Section

The subsurface thermal boundary associated with isotherms of 11~14℃ between Station 6 and 14 divided the upper 100 m into two regions; a warm region south of Station 14 and a cold region

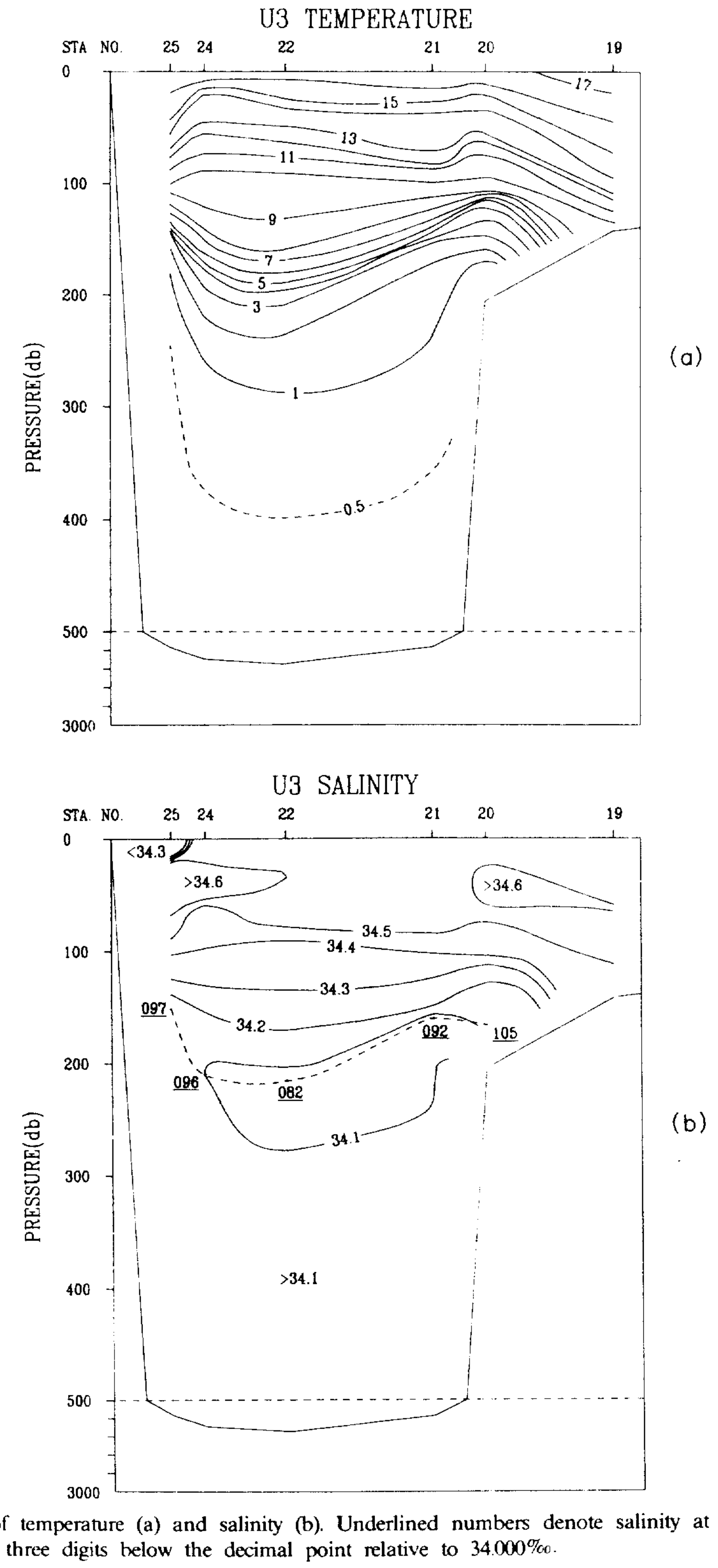
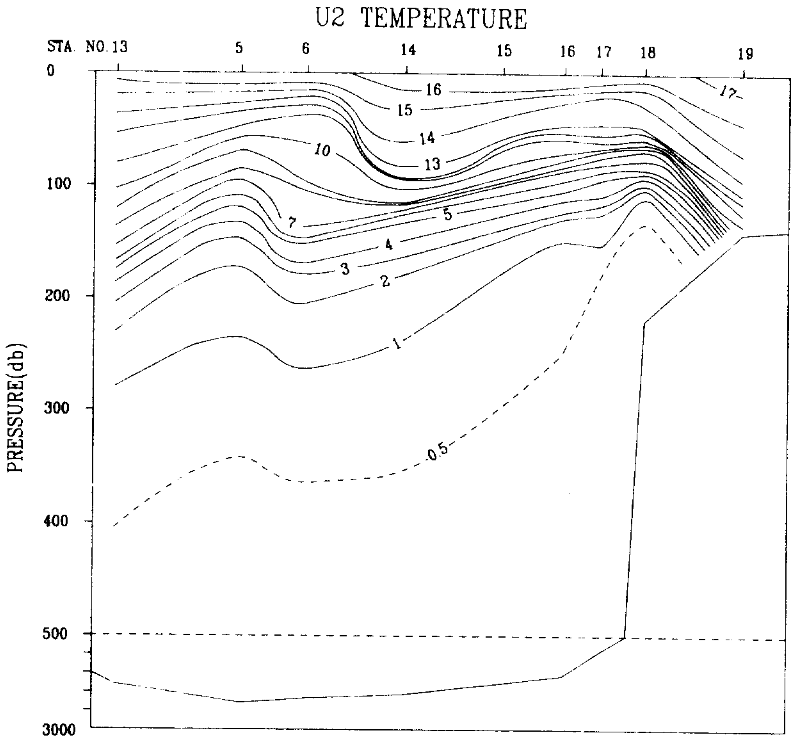
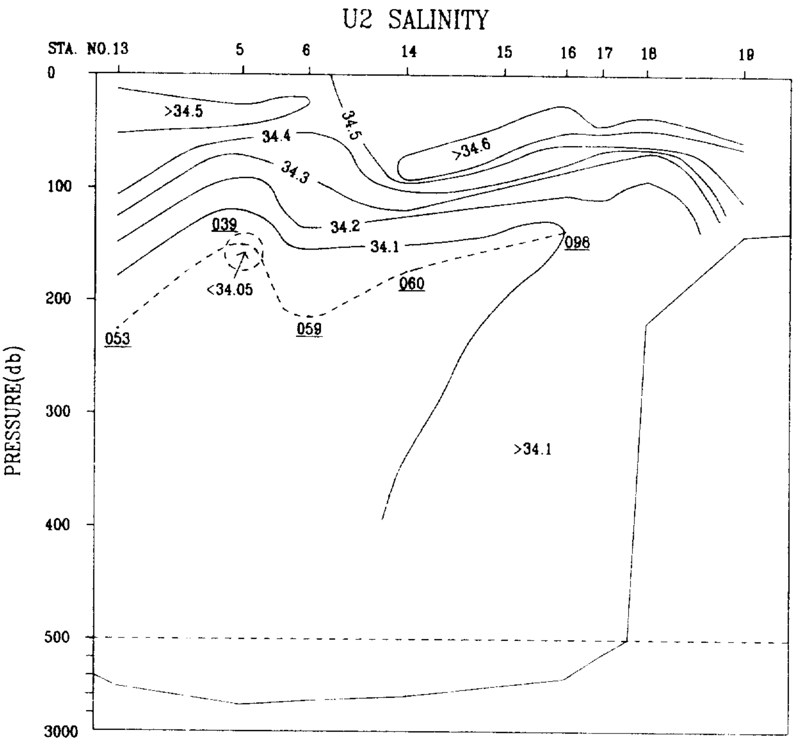


