Bull. Fac. Agr., Saga Univ. No. 94 : 1～13 (2009)

Study on the Occurrence Mechanism of Hypoxic Water in the Western Interior Parts of the Ariake Sea using a Two-Layer Box Model

Masumi KORIYAMA, Masahiro SEGUCHI, Tetuhiro ISHITANI and Nguyen Dnag THIEN
(Laboratory of Environment of Shallow Sea and Tidal Flat)
Received November 28, 2008

Summary

In this study, the physical and biochemical parameters concerned with the occurrence of hypoxic water in the western interior parts of the Ariake Sea are analyzed by a two-layer box model using the Saga Prefecture research data in 1972-2004, and the occurrence mechanism of hypoxic water is investigated based on the above analytical results. As a result, the monthly variations of an average year value over 1972-2004 for advection velocity, vertical diffusion coefficient (K_z) and biochemical oxygen consumption rate (R) are clarified, and K_z and R contribute greatly to the temporal variation of DO concentration in lower layer box in summer. Next, the monthly variations of an average value for density stratification degree (P), K_z and R in the 1970s (1972-1980), the 1980s (1981-1990) and the 1990s-early 2000s (1991-2004) are analyzed. As a result, in summer, P and K_z do not have precise change among the calculated periods, but R between the 1970s and from the 1980s on is clearly different. It is considered that one factor which changes R in summer since the 1980s is an increase of organic matter amount and the change of decomposition process of organic matter in the study area.

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

Introduction

After the 1990s, the annual occurrence numbers of red tide have a tendency to increase in the Ariake Sea. The environmental problem of the Ariake Sea is one of socially great interest due to bad harvest of laver in 2000-2001. The large scale of hypoxic water was observed frequently in the Ariake Sea from the field observations after 2001[1),2)]. Presently, hypoxic water is one of the most important phenomena in water quality and ecosystem near sea bottom, and the negative effects of hypoxic water on the sea water environment and fishery resources in the Ariake Sea become anxious[3)].

Recently, there are many researches for hypoxic water in the Ariake Sea, and its actual state is becoming clear. For example, Seguchi et al.[4)], Koriyama et al.[5)] and Ishitani et al.[6)] investigated the variation of bottom dissolved oxygen (DO) in the western interior parts of the Ariake Sea (WIAS) and clarified the relationship between the hypoxic water occurrence and the density stratification based on the Saga Prefecture research data and the field observation data. Koriyama et al.[7)] clarified the vertical diffusion coefficient profiles in the water column under the formation of density stratification using the measured vertical velocity component in WIAS. Furthermore, Koriyama et al.[7)] found that the oxygen consumption was mainly caused by high consumption rate in the bottom water below pycnocline and showed that the oxygen consumption rate of bottom water was greatly dependent on the particulate organic carbon (POC). Moreover, Tokunaga et al. [8] indicated that the oxygen consumption rate of suspended solids (SS) was 7 times of one of bottom sediment surface in the western parts of Ariake Sea from the oxygen consumption experiment in laboratory.

These researches are significant studies with regard to grasp of the actual occurrence condition of hypoxic water and to clarification of its mechanism in the interior parts of the Ariake Sea. However, it is necessary to investigate in more detail the hypoxic water based on the quantitative assessments of physical and biochemical processes concerned with the hypoxic water occurrence in order to clarify the occurrence mechanism of that in WIAS.

The purpose of this paper is to analyze the physical amounts concerned with the occurrence of hypoxic water in WIAS by a two-layer box model using the field data and to make clear the occurrence mechanism of one. Firstly, the seasonal variations of an average year value over 1972-2004 for advection velocity, vertical diffusion coefficient and biochemical oxygen consumption rate are clarified by a two-layer box model using the Saga Prefecture research data in 1972-2004. Secondly, the contributions of physical and biochemical processes affecting the temporal variation of DO concentration in lower layer box are quantified and the occurrence mechanism of hypoxic water in the study area is discussed. Finally, the variations of monthly average value about every 10 years for vertical diffusion coefficient and biochemical oxygen consumption rate that are important parameters for hypoxic water occurrence in WIAS are investigated.

Analysis of hypoxic water by a two-layer box model

1. Used data

The analysis area (surrounded by broken line) in WIAS are shown in Fig.1. To investigate the outline of the occurrence mechanism of hypoxic water in this sea area, field observation data were analyzed using a two-layer box model. Temperature (T), Salinity (S) and DO concentration

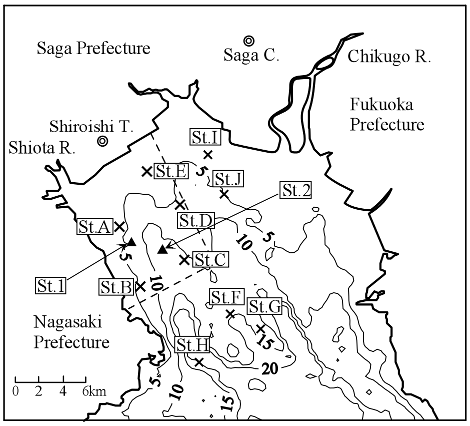

Fig.1 Measurement points, analysis area (surrounded by broken lines) and water depth (unit: m) in western interior parts of the Ariake Sea. St.A ～J are the measurement points of Saga Prefecture, and St1. and 2 are sample point in oxygen consumption experiment.

that were used in this analysis were obtained by Saga Prefecture at St.A～J in Fig.1 from 1972 to 2004. These data measured at 0, 5, 10, 20, 30 and 40m depth from sea water surface were interpolated linearly every 1m depth. The sea water density (ρ) was calculated using the measured T and S [6].

