Stratification Variation of Summer and Winter in the South Waters of Korea

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ABSTRACT : *In order to calculate the strength and to see the variation of the stratification in the Southern Waters of Korea, the stratification parameter defined as potential energy anomaly (PEA, V(J/m³)) introduced by Simpson and Hunter (1974) was used. The data used in this paper were observed in August 1999 and February 2000 by National Fisheries Research and Development Institute (NFRDI). Also, to know the effects of the temperature and the salinity on the stratification respectively, averaged temperature and salinity were used in the process of calculation the parameter. V is generally high in the onshore and low in the offshore. However, in February, V in the onshore is higher than that of the offshore due to the vertical temperature gradient caused by the expansion of South Korean Coastal Waters (SKCW). In the summer, the increase of the atmospheric heating, the temperature inversion phenomenon act on the stratification as the buoyancy forcing. In most cases, the effect of the temperature on the stratification is stronger than that of the salinity. The temperature effect is predominantly due to the extent of the intrusion of Tsushima Warm Current into the study area. However, at stations where V is high the effect of the salinity is also significant. In the winter, V is very low due to the decrease of the buoyancy forcing, but some stations show the relatively high V due to the expansion of SKCW and Tsushima Warm Current.*

KEY WORDS : Stratification, Southern Waters of Korea, Temperature, Salinity, Tsushima Warm Current

1. Introduction

In general oceanic stratification, means density distribution of the fluid in the gravity field, is formed in the temperate latitudes by the increase of the sun's radiation (heat flux), the input of fresh-water or low-saline water (net fresh water) from the land (buoyancy forcing hereafter), and the decrease of the wind speed.

Stratification-destratification phenomenon (namely SD phenomenon) and the strength of stratification affect the material transfer between the upper and the lower water mass. Also, biological activities are influenced by the strength of stratification. After being stratified, the material transfer and circulation between the upper and the lower water mass are hindered[1]. In the beginning of the creation of stratification, the amount of phytoplankton is increased temporarily by the increase of the sun's radiation in the surface mixed layer. However, as the stratification is stronger, it limits the vertical movement of phytoplankton as a physical barrier. This cause the decrease of the primary production in a water mass[2]. In addition, stratification provides a barrier for nutrients between the generally nutrient-depleted surface layer and the nutrient-rich deeper layer[1].

Studies of the mechanism of SD phenomenon have been done in many areas. First, the concept of stratification parameter was introduced to understand the strength of stratification quantitatively in the Irish Sea[3], although it has been used basically to locate positions of tidal fronts. They constructed an energy argument and estimated the amount of energy to mix a stratified column by calculating the difference in the potential energy of the water column before and after mixing. The energy calculated is what is required to mix the stratified column. On the basis of the calculation, many works have been done in many areas[3-4]. Second, studies on the creation and maintenance of stratification, also, have been done so far in many aspects. The creation and maintenance of stratification has a close relationship with factors such as heat flux, wind speed, and tidal current[2,5-8]. Studies on biological aspects is the third. As mentioned above, stratification affects directly biological processes and material transfers between the upper and the lower layer in the ocean. The existence of stratification limit new production in continental shelf seas[9]. The growth of phytoplankton is partly dependent on stratification[10-11]. Fourth, in a point of physical view, Masuda *et al.*[12] suggested that stratification caused the change of Kuroshio current path. Guo *et al.*[13] reported that the effect of stratification on shelf edge flow. The understanding of stratification needs to tackle the propagation and the analysis of internal waves[14]

In order to acquire the knowledge of stratification in the Southern Waters of Korea quantitatively, Simpson and Hunter's equations were used. The strength and the distribution of stratification can be calculated by the equations. In a point of oceanographic view, the study area is the sea showing quite a complex characteristics because of advection, expansion, mixing, and diffusion (variation of water masses hereafter) among water masses. The variation of water masses may influence on the strength and the distribution of the study area. Since Simpson and Hunter's equations compute the strength of stratification by using density values at depths, results calculated by the equations will reflect the influence of the variation on stratification. The sea water density depends not only the temperature but also on the salinity, the structure of temperature and salinity of the water will affect stratification respectively. So stratification parameters at each stations were recalculated by using density values calculated by the averaged temperature or salinity ones.

