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Estimation of vertical diffusion coefficient and oxygen consumption rate in the interior western parts of Ariake Sea

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Summary

In this study, in order to clarify the generation mechanism of hypoxic water that occurs frequently in the interior parts of Ariake Sea, various field observations were conducted in summer of 2005 and vertical diffusion coefficient and oxygen consumption rate in the study area were analyzed by the two-layer box model using Saga Prefecture research data in 1972-2000.

Temporal variations of DO near sea bottom during 23 July-17 August in 2005 were strongly influenced by typhoons and strong wind-induced mixing of sea water and by the advection of hypoxic water from offshore area, besides tide and current velocity. From the data observed on 16 August in 2005, mixing condition of water column in the west coastal area was the weakly mixed-type and density stratification and pycnocline were formed at 3-5m depth from surface sea water at the time of occurrence of hypoxic water. There was a relationship between vertical diffusion coefficient obtained by the thermal stratification model and stratification parameter. That is, vertical diffusion coefficient decreased exponentially with increasing of stratification parameter. Thus, the development of density stratification in the water column was considered to restrict the ability supply of O_2 from surface to lower layers.

From Saga Prefecture research data in 1972-2000, seasonal variations of density difference between surface and lower layers and density stratification parameter in the interior western parts of Ariake Sea were clarified. That is, density difference raised and density stratification parameter became high values in summer due to increasing of freshwater input and surface warming. Conversely, density difference dropped and density stratification parameter became low values in winter due to decreasing of freshwater input and surface cooling. Next, vertical diffusion coefficient and oxygen consumption rate in the study area were analyzed by the two-layer box model. As a result, seasonal variations of vertical diffusion coefficient were closely related to that of density stratification parameter. That is, vertical diffusion coefficient tended to increase in summer-autumn and to decrease in winter-spring. On the other hand, oxygen consumption rate tended to be positive (O_2 consumption) in spring-summer and to be negative (O_2 production) in autumn-winter.

Key words: hypoxic water, vertical diffusion coefficient, oxygen consumption rate, two-layer box model, Ariake Sea

Introduction

In resent years, water quality environment and fisheries in the interior parts of Ariake Sea become serious[1,2], and occurrence of hypoxic water has very important effects on the above-mentioned problems. Generally, density stratification is easy to develop and seawater mixing between upper and lower layer decreases easily at summer in the closed sea area. As a result, seawater become easily oxygen depression in bottom layer, because the ability to supply O_2 from surface to lower layer decreases and O_2 near bottom layer is consumed by biochemical oxygen-consumption processes. Oxygen depression in bottom layer deteriorates the environmental condition of habit of benthos such as clam and accelerates the elusion of nutrient and sulfide from bottom sediment. Thus, it is considered that hypoxic water induces the deterioration of water quality environment and ecosystem in the closed sea area.

In this paper, in order to clarify the generation mechanism of hypoxic water that occurs frequently at summer in the interior western parts of Ariake Sea, temporal and spatial distribution of DO near bottom and the sea structure under occurrence of hypoxic water in the sea area were investigated by the field observations in 2005. Then, the vertical diffusion coefficient and the oxygen consumption rate in the study area were analyzed by the two-layer box model using Saga and Fukuoka Prefecture research data in 1972-2000, and their seasonal variations were discussed.

Outline of the field observations and material

Fig.1 shows the occurrence frequency of hypoxic water (DO<40% saturation) and the horizontal distributions of mud content and CODsed in bottom sediment in the interior parts of Ariake Sea. The occurrence frequency of hypoxic water and bottom sediment data were obtained by Saga and Fukuoka Prefecture research data in 1972-2000 and the Ministry of the Environment in August 2002, respectively. As shown in this figure, hypoxic water occurred frequently in the interior western parts of Ariake Sea with high CODsed and mud content in bottom sediment.

