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Thermohaline Structure of the Shelf Front in the Korea Strait in Early Winter

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초겨울 大韓海峽에서 形成되는 淺海前線의 構造

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Abstract: Mesoscale thermohaline structures of the meandering front in the Korea Strait during November 1976, 1980 and 1982 are studied by means of closely spaced oceanographic observations and the satellite infrared images. Strong thermal and salinity fronts coincide each other and show a wavelike meander motion with wavelengths of 40-60km and amplitudes of, 15-20km. Salinity minimum band of less than 33.0‰ is found along the onshore edge of the front. Width of the frontal zone corresponds approximately to the internal radius of deformation (R=5-10km) and the slope of density interface is confined to about 2R. A series of satellite infrared images with the interval of 4-5 days show a noticeable growth of frontal meander over the flat shelf west of the Korea Strait. Possible mechanisms of frontal meander and its growth are discussed.

要約 : 1976년, 1980년, 1982년 11월에 실시된 해양관측 자료와 인공위성에 의한 적외선 사진을 이용하여 대한해협 근해의 전선구조에 대하여 연구하였다. 수온 및 염분전선의 위치는 서로 일치하며 40∼60km의 파장과 15∼20km의 진폭을 갖는 사행운동을 한다. 전선대의 연안쪽 경계를 따라서 33‰ 미만의 염분극소지역이 나타난다. 전선대의 폭은 대체로 내부변형반경인 5∼10km에, 밀도전선면이 경사진 폭은 내부변형반경의 두배에 해당된다. 4∼5일 간격으로 찍은 일련의 적외선 사진들은 해저지형이 매우 완만한 대한해협 서쪽 해역에서 전선대의 변형이 특히 심하게 일어남을 보여준다.

INTRODUCTION

Enhanced heat flux from sea surface to atmosphere in late fall destroys the summer stratification so that both of the shelf water and the Kuroshio Current water become vertically homogeneous (Nishida and Iwanaga, 1978). Since the winter cooling is most effective in the shallow northern and eastern Yellow Sea, the coldest West Korean Coastal Current driven by the northerly monsoon flows southward and enters the south sea of Korea through the Cheju Strait (Huh, 1982) to constitute the South Korean Coastal Water. The South Korean Coastal Front with strong temperature and salinity gradients is found between this cold coastal water diluted with the river runoff and the warmer and saline Tsushima Current (Gong, 1971; Huh, 1982).

Because of the compensating effect of temperature and salinity on density (Mooers et al., 1978), the existence of density front at the thermohaline front depends on the relative intensity of cross-frontal temperature and salinity contrasts. Thermohaline front in winter with no density front was observed in the Kii Channel (Yoshioka, 1971) and in the Sea of Iyo (Yanagi, 1980), and the numerical experiments on the frontogenesis in these regions were made by Endoh (1977), Harashima et al. (1978) and Harashima and Oonishi (1981). The Oyashio front and the subarctic front in the central

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Pacific are known to have very weak density gradient resulting in the absence of baroclinic jets (Roden, 1975, 1977), while the Pacific Subtropical Front in winter has a moderate density contrast (Roden, 1981). Off the south coast of Korea, density front may develop as far as the magnitude of cross-frontal temperature gradient exceeds the compensation by salinity contrast.

Due to the increased surface cooling and turbulent mixing in late fall through winter, destratification process over the shallow shelf is completed by at least early December. Consequently the thermohaline structure having strong summer stratification until October undergoes a radical alteration during November. Moreover, the front in early winter has some characteristic aspects including the salinity minimum band which are not found in mid-winter (Lim, 1976).

The purpose of this paper is to describe the mesoscale thermohaline structure of front in the Korea Strait and its temporal change due to the strong wind during November, and to discuss the frontal dynamics governing the meander motion and its instability.

OBSERVATIONS

Oceanographic observations with closely spaced stations suitable for the description of mesoscale feature of front were carried out in November of 1976, 1980 and 1982. Fig. 1 shows the stations of Nansen casting in 1976. Station spacing is 5 km in the cross-shelf direction and 20-30 km in the along-shelf direction. In 1980, simultaneous observations employing two vessels were made (Fig. 2). Lines of Q, R and S were covered twice two weeks after the first cruise by means of the MARTEK-STD system. L-82 denotes the stations of Nansen casting conducted twice with the interval of 5 days in November 1982. Here the spacing of stations is 10-20 km.

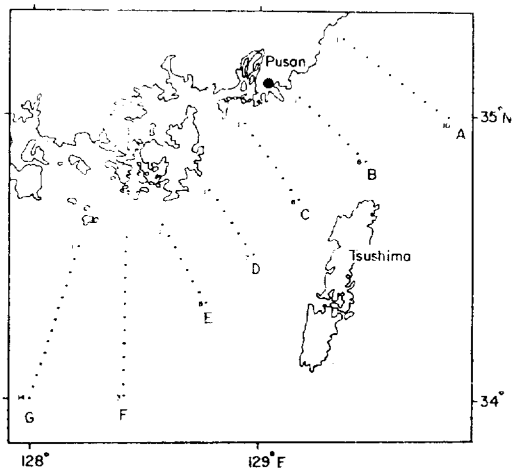


Fig. 1. Stations of Nansen casting (dots) in Nov. 1976.

