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Seasonal Variation of Kinetic and Potential Energy of Residual Flow Field in Suyoung Bay, Korea

Dong-Sun Kim and Tetsuo Yanagi*
Research Center for Ocean Industrial Development(RCOID) Pukyong National University, Pusan 608-737, Korea
**Department of Civil and Ocean Engineering, Ehime University, Matsuyama 790, Japan*
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In order to study the seasonal variation of kinetic and potential energy of residual flow field in Suyoung Bay of Korea, we calculated its energy budget and compared it with the tidal energy there. The potential energy shows the large value in winter and spring and the small one in summer and early autumn when the density stratification is developed. The kinetic energy of residual flow varies seasonally and the seasonally averaged kinetic energy of residual flow per unit area is 6.4×10^{-4}ergs $s^{-1}cm^{-2}$. It is mainly governed by the density-driven current with the exception of that in November when the kinetic energy of tide-induced residual current is larger than those of density-driven current and wind-driven current. An averaged fraction of the kinetic energy of tide-induced residual current, wind-driven current and density-driven current, which are the major components of residual flow, is 29.1%, 3.4%, 67.5%, respectively, to the kinetic energy of residual flow. The fraction of kinetic energy of residual flow, potential energy and tidal energy per unit area is 1.0 : 6.7×10^{3}: 8.2×10^{4}, respectively.

Key-words : Seasonal variation, Suyoung Bay, Potential energy, Kinetic energy

1. Introduction

Ocean energy consists of thermal, waves, currents, and tides, ets. Among such ocean energies, the tidal energy has its origin in the relative motion between the moon and the earth, the sun but the others the heat from the sun.

Until now, the researchs about the ocean energy have been on the heat, tides, and waves, etc. But there has been no study on the kinetic and potential energy of residual flow field. The major components of the residual flow in the coastal sea are the tide-induced residual current, the wind-driven current and the density-driven current. The seasonal variation of residual flow in Suyoung Bay has been studied by Kim et al.(1996) and it is thought to be interesting to make clear the seasonal variations of kinetic and potential energy of resisual flow field in Suyoung Bay.

Accordingly, our objective in this study is to investigate the seasonal variation of kinetic and potential energy of residual flow field in Suyoung Bay which is situated at the south-eastern coastal area of Korea(Fig.1). Also, we study the seasonal variation of kinetic energy of tide-induced residual current, wind-driven current and density-driven current which are the major components of residual flow, and to inqure into the fraction of their energy to the kinetic energy of residual flow.

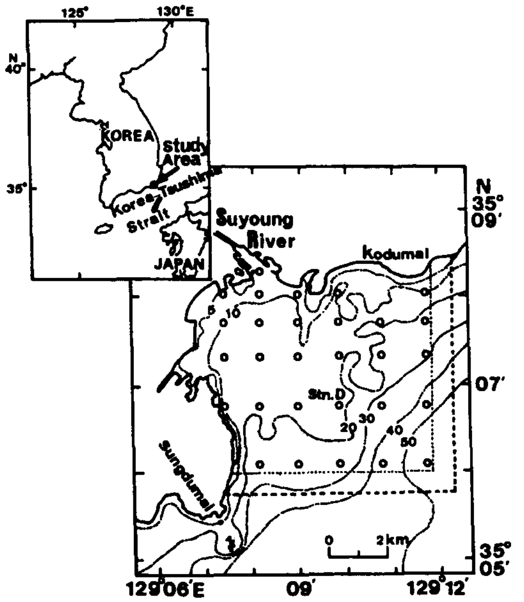

Fig. 1. Location of observation points in Suyoung Bay. The thick dotted line represents the open boundary of the numerical model and thin dotted line represents the observation area where the calculated results are shown. Numbers show the depth in meter.

Finally, we look around the seasonal variation of kinetic energy of each per unit area and to compare them with M_2 tidal energy per unit area estimated by Kim and Yanagi(1996).