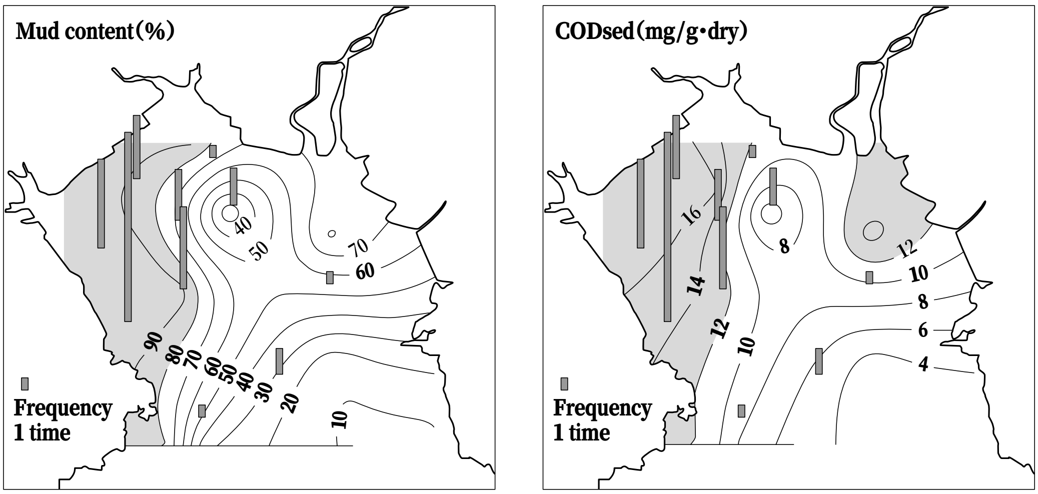


Fig. 1 Occurrence frequency of hypoxic water during 1972-2000 and distributions of mud content and CODsed in 2002.

Field observations were conducted at St.1 in Fig.2, where hypoxic water occurred frequently in summer, using the field observation apparatus with DoPa transmission units during 16 July-11 August in 2005 to investigate the temporal variations of water quality and current velocity near sea bottom. And, mooring observations were conducted at St.1 using the multi-type water quality meter on 23 July and 17 August in 2005 to clarify the relationship between density stratification parameter and vertical diffusion coefficient. Moreover, water quality profiles along Line A in Fig.2 were observed using the multi-type water quality meter on 9 August and 16 August in 2005 to make clear the sea structure under occurrence of hypoxic water in the interior western parts of Ariake Sea.

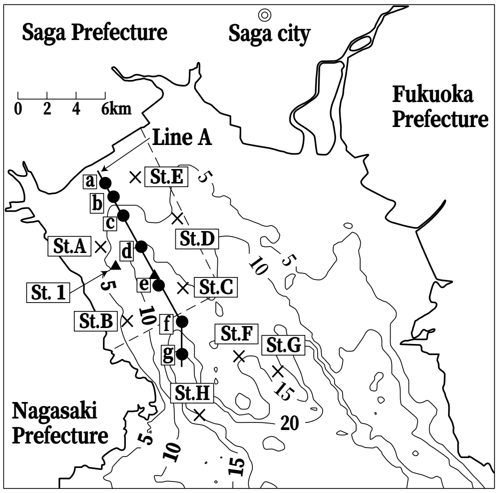


Fig. 2 Observation stations and study area in the interior parts of the Ariake Sea (sea area surround by broken lines). Two crosses (×) represent observation stations by Saga Prefecture.

On the other hand, in order to estimate the vertical diffusion coefficient (K) and the oxygen consumption rate (R) in the interior western parts of Ariake Sea, water temperature (T), salinity (S) and dissolved oxygen (DO) at St.A-H as shown in Fig.2 were used in this study. These data were observed at the time of a flood tide every month by the Ariake Fisheries Research Agency of Saga Prefecture. T, S and DO at each station were measured at 0m, 5m, 10m, 20m and 40m depth from surface water. In this study, these data were interpolated by a linear interpolation at intervals of 1m depth. Seawater density (ρ_S) was calculated by the following equation using T and S.

$$\rho_S = 1 + 10^{-3}\sigma_S \qquad (1)$$

where $\sigma_S = \frac{(T-3.98)^2}{503.570} \cdot \frac{T+283.0}{T+67.26} + (\sigma_{S0}+0.1324)\{1-A_t+B_t(\sigma_{S0}-0.1324)\}$,

$\sigma_{S0} = -0.0939 + 0.8149S - 0.0005S^2 + 0.0000066S^3$,

$A_t = T(4.7869 - 0.098185T + 0.010843T^2) \times 10^{-3}$ and

$B_t = T(18.030 - 0.8164T + 0.01667T^2) \times 10^{-6}$

Monthly meteorological data in Saga weather station were used and river flows that come in the interior western parts of Ariake Sea were estimated by monthly precipitation and catchment area.

Two-layer box model

The study area that hypoxic water occurred frequently, which surrounded with broken lines in Fig.2, was assumed to be the two-layer box model shown by Fig.3 in this study. Boundary depth between upper and lower layer (H_1) was corresponded to the depth of pycnocline in the study area obtained by our field research data in August, 2005. The contribution rate to the density difference between surface and bottom layer (σ_{tb}-σ_{ts}) of salinity difference and water temperature difference was 76.4% and 23.6%, respectively[3]. Thus, S was used in construction of two-layer box model. S_1 and C_1 (S_2 and C_2) are the averaged salinity and DO values in Box1 (Box2) that obtained from S and DO profiles at St.A-E (Fig.2). S_3 and C_3 (S_4 and C_4) are the averaged salinity and DO values in the upper (lower) layer outside of box that obtained from S and DO profiles at St.F-H (Fig.2).

