The Journal of the Oceanological Society of Korea,
Vol.17, No.2, p.59~68, December 1982.

VERTICALLY HOMOGENEOUS WATER ALONG THE WEST COAST OF JEJU ISLAND

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ABSTRACT

Vertically homogeneous water was found around the convex coast of Jeju Island on its west side from hydrographic surveys conducted in June and October 1980, and June 1981. This is the first time that this hydrographic structure is observed. Historical data do not show this water, since they were taken far from the island. The presence of this homogeneous water is explained in terms of tidal mixing for the lower half of the water column and upwelling for the upper half of the column which occurs to conserve vorticity as currents flow clockwise around the island. Direct measurement in future is required to prove the upwelling mechanism.

I. INTRODUCTION

Hydrography of the Yellow Sea has been investigated since the 1930's and the spatial and temporal variations of temperature and salinity are fairly well documented (Nakao, 1977). However, most data were collected in relation to fisheries and hydrographic stations are not spaced closely to resolve local processes.

In June 1980 hydrographic stations were made in a small area of the southern Yellow Sea in order to look into the synoptic structure (see Fig. 1). One of important findings from this survey is the presence of vertically homogeneous water around the convex coast of Jeju Island along its west side. Relatively cold water was evident at surface and warm water at the bottom, as a strong seasonal thermocline was developing offshore. This feature was reexamined by visiting the same area in October of the same year. Interestingly enough there had been essentially no change in the basic structure in four months. Persistence of the homogeneous water suggests strongly that this structure is produced locally. The purpose of this paper is to descirbe the detailed hydrography of this water and to suggest possible mechanisms which produce the observed structure.

Around the British Isles where tidal currents are strong Simpson and Hunter(1974) have shown that tidal mixing can destroy the stratification and fronts are formed between mixed and stratified areas. The location of fronts is determined by the parameter, H/u_s^3, where H is the water depth and u_s the amplitude of the tidal stream. Later Pingree and Griffiths (1978) and Simpson and Bowers(1979) show that the predicted position of fronts agrees with the satellite images very well. Since Choi(1980) has shown that the tidal energy dissipation is substantial around Jeju Island, we have examined the importance of tidal mixing in this paper. In the central part of the Yellow Sea a homogeneous bottom water with a thickness of 30~40m being found below the strong seasonal thermocline(Nakao, 1977), the tidal mixing seems to take place primarily in the lower half of water column west of Jeju Island where the water depth is about 100m.

Several authors explained the appearance of the cold water at surface in terms of upwelling which is induced to conserve vorticity in vicinities of capes. Arthur(1965) first showed a possibility of this mechanism in relation to the upwelling off Baja California. Johnson, Fonseca and Sievers(1980) and Blanton, Atkinson, Pietrafesa and Lee(1981) applied Arthur's idea successfuly for upwellings at Punta Curaumilla, Chile and off North Carolina of the United States, respectively. It should be made clear that for this mechanism horizontal curents are prerequisite. Around the west coast of Jeju Island where the homogeneous water is found there are clear indications of a current of about 25cm/sec. Therefore it seems quite possible that an upwelling also occurs as found elsewhere previously.

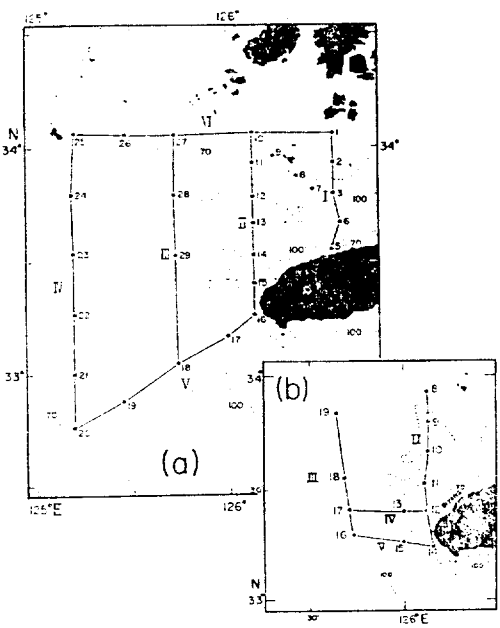


Fig. 1. Locations of hydrographic stations taken in June (a) and October (b), 1980.

