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Temporal Variations of Stratification-Destratification in the Deukryang Bay, Korea

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Abstract

The quantitative estimations of the stratification - destratification(SD) phenomena in Deukryang Bay, Korea have been carried out based on the data of wind speed, heat flux through the sea surface and tidal current amplitude. To find out the main factors causing SD, we introduce the rate of energy balance of the surface heat flux, tidal and wind stirring proposed by Simpson and Hunter(1974). The calculated potential energy of three terms are compared, from which the energy of wind stirring effect was one order smaller than the heat flux and the tidal stirring. Using the results, we complement time integration of the potential energy with the several ε values of 0.010~0.014 at interval 0.001 and with wind speeds of 1.5 and 2.0 times larger than observation values at land. It shows that the variation of SD phenomena in the bay mainly depended on tidal stirring and sea surface heating in summer if there is no exceptionally strong wind event like Typhoon. The stratification become to be formed from about 5 July although the stratification a little decreases during the second spring tidal period of middle of July.

Key Words : Stratification, Destratification, Heat Flux, Tidal and Wind Stirring, Potnetial Energy, Spring Tide, ε-values

Introduction

The temporal variation of stratification in a coastal zone or estuaries can be divided into the seasonal and the spring-neap tidal cycle variation if the wind stress is not so dominant. In such condition, the tidal cycle change is basically very important to the variation of stratification since it is always primarily responsible for the vertical mixing.

Many oceanographers have studied stratification-destratification(SD) phenomena during spring-neap tidal cycle(Griffin *et al.*, 1990; Uncle *et al.*, 1990; Mackay *et al.*, 1990; Largier and Taljaard, 1991) since Simpson and Hunter (1974) proposed the governing equation on the balance between the time rate of change of the potential energy lost and gain in a water column. Particularly, SD phenomena in a tropical estuary has been observed and analyzed based on observation data by Uncles *et al.*(1990). Most of the study area, however was confirmed in a coastal zone and estuaries associated with fresh river water discharge or high salinity area. Basically they tried to explain the temporal variation of a front formed by the horizontal juxtaposition of two distinct water masses and the interaction between the different water mass. It means that the tidal effect in above study area was highly localized and geographically fixed. However, inner side of a small semi-enclosed bay or gulf in which Coriolis force is not dominant, not only the vertical mixing and stratification conditions can be changed abruptly for the all domain, but also fully stratified and fully mixed waters takes place over short time periods, respectively.

Samarasinghe(1989) pointed out temporal changes of salt-wedges movements of the whole domain during spring-neap tidal cycle at the Shark Bay in the Australian Bight, and explained the phenomena based on a density current effect. But he did not show the critical changes of stratification during spring and neap tidal periods in the bay and did not estimate the relationship of other environmental factors.

In Korea, there are so many bays near southern part of the country and their sizes are mostly less than $1000km^2$, where tidal current is predominant and affects oceanic phenomena for the whole domain of the bays. The Deukryang Bay, one of such bays is a semi-enclosed with three open channels. The area is approximately $374.4km^2$ and the average depth 7.5m(Fig. 1). The eastern part of the bay dips steeply about 30m while depth decreases slowly on western part less than 5m depth. Due to its geographical shape, the bay seems to be subjected to tidal current effect so much.

The general hydrographical and meteorological data in the bay had been collected by KODC (1989) and Kim (1992). From the data, we found that the average temperature difference between the surface and the bottom in summer is within 3 ℃ and the salinity is less than 1 PSU and a little fresh water discharges from near Soomoonri at western part of the bay (Fig.1). It means that surface water is a little warmer and fresher and the lower is colder and more saline. However, the averaged vertical density stratification is not strong. The monthly averaged air temperature is 26℃ and wind speed is less than 2m/sec in summer. According to the data, meteorological factors were not critically changed during summer.