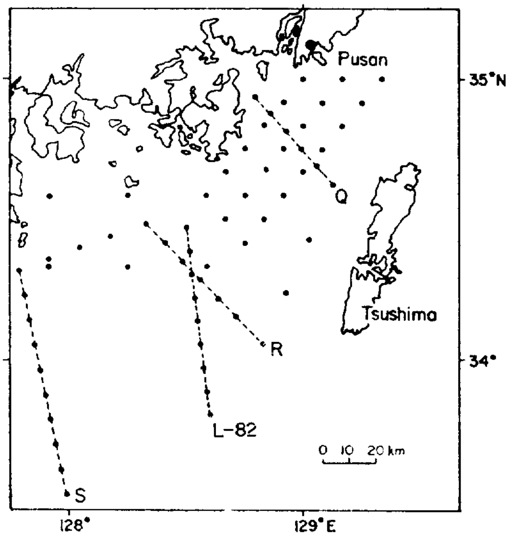
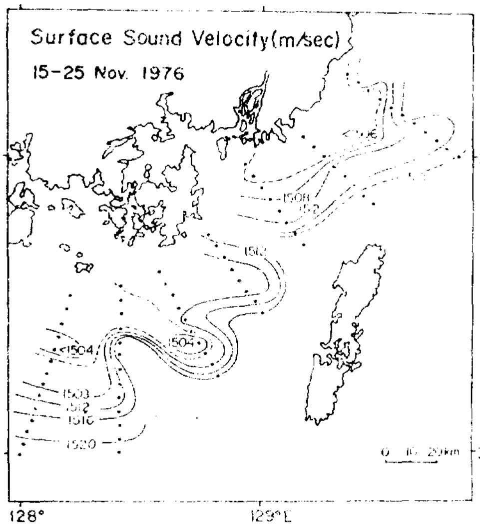
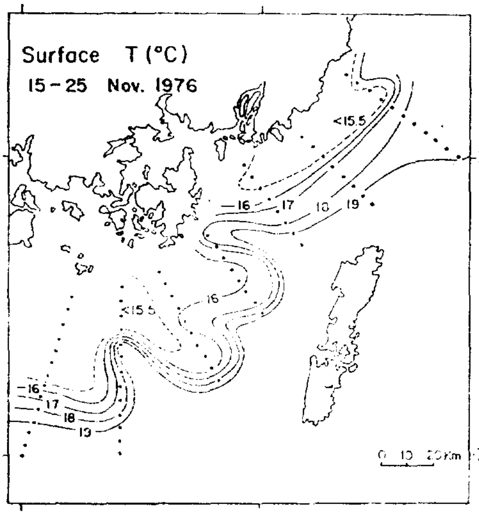


Fig. 2. Stations of hydrographic observation (dot) in Nov. 1980. L-82 denotes the stations of Nansen casting in Nov. 1982.

HORIZONTAL STRUCTURE OF THE FRONT

Mesoscale meander of the coincident thermohaline and sound velocity front with wavelengths of 40-60km and amplitudes of 15-20km is shown in Fig. 3. A strong front develops between the cold, less saline coastal water ($T<16°C$; $S<33.4‰$) and the warm and saline Tsushima Current water ($T>19°C$; $S>34.0‰$). Maximum gradients of temperature, salinity and sound velocity at Line-F are 0.76°C, 0.24‰ and 2.6 m/s per kilometer respectively. These cross-frontal gradients are very sharp compared with other fronts (Yoshioka, 1971; Yanagi, 1980; Roden, 1975). Discontinuous salinity minimum band detached by the meander motion is found along the northern edge of the front. Similar features in terms of meander and salinity minimum band were also found in November 1980 (Fig. 4). In this case, the wavelength and temperature contrast are greater than those in 1976. Maximum gradients of 0.52°C/km in temperature, 0.09‰/km and 1.4m/s per kilometer in sound velocity are of smaller magnitudes than those of 1976. An almost detached cold eddy of low salinity northwest of Tsushima and a southward intrusion of rather warm and saline water along the Korean coast are recognized (Fig. 4). These phenomena are also found in the satellite infrared images taken just before and during the hydrographic surveys (Fig. 5a-d).





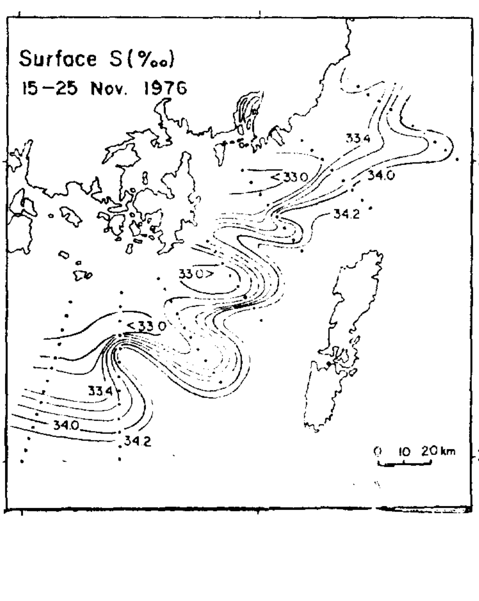


Fig. 3. Distributions of temperature, salinity and sound velocity at sea surface in Nov. 1976.

Infrared photographs (Fig. 5a-d) show an evolution of frontal meander. The most interesting fact is that the wavelike undulations show a noticeable growth over the shelf with gentle bottom slope west of the Korea Strait. Fig. 5-d shows an extremity of the frontal wave growth west of Tsushima with an elongated tongue of warm water. Unfortunately, any cross-shelf line of STD observation did not intersect this mutual intrusion.

VERTICAL STRUCTURE OF THE FRONT

a. Temperature and salinity

Temperature and salinity sections along the Line-F (Fig. 6) in November 1976 are chosen as the relevant examples to illustrate the vertical structure of the meandering front. Salinity minimum zone (S<33.0‰) coincident with the temperature minimum is hatched and the

