해양환경안전학회 제15권 제3호, pp. 165-171, 2009. 9. 30. (ISSN 1229-3431)
Journal of the Korean Society of Marine Environment & Safety

Effects of Water Temperature Inversion on the Stratification Variation in October and December in the South Sea of Korea

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한국 남해에서 10월과 12월의 수온역전현상이 성층변동에 미치는 영향

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요 약 : 1999년 10월, 12월의 국립수산과학원 정선관측 자료를 이용하여 수온역전 현상이 성층변동에 미치는 영향을 분석하였다. 10월, 12월 모두 수심 25-75m사이에서 수온역전현상이 빈번하게 발생하며, 12월에는 표층 부근에도 수온역전현상이 나타났다. 고온, 고염분수인 쓰시마난류의 수평 이류가 10월, 12월에 나타나는 수온역전현상의 주원인으로 작용하며, 12월에는 연안역에서 외양역으로 수송되는 차가운 표층수의 영향이 함께 작용한다. 10월에는 북풍이 지속적으로 불지만 남해연안수가 외해역으로 확장하는 현상이 뚜렷하지 않는 반면, 북서풍계열의 풍속이 강해지고 쓰시마난류의 세력이 약해지는 12월에는 남해연안수가 상층부를 통해 외해역으로 확장하면서 수온역전현상을 나타나게 한다. 10월과 12월 모두 수온역전현상이 발생하는 해역을 따라 성층의 변동 폭이 크게 나타난다.

핵심용어 : 수온역전, 성층, 북풍, 쓰시마난류, 남해연안수

Abstract : *In order to illustrate the effects of water temperature inversion on the stratification variation in the South Sea of Korea, water temperature, salinity, and density measured in October and December 1999 by National Fisheries Research and Development Institute were reviewed. In October and December of 1999, temperature inversion occurred mainly between 25m and 75m, and in particular in depth of water, in December temperature inversion layer also was formed in the surface layer. In case of October and December, the Tsushima Warm Current (TWC), warm and saline water, was one of factors, and in December, influence of surface cold water was added. Although northerly wind prevails in October and December, in October, expanding of the South Korean Coastal Waters (SKCW) towards offshore is not clear, but in December when wind speed is relatively greater than that in October and strength of the TWC become weak, the SKCW spreads towards offshore through the upper layer. Stratification variation was higher along the area where temperature inversion occurred.*

Key Words : *Temperature inversion, Stratification, Northerly wind, Tsushima Warm Current, South Korean Coastal Waters*

1. Introduction

In the previous study, the authors described the difference of stratification strength in summer and winter, contribution of water temperature(temperature) and salinity on the change of stratification and expansion and shrinking of current(Lee et al., 2007). According to the result, stratification strength in summer and winter can be changed by buoyancy forcing due to the difference of temperature and salinity between sea surface and bottom, and horizontal advection of current which has different characteristics is considered as main factor leading to the difference of environmental factors between the layers. That is, change in current system with season may change the vertical structure of temperature and salinity. However, the paper did not deal with a change in vertical structure of temperature.

This study considers effect of change in vertical structure on stratification strength in October and December when northerly wind prevails.

Usually, temperature decrease with depth. That is, within the upper layer the water mass near the surface of the

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Earth is warmer than the water mass below it, largely because the upper layer is heated from above as solar radiation warms the sea surface, which in turn then warms the lower layer e.g. by convective heat transfer.

However, under certain conditions, the normal vertical temperature gradient is inverted such that the water mass is colder below the lower layer(Fig. 1). Temperature inversions in ocean which occur where the temperature profile with increasing depth, △T(T2-T1), changes from negative to positive are frequently observed in the surface layer of the sea adjacent to Korea (Nagata, 1967; Kim and Yug, 1983) (Fig. 1). Temperature inversion occurs mainly by sea surface cooling, advection of water, oceanic upwelling and it causes change of vertical structure and instability of water mass(Cho and Park, 1990).