2. Field Observation

Horizontal distributions of water density at the surface layer(0m-5m) in four seasons(Kim et al.,1996) are shown in Fig. 2. In spring(15 May, 1989, 17 March, 1990 and 15 April, 1990), water density is low in the inner bay due to the fresh water run-off from the Suyoung River. In summer(15 June, 19 July and 17 August, 1989), the difference of water density between the inner bay and the outer bay is large, that is, the water density in the inner bay is much lower than that in the outer bay due to the large fresh water run-off from river. In autumn(22 September, 20 October and 25 November, 1989), the difference of water density between the inner bay and the outer bay is small. This is because that the river discharge and the solar radiation are weaker than those in summer. The water density is high in winter(27 February,1990) and the difference of water density between the inner bay and the outer bay is a little.

Figure 3 shows the seasonal variations of vertical distributions of water temperature, salinity and density at Stn.D(see Fig.1) which is the transient region

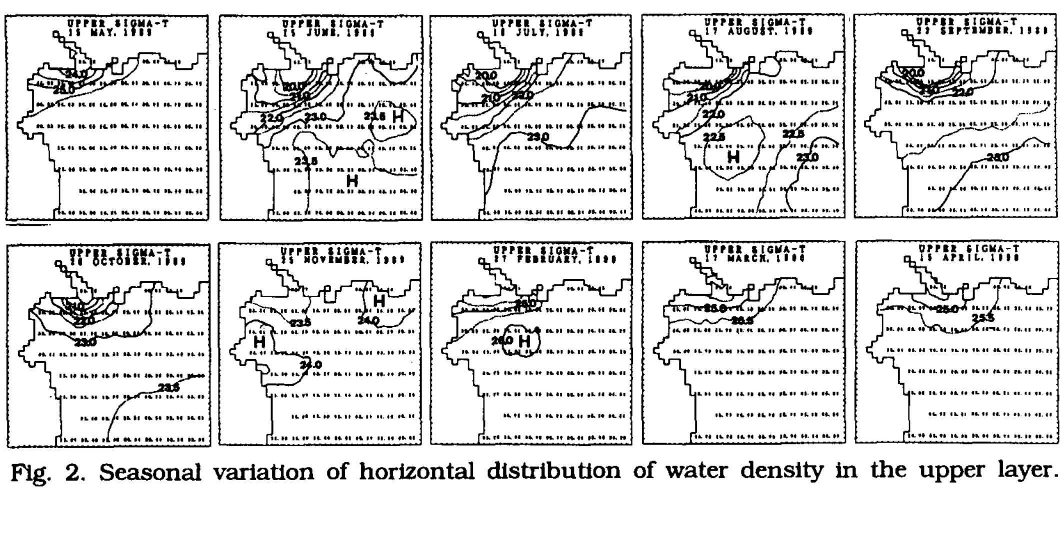

Fig. 2. Seasonal variation of horizontal distribution of water density in the upper layer.

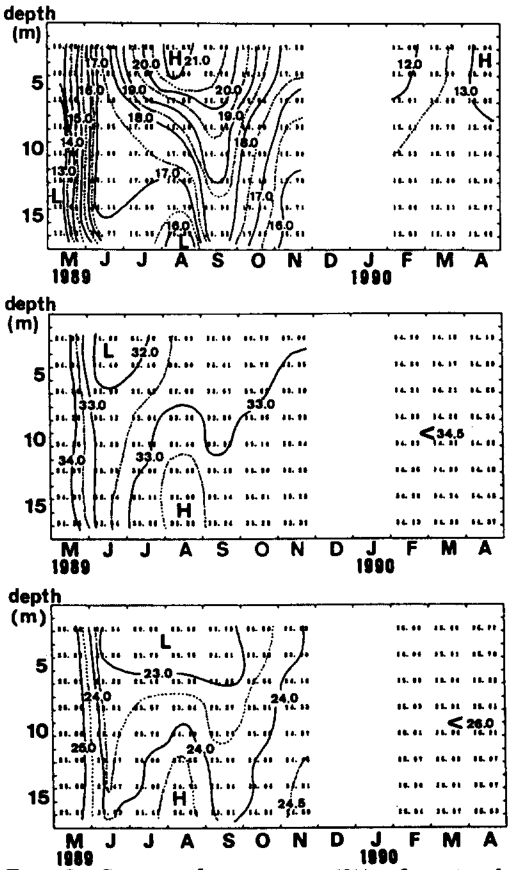

Fig. 3. Seasonal variations(%) of vertical distribution of water temperature (upper), salinity(middle) and density(lower) at Stn.D.