In summary, the aims of this paper are to illuminate the seasonal distribution and the strength of stratification in the Southern Waters of Korea by Simpson and Hunter's equations, and to understand the relationship between the distribution of stratification parameter and the variation of water masses.

2. Data and methods

2.1. Oceanographic Data

The data set observed by NFRDI (National Fisheries Research and Development Institute) from August 1999 to April 2000 for this study were used to know the strength and the distribution of stratification. On all of the cruises has been done by NFRDI in the study area, there are seven observation lines. The data obtained with CTD casts are consist of temperature (℃), salinity (psu), and density (σ_t). Fig. 1 shows the locations of NFRDI stations of the study area.

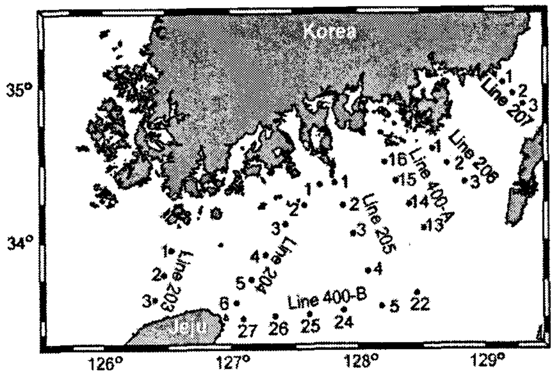

Fig. 1. Map showing the locations of oceanographic stations.

2.2. Meteorological Data

The month-averaged air temperature, the month-averaged wind speed, total precipitation in August 1999 and February 2000 were used in the monthly data report issued by KMA (Korea Meteorological Agency). Note that the month-averaged air temperature were used because there are no heat flux data. It is better, of course, to use the meteorological data observed at the same time with the ocean data. The local data of five weather stations near the study area were used. Table 1 shows the locations of weather stations.

Table 1. Location of weather observation stations

Location	Latitude	Longitude
Busan	35°06′N	129°02′E
Ulsan	35°33′N	129°19′E
Mokpo	34°49′N	126°22′E
Yeosu	34°44′N	127°45′E
Cheju	33°30′N	126°32′E

2.3. Methods

Calculation of stratification parameter

In order to know strength of stratification, stratification parameters on each station were calculated by the following equations. Stratification parameter or stratification index is can be defined as potential energy anomaly (PEA, V (J/m^3), Simpson and Hunter, 1974). It is the difference in the potential energy of the water column before and after mixing. In other words, the amount of energy required to mix a stratified column by the stratification (Mann and Lazier, 1996).

$$V = \frac{1}{h}\int_{-h}^{0}(\rho - \bar{\rho})gz\,dz \quad (J/m^3) \qquad (1)$$

where

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

h is the water depth, ρ is the density (kg/m^3), g is the gravity acceleration (m/s^2), and z is defined as positive up (m). For a vertically mixed system, $V = 0$, and for increasingly stable stratification, V becomes negative. When $V < 0$, tidal stirring and mixing due to wind stress bring about positive change in V[15]. V is meaningful measure of density stratification than the total surface to bottom (or to some arbitrary depth) density contrast, $\Delta\rho$, in that it takes into account the full density profile[3], usually. V in each month were represented as bar graph and contour at the same time.

In this paper, in order to examine the effects of temperature and salinity on V separately, V was computed in three different ways. Averaged temperature and salinity of the water columns were used through the process of the density calculation. And then V was recalculated by equations ((1) and (2)) with the density computed by averaged temperature and salinity. So three types of V were produced. To explain simply three types of notations will be used in this paper. First, V_{tot} represents V that calculated by using all temperature and salinity profiles. Second, V_{tem} shows the effect of temperature. The last one is V_{sal} that shows the effect of temperature. These were also represented as bar graph and contour monthly at the same time.