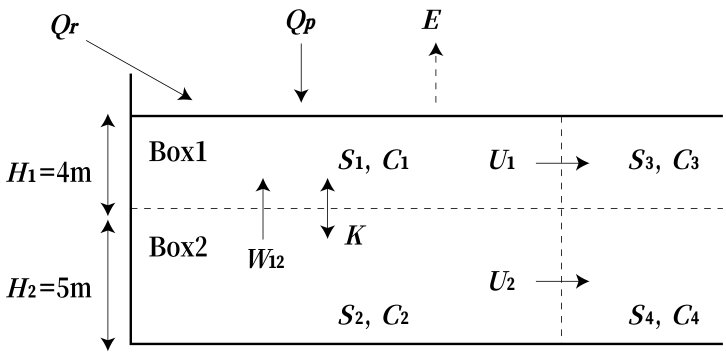


Fig. 3 Schematic diagram of the two-layer box model

If we assume that the salinity balance in each box is controlled by the horizontal velocities in upper and lower layers (U_1 and U_2), the vertical velocity between upper and lower layers (W_{12}) and K, then the salinity balance equations in Box1 and Box2 are expressed as follows, respectively[4].

Box1

$$V_1\frac{\partial S_1}{\partial t} = -A_1U_1\frac{S_1+S_3}{2}+A_{12}W_{12}\frac{S_1+S_2}{2}+A_{12}K\frac{S_2-S_1}{Z_{12}} \quad (2)$$

$$A_1U_1 = A_{12}W_{12}+Q,\ \ Q = Q_r+Q_p-E \quad (3)$$

Box2

$$V_2\frac{\partial S_2}{\partial t} = -A_2U_2\frac{S_2+S_4}{2}-A_{12}W_{12}\frac{S_1+S_2}{2}-A_{12}K\frac{S_2-S_1}{Z_{12}} \quad (4)$$

$$A_2U_2 = -A_{12}W_{12} \quad (5)$$

where V_1 and V_2 are the volume in upper and lower layers, A_1 and A_2 are the cross section area in upper and lower layers, A_{12} is the interface area between upper and lower layers, Z_{12} is the vertical distance between mid-point of upper and lower layers, and Q is the total freshwater flux into the upper layer that is calculated by river flow (Q_r), precipitation (Q_p) and evaporation (E), which is obtained by the following equation.

$$E = k\ (E_s - E_a)\, W \tag{6}$$

where k is the evaporation coefficient (=0.17 $mmd^{-1}hPa^{-1}cm^{-1}$)[5), E_s is the saturation vapor pressure calculated using surface water temperature, E_a is the atmospheric vapor pressure and W is the wind velocity.

DO balance equation in Box2 is expressed by the following equation.

$$V_2 \frac{\partial C_2}{\partial t} = -A_2 U_2 \frac{C_2 + C_4}{2} - A_{12} W_{12} \frac{C_1 + C_2}{2} + A_{12} K \frac{C_1 - C_2}{Z_{12}} - V_2 R \tag{7}$$

where R is the biochemical oxygen consumption rate.

Dimensions of boxes in the study area are listed in Table.1.

Table. 1 Dimensions of two-layer box model

Volume (km^3)	V_1	0.426
	V_2	0.533
Interface area (km^2)	A_{12}	106.56
Cross section area (km^2)	A_1	0.029
	A_2	0.037
Vertical distance (m)	Z_{12}	4.50

Results and discussion

1. Temporal and spatial distribution of DO

Fig.4 shows the temporal variations of DO, water level, velocity, wind direction, wind speed, wave height and turbidity at St.1 during 16 July-11 August in 2005. As shown in this figure, DO near bottom became hypoxic around the neap tide (16 July-20 July) and increased rapidly and largely around the spring tide (20 July-24 July). However, DO was high value before and after neap tide (25 July-4 August) and tended to decrease around the spring tide (5 August-8 August). The high values of DO near bottom around the neap tide (25 July-4 August) were closely related to the wind velocity. That is, south wind more than 5m/s blew continuously between 25 July and 4 August and wave heights in this period were high in comparison with other observation periods. Therefore, it was considered that the stirring and mixing actions in the water column due to wind and waves accelerated resulting in a rise of O_2 supply from surface to bottom layers.

