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Estimation of current driving force in Suo Sea, the Seto Inland Sea, Japan

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Abstract

The characteristic of seawater exchange in the Suo Sea was investigated from observation results. The seawater exchange in the Suo Sea is strongly influenced by the river discharge and the intrusion of open seawater through the Bungo Channel. The seawater exchange around the Suo Sea is influenced by the annual cycle of the current field in overall the Seto Inland Sea. The close relationship among the annual cycle of sea level height (SLH) in the Seto Inland Sea, SLP and density was indicated from observation results. Based on the results, in order to estimate the annual cycle of current field in the Inland Sea, the two-dimensional numerical model reflected the annual cycle of density and sea level pressure (SLP) distributions and SLH at the boundaries facing the Pacific as the driving force was developed. The importance of the seasonal current driving force to the seawater exchange around the Suo Sea was indicated by two-dimensional numerical simulation.

1 Introduction

The Seto Inland Sea with the surface area of about 22,000 km^2, the mean depth of about 37m connects with open sea (the Pacific or Japan Sea) through Kii Channel, Bungo Channel and Kanmon Strait, and there are several regions separated by straits and 23 first-grade rivers (first-grade rivers are under the supervision of the Minister of Land, Infrastructure and Transport). The normal amount of evaporation on the Inland Sea is about 1,500mm/year (Ishizaki and Saito, 1978), and the amount of precipitation on the Inland Sea is about 1,400mm/year (Yanagi, 1997 [1]). According to them, the water budget on the sea surface is estimated about plus 100mm/year. The total river discharge of first-grade river is about 2.9×10^{10}m^3/year which corresponds to one thirtieth of the volume of the Inland Sea (8.0×10^{11}m^3). The regions have different topographic features and the

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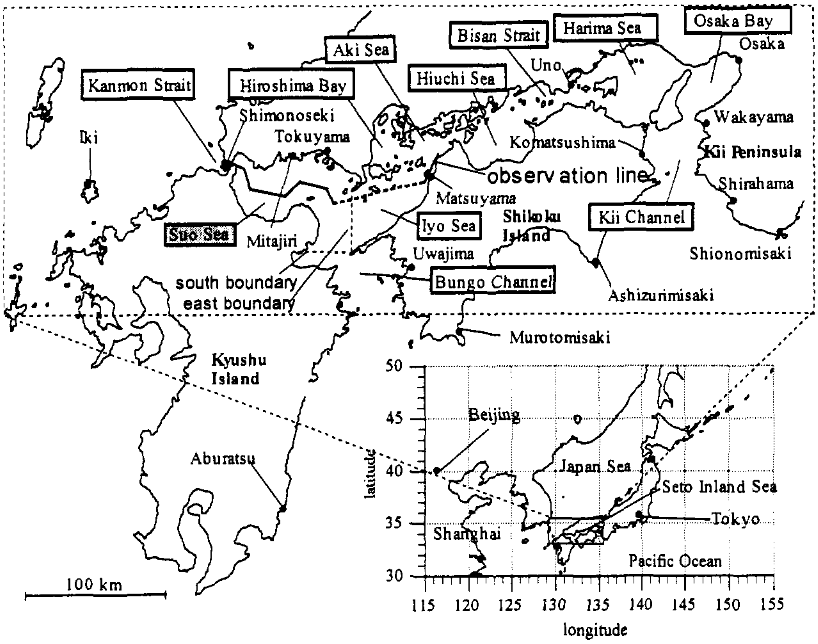

Figure 1 Location and topography of the Seto Inland Sea (Observation line in Figure 2 and Observatories at Mitajiri, Shimonoseki, Matsuyama and Iki in Figure 3 and tide stations observed by Japan Coast Guard (JCG) and Japan Meteorological Agency (JMA) are presented.)

seawater exchanges among them.

The Suo Sea is located on the western Inland Sea. Figure 1 shows the location and topography of the Inland Sea. Seawater exchanges among regions in the Inland Sea will be caused by weather, climate and tide and they are considered to be play important roles for the circulation of nutrients and toxic substance. Therefore it is important for the port improvement that can reduce loads to environment and conserve the ecosystem as possible making use of nature power to evaluate the seasonal fluctuation of seawater exchange over the Inland Sea scale. In the Suo Sea, at the water exchangeable breakwaters with openings in Mitajiri port, the exchange efficiency through the openings of breakwaters had been observed in April and October 1998. The observed results suggests that the efficiency varies with seasonal changes of current direction behind the coast of the Mitajiri port, such as the current parallels the breakwaters in April and the current flows perpendicularly to the breakwaters in October [2].