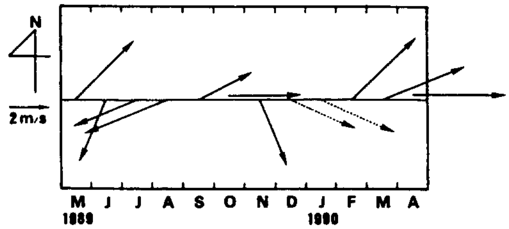

Fig. 4. The daily averaged wind speed and direction on each observation day. The dotted arrows represent the monthly averaged data.

between the inner bay and the outer bay. The vertically well-mixed state apperaed from late autumn to spring and the strong stratification was formed around the 5m depth from summer to early autumn. The intrusion of high density water mass(>24.5σ_t) appeared near the bottom in August, 1989.

Figure 4 shows the daily averaged wind speed and direction on each observation day at Pusan(Meteorological Observation Data of Korea, 1989, 1990) except for those in December, 1989 and January, 1990 which are the monthly averaged data(the dotted arrows). The field observation was not carried out in December 1989 and January 1990 due to bad weather. The maximum wind speed was 4. 7m s^{-1}in April, 1990 and the minimum one was 3.5m s^{-1} in June, 1989. The wind directions are the southwesterly in spring, the northeasterly in summer, the sou thwesterly-northwesterly in autumn and the northwesterly-southwesterly in winter, respectively.

3. Numerical Experiments

3.1. The Calculation of Residual Flow

In order to investigate the seasonal variation of residual flow field in Suyoung Bay, we have used a three-dimensional robust diagnostic numerical model which includes the effects of tide, wind and buoyancy. The model, as described in Kim et al.(1996), solves the three-dimensional equations of momentum, continuity, temperature and salinity. The model domain shown in Fig.1 is divided by the horizontal square mesh of 0.2km length and by the vertical three layers, 0-5m, 5-20m and 20m-bottom because the main pycnocline developed at the depth of 5m as shown in Fig.3.

The boundary condition for the momentum is no-slip condition at the lateral wall. Along the open boundaries of numerical model, which are shown by the thick dotted line in Fig.1, we used a radiation condition and the horizontal gradient of water

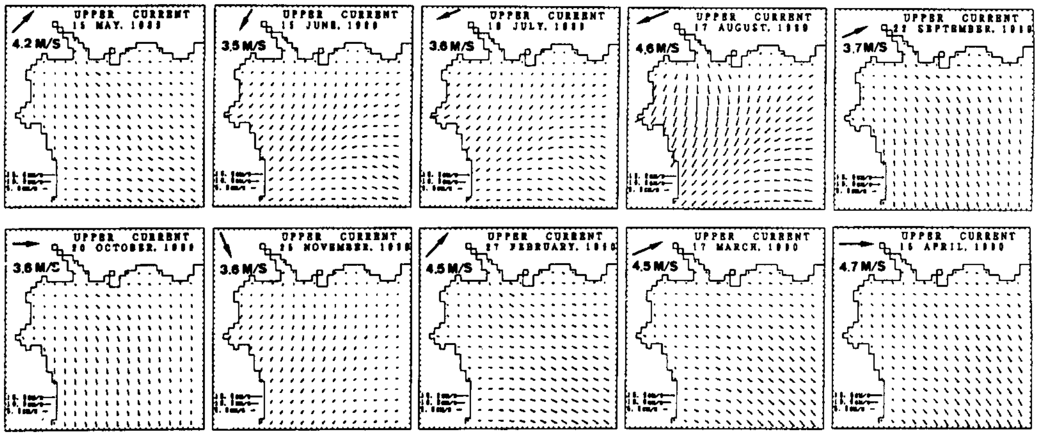

Fig. 5(a). Seasonal variation of horizontal distribution of residual flow in the upper layer.

temperature and salinity are assumed to be zero. The central difference scheme is adopted for the advection term and the semi-implicit scheme is used for the calculation of the sea surface elevation (Backhaus, 1983).

