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Ratio of Mixing Effects due to Wind, Surface Cooling, and Tide on West Coast of Korea in December, 1998

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Data obtained from a cruise from 4 ~ 12 December, 1998 was analyzed to estimate the mixing effects of wind, surface cooling, and tide. A band denoting a mixing area with a temperature difference of less than 1℃ between the sea surface and the bottom extended 40 ~ 60 km from the coast into the open sea, following 125° 30′ E in longitude. This band was divided into two areas; a well-mixed area close to the coast and a stratified region in the open sea. The mixing effect due to the surface cooling was about 30%, that is, one third of the total mixing effect. The mixing effect due to the wind was only 2%, yet the mixing effect due to the tides was about 68%. This indicates that surface cooling and tides were the major factors involved in the mixing mechanism on the west coast during the cooling season.

Key words : well-mixed area, mixing effect, surface cooling, stratified region, mixing mechanism.

1. Introduction

The water lying over the shelf in the Yellow Sea is strongly stratified except for a tidally mixed area near the coast. This water stratification along the coastal region is mainly controlled by heat flux from the surface of the sea plus tidal currents when the wind stress is not dominant. Normally, a spatial mixing and stratification problem in a coastal zone is strongly related to tidal forcing and solar heating effects. The boundary between a well mixed area and a stratified region can usually be classified according to the formula developed by [9]. Their criterion can be used for both the position of the tidal front and defining the stratification and destratification(S-D) problem along a coast[1,4,5,9].

The west sea of Korea has a strong tidal current and the mean depth is about 44 m. As such, the air-sea interaction is dominant and the distribution and properties of the water in this area are immediately influenced by seasonal or temporal variations in the weather conditions or tides, especially in the coastal region[2,6]. Stratification and mixing in a coastal area can be defined using the criterion of Simpson and Hunter(1974). In the west sea of Korea, the mixed layer starts to deepen in the autumn when surface cooling occurs during outbreaks of cold air. As a result, the low stability area is enlarged in autumn as compared to its size in spring. Furthermore, in autumn convective mixing due to surface cooling must be considered together with tidal mixing[6].

This study investigated mixing and stratification on the west coast of Korea during the winter season to determine the mixing effects of wind, surface cooling, and tides using observation data and the criterion of [9].

2. Data and Methods

The observations on the west sea were conducted by the West Sea Fisheries Research Institute (WSFRI), National Fisheries Research, and Development Institute(NFRDI) from 4 to 12 December, 1998. The temperature and salinity were monitored using a CTD(Guildline Co., Ltd., Canada) mounted on an R/V Incheon 888. This field observation was carried out as part of a bimonthly survey of the fisheries oceanographic environment in the west sea by the WSFRI. The weather data at Kunsan was taken from the monthly weather report of the Korea Meteorological Administration(KMA). The daily sea surface temperature at Kunsan was used for estimating the heat flux relative to the weather data during December.

The data analyses were focused on the mixing effects from wind, net surface cooling, and tides based on the formula developed by [9].

The equation of the mixing effect is as follows(Lee, 1996) :

$$\frac{dE_c}{dt} = \frac{g\alpha}{2C_p} Q_T H - eC_A\rho_a W^3 - \varepsilon C_D \rho_w U^3 \quad (1)$$

where ρ_a and ρ_w are the air and water densities, respectively, C_A and C_D are the surface and bottom drag coefficients, respectively, Q_T is the heat budget, g is the gravitational acceleration, H is the depth, e and ε are the efficiencies of the surface and bottom mixing processes, respectively, α is the thermal expansion, C_P is the specific heat coefficient, and W and U are the wind and tidal speeds, respectively.

The first term on the right hand side of equation (1) is the loss of potential energy due to surface heating, whereas the second and third terms are the rates change of kinematic energy due to wind and tidal currents, respectively.

Although this formula is usually used for defining a tidal front, many researchers have also used this formula to determine the division between a well-mixed area and a stratified area in a coastal region[1,4,5,9]. Therefore, it is assumed that other characteristics(e.g. advection, diffusion, etc.) are not concerned in the mixing, although these are important in the mixing mechanisms.

