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INVERSION PHENOMENA OF DENSITY IN THE JAPAN SEA

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ABSTRACT

Density inversions are investigated by using the oceanographic data of temperature and salinity obtained in the Japan Sea from 1965 to 1979. The density inversions are found more frequently in winter than summer. About one half of the Japan Sea has the density inversions in winter, while in summer, they appear only in the small part of the Korean Strait. The inversions are usually formed in surface layers of a few tens of meters. Such phenomena can be explained by the advection of cold water in the surface layer by Ekman drift: In winter, the southward flow of surface cold water due to northwesterly monsoon causes the density inversions, and in summer, the offshore flow of bottom cold water upwelled near coast due to southwesterly wind makes the surface layer of the Korean Strait unstable.

INTRODUCTION

A density of sea water in the upper layer of the ocean is mainly determined by its temperature and salinity. The density of sea water generally increases as depth increases. In other words, density inversions, which mean an inverted distribution of density, rarely take place in the open ocean. However, we found the density inversions through the investigation of the oceanographic data obtained in the Japan Sea.

Temperature inversions, which imply that the temperature increases with depth, can be found in the surface mixed layer as diurnal variations (Delnore, 1972), near the frontal zone in coastal upwelling regions (Collins *et al.*, 1968), and in the regions of the intrusion of more saline water (Fedorov, 1978). However, the vertical distributions of density are usually still stably stratified, because the inverted distributions of temperature are compensated by an increase in salinity (Nagata, 1970). In contrast, for the case of density inversions in the Japan Sea, especially in winter, the temperature increases and the salinity decreases with depth in the surface layer, and both temperature and salinity distributions contribute to unstable stratifications.

In this paper, we describe the inversion phenomena of density in the Japan Sea, and also discuss the formation mechanism of the inversion layers.

DATA AND METHOD

As mentioned before, it is usually found that the inverted distribution of temperature in the surface layer is not compensated by the increase in salinity in the Japan Sea. So the temperature inversions agree nearly with the density inversions.

Fig.1 shows a schematic temperature profile with a temperature inversion in the surface layer. We can read the depth of the lower end

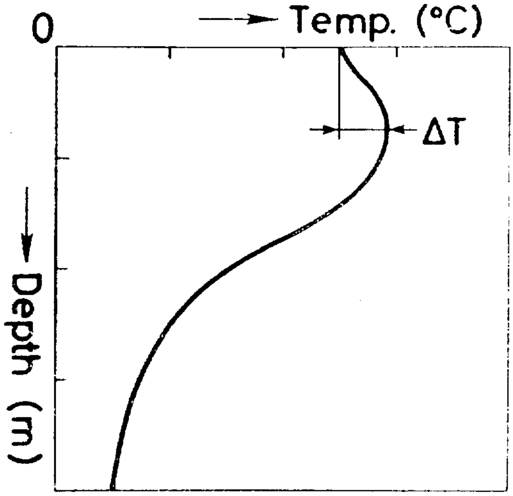

Fig. 1. Schematic view of temperature profile. A temperature inversion is typically showed in surface layer. ΔT represents the temperature difference of the inversion.

of temperature inversion layer and also can compute the temperature difference (ΔT) of the inversion from vertical profiles of temperature. These informations are obtained on the basis of the oceanographic data taken by the Fisheries Research and Development Agency in Korea(FRDAK) from 1965 to 1979.

We calculate the sea water density σ_t and the Brunt-Väisälä (B-V) frequency $N(\mathrm{sec}^{-1})$ which indicates a vertical stability of sea water. The frequency N is given by

$$N^2=-g/\rho_0(\partial\rho/\partial z-g/c^2), \qquad (1)$$

where g is the gravity, ρ_0 is the reference density, $\rho(z)$ is the in situ density and c is the sound velocity, and the positive z axis points upward.