On the other hand, the meteorological data were the monthly mean ones which were measured by Saga region meteorology observation. Moreover, the river discharges were estimated from the water-shed area and monthly precipitation.

2. Outline of a two-layer box model

It is considered that DO concentration in the bottom layer depends on the balance between supply and consumption of oxygen due to advection and diffusion process or biochemical process. Therefore, it is necessary to quantify the effect of physical and biochemical processes on the temporal variation of DO concentration in the bottom layer to clarify the occurrence mechanism of hypoxic water. So, firstly, the seasonal variations of an average year value over 1972-2004 for advection velocity, vertical diffusion coefficient and biochemical oxygen consumption rate in WIAS are clarified by a two-layer box model using in site measured data. Secondly, the effect of physical and biochemical processes on the temporal variation of DO concentration in bottom layer is estimated, and then the occurrence mechanism of hypoxic water is investigated.

As shown in Fig.2, the density pycnocline is developed, and the vertical profile of field density (σ_t) shows a remarkable two-layer structure at the occurrence of hypoxic water in summer. Thus, a two-layer box model is applied to the sea area surrounded by broken lines in Fig.1. The

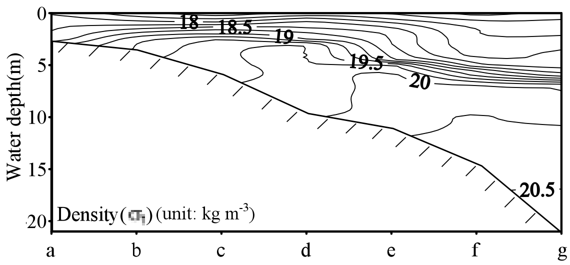

Fig.2 Vertical profiles of σ_t under the occurrence of hypoxic water in the western interior parts of the Ariake Sea (16 August, 2005).

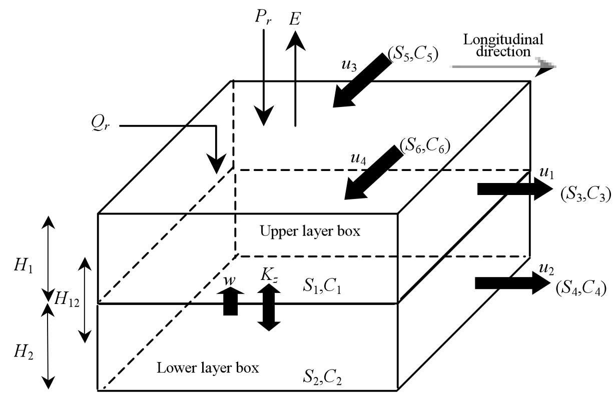

Fig.3 Schematic diagram of a two-layer box model in the study area.

schematic of a two-layer box model is illustrated in Fig.3. The thickness of upper layer box (H_1) is 4m, which is the depth from the sea water surface to the center of density pynocline, and that of lower layer box (H_2) is 5m, which is the depth from the lower end of upper layer box to the sea bottom. H_1 is determined based on the average vertical profile of sea water density in the interior parts of the Ariake Sea in summer, 1990-2000[9], and in site measured data in 2004-2007[6].

The mean salinity (S_1) and DO concentration (C_1) in the upper layer box, and the mean salinity (S_2) and DO concentration (C_2) in the lower layer box are calculated from the data at St.A～E presented in Fig.1. Then, the mean salinity (S_3) and DO concentration (C_3) in the north-south direction outside the upper layer box, and the mean salinity (S_4) and DO concentration (C_4) in the north-south direction outside the lower layer box are calculated from the data at St.F～H. On the other hand, the mean salinity (S_5) and DO concentration (C_5) in the east-west direction outside the upper layer box, and the mean salinity (S_6) and DO concentration (C_6) in the east-west direction outside the lower layer box are calculated from the data at St.I and J. The specifications of each box are listed in Table 1.

Table 1 Dimensions of a 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
(Longitudinal)	A_2	0.037
Cross Section Area (km^2)	B_1	0.058
(Lateral)	B_2	0.072

The salinity and water balances in each box are expressed by Eqs.(1)～(5) as follows.