3. Results and Discussion

The temperature difference between the surface and the bottom is the most direct measure of how well-mixed a water column is. Fig. 1 shows the surface to bottom temperature difference in the west sea of Korea in December 1998. The distribution of a temperature difference of less than 1℃ between the surface and the bottom showed a coastal band in the west sea with vertically well-mixed conditions. The well-mixed area extended from the Taean peninsula to south of Mokpo, following approximately 125° 30′ E in longitude. The distribution of a 1℃ isopleth in temperature difference is similar to the position of a 40~50 m isobath, which corresponds to a tidal front or turbidity front[3,7].

To visualize the vertical structure of the water column, the vertical distributions of temperature, salinity, and density along line 309 are shown in Fig. 2. The homogeneous water column was clear in the coastal region, and the well-mixed and stratified regions were separated from each other centered around station 4.

Figs. 1 and 2 confirmed the existence stratification for a long way offshore from the coastal region, even though mixing starts from October in the Korea coastal area. This means that the tidal currents or wind cannot destroy the offshore stratification until December along the west coast of Korea. Therefore, it was decided to estimate the tidal current potential energy and heating in one particular area.

The predicted tidal height in the outer port of Kunsan from 1 to 15 December, 1998 is shown in Fig. 3. The observation date in line 309 was

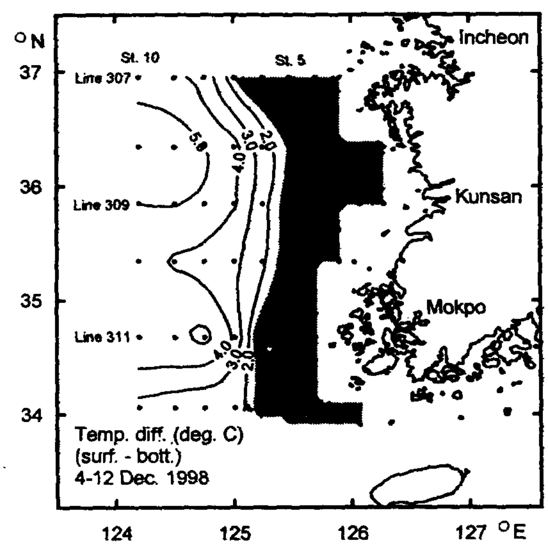

Fig. 1. Surface to bottom temperature differences in west sea of Korea from 4 to 12 December 1998. The hatched area denotes temperature differences of less than 1℃. The station numbers are the same in each line.

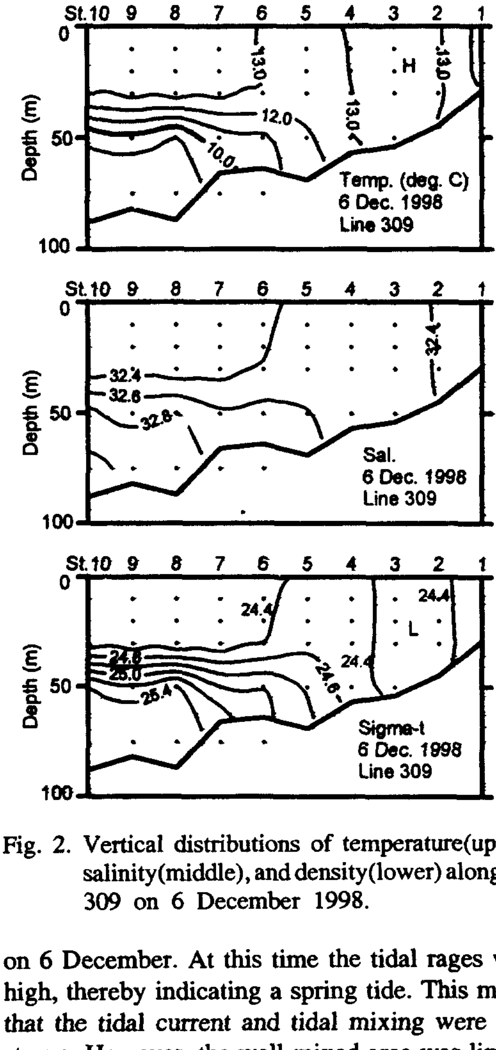

Fig. 2. Vertical distributions of temperature(upper), salinity(middle), and density(lower) along line 309 on 6 December 1998.