Ⅱ. DATA

June 1980

A synoptic hydrography observed in the southwestern sea off Korea in June 1980 has been reported by Kim(1980). The T-S diagram of the entire data clearly reveals a distinct water mass which is easily identified because of its high temperature and high salinity as shown in Fig. 2. It is interesting that this water was found at stations 5, 6, 14, 15, 16 and 17 (see Fig. 1 for positions of these stations) all of which are located within 10 miles from the western coast of Jeju Island. Typically this water contains the dissolved oxygen less than 5.5ml/l. Based upon these characteristics

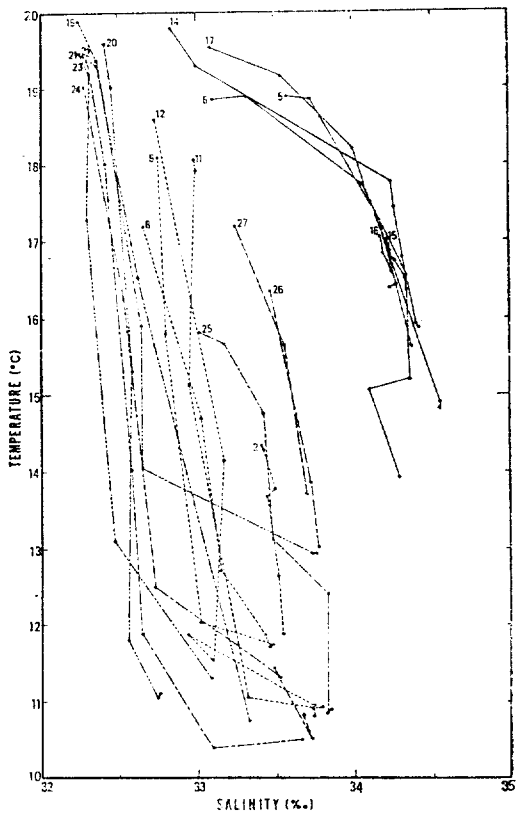
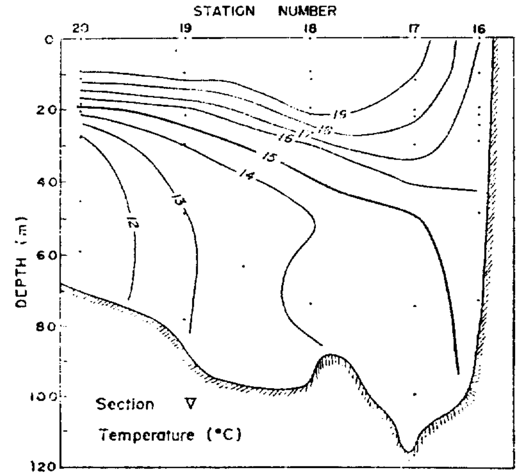


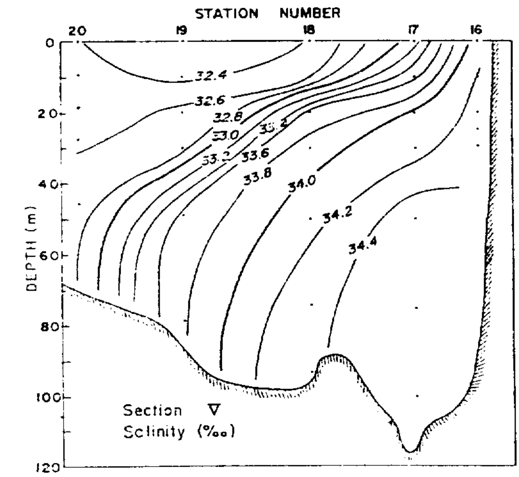
Fig. 2. Temperature-Salinity diagram for data taken in June 1980. Numbers indicate station.