In this study, we approximate N^2 to

$$N^2\simeq-\Delta\sigma_t/\Delta z, \qquad (2)$$

where $\sigma_t=(\rho_{S,T,0}-1)\times10^3$, $\rho_{S,T,0}$ is the density that the particle of water would have if it were at atmospheric pressure (zero gauge pressure), and Δ represents the difference of successive two values in consideration. N^2 is calculated by using the oceanographic data taken by FRDAK in 1978 and 1979, and the Japan Meteorological Agency (JMA) in 1979. The observation stations of FRDAK and JMA are shown in Fig. 2.

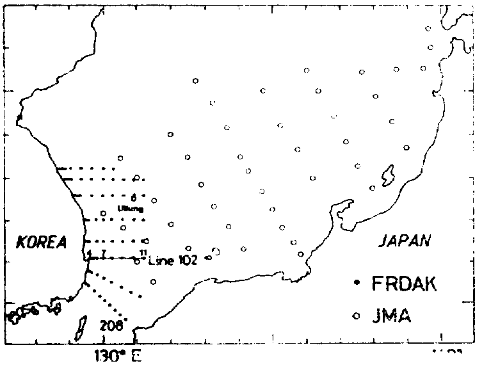

Fig. 2. Stations of oceanographic observation. FRDAK and JMA indicate the Fisheries Research and Development Agency in Korea and the Japan Meterological Agency, respectively.

RESULTS

1. Temperature Inversions

A mean vertical profile of temperature in summer is much different from that in winter. The characteristics of the temperature inversion layers, therefore, will be different from season to season. In this paper, we study the temperature inversions appearing in summer and winter. The inversions in July to September are referred to as summer inversions, and those in January to March are referred to as winter inversions. The statistical characters about the inversion layers are obtained for summer and winter inversions and compared with each other.

Fig. 3 shows the frequency distribution of the temperature difference (ΔT) and that of the depth (Dl) of lower end of the inversion layers. The frequency of occurrence for winter inversions is much higher than that for

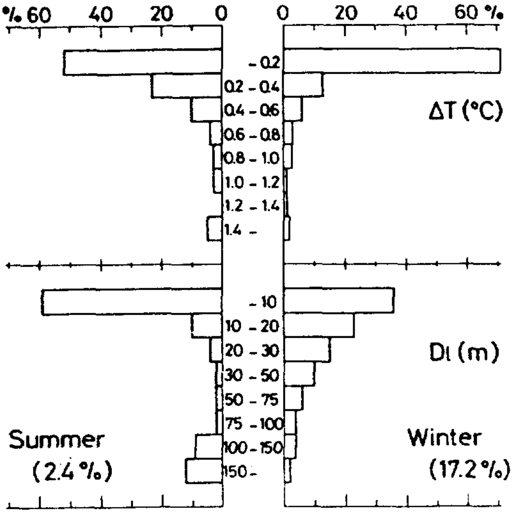

Fig. 3. Frequency distribution of the temperature difference (ΔT) between the upper and lower ends, and the depth(Dl) of lower end of the inversion layer.

summer: the winter inversions take place in almost all area of the Japan Sea, while the summer inversions can be found only in the small part of the Korean Strait. It should be noted that the most frequent inversions have ΔT less than 0.2°C and Dl shallower than 20m for both summer and winter inversions.

As an example of the temperature inversions, a temperature profile along 36°05′ N (line 102) in February 1979 is shown in Fig. 4. The temperature inversions are concentrated in the surface layer, and almost all of the surface layer is occupied by the inversions. Such inversion phenomena occur frequently in the Japan Sea during winter, while not so during summer.

2. Density Inversions in Winter

In order to investigate the density inversions, we calculate B-V frequency (N^2) by equation (2). As an example of the density inversions, a B-V frequency profile is shown in Fig. 5. These data are also obtained along 36°05′ N (line 102) in February 1979. The density inversions are concentrated in the surface layer of less than 100m, and almost all of the top surface layer up to 50m is occupied by the inversion layers.