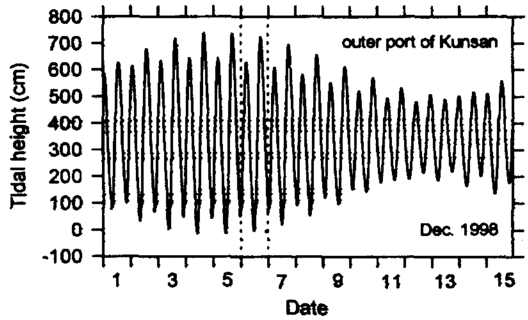

Fig. 3. Predicted tidal height for outer port of Kunsan from 1 to 15 December 1998. The vertical dashed lines denote the date of observation in line 309.

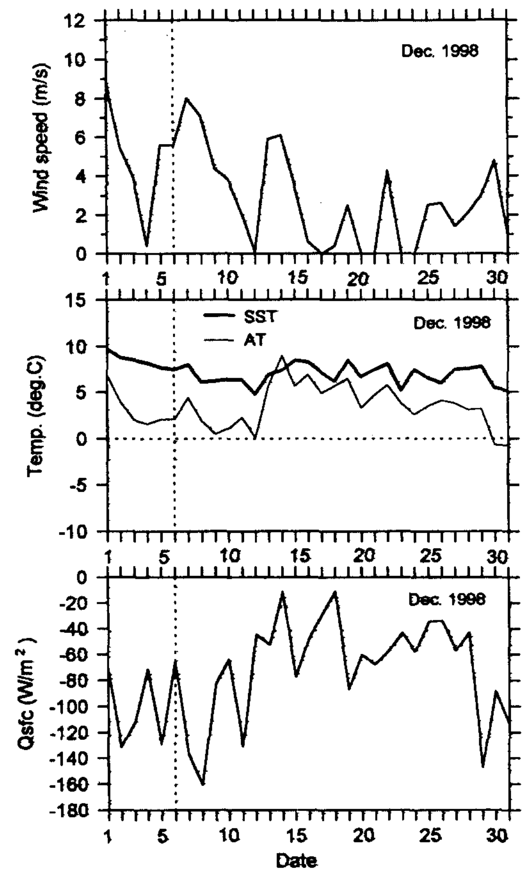

Fig. 4. Daily variations of wind speed(upper), sea surface temperature(full line), air temperature (dotted line)(middle), and net heat flux at sea surface(lower) at Kunsan from 1 to 31 December 1998. Dashed lines denote the date of observation in line 309.

on 6 December. At this time the tidal rages were high, thereby indicating a spring tide. This means that the tidal current and tidal mixing were very strong. However, the well-mixed area was limited to the coastal region, as shown in Fig. 2. [10] reported that the strength of a tidal current in the deep central part is weaker than that in the surrounding shallow part. This means that the vertical mixing effect induced by a tidal current in the deep central part is weaker than that in the surrounding shallow part. They also suggested that the vertical temperature distribution is affected by the horizontal difference of the vertical mixing induced by the tidal current. As a result, the mixing area is limited to the coastal region due to the strength of the tidal current as a result of the depth difference.

The observations were conducted in December in the winter season. Convective mixing due to surface cooling is very effective in winter in the

Yellow Sea, because its depth is shallow, the monsoon season is cool, and it's dry in winter. Convective mixing due to surface cooling is not negligible[6]. Therefore, this study examined the effect of certain weather factors, including wind and heat flux, on the sea surface.

Fig. 4 shows the daily variations in the wind speed, sea surface temperature, air temperature, and net heat flux on the sea surface at Kunsan during December. The wind speed was about 5～8 m/s, the temperature difference between the sea surface temperature and the air temperature was about 3～5℃, and the net heat flux was about -60～-90 W/m^2 before and after 6 December. This means that the wind speed was a little high, the heat loss through the sea surface by conduction was substantial, and the sea surface cooling proceeded more effectively in the beginning of December than at end of the month.