of physical and chemical properties Kim(1980) has concluded that this water originates from the Kuroshio and enters the Jeju Strait after turning around the convex coast of Jeju Island. Later drogue and current measurements over a tidal cycle in the Jeju Strait produce a mean current of about half a knot due east consistent with Kim's conclusion (Professor Rho of the Jeju University and Hydrographic Office of Korea, Personal Communication).

This paper is particulary concerned with the hydrographic structure of the above-mentioned water mass near Jeju Island. Section V which runs southwest from Jeju Island towards the mouth of the Yangtse River shows the structure of interest most clearly(Fig.-3). Seasonal thermocline is found at 20m offshore and towards Jeju Island isotherms of 17~19°C rise to surface forming a strong surface front as others dip to bottom. At station 16, which is located closest to the island, water is homogeneous as temperature changes little vertically. Near the island salinity variation shows a very similar structure with temperature; isohalines surface towards the island and salinity is constant at station 16. Density(σ_t) varies likewise.

The three-dimensional structures of temperature and salinity field in Fig. 4a and b seen from the west of the Jeju Island are useful to understand the locality of processes of interest. At surface the coldest water with temperature less than 17°C is found in a confined area within 5 miles from the western tip of Jeju Island and a front surrounds this water. The same water is easily identified by its highest salinity. On the other hand the warm and relatively less saline water prevails offshore. The low salinity indicates that this water is under a significant influence of the fresh water





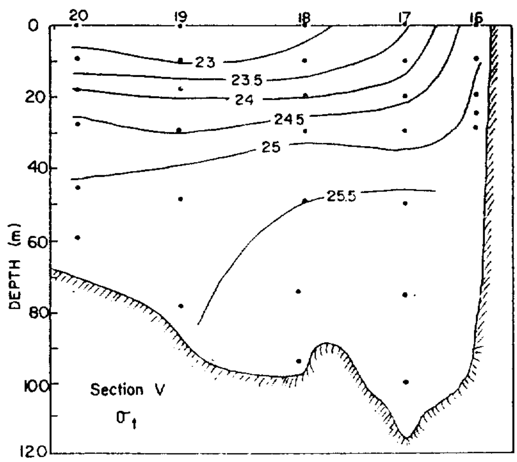
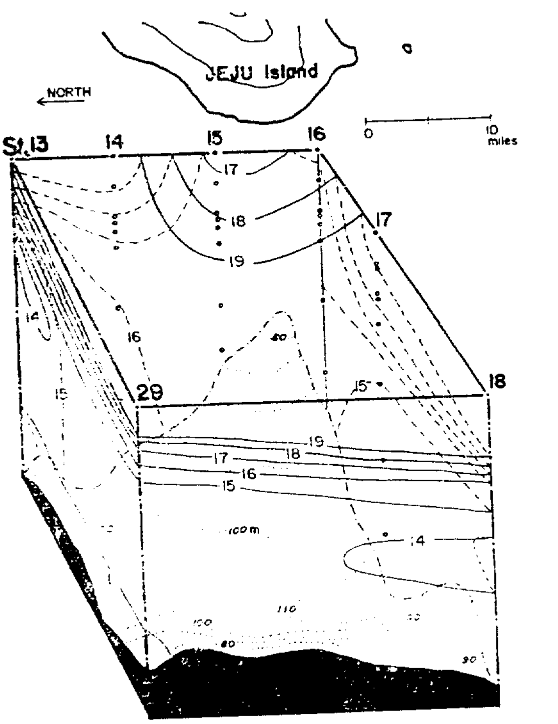


Fig. 3. Vertical profiles of temperature, salinity and density (σ_t) in June 1980.

discharged from the Yangtse River. The fact that temperature and salinity are different markedly in a very small area means that there are some local processes which counteract the prevalence of the seasonal warming and the effect of the runoff from the Yangtse River. It should be noticed that the locality remains true vertically at all depth; it is in the same area where the cold surface water exists that vertically homogeneous water is found. Therefore it is reasonal to speculate that some processes are occurring for the entire water column.