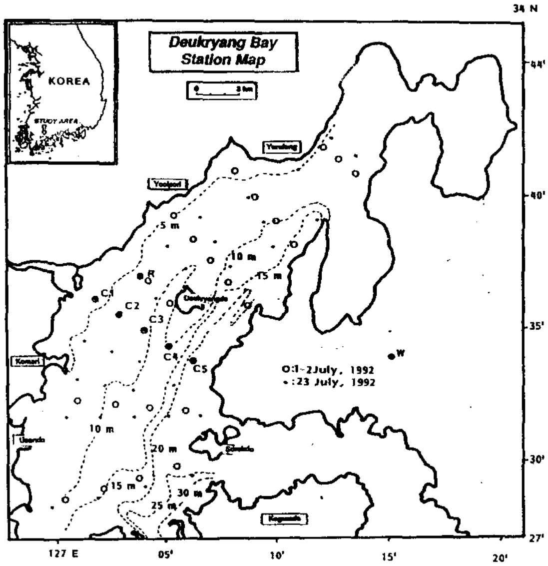

Fig. 1. Location of the Deukryang Bay and Observation Points in 1-2 July and 23 July, 1992.

Tidal elevation ranges are less than 2m and the tidal current ranges from 0.2m/sec in neap tide to 0.6m/sec in spring tide in which semi-diurnal component is dominant(Lee, 1992). Regarding these, it is expected that the effect of tidal current for driving the vertical mixing will be drastically changed in summer.

The objectives of this paper are first to show the drastic changes of SD phenomena during short periods between spring - neap tidal cycle, and second we check the magnitudes and variations of wind speed, sea surface heat flux and tidal current amplitude. Finally, we estimate the rate of potential and kinetic energy balance from observed data, in addition to predict the beginning and the end time of SD phenomena.

Hydrographic Structures in Spring and Neap Tidal Periods

We observed temperature and salinity 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.

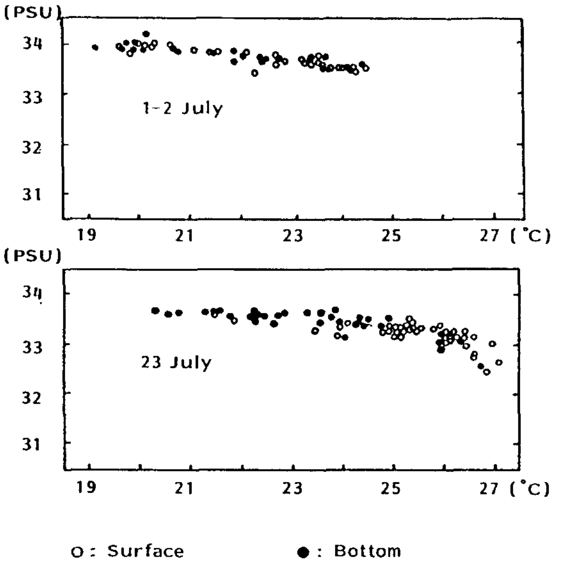

Fig. 2. The Variations of Temperature and Salinity from Bottom to Surface(T-S diagram) during Spring and Neap Tidal Cycle.

Fig. 2 presents T-S diagrams for the observation data at all station of 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 bottom 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.

Fig. 3 was constructed to present vertical temperature, salinity and density distributions, along section C. The data indicated the drastic changes of vertical structures between two observation periods. From the figure, the vertical temperature and density gradients in neap tide showed strong stratification while in spring tide vertically well mixing. The temperature variations at spring and neap tide are larger than the salinity one so that the temperature is more effective to form vertical stratification in the periods. At C1, C2, and C3, the partially mixed form in neap tide appeared that is probably caused by the vertical mixing of weak tidal or wind stress because of shallow water depth, and the relatively low salinity seemed to be affected by fresh water discharged from land. However, it looks like local phenomena since it occurred only shallow region limited less than 5 m depth. Regarding this, SD characteristics in the bay can be mainly controlled by the the heat flux through

