Applicability of a Three-Dimensional Dissolved Oxygen Model

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Abstract

Because of the eutrophication accompanying the high economic growth in the 1960s, the occurrence of anoxic water masses in semi-enclosed bays in Japan has been a serious problem, and its dynamic analysis is an urgent issue. The ecosystem model is currently the most widely used model for analyzing the dynamics of anoxic water masses. The ecosystem model can model material circulation in a target area in detail and can analyze the influential factors precisely. However, as the number of required state variables increases, the number of parameters to be determined also increases. Therefore, the ecosystem model requires not only time-intensive calculations but also a considerable period to build the model. Therefore, in this study, a three-dimensional dissolved oxygen (DO) model was constructed for the Ariake Sea, for which a dynamic analysis of anoxic water masses is required. The DO model adds a net oxygen consumption term to the turbulent DO diffusion equation and is much simpler than an ecosystem model. As a result, it was possible to reproduce the anoxic water mass generated in 2010 in the Ariake Sea. Although the reproduction of the short-term fluctuations of the DO is a future task, the DO model developed in this study is an effective method for analyzing the dynamics of the anoxic water mass in the Ariake Sea.

Keywords: *Dissolved oxygen model, Three-dimensional sigma coordinate model, Anoxic water mass, Ariake Sea*

Introduction

Semi-enclosed bay areas are greatly affected by river inflow loads because the seawater exchange is low and the residence time of substances is long. In such areas in Japan, due to the rapid economic growth in the 1960s, the infiltration of nutrients into seas increased as the urbanization progressed. As a result, eutrophication problems became manifest in many sea areas. One of the eutrophication problems is the generation of anoxic water masses. In summer, the dead bodies of phytoplankton, which have grown due to eutrophication, accumulate in the bottom layer, and oxygen is consumed in their decomposition. However, due to stratification, the amount of dissolved oxygen (DO) decreases near the sea bottom. This water mass with little DO is called an anoxic water mass. It causes serious damage to fishery resources and is observed at various sites (Suzuki et al., 1998; Ariyama et al., 1997). Therefore, because anoxic water masses cause enormous damage in various coastal areas, it is essential to grasp their characteristics such as occurrence areas and seasonal fluctuations by analyzing their dynamics.

Currently, the ecosystem model is the most commonly used model for analyzing the dynamics of DO in coastal areas (Sohma et al., 2006; Nagao and Takeuchi, 2011). This ecosystem model can model the material circulation in a target area and analyze the influential factors in detail. Physical processes, such as advection and diffusion, and biochemical processes, such as photosynthesis, respiration, and organic matter decomposition, intricately form the anoxic water mass in the inner bay. In the ecosystem model, the dynamics of DO are analyzed by modeling these complex physical and biochemical processes with numerous parameters. However, because of the large number of parameters involved, a lot of time is spent determining these parameters. In addition, because there are many state variables to handle, a considerable amount of calculation is required, and analyzing the seasonal fluctuation of anoxic water masses takes a long time.

On the other hand, the DO model concentrates on the biochemical processes and assumes the DO increase/decrease as a net oxygen consumption. Sasaki et al. (1993) have proven that seasonal changes in DO can be well reproduced with the DO model. Since the DO model simply describes the increase/decrease in DO as the net oxygen consumption, it is significant to determine how to set the oxygen consumption rate in the model. Sasaki et al. (1993) used a constant value for the oxygen consumption rate, while Adachi and Kohashi (2011) employed a simple formula using the organic matter concentration of particulate organic carbon. In this study, a new determination method was devised considering the seasonal and locational changes in the oxygen consumption rate. In addition, most of the DO models developed so far have been vertical one-dimensional models. Therefore, this research extended the model to a three-dimensional flow field, and its applicability study was carried out in the Ariake Sea, one of the coastal areas suffering from fishery resource degradation due to the occurrence of an anoxic water mass.