Fig. 4. U3 Section of temperature (a) and salinity (b). Underlined numbers denote salinity at the layer of salinity minimum in three digits below the decimal point relative to 34.000‰.



(a)



(b)

Fig. 5. Same as Fig. 4 except for U2 Section.

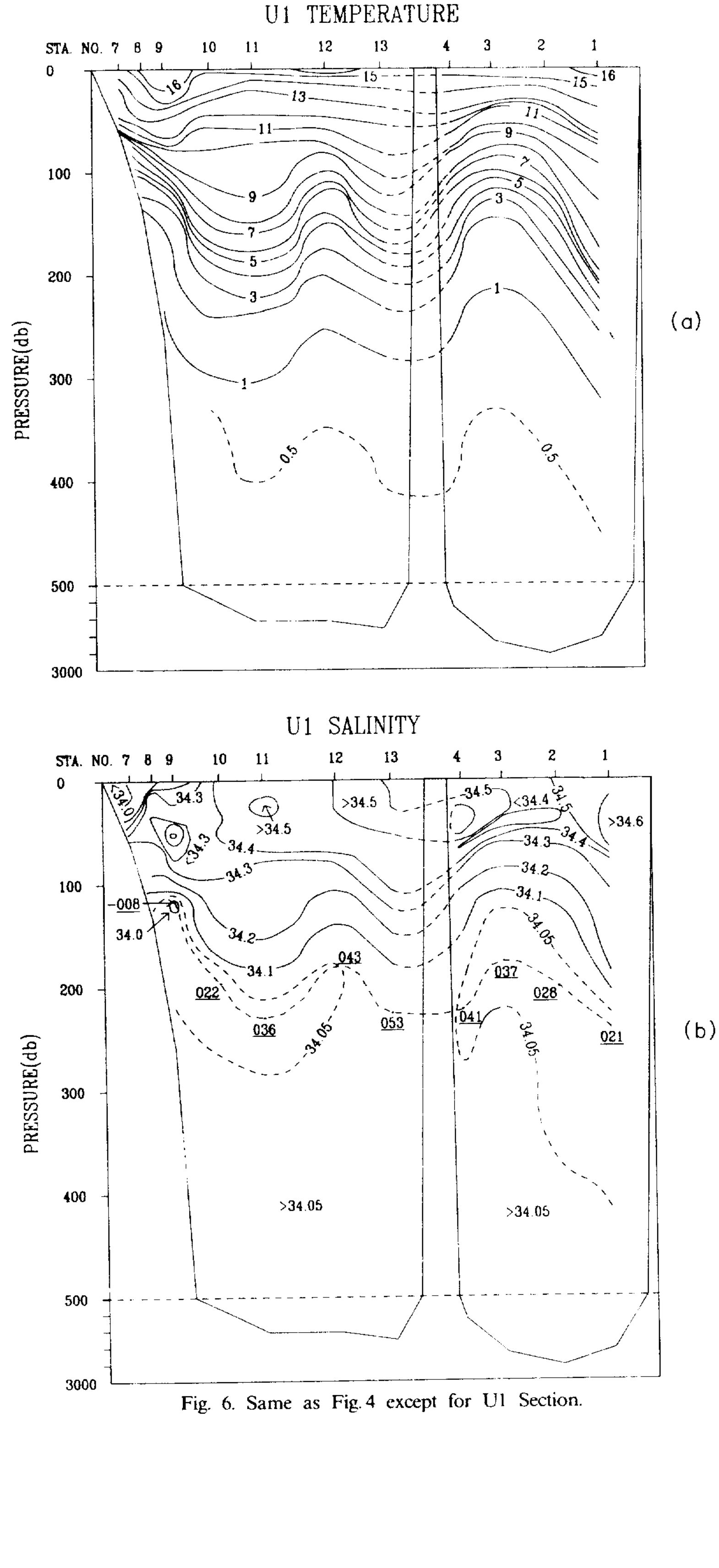


Fig. 6. Same as Fig. 4 except for U1 Section.

north of Station 6 (Fig. 5a). In the warm region a core of salinity maximum (S>34.6‰) is located at mid-depth which varies somewhat from station to station (Fig. 5b). From the warm and saline character it is not too difficult to imagine that the warm region is under the influence of the Tsushima Current. Then where is the main stream of the Tsushima Current? It has been known that the Tsushima Current flows on the continental shelf off Honshu (Kawabe, 1982a). The large horizontal change of temperature and salinity between Station 18 and 19 on the shelf probably supports a strong geostrophic shear of the Tsushima Current. An estimate of speed is about 50 cm/sec at the surface due east relative to the bottom, which is as large a current as ever been observed in this area.

Cross-stream structure between Stations 18 and 19 may be explained in terms of a geostrophic adjustment. Approximating the vertical density field as two-layers with density difference $\Delta\rho$ and depths of each layer H_1 and H_2 (subscripts 1 and 2 refer the upper and lower layers), we find the local radius of Rossby deformation is about 8 km for $\Delta\rho=10^{-3}$ g/cm^3, $H_1=H_2=100$ m, $g=9.8$ m/sec^2, and $f=8.6\times10^{-5}$ sec^{-1}. The horizontal scale of the density variation between Stations 18 and 19 is about 20 km, twice the radius of deformation. This means that the density structure between Station 18 and 19 has been adjusted geostrophically as the light (warm) water of the Tsushima Current meets the resident dense (cold) water on the continental shalf.

The salinity-minimum layer is also found in this section except Stations 17, 18 and 19 (Fig. 5b). The depth of this layer is about 200 m and tends to rise to south. The salinity of this layer is lowest at Station 5 and gradually increases southward. Since the temperature at the salinity minimum layer is about 2℃, waters of this property must have reached the Ulleung Basin originating from north of the basin. We can use the salinity minimum as a tracer to follow the movement of the cold waters in the East Sea as suggested by Kim and Chung (1984).

It is most conspicuous that isotherms of 1~7℃ rise southward from Station 6 towards Station 18. The salinity section in these temperature range varies essentially in the same way as the temperature section and so does the density section which is not shown here. This hydrographic structure must put some constraints on the movement of the cold waters because these isotherms make the upper boundary of the deep cold waters. First of all it is informative to compare the horizontal scale of the temperature (or density) field with the radius of deformation. In the basin the local radius of deformation is 8 km for two layers with $H_1=100$ m, $H_2=2{,}000$ m and the same values of other variables as already indicated. The distance between Station 6 and 18 is about 120 km, which is on order of magnitude larger than the deformation scale. It is clear that the rise of the permanent thermocline is not a phenomenon of a geostrophic eddy-scale, but of a basin scale.

Another basin-scale variation of importance is the change of bottom topography. Simple calculation can show how important the topographic control on the movement of the cold waters is in Ulleung Basin. Neglecting external forcing and friction, we may assume that quasi-geostrophic motions of an uniform density for the deep water conserve potential vorticity.

$$\frac{f}{H}=\frac{f_o}{H_o}\left(1+\frac{\beta}{f_o}y-\frac{\alpha}{H_o}y\right)=\text{const.}$$

Here β is the beta-effect, α is the slope of the bottom and H_o is the mean depth. For local values of $\beta/f_o=10^{-9}$ cm^{-1}, $\alpha/H_o=2.5\times10^{-9}\sim2.5\times10^{-8}$ cm^{-1} we find that the topographic beta effect is substantially or order of magnitude larger than the planetary beta-effect. Therefore, quasi-geostrophic motions tend to follow isobaths (Pedlosky, 1987). We expect that motions will be in or out of U2 section, since the section is almost perpendicular to isobaths. Any motion on this section constitutes part of the circulation in the Ulleung Basin, which is discussed later.