< Upper layer box >

$$V_1 \frac{dS_1}{dt} = -u_1A_1S_{13} + wA_{12}S_{12} + u_3B_1S_{13} + \frac{K_z(S_2 - S_1A_{12})}{H_{12}} \quad (1)$$

$$u_1A_1 = Q + wA_{12} + u_3B_1 \quad (2)$$

$$Q = Q_r + (P_r - E)A \quad (3)$$

< Lower layer box >

$$V_2 \frac{dS_2}{dt} = -u_2A_2S_{24} + wA_{12}S_{12} + u_4B_2S_{26} + \frac{K_z(S_1 - S_2A_{12})}{H_{12}} \quad (4)$$

$$u_2A_2 = wA_{12} + u_4B_2 \quad (5)$$

where V_1 and V_2 are the volumes of upper and lower layer, respectively, A_{12} is the area of horizontal cross section between the upper and lower layer boxes, respectively, A_1 and A_2 are the areas of vertical cross section in the north-south direction of the upper and lower layer boxes, respectively, B_1 and B_2 are the areas of vertical cross section in the east-west direction of the upper and lower layer boxes, respectively, u_1 and u_2 are the mean velocities of vertical cross section in the north-south direction of the upper and lower layers boxes, respectively, u_3 and u_4 are the mean velocities of vertical cross section in the east-west direction of the upper and lower layers boxes, respectively, w is the mean velocity in the vertical direction at the horizontal cross section between the upper and lower layer boxes, H_{12} is the distance between the centers of the upper and lower layer boxes, $S_{ij}=(S_i+S_j)/2$, and Q is the inflow of fresh water into the upper layer box which consists of the river discharge (Q_r), precipitation (P_r) , evaporation (E) and surface area of upper layer box (A). E is given by Eq.(6).

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

where k is the evaporation coefficient (=0.17mmd^{-1} hPa^{-1} sm^{-1}), E_s is the saturation vapor pressure calculated from in site measured sea water surface temperature, E_a and W are the monthly mean atmosphere vapor pressure and monthly mean wind velocity measured at Saga local meteorology station, respectively.

On the other hand, DO concentration balance in lower layer box is expressed as follows.

$$V_2\frac{dC_2}{dt}=-u_2A_2C_{24}-wA_{12}C_{12}+u_4B_2C_{26}+\frac{K_z(C_1-C_2)A_{12}}{H_{12}}-V_2R \tag{7}$$

where $C_{ij}=(C_i+C_j)/2$ and R is the biochemical oxygen consumption rate.

3. Analytical method

As indicated from Eqs.(1),(2),(4) and (5), there are six unknowns ($u_1 \sim u_4$, w and K_z) in these equations. Therefore, these unknowns can not be obtained analytically by solving the above mentioned four equations. In this study, these six unknowns in each month were calculated by the least-squared error method[10] using 33 data for S_1, S_2, S_{13}, S_{15}, S_{24}, S_{26}, and Q at each month in 1972 -2004 as follows.

First, substituting Eqs.(2) and (5) into Eqs.(1) and (4), we obtain the following equation.

$$m_t=u_2a_t+u_3b_t+u_4c_t \tag{8}$$

where , $m_t=V_1\frac{dS_1}{dt}+V_2\frac{dS_2}{dt}+QS_{13}$, $a_t=A_2(S_{13}-S_{24})$, $b_t=B_1(S_{15}-S_{13})$ and $c_t=B_2(S_{26}-S_{13})$.

Eq.(8) (t=1～33) at each month for 33 years during 1972 to 2004 is represented by the following matrix as Eq.(9). Then, the equation for the error between the left and right-hand side terms in Eq.(8) is obtained by Eq.(10).

$$\mathbf{A}=\begin{pmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ a_{33} & b_{33} & c_{33} \end{pmatrix},\ \mathbf{X}=\begin{pmatrix} u_2 \\ u_3 \\ u_4 \end{pmatrix},\ \mathbf{L}=\begin{pmatrix} m_1 \\ m_2 \\ \cdot \\ \cdot \\ m_{33} \end{pmatrix} \tag{9}$$

$$\mathbf{V}=\mathbf{L}-\mathbf{AX},\ \mathbf{V}=\begin{pmatrix}\varepsilon_1\\ \varepsilon_2\\ \cdot\\ \cdot\\ \varepsilon_{33}\end{pmatrix} \tag{10}$$

The squared error (**S**) is expressed as the following equation.

$$\mathbf{S}=\mathbf{V}^t\mathbf{V}=(\mathbf{L}-\mathbf{AX})^t(\mathbf{L}-\mathbf{AX})$$
$$=\mathbf{L}^t\mathbf{L}-2\mathbf{X}^t\mathbf{A}^t\mathbf{L}+\mathbf{X}^t\mathbf{A}^t\mathbf{AX} \tag{11}$$

The condition for the least squared error is expressed by Eq.(12), u_2, u_3 and u_4 that reproduce sufficiently the salinity and water balances in the study area are obtained by Eq.(13).

$$\frac{\partial\,\mathbf{V}^t\mathbf{V}}{\partial\,\mathbf{X}}=-2\mathbf{A}^t\mathbf{L}+2\mathbf{A}^t\mathbf{AX}=0 \tag{12}$$

$$\mathbf{X}=(\mathbf{A}^t\mathbf{A})^{-1}\mathbf{A}^t\mathbf{L} \tag{13}$$

Substituting u_2, u_3 and u_4 obtained the above mentioned into Eqs.(1), (2) and (4), the rest unknowns (u_1, w and K_z) are obtained. And then, substituting u_2, u_4, w, K_z and the average year value of DO concentration in lower layer box at each month in 1972-2004 into Eq.(7), R can be calculated.