The calculated residual flow patterns in the upper, middle and bottom layers are shown in Fig.5. The flow patterns in spring(15 May, 1989, 17 March, 1990 and 15 April, 1990) show the south-eastward flow from the inner bay to the outer bay in the upper layer. In summer(15 June, 19 July and 17 August, 1989), the flow patterns in the upper layer show the southward flow from the inner bay and the south-westward, the westward flow in the central and outer bay, respectively.

The results in autumn(22 September, 20 October and 25 November, 1989) show the south-eastward flow from the inner bay to the outer bay in the upper layer but that during November, 1989 is similiar to those in summer although the speed is weaker than that in summer. The flow pattern in the upper layer during winter(only on 27 February, 1990) shows the south-eastward flow from the inner bay to the outer bay. On the other hand, the flow patterns in the middle layer show the replenishment flow opposite to those in the upper layer, that is, when the flow is outflow in the upper layer that is inflow in the middle layer as shown in Fig.5(b). The water is nearly at rest in the bottom layer throughout the year as shown in Fig.5(c).

3.2 Energy Budget

The kinetic energy(KE) of residual flow is estimated as follow,

$$KE = \frac{1}{2}\int_i\int_j\sum_{k=1}^{3}\rho(i,j,k)\times h_k \times V(i,j,k)^2 dxdy \qquad (1)$$

Following the approach of Simpson et al. (1978), we consider the variation in the potential energy(PE) relative to the mixed condition, defined by

$$PE = \int_i\int_j\int_\phi^z\sum_{k=1}^{3}|\{\rho(i,j,k)-\bar{\rho}(i,j)\}\times g \times Z\,|dzdxdy \quad (2)$$

where $\rho(i,j,k)$ is the water density at the (i,j) grid of the k-th layer, $\bar{\rho}(i,j)$ the averaged water density at the (i,j) grid, h_k the thickness of the k-th layer, Z the water depth, $V(i,j,k)$ the velocity of residual flow at the (i,j) grid of the k-th layer, and g(=980 cm s^{-2}) the gravitational acceleration.

In the coastal sea, the residual flow consists of the tide-induced residual current,

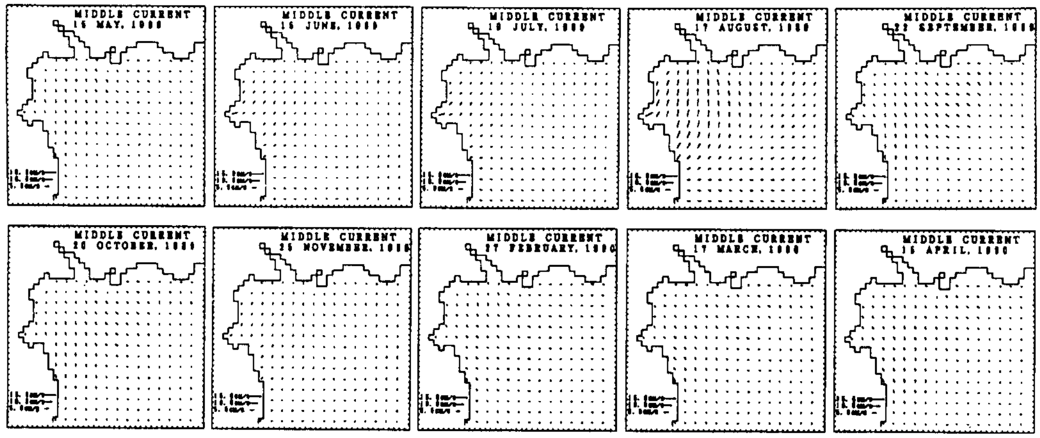

Fig. 5(b). Seasonal variation of horizontal distribution of residual flow in the middle layer.