The purpose of this study is to understand the characteristics of seawater exchanges around the Suo Sea, and to evaluate the current driving force caused by the annual cycles of distribution of seawater density and SLP in the Inland Sea and SLH at the boundary of the Inland Sea. In this paper, the seasonal cycle of seawater exchanges among the Suo Sea, the Bungo Channel, the Iyo Sea and the

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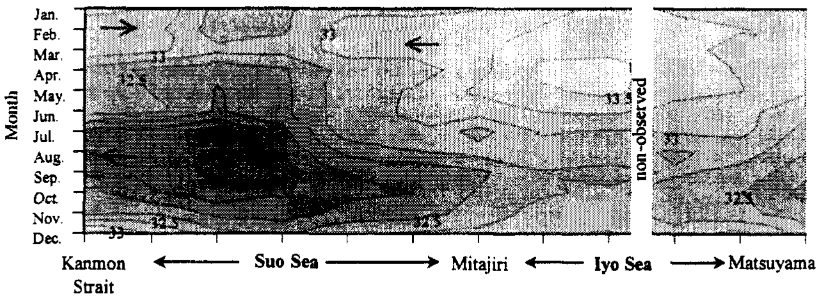
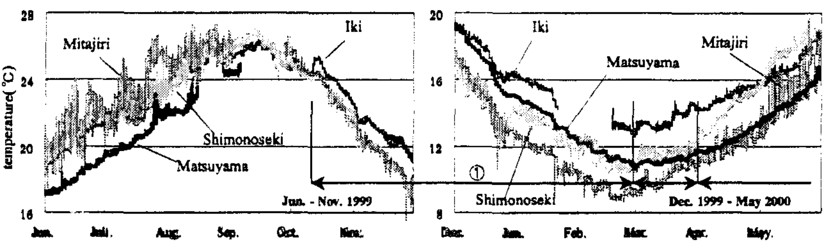


Figure 2 Annual mean cycle of monthly mean salinity averaged from 1983 to 1993 at bottom layer from the Kanmon Strait through Matsuyama along the observation line shown in Figure 1



(a) June - November 1999 (b) December 1999 – May 2000

Figures 3 Time series of seawater temperature at four observatories (10 m depth, Shimonoseki, Mitajiri, Matsuyama and Iki shown in Figure 1)

Japan Sea are investigated from annual mean cycle of salinity distribution in the western Inland Sea obtained from the periodical observation results from 1983 to 1993 and monitoring results of seawater temperature from June 1999 to May 2000 around the Suo Sea. Then, to evaluate the driving force, the correlation among density, SLP and SLH is clarified, and the seasonal cycle of flow amount through the east and west boundaries of the Suo Sea are estimated by two-dimensional numerical model.

2 Seasonal cycle of seawater exchange around the Suo Sea

Figure 2 shows the annual cycles of monthly mean salinity averaged from 1983 to 1993 at the bottom layer along the observation line shown in Figure 1. The lower salinity area (under 32.5) in Figure 2 indicates the water affected by the river discharge (The normal river discharge averaged from 1983 to 1997 is about $42m^3/s$). From December to March, the higher salinity water (over 33) intrudes into the west region in the Suo Sea through the Kanmon Strait, while the higher salinity water (over 33) from the Iyo Sea strongly affects to the eastern Suo Sea from December to June. From June to October, the lower salinity water (under 32.5) discharges toward the Japan Sea through the Kanmon Strait.

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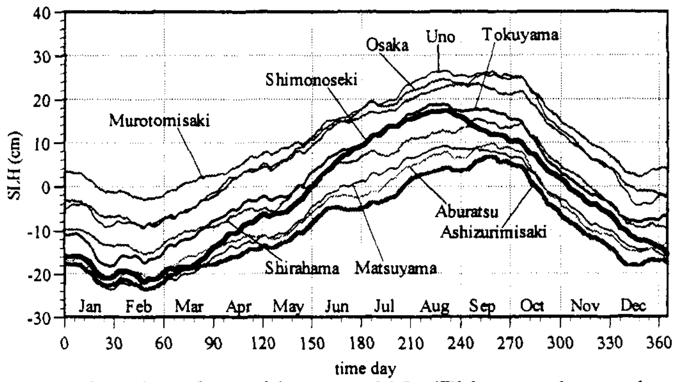

Figure 4 Annual cycles of monthly mean SLH (Tide records are observed by JCG and JMA averaged from 1985 to 1999. SLH indicates sea level height above mean sea level of Tokyo Bay that is the reference level of the ground in Japan.)