U1 Section

The surface temperature in U1 Section is about 15℃ at most stations except for Station 1 and 9

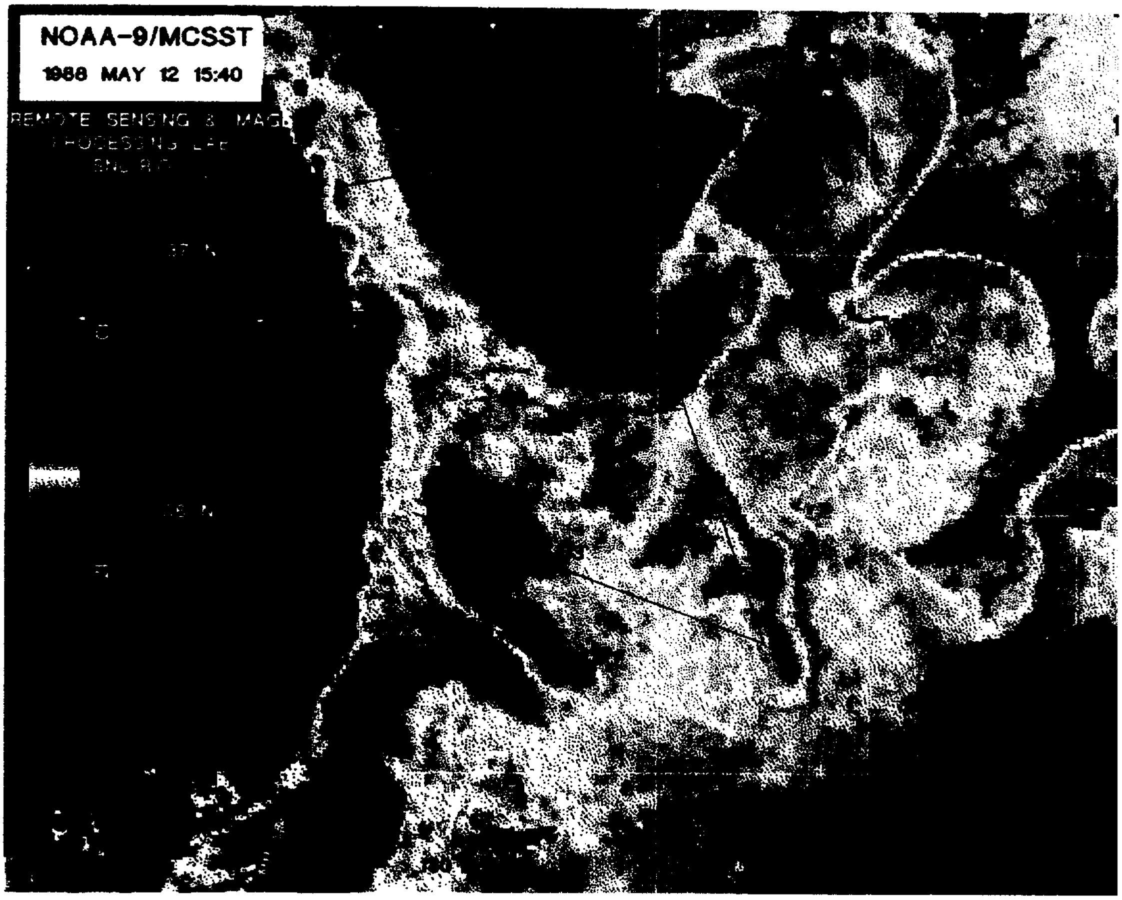


Fig. 7. Satellite image of sea surface temperature on May 12, 1988.

where it exceeds 16℃ (Fig. 6a). The highest temperature at Station 1 is a surface expression of the relatively warm water present at all depths. The same temperature at Station 9 makes the core of the warm lens in the upper 50 m. Temperatures higher than 16℃ are also found at the surface of the entire Section U3 and the southern stations of Section U2. This indicates a possibilty that the highest temperatures at Stations 1 and 9 are related to the Tsushima Current.

A cloud-free image of sea surface temperature (SST) taken on May 12, 1988 is illustrative of the flow pattern of the Tsushima Current (Fig. 7). As the image is made with NOAA-9 data taken about a week before the completion of U1 Section, the SST from the satellite shown in Fig. 7 is in general lower than that of the section by 1~2℃. Having found similar differences between a hydrographic survey and a satellite image in this area in April 1981, Kim and Legeckis (1986) attributed the difference to the vernal warming. Therefore we will be concerned with the difference in temperature only.

