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The Spatial Characteristics of Stratification in Deukryang Bay, Korea

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The spatial characteristics of stratification in Deukryang Bay were studied using observed data and analytical models. From the description of the density structure and its the potential energy anomaly (PEA) from observed data along longitudinal direction (from the mouth to head of the bay), we found that the stratification intensity could be changed strongly by density current effect during the spring-neap tidal cycle, and depth variation. To find out density current effect for the formation of the stratification in detail, we implemented a diagnostic approach by using the modified analytical model including density current, tidal current, surface heating and wind stirring. The model allowed for the observed similarities for the whole domain in the bay and increased tidal mixing efficiency value ε up to 0.006 - 0.007 as compared to the results without density current effect. We found that the density current effect was also an important key factor in determining the formation of the spatial distribution of stratification.

Key words : potential energy anomaly(PEA), stratification, density current, spatial distribution.

1. Introduction

The spatial mixing and stratification problem in coastal zone or estuaries is thought to be strongly related with surface heating, tidal and wind stirring and buoyancy effect by fresh water discharge or intrusion of high density water. In these, the vertical stirring associated with tidal current and wind stress has been easily touched in some areas to mixing and stratification made by the surface heating because of their barotropic characteristics. However, if we include density current effect for the stratification problem, that becomes so complex as it is hard to present the spatial distribution of stratification because the buoyancy input is localized at the lateral boundaries rather than being uniformly distributed over the surface and its strong baroclinic effects (Nunes et al. 1989; Simpson et al. 1991). Therefore, It can be only applied for the exceptional case.

After Simpson and Hunter(1974) prospposed a potential energy anomaly (PEA) intensity of sea water using a stratification parameter for the relation between the intensity of the bottom - generated turbulence induced by tidal energy dissipation and that of the surface heating for the stability of the water column in front region, there have been a lot of modified equation applied in continetal shelf sea. For example, Elliot and Clarke(1991) studied the spatial distribution of stratification and vertical mixing phenomena by the contributions of surface heating, wind stress and tidal stirring seasonally, Yanagi and Tamaru(1990) showed short periods of temporal and spatial changes of stratification in a channel, Czitrom et. al(1988) and Yanagi and Takahashi(1988) showed the effects of the buoyancy induced by river run off for the stratification intensity and Samagasinhe(1989) and Yanagi and Tamaru(1988) showed temporal and spring-neap tidal change of stratification for the bay. These results strongly supported that temporal and spatial changes of stratification intensity can be dominant phenomena in a bay unlike continental shelf area is sustained until autumn of which convective overturning and increasing wind speed eventually destroy the stratification. However, their studies of the bay are not enough for showing whole spatial characteristics of stratification effected by buoyancy effect induced by density current or river discharge. And Lee et al.(1996) showed the statification structure variations of one observation point in Deukryang Bay, Korea during tidal cycle, however they did'nt understand that the spatial stratification characteristics in the bay so that they did'nt understand what were main control factors to make stratification destriatication.