Fig.5 shows the daily variations in horizontal distributions of waters of DO<50% saturation and salinity>29psu near sea bottom in the interior parts of Ariake Sea during 4 August-7 August, 2005. As shown in this figure, waters of salinity>29psu moved to the northwest area in the interior parts of bay from Oura offing with the passage of day, and waters of DO<50% saturation also went north along the west coastal area. Thus, we considered that the drop of DO at St.1 around the spring tide (5 August-8 August) was related to the entering of low DO waters due to advection from the bay mouth of Isahaya Bay.

2. Sea structure under the occurrence of hypoxic water

Fig.6 shows the vertical distributions of density (σ_t) and DO along Line A at the time of no occur-

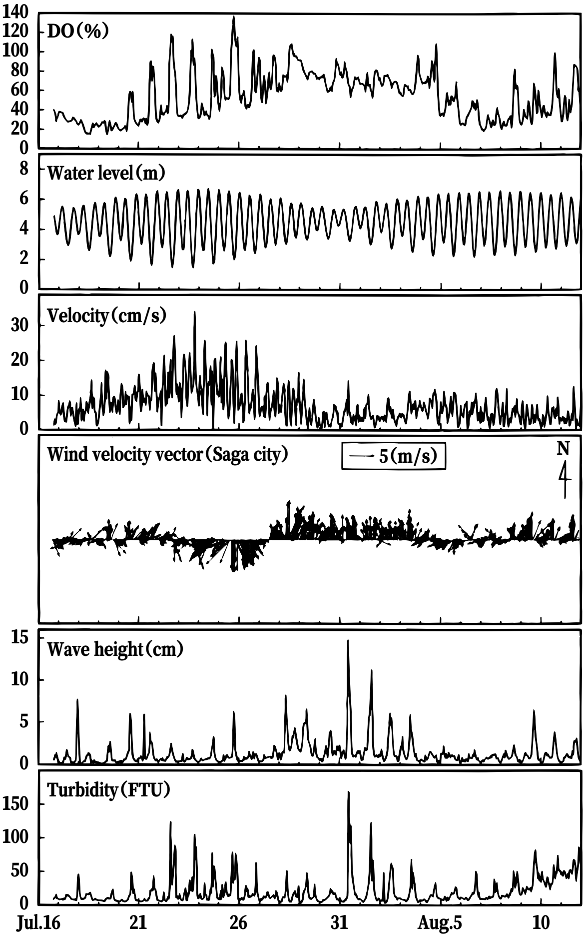


Fig. 4 Temporal variations of DO, water level, velocity, wind direction, wind speed, wave height and turbidity at St.1.

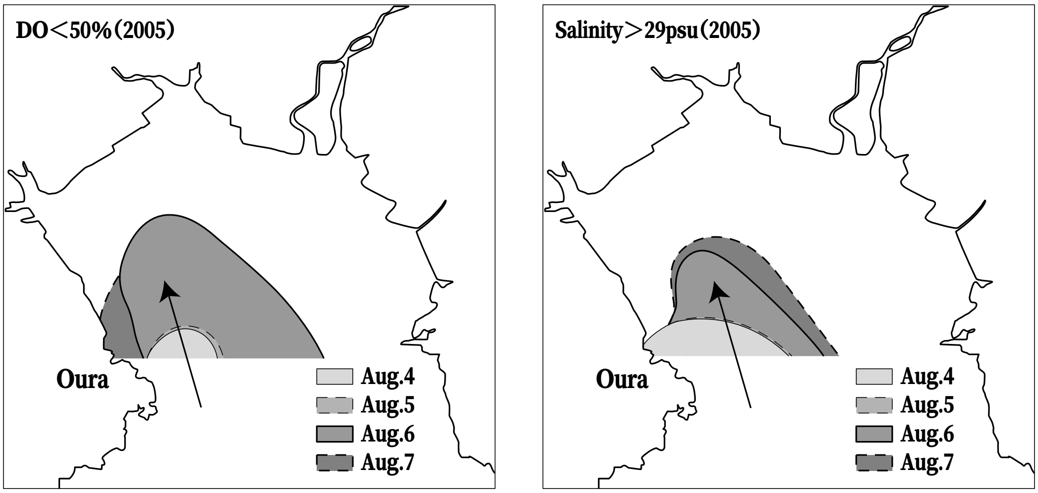
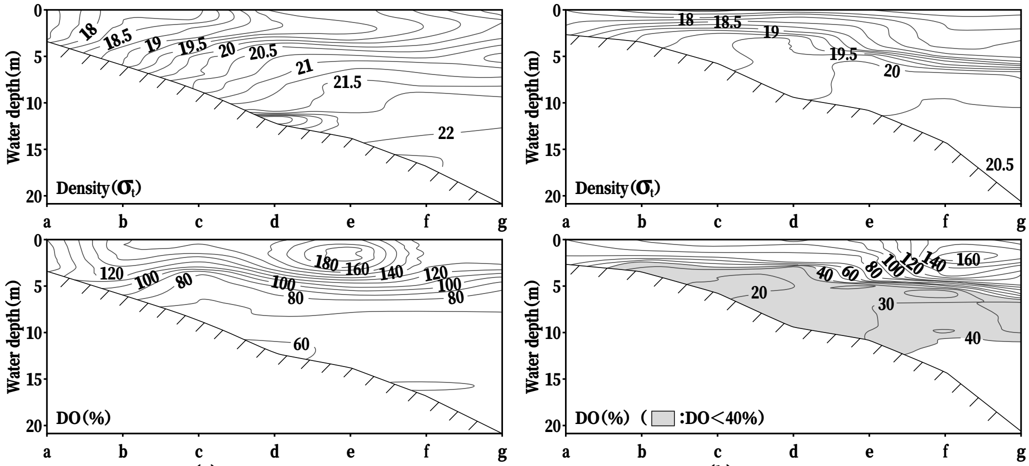