The satellite image also shows a possibility that the high temperature ($T>16$℃) at the surface of Station 1 is part of an eddy with a much larger horizontal scale. Around Dok-Do a warm eddy is present in the image, which is 100 km long and 60 km wide approximately. This eddy is not an isolated feature, but one of three warm eddies which are connected meridionally to the warm current flowing along Honshu. The high salinity ($S>34.6$‰) in the upper 60 m at Station 1 indicates that this water originates from the Tsushima Cur-

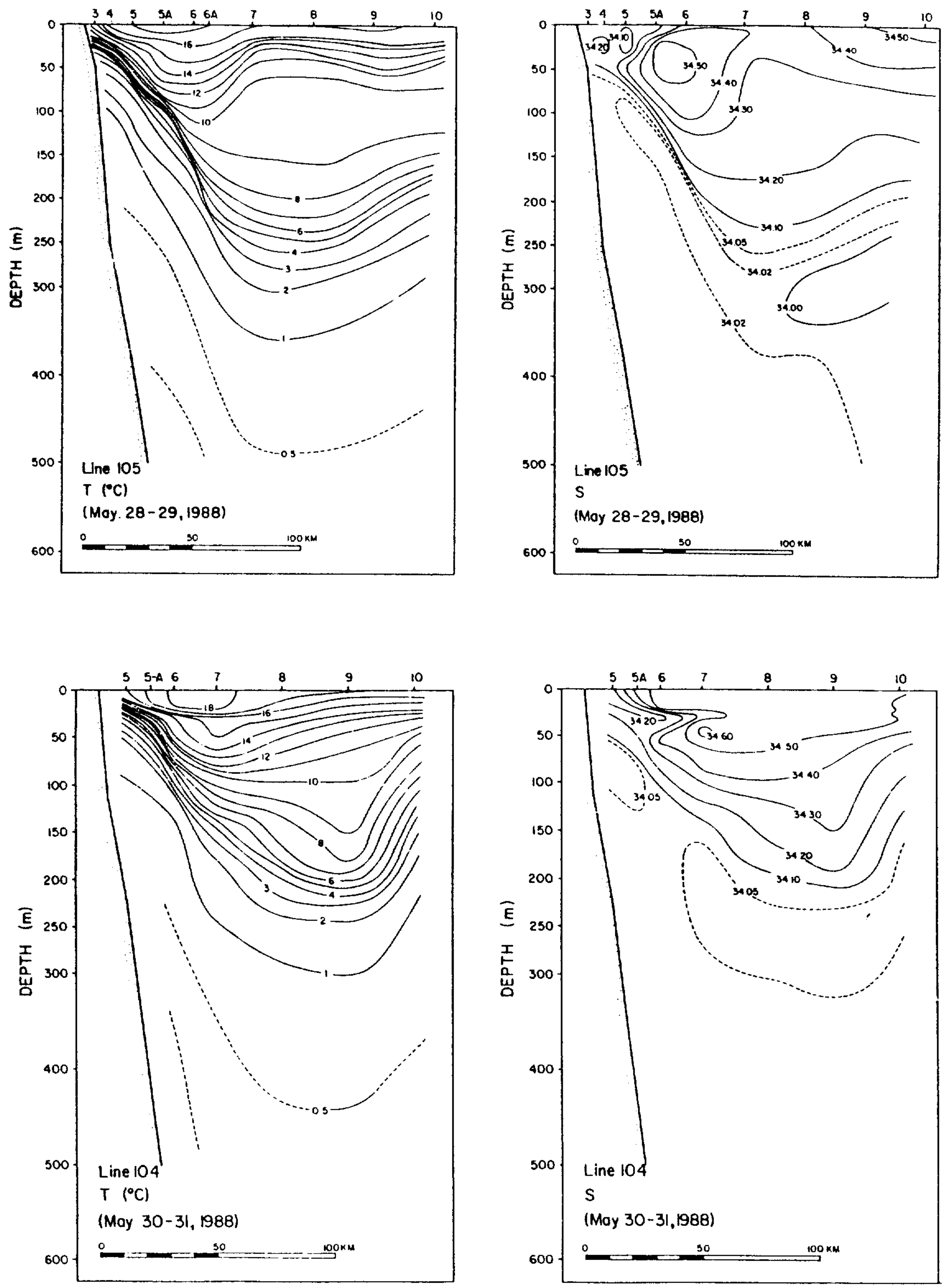


Fig. 8. Sections along Line 105 and 104 by KORDI (1989)

rent.

Associated with the cold waters below the permanent thermocline the salinity-minimum layer is present at all stations in U1 Section except at Station 7 and 8 which are located on the narrow shelf off the east coast of Korea (Fig. 6b). Depth of this layer is as shallow as 116 m at Staion 9 and as deep as 240 m at Station 1. About 10 days after this observation Kim *et al.* (1990) also found this layer in a section taken along 37° 33'N (Line 105) west of Ulleng-Do. Another section along 37° 03'N (Line 104) shows this layer too (KORDI, 1989). Locations of these lines are shown in Fig. 2.

Since the latter two sections were separated only 30 nautical miles apart and taken north and south of U1 Section, comparison of these two section (Fig. 8) with U1 Section is very useful. The SST of Line 105 and 104 is higher than that of U1 Section by 1℃ or 2℃ respectively which must be an effect of vernal warming as indicated already. The lens-like temperature structure near Korea in U1 Section are noted on both lines.