Analytical results and discussions

Fig.4 shows the monthly variations of u_1~u_4 obtained by a two-layer box model analysis. Positive values of u_1 and u_2 indicate the outflow from upper and lower layer boxes, respectively, and negative values of those indicate the inflow into upper and lower layer boxes, respectively. On the other hand, positive values of u_3 and u_4 indicate the inflow into upper and lower layer boxes, respectively, and negative values of those indicate the outflow into upper and lower layer boxes, respectively. As shown in results of u_1 and u_2, estuary circulation is developed gradually

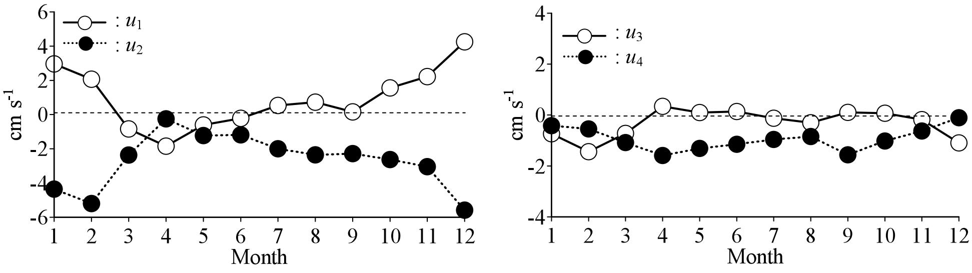

Fig.4 Monthly variations of u_1~u_4 (average over 1972-2004).
u_1 and u_2 are the mean velocities of vertical cross section in the north-south direction of the upper and lower layer boxes. u_3 and u_4 are the mean velocities of vertical cross section in the east-west direction of the upper and lower layer boxes.

with landward advection flow in bottom layer and seaward advection flow in surface layer from summer to winter. Seasonal variations of u_1 and u_2 are similar to the observation results obtained by Ohgushi et al. [11].

Fig.5 shows the seasonal variations of w, K_z and density stratification degree (P). P is defined by Eqs.(14) and (15)[9]. P indicates the difference between the potential energy in stratified water column and the potential energy in vertical well-mixed water column[12]. Thus, density stratification in the water column is stronger and stable density stratification is formed for long periods with increasing P. Conversely, vertical mixing in the water column is enhanced and density stratification disappears with decreasing P.

$$P = \int_0^H |\rho(z) - \overline{\rho}| g dz \tag{14}$$

$$\overline{\rho} = \frac{1}{H}\int_0^H \rho(z)\, dz \tag{15}$$

where H is the mean water depth in the study area, z is the height from sea bottom and g is the gravity acceleration.

Seasonal variations of w and K_z show the reverse that of P. That is, w and K_z decrease in increasing P and increase with decreasing P. Vertical mixing in the water column and advection between upper and lower layers are inhibited with development of density stratification due to increasing of fresh water input and surface warming, so that w and K_z decrease in summer-autumn. Conversely, vertical mixing and advection are enhanced with decay of density stratification due to decreasing of fresh water input and surface cooling, so that w and K_z increase in winter-spring.

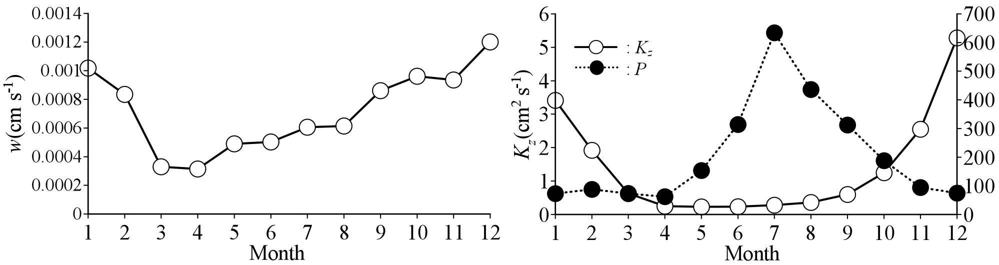

Fig.5 Monthly variations of w, vertical diffusion coefficient (K_z) and density stratification degree (P) (average over 1972-2004).
w is the mean velocity in the vertical direction at the horizontal cross section between the upper and lower layer boxes.