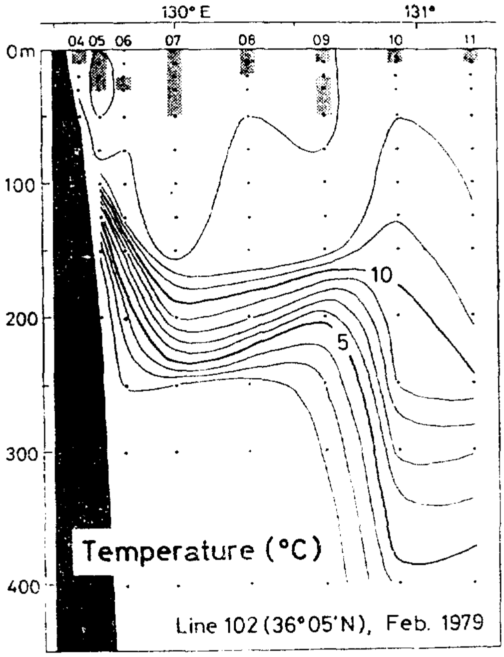

Fig. 4. Temperature profile along 36°05′ N (line 102) in February 1979. Shaded areas indicate positions of temperature inversion layers.

These inversion layers can be grouped into two types. One type exists just below sea surface and is primarily related with the temperature inversion layers shown in Fig. 4. The other type exists in deeper region and is formed by the intrusion of more saline water. The former is more unstable than the latter because the shallower inversion layer is formed not only by a decrease of salinity with depth but also by an increase of temperature.

In order to investigate the horizontal distribution of density inversions, we next calculate N^2 for the southwestern part of the Japan Sea where fairly dense observations are made by FRDAK. The temperature inversions occur most frequently in 0~10m as shown in Fig.3. The horizontal distribution of N^2 in 0~10m is calculated and shown in Fig. 6. Generally speaking, almost all area, except a part along 130° E up to 36° N, is occupied by unstable layers at surface in winter. For the sake of convenience, the unstably stratified regions are seperated into two kinds in Fig. 6. One is a comparatively weak unstable regions of $0 > N^2 \geq -0.5 \times 10^{-4}$ sec^{-2} and corresponds to the diagonally-lined portions. The other is a comparatively strong unstable regions of $N^2 < -0.5 \times 10^{-4}$ sec^{-2} and corresponds to the hatched portions. The latter exists near the coast area and southeastern offshore of Korea.

Fig. 7 shows the horizontal distribution of N^2 averaged in the upper 50m. The unstably stratified regions can be found in a large part of the research area even though we consider

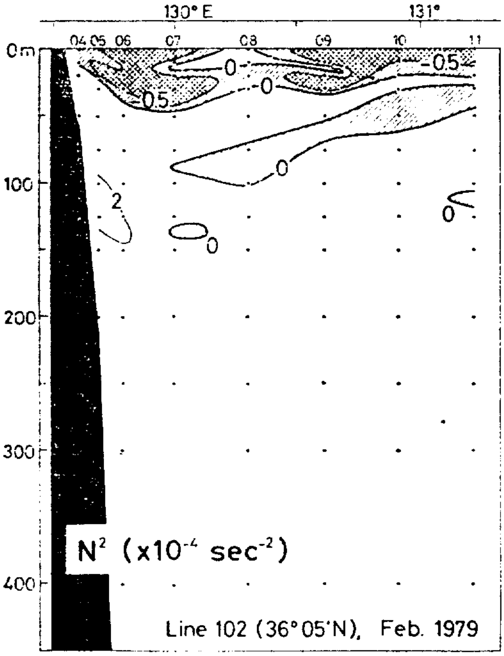

Fig. 5. Brunt-Väisälä frequency (N^2) profile along 36°05′ N(line 102) in February 1979. Diagonally-lined and hatched areas indicate regions with $0 > N^2 \geq -0.5 \times 10^{-4}$ sec^{-2} and $N^2 < -0.5 \times 10^{-4}$ sec^{-2}, respectively.