There are also some changes occurred in deep waters. Near the Korean coast isotherms of 1~8℃ are much shallower in Line 105 and 104 compared with U1 Section. For example 1℃ is 100 m deep in Line 105 and 104 where as it is 230 m deep in U1 Section. The isotherm of 5° becomes as shallow as 25~50 m from 100 m in 10 days. Another significant change is apparent near Ulleung-Do. The dome structure of the permanent thermocline centered at Station 12 in U1 Section is completely absent in the temperature section of Line 105. Instead an extensive layer of isostad is found between the permanent thermocline and the warm layer in the upper 50 m of Line 105. The temperature of the isostad is about 9.4℃. This change occurred at the same time as the permanent thermocline deepened about 50 m near Ulleung-Do. The deepening can be found by comparing Station 13 of U1 Section with Station 9 of Line 105, which are only 10 km apart. It is important to note that despite significant changes in deep hydrography the two independent CTD surveys confirm the layer of the salinity minimum between the east coast of Korea and Ulleung-Do.

U1 Section is particularly revealing the presence of the salinity minimum layer east of Ulleung-Do as shown is Fig. 6b. This is the first observation of this layer between Ulleung-Do and Dok-Do. The salinity-minimum waters found in the central and southern part of the Ulleung Basin may flow into this region not only along the east coast of Korea but also through the channel between Ulleung-Do and Dok-Do which is a natural passage connecting the Ulleung Basin to the Japan Basin.

Close examination of salinity at the minimum layer in U1 Secton is worthy in relation to the origin of this water. The lowest salinity of 33.992‰ is observed at Station 9 near the Korean coast. Then it increases monotonically offshore and becomes as large as 34.053‰ at Station 13 near Ulleung-Do. At Station 4 which is on the other side of Ulleung-Do the minimum salinity is 34.041‰, decreasing gradually to 34.021‰ at Station 1 near Dok-Do. The range of variation is 0.061‰, which is as large as that at 200 m across the Ulleung Basin and Japan Basin over 1,000 km reported by Sudo (1986, Fig. 5b). Therefore the variation in U1 Section is very significant. From the same point of view its southward increase from 34.039‰ at Station 5 to 34.098‰ at Station 16 in U2 Section and its high values in U3 Section should be looked into together with U1 Section.

The extremely low salinity found at mid-depth of Station 9 is similar to what Kim and Kim (1983) showed previously along the east coast of Korea. This is probably an indication of the North Korean Cold Current flowing southward underneath the EKWC, as suggested by Kim and Kim (1983).

The second lowest salinity of U1 Section is found at Station 1, which is located at the other end of the section. It is interesting to compare the two salinity minima. The minimum at Station 9 is warmer (T=4.39℃) and less saline (S=33.992‰) than that (T=2.65℃, S=34.021‰) at Station 1. The T-S diagram for the salinity minima from all stations (Fig. 9a) shows that Station 9 are very different in its physical properties from not only Station 1 but also the rest of stations. Temperature and salinity of the salinity-minimum water vary

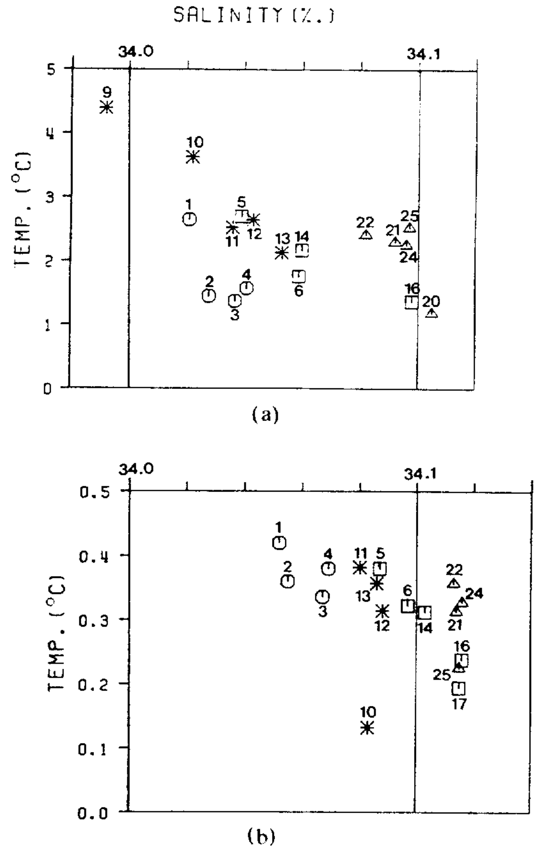


Fig. 9. Temperature and salinity at the layer of salinity minimum (a) and 500db (b). Numbers denote stations and symbols indicate locations of stations; ✳: west of Ulleung-Do on U1 Section, ⊕: east of Ulleung-Do on U1 Section, ⊞: U2 Section, △: U3 Section.

in a range of 1.2~2.7℃ and 34.02~34.11‰ except Station 9 and 10. At Station 9 salinity is as low as 33.992‰ and temperature is as high as 4.39℃. Station 10 is a midpoint between Station 9 and other stations.

Although the physical properties of Station 9 and 10 are out of ranges in which most of the salinity-minimum waters are found, they are not exceptional. Temperature as high as 4~5℃ for salinity less than 34.00‰ was shown previously (Kim and Kim, 1983; Fig. 3 and 4). However, it is clear in Fig. 9a that the high temperature is not common. The properties of waters associated with the North Korean Cold Current (NKCC) seems to be different from the East Sea Intermediate Water, which Kim and Chung (1984) characterized with temperature in 1~3℃. Temperature of the ESIW in the central part of the East Sea is 1~6℃ or 1~4℃ according to Miyazaki (1953) and Kaziura (1958). It will be interesting to look for a possibility of two modes of waters for the layer of salinity minimum.