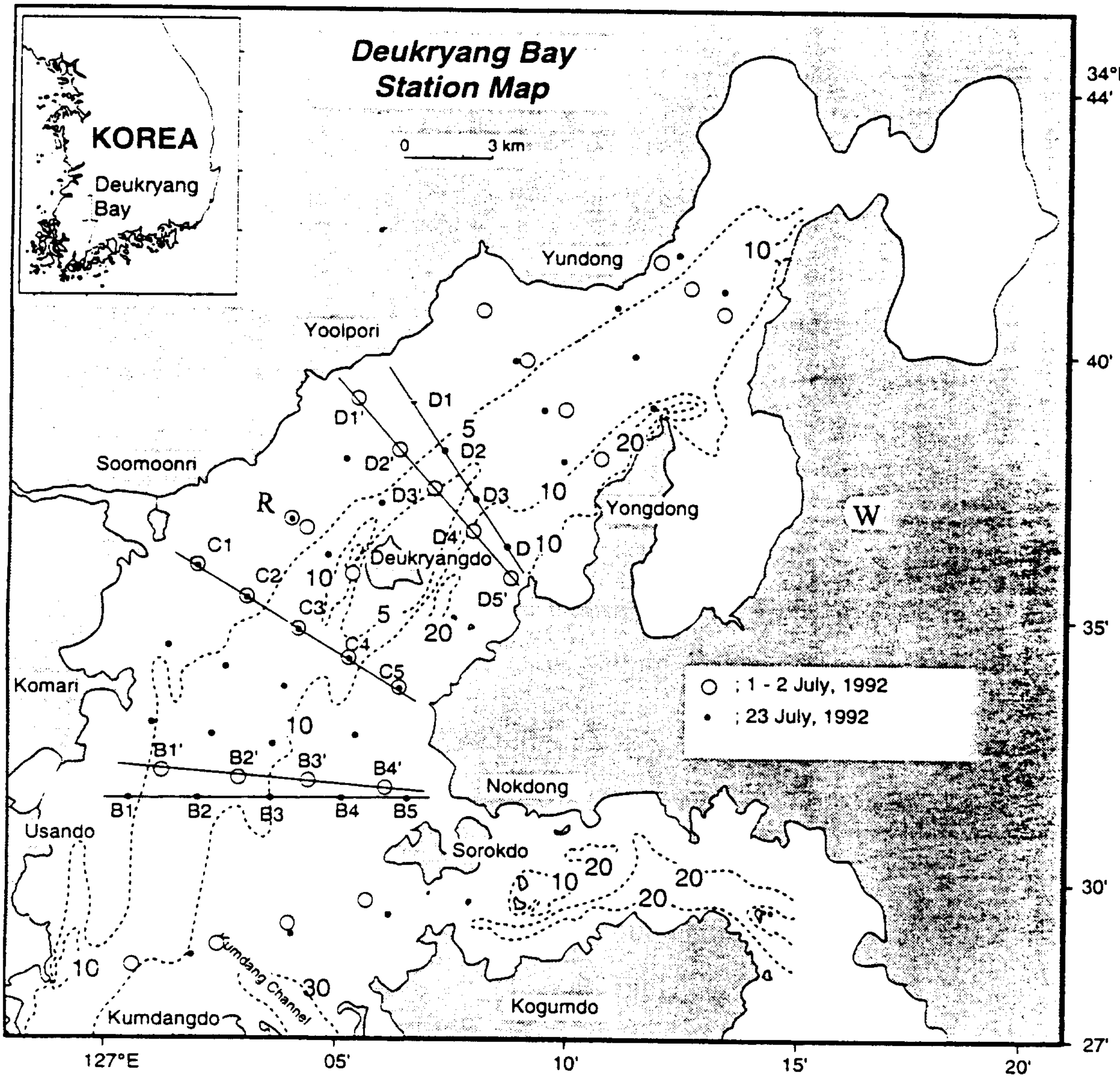

Fig. 1. Location of Observation Points in Deukryang Bay.

Our study area, Deukryang Bay, Korea(Fig.1) is small, less than 1000 km^2 and the depth consists of mainly two parts, deeper than 20 m in mouth and eastern side of the bay while shallower than 10 m in the head and western side although the averaged depth is only 7.5 m. Due to its geographic shape it though to be an area of intense tidal mixing and seems that buoyancy induced by density current and tidal stirring effects can be divided into two part, shallow and deep region. However, generally it is very hard to expect that the mainfest front line can be sustained continuously in summer as English Channel in U.K. or other large continetal shelf area since the strong tidal current in spring tide affects the whole depth of the bay as almost the same strength and results in strong vertical mixing.

In this paper, we compared the spatial distribution of potential energy anomaly(PEA) based on observation data with that by the numerical computation during spring-neap tidal cycle. We estimated what fraction of tidal power must be expended in mixing to prevent the formation of stratification as considering the tidal current, the density current and wind stress factors in the bay. Finally, we draw some results from PEA spatial dis-