In this study, we use the data obtained during the CREAMS cruise in the southern part of the East Sea from June 10th to June 20th 1996 (all locations and topographic features are given in Fig. 2). Temperature (℃), salinity (psu), and dissolved oxygen (ml/l) were measured by CTD (Mark B type, Neil Brown) and the Rosette water sampler was used to calibrate the concentration level of salinity and dissolved oxygen.

The findings from the CREAMS cruise alone are insufficient for the analysis of the TWC's oceanic conditions in the southern part of the East Sea. Accordingly, temperatures measured by the Japan Meteorological Agency (JMA) in June of 1996 and the mean temperature averaged during the period from 1966 to 1995 in the East Sea, 30′ X 30′ resolution, by the Japan Sea National Fisheries Research Institute (JSNFRI) are used for areas the CREAMS cruise had not covered in the study area (Fig. 2).

3. Results and Discussion

3.1 Distribution of stratification parameter

Summer (August 1999)

In August, due to the higher atmospheric heating (Fig. 2), the buoyancy forcing increase in this season. V_{tot} is high in the offshore, and low in the onshore. Instead of the effect of the tidal currents, it is expected that the buoyancy forcing by the atmospheric heating and the fresh water made the stratification stronger in the onshore.

The maximum value is 836 J/㎥ at 205-05. The minimum is 53 J/㎥ at 204-02 (Fig. 3). The maximum and minimum values are highest during the year. V_{tot} is high in the northern area of Jeju island. It is though that the expansion of Tsushima Warm Current might affect to this area as a supplier of the buoyancy forcing. Fig. 3 shows the effect of temperature and salinity on the stratification in August respectively. As shown in the figures, the effect of temperature is stronger than that of salinity. The distribution of V_{tem} is much similar to that of V_{tot} (Fig. 3). Also, the values of V_{tem} is much higher than that of V_{sal}.

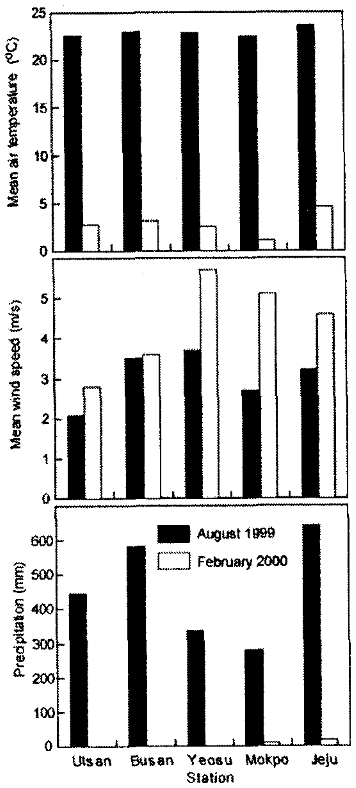

Fig. 2. Variation of mean air temperature (top), mean wind speed (middle) and precipitation (bottom) in August 1999 (■) and February 2000 (□) at weather stations located on Ulsan, Busan, Yeosu, Mokpo and Jeju.

Winter (February 2000)

The stratification is weakest in February. So V_{tot} is very low in this season due to the decrease of the atmospheric forcing (Fig. 2) and the strong winds (Fig. 2) even at stations in the offshore. The maximum value is 27 J/m³ at 204-03. The minimum is -7 J/m³ at 400B-25 (Fig. 4).

So the difference of the temperature and the salinity between the upper and the lower layers might cause the stratification. On line 400-A, the relatively low temperature (<13℃), low salinity (34.3) water exists in the onshore. At station 15 the effect of the temperature is strong due to the existence of the relatively warm water compared to the surroundings. However, at station 15, due to the salty water, the effect of the salinity is weak. Also, at stations 14 and 16, the salinity effect is strong. The isotherms along line 207 are declined from the onshore to the offshore, but not parallel to the surface. So V_{tem}, hence then V_{tot} is strong.