DISCUSSION AND A CONCEPTUAL CIRCULATION

Precise measurements of temperature and salinity by using CTD make it possible to delineate the characteristics of the ESIW and the ESPW. Since the salinity-minimum is the main property of the ESIW (Miyazaki, 1953; Kim and Chung, 1984), the most conservative way to define the ESPW is to avoid any possibility to include the range of the salinity-minimum layer. Therefore the ESPW may be characterized to be colder than 1℃ (Fig. 9a and b). The ESPW as having temperature below 2℃ (Sudo, 1986) may not be adequate in parts of the East Sea. In the T-S diagram (Fig. 2) salinity increases as temperature decrease below 1℃, but the increment of salinity with depth at each station is only 0.02~0.04‰. This is substantially smaller than its horizontal variation of 0.06~0.10‰ in deep waters, which is evident in Figs. 9a and 9b. Salinity itself is not adequate to make distinction between the ESIW and the ESPW. The overlap between Fig. 9a and 9b in the ranges of salinity variation demonstrate clearly this point.

It is noticed that the salinity of the minimum layer is low in the northern section and tends to increase south (Fig. 9a). This implies that the waters of this property, identified as the ESIW, are brought into the basin from north. The ESIW is probably formed at the polar front parallel to 40° N as suggested Miyazaki (1953) and Kajiura (1958). Meridional Section (Moriyazu, 1972; Maizura Marine Observatory, 1985; Sudo, 1986) show subduction of this water below the warm waters at the polar front. It is interesting that salinity at 500 db also increases southward in Fig. 9b. This is an indirect evidence that the ESPW is formed in the northern basin of the East sea and brought into the Ulleung Basin. As presented in the introduction, the high content of the dissolved oxygen below the permanent thermocline indicates a rapid renewal of the both ESIW and ESPW. The incised bottom between Ulleung-Do and Dok-Do is a result of strong bottom currents, which must extend vertically because of the earth rotation. Incorporating these circumstantial evidence with the present CTD data makes a strong case that the deep channel between Ulleung-Do and Dok-Do is probably the major passage of the cold waters entering the Ulleung Basin. Shallow plateaus north and northwest of Ulleung-Do (Fig. 1) do not allow free movements of cold waters which are subject to the topographic control.

The most visible effect of topography is the upwelling, which is reflected in the relatively shallow thermocline and the salinity-minimum layer in three sections on the slope. This effect can be also seen at 500 db (Fig. 9b). At the stations on the slope, particularly Stations 16, 17 and 25, the temperature is lower and salinity is higher compared with those at northern stations in deep waters such as Stations 1, 2, 3 and 4. Therefore, the upwelling seems to occur at all depths below the permanent thermocline on the slope. The difference of -0.2°C between Station 17 and Station 1 corresponds to a upward displacement of about 170 m. However, this displacement is very small compared with the bottom shoaling, which changes from 2,100 m at Station 1 and 6 to 920 m at Station 17 and to 220 m at Station 18. As shown in the preceding section, therefore, the topographic beta effect dominates the planetary beta effect in quasi-geostrophic motions below the permanent thermocline. There is no current data to infer the circulation in the Ulleung Basin, but there are enough evidences to indicate the necessity of such motions as presented.

The geostrophic current between Station 6 and Station 17 in U2 Section relative to 500 db is mostly westward with a maximum speed of about 10 cm/sec (Fig. 10). To determine the absolute current we need to know the motion at 500 db. If there is a significant inflow of cold waters into the Ulleung Basin through Ulleung-Do and Dok-Do as

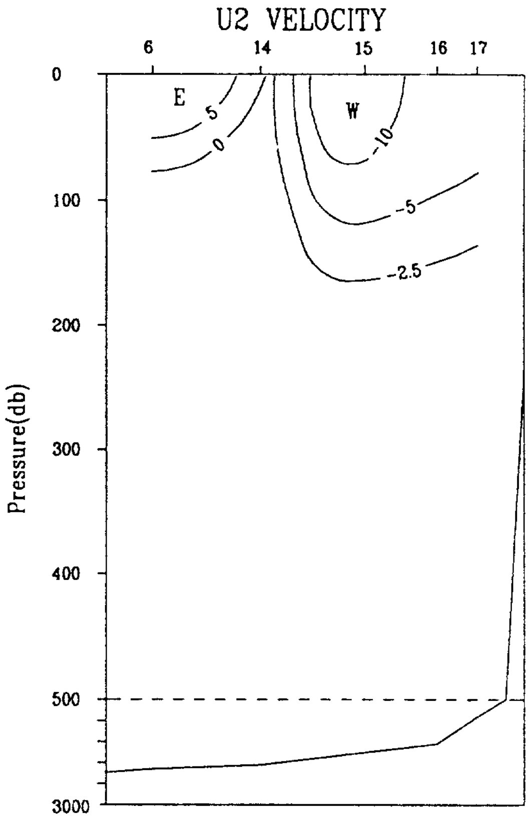


Fig. 10. Geostrophic current on U2 Section relative to 500db in units of cm/sec. "E" and "W" indicate the eastward and westward currents.

suggested, we should expect subsequent motions of cold waters, both ESIW and ESPW, in the basin. Thus, it is worthwhile to speculate a current system which is consistent with given topography, hydrography, and the property distribution in the basin.