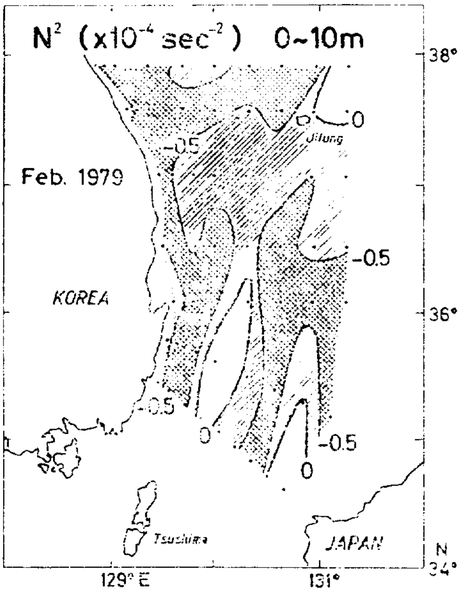

Fig. 6. Brunt-Väisälä frequency (N^2) distribution in the upper 10m in February 1979. Diagonally-lined and hatched areas indicate regions with $0 > N^2 \geq -0.5 \times 10^{-4}$ sec^{-2} and $N^2 < -0.5 \times 10^{-4}$ sec^{-2}, respectively.

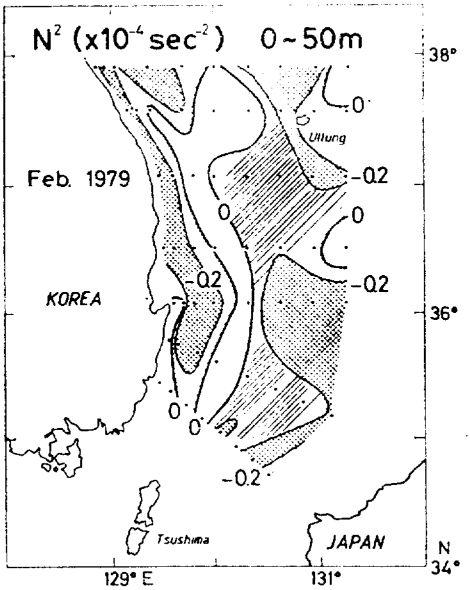

Fig. 7. Average Brunt-Väisälä frequency (N^2) distribution in the upper 50m in February 1979. Diagonally-lined and hatched areas indicate regions with $0 > N^2 \geq -0.2 \times 10^{-4}$ sec^{-2} and $N^2 < -0.2 \times 10^{-4}$ sec^{-2}, respectively.

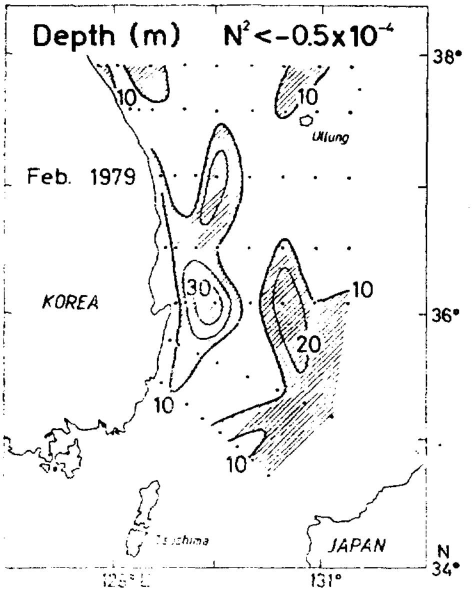

Fig. 8. Contours of depth with $N^2 < -0.5\times10^{-4}$ sec^{-2}, where N is Brunt-Väisälä frequency. Diagonally-lined areas indicate regions of comparatively strong inversion where inversion depth is deeper than 10m.

up to 50m. A comparison of Figs. 6 and 7 shows that the unstably stratified regions reduce with depth. Fig. 8 shows the distribution of the inversion depth which coincide with the strong unstably stratified regions of $N^2 < -0.5\times10^{-4}$ sec^{-2}. These unstable layers reach up to a few tens of meters in two parts along 36° N.

3. Density Inversions in Summer

As shown in Fig. 3, the frequency of temperature inversions in summer is much less than that in winter. So it seems that the density inversions hardly occur in summer. Fig. 9 shows a typical B-V frequency profile along the same section as in Fig. 5 in August 1979. A conspicuous vertical stability is formed in the surface layer because of the development of stratification. The small part near 250m of weakly unstable stratification seems to be resulted from data error.