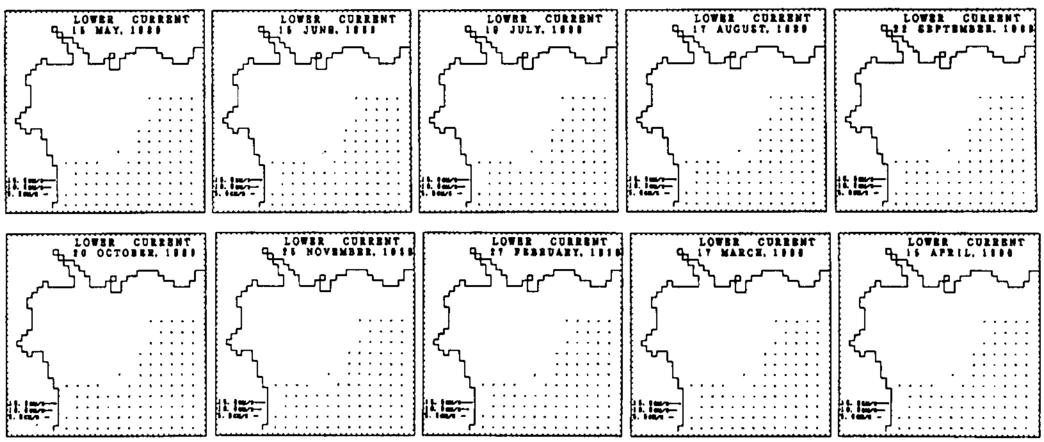

Fig. 5(c). Seasonal variation of horizontal distribution of residual flow in the lower layer.

the wind-driven current and the density-driven current. The tide-induced residual current is generated by the nonlinearity of tidal current, the wind-driven current by the wind stress at the sea surface and the density-driven current by the horizontal gradient of water density. In this study, as a first approximation, to estimate the energy fraction of the major components of residual flow field, we assumed that the three components of residual flow may be superimposed linearly, though these three components are nonlinearly superimposed in the real field. The tide-induced residual current, generated by the M_2 tidal current, is obtained by averaging calculated tidal current over one-tidal cycle(Kim & Yanagi, 1996). And the wind-driven current is calculated under the uniformed density condition in the basic calculation of residual flow.

Therefore, the kinetic energy of tide-induced residual current and wind-driven current are calculated independently. And we estimated the kinetic energy of density-driven current by the difference between the kinetic energy of residual flow and the kinetic energy of tide-induced residual current and wind-driven current.

Figure 6 shows the seasonal variations of the kinetic energy of residual flow(A)