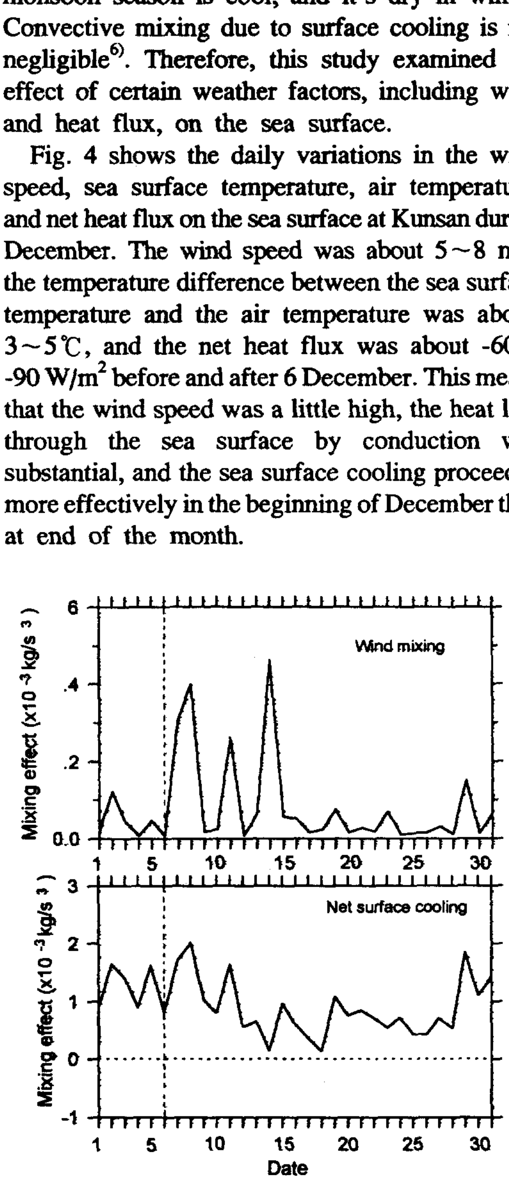

Fig. 5. Calculated mixing effects of wind(upper) and net surface cooling(lower) from 1 to 31 December 1998. The vertical dashed lines denote the date of observation in line 309.

Fig. 5 shows the estimated mixing effects of the wind and net surface cooling based on the data from Fig. 4. The mixing effect due to the wind was about 0～0.25 kg/s^3. The mixing effect due to the net surface cooling was about 0.2～2.0 kg/s^3. This indicates that the mixing effect due to the net surface cooling was stronger than that of the wind.

Fig. 6 shows the percentages of the mixing effect of the tides, net surface cooling, and wind during December. The mixing effect due to the tides was calculated as 0.5 m/s based on the tidal current off the west coast of Korea[3]. The percentages in brackets are the averages during December. The mixing effect due to tides was the most significant among the other factors. The mixing effect due to the net surface cooling was about 30%, that is, about one third of the mixing factors. However, the mixing effect due to the wind was only 2%, although this should not be neglected in the case of a gale or typhoon as special cases in the mixing mechanism.

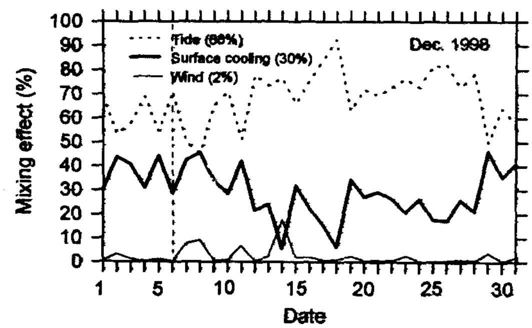

Fig. 6. Percentages of mixing effects of tide(thin dot line), net surface cooling(full line), and wind (thick dot line) from 1 to 31 December 1998. The vertical dashed line denotes the date of observation in line 309. The percentages in brackets are the mean values in December 1998.

4. Conclusions

The mixing area, denoted by a temperature difference of less than 1℃ between the sea surface and the bottom, was found to extend out into the open sea basically following 125° 30′ E in longitude. The extent of this band was limited to a 40～50 m isobath. Since this observation was conducted during the spring tide, the tidal current seemed to be the main factor for the mixing effects. Tidal mixing accounted for 68% of the mixing effects. Even though the mixing effect of the wind was very small at about 2%, the wind over the ocean was much stronger than that over the land. Therefore, the wind may have had more effect on the vertical mixing in the open sea. However, this issue needs further.

The mixing effect due to the surface cooling was about 30%, which was certainly not negligible. The net surface cooling is severe in the winter season because the Yellow Sea is shallow and has the characteristics of a semi-enclosed bay. Accordingly, it would appear that the mixing of the entire water column in February is responsible for the net surface cooling and an important factor in the mixing effect. Further study is needed to quantify the mixing effects throughout the year including seasonal variations.

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