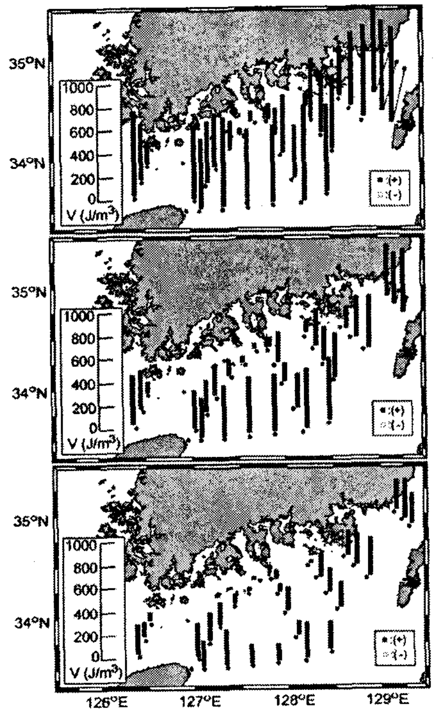

Fig. 3. Distribution of potential energy anomaly (PEA, J/m3) in August 1999 (top: PEA, middle: PEA calculated using average temperature values, bottom: PEA calculated using average salinity values).

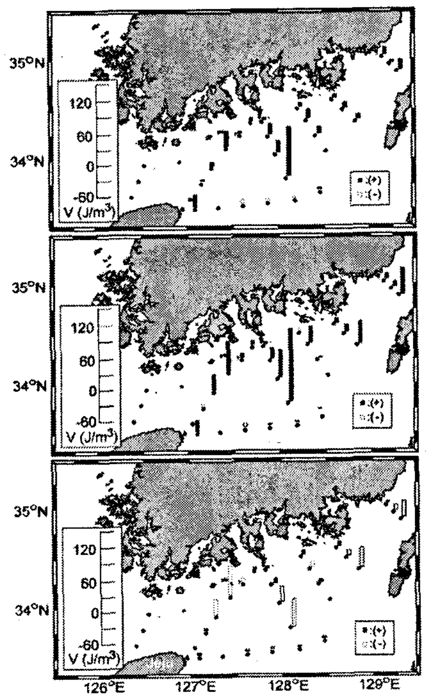

Fig. 4. Distribution of potential energy anomaly (PEA, J/m³) in February 2000 (top: PEA, middle: PEA calculated using average temperature values, bottom: PEA calculated using average salinity values).

Fig. 4 show the effect of temperature and salinity on the stratification in February respectively. The distributions of V_{tem} is similar to that of V_{tot}. Also, the regions where V_{tot} is high are predominantly affected by the temperature.

4. Discussion

4.1. Summer (August 1999)

Fig. 3 shows the distribution of V_{tot}, V_{tem}, and V_{sal} respectively in August 1999. As shown in the figure, the effect of the temperature is more apparent than that of the salinity in this season. However, the effect of the salinity is also seen unlike the previous month. In the area between line 204 and line 205, stations 25 and 24 along line 400-B, the effect of the salinity is weaker. The high temperature (>24 ℃) and salty (>32.8) water from the south flows into the study area (Fig. 5). So this water may result in some effect on V_{tot}. However, the differences of the temperature is significant in this area. For the case of the salinity, it is not significant in the Fig. 6. On the contrary, the value is lower compared to the other areas. In particular, V_{tot} along line 207 is strongest in this season. From Fig. 5, the intrusion of the water from the south is seen. In addition, the differences of the temperature and the salinity between the surface and the bottom are significant (Fig. 6). Also, the separation between the upper and the lower layers is apparent in figure 15. The relatively high temperature (>18 ℃) and less saline (<33.6) water places in the upper. Below the depth of 40 m, the relatively cold temperature (<17℃) and salty (>33.8) water exists. Therefore, V_{tot} of this region is highest due to the effects of the temperature and the salinity at the same time.

In general, the distribution of V_{tot} is controlled by the temperature and the salinity at the same time. However, the effect of the temperature is much significant. In other words, the vertical density distribution mainly by the vertical temperature plays a role in determining the strength of the stratification (i.e. V_{tot}).