It is important to note that the core of salinity which is higher than 34.4‰ is found in the bottom layer at stations 14 and 17. Kim (1980) has conjectured that the axis of a branch of the Kuroshio passes these stations closely. Lee(1982) showed that a broad geostrophic current of the order of 10cm/sec flows around Jeju Island clockwise at 30m depth relative to 75m. However, this geostrophic current probably makes only part of the current in this area, because in shallow water there are other forces which are as important as the coriolis force. The existence of salinity core implies that a significant bottom current exists and the current in the upper part can be even greater than the estimate made by Lee(1982).

In order to elucidate the locality we calculate average properties for a water column from surface to 75m depth whose variations are shown in Fig.5. It is most interesting that the mean temperature has a minimum at station 16, which is the closest station to Jeju Island. At stations 14 and 17 which are located about 10 miles off the island two maxi-



Figa. 4. Three-dimensional distribution of temperature in June 1980. Solid and broken lines denote isotherms and dotted lines isobaths.

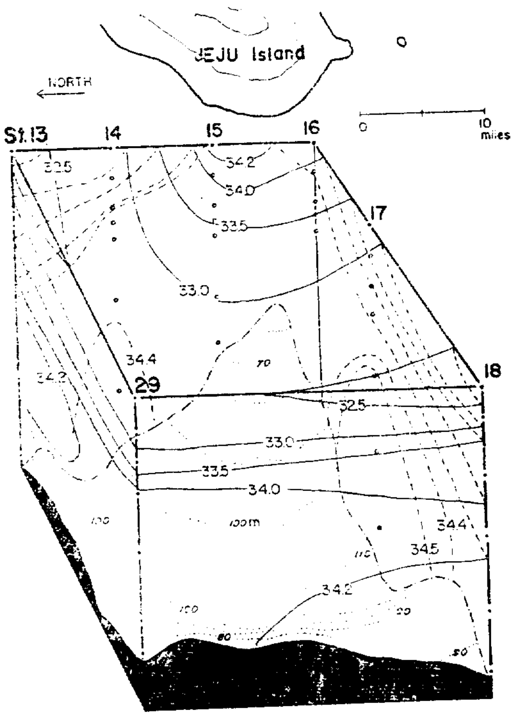


Fig. 4b. Three-dimensional distribution of salinity in June 1980. Solid and broken lines denote isotherms and dotted lines isobaths.

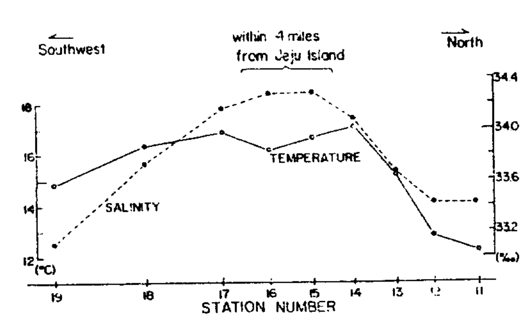


Fig. 5. Horizontal variation of mean properties in June 1980.

ma of the mean temperature are found. It has been pointed out already that these are the stations where the core of the highest salinity is found and the axis of a branch of the Kuroshio probably passes these stations. However, it is important to note that the mean salinity has its maximum inside of these stations in coincidence with the minimum of the mean temperature. There is no apparent source in this area for the minimum of temperature and maximum of salinity and these should be explained in terms of some other local processes. As Choi(1980) has found that a significant dissipation of tidal energy occurs in this area, the vertical homogeneity may be accounted for as a result of tidal stirring. However, the mixing may occur evenly in the area and the horizontal variations of mean temperature and mean salinity can not be produced by the mixing. Therefore it is believed that an upwelling occurs also. Results of biological study carried out simultaneously in the same area suggested an upwelling(Park, 1981).