Fig. 5 Daily variation of horizontal distributions of DO<50% saturation and salinity>29psu. (August, 2005; Daily averaged value.)

rence (9 August) and occurrence (16 August) of hypoxic water. As shown in this figure, σ_t changed from partially mixed-type into weekly mixed-type with the progress of observation point from a to g at the no hypoxic water condition. However, at the occurrence of hypoxic water, σ_t was weakly mixed-type in all observation points and there was a remarkable pycnocline at 3-5m depth from surface water. Although DO was supersaturation above the pycnocline, DO decreased rapidly to about 20% saturation below the pycnocline and large scale hypoxic water was observed from middle to bottom layers.



(a) August 9, 2005 (b) August 16, 2005

Fig. 6 Vertical distributions of σ_t and DO along Line A.

Fig.7 shows the relationship between the density stratification parameter (P)[6] that indicates the potential energy of water column per unit water depth and K that is ability supply of O_2 between surface and bottom layers, which are obtained from the measured T and S profiles at St.1 on 21 August and 27 August in 2004 and 23 July and 17 August in 2005. Here, P was given by equations (8) and (9).

$$P = \frac{1}{H}\int_{-H}^{0} |\rho(z) - \overline{\rho}| gz dz \tag{8}$$

$$\overline{\rho} = \frac{1}{H}\int_{-H}^{0} \rho(z) dz \tag{9}$$

where H is the water depth, g is the gravity acceleration and z is the vertical coordinate.

Moreover, if we assumed that sea water temperature profile of St.1 was considered as the two stratification layer as shown in Fig.8, K was calculated by equation (10)[7].

$$H_L \frac{dT_L}{dt} = K\left(\frac{T_U - T_L}{H_{UL}}\right) \tag{10}$$

where H_L is the lower layer thickness, t is the time, T_U and T_L are the averaged water temperature in upper and lower layers and H_{UL} is the vertical distance between mid-point of upper and lower layers.

As shown in Fig.7, K tended to decrease exponentially with increasing P. The fact indicated that the ability to supply O_2 between surface and lower layers dropped rapidly with the development of density stratification. Thus, formation of pycnocline or density stratification caused a drop of mixing in the water column and a pycnocline barrier in the water column restricted O_2 supply from surface to bottom layers.

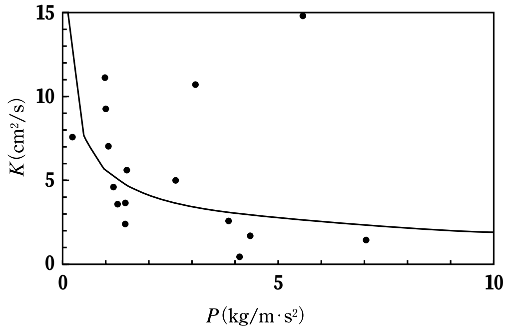


Fig. 7 Relationship between P and K.

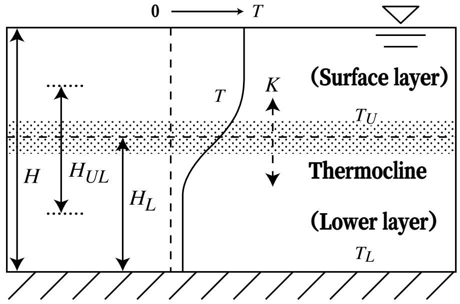


Fig. 8 Conceptual illustration of thermal stratification model for sea water temperature.