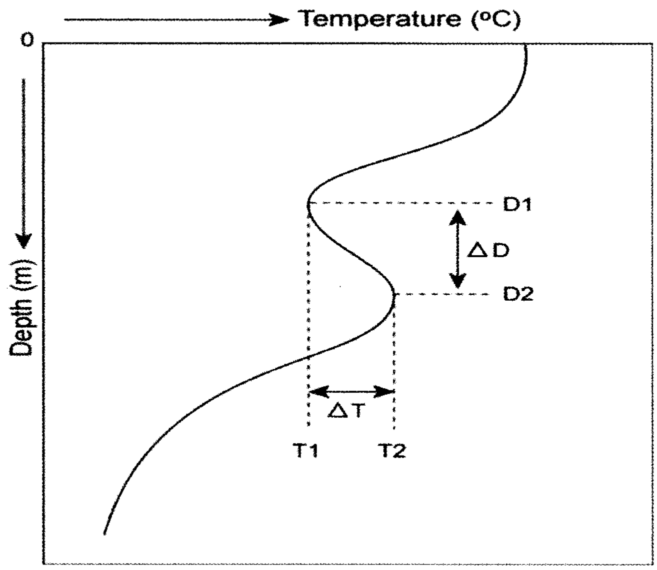

Fig. 1. Schematic view of the temperature inversion layer. T1 and T2 indicate temperature at depth D1 and D2, respectively.

Stratification-destratification phenomenon correlated with instability of water column have been done in many fields (Simpson and Hunter, 1974; Simpson and Bowers, 1979; Simpson and Bowers, 1981; Choi and Hong, 1997; Elliot and Clarke, 1991). The concept of stratification was introduced to understand the strength of stratification in the Irish Sea by Simpson and Hunter(1974).

The study area, South Sea of Korea, is the sea showing quite a complex characteristics because of advection, expansion, mixing, and diffusion(Kim and Yug, 1983; Lee et al., 2007). According to Lee et al.(2007), atmospheric heating and intrusion of the Tsushima Warm Current (TWC) in summer is one of cause affecting the change of stratification, and atmospheric cooling and expanding of the South Korean Coastal Waters(SKCW) in winter is considered as main factor causing the change of the stratification through water column. In particular, in summer, stratification increase under the influence of water temperature and salinity, however in December salinity makes the stratification weak. That is, expanding and shrinking of the SKCW and the TWC have influence on the change of stratification.

The aims of this paper are to illuminate the effect of temperature inversion by expanding and shrinking of the SKCW and the TWC on the stratification variation in October and December in the South Sea of Korea, 1999.

2. Data and methods

2.1. Oceanographic and wind Data

The data set observed by National Fisheries Research and Development Institute(NFRDI) in October and December 1999 along seven observation lines were used to illustrate stability of water column and temperature profile. CTD casts are consist of temperature(℃), salinity(psu), and density(σ_t) with depth interval of 1m. To grasp hydrographic condition broadly the infrared National Oceanographic and Atmospheric Administration-Advanced Very High Resolution Radiometers(NOAA-AVHRR) Sea Surface Temperature(SST) images from NFRDI near the observed time. Fig. 2 shows the locations of NFRDI stations.

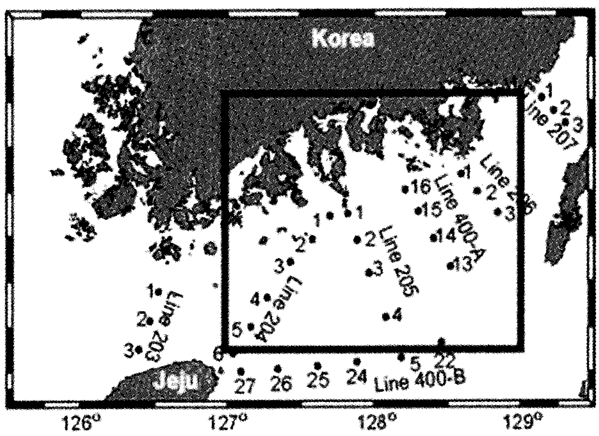

Fig. 2. Map showing the locations of oceanographic stations. Numerals indicate the station number and a rectangular represents the region W for NCEP wind data.