October 1980

In order to examine steadiness of the local structure another hydrographic survey was conducted in the area October 1980. Fig. 6 shows temperature, salinity and density field of the section which is due west from Jeju Island(see Fig. 1-b for the location of this section). Properties have changed somewhat over a period of four months. But it is obvious that the basic structure of interest remains the same. At station 12 temperature varies less than 0.4°C vertically and the range of salinity variation is 0.05‰. In June the vertical ranges of variation at station 16 are 1.5°C and 0.1‰ in Fig. 3. The difference in the range reflects the overall temporal variation. For both surveys it is reasonable to say that the water is homogeneous compared with the offshore variation of properties.

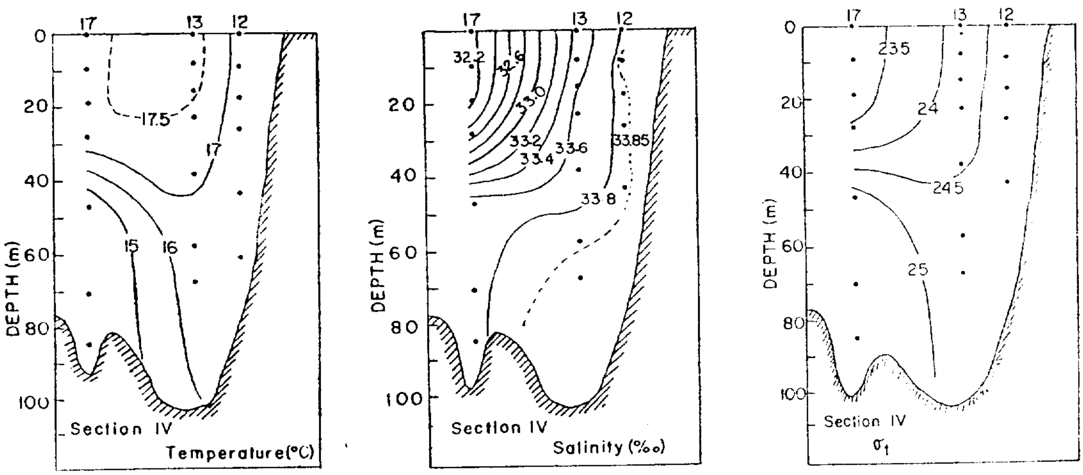


Fig. 6. Vertical sections taken in October 1980 (see Fig. 1. for location of stations).

For horizontal distribution Fig.7 shows that a cold and saline water appears at 10m locally off the western tip of the island. This structure is very similar to what has been observed in June and confirms the existence of some processes which maintain the local structure the same from June though October as a large seasonal change is under way off-shore. It seems that local processes persist year-round, although we need the data taken in winter and spring to substantiate this.

June 1981

As the two surveys in 1980 reveal an interesting local structure a third synoptic survey data taken in June 1981 shows a consistent distribution. Since the survey extends the area to south, this data is very valuable to prove the locality. In Fig. 8 the surface temperature off the western tip of Jeju Island is about 15°C, which is the lowest found in the entire area. It is clear from the distribution of isotherms that the cold surface water is confined in a very small area. There is no apparent local source for the cold water and horizontal processes such as advection or mixing is not likely to produce the observed temperature distribution. The water should be drawn upward from the lower layer through some vertical processes. At 75m temperature is distributed in a much simpler way. Most Isotherms run parallel to the topography with warm water towards Jeju Island. However it should be noticed that lower temperature is found to south of Jeju Island where it is the upstream direction for the proposed branch of the Kuroshio which is supposed to flow clockwise around the west coast of the island. This again indicates the necessity of some local processes which make water warm off the western tip of the island.