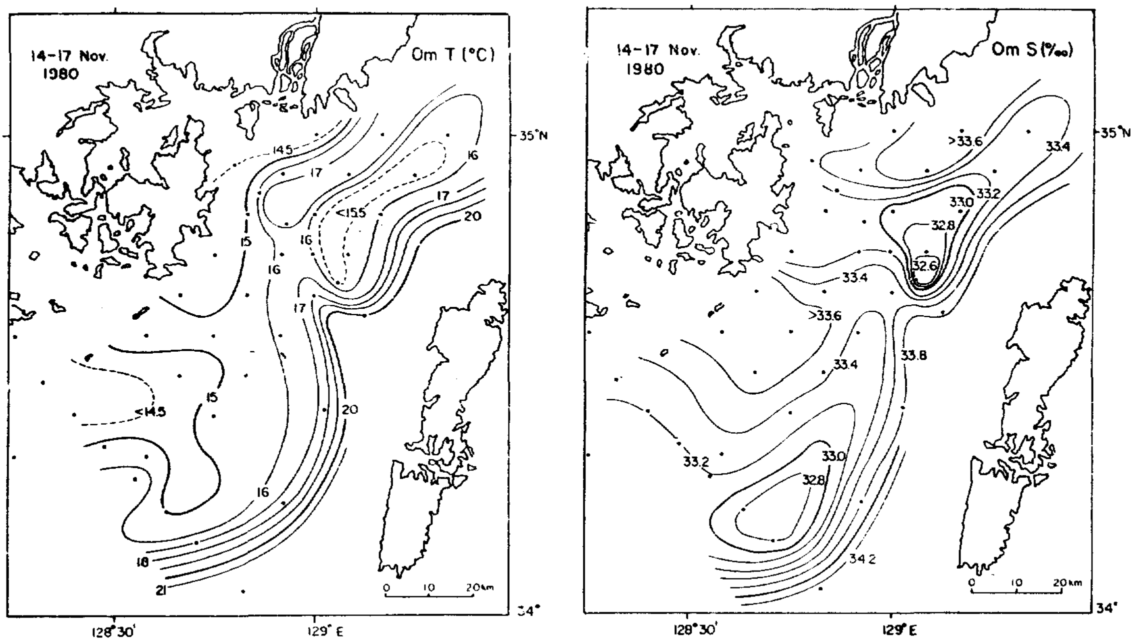


Fig. 4. Distributions of temperature and salinity at the sea surface in Nov. 1980.

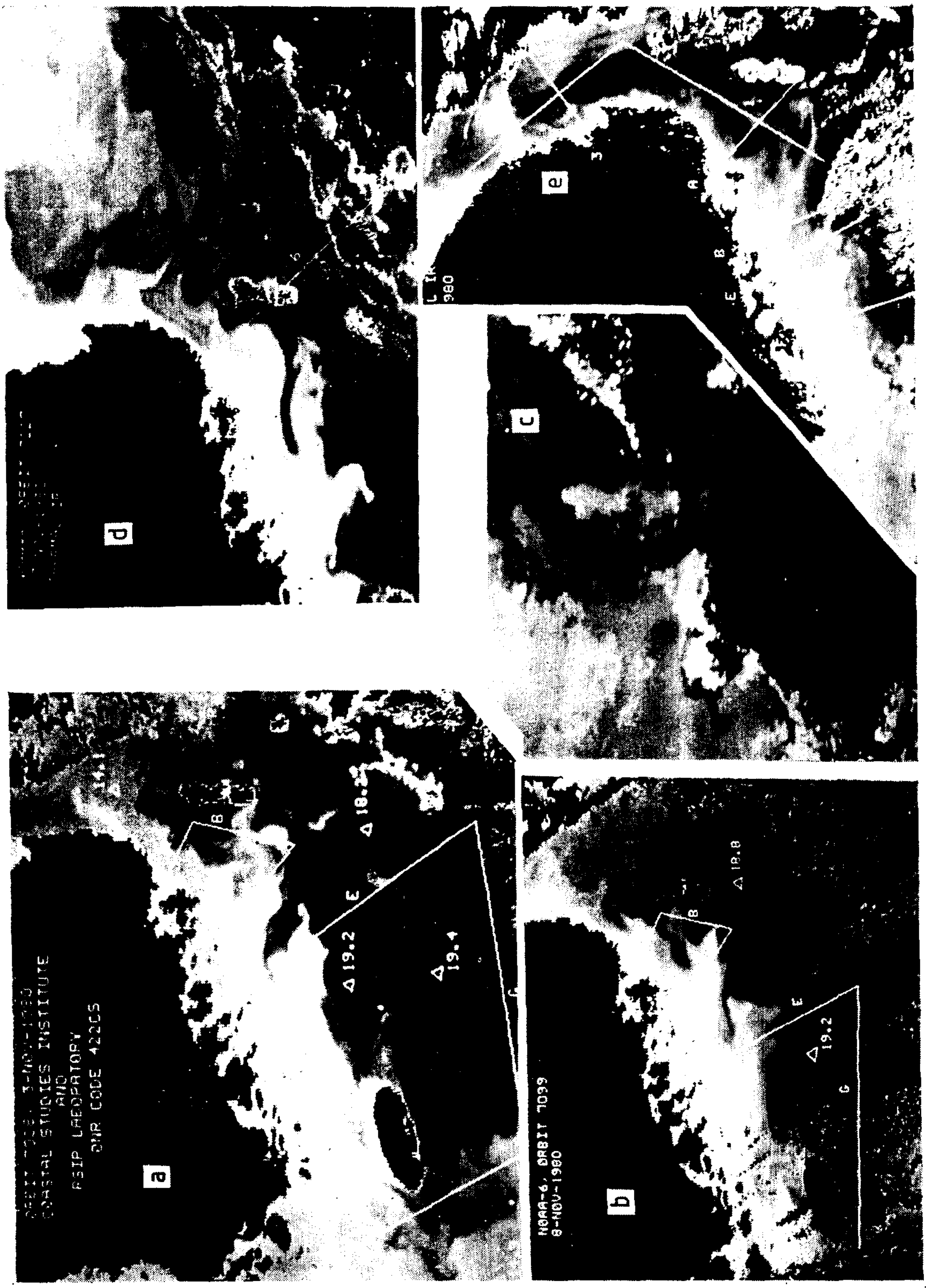
warm and saline waters (T>18°C; S>34.0‰) are stippled. First of all, a surface to bottom front is very sharp between St.4 and St.5. Deep inversions of temperature and salinity from St.11 to St.13 and the upwelled isotherm of 17°C at the center of the cyclonic motion are also notable. Destratification penetrates down to about 60m depth.