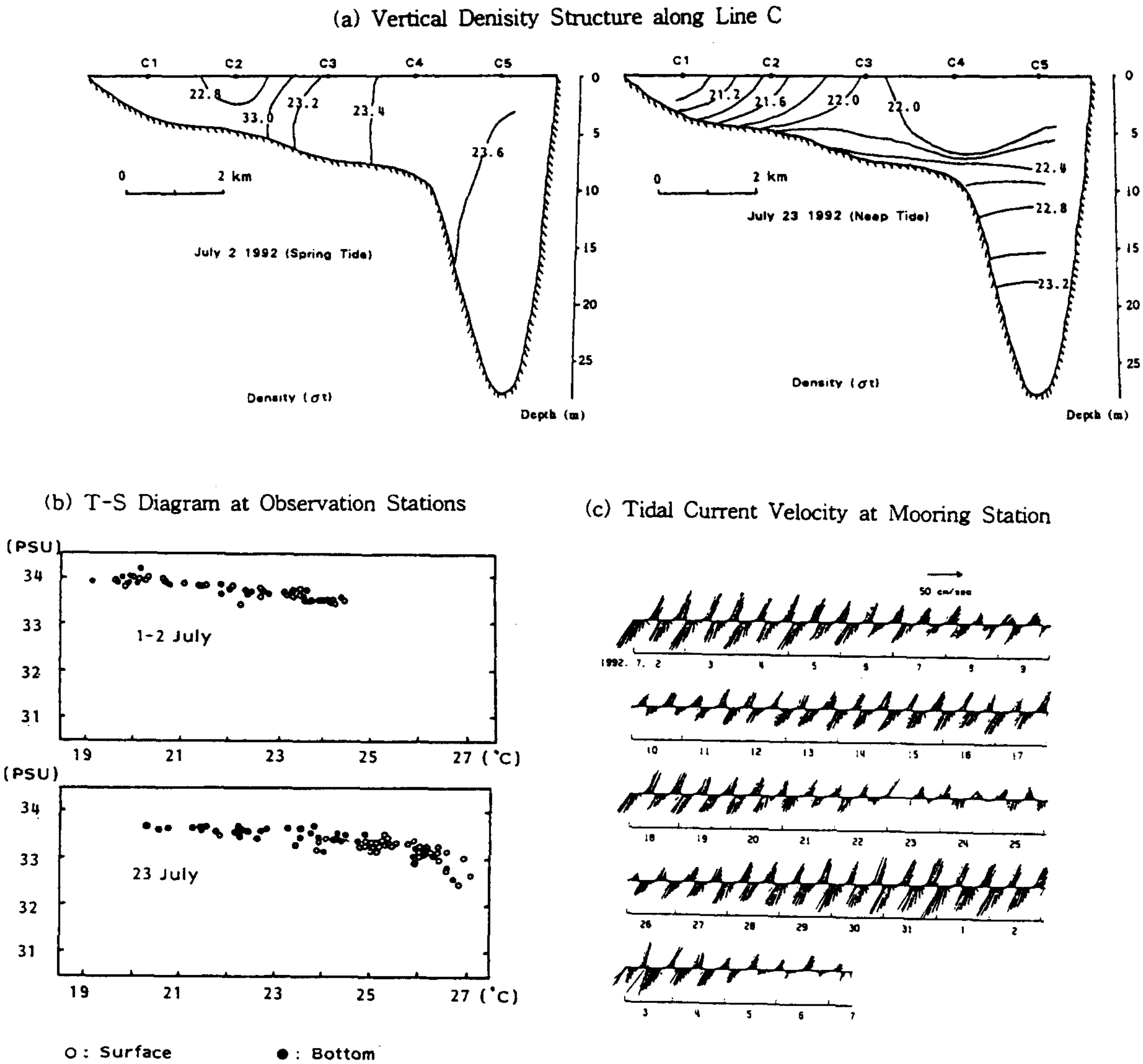

Fig. 2. Vertical Density Structure along C-line, T-S Diagram of Bottom and Surface, and Tidal Current Velocity from Spring to Neap Tide.

crepancy between the contours of the observation and those of the compuation. From the result, we predict PEA distribution and its constribution for the stratification intensity.

2. Data and Method

We observed temperature, salinity and density twice in 1-2 July (spring) and 23 July (neap), 1992, respectively. The selected stations were shown in Fig. 1 in which the first observation points were 27 and the second were extended to 37 for more detail observation so that the station positions between the first and the second were different except transect C. The mooring station of current meter was R and the wind speed was W, and the solar radiation S was selected at Kwangju City located far from the study area about 100 km since there is no meteorological center including the solar radiation data near the study area.

Fig. 2 presents T-S diagrams, vertical density structure along line C and tidal current using the observation data of the surface and bottom during the spring and the neap tidal periods. In the figure, the salinity variations were less than 1 PSU at twice observations and appeared to be insignificant compared to the temperature ones. The temperature in spring tide, ranged from 19 to 25 ℃ and the character of water mass between bot-

Table 1. PEA anomaly not including density effect based on several ε-Values (unit : kg sec^{-1})

ε-value	0.008	0.009	0.01	0.011	0.012	0.013	0.014
S	21.0	8.50	-4.9	-10.4	-18.6	-19.1	-20.8
D	-101.0	-127.2	-150.1	-163.2	-184.5	-192.4	-201.2
A	-40.1	-59.4	-77.5	-86.8	-101.6	-108.7	-111.0

S: shallow region. D: deep region. T: averaged values of S and D.