Fig.6 shows the monthly variation of R. R tends to be positive value (O_2 consumption) in spring-summer and to be negative value (O_2 production) in autumn-winter. The seasonal variation of R indicates those of biochemical consumption and production of DO in lower layer box. That is, it is considered that DO consumption in spring-summer is closely related to enhance of aerobic decomposition by bacteria with increasing in sea water temperature and organic matter amount, and DO production in autumn-winter is caused by activation of photosynthesis by phytoplankton with rise in transparency. R obtained by this model ranges from 0.30 to 0.46 mg $L^{-1}d^{-1}$ during May to August. On the other hand, measured values of R below the pycnocline are ob-

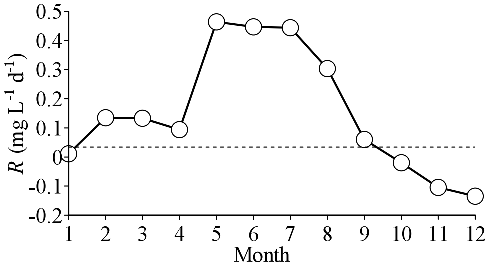

Fig.6 Monthly variations of biochemical oxygen consumption rate (R) (average over 1972-2004).

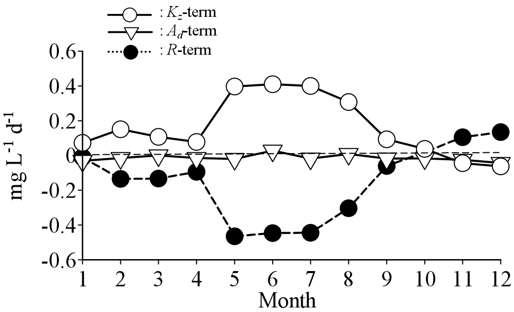

Fig.7 Monthly variations of the vertical diffusion term (K_z-term), the advection term (A_d-term) and the biochemical oxygen consumption term (R-term) in Eq.(7) (average over 1972-2004).

tained from the laboratory oxygen consumption experiment using collected sample at St.1 and St.2 (Fig.1) are 0.62-2.36 mg $L^{-1}d^{-1}$ and 0.16-2.32 mg $L^{-1}d^{-1}$, respectively[7]. Analytical value of R is same order as the experimental results.

Fig.7 shows the monthly variations of advection (A_d-term), vertical diffusion (K_z-term) and biochemical oxygen consumption terms (R-term) in Eq.(7) that are related to the temporal variation of DO concentration in lower layer box. Here, A_d-term, K_z-term and R-term are obtained by dividing the sum of from the first to the third terms, the fourth term and the fifth term in right side of Eq.(7) by V_2, respectively. As shown in this figure, A_d-term is low value throughout the year. Although K_z-term is low value in spring and winter, it is high positive value during summer. On the other hand, the seasonal variation of R-term shows the opposite that of K_z-term, and R-term is high negative value during summer. So, it is considered that DO concentration difference between upper and lower layer boxes and an increase of oxygen consumption amount in lower layer box contribute to increase in K_z-term and R-term during summer.

Next, we investigate the seasonal variations of degree that three terms contribute to the temporal variation of DO concentration in lower layer box. In winter (December-February), A_d-term, K_z-term and R-term is -0.03mg $L^{-1}d^{-1}$, -0.03mg $L^{-1}d^{-1}$ and 0.08mg $L^{-1}d^{-1}$, on average, respectively. So, DO supply due to R-term is high, and DO transportation to outside of lower layer box due to A_d-term is the same order as that due to K_z-term in winter. However, in summer (May-August), A_d-term, K_z-term and R-term is 0.0003mg $L^{-1}d^{-1}$, 0.37mg $L^{-1}d^{-1}$ and -0.42mg $L^{-1}d^{-1}$, on average, respectively. Thus, K_z-term and R-term have a great effect on the temporal

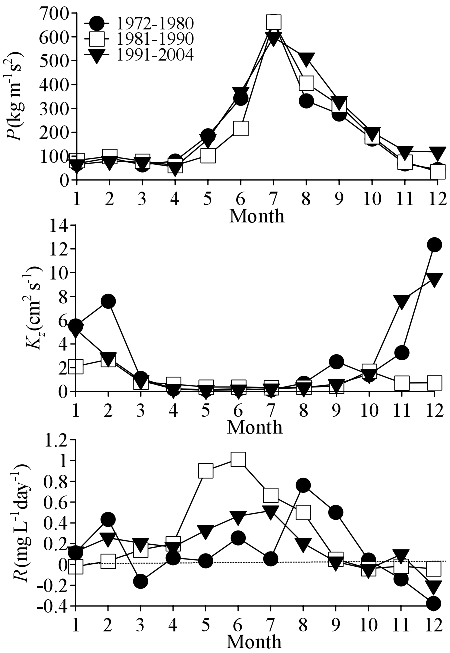

Fig.8 Monthly variations of the density stratification degree (P), the vertical diffusion coefficient (K_z) and the biochemical oxygen consumption rate (R) in the 1970s, the 1980s and the 1990s-early 2000s

variation of DO concentration in lower layer box during summer.