Fig. 10 shows the horizontal distribution of

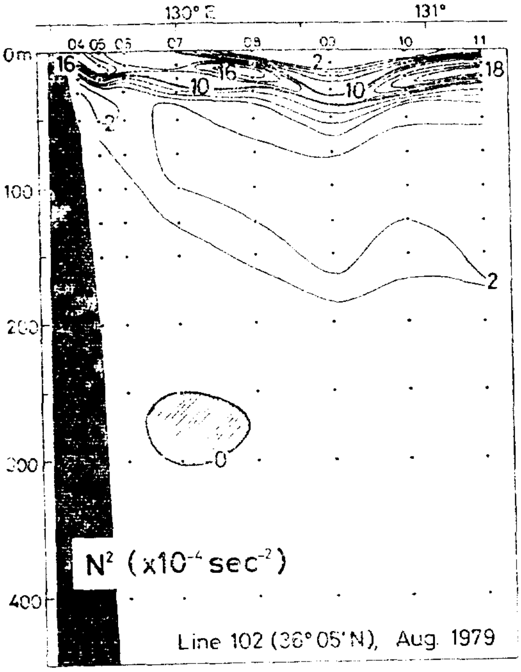

Fig. 9. Brunt-Väisälä frequency(N^2) profile along 36°05′ N (line 102) in August 1979. A diagonally-lined area indicates a region with negative values of N^2.

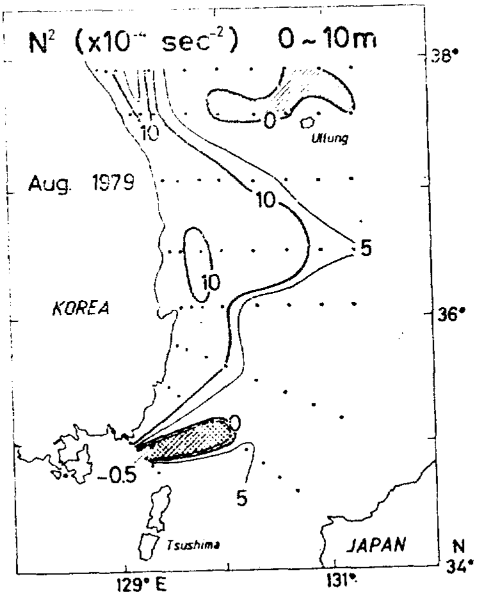

Fig. 10. Brunt-Väisälä frequency (N^2) distribution in the upper 10m in August 1979. Diagonally-lined and hatched areas indicate regions with $0>N^2\geq-0.5\times10^{-4}$ sec^{-2} and $N^2<-0.5\times10^{-4}$ sec^{-2}, respectively.

N^2 in the top 10m in August 1979. Almost all of the investigated area has stably stratified except small parts of north of the Tsushima Island and north of the Ullung Island. The region of north of the Tsushima Island is much unstable than that of the Ullung Island. Such unstable phenomena are found almost every year in the north of the Tsushima Island, but not so in the north of the Ullung Island. A major contribution of temperature inversions in summer shown in Fig. 3 is resulted from the temperature inversion in the north of the Tsushima Island. The density inversions in this region seems to occur due to a regional characteristic in summer.

DISCUSSION

1. Winter Inversions

The frequency distribution of temperature inversions indicates that the inversion phenomena frequently occur in surface layer during winter. So in the surface layer, the density inversions seem to be common phenomena near Korea in the Japan Sea in winter. In fact, as shown in Fig. 11, such inversion phenomena can be also found in February 1978, while the pattern of unstably stratified regions in 1978 is not the same as that in 1979.

So far we have considered the density inversions in the sea near Korea. Then we investigate the data obtained by JMA in February through March of 1979 in order to check whether the density inversions are ordinary phenomena in the Japan Sea or not. Fig. 12 shows the horizontal distribution of unstable layers in the Japan Sea. About one half of the Japan Sea is occupied by unstably stratified regions in winter. From Figs. 11 and 12, we can find that the density inversion phenomena in winter are not necessarily confined to specific area or time.