Figures 3 show the time series of seawater temperature at four observatories (Shimonoseki, Mitajiri, Matsuyama and Iki) from June 1999 to June 2000. From Figures 3, from October to March (□ period), the seawater temperature at Matsuyama is considered to rise with the intrusion of warm open seawater into the Iyo Sea (as shown in Figure 2), because the Inland seawater is cooled more than open seawater by long wave radiation from sea surface in winter season. Late December, the seawater temperature at Shimonoseki rises with the intrusion of warm open seawater through the Kanmon Strait (as shown in Figure 2) and the water stagnates around the Kanmon Strait. From April to August, the seawater temperature at Mitajiri vibrates with the stagnation of the Iyo Sea water and the Suo Sea water around Mitajiri. The seawater temperature at Mitajiri vibrates only from April to October from observation results for three years [2].
These observation results suggest that the annual cycles of salinity and water temperature in the Suo Sea are strongly affected by open seawater through the Bungo Channel and river discharge, and the influence of open seawater through the Kanmon Strait on the Suo Sea water is limited in the west end of the sea.

3 Effect of seawater density and SLP on SLH

Seasonal seawater exchange around the Suo Sea is considered to be affected by the annual cycle of SLH due to current field variation overall the Seto Inland Sea. Nomitsu & Okamoto revealed that the causes of the SLH cycle along the Japanese coast are mainly the density variation and secondly the SLP [3]. Unoki indicates that the importance of the effects of wind friction in inner bay [4][5].
Figure 4 shows the annual cycles of daily mean SLH averaged from 1985 to 1998 at tide stations around the Inland Sea shown in Figure 1. The highest peaks of SLH appear in August and the lowest peaks appear in February in the inner regions of the Inland Sea (Osaka, Uno, Matsuyama, Tokuyama and Shimonoseki),

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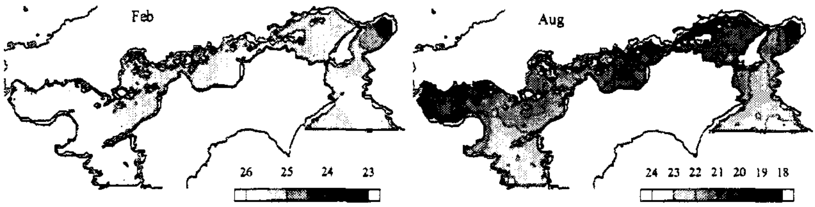
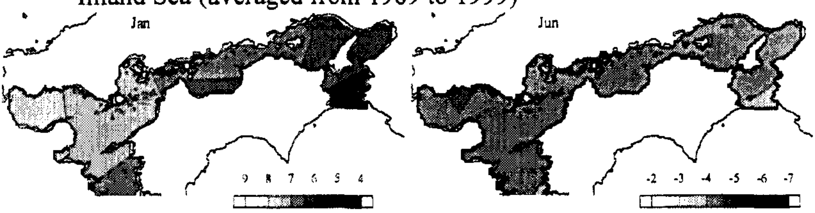


(a) February (b) August

Figure 5 Distribution of depth-averaged seawater density (σ_t) in the Seto Inland Sea (averaged from 1989 to 1999)



(a) January (b) June

Figure 6 Distribution of SLP over the Seto Inland Sea (averaged from 1989 to 1999, hPa-1013

while the highest peaks of SLH at the boundary facing the Pacific (Shirahama, Murotomisaki, Ashizurimisaki and Aburatsu) appear in September, because it is strongly affected by the seasonal movement of the Kuroshio path (approach toward the south coast of Kyushu – Shikoku Islands). The annual range of sea level cycle in the west and center regions of the Inland Sea is larger (Tokuyama: 37cm, Uno: 38cm) than that in the east region (Osaka: 34cm).