Generally, vertical DO transportation is most important in considering the oxygen budget in stratified water column[13] in summer. Isobe et al.[14] reported that 80% of DO transportation to bottom layer is caused by vertical diffusion in the Seto Inland Sea and the Suo-nada that inhomogeneous horizontal distribution of salinity is noticeable in summer. In this study, around 99% of DO supply to lower layer box is caused by K_z-term in summer. Thus, we consider that the hypoxic water in the study area occurs basically when biochemical oxygen consumption amount in bottom layer is greater than DO supply amount from surface to bottom layers due to vertical diffusion.

Fig.8 shows the monthly variations of an average year value for P, K_z and R in the 1970s (1972-1980), the 1980s (1981-1990) and the 1990s-early 2000s (1991-2004) that are obtained by a two-layer box model. As shown in this figure, P and K_z do not have significant difference in summer among the calculated periods. However, there is significant difference in R between the 1970s and from the 1980s on. That is, R becomes high positive value in August-September in the 1970s. Since the 1980s, the period of high positive R shifts in May-August and keeps for long time as compared to that of the 1970s. DO concentration in the bottom layer is determined by the balance between DO supply due to advection and vertical diffusion processes and DO consumption due to biochemical process. Therefore, we presume that the oxygen depression in bottom water of the study area is attributable to the early and long-term of DO consumption period in summer, because P and K_z little change in summer during 1972-2004.

Next, we investigate the change of R in summer since the 1980s. Basically, it is considered that R is closely related to sea water temperature and quantity and quality of organic matter.

Fig.9 shows the variations of the catch of shellfish and the settling of plankton in the Ariake Sea in 1970-2005. As shown in this figure, the catch of selfish decreased rapidly since near 1985. Conversely, the settling of plankton tended to increase gradually since the latter of 1980s. Thus, we consider that decrease sharply of shellfish, which is suspension feeder, causes an increase in organic matter amount in sea water.

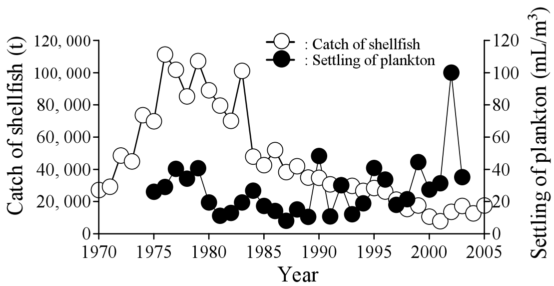

Fig.9 Temporal variations of catch of shellfish and settling of plankton in 1970-2005.

Fig.10 shows the temporal variations of COD of surface and bottom water in WIAS during summer (June-August) in 1972-2004. COD is the mean value using the data at St.A～E presented Fig.1. As shown in this figure, both COD in the study area tend to increase significantly. According to the laver independent committee[15], COD of inflow load amount from catchment area of Ariake Sea and internal load amount in the Ariake Sea do not have a significant change from

1970 to 2000. Thus, we guess that increased COD of sea water in the study area is caused by the mechanism that the organic matter, flows into and products in the Ariake Sea, is accumulated in WIAS.

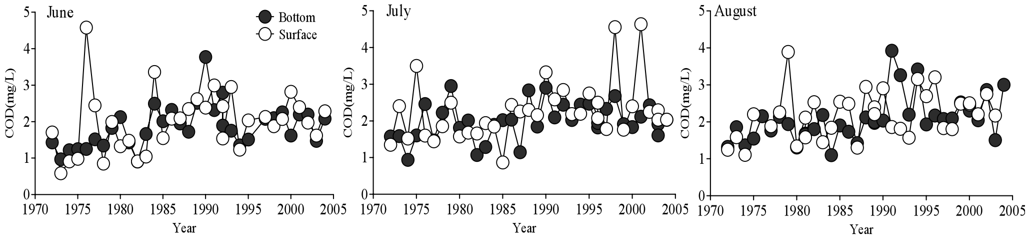

Fig.10 Temporal variations of COD of surface and bottom water in the western interior parts of the Ariake Sea during June-August (1972-2004)

In oceanography, the relationship between decomposition of organic matter and oxygen consumption is often expressed by the concept of the apparent oxygen utilization (AOU) [16]. So, the relationship between AOU and dissolved inorganic nitrogen (DIN) and between AOU and PO_4-P in the study area during June-August of the calculated periods are illustrated in Fig.11. As shown in this figure, there are significant positive correlations for the above-mentioned relationship at each the calculated periods. The facts indicate that DIN and PO_4-P are approximately proportional to the oxygen consumption amount in decomposing of organic matter. Kuwana[16] suggested that the ratio of AOU to nutrients may be approximately equal in the same sea at all times. However,