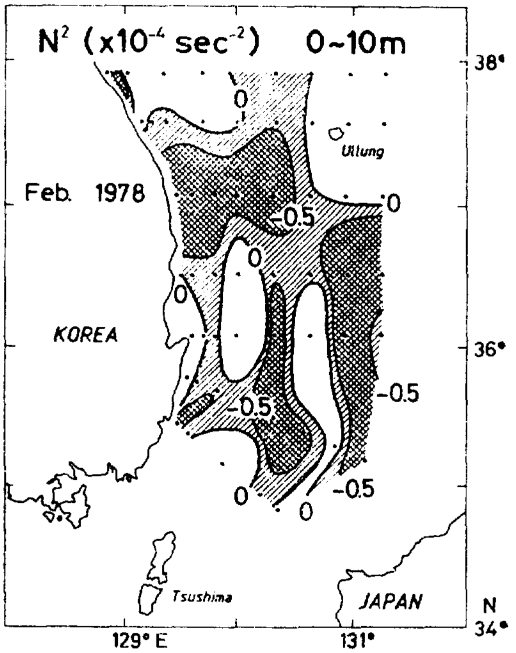

Fig. 11. Brunt-Väisälä frequency (N^2) distribution in the upper 10m in February 1978. Diagonally-lined and hatched areas indicate regions with $0>N^2\geq-0.5\times10^{-4}$ sec^{-2} and $N^2<-0.5\times10^{-4}$ sec^{-2}, respectively.

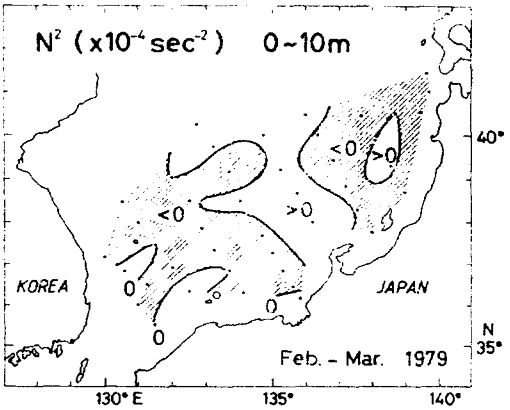

Fig. 12. Brunt-Väisälä frequency (N^2) distribution in the upper 10m in February through March 1979. Diagonally-lined areas indicate regions with negative values of N^2.

Kang's(1982) theoretical models show that the surface temperature inversion layer in winter can be generated by 1) the net heat

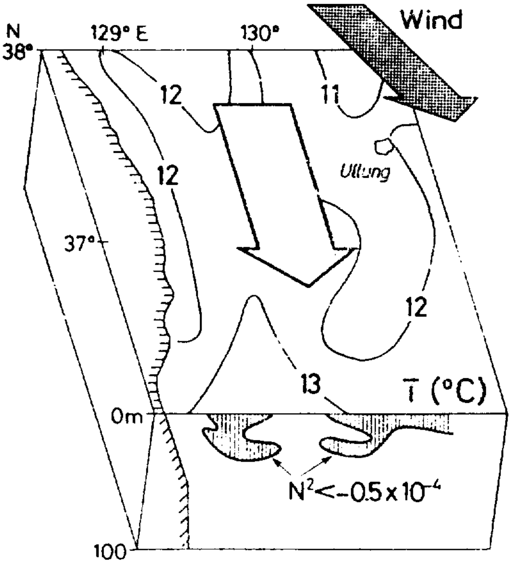

Fig. 13. Schematic representation explaining the formation mechanism of density inversion layer due to wind-driven Ekman current in the Japan Sea in winter.

loss at the sea surface, 2) the downward propagation of the seasonal temparature variations, and 3) the advection of cold water. Fig. 13, for example, shows the schematic formation mechanism of the surface density inversions associated with the advection of cold water. When a strong northwesterly monsoon sets in the Japan Sea in winter, the surface cold water advects southward due to wind-driven Ekman current, and cause the density inversions.