Wind data released from NCEP(National Centers for Environmental Prediction, data set is available at http://www.ncep.noaa.gov/) at the region W were used to illustrate the time-series change of wind speed and direction. According to Kim and Yug(1983), Na et al.(1990) and Lee et al.(2007), northerly(northwesterly) wind has influence on the expansion of SKCW.

2.2 Methods

In order to illustrate influence of temperature inversion on the stratification variation with month, stratification parameters on each station were calculated using Eqs.(1) and (2). Stratification strength is can be expressed as stratification parameter or stratification index which is defined as potential energy anomaly(PEA, $V(J/m^3)$, Simpson and Hunter, 1974). Potential energy anomaly is the difference in the potential energy of the water column before and after mixing.

$$V = \frac{1}{h}\int_{-h}^{0}(\rho-\overline{\rho})gzdz \quad (J/m^3) \qquad (1)$$

where

$$\overline{\rho} = \frac{1}{h}\int_{-h}^{0}\rho dz \quad (kg/m^3), \qquad (2)$$

h is depth, ρ is density(kg/m^3), g is gravity acceleration (m/s^2), and z is defined as positive up(m). Lee et al.(2007) explains in detail the parameters used in Eqs (1) and (2). The paper will be helpful to readers in understanding the equations. In particular, in order to illustrate the influence of temperature and salinity on V, V was calculated in three different ways;

V_{tot} indicate V calculated by using temperature and salinity, V_{tem} and V_{sal} represent the effect of temperature and salinity, respectively.

In this study, temperature inversion is defined as $\triangle T$ (T2-T1) changes from negative to positive(see Fig. 1). This inversion layer were display from vertical profile of temperature.

Daily wind direction and speed in October and December 1999 were calculated to explain the expansion of SKCW

3. Results and discussion

3.1 October 1999

Fig. 3 shows the distribution of V_{tot}, V_{tem}, and V_{sal} respectively in October 1999. V_{tot} increased toward the offshore. The distribution pattern of V_{tot} along inshore is similar to that of salinity, but along offshore the effect of the temperature is more apparent than that of the salinity.

V_{tot} is high(greater than 700J/m^3) especially in the western of Tsushima island and in the Korea straight, and this phenomenon seems to be caused by the large difference of temperature and salinity between surface and bottom layer(Fig. 4).

V_{tot} at stations located along offshore in the eastern part(Lines 206, 207, 400-A) of the study area is higher compared to those of the western part(Lines 203, 204, 205, 400-B). This can be explained by the expansion of Tsushima Warm Current. Fig. 5 is the 6-day averaged NOAA SST image. In this image, one can see the spatial difference of SST and the TWC push the SKCW toward the coast. SST in the western part is under 22 ℃, but SST in the eastern is from 24 to 25 ℃. In general, the distribution of SST matches well with that of V_{tem}, in particular along offshore where warm water mass moves towards the coastal waters. In addition, SST's pattern is similar to that of V_{tem} to some extent, and it means that large variation of temperature compared to salinity have much influence on V_{tot}.

This difference may cause the difference in V_{tot} in this season. V_{tot} is also high(greater than 480J/m^3) in the northeastern part of Jeju island, especially, stations 5, 6 along line 204. The difference between the surface and the bottom is also high(temperature: greater than 5 ℃, salinity: greater than 2 psu) in this area(Fig. 4). It seems that the difference between surface and bottom layer is correlated with horizontal advection of Tsushima Warm Current and this advection influence on the change of vertical profile of water properties(Figs, 5 and 6). That is, intrusion of warm water mass below the surface layer towards the coastal waters which relatively lower water mass occupies makes the difference be increase.