Figures 5 illustrate the distributions of depth-averaged density (a) in February and (b) in August. Density is calculated from temperature and salinity of two data at 2m below sea surface and at 2m above bottom averaged from 1989 to 1999 (observed by Ministry of Land, Infrastructure and Transport, Japan in February, May, August and October at 142 points located on 3km * 3km grid). In February (dry season) the lowest density ($\sigma_t = 23$) appears in the Osaka Bay and the Harima Sea with river discharges ($1.0\times10^{10}m^3$/year) and the highest ($\sigma_t = 26$) from the Bungo Channel. In August (rainy season), the density decreases especially in the Suo Sea and the Bisan Strait with increasing of river discharge ($0.1\times10^{10}m^3$/year in the Suo Sea, $0.8\times10^{10}m^3$/year in the Bisan Strait) and solar radiation.

Figures 6 illustrate the distributions of monthly mean SLP (a) in February and (b) in August over the Inland Sea, where SLP is obtained by the interpolation method of distance-weighted average of monthly mean SLP at 23 observatories over the Inland Sea by JMA. In January, the pressure difference over the Inland Sea

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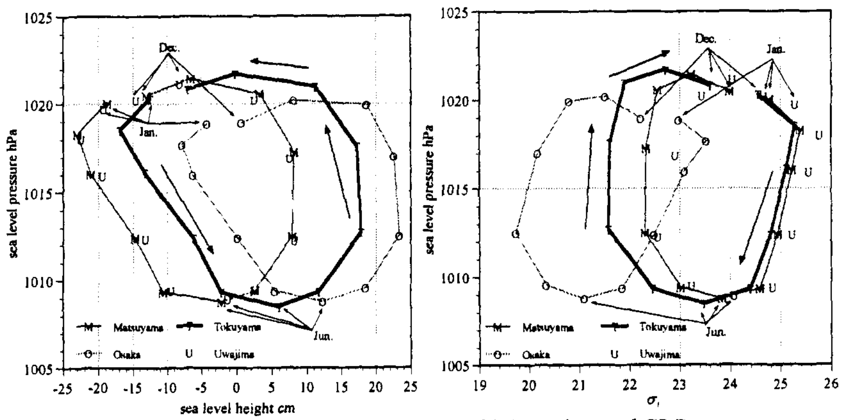

(a) SLH and SLP (b) Density and SLP

Figure 7 Correlation between (a) SLH and SLP and (b) depth-averaged density and SLP at Matsuyama (the Iyo Sea), Tokuyama (the Suo Sea), Osaka (the Osaka Bay) and Uwajima (the Bungo Channel) averaged from 1989 to 1999

reaches about 4 hPa because of the west high - east low pressure distribution that is typical winter pressure system. In June, the pressure difference over the Inland Sea is less than 1 hPa. Considering the 1 hPa of SLP corresponds to 1 cm pressure head, the peak of driving force by SLP produces about 4 cm of pressure head over the Inland Sea in January.

The Correlations (a) between monthly mean SLH and monthly mean SLP and (b) between depth-averaged density and monthly mean SLP in Matsuyama (the Iyo Sea), Tokuyama (the Suo Sea), Osaka (the Osaka Bay) and Uwajima (the Bungo Channel) are presented in Figures 7. In Figure 7 (a), The highest peaks of SLP appear in November, and the lowest peaks of SLP appear in June. On the other hand, the highest peaks of density appear in February and the lowest peaks of density appear in August in all regions in Figure 7 (b). The variation rate of SLH to SLP is nearly –1 cm/hPa from February to May, however the SLH is strongly related to density since the peaks of SLH are good agreement with the inverse peaks of density.

Considering the effect of seasonal cycle of density and SLP on the static field, SLH rises with decreasing of density (seawater deflation) and SLP (suck up), and SLH falls with increasing of density (seawater dilation) and SLP (press down). Assuming static field, the sea level deviation with density variation depends on the bathymetry. However, the main causes of density variation are considered to be not only seawater deflation and dilation but also seawater exchange. Therefore, the stable assumption is not definitely appropriate to estimate the flow amount among regions

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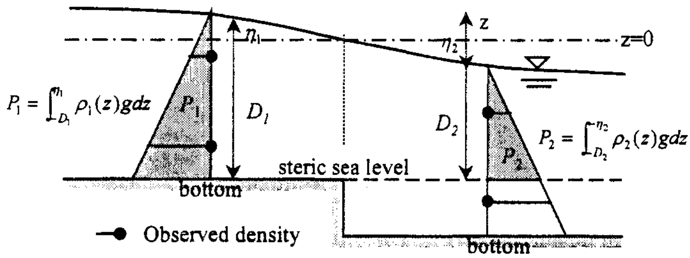

Figure 8 Calculation method of depth-averaged pressure

4 Estimation of seasonal current driving force in Suo Sea

The current field in the Suo Sea will be determined from overall the Inland Sea current field. The influence of annual cycle of open sea level, density and SLP on the current field will be estimated by solving the equations of motion and continuity numerically. In this section, we estimate the current driving forces of normal annual cycle of SLH and flow amount quantitatively with two-dimensional numerical model considering annual cycle density and SLP distributions, and open sea level facing the Pacific.