Figs. 7, 8 and 9 show the cross-frontal distributions of temperature and salinity at lines Q, R and S respectively in November 1980. Vertical wall of thermal front reaches down to 80-100m depth. Zones of salinity and temperature minimum coincide with each other just at the onshore side of the front. Both of the temperature and salinity inversions near the front, and the onshore intrusion of saline bottom water are commonly observed at every section. Width of the frotal zone is generally about 5-10km.

b. Density (σ_t)

Fig. 10 shows that the density contrast at the surface across the front at Line-F is less than 0.2 sigma-t units in November 1976. For this case, the effect of temperature gradient on density is balanced by the compensating effect of salinity. Calculated baroclinic surface velocity relative to the bottom is 24.3cm/sec within the front. Cross-frontal temperature contrast in November 1976 of about 4°C is smaller than that of 1980 (about 6°C) because the Tsushima Current was not so warm then (Figs. 6-9). Salinity contrast is about 1.2‰ for both cases. Accordingly the temperature difference surpassed the compensation by salinity so that the density front of considerable strength was formed along the thermohaline front in November 1980 (Fig. 10). This Margules-type density front has a frontal jet with the baroclinic velocity of 79-85 cm/sec at the surface. Width of the sloping interface is roughly 20km.

Fig. 5. NOAA-6 satellite infrared images: (a) 3 Nov. 1980, (b) 8 Nov. 1980, (c) 12 Nov. 1980, (d) 17 Nov. 1980, (e) 26 Nov. 1980. Darker tone depicts the warmer region.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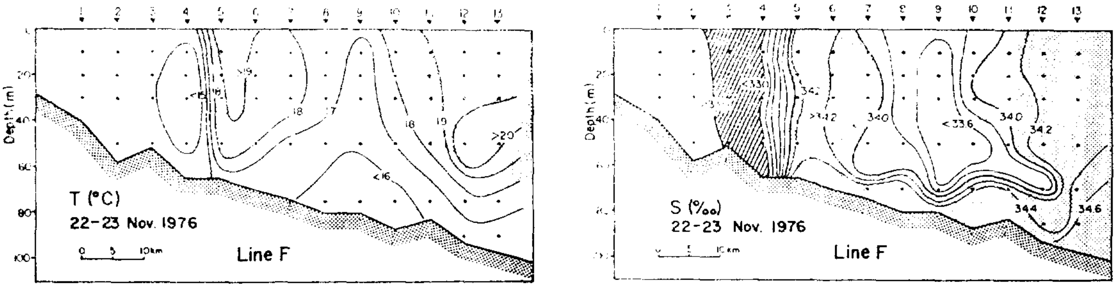

Fig. 6. Vertical sections of temperature and salinity at Line-F. Salinity minimum band (<33.0‰) is hatched. Warm (>18°C) and saline (>34.0‰) waters are stippled.

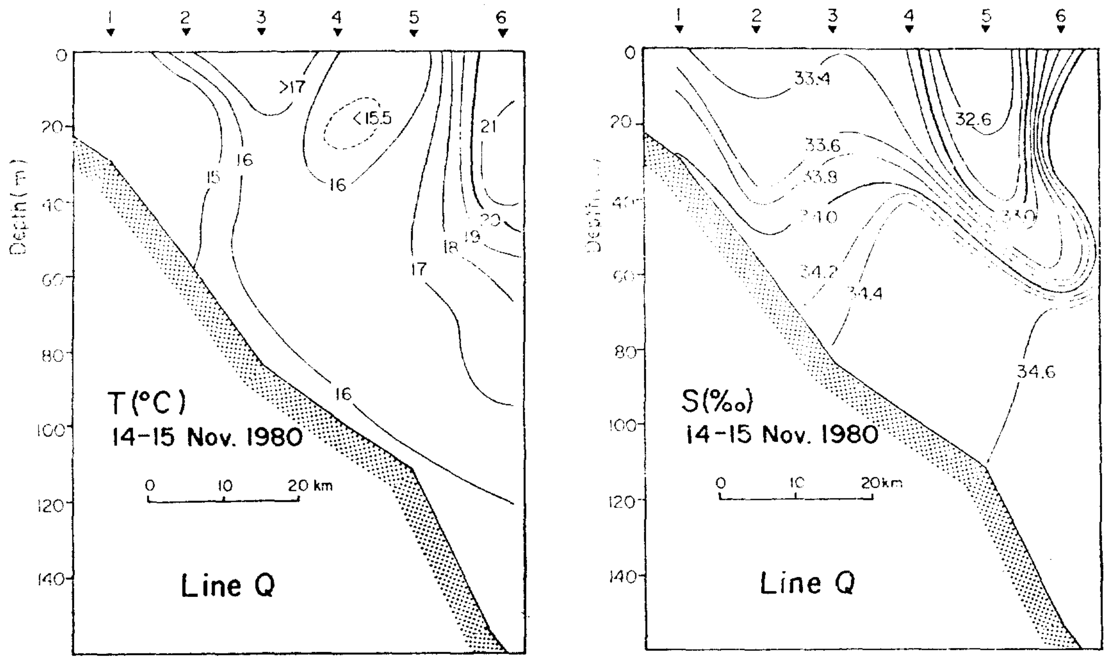

Fig. 7. Vertical sections of temperature and salinity at Line-Q.