The temperature inversion phenomena were observed in October(Fig. 6). At stations where the phenomenon occurred, V_{tot} is high(greater than 480 J/m^3), especially toward offshore. This area is also affected by the temperature and the salinity at the same time. The reason is the buoyancy forcing by intrusion of the relatively higher temperature and higher salinity water below surface layer from offshore.

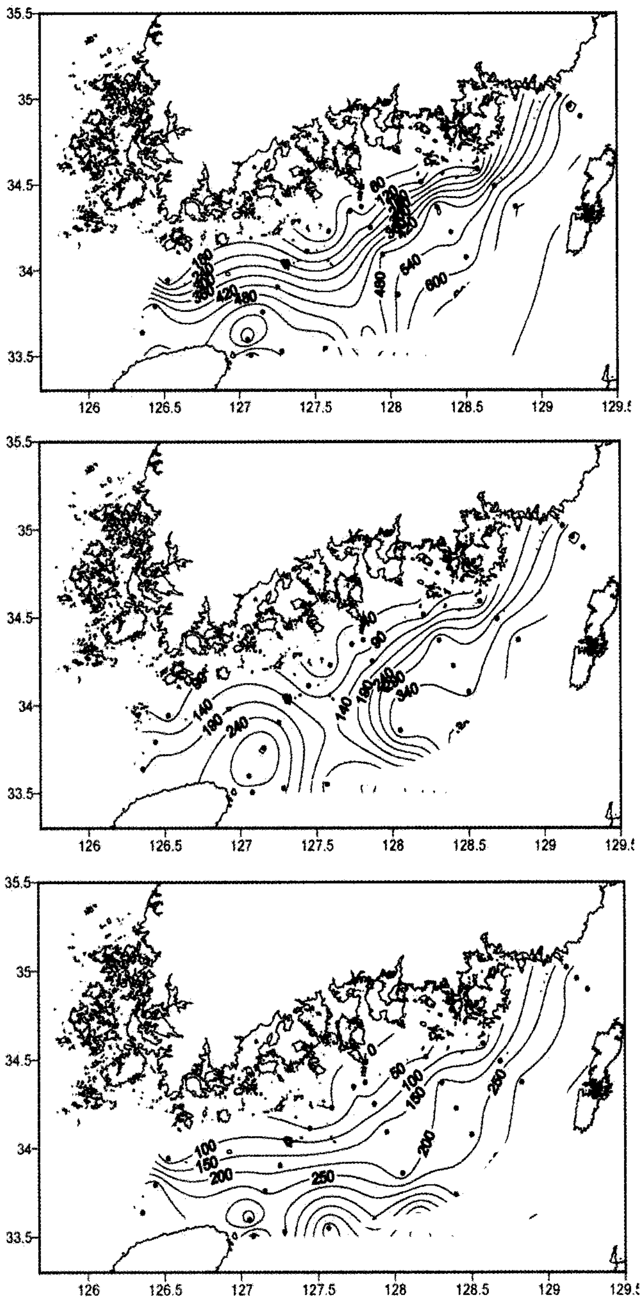

Fig. 3. Contour map of PEA(Potential Energy anomaly, J/m^3) in October 1999. Top: PEA(V_{tot}), Middle: PEA calculated using averaged temperature values(V_{tem}), Bottom: PEA calculated using averaged salinity values(V_{sal}).

Temperature inversion occurred mainly between 25 m and 75 m in the western and eastern part of the study area. According to Koo(2002), low salinity water lower than 32.6 psu occupies on the surface layer in October, 1999 in the northern part of Jeju island. As mentioned above, the advection of relatively high temperature and high salinity water from offshore is important factor changing the vertical structure.