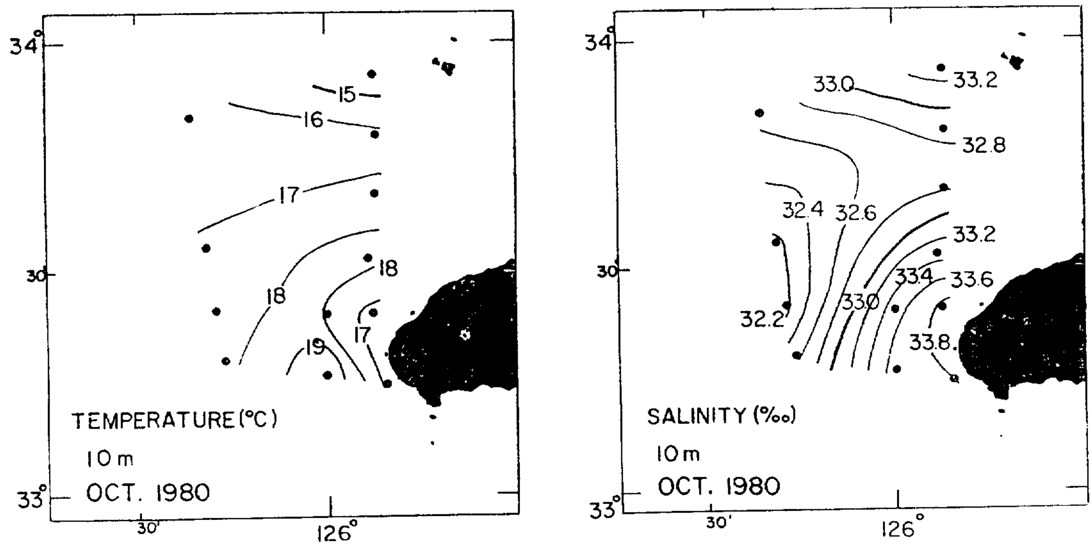


Fig. 7. Horizontal distribution of properties at 10m depth in October 1980.

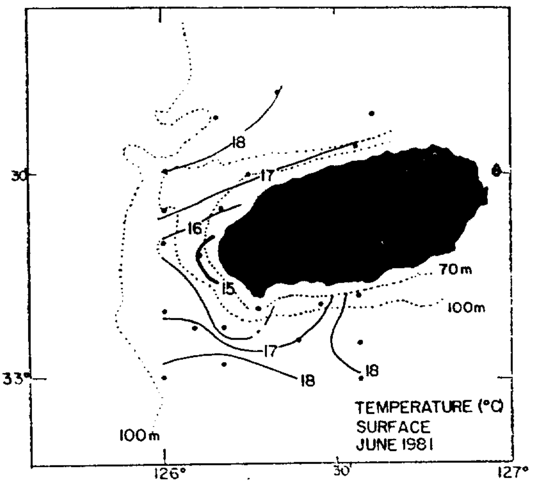


Fig. 8a. Horizontal distribution of surface temperature in June 1981.

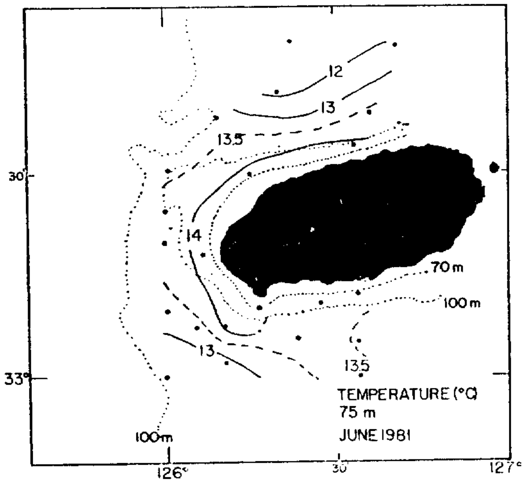


Fig. 8b. Horizontal distribution of temperature at 75m in June 1981.