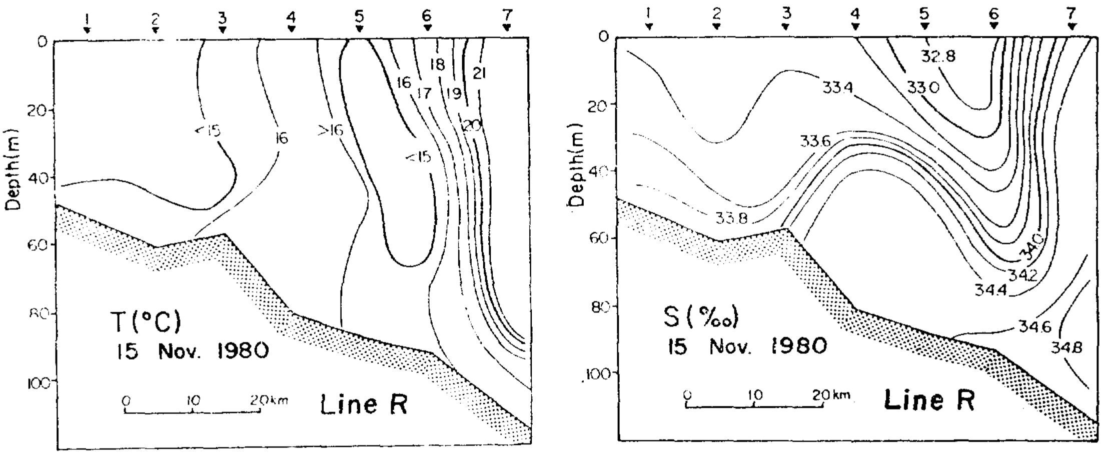

Fig. 8. Vertical sections of temperature and salinity at Line-R.

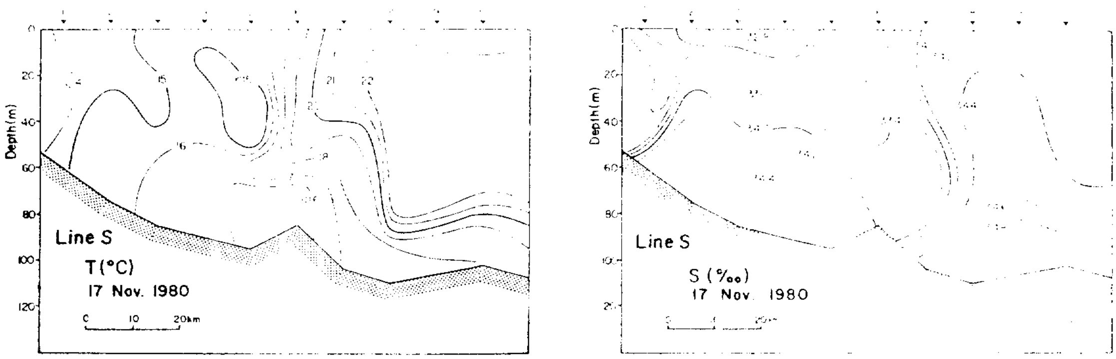

Fig. 9. Vertical sections of temperature and salinity at Line-S.

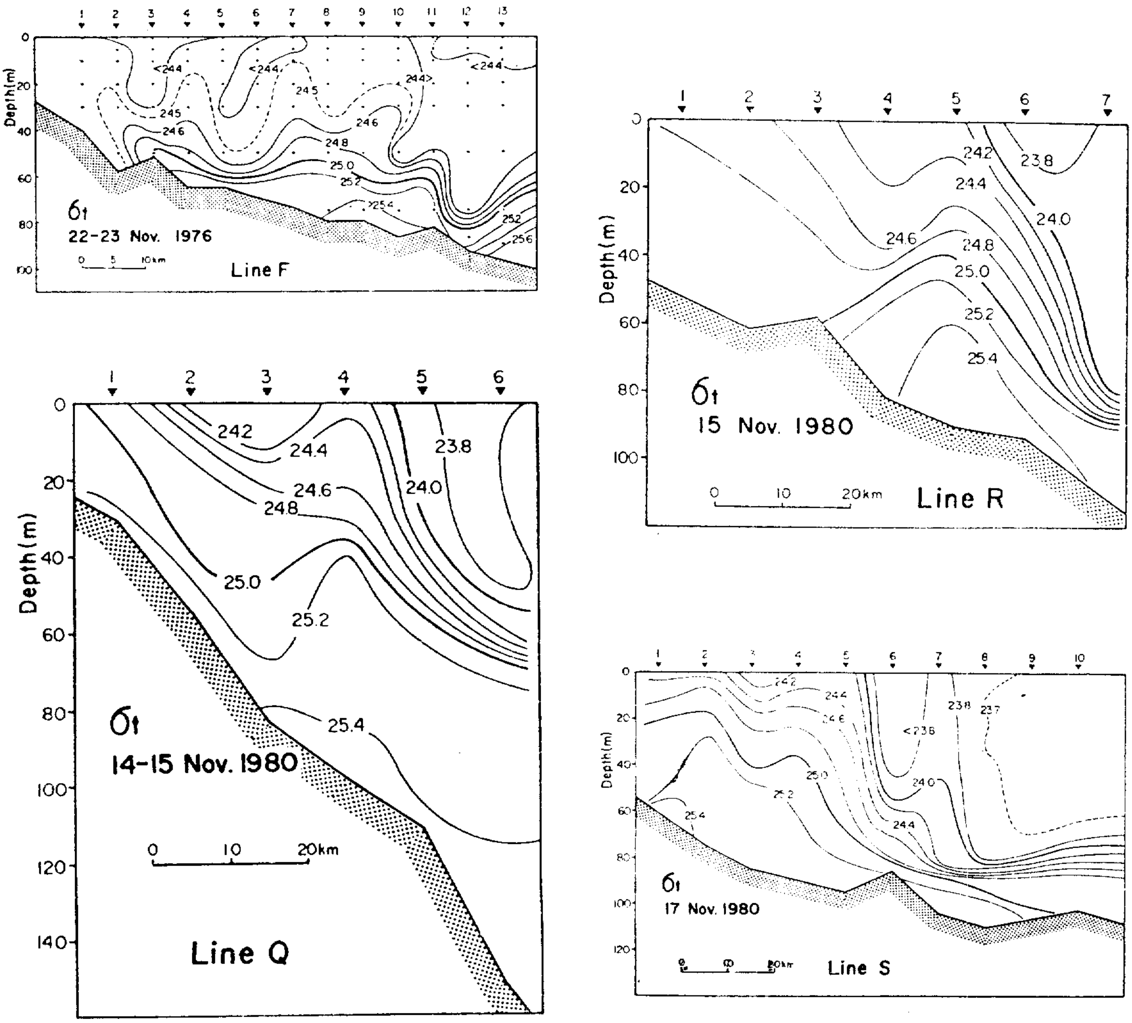

Fig. 10. Vertical sections of density at Line-F in Nov. 1976, Line-Q, Line-R and Line-S in Nov. 1980.