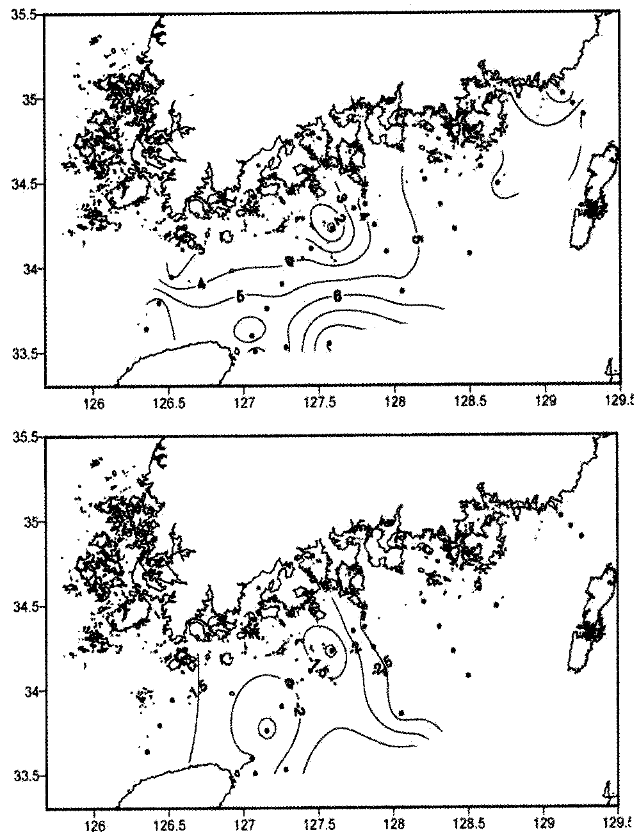

Fig. 4. Difference in temperature(upper) and salinity(lower) between surface and bottom layer in October 1999.

Fig. 5. Synthesized NOAA SST image from 14 October to 19 October including study area.

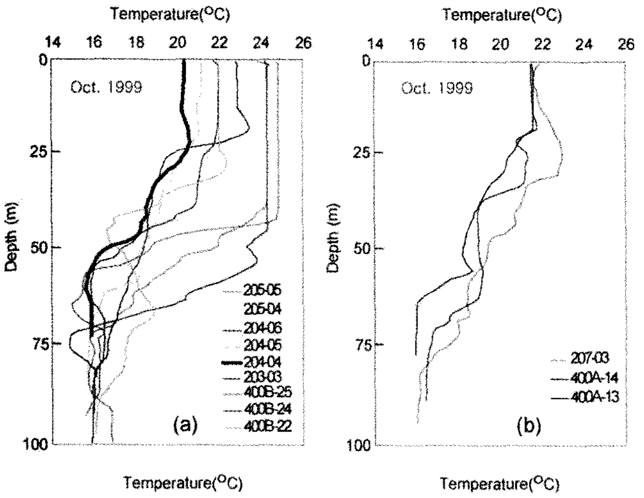

Fig. 6. Vertical temperature profiles of stations at which the temperature inversion phenomenon occurred in the western (a) and eastern (b) portion of the study area.

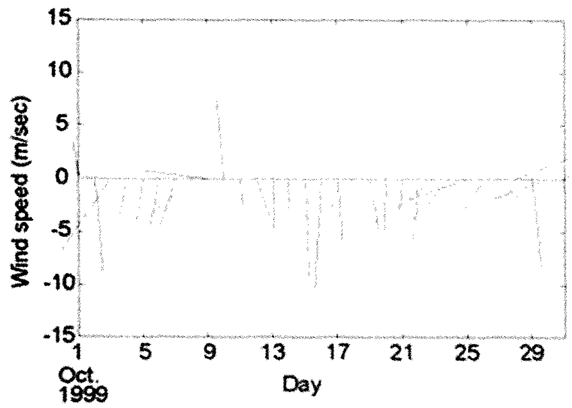

Fig. 7. Time-series of wind vector diagram from October 1st, 1999 to October 31th, 1999 in the region W.