Target area

The Ariake Sea is the largest inland bay in Kyushu and is shown in Fig. 1. Owing to its shape, the oscillation period of the inner bay of the Ariake Sea (12.4 h) resonates with the semidiurnal tide in the outer sea (Inoue, 1980). Therefore, the Ariake Sea has the largest tidal range in Japan, reaching up to 6 m. Furthermore, there are inflows from many rivers, and the annual freshwater inflow amount is 8.0×10^9 m^3. The total catchment area covers 8420 km^2; so many nutrients flow into the Ariake Sea. Hence, the Ariake Sea is a homeostatic eutrophic area. Eutrophic areas tend to suffer from the formation of red tides or the appearance of anoxic water masses leading to a decrease in fish production. Because of its unique character, the Ariake Sea did not suffer from any of these issues until 2000. However, after the outbreak of the malnutrition of Nori (edible seaweed) aquaculture in 2000, many environmental issues induced by eutrophication spread out into the Ariake Sea. In 2006, large-scale anoxic water masses have occurred in the Ariake Sea (Hamada et al., 2006) and greatly affected the fishery resources. In particular, creatures inhabiting the sea floor such as bivalves are directly influenced by hypoxia, so the production of bivalves in recent years has been reduced to approximately one-tenth of its peak. Therefore, the Ariake Sea was set as the target area because it can be concluded that it is one of the coastal areas where a dynamic analysis of the anoxic water mass is urgently needed for the recovery of the fishery resources.

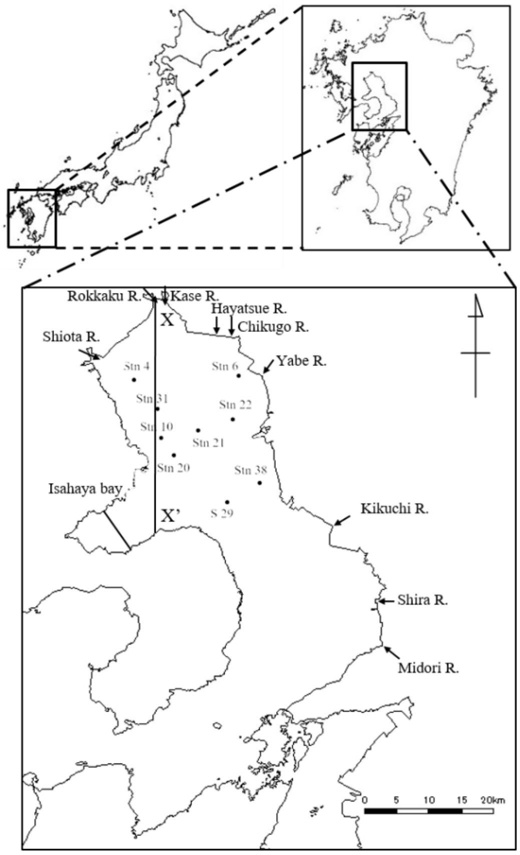

Fig. 1 Locations of the Ariake Sea, river inflow, and observation station.

Governing equations

The model analyzed the three-dimensional flow field assuming the Boussinesq approximation and hydrostatic pressure. The governing equations of the model, applying the σ-coordinate system — ($\sigma = (z + h)/H$) — in vertical direction, are as follows:

$$\frac{\partial\eta}{\partial t}+\int_0^1\frac{\partial\tilde{u}}{\partial x}d\sigma+\int_0^1\frac{\partial\tilde{v}}{\partial y}d\sigma=0 \tag{1}$$

$$\begin{aligned}&\frac{\partial(Hu)}{\partial t}+\frac{\partial(Huu)}{\partial x}+\frac{\partial(Huv)}{\partial y}+\frac{\partial(Hw_s u)}{\partial\sigma}\\&=Hfv-\frac{gH}{\rho}\left[(\rho_0+\rho'\sigma)\frac{\partial\eta}{\partial x}-\rho'(\sigma-1)\frac{\partial h}{\partial x}-\frac{\partial}{\partial x}\left\{(\eta+h)\int_\sigma^1\rho' d\sigma\right\}\right]\\&+\frac{1}{H}\frac{\partial}{\partial\sigma}\left(A_\sigma\frac{\partial u}{\partial\sigma}\right)+HA_h\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)\end{aligned} \tag{2}$$

$$\begin{aligned}&\frac{\partial(Hv)}{\partial t}+\frac{\partial(Huv)}{\partial x}+\frac{\partial(Hvv)}{\partial y}+\frac{\partial(Hw_s v)}{\partial\sigma}\\&=-Hfu-\frac{gH}{\rho}\left[(\rho_0+\rho'\sigma)\frac{\partial\eta}{\partial y}-\rho'(\sigma-1)\frac{\partial h}{\partial y}-\frac{\partial}{\partial y}\left\{(\eta+h)\int_\sigma^1\rho' d\sigma\right\}\right]\\&+\frac{1}{H}\frac{\partial}{\partial\sigma}\left(A_\sigma\frac{\partial v}{\partial\sigma}\right)+HA_h\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)\end{aligned} \tag{3}$$

where η is the water level, t is the time, ρ is the density of water, h is the elevation, H ($=\eta + h$) is the water depth, f is the Coriolis parameter, g is the acceleration of gravity, A_h is the coefficient of horizontal eddy viscosity, and A_σ is the coefficient of vertical eddy viscosity. Furthermore, u and v are the horizontal velocity components in the x and y directions, respectively, and w_s is equivalent to the velocity in the vertical direction of the σ-coordinate system. It is expressed by the following equation.