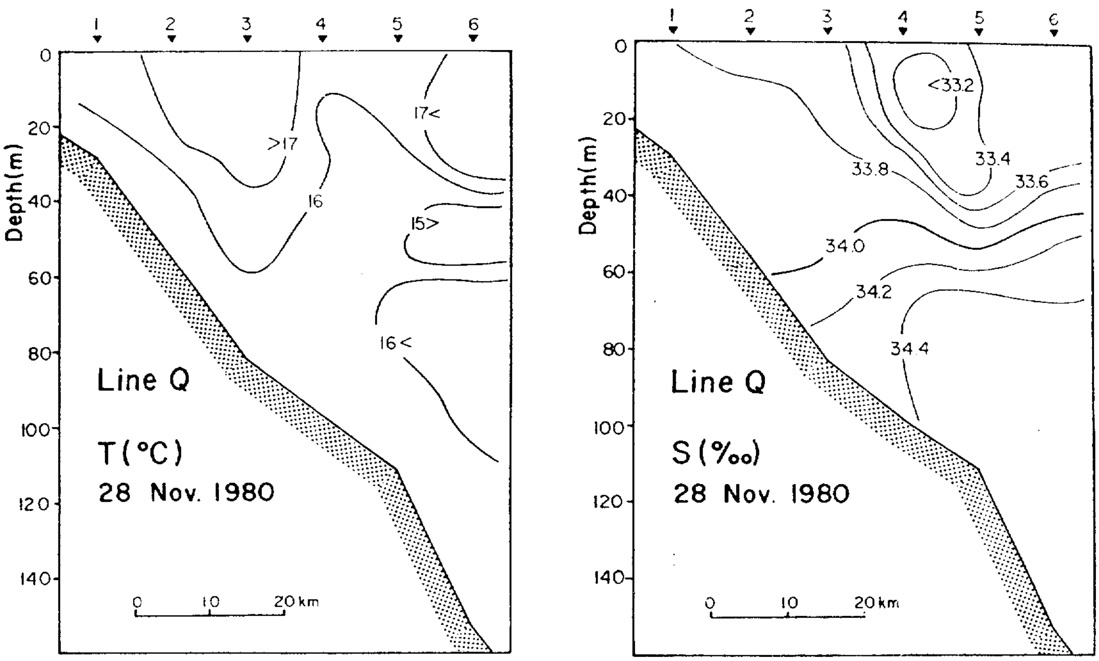

Fig. 11. Vertical sections of temperature and salinity at Line-Q on 28 Nov. 1980.

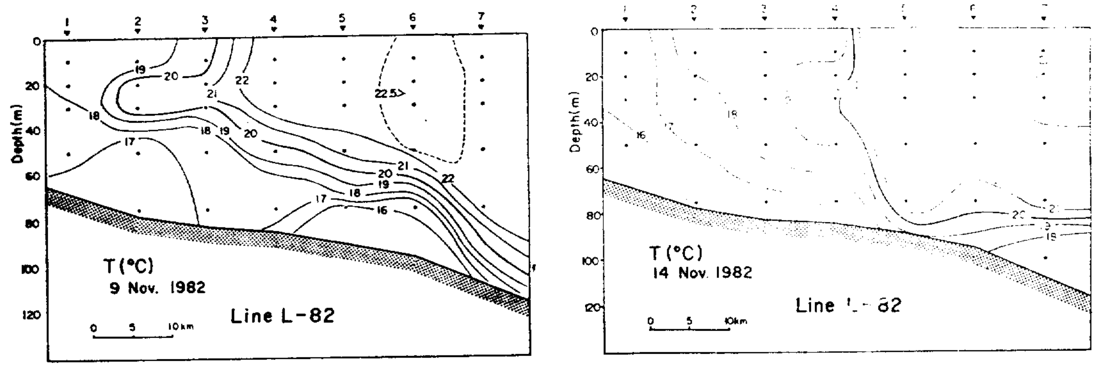

Fig. 12. Vertical sections of temperature at Line L-82 on 9 Nov. 1982 and 14 Nov. 1982.

STRUCTURAL CHANGES DUE TO WIND FORCING

A satellite infrared imagery taken on 26 November 1980 (Fig. 5e) shows how a vigorous storm changes the shape of front drastically compared with the other IR pictures. After the passage of an atmospheric front, strong NNE wind persisted from the morning of 21 till the midnight of 22 November. Because of this storm we had to give up further observations of front in the Cheju Strait. Afterwards there was another wind forcing from the NNW direction during 24-25 November. Cold coastal waters extending offshore due to the northerly winds are shown in Fig. 5e. Fig. 11 is a result of the second cruise occupied on 28 November over the Line-Q. Frontal structure of temperature and salinity, which had existed in Fig. 7 disappeared substantially due to the active cooling and mixing processes, but the salinity minimum zone still remained. Deep temperature inversion