In October, although northerly wind prevails(Fig. 7), expansion of SKCW towards offshore is not clear(Fig. 5). Approaching of the TWC to the coastal waters is dominant through the whole area of the study area except the western part of the Jeju island. In the South Sea of Korea, spreading of warm water towards the coast has close correlation with the speed and volume transport of the TWC with season. It will be addressed in section 3.2

3.2 December 1999

Fig. 8 shows the distribution of V_{tot}, V_{tem}, and V_{sal} respectively in December 1999. As shown in the figure, V_{tot} is much lower than that of the previous months, and this phenomenon is mainly derived from difference of temperature and salinity between upper layer and bottom layer. In Fig. 9, the difference of temperature and salinity is lower than that in October. It means that convective heat transfer through the water column is lively compared to that in October.

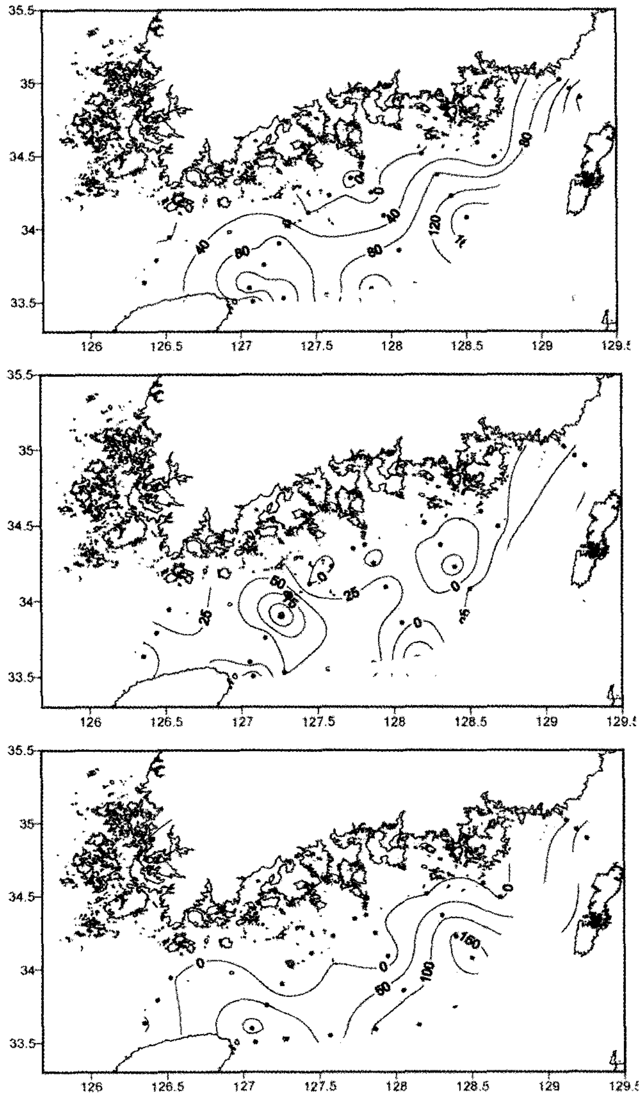

Fig. 8. Contour map of PEA(Potential Energy anomaly, J/m^3) in December 1999. Top: PEA(V_{tot}), Bottom: PEA calculated using averaged temperature values(V_{tem}), Middle: PEA calculated using averaged salinity values(V_{sal}).

The trend showing the increase of V_{tot} toward the offshore is similar. V_{tem} is high along line 400-B and in the Korea straight. V_{sal} is high in the western part of Tsushima island and line 204. The temperature of this region is high in the NOAA SST image. In the Korea straight, V_{tem} is a quite high(greater than 24 ℃). It seems that this phenomenon is also caused by the intrusion of the warm water just like line 400-B(Fig. 10).