The velocity field satisfies a discrete form of the equations of motion and continuity integrated vertically obtained by finite difference method applied to a staggered grid. The simulation was run with 60 cells in longitude and 120 cells in latitude ($\Delta x = \Delta y = 3600$ m). The threshold depth in calculation is 400 m and Δt keeps 10 seconds.

4.1 Boundary condition facing open sea

The boundary condition of sea level applied in the cross section of the Kii Channel and the Bungo Channel to open sea given by 15 days moving-averaged daily mean tide record from 1985 to 1998 observed at Shirahama and Komatsushima (the Kii Channel), and at Ashizurimisaki and Aburatsu (the Bungo Channel). The effect of the inflow through the Kanmon Strait is reflected in the density distribution, while the flow amount is assumed to be negligible because of its small cross-sectional area. The equivalence between the amounts of evaporation and precipitation is assumed over the Inland Sea surface. The main calculation was run after the calculation for a year to remove first perturbation.

4.2 Modeling of density distribution

Since the horizontal pressure gradient field is important for current driving force, the density profile should be reflected in the density field especially during warm and rainy season. In the numerical model, the observed density field is given, that means to give the external force field corresponding to observed density field.

The density profile can be assumed approximately by linear with two points of

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observed at 2m below sea surface and at 2m above bottom in August except for the eastern Inland Sea (a part of the Osaka Bay and the Harima Sea) with strong pycnocline. In the simulation, the linear density profile was assumed allowing under-estimation of depth-averaged density in some parts of waters.

To represent the effect of density distribution in two-dimensional model, the equations of motion should be integrated vertically considering density profile while apparent pressure gradient caused by the difference of integrated depth will be produced in steep bottom area. Therefore, the reference pressure level (the steric sea level) is defined at the bottom depth of the shallower neighbor grid to calculate pressure gradient as shown in Figure 8.

The reference density is defined by 1024 kg/m^3 and the time series of density is obtained from linear interpolation of normal density averaged in February, May, August and October from 1989 to 1999, and the horizontal distribution is obtained from the weighted-mean of distance of observed.

4.3 Modeling of SLP distribution

Since the horizontal scale of the effect of SLP will be more than the scale of the Inland Sea, the effect will represent on the open sea level in boundary condition. However the effect of the Inland Sea scale of SLP should be modeled in numerical simulation, since the maximum effect is about 4cm over the Inland Sea in January as shown in Figure 6.

The time series of SLP is obtained from the linear interpolation from daily SLP observed around the Inland Sea, and its horizontal distribution is interpolated by weighted mean of distance. The reference SLP is defined in June when the minimum SLP gradient appears over the Inland Sea [6] as shown in Figure 7, and SLP is included in the pressure term of equation of motions (1 hPa = 1 cm).

4.4 Estimation of current driving force due to density and SLP

Figures 9 show the comparison between the observed results and calculation results with (a) annual ranges of SLH cycle and (b) phase of the highest peak of SLH at tide stations around the Inland Sea. The annual range and the phase of SLH cycle in numerical simulation are good agreement with observed.

Figure 10 shows the annual cycle of inflow to the Suo Sea through three cross sections shown in Figure 1. In Figure 10, the open seawater inflows through the south boundary and the inland seawater outflows through the east boundary all year around. Since the decreasing of the storage amount into the Suo Sea from October to February seems to be accompanied with the seasonal fluctuation of efficiency of seawater exchange and the vibration of seawater temperature at Mitajiri port as shown in Figures 3, the importance of the annual cycle of density, SLP and open sea level to the seawater exchange is indicated.