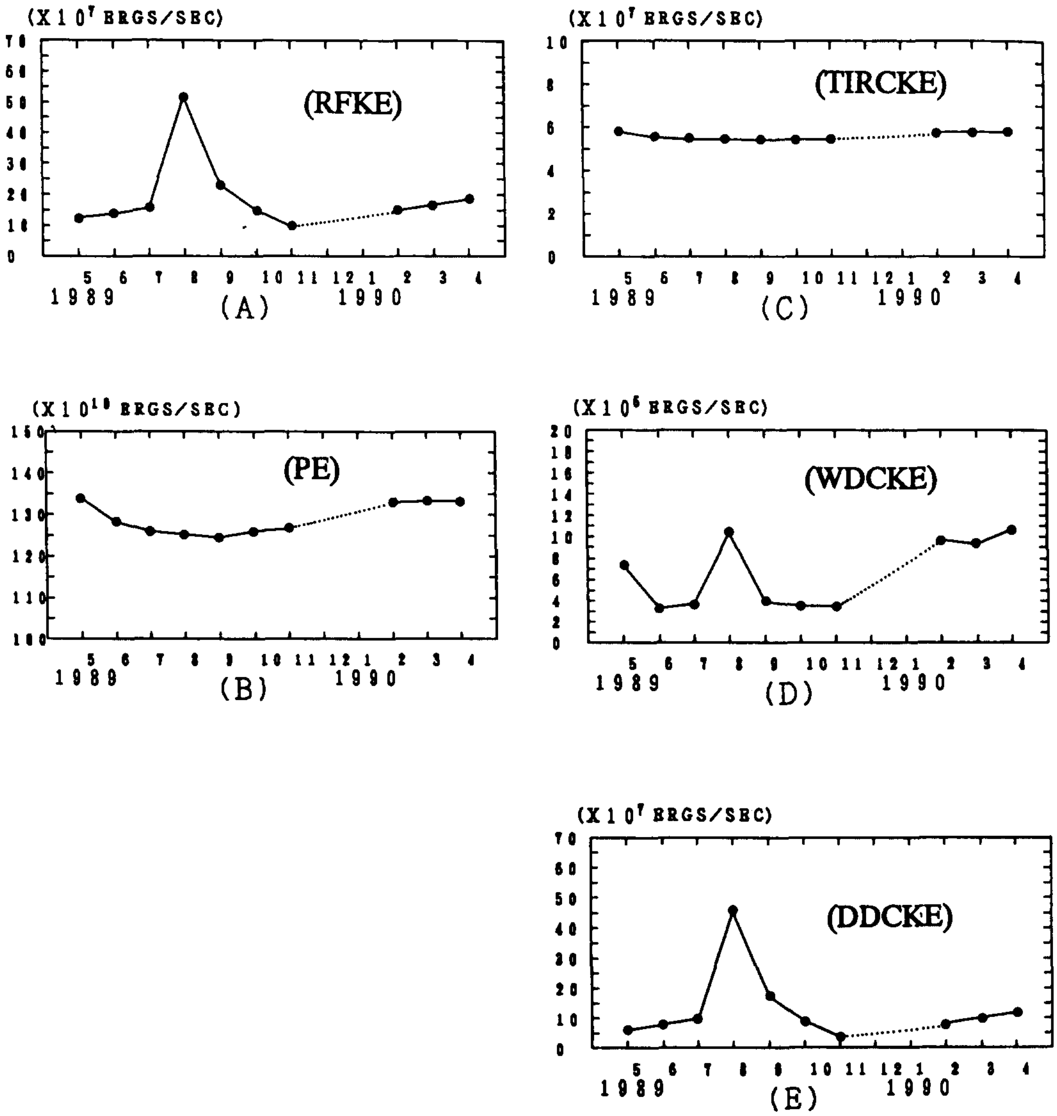

Fig. 6. Seasonal variations of kinetic energy of residual flow(A), potential energy(B), kinetic energy of tide-induced residual current(C), that of wind-driven current(D) and that of density-driven current(E).

and the potential energy(B), the kinetic energy of tide-induced residual current(C), wind-driven current(D) and density-driven current(E). The potential energy shows the large value in winter and spring and the small one in summer and early autumn when the density stratification is developed. The kinetic energy of residual flow varies seasonally, that is, it shows the maximum value in August and the minimum value in November. It shows the large value in summer and early autumn when the density stratification is developed and the small one in winter and spring when the vertically well-mixed state appears. The seasonal variations of kinetic energy of tide-induced residual current, wind-driven current and density-driven current, which are the major components of residual flow, are as follows; The seasonal variation of kinetic energy of tide-induced current(C), although the density varies seasonally, is not variable because the tide-induced residual current is stable throughout the year. The seasonal variation of kinetic energy of wind-driven current(D) shows the maximum value in April when the wind speed is large and the minimum value in June when the wind speed is very weak(see Fig.4). On the other hand, the seasonal variation of kinetic energy of density-driven current(E) is similiar to that of residual flow, that is, it shows the maximum value in August because the density difference between the inner bay and the outer bay is large and the minimum value in November because the density difference between the inner bay and the outer bay is relatively small(see Fig.2).

4. Discussions

We inquired into the seasonal variations of kinetic and potential energy of residual flow and the kinetic energy of tide-induced residual current, wind-driven current and density-driven current which are the major components of residual flow.