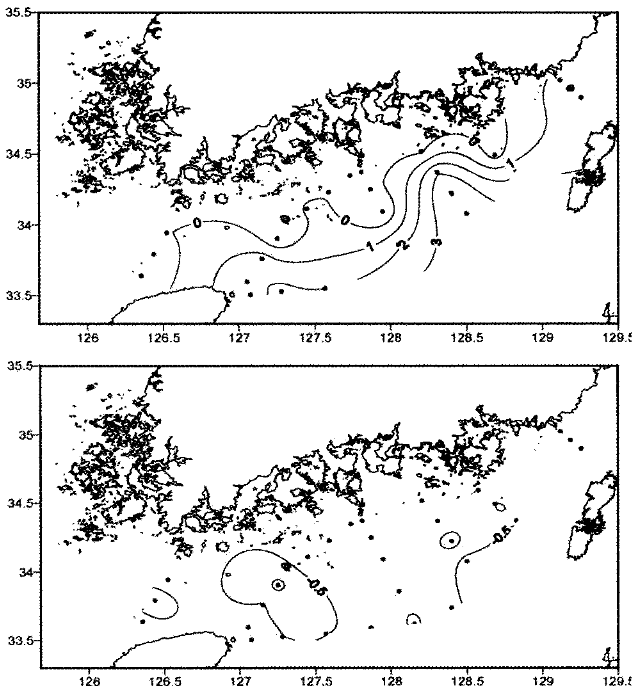

Fig. 9. Contour map of the differences between surface and bottom temperature(upper), and salinity in December 1999(lower).

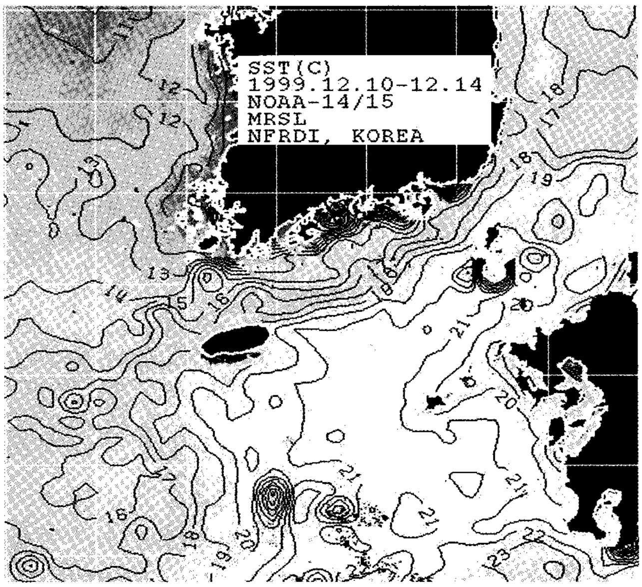

Fig. 10. Synthesized NOAA SST image from 10 December to 14 December including study area.

V_{sal} is high in the western part of Tsushima island and on line 204, and difference of the salinity between the surface and the bottom in the area is relatively high(Fig. 9). Therefore the vertical structure of the salinity causes the high V_{sal} in this region. In other words, the separation between the less saline upper layer and the more saline lower layer makes the stratification keep strong. The temperature inversion phenomena also observed in December(Fig. 11). Like that in October, temperature inversion layer formed mainly between 25 m and 75 m. However, in the surface layer, there was temperature inversion layer. It seems that drift of cold water from onshore is considered as main factor. According to Kim and Yug(1983) and Na et al.(1990), in winter, northerly wind prevails, and it makes bottom cold water be upwelled to the surface layer and then transported toward offshore. In the vertical profiles, the low temperature layer exists at the surface, and then the mixed layer and the thermocline exists in sequence. Beneath the thermocline, the warm water exists(i.e. the inversion). The lines linking the stations at which the inversion occurred is consistent with the isoline of zero of V_{tot}. The stratification is still remains because of the consistent intrusion of the TWC from offshore(the buoyancy forcing).