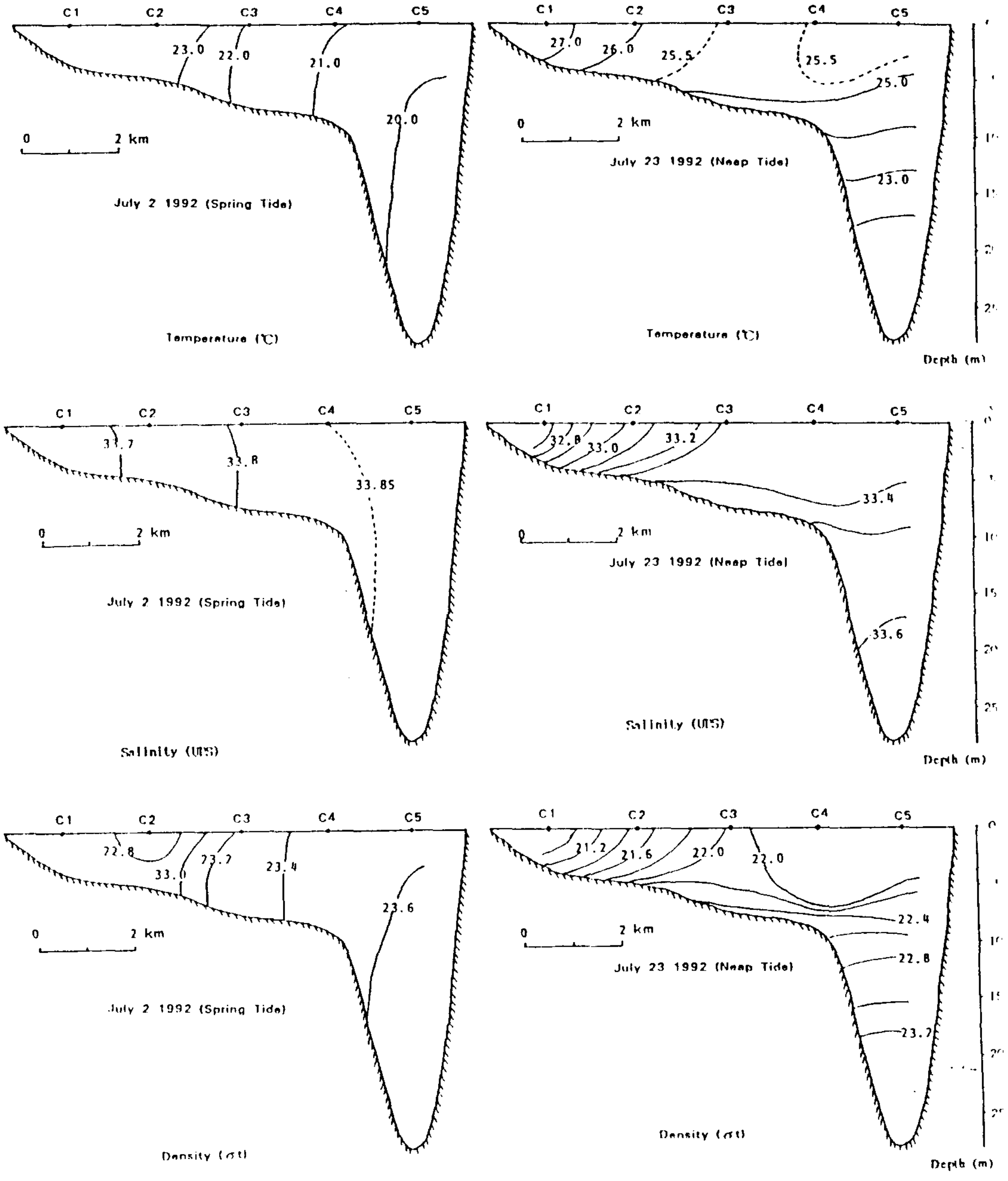

Fig. 3. The Hydrographic Profile during Spring and Neap Tidal Cycle at Typical Central Part of the Deukryang Bay along Section-C.

the sea surface, tidal and wind stirring effects.

Heat Flux, Wind and Current Variations during Spring-Neap Tidal Cycle

Oceanographical and meteorological data were compared for estimating the variability of SD phenomena during spring-neap tidal cycle. Wind speed, surface heat flux, and tidal current variations were shown in Fig. 4.