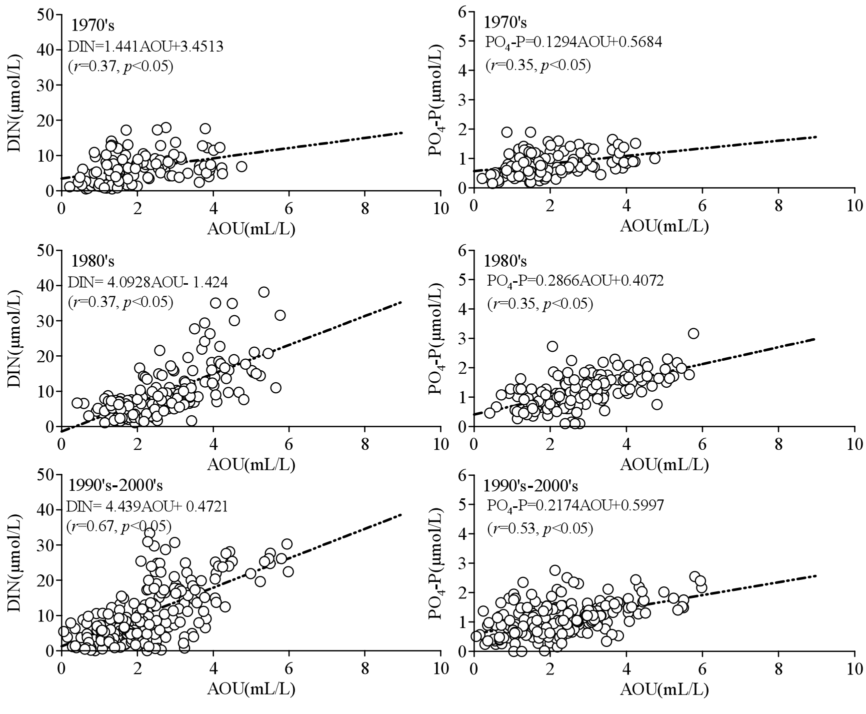

Fig. 11 The relationships between the apparent oxygen utilization (AOU) and the dissolved inorganic nitrogen (DIN) and between AOU and PO_4-P in the calculated periods

DIN/AOU ratio and PO_4-P/AOU ratio in WIAS are different in the calculated periods. That is, both ratios are approximately equal in the 1980s and the 1990s-early 2000s; DIN/AOU ratio and PO_4-P/AOU ratio are 4.09-4.44 and 0.22-0.29, respectively. On the other hand, in the 1970s, DIN/AOU ratio and PO_4-P/AOU ratio are 1.44 and 0.13, respectively, and both ratios are lower than that since the 1980s. We consider that the fact in attributed to the difference in decomposition process of organic matter between the 1970s and from the 1980s on. From the results, we consider that one factor which changes R in summer since the 1980s is the decrease rapidly of catch of shellfish since near 1980, the accumulation of organic matter in the study area due to transportation property of material in the interior parts of the Ariake Sea, and the change of decomposition property of organic matter between the 1970s and from the 1980s on. From the future, it is necessary to investigate in detail the relationship between the variations of quantity and quality of organic matter in the interior parts of Ariake Sea and oxygen depression of bottom water.

Conclusions

From the investigation of the occurrence mechanism of hypoxic water in WIAS based on the analysis results by a two-layer box model using the Saga Prefecture research data in 1972-2004, the following can be concluded.

(1). The physical parameters that relate to the occurrence of hypoxic water in the study area are analyzed by a two-layer box model using the Saga Prefecture research data in 1972-2004. As a result, the seasonal variations of an average year value over 1972-2004 for P, K_z and R are clarified. It is found that w and K_z are closely related to P. That is, w and K_z decrease with increasing P due to development of density stratification in summer. Conversely, w and K_z increase with decreasing P due to decay or disappearance of density stratification in winter.

(2). The physical and biochemical processes that are related to the temporal variation of DO concentration in lower layer box are estimated quantitatively. As a result, the temporal variation of DO concentration in lower layer is significantly effected by K_z-term and R-term in Eq.(7) in the study area during summer. It is found that around 99% of DO supply into lower layer box is caused by K_z-term. Furthermore, it is considered that hypoxic water occurs in the study area during summer when DO consumption amount due to biochemical process in bottom layer is greater than DO supply amount from surface to bottom layer due to vertical diffusion.

(3). The monthly variations of an average year value for P, K_z and R in the 1970s, the 1980s and the 1990s-early 2000s are clarified. That is, in summer, P and K_z do not have precise change among the calculated periods, but R between the 1970s and from the 1980s on is clearly different. It is considered that one factor which changes R in summer since the 1980s is the decrease rapidly of catch of shellfish since near 1985, the accumulation of organic matter in the study area due to transportation property of material in the interior parts of the Ariake Sea, and the change of decomposition property of organic matter between the 1970s and from the 1980s on.

Acknowledgements

The present study was carried out under the financial support by Ariake Sea Research Project of Saga University. We would like to thank for this financial supports heartily.