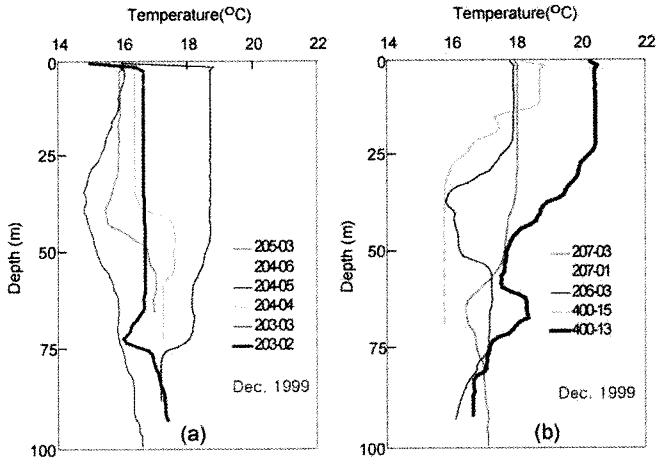

Fig. 11. Vertical temperature profiles of stations at which the temperature inversion phenomenon occurred in the western (a) and eastern (b) portion of the study area.

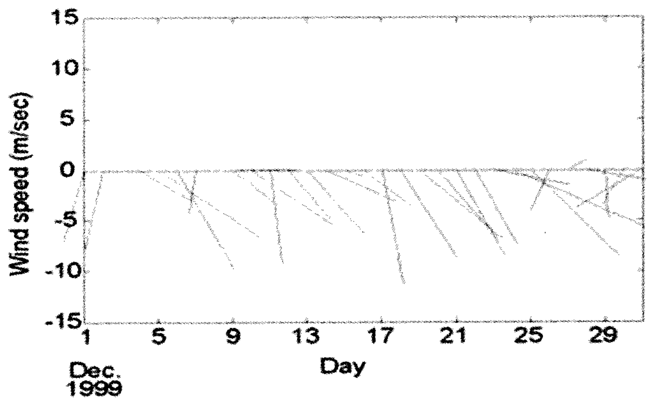

Fig. 12. Time-series of wind vector diagram from December 1st, 1999 to December 31th, 1999 in region W.

In December, northwesterly wind prevails and mean velocity, 5.82m/s, is greater than that in October, 3.73m/s(Figs. 7 and 12). According to Kim (2001), volume transport and current speed of the TWC in the western channel of Korea strait is maximum in October and minimum in January. Unlike October, in case of December, wind speed is strong compared to that in October, and strength of the TWC is more weak than that in October. This pattern in wind and current system may cause the difference in expansion and shrinking of the SKCW and the TWC in October and December. These movements cause the temperature inversion and the change in stability of water column. In particular, although northwesterly wind also prevails in October, spreading of SKCW towards offshore shrank up, and it seems that expanding of TWC is preventing SKCW from spreading towards offshore.

4. Conclusion

Temperature inversion is main factor causing change of vertical structure in water column, and this inversion occurs frequently around front. In particular, in the South Sea of Korea, water masses which have different properties occupy, and expanding and shrinking of these water masses vary with season. The SKCW, the TWC, monsoon are considered main factors changing oceanic conditions.

In the coastal waters, the boundary between the SKCW and the TWC is formed, and around the front temperature inversion occurs. Although northerly wind prevails in October and December, the extent of SKCW expanding is different. In October, the SKCW shrink up towards inshore, on the other hand it expands towards offshore in December when strength of TWC become weak. That is, unlike October, spreading of the SKCW towards offshore through the surface layer cause a temperature inversion in the surface layer.

Acknowledgements

This work was supported by the Korea Research Foundation Grant funded by Korea Government(MOEHRD, Basic Research Promotion Fund) (KRF-2008-331-F00038) and by Gangnung-Wonju National University.

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원고접수일 : 2009년 07월 20일
원고수정일 : 2009년 08월 06일 (1차)
2009년 09월 03일 (2차)
게재확정일 : 2009년 09월 24일