2. Summer Inversions

As already mentioned above, temperature inversions are found in the Korean Strait in summer. This area is famous as the region of coastal upwelling (e.g., Lim and Chang, 1969; An, 1974; Seung, 1974; Lee, 1978; Park, 1978), that is, the coastal cold water near Ulsan appears almost always in summer. The upwelling mechanism of cold water, however, seems to be different from each investigator.

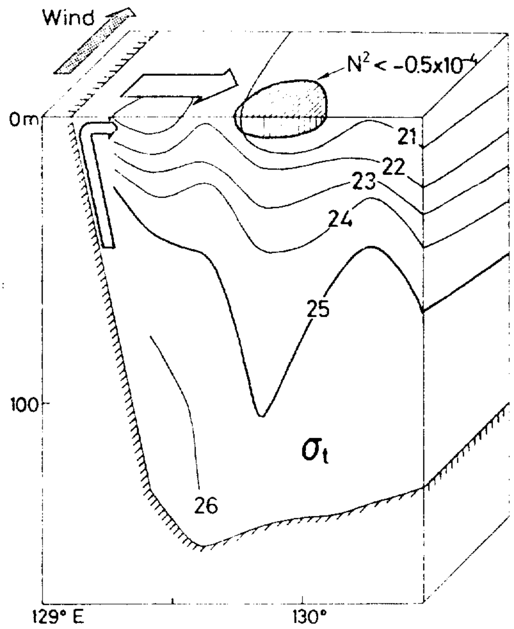

Fig. 14. Schematic representation explaining the formation mechanism of density inversion layer due to wind-driven Ekman drift in the offshore of the Korean Strait in summer.

Lee(1978) reported the temperature inversions in comparatively deep layer (between 50m and 120m) as a proof of the upwelling. As we see in Fig.3, however, the temperature inversions can be found not only in the comparatively deep layer but also in the top surface layer (within 20m), and these layers are usually formed in the offshore of the Korean Strait (Fig. 10).

From those observations, the density inversions in summer also seems to be formed by the advection of cold water due to the wind-driven Ekman current. This mechanism associated with the Ekman drift is shown in Fig. 14. The bottom cold water upwelled near Ulsan coast is supplied to the offshore of the Korean Strait due to a southwesterly wind, and as a result, it makes the surface layer unstable.

SUMMARY

The density inversions are found in the Japan Sea by investigating the oceanographic data of temperature and salinity from 1965 to 1979. In winter, the vertical distributions of both temperature and salinity in surface layer lead to the density inversions. The inversions occur at about one half of the Japan Sea, and they reach up to a few tens of meters in the surface layer. In Summer, however, the inversion layers are not formed except in the small part of the Korean Strait.

Such inversion phenomena can be explained by the advection of cold water in surface layer by the wind-driven Ekman current: In winter, the surface cold water flows southward along surface due to the strong northwesterly monsoon and causes the density inversions. In summer, the bottom cold water upwelled near Ulsan coast is supplied to the offshore of the Korean Strait due to the southwesterly wind and makes the surface layer unstable.

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한국 동해의 밀도역전 현상

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요약 : 1965년부터 1979년까지 한국 동해에서 관측된 온도 및 염분 자료를 이용하여 밀도역전 현상을 조사하였다. 그 결과 밀도역전은 여름보다 겨울에 많은 것으로 나타났다. 겨울에는 동해 전 해역의 절반정도에서 역전층이 형성되며, 여름에는 대한해협의 일부해협에서만 일어난다. 또한 역전층의 깊이는 보통 표층에서 수십m까지이다. 이와같은 역전현상은 표층 Ekman 수송에 의한 냉수의 이류로 설명할 수 있다. 즉, 겨울에는 북서 계절풍에 의한 표층 냉수의 남하로 인하여 생기며, 여름에는 남서풍에 의해서 연안 근처에서 용승된 저층 냉수가 대한해협 쪽으로 공급되어 일어난다고 생각된다.