Table 2. The Averaged PEA of Density Current at Deep and Shallow Area (unit : kg sec^{-2})

Shallow	Deep	Ratio(Deep/Shallow)
88.9	530.0	6.0

tom and surface is almost the same while in neap tide the temperature from 20 to 27 ℃, water masses are separated into two parts. The intensity of the surface and bottom temperature gradient between neap and spring tidal periods was so much different. It seems that the thermal stratification was sufficiently developed in neap tide in spite of well mixed water in spring tide.

The vertical density structure indicated the drastic changes of vertical structures between two observation periods. From the figure, the vertical density structure in neap tide showed strong stratification while in spring tide vertically well mixing.

The tidal current variations is periodically changed during spring and neap tidal cycle. It gives that tidal current can be important role for the stratification in summer (Lee, 1996). Regarding this, SD characteristics in the bay can be mainly controlled by the the heat flux through the sea surface, tidal and wind stirring effects.

3. PEA Distribution from the Observation Data and Analytical Model including Sea Surface Heating, Tide and Wind Stress

To show the changes of stratification intensities spatially being based on twice observation data between spring-neap tidal cycle, we used PEA, which is called sometime the stratification parameter, proposed by Simpson et al.(1977) as,

$$E_s = \int_{-h}^{0} (\rho - \rho')gzdz \qquad (1)$$

where

$$\rho' = \frac{1}{h}\int_{-h}^{0} \rho dz$$

ρ is a density of a depth, *rho'* is averaged density of a total water column, h is total depth. The stratification parameter Es of Eq. (1) was calculated at every CTD observation points. Here, Es is the amount of work that would have to be carried out to bring about a vertically homogeneous distribution of sea waters.

As we assumed that stratification in the bay can be controlled by surface heating, tidal current amplitude and wind stress, the following formulae by Simpson et al.(1978) and Elliott and Clake (1991) was applied for a water column at station by station;

$$E_c = \int_{t0}^{t1} (\frac{g\alpha}{C_p} Q_t H - eC_a P_a U^3) dt \qquad (2)$$

where E_c is potential energy, t is time, Cp is the specific heat of seawater, U is the current velocity near bottom, α is the thermal expansion of seawater, Qt is the solar heating rate, H is the water depth, g is gavitaional velocity, and ρ_a are ρ_x the air and the water density, e and ε are surface and bottom efficiency of wind stress and tidal current Ca and Cd are the surface and bottom stress.

In equation (2), surface heating and wind stress have constant values for the space and are changed only by time so that we can easily estimate the rate of PEA induced by two terms spatially and temporary. However, tidal amplitude U is changed by space and time periodically from spring to neap tide. To solve the problem, we implemented the numerical model experiment using two-dimensional barotropic model of M tide proposed by Lee et al. (1992). That is, the ratio r(i,j) of the numerically calculated velocity amplitude of M tide at mooring point to that at other points is introduced as following,

$$U(i,j) = r(i,j)U_{obs(t)} \qquad (3)$$

$$r(i,j) = \frac{U(i,j)}{U_0} \qquad (4)$$

where U_0 is the calculated amplitude of M_2 tidal current at the grid point of mooring station, u(i,j) is that at other grid point in numerical domain. $U_{obs(t)}$ is the observed velocity amplitude from spring to neap tide at mooring station. From the equations, we can compute the strength of tidal current amplitude and roughly estimate the tidal velocity amplitude variation from spring to neap tide. The calculated M_2 tidal amplitude are shown (Lee, 1992). In the figure, the strong tidal current existed at east side (deep area), at mouth of the bay comparing to west side (shallow area). The general pattern of velocity reflects the characteristic of geometry of the bay. However, near the