As mentioned above, the differences of the onshore and the offshore V_{tot} are great. This phenomenon is also explained by the expansion of Tsushima current. In the summer, Tsushima current that is warmer and salty intrudes into South Korean Coastal Waters that is colder and less saline, or South Korean Coastal Water intrudes into Tsushima current. These intrusions cause the temperature inversion phenomena[16], and it may cause the increase in the strength of the stratification in some regions where the two different water masses meet can be stronger than the other areas due to the buoyancy forcing by the inversion phenomenon.

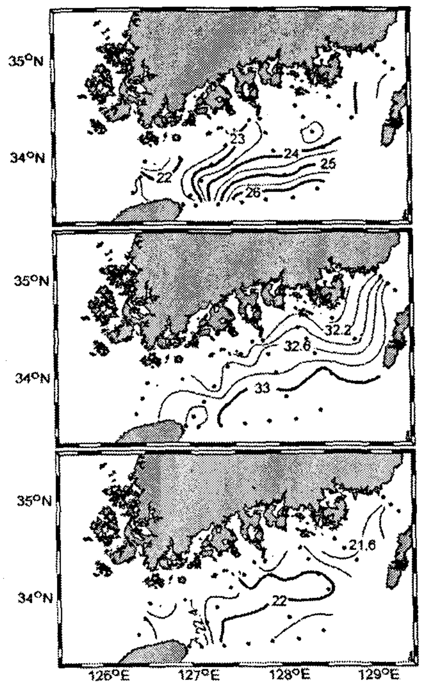

Fig. 5. Contour map of temperature (a), salinity (b), and density (c) at the surface in August 1999.

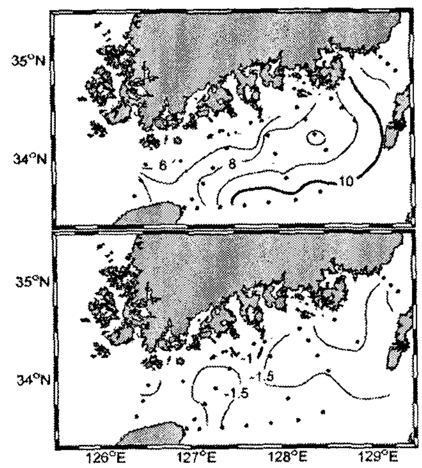

Fig. 6. Contour map of the differences between surface and bottom temperature (a), and salinity in August 1999.

4.2. Winter (February 2000)

Fig. 4 shows the distribution of V_{tot}, V_{tem}, and V_{sal} respectively in February 2000. V_{tot} is lowest in the year. As shown in the figure, the effect of the temperature is more apparent in this season. The distribution of V_{tot} is similar to that of V_{tem}. The trend showing the increase of V_{tot} toward the offshore is similar. The values of V_{sal} are almost negative almost all stations except for stations in the onshore. Therefore, it is concluded that the effect of the salinity is negligible in this season. The characteristic of the distribution of V_{tot} is that V_{tot} is higher in the onshore. In particular, V_{tot} is high on line 204, station 3 on line 204, stations 3 and 4 on line 205, and station 2 on line 400-A. According to the distribution of the temperature and the salinity at the surface (Fig. 7), the cold and less saline water exists in the onshore. On line 204, the stratification is developed at station 3. The water existing at the bottom shows the characteristics of South Korean Coastal Waters (SKCW) reported by Na *et al.*[17]. They reported that SKCW of which the temperature is <11 ℃ and the salinity is from 34.0 to 34.2. is formed by the cooling in the winter, and then it expands in sink or in drift by the northwesterly wind (Fig. 32, 33, and 34). Due to the existence of the SKCW in this season, the vertical gradient of the temperature between the upper and the lower layers occurs. Because of the gradient, the stratification is weakly formed although it is not strong. Also, SKCW was found on line 205. On line 205, the vertical gradient of the temperature causes the stratification. Where SKCW exists, the difference of the temperature between the upper and the lower layers is relatively high (Fig. 8). At station 2 on line 400-A, the water of 13 ℃ and 34.3 seems like drifting. The origin of this drifting mass is not clear, but the stratification is formed in this area due to this water.