$$w_s = \frac{1}{H}\left[\sigma\int_0^1 \frac{\partial(Hu)}{\partial x}d\sigma + \sigma\int_0^1 \frac{\partial(Hv)}{\partial y}d\sigma - \int_0^\sigma \frac{\partial(Hu)}{\partial x}d\sigma - \int_0^\sigma \frac{\partial(Hv)}{\partial y}d\sigma\right] \tag{4}$$

As boundary conditions, a von Neumann type on the wall and a Dirichlet type on the open boundary were adopted. The friction stress was considered for the seabed boundary condition, while the wind stress for the water surface was excluded. For the numerical solution, an efficient algorithm based on the semi-implicit method proposed by Sasaki et al. (1996) was adopted. Because of the big tidal difference in the Ariake Sea, to reproduce the appearance of the tideland, the wet and dry scheme by Uchiyama (2004) was introduced.

Because the vertical distribution of the DO in the inner bay has a strong correlation with the density stratification, the density field in the Ariake Sea was calculated using the three-dimensional turbulent flow diffusion equations of salinity and water temperature as follows:

$$\begin{aligned}&\frac{\partial(HS)}{\partial t} + \frac{\partial(HuS)}{\partial x} + \frac{\partial(HvS)}{\partial y} + \frac{\partial(Hw_sS)}{\partial \sigma}\\ &\quad = \frac{\partial}{\partial x}\left(K_H\frac{\partial(HS)}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_H\frac{\partial(HS)}{\partial y}\right) + \frac{1}{H^2}\frac{\partial}{\partial \sigma}\left(K_\sigma\frac{\partial(HS)}{\partial \sigma}\right)\end{aligned} \tag{5}$$

$$\begin{aligned}&\frac{\partial(HT)}{\partial t} + \frac{\partial(HuT)}{\partial x} + \frac{\partial(HvT)}{\partial y} + \frac{\partial(Hw_sT)}{\partial \sigma}\\ &\quad = \frac{1}{H^2}\frac{\partial}{\partial \sigma}\left(K_\sigma\frac{\partial(HT)}{\partial \sigma}\right) + HK_{\mathrm{H}}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + \frac{1}{\rho C_p}\frac{\partial q(\sigma)}{\partial \sigma}\end{aligned} \tag{6}$$

where S is the salinity, T is the water temperature, K_{H} is the horizontal eddy diffusion coefficient, K_σ is the vertical eddy diffusion coefficient, q is the underwater heat flux by short wave radiation, and C_{p} is the specific heat. Precipitation and evaporation were considered as the water surface boundaries for calculating the salinity. The average monthly inflow amount from nine rivers (Fig. 1) was used for calculations. For evaluating the coefficients of the horizontal eddy viscosity and diffusion, the Smagorinsky model (1963) shown below was utilized. In addition, to consider the influence of the density stratification, a stratification function using the Richardson number (R_{i}) (Henderson-Sellors, 1985) was used for calculating the coefficients of the vertical eddy viscosity and diffusion.

Dissolved oxygen model

The DO model utilized in this study is as follows:

$$\begin{aligned}&\frac{\partial(HC)}{\partial t} + \frac{\partial(HuC)}{\partial x} + \frac{\partial(HvC)}{\partial y} + \frac{\partial(Hw_sC)}{\partial \sigma}\\ &\quad = \frac{1}{H^2}\frac{\partial}{\partial \sigma}\left(K_\sigma\frac{\partial(HC)}{\partial \sigma}\right) + HK_{\mathrm{H}}\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2}\right) - D_w\end{aligned} \tag{7}$$

where C is the DO, and D_{w} is the net oxygen consumption rate. Sasaki et al. (1993) used a constant value for the oxygen consumption rate, while Adachi et al. (2011) obtained it from the relational expression that considers the organic matter concentration. However, in this study, the oxygen consumption rate was set by a new method. Because the calculation period was set at one year, the seasonal change was considered in the oxygen consumption rate. In addition, it is not appropriate to use a uniform value for the entire mesh in the vast Ariake Sea.