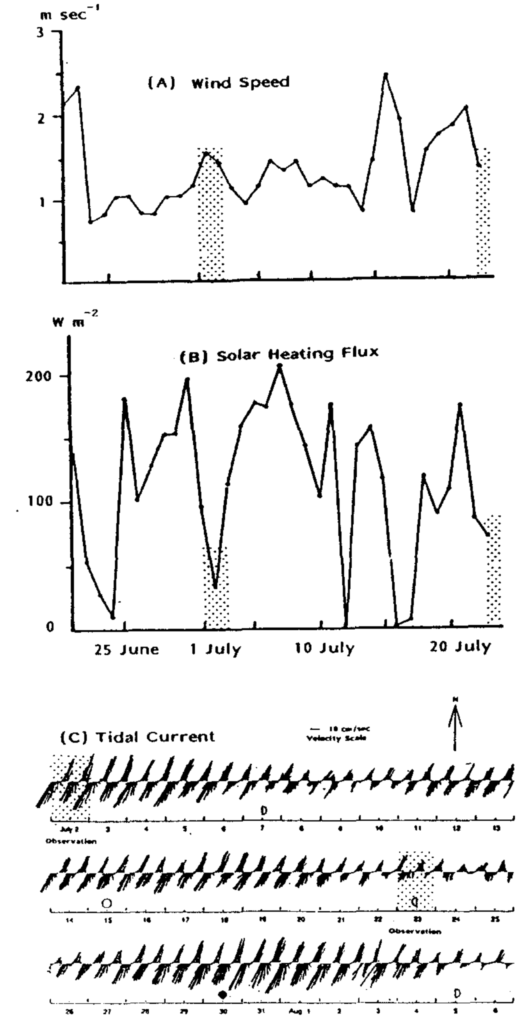

Fig. 4. The Time Variations of the Wind Speed, the Heat Flux and Tidal Current Amplitute. ▨ : Observation Periods of Hydrographic Data.

The procedures of the heat flux calculation were presented in Appendix based on the method of Yanagi (1982) and Gill (1984), and daily mean variation of sea surface water temperature was calculated from linear interpolation and extrapolation methods using two times' observation on 1-2 July and 23 July. In Fig. 4, the wind speed ranges approximately from 1 to 2 m/sec, the heat flux from 0 to 200 Watt/m^2, the tidal current amplitude from 0.1 to 0.6 m/sec. Wind speed from 21 June to 23 July are not strong and so much changed comparing to other factors. Moreover, the wind in periods of the strong stratification was stronger than that of vertically well mixed condition. It gives an account of that the wind stirring effect for the stratification may be not main factor in the bay.

The fluctuation of the heat flux was very large in spite of monthly average of 124 Watt/m^2, sometimes zero values happened because of a lot of cloud effects that prohibits the solar heating through the sea surface. The average heat flux from 1 July to 23 July was about 120 Watt/m^2 that increases water temperature about 2.5 ℃/m^3/day since 1 Watt/m^2 is equal to 2.39×10^{-5} cal cm^{-2} sec^{-1}, so that during 20 days total increasing of water temperature may be up to 4-5 ℃ for about 10 m averaged water depth. From this, the surface heating effect accompanied with low tidal velocity during neap tide directly intended to improve the strong stratification in the bay.

The stick current velocity diagram in the figure showed the manifest fluctuations of tidal current amplitude, particularly M_2 tidal current was dominated. The current amplitude was the largest in the first observation time while in the second the velocity was the lowest. From

13 to 20 July, the current was relatively weaker compared to that around 1 July. This may be related to the tidal component superposition, so that presumably comparatively low tidal mixing occurred at the periods.

The Rate of Potential and Kinetic Energy Variations during Spring-Neap Tidal Cycle

It was clear that the temporal variations of SD during spring-neap tidal cycle existed in Deukryang Bay from previously results. We showed that the phenomena were related to mostly the heat flux, the wind and the tidal current amplitude from data analysis of the tidal observation.

If we would like to estimate the intensity of the temporal variations of SD, it is obviously important for comparing the rate of change of kinetic energy supplied by the wind and the tidal current to the rate of change of potential energy of surface heating. Here, although the strong wind speed did not occur during our observation period, we though that it was necessary to measure quantitatively the wind stirring energy contribution for the whole energy balance. To introduce the mixing and heating energy concepts due to three factors, we used basically the simple potential energy arguments given by Simpson and Hunter (1974), Elliott (1991), and Takeoka *et al.*(1993) who studied at European Shelf and at Bungo Channel in Japan.

If we assume that the total rate of change of potential energy E is only influenced by the wind and the tidal stirring and the surface heating, the daily mean rate of change of the energy E will be given by (Elliott, 1991)

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

The first term in the right hand of equation (1) is the loss of potential energy by the surface heating, the second and the third are the rate of change of kinetic energy from the wind speed and tidal current, where g is gravitational acceleration, α is thermal expansion coefficient, ρ_a and ρ_w are air and water density, e and ε are efficiencies of surface and bottom mixing process, C_A and C_D represent the surface and bottom drag coefficients. W is wind speed, U is the absolute current speed. H is 10 m water depth. If the first terms is larger than the second and third, stratification is sustained. However, vice versa, vertical mixing becomes strong.