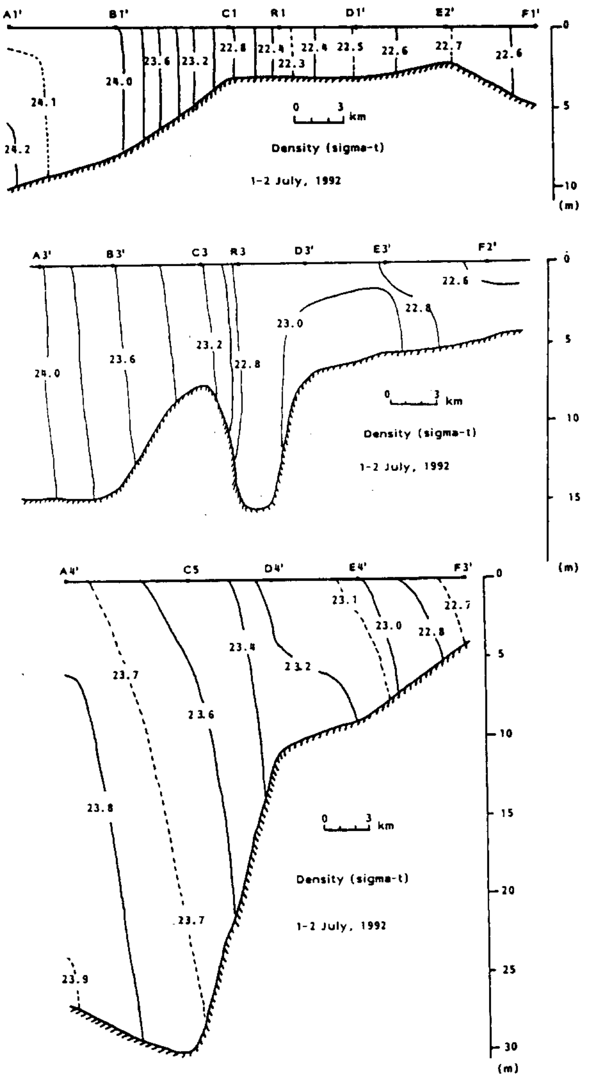

Fig. 3. Longitudinal density Structure for the Shallow, Middle and Deep Regions at Spring Tide.

mouth of bay it is very hard to see general flow pattern since the flows from three channel are mixed at the place.

Next, we integrated temporally Eq. (2) based on Eq. (4) from 1 July (spring) to 23 July (neap) in which we used tidal current efficiency ε = 0.008-0.014 since Lee et al. (1996) already estimated the values from observation values along transection C.

To check the discrepancy between the numerical and the observed results in whole domain more detail, we implemented that the observation results minus computation one at every observation station points directly as (log Es - log Ec). The difference between numerical model and observation data is shown in Table 1 where the plus value means that the observation PEA is larger than the computation i.e., the observed stratification is stronger than the expected one, while minus values is vice versa.

In the table, discrepancy shows plus values although at shallow region less than 10 m water depth and near open boundary discrepancy is 0 or mines value. Therefore, we notice that our numerical results underestimate the development of stratification except western shallow region. We assumed that the discrepancy occurred by two factors, one is the selected value proposed by Lee et al. (1996) is not reasonable since they chose the value from only transection C line, the other is the effect of density current.

However, when we tested, in Table 2, the discrepancy of PEA with respect to some values at two part, the shallow (less than 10 m) and the deep (more than 10 m) which can be characterized by different tidal stirring intensity and depths, there is no clear evidence of showing the similar pattern of observation because the averaged discrepancy between two part remains large according to selected several values although the averaged discrepancy is a little decreased.

4. PEA Distribution of Density Current

Our model including only surface heating, tidal and wind stirring factors predicted a litter distorted pattern and lower estimated values of PEA comparing to observed one, particularly around deeper part and Deukryang bay of the bay. The pattern is also not much changed by some ε -values. So we tried to consider the density current effect for the stratification.

To verify the density current effect qualitatively at first, we show the longitudinally vertical density structure along Shallow (S), Middle (M) and Deep (D)-lines shown in Fig. 3 and 4, respectively. The density structures at neap tide in Fig. 4 shows well-known general pattern of density current structure along the M and D lines where high density water intruded into downward from open ocean and lower density moved on upward from inner bay which results in a strong stratification and adds to PEA for a water column. At spring tide in Fig. 3, the vertical homogeneity prevails at all lines. However, the averaged density difference from mouth to head of bay at spring and neap tide is almost same although along shallow region (less than 10 m) a little difference occured com-

Table 3. Difference of PEA anomaly between observation and computation of ε-Values (unit : kg sec^{-1})

ε-value	0.013	0.015	0.016	0.017	0.018	0.019	0.020	0.021
S	26.5	22.4	13.2	8.4	1.5	-1.2	-3.9	-6.6
D	152.4	131.2	101.3	77.2	49.5	17.1	8.8	-7.5
A	89.5	76.8	57.3	42.8	25.5	8.0	2.5	-7.1

S: shallow region, D: deep region, A: averaged values of S and D.