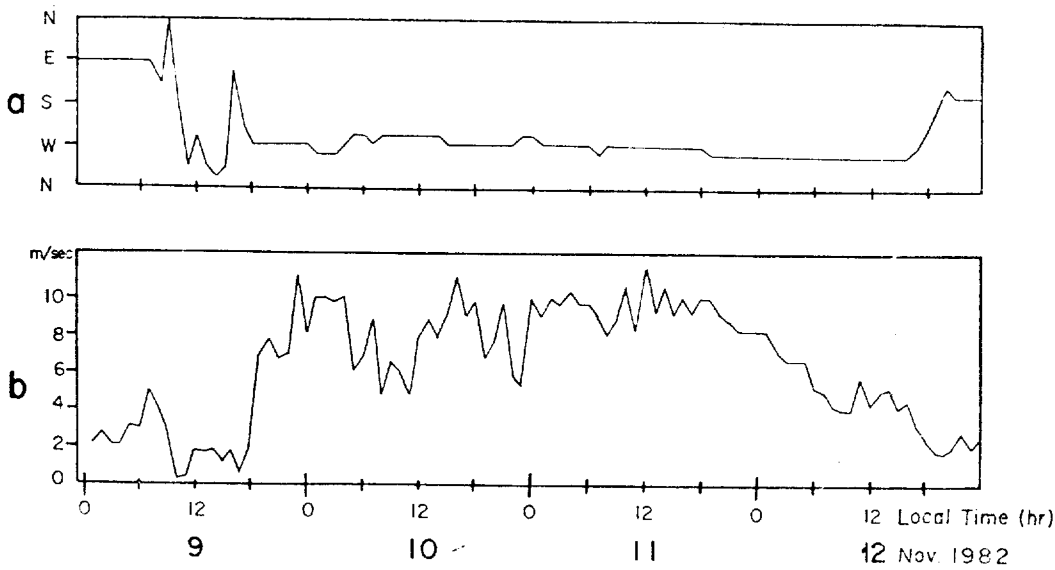

Fig. 13. Direction and speed of hourly wind at Cheju in Nov. 1982.

offshore is also noted.

Fig. 12 illustrates the change in temperature fields that took place in 5 days. During the first cruise on 9 November 1982, a wide front accompanied with strong inversion was found near the St.3. The following changes appeared in Fig. 13-b after the strong westerly wind from 9 to 11 November (Fig. 13). (1) The extent of temperature inversion was diminished greatly and the stratification was destroyed because of the turbulent vertical mixing evoked by the strong wind. (2) Front moved about 7km offshore probably due to the offshore Ekman transport by the westerly wind parallel to the shelf and/or the frontal oscillation itself. (3) Front width and temperature contrast were decreased considerably. Wind data at Cheju were selected because they were representative of the marine wind and, moreover, the meteorological station is open to the westerly wind.

DISCUSSION AND CONCLUSIONS

It is a common feature that the discontinuous salinity minimum band detached by the meander motion is usually observed along the northern edge of the thermohaline front. A salinity minimum band like this is found in the Cheju Strait even during September (Fig. 3 in Gong, 1971). This reminds us of the discontinuous salinity minimum band originated from the shelf water along the edge of the Gulf Stream (Ford et al., 1952; Kupferman and Garfield, 1977). Lee (1983) discussed the same phenomenon at the front west of the Cheju Strait and concluded that this low salinity water originated from the East China Sea Water. The preservation of salinity minimum band to the Korea Strait suggests that the along-front flow is very fast compared with the effects of cross-frontal dispersion of properties. Therefore we can suppose that any object drifting with current will tend to follow the frontal zone as shown by Roden (1981) and Niiler (1982) in the sutropical front of the central North Pacific which occurred over the thermocline at about 100~150m depth in winter. This low salinity band disappears in mid-winter as the enhanced air-sea interaction continues (Lim, 1976).

In general, temperature and salinity distributions in the surface to bottom front in winter tend to have much larger horizontal gradient of sound velocity than the vertical one.

Presence of the cold salinity minimum band at the front contributes to the intensification of the cross-frontal sound velocity gradient. Consequently an enormously large gradient with the maximum value of 1.4−2.6m/s per kilometer is produced, and when coupled with the meander or eddy motion of front, it can cause a serious deflection problems for the horizontally propagating sound waves (James, 1972; Woods, 1978; Munk, 1980).

This fornt, much stronger than the Oyashio front (Roden, 1975), is apparently generated and maintained by the continuous supply of the effectively chilled shelf water through the Cheju Strait in addition to the formation of cold water off the south coast(Lim, 1976), and of the warm Tsushima Current from south. Inversions of both temperature and salinity are quite prevalent near the front. Surface cooling in early winter is evidently favorable for the formation of inversion layer. However, Fig. 12 suggests that the southward Ekman transport of surface cold water across the front driven by the northerly prevailing wind may be more favorable(Kang, 1982; Kim and Yuk, 1983).

Occurrence of density front depends upon the difference in the compensating effects on density by temperature and salinity. When the Tsushima Current is not so warm either inherently or due to the enhanced vertical mixing and heat loss, density front will not develop as in the case of 1976. For the frontogenesis of this case, numerical experiments by Endoh (1977), and Harashima and Oonishi (1981) are applicable. On the other hand, when there is an appreciable density gradient, geostrophic adjustment process between the two homogeneous water masses separated initially by an imaginary vertical barrier (Stommel and Veronis, 1980: Griffiths and Linden, 1982; Ou, 1983) is more adequate to understand the frontal dynamics.

According to the geostrophic adjustment models, the frontal width is roughly given by the internal radius of deformation regardless of the bottom slope (Ou, 1983). The internal radius of deformation is defined by $R=\frac{\sqrt{g'H}}{f}$ where g' is the reduced gravity $\left(g\frac{\Delta\rho}{\rho}\right)$, H the shelf depth and f the Coriolis parameter. Besides, the width of sloping interface and the wavelength of meander are of the order of $2R$ and $2\pi R$ respectively (Griffiths and Linden, 1982). For the front of 1976, we can use $\Delta\rho\approx 0.2\times10^{-3}\mathrm{g/cm^3}$ and $H=80\mathrm{m}$, then the internal radius of deformation and the wavelength of meander are estimated to be about 5km and 40 km respectively, which are fairly consistent with the observations(Figs. 3 and 6). In the case of 1980, we can use $\Delta\rho\approx 0.8\times10^{-3}\mathrm{g/cm^3}$ and $H=80\mathrm{m}$, then R is about 9.5km. This figure roughly corresponds to the actual front width (Fig. 7) and the width of the interface slope is about $2R$ (Fig. 10).