The potential energy is very sensitive to the river run-off and the solar-radiation and it is small in August and September, and large in spring and winter when the density stratification disappears. The kinetic energy of residual flow, wind-driven current and density-driven current varies seasonally but the kinetic energy of tide-induced residual current does not show the distinguished seasonal variation. That is to say, the kinetic energy of residual flow is large in August and September when the difference of density between the inner bay and the outer bay is large but it is small in spring and winter when the difference of density is small. And the seasonal variation of kinetic energy of wind-driven current is governed by the wind speed but it is relatively smaller than that of density-driven current. The kinetic energy of density-driven current conspiciously varies seasonally and its magnitude is larger than that of the tide-induced residual current and the wind-driven current. Therefore, the seasonal variation of kinetic energy of residual flow is mainly controlled by the density-driven current because the kinetic energy of the tide-induced residual current is stable throughout the year and the magnitude of kinetic energy of tide-induced residual current and the wind-driven current is smaller than that of density-driven current.

Table 1 shows the seasonal variations of the kinetic energy of residual flow, the potential energy and the M_2 tidal energy per unit area. Kim and Yanagi(1996) es-

Table 1. Seasonal variations of kinetic(RFKE) and potential energy(PE) of residual flow field and M_2 tidal energy per unit area in Suyoung Bay

UNIT (ergs $s^{-1}cm^{-2}$)	May 1989	Jun	Jul	Aug	Sep	Oct	Nov	Feb 1990	Mar	Apr	Average
RFKE($\times 10^{-4}$)	4.2	4.6	5.2	17.3	7.7	5.0	3.2	5.0	5.6	6.2	6.4
PE	4.5	4.3	4.2	4.2	4.1	4.2	4.2	4.4	4.4	4.4	4.3

Table 2. Seasonal variations of kinetic energy of residual flow(RFKE), that of tide-induced residual current(TIRCKE), that of wind-driven current(WDCKE) and that of density-driven current(DDCKE) and a fraction(%) of tide-induced residual current, wind-driven current and density-driven current to that of residual flow per unit area in Suyoung Bay(Surface Area: 30㎢)

DATE & ITEMS UNIT: $\times 10^{-4}$ ergs $s^{-1}cm^{-2}$	RFKE (%)	TIRCKE (%)	WDCKE (%)	DDCKE (%)
May, 1989	4.2 (100)	1.9 (46.1)	0.3 (6.0)	2.0 (47.9)
June	4.6 (100)	1.9 (40.0)	0.1 (2.4)	2.7 (57.6)
July	5.2 (100)	1.8 (34.6)	0.1 (2.3)	3.3 (62.9)
August	17.3 (100)	1.8 (10.5)	0.4 (2.0)	15.1 (87.5)
September	7.7 (100)	1.8 (23.6)	0.1 (1.7)	5.8 (74.7)
October	5.0 (100)	1.8 (36.5)	0.1 (2.4)	3.0 (61.1)
November	3.2 (100)	1.8 (56.8)	0.1 (3.7)	1.3 (39.5)
February, 1990	5.0 (100)	1.9 (38.6)	0.3 (6.5)	2.7 (54.9)
March	5.6 (100)	1.9 (34.5)	0.3 (5.6)	3.3 (59.9)
April	6.2 (100)	1.9 (30.9)	0.4 (5.8)	3.9 (63.3)
Average	6.4 (100)	1.9 (29.1)	0.2 (3.4)	4.3 (67.5)

timated the M_2 tidal energy as 52.7 ergs $s^{-1}cm^{-2}$ in Suyoung Bay. The kinetic energy of residual flow(RFKE) per unit area shows the maximum and minimum value of 17.3×10^{-4}ergs $s^{-1}cm^{-2}$, 3.2×10^{-4}ergs s^{-1} cm^{-2} in August and November, respectively and the seasonally averaged value is 6.4×10^{-4}ergs $s^{-1}cm^{-2}$. The potential energy per unit area is small in summer and autumn, large in winter and spring and the averaged value is about 4.3 ergs $s^{-1}cm^{-2}$.