In calculation procedure of above equation, we used tentatively 0.015 ε value proposed by Yanagi and Tamaru (1990) because they successfully applied the value to Bungo Channel, Japan. C_D and C_A are given as 0.0025 and 0.000065 of Simpson and Bowers (1981). The tidal energy values from 20 to 30 June are extrapolated assuming that tidal change pattern from 20 to 30 June is the same as the pattern from 1 to 10 July because of the symmetric characteristics of tidal current amplitude in time.

The calculated results are shown in Fig. 5. As we expected previously, the wind stirring effect is approximately one order of magnitude smaller than the surface heating and the tidal stirring one. As considering the rate of potential energy derived by wind stress, we argue that the wind effect in summer can be omitted for analyzing SD phenomena durign observation periods. In the figure, the averaged rate of change of heating energy from 20 June to 23 July was 3.2 kg s^{-3} , although in the middle of

July it had larger value causing the rate of potential energy increasing much. Comparing the energy of the tidal stirring to the surface heating, during first spring tidal period approximately from 27 June to 5 July, the tidal energy was larger than the heating energy while in the second spring tide of middle of July, the tidal energy was similar to the heating in which it seems to be impossible to destroy the stratification already made by surface heating. Therefore, the stratification of first neap tide from 7 to 13 July may also be weaker than that of second neap tide. Possibly, destratification sustained from end of June to early of July, and stratification became to be formed from early July if the surface heating was continually stable.

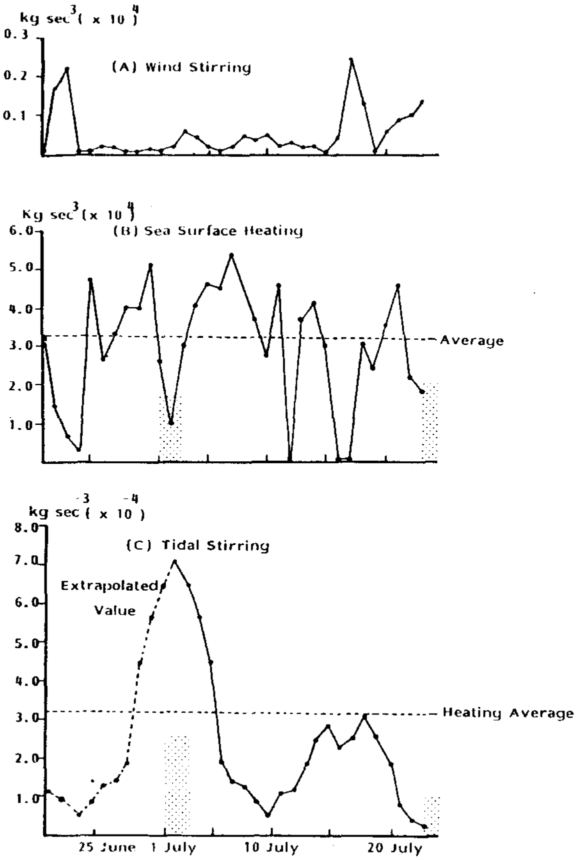

Fig. 5. The Time Variations of the Rate of Potential Energy Anomaly of a Water Column based on Fig.4. ▨ : Observation Periods of Hydrographic Data.

Discussion

Our hydrographic data of Deukryang Bay showed critical changes of vertical structure of temperature, salinity and density between spring and neap tidal periods. As we analyzed meteorological and oceanographical data using the energy equation, it was found that the tidal stirring and the surface heating played important roles for the stratifying and mixing processes while wind stirring effect was one order smaller than the previous two factors. The evidence of discrepancy between spring and neap tidal current amplitude associated with strong semi-diurnal components derived the periodic SD phenomena. However, for more accurate estimates of the effects of surface heating and wind and tidal stirring in the bay, we tried to undertake integrate of the rate of potential energy variation between spring-neap tidal cycle, and then estimate the stratification intensity quantitatively.