Several speculations are possible on the cause of the meander motion of front. The kinetic energy associated with the significant horizontal shear of baroclinic jet in the front is a probable source of energy for the perturbations when the front width is comparable to the Rossby radius (Griffiths and Linden, 1982). Further increase in shear may cause the frontal meander to be unstable and eventually to generate the eddies (Roden, 1981). Perhaps the frequent storms in winter may also excite the frontal oscillations (Flagg and Beardsley, 1978).

We observed the temporal changes of frontal structures due to the vigorous wind forcing(Figs. 11 and 12). Overturning down to the bottom was undoubtedly caused by the strong wind persisted for about 3 days. Both of the Ekman transport and the frontal oscillation itself seem to be responsible for the offshore shift of frontal zone. Furthermore, it is remarkable that the front width which is independent of the bottom slope decreased significantly owing to the strong westerly wind parallel to the front. Winds parallel to the geostrophic flow in the front result in a decrease of the frontal width, thus intensify the baroclinic velocity (Csanady, 1978; Hsueh and Cushman-Roisin, 1983).

Finally, our attention is focused on the growth of the frontal meander over the flat shelf west of the Korea Strait as shown in a series of IR pictures(Fig. 5a-d). This phenomenon may be related to the fact that an increase in bottom slope tends to stabilize the frontal oscillations (Flagg and Beardsley, 1978). The gentle slope of about 5×10^{-4} off the south coast, therefore, would be one of the favorable conditions for the frontal instability. In summary, three factors of the flat bottom topography, the wind impulse and the baroclinic instability due to the strong geostrophic flow seem to be responsible for the frontal meander and its growth.

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REFERENCES

Csanady, G.T., 1978. Wind effects on surface to bottom fronts. J. Geophys. Res., 83:4633-4640.

Endoh, M., 1977. Formation of thermohaline front by cooling of the sea surface and inflow of the fresh water. J. Oceanogr. Soc. Japan, 33:6-15.

Flagg, C.N. and R.C. Beardsley, 1978. On the stability of the shelf water/slope water front south of New England. J. Geophys. Res., 83:4623-4631.

Ford, W.L., J.R. Longard and R.E. Banks, 1952. On the nature, occurrence and origin of cold low salinity water along the edge of the Gulf Stream. J. Mar. Res., 11:281-293.

Gong, Y., 1971. A study on the South Korean coastal front. J. Oceanol. Soc. Korea, 6:25-36.

Griffiths, R.W. and P.F. Linden, 1982. Laboratory experiments on fronts. Geophys. Astrophys. Fluid Dynamics, 19:159-187.

Harashima, A., Y. Oonishi and H. Kunishi, 1978. Formation of water mass and fronts due to density-induced current system. J. Oceanogr. Soc. Japan, 34:57-66.

Harashima, A. and Y. Oonishi, 1981. The Coriolis effect against frontogenesis in steady buoyancy-driven circulation. J. Oceanogr. Soc. Japan, 37:49-59.

Hsueh, Y. and B. Cushman-Roisin, 1983. On the formation of surface to bottom fronts over steep topography. J. Geophys. Res., 88:743-750.

Huh, O.K., 1982. Satellite observations and the annual cycle of surface circulation in the Yellow Sea, East China Sea and Korea Strait. La mer, 20:210-222.

James, R.W., 1972. Criticality of ocean fronts to ASW operations. NAVOCEANO Technical Note 7700-3-72, 28p.

Kang, Y.Q., 1983. On the generation of temperature inversions in the upper layer of the ocean. J. Oceanol. Soc. Korea, 18:43-48.

Kim, H.J. and S.S. Yug, 1983. Inversion phenomena of temperature in the southern sea of Korea. Bull. Korean Fish. Soc., 16:111-116.

Kupferman, S.L. and N. Garfield, 1977. Transport of low-salinity water at the slope water-Gulf Stream boundary. J. Geophys. Res., 82:3481-3486.

Lee, J.C., 1983. Characteristics of front near the Cheju Strait in early winter. Bull. Korean Fish. Soc., 16:51-58.

Lim, D.B., 1976. Movement of the waters off the south coast of Korea. J. Oceanol. Soc. Korea, 11:77-88.

Mooers, C.N.K., C.N. Flagg and W.C. Boicourt, 1978. Prograde and retrograde fronts, *Oceanic fronts in coastal processes*, ed. Bowman, M.J. and W.E. Esaias, Springer-Verlag, 144p.

Munk, W.H., 1980. Horizontal deflection of acoustic paths by mesoscale eddies. J. Phys. Oceanogr., 10:596-604.

Niiler, P., 1982. FRONTS-80, A study of the North Pacific Subtropical Front. Naval Res. Rev., 34:42-50.

Nishida, H. and Y. Iwanaga, 1978. On the water mass characteristics in autumn on the continental shelf of East China Sea. Rep. Hydrogr. Res., 13: 37-49.

Ou, H.W., 1983. Some two-layer models of the shelf-slope front: Geostrophic adjustment and its maintenance. J. Phys. Oceanogr., 13:1798-1808.

Roden, G.I., 1975. On North Pacific temperature, salinity, sound velocity and density fronts and their relation to the wind and energy flux fields. J. Phys. Oceanogr., 5:557-571.

Roden, G.I., 1977. Oceanic subarctic fronts of the Central Pacific: Structure of and response to atmospheric forcing. J. Phys. Oceanogr., 7:761-778.

Roden, G.I., 1981. Mesoscale thermohaline, sound velocity and baroclinic flow structure of the Pacific Subtropical Front during the winter of 1980. J. Phys. Oceanogr., 11:658-675.

Stommel, H. and G. Veronis, 1980. Barotropic response to cooling. J. Geophys. Res., 85:6661-6666.

Woods, J.D., 1977. Turbulence as a factor in sound scattering in the upper ocean, *Oceanic Sound Scattering Prediction*, ed. Andersen, N.R. and B.J. Zahuranec. Plenum Press, 859p.

Yanagi, T., 1980. A coastal front in the Sea of Iyo. J. Oceanogr. Soc. Japan, 35:253-260.

Yoshioka, H., 1971. Oceanic front at Kii-Suido in winter (I). Umi to Sora, 46:31-44.