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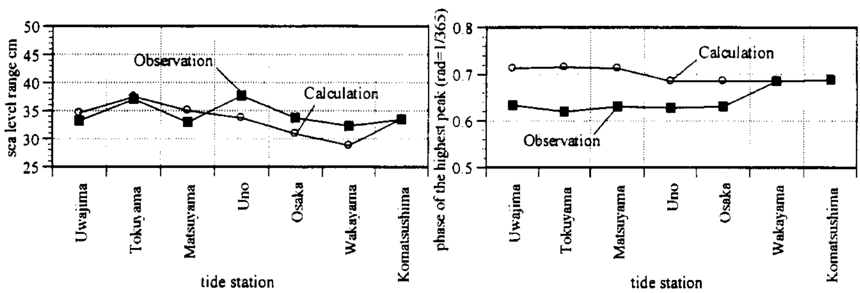

(a) Annual range of SLH cycle (b) Phase of the highest peak of SLH

Figure 9 Comparison between observation results and calculation results

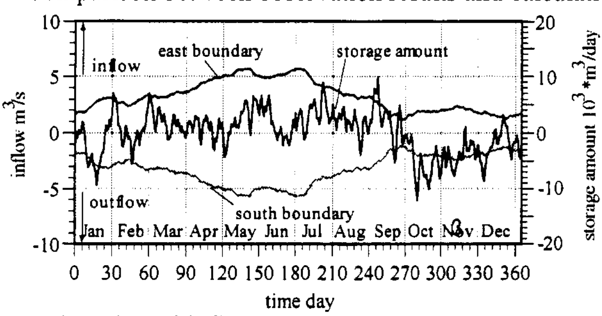

Figure 10 Annual cycles of inflow to the Suo Sea through the east boundary and through the south boundary shown in Figure 1, and storage amount in the Suo Sea by numerical simulation

5 Conclusions

1) The characteristic of seawater exchange in the Suo Sea was investigated from observation results. The seawater exchange in the Suo Sea is strongly influenced by the river discharge and the intrusion of open seawater through the Bungo Channel.
2) The close relationship among the annual cycle of SLH in the Inland Sea, SLP and density was indicated from observation results. Based on the results, in order to estimate the annual cycle of current field in the Inland Sea, the two-dimensional numerical model reflected the annual cycle of density and SLP distributions and SLH at the boundaries facing the Pacific as the driving force was developed.
3) The importance of seasonal current driving force to the seawater exchange around the Suo Sea due to density, SLP and SLH at the boundaries facing the Pacific was indicated by two-dimensional numerical simulation.

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The tide records around the Seto Inland Sea are obtained from the homepage of JODC, and the records of SLP over the Seto Inland Sea are obtained from CD-

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ROM by Japan Meteorological Agency. The density distribution around the Bungo Channel and the Suo Sea is interpolated by the data sets observed by Japan Fisheries Agency averaged from 1983 to 1993. The authors express sincere appreciation to all the principals and engineers who assisted with data collection for this study by taking the time to complete the survey.

References

[1] Yanagi T.: Budgets of fresh water, Nitrogen and phosphorus in the Seto Inland Sea, *Umi no Kenkyu*, **6(3)**, pp.157-161, 1997 (in Japanese).

[2] Nishimori, D., Hibino T., Toyama, M., Hosokawa, Y., Ishihara, H., Morishita, M. & Tsuruya, H.: Estimation of water mass exchanged through water exchangeable breakwater, *Report of Port and Harbour Research Institute*, **38(2)**, 1999 (in Japanese).

[3] Nomitsu, T. & Okamoto, M.: The causes of the annual variation of the mean sea level along the Japanese coast, *Memoirs of the College of Science Kyoto Imperial University Series A*, **10**, pp.125-161, 1927.

[4] Unoki, S. & Isozaki, I.: Mean Sea Level in Bays, with Special Reference to the Mean Slope of Sea Surface due to the Standing Oscillation of Tide, *The Oceanographical Magazine*, **17**, pp.11-35, 1965.

[5] Unoki, S.: Annual Variation of the Mean Sea Level and Its Inclination in a Bay, *Coastal Engineering in Japan*, **26**, pp.219-234, 1983.

[6] Komai, K. Hibino, T. & Asai, T.: Estimation of Mean Sea Level in the Seto Inland Sea, *Proc. of the 1st Asian and Pacific Coastal Engineering conference*, pp. 297-304, 2001.

[7] Hibino, T. and Furukawa, K.: Preliminary Use of Global Meteorological Information as an Indicator for Long Term Water Exchange in an Estuary – Development of Aleutian Low and Ocean Current -, *Proc. of the 27th International Conference on Coastal Engineering*, ASCE, **211**, 2000.