Ⅲ. POSSIBLE MECHANISMS

Vertical homogeneity found off the western tip of Jeju Island seems very persistent in summer. This distribution is possible only through some dynamical processes. Otherwise a strong thermocline should prevail in the study area. There are two physical processes which are believed to be related to the observed homogeneity.

Tidal Mixing

In the Yellow Sea the tidal currents are quite strong (Choi, 1980). As Simpson and Hunter (1974) found around the British Isles, it is likely that the vertically mixed state is maintained in the study area by the production of potential energy due to tidal mixing. Following Simpson and Hunter(1974) we calculate H/u_s^3 where H is the water depth and u_s is a tidal stream. For H and u_s a navigation chart has been used(Hydrographic Office of Korea Chart No. 235). In Fig. 9 it is interesting to note that values of H/u_s^3 are small only in a limited area along the west coast of Jeju Island. To be consistent with observations a transition seems to occur for $\log H/u_s^3 \approx 1.85$. South of the island $\log H/u_s^3$ is much larger than 2, which indicates that this area is stratified. Observations in June 1981 agree with this prediction. The critical value of H/u_s^3 is similar to Simpson and Hunter's observation.

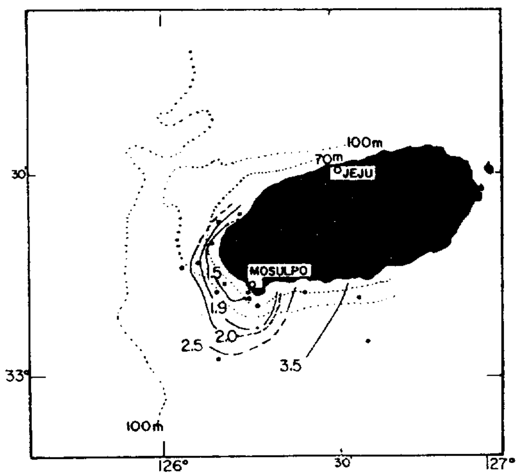


Fig. 9. Distribution of the mixing parameter, log H/u_s^3, around Jeju Island.

Upwelling

We have found in Fig. 5 that mean temperature and salinity averaged for water column have the minimum and maximum respectively. If the tidal mixing is the only cause for the vertical homogeneity, such minimum or maximum can not exist. In other word mean value should be the same in the area. The concurrent appearance of mean temperature minimum and mean salinity maximum suggests strongly a possibility of horizontal advection of relatively cold and saline water at mid-depth towards Jeju Island. This advection can be induced as upwelling occurs in a similar way suggested by Arthur(1965).

Kim(1980) suggested a belt-like warm current flowing around the west coast of Jeju Island. Later Kho(private communication) has found a mean current of about 25cm/sec in the Jeju Strait consistent with Kim's suggestion. Lee(1982) calculated a geostrophic current of about 10cm/sec at 30m relative to 75m in the study area. As water flows around the convex coast an upwelling occurs to conserve vorticity. The equation for conservation of vorticity is(Arthur, 1965)

$$f\frac{\partial w}{\partial z}=\frac{D\xi}{Dt}+\beta v$$

where $\frac{D\xi}{Dt}\simeq\frac{\partial\xi}{\partial t}+u\frac{\partial\xi}{\partial x}+v\frac{\partial\xi}{\partial y}$. Here f is the local Coriolis parameter and $\beta=\frac{df}{dy}$ and ξ is the vertical component of relative vorticity. Rectangular coordinates (x, y, z) denote eastward, northward, and upward distances and (u, v, w) are corresponding velocity components. The vorticity can be expressed in natural coordinates

$$\xi=\frac{V}{R}-\frac{\partial V}{\partial n}$$

where V is the speed, R is the radius of curvature of the stream line, and $\frac{\partial V}{\partial n}$ is the velocity gradient normal to the stream line.