Progress in understanding the dynamics of currents and circulation in the Alboran Sea, which have been extensively studied last 20 years (Kinder and Bryden, 1990), may be very useful to make a conceptual model of the circulation in the Ulleung Basin. The Western Mediteranean Deep Water (WMDW) formed south of France in winter makes a westward current of 5 cm/sec banking against the African slope along Morocco, whose path is controlled topographically, rising from 400 m to 200 m to flow out through the Strait of Gibraltar. Bryden and Stommel (1982) suggested that the shoaling bottom induces the bottom upward velocity, which generates anticyclonic vorticity in the water column above because of the shrinking of vortex lines. Results of extensive field, numerical and laboratory experiments (Parrilla *et al.*, 1986; Preller, 1986; Kinder *et al.*, 1986) seem to agree with Bryden and Stommel (1982).

In the Ulleung Basin the ESPW plays the role of the WMDW in Alboran Sea, although the ESPW probably does not flow out of the East Sea through the Korea Strait. If the ESIW and the ESPW flow into the Ulleung Basin through Ulleung-Do and Dok-Do, the spreading of cold waters is subjected to the effect of the shoaling bottom. Since the Ulleung Basin is deeper than the Alboran Sea by about 700 m, the topographic effect would be even stronger in the Ulleung Basin.

The permanent thermocline in the U2 Section sloping up from the center of the basin toward south (Fig. 5a) is similar to the rising isotherms of the WMDW and consistent with the anticyclonic circulation. The bowl-shaped structure of the permanent thermocline and the layer of the salinity-minimum found in U3 Section (Fig. 4a and b) agree also with the anticyclonic circulation.

At 500 db temperature at Station 10 is exceptionally lower than that at any other station of U1 Section (Fig. 9b). On this regard it should be recalled that the salinity-minimum layer at Station 9 and 10 are warmer and less saline than other stations. Vertical sections (Fig. 6a and b) show that these peculiar properties are associated with the rising isotherms and isohalines toward the Korean coast. This structure is about 50 km wide and extends from the permanent thermocline to 500 db which is the limit of observation. Probably this structure extends to the bottom, because there is little variation of density in deep waters. It is important to note that a persistent current flowing southeast with a speed of about 3 cm/sec from August 26 to November 7 in 1986 at depths of 620 m and 790 m in waters of 840 m deep (Lie *et al.*, 1989) was observed from a mooring located 50 km northwest of Station 10 as shown in Fig. 2.

The observed hydrography and currents near the Korean coast lead us to propose a cold current system flowing southward, confined on the continental slope and shelf, apart from the basic circulation in the Ulleung Basin. Previously a southward current such as the NKCC was considered as one of major currents in the East Sea, but it was thought to flow southward at surface off North Korea (Uda, 1934) and at intermediate depths under the EKWC in the southern part of the East Sea (Kim and Kim, 1983), identified by the layer of salinity-minimum at depths of 100~300 m. It seems that the current is not limited in the intermediate layer, but extends to the bottom. Dynamically this current is equivalent to the deep western boundary current in the North Atlantic and other major world oceans. The cold current system and the anticyclonic circulation probably meet the Tsushima Current as it leaves the Korea Strait. Particularly the continuity requires the inflow of the cold waters into the Ulleung Basin to be accounted by mixing, entrainment and a return current. Direct measurements are required to understand the complex current system in this area.

Recently there have been a couple of noteworthy investigations concerning the salinity-minimum layer and the circulation in the Ulleung Basin. Kim *et al.* (1990) reported the widespread presence of the salinity-minimum layer in the western half of the basin in August 1986. A couple of sections taken in one week after our survey (KORDI, 1989) have been extremely useful to show the minimum layer between the east coast of Korea and Ulleung-Do and its temporal variation as presented in preceding sections.

Recognizing a warm core (deep thermocline) in the basin, Na (1988) suggested that the convergence of warm water by the wind-stress curl may form it. However, Na (1988) also indicated the need to include a vertical motion and thermohaline mechanism. A numerical model in which only the thermohaline circulation is considered in a closed basin (Kim and Chung, 1989) produced indeed an anticyclonic (clockwise) circulation in the southwestern part of the East Sea, roughly corresponding to the Ulleung Basin. An analytical model also showed the importance of the air-sea heat exchange to generate a cold cyclonic gyre in the northern part of the East Sea (Seung and Kim, 1988). Variable wind-stress curl is not considered in both studies (Seung and Kim, 1989; Kim and Chung, 1989) and further investigations are needed to evaluate the relative importance of the wind and thermohaline forcing. As there are indications of significant year-to-year variations associated with the movement of cold waters in the Ulleung Basin (Ro, 1989), results of a single survey may not represent a permanent structure. But the inclined thermocline in the Ulleung Basin pointed out by Na (1988) is a robust mean structure, which deserves a clear explanation. Water mass analysis and a conceptual circulation model proposed in this study may provide a framework for further investigations.

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