The integral equation of (1) can be presented as following equation,

$$E_c = \int_{t1}^{t2} [\ \frac{g\alpha}{2C_p} Q_T H - eC_A \rho_a W^3 - \varepsilon C_D \rho_w U^3]\ dt \qquad (2)$$

where t1 will be the start time of stratification, which start time can be defined as the heating energy becomes larger than the sum of the wind and tidal stirring energy of equation (1) from 1 July, and t2 is a time of the observed stratification, in this study 23, July. E_c is the calculated potential energy anomaly. In order to find out an optimal ε

Table 1. The Potential Energy Anomaly Changes for the Coefficients of Tidal Efficiency and Wind Speed (W_L is observation wind at land, W_S is expected wind at sea) Unit: kg sec^{-2}

Model							Obser.
Wind(W_s/W_L) \ ε Value	0.010	0.011	0.012	0.013	0.014	0.015	
1.0	262.66	241.84	221.73	201.62	181.51	162.60	194.56
1.5	238.02	217.91	197.80	177.69	157.58	139.18	
2.0	191.43	171.32	151.21	131.10	111.11	93.56	

values for the Deukryang Bay, equation (2) following several ε values of 0.010~0.014 at 0.001 interval was calculated and its results were compared with observation in Table 1.

To comparing the calculated result to the observed one, the potential energy anomaly E_0 of observation data was obtained from the following equation (Bownden, 1984):

$$E_0 = \int_{-h}^{0} [\ \rho - \overline{\rho}\ ]\ gz\ dz \qquad (3)$$

where $\overline{\rho} = \frac{1}{h}\int_{-h}^{0} \rho\, dz$

ρ is a density of a depth, $\bar{\rho}$ is averaged density of a total water column. In the calculation, the data of section C located at the nearest stations from the current meter mooring were averaged.

We also showed, in Table 1, the potential energy variations according to the several wind

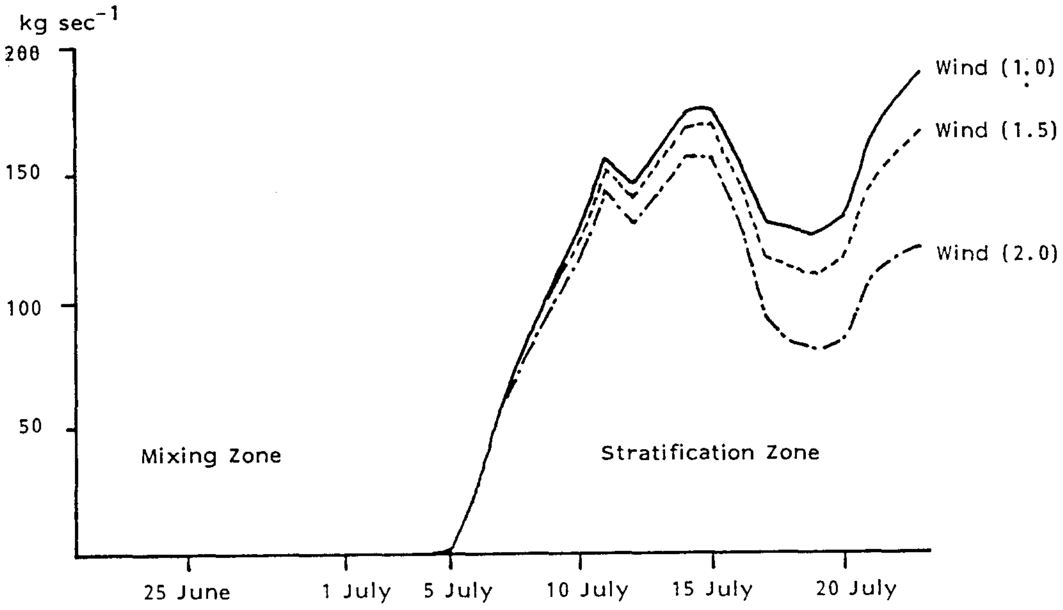

Fig. 6. Potential Energy Anomaly Variation from 5 July to 23 July (ε=0.014). The Number of ( ) Indicated Wind Speed Intensity of Ratio of Wind at Sea Surface and Wind at Land.

speed conditions, because following Yanagi (1980) and Imanuki (1982), the wind speed at sea surface is different from that at land and about 1.5 or 2 times larger at the sea surface than at the land related to surface roughness differences. In Table 1, the potential energies of that wind is 1.0 and ε = 0.014, wind 1.5 and ε = 0.012 and wind 2.0 and ε = 0.010 are very simliar to the observation result. The table allowed us to identify a reasonable ε value according to wind speed.