3. Formation of density stratification

Fig.9 shows the year-to-year variations in DO near bottom and (σ_{tb}-σ_{ts}) during 1972-2000 in the interior western parts of Ariake Sea. DO and (σ_{tb}-σ_{ts}) are averaged values using the observed data of St.A-E in Fig.2. As shown in this figure, DO near bottom dropped with increasing of (σ_{tb}-σ_{ts}) in summer and raised with decreasing of (σ_{tb}-σ_{ts}) in winter.

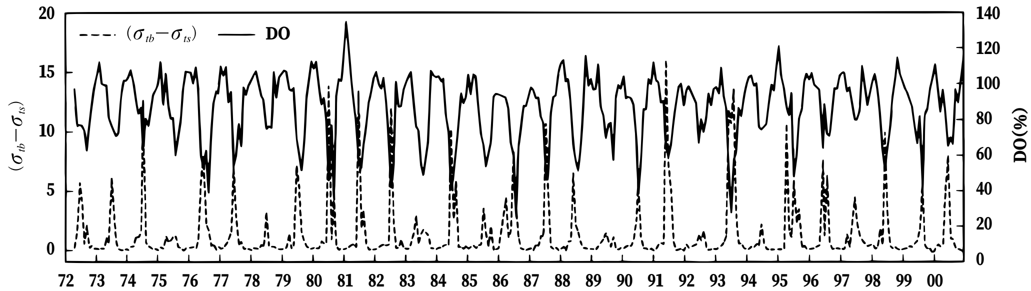


Fig. 9 Year-to-year variations in the DO near bottom and (σ_{tb}-σ_{ts}) during 1972-2000.

Fig.10 shows the relationship between DO near bottom and (σ_{tb}-σ_{ts}) in summer (June-August) during 1972-2000. DO tended to decrease with increasing of (σ_{tb}-σ_{ts}). Thus, we considered that the stability of density stratification was enhanced with increasing of (σ_{tb}-σ_{ts}), so that O_2 supply between surface and bottom layers was restricted due to a drop of vertical mixing in the water column.

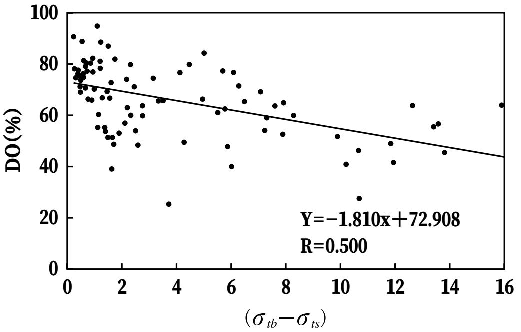


Fig. 10 Relationship between DO near bottom and (σ_{tb}-σ_{ts}) in summer during 1972−2000.

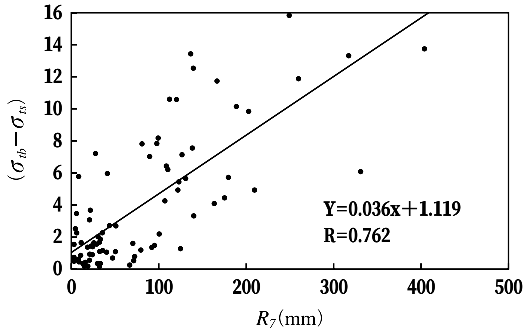


Fig. 11 Relationship between (σ_{tb}-σ_{ts}) and R_7 in summer during 1972−2000.

Fig.11 shows the relationship between (σ_{tb}-σ_{ts}) and R_7 that is the total amount of precipitation in Saga City for 7 days before Saga Prefecture research date. From this figure, we found that (σ_{tb}-σ_{ts}) tended to increase with precipitation. That is, surface layer salinity decreased with increasing of precipitation and river flow, so that the density stratification or pycnocline was formed with increasing of (σ_{tb}-σ_{ts}).

Fig.12 shows the seasonal variations of P, which are the monthly average values during 1972-2000, in the interior western parts of Ariake Sea. As shown in this figure, P increased rapidly in summer and decreased in winter. In summer, (σ_{tb}-σ_{ts}) increased and stable density stratification was formed due to increase in precipitation and river flow and surface warming, so that P became high values. However, in winter, the water column was almost homogeneously mixed down to a lower layer due to decrease in precipitation and river flow and surface cooling, so that density stratification was broken down and P became low values.