Table 1. Estimates of parameters for upwelling west of Jeju Island.

V	20 cm sec^{-1}
R	2.5×10^{6} cm
H	4×10^{3} cm
f	8×10^{-5} sec^{-1}
ξ	8×10^{-6} sec^{-1}
βv	4×10^{-21} sec^{-2}
$\frac{D\xi}{Dt}$	-8.4×10^{-11} sec^{-2}
w_{40m}	4×10^{-3}cm sec^{-1}

For the present study $\frac{\partial V}{\partial n}$ is neglected compared with $\frac{V}{R}$ and relevant parameters are listed in Table 1. It is noticed that the change of relative vorticity is much larger than the change of planetary vorticity. The upward velocity of about 4×10^{-3}cm/sec at 40m corresponds to 3.5m/day and comparable to other estimates, e.g., Smith(1968). In the upper part of the study area a cold and saline water may appear as a result of this upwelling.

IV. DISCUSSION AND CONCLUSIONS

The presence of verically homogeneous water around the west coast of Jeju Island is attributed to tidal mixing and upwelling. This water is confined within 10 miles from the island and has not been found before, because previous hydrographic data were taken far off the island. At surface this water is distinguished by its low temperature and high salinity. Near bottom the opposite is true with relatively high temperature and low salinity.

In other parts of the world ocean the appearance of cold surface water has been explained in terms of tidal mixing or upwelling depending upon the oceanographic condition of the area under investigation. Tidal mixing model has been very successful to account for the existence of front as a transition between stratified and well-mixed areas around the British Isles. On the other hand along California and North Carolina of the U.S., or Chile the upwelling is intensified due to capes or topographic irregularities in association with strong boundary currents.

The present study area is unique in which tidal currents are strong and a narrow mean current is expected. It is believed that the tidal mixing occurs primarily in the lower half of the water column and the upwelling in the upper half for a water depth of about 100m. In the study area the tidal mixing alone may not produce the vertical homogeneity for the entire water column, since the water depth of 100m is too big. In summer the bottom of the seasonal thermocline lies at the depth of 30m and below this depth water is near homogeneous in the bottom layer of about 50m in the central part of the Yellow Sea. It seems that tidal mixing determines the thickness of this homogeneous layer as suggested by Pingree(1980). The same mechanism probably works in the study area. A second upwelling mechanism suggested by Garrett and Loucks(1976) may not be important west of Jeju Island, since tidal currents have a kind of stagnation point on the west coast of Jeju Island as shown by Choi(1980). In future it is essential to measure currents directly to validate the upwelling mechanism.

ACKNOWLEDGEMENTS

Authors are thankful to Drs. Simpson and Garrett for providing literature. Professor Rho of Jeju University kindly made available unpublished data taken in June 1981. Captain and crews of Training-ship Baekungho helped us to collect hydrographic data. This ressarch has been supported by the Korean Science and Engineering Foundation.

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제주도 서안에 존재하는 균질해수

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요약: 1980년 6월과 10월 및 1981년 6월에 실시된 정밀 해양 관측의 결과로 제주도 서안 10해리 이내에 존재하는 수직으로 균질한 해수가 발견되었다. 이제까지의 연구는 제주도 외해역에 집중되었기 때문에 이러한 해수의 존재가 알려지지 않았던 것 같다. 이 해수가 존재하는 이유는 저층에서 일어나는 조류에 의한 혼합과 표층의 용승현상으로 사료된다. 용승은 해류가 제주도 서안을 시계방향으로 흐를 때 소용돌이를 보존하기 위하여 일어나는 것으로 믿어지며 이를 증명하기 위하여 앞으로 정밀 해류 관측이 요구된다.