References

1. Tutumi, H., C. Kimura, S. Ngata, M. Tsukuda, H. Yamaguchi, T. Takahashi, S. Kimura, M. Tachibana, T. Komatsu and S. Montani (2006). Mechanisms causing frequent large-scale red tides in inner areas of Ariake Bay. *Oceanography in Japan*, **15(2)**, 165-189.
2. Sato, M (2001). What's happenning/what happened around Isahaya Bay in Ariake Bay? (Isahayawan, Ariakekai de naniga okotteirunoka?). *Kagaku*. **71**, 882-894.
3. Tutumi, 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.
4. Seguchi, M., M. Koriyama, M. J. Dantje, M.I. Jasin and T. Ishitani (2005). Occurrence of hypoxic water in the interior parts of the Ariake Sea and its preventive measures. *Bulletin of the Faculty of Agriculture, Saga University*, **90**, 63-76.
5. Koriyama, M., M. Seguchi, T. Ishitani, A. S. Syam and O. Kato (2006). Estimation of vertical diffusion coefficient and oxygen consumption rate in the interior western parts of Ariake Sea. *Bulletin of the Faculty of Agriculture, Saga University*, **92**. 33-44.
6. Ishitani, T., M. Seguchi, M. Koriyama and O. Kato (2007). Occurrence of hypoxic water and density stratification in the western interior parts of Ariake Sea. *Transactions of the Japanese Society of Irrigation, Drainage and Rural Engineering*, **247**, 65-72.
7. Koriyama. M., M. Seguchi, T. Ishitani and O. Kato (2007). Vertical diffusion coefficient and oxygen consumption rate under the occurrence of hypoxic water in the interior western parts of the Ariake Sea. *Journal of Hydroscience and Hydraulic Engineering*, **51**, 1463-1468.
8. Tokunaga, T., N. Matsunaga, A. Abe, M. Kodama and H. Yasuda (2005). Field observations of a high turbidity layer in western Ariake Sea and laboratory experiments oxygen consumption by suspended solids. *Proceedings of JSCE* , **782**, 117-129.
9. Yanagi. T. and M. Shimomura (2004). Year-to-year variation in stratification of Ariake Bay. *Oceanography in Japan*, **13(6)**, 575-581.
10. Koriyama. M., M. Seguchi and T. Ishitani (2008). Study on the occurrence mechanism of hypoxic water in the interior western parts of the Ariake Sea using the box model. *Transactions of the Japanese Society of Irrigation, Drainage and Rural Engineering*, **255**, 41-49.
11. Ohgushi. K., Y. Hayami, K. Hamada, K. Yamamoto, R. Hirakawa and Y. Tsuruta (2007). Observations of residual distribution in the interior parts of the Ariake Sea and runoff analyses of the Chikugo river basin using land use GIS. *Report of Ariake Sea Research Project, Saga University*, **3**, 93-100.
12. Futamura. A., H. Takeoka and X. Guo (2005). Current, water exchange and heat budget in the stratified region of Hiuchi-Nada. *Oceanography in Japan*, **14(3)**, 429-440.
13. Yanagi. T (2004). Hypoxia - the chemical and biological consequences of the mechanisms of its generation, maintenance, variability and disappearance. *Oceanography in Japan*. **13(5)**, 451-460.
14. Isobe. Atuhiko., M. Kamizono and S. Tawara (1993). An oxygen-deficient water mass in the southwestern part of the Suo Sea. *Bulletin on Coastal Oceanography*, **31**, 109-119.
15. The Oceanographic Society of Japan (2005). The aim of ecosystem reproduction in the Ariake Sea. Koseisha Koseikaku, Tokyo, 12.
16. Kawana. K (1982). Aqua-benthic environment during summer stratification period in the Seto Inland Sea. *Bulletin on Coastal Oceanography*, **20**, 53-62.

２層ボックスモデルを用いた有明海奥部西岸域における貧酸素水塊発生機構の研究

郡山　益実・瀬口　昌洋・石谷　哲寛・グゥエン ダン ティエン
（浅海干潟環境学研究室）
平成20年11月28日　受理

摘　　要

本研究では，1972～2004年の浅海定線調査データを用いて２層ボックスモデルより有明海奥部西岸域の貧酸素水塊発生に関わる物理的・生化学的過程に関するパラメータを定量化し，それに基づいて貧酸素水塊の発生機構を検討した．その結果，1972～2004年の期間における対象海域の移流速度，鉛直拡散係数及び生化学的酸素消費速度の平年値の月変動が明らかにされた．また，これらのパラメータの下層ボックスの DO 濃度の時間変動に及ぼす寄与量を解析した結果，夏季において鉛直拡散と生化学的酸素消費の寄与が大きかった．次に，貧酸素水塊発生の主要パラメータである鉛直拡散係数，成層強度及び生化学的酸素消費速度の約10年毎の月平均値の経年変動を解析した．その結果，鉛直拡散係数及び成層強度については，約10年毎の経年変動に伴う大きな変化は見られなかった．しかし，生化学的酸素消費速度については，1980年代以降，DO 消費期間の早期化と長期化が見られた．その要因の１つとして，対象海域における有機物量の増大と有機物の分解過程の変化が推察された．