Table 2 shows the seasonal variations of kinetic energy of residual flow(RFKE), tide-induced residual current(TIRCKE), wind-driven current(WDCKE) and density-driven current(DDCKE) per unit area and a fraction(%) of kinetic energy of tide-induced residual current, wind-driven current and density-driven current to that of residual flow in Suyoung Bay. The kinetic energy of density-driven current(DDCKE: 15.1×10^{-4}ergs s^{-1} cm^{-2}) is large and that of tide-induced residual current(TIRCKE: 10.5×10^{-4}ergs $s^{-1}cm^{-2}$) is small when the kinetic energy of residual flow is large in August. Also, the kinetic energy of tide-induced residual flow(TIRCKE: 1.8×10^{-4}ergs $s^{-1}cm^{-2}$) is large and its fraction(TIRCKE: 56.8%) is larger than that of the density-driven current(DDCKE: 39.5%) and the wind-driven current(WDCKE: 3.7%) in November. In February, a fraction of the kinetic energy of wind-driven current

(WDCKE: 6.5%) shows larger value than those in other months but its magnitude (WDCKE: 0.3×10^{-4}ergs $s^{-1}cm^{-2}$) is smaller than the kinetic energy of tide-induced residual current(TIRCKE: 1.9×10^{-4}ergs $s^{-1}cm^{-2}$) and density-driven current(DDCKE: 2.3×10^{-4}ergs $s^{-1}cm^{-2}$). Thus, the averaged fraction of kinetic energy of wind-driven current(WDCKE), tide-induced residual current(TIRCKE) and density-driven current(DDCKE) to the kinetic energy of residual flow per unit area in Suyoung Bay is 1.0(3.4%) : 9.5(29.1%) : 21.5(67.5%), respectively.

The calculation in this paper reveals several features of kinetic and potential energy of residual flow field in Suyoung Bay. First, the potential energy per unit area is samll in August and September and large from February to May because it is affected by the river run-off and the solar-radiation. Second, the kinetic energy of residual flow varies seasonally and the seasonally averaged kinetic energy of residual flow per unit area is 6.4×10^{-4}ergs $s^{-1}cm^{-2}$. And it is mainly governed by the density-driven current with the exception of that in November when the kinetic energy of tide-induced residual current is larger than that of density-driven current. Third, an averaged fraction of the kinetic energy of tide-induced residual current, wind-driven current and density-driven current, which are the major components of residual flow, is 29.1%, 3.4%, 67.5%, respectively, to the kinetic energy of residual flow. Finally, the fraction of kinetic energy of residual flow, potential energy and tidal energy per unit area is 1.0 : 6.7×10^{3} : 8.2×10^{4} , respectively.

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한국수영만에서 잔차류장의 운동 · 위치에너지의 계절변화

김 동 선* · 柳 哲 雄
*부경대 해양산업개발연구소 · 일본 에히메대학 환경건설공학과

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한국수영만에서 잔차류장의 운동 · 위치에너지의 계절변화를 연구하기 위하여 우리는 에너지의 수지를 계산하고 조석에너지와 비교했다. 위치에너지는 겨울과 봄철에 크며, 밀도성층이 형성된 여름과 초가을에 작게 나타났다. 잔차류의 운동에너지는 계절적인 변화를 보이고 있으며, 단위면적당 잔차류의 평균 운동에너지는 6.4×10^{-4}ergs $s^{-1}cm^{-2}$ 이다. 수영만에서 잔차류장의 계절변동은 조석잔차류의 운동에너지가 밀도류나 취송류의 운동에너지보다 큰 11월을 제외하고는 밀도류가 지배하고 있다. 잔차류의 주성분인 조석잔차류, 취송류 및 밀도류의 운동에너지의 평균백분율은 잔차류의 운동에너지에 대하여 각각 29.1%, 3.4%, 67.5% 이다. 단위면적당 잔차류의 운동에너지, 위치에너지 및 조석에너지의 비는 각각 1.0 : 6.7×10^{3} : 8.2×10^{4} 이다.