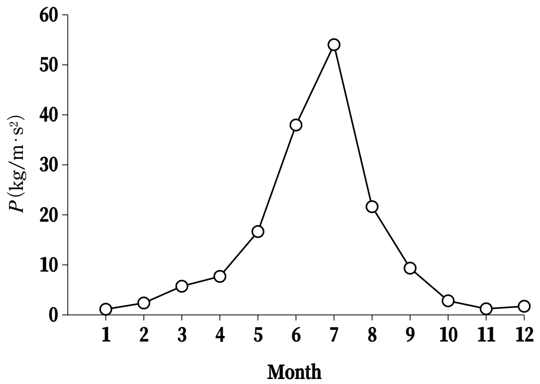


Fig. 12 Seasonal variation in P (average over 1972-2000).

4. Seasonal variations in *K* and *R*

Fig.13 shows the seasonal variations of K and R that calculated by the two-layer box model in the study area. They are monthly average values for 1972-2000. As shown in this figure, K tended to decrease in summer-autumn and to increase in winter-spring. The seasonal variations of K were closely related to that of P. That is, vertical mixing of sea water was restricted and K decreased in summer-autumn, because density stratification was enhanced due to increasing freshwater input and surface warming. However, vertical mixing of sea water was accelerated and K increased in autumn-winter, because density stratification was alleviated or eliminated due to decreasing freshwater input, wind-induced mixing and surface cooling.

On the other hand, R tended to be positive (O_2 consumption) in spring-summer and to be negative (O_2 production) in autumn-winter. O_2 consumption in spring-summer was considered to relate to rising water temperature and increasing organic matter in the water column. And, O_2 production in autumn-winter was considered to relate to dropping water temperature and activation of photosynthesis by phytoplankton with increasing transparency. R calculated by this model ranged from 1.0 to 1.5 $mgL^{-1}d^{-1}$in summer. It was the same order as one reported in other sea area such as Tokyo Bay, Mikawa Bay and Suo-Nada[8]. However, it was anticipated that R under occurrence of hypoxic water at a neap tide was higher than that obtained by this study, because Saga Prefecture research data used in this study were observed at the time of spring tide.

From now on, it is necessary to collect the detailed field research data in summer and to construct the model including the advection from interior eastern parts of Ariake Sea.

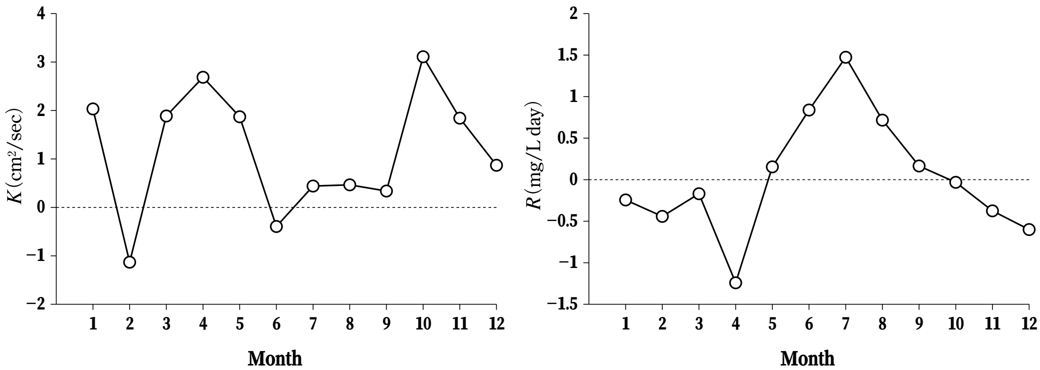


Fig. 13 Seasonal variations in K and R (average over 1972-2000).

Conclusions

In this study, field observations were carried out in the interior western parts of Ariake Sea and temporal and spatial distribution of DO near bottom and sea structure under the occurrence of hypoxic water in the study area were investigated on the basis of the field data. Moreover, seasonal variations of (σ_{tb}-σ_{ts}) and P in the study area were clarified using the Saga Prefecture research data in 1972-2000, and K and R were analyzed by the two-layer box model. The results obtained by this study are summarized as follows;

(1). Hypoxic water occurred frequently in the interior western parts of Ariake Sea with high mud content and CODsed in bottom sediment.

(2). Temporal variations of DO near bottom at St.1 were strongly influenced by wave and wind velocity besides tide and current velocity.

(3). When pycnocline was formed at the time of neap tide in summer, large scale hypoxic water was observed below the pycnocline.

(4). K obtained by the thermal stratification model decreased exponentially with increasing of P. Thus, stable density stratification in the water column was considered to restrict the ability to supply O_2 from surface to bottom layers.