Fig. 6 indicated the potential energy variability of 0.014 ε in which the start time t1 was 5 July since from the day the heating energy was larger than the wind and tidal energy. The figure showed gradually increasing stratification as time increasing. However, during second spring tide, the stratification became decrease by strong tidal current amplitude although it could not overcome the total potential energy gain caused by the surface heating so that stratification continusly sustained in the periods. The patterns of other energy variations following the other ε values, those were not included in this paper, should resemble the energy one of ε = 0.014, although amount of total energy might be different during the same periods.

From the results, we supposed that ε-value ranges from 0.010 to 0.014, and from 5 or 6 July the stratification had been started by the surface heating. It was emphasized that strong surface heating in summer permitted only a short time to the vertically well mixed pattern and it might be less than one week based on the rate of energy variations.

However, for more exactly estimation of the SD phenomena and its life time, we should carried out more detailed observation of the bay in time and space.

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Appendix

The surface heat flux is written as (Gill, 1981)

Q_{in}: the incoming of energy to the water

$$\boxed{Q_{in} = Q_s\ (1-A) - Q_{ex}}$$

A : Albedo (reflection coefficient), in our case, A = 0.1.

Q_s : the energy is imparted to the sea by sunlight in the visible spectrum.

Q_{ex} : total expenditure energy from surface water

$$Q_{ex} = Q_b + Q_e + Q_h$$

Q_b is the radiative heat, will be proportional to the fourth powers of absolute temperature (Budyko's experiment equation)

$$\boxed{Q_b = s\sigma T^4(0.39-0.05e_a^{1/2})(1-0.6CL^2)+4s\sigma T_a^3(T_w-T_a)}$$

$$s=0.985,\ T_a = 273+t_a,\ T_w = 273+t_w$$

t_w : the water temperature

t_a : the air temperature

σ : Stefan's constant

$$\sigma = 5.7\text{x}10^{-8}\ \text{W m}^{-2}\ \text{K}^{-1}$$

xCL : the cloud amount (1/10)

Q_e is the energy used in evaporation as (Yanagi, 1981)

$$\boxed{Q_e = 0.622\rho_a L C_E (e_w-e_a) W/AP}$$

ρ_a: the density of air

$$\rho_a = 1.25\ \text{kg m}^{-3}$$

L : the latent heat of vaporisation of water

$$L = 2.46\ \text{x}\ 10^6\ \text{J kg}^{-1}$$

C_E : the Dalton number

$$C_E = 1.1\ \text{x}\ 10^{-3}$$

AP : the atmospheric pressure (mb)

W : wind speed (m/sec)

e_w : vapor pressure at the water surface

e_w = define from Table (Smithsonian Meteorological Tables)

e_a : vapor pressure in the air at ship height (10m)

$$e_a = RH\ e_w$$

RH : the relative humidity (1/100)

$$RH = e_a/e_w$$

Q_h is heat energy transferred to the atmosphere by conduction and convection, sensible heat as (Yanagi, 1981)

$$\boxed{Q_h = \rho_a C_p C_H (t_w - t_a) W}$$

C_p: the specific heat at constant pressure

$$C_p = 1004.6\ \mathrm{J\ kg^{-1}\ ℃^{-1}}$$

C_H : the Stanton number

$$C_H = 1.1 \times 10^{-3}$$

하계 득량만의 연직성층해양의 시간적 변동 특성

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한국남해 연안에 위치한 득량만에 있어서 하계의 태양복사, 바람, 조류에 의한 해양의 연직성층 및 연직혼합현상의 시간적 변동특성을 밝히기 위한 연구를 수행하였다. 이를 위하여 27개 정점에서 관측된 수온, 염분, 밀도값을 분석하였고, Simpson과 Hunter(1974)가 제안한 위치에너지 개념을 도입한 에너지 방정식을 이용하여 태양복사, 바람, 조류에너지를 각각 계산하였다. 그 결과 하계 득량만 해양의 연직 성층 및 혼합현상은 태양복사에너지가 일정하다고 할때 바람보다는 조류에 의해 크게 좌우됨을 알 수 있었고, 조류에너지에 의한 수괴의 연직혼합에너지기여율 ε의 값은 약 0.010 ~ 0.014사이를 나타내고 있었다.