Table 4. Difference of PEA anomaly between observation and computation of ε-Values with 1.5 large wind speed (unit : kg^3 sec^{-1})

ε-value	0.013	0.015	0.016	0.017	0.018	0.019	0.020	0.021
S	18.5	9.3	2.3	-1.3	-5.2	-9.6	-11.9	-13.1
D	142.1	111.1	90.4	57.2	39.5	14.1	-1.2	-17.7
A	80.3	60.2	46.4	28.0	17.2	2.3	-6.6	-15.4

S: shallow region, D: deep region, A: averaged values of S and D.

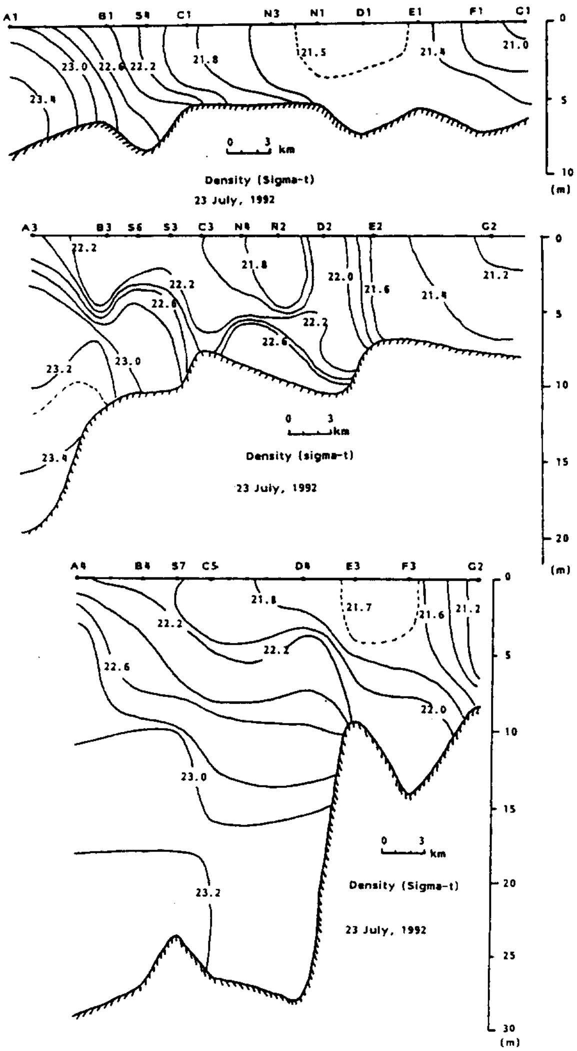

Fig. 4. Longitudinal Density Structure for the Shallow, Middle and Deep Regions at Neap Tide.

paring to deep one. This represents the averaged longitudinal density current gradient in the bay is similar. PEA induced by density current, however should be critically different since vertical density structure different from spring and neap tide.

Based on the general theory of density current which is proportional to depth and density difference according to Office (1978), Samaranasinghe (1989), Bowdwen (1979), the density current strength strongly depends on the depth variation, the density deference between the mouth and the head of bay and vertical eddy coefficient as following;

$$U_d = \frac{gh^3}{48<N_z>\rho}\frac{\partial\rho}{\partial x}(8z^3+9z^2-1) \quad (5)$$

N(t) = 0.017U(t)

where Z = z/h, z is arbitrary depth, N(t) is vertical eddy coefficient.

From the Eq. (5), we know that depth and density gradient are proportional to density velocity while the eddy coefficient is inverse to the velocity. It means that longitudinal direction of density current effect can be much changed from western part (shallow) to eastern part (deep) and the eddy coefficient in the bay and from spring to neap tidal cycle.

Using Eq. (5), Samaransighe (1989) proposed the following equation for PEA induced by density current and applied it to a Gulf St Viccent successfully.

$$\frac{ds}{dt} = g(\frac{\partial\rho}{\partial x})^2\frac{h^5}{320<N_z>\rho} \quad (6)$$

where U is in our case a day averaged tidal current amplitude from spring to neap tidal cycle so that the potential energy is small in spring and large in neap tide, respectively.

In procedure of density current calculation at station by station, we assumed that the longitudinal density gradient from mouth to head of the bay prevails than lateral one and is not changed during spring and neap tidal cycle which can be resticted as a predictive tool. However, in this case, the changes of PEA induced by density current is calculated by considering variation of eddy coefficient N(t) during spring-neap tidal cycle so that the main features of PEA distribution by density current will shown.