(5). Seasonal variations of (σ_{tb}-σ_{ts}) were the opposite of that of DO near bottom in the study area during 1972-2000. (σ_{tb}-σ_{ts}) tended to increase with increasing of precipitation.

(6). Seasonal variations of P were clarified in the study area during 1972-2000. That is, P increased rapidly in summer due to formation of stable density stratification and decreased in winter due to alleviation or elimination of density stratification.

(7). K and R were analyzed by the two-layer box model in the study area. As a result, seasonal variations of K were closely related to that of P. That is, K tended to decrease in summer-autumn and to increase in winter-spring. On the other hand, R tended to be positive (O_2 consumption) in spring-summer and to be negative (O_2 production) in autumn-winter.

References

1. Sekiguchi, H and R. Ishii (2003). Drastic decreasing of annual catch yields of the manila clam *Ruditapes hilippinarum* in Ariake sound, southern Japan. *Oceanography in Japan*. **12(1)**, 21-36.
2. Tsutsumi, H., E. Okamura, M. Ogawa, T. Takahashi, H. Yamaguchi, S. Montani, N. Kohashi, T. Adachi and T. Komatsu (2003). Studies of the cross section of water in the innermost areas of Ariake Bay with the recent occurrence of hypoxic water and red tide. *Oceanography in Japan*. **12(3)**, 291-305.
3. Kajihara, Y., T. Tomita, T. Nakano and M. Isobe (2003). Occurrence of hypoxic water in the inner area of Ariake Bay in the summer of 2002. *Journals of the Japan Society of Civil Engineers*. **747**, 187-196.
4. Yamaguchi, S. and Y. Kyozuka (2006). Generation mechanism of hypoxia in Isahaya Bay. *Oceanography in Japan*. **15(1)**, 37-51.
5. Yanagi, T. and R. Abe (2005). Year-to-year variations in salinity and in the budgets of dissolved inorganic phosphorus and dissolved inorganic nitrogen in the head of Ariake Bay. *Oceanography in Japan*. **14(1)**, 21-33.
6. Hill, A.E., Brown, J. and Fernand, L (1997). The summer gyre in the western Irish Sea, *shelf sea paradigms and management implications. Est. Coast. Shelf Sci*, **44**, 83-95.
7. Takeoka, H., T. Ochi, and K, Takatani (1986). The anoxic water mass in Hiuchi-nada Part2, *The heat and oxygen budget model. J. Oceanogr. Soc. Japan*, **42**, 12-21.
8. Tetsuo Yanagi (2004). Hypoxia - the chemical and biological consequences of the mechanisms of its generation, maintenance, variability and disappearance. *Oceanography in Japan*. **13(5)**, 451-460.

有明海奥部西岸域における鉛直拡散係数及び酸素消費速度の推定

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摘　　　要

本研究では，有明海奥部で頻発する貧酸素水塊の発生メカニズムを明らかにするために，2005年夏季に種々の現地観測を行うと同時に，1972～2000年の浅海定線調査データを用いて２層ボックスモデルによる奥部西岸域の鉛直拡散係数及び酸素消費速度の解析が行われた．

2005年７月23日～８月17日における底層ＤＯの時間的変動は，潮位や流速以外に台風や強風による海水の撹拌や沖合域からの貧酸素水塊の移流に大きく左右された．また，2005年８月16日の現地観測より，貧酸素水塊の発生時において西岸域の混合状態は弱混合となり，水深３～５ｍ付近に顕著な密度成層さらには密度躍層の形成が見られた．水温成層モデルより得られた鉛直拡散係数と成層強度との間には関連性が見られ，鉛直拡散係数は成層強度の増加に伴って指数関数的に減少した．このことから，海水の密度成層の発達は，表層から下層へのO_2の供給能力を制限するものと考えられた．

1972～2000年の浅海定線調査データより，有明海奥部西岸域における表底密度差や成層強度の季節変動が明らかにされた．すなわち，夏季では淡水流入量の増加や海面加熱により表底密度差が上昇し，成層強度は増大した．一方，冬季では淡水流入量の減少や海面冷却により表底密度差は低下し，成層強度は減少した．また，２層ボックスモデルにより奥部西岸域における鉛直拡散係数及び酸素消費速度が解析された．その結果，鉛直拡散係数の季節変動は成層強度のそれと密接に関連し，夏季～秋季に減少し，冬季～春季に増加する変動傾向を示した．また，酸素消費速度は春季～夏季に正（O_2消費），秋季～冬季に負（O_2生産）となる季節変動を示した．