In this study, the authors didn't consider the factors like tidal current, heat flux, wind, fresh water. However, because the water depth of the study area is mostly above 200 m, tidal current should be considered in the SD phenomenon. According to the previous studies, the strength of stratification is strongly dependent on the spring-neap tidal cycle in Deukryang Bay[18]. Pingree *et al.*[19] approached destratification from the point of view of the turbulent energy dissipation rate due to tidal flow on the continental shelf around British Isles.

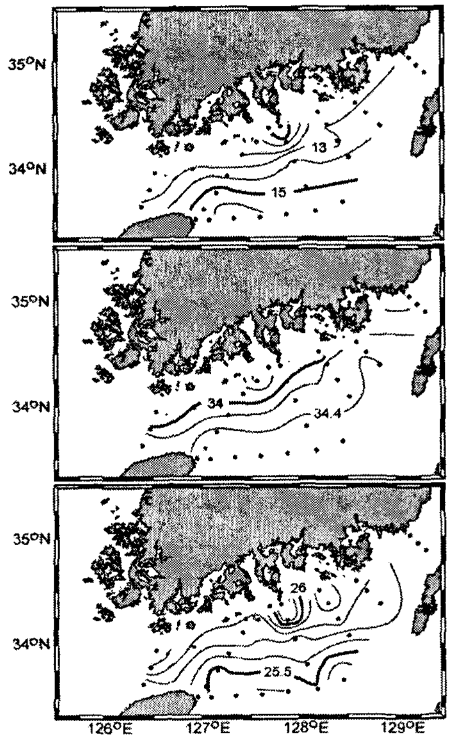

Fig. 7. Contour map of temperature (top), salinity (middle), and density (bottom) at the surface in February 2000.

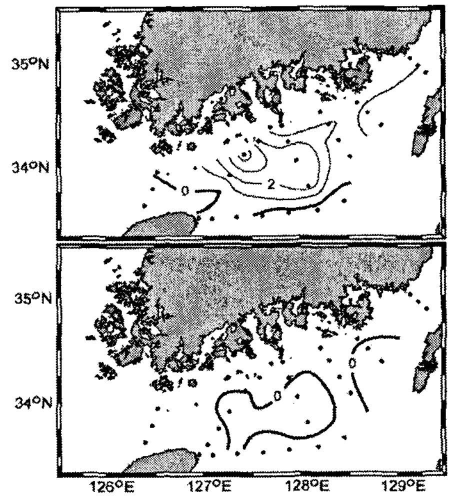

Fig. 8. Contour map of the differences between surface and bottom temperature (a), and salinity in February 2000.

Simpson and Bowers (1981) also reported that tidal current is a significant factor of destratification on the continental shelf around British Isles. Therefore, the role of tidal current might be important in the Southern Waters of Korea. As described above, the difference in stratification parameter between the coast and the open ocean is believed to be induced by tidal current. When a reliable observation of tidal current in the study area, the relation between tidal flows and stratification will be studied quantitatively.

Also, atmospheric heating of a water body induced by sun's radiation is related to SD phenomenon. For example, Bisagni[7-8], who studied the relation in Georges Bank, showed that interannual variability of V was controlled largely by interannual variability of heat flux, explaining up to ~80% of the variance, with interannual variability of wind mixing being of secondary importance.

A strong wind blowing for many hours can produce a surface mixed layer of a few tens of meters on the top of a stratified ocean. The thickness of this mixed layer is not greatly reduced by surface heating[20].

The buoyancy forcing into the sea surface due to precipitation or fresh water runoff sometimes plays an important role in producing stratification in the local area. For example, Garrett *et al.*[5] reported that the river discharge in May of $3.1\times10^3 m^3 s^{-1}$ produces a buoyancy forcing to the Bay of Fundy equivalent to the heat flux of 200 W^{-2} over an area of about 10,000 km^2. However, all the stations in the study area are far from the coast, so it is expected that the buoyancy forcing by fresh water input is not significant even in the summer.

Further work is required to produce more reliable results of the stratification phenomenon in the Southern Waters of Korea. If other factors are considered in the further work with more quantitative results, the parametric study that estimates the relative importance of each factor could be enabled.

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