Using Eq.(6), we check PEA derived from density current at shallow and deep region respectively. The results show in Table 2. The deep is 7 times larger than the shallow one so that density current effect can be critically divided into two part.

5. PEA distribution from the Observation Data and Analytical Model including Sea Surface Heating, Tide, Wind Stress and Density Current

From previous study, PEA distribution induced by surface heating, tidal and wind stirring and density current constitutes a key determination of stratification in the bay was found at two chosen area, less than 10 m and more than 10 m. However, to understand the formation process of stratification in the bay quantitatively it is necessary to implement diagnostic approach using numerical model including four factors and then from its results to redefine new tidal mixing efficiency value.

The calculation procedures were carried out resulting from assimilation by Eq. (2) and Eq. (5) at station by station. So that we derived new equation as following;

$$E_c = \int_{t0}^{t1} \left(\frac{g\alpha}{2C_p} Q_T H - eC_A \rho_a W^3 - \varepsilon C_d \rho_w U^3 + \frac{(g\frac{\partial \rho}{\partial x})^2 h^5}{320 <\overline{N}_z> \rho} \right) dt \qquad (7)$$

Eq.(7) are complex form of Eq.(2) and (5). Using Eq.(7), we compared the observation results to analytical model. Then, the averaged values of that the observation PEA mines the computation one were taken at two chosen area, shallow(less than 10 m) and deep(larger than 10 m). The results are presented in Table 3 and 4, respecitively. In Table 4, W = 1.5 is wind is 1.5 time larger value taken than the observation one because the wind speed at land can be underestimated about half times comparing to on the sea surface (Yanagi, 1980; Imanuki, 1992). From the tables we can select an optimal values of tidal mixing efficiency and estimate wind stress effect. The table suggests that the reasonable tidal mixing efficiency is about ε = 0.0020 that is much increased up to 0.006 than case of without density current effect since in the study of Lee. et al. (1996) they assumed that the stratification is formed only by surface heating which derives underestimated stratification value in calculation procedure. However, as we included denstiy current effect for the formation of stratifiction, value is increased. The discrepancy values in the table between the deep and the shallow region is smaller than that of Table 1. It means that in this study density current can play an important role to define the formation of stratification and to select tidal mixing efficiency value while wind stress effect is not so dominant. Sign of ε value at shallow depth is faster changed than that of deep one. That is, vertical mixing induced by tidal stirring intensity is much effective at shallow than deep area. Therefore, the tidal stirring can destroy the stratification easily at shallow than at deep region.

Finally, we noticed that generally the pattern of stratification is much improved depending mainly on the balance between the stratifying influence by density current and the mixing influence of tidal current at deep region. At shallow the tidal mixing mainly affect the stratification phenomena.

6. Summary and Conclusion

Diagnostic approach using a modified model of Simpson and Hunter's equation (1974) was applied for the stratification phenomena during spring-neap tidal cycle in Deukryang bay. For reasonable estimation of contribution of surface heating, tidal and wind stirring and density current effects, we employed two dimensional model and Samaransinghe (1989)'s equation.

At first, PEA was computed by the model without density current effect and its result compared to the observation. The discrepancy between the observation and computation occurred, particularly deep region and around head of the bay. The computation results are underestimated comparing to mostly observation except western shallow region in the bay. It seems to be occured by neglecting density current effect or unresasonable estimated value. However, we check variation of PEA for the serveral values, the discrepancy is not so changed.

Next, we estimate the density current effect only to check the possibility of the contribution for the formation of stratification in the bay using the description of vertical structure of density. The results shows possibility of the density current effect for the stratification. The effect is critically divided into two part at shallow and deep region. The averaged PEA at deep is almost 6 times larger than that at the shallow. This suggests that the deep is an important route for the density current intrusion.

We finally tried to touch the diagnostic approach using numerical model including four factors, surface heating, density current, tidal and wind stirring for simulating the observation at all stations. The model successfully simulated the stratification characteristic comparing to observation one, particularly around upper part of Deukryang the bay and deep region. The model also allows that the deep part plays major role and the shallow minimal role. In procedure of the computation, the averaged discrepancy PEA between the calculation and the observation at shallow and deep, the PEA at shallow part is changed faster and smaller than that at deep one according to several values. It can be explained that the tidal current stirring intensity is more effective at the shallow than at the deep. Therefore, at shallow region tidal stirring effect is easily to overcome stratification formed in neap tide.

e also found that the reasonable ε value is about 0.020 which is about 0.006 increased ε values than without considering density current effects. It can be explained that the density current strongly contributed the formation of stratification, particularly at upper region of Deukryang bay and deep region.

From the study, the formation and intensity of stratification is mainly controlled and maintained by virtue of density current effect. Therefore, without considering density current effect, it is impossible to predict the stratification - destratification phenomena in the bay.

References

Bowden, K.F.(1983): Physical Oceanography of Coastal Water, John Wiley & Sons Inc., Brisbane, pp. 302.

Czitrom, S.P.R., Budeus, G. and G. Krause (1988): A Tidal Mixing Front in a Area Influenced by Land Runoff, Continental Shelf Research, 8, 225-237.

Elliott, A. J. and T. Clarke (1991): Seasonal Stratification in the Northwest European Shelf Seas, Continental Shelf Research 11, 467-492.

Griffin, D. A. and P. H. Leblond (1990): Estuary/Ocean Exchange Controlled by Spring-Neap Tidal Mixing, Estuarine, Coastal and Shelf Science 30, 275-297.

Imanuki, A. (1982): Turbulence and Atmosphere, Tokyodou Press, Tokyo, 191 pp. (in Japanese).

Lee, B. G., Hong, C. H. and K. D. Cho (1992): Two-Dimensional M_2 Tidal Current in Deukryang Bay, Korea, Abstract of 1st Domestic Conference of Research Center for Ocean Industrial Development, 5,

Lee, B. -G., Yanagi T., Takeoka, T., and K.-D. Cho (1996): The Stratification Variations during Spring and Neap Tidal Periods in Deukryang Bay, Korea. Bulletin de la Societe franco-japonaise d'oceanographie. 183-191.

Nunes Vaz, R.A., Lennon, G.W. and J.R. de Silva Samarasinghe (1989): The Negative Role of Turbulence in Estuarines Mass Transport, Estuarine, Coastal and Shelf Science, 28, 361-377.

Office, C. B. (1976): Physical Oceanography of Estuaries (and Associated Coastal Waters), New York: John Wiley, 465p.

Samarasinghe, J.R. de Silva (1989): Transient Salt-Wedges in a Tidal Gulf: A Criterion for Their Formation, Estuarine, Coastal and Shelf Science, 28, 129-148.

Simpson, J. H., Allen, C. M. and N. C. G. Morris (1978): Fronts on the Continental Shelf, Journal of Geophysical Research, 83, 4607-4614.

Simpson, J. H. and D. Bowers (1981): Models of Stratification and Frontal Movement in Shelf Seas, Deep Sea Research 28A, 727-738.

Simpson, J. H., Sharples, J. and T. P. Rippeth (1991): A Prescriptive Model for Stratification Induced by Freshwater Runoff, Estuarine, Coastal and Shelf Science, 33, 23-35.

Simpson, J. H. and J. R. Hunter (1974): Fronts in Irish Sea. Nature, 250, 404-406.

Yanagi, T. (1980): Variability of the Constant Flow in Osaka Bay, Journal of the Oceanographical Society of Japan 36, 246-252.

Yanagi, T (1981): Heat Budget of Uwajima Bay, Umi to Sora (Sea and Sky) 58, 13-20 (in Japanese).

Yanagi, T and H. Tamaru (1990): Temporal and Spatial Variation in a Tidal Front, Continental Shelf Research 7, 61-627.

Yanagi, T. and S. Takahasi (1988): A Tidal Front influenced by River Discharge, Dynamics of Atmosphere and Oceans, 12, 191-206.

The Spatial Characteristics of Stratification in Deukryang Bay, Korea

밀도류 효과에 의한 득량만의 성층변동 특성

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(1998년 1월 17일 접수)

득량만의 조석주기에 따른 성층특성을 연구하기 위하여 우선 30여개 관측점에서 관측된 수온, 염분, 밀도, 해류, 열수지, 바람, 밀도류 자료를 조사하였다. 이 관측자료를 토대로 성층현상을 규명할 수 있는 해석적 모델을 개발하였으며, 이 해석적모델을 이용하여 얻어진 연구결과에 따르면, 득량만의 성층을 이루는 요인은 조석, 태양열, 밀도류인 것으로 나타났으며, 성층을 파괴할 수 있는 조석에너지의 혼합에너지의 에너지 기여율 ε은 약 0.020 - 0.021정도 되는 것으로 나타났다.