In this study, in consideration of the temperature dependence of the biochemical process related to oxygen consumption, the sine curve model of the annual cycle with the maximum value in summer was used, and the value was set by month. Furthermore, the oxygen consumption rates in the water and on the bottom were separately modeled by sine curves. The oxygen consumption rate for water was considered uniform across the entire mesh irrespective of depth, and the oxygen consumption rate for the bottom mud was calculated by adding it to the mesh just above the seabed. At the water surface layer, the dissolved oxygen was set at a constant value (10.0 mg/L), considering the oxygen production by photosynthesis and reaeration. Keeping in view the locational characteristics, the maximum and minimum values of the sine curve in each area were determined based on the results of the cluster analysis was carried out for the results which were obtained in the past experiments in the Ariake Sea. Additionally, in winter, assuming that the oxygen production exceeds its consumption, a negative oxygen consumption rate was set, and oxygen production was allowed. In this study, the oxygen consumption rate in the seabed was determined based on the experiments conducted by Sasaki et al. (Abe et al., 2003). The oxygen consumption rate in the water was calculated by the same method based on the results of the field experiments of Nakayama et al. (2003).

Model validation

The results calculated by the constructed three-dimensional sigma-coordinate model were validated with the observed data. Although the simulated results underestimated the observed velocity at some points, the model showed a good reproducibility in both flow velocity and direction at many other stations. Moreover, the model showed a good reproducibility for simulating both salinities and temperatures. The density field in the Ariake Sea was well reproduced by introducing the turbulent diffusion equations of salinity and water temperature.

The DO model was applied to reproduce the anoxic water that occurred in the Ariake Sea in 2010. In 2010, a huge anoxic water mass occurred in the western part of the bay in August, and a large amount of pen shell disappeared. Fig. 2 represents the vertical distribution of the DO for the X−X' section (Fig. 1) in the western area of the Ariake Bay at 15:00 on July 15, 2013 and at 15:00 on August 5, 2013. An anoxic water mass was confirmed on July 15, but there was a layer in which a lower DO appeared. In the model, as the DO supply source is from the surface layer with a constant DO value of 10, it was inferred that this occurrence of hypoxia was due to the density stratification. Because the density stratification developed in the vicinity of 6 m, vertical mixing was suppressed so that the DO supply from the surface to bottom layer was stopped. In August, it can be seen that further DO consumption progressed in areas deeper than 6 m, and anoxic water masses were formed. In addition, it seems that the size of the lower DO water area enlarged. In fact, in the field survey results of 2010, an anoxic water mass close to an anaerobic condition had been confirmed over a wide area, which was consistent with the calculated result. The seasonal variation in the vertical distribution of the DO at station 20 (Fig. 1) is shown in

Fig. 3. It can be confirmed that the DO decrease accompanying the formation of the density stratification starts at the end of May, and the formation of the anoxic water mass began at the end of July. In addition, it can be seen that the anaerobic state continues after August and was resolved in late September. According to past investigations, the oxygen reduction started in June, and the anoxic water mass was intermittently generated from late July until the middle of September, which was consistent with the calculated results. From the above results, it was possible to grasp the seasonal change and the vertical distribution of the DO with a DO model.

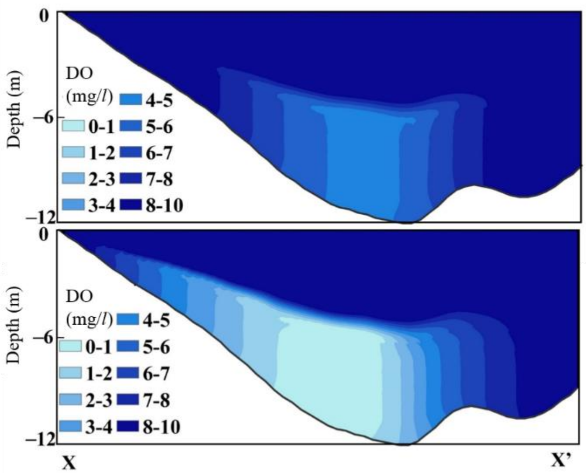

Fig. 2 Vertical distribution of the DO of X–X' section (Fig. 1) in the Ariake Sea at 15:00 on July 15, 2010 (upper) and 15:00 August 5, 2010 (lower).

Applicability of DO model

The applicability of the DO model developed in this study was examined. From the continuous observation of the DO, it was understood that the DO decreased over the long term while repeatedly decreasing and increasing in the short term from July to September. This short-term DO fluctuation is due to the tidal currents. While repeating a 12 h cycle of increasing and decreasing by the tide, the DO decreases to form hypoxia during the neap tide, and it increases during the spring tide. In this study, a DO model was combined with a three-dimensional precise flow model. Although it could reproduce the seasonal change in the DO, a short-term DO fluctuation mentioned above could not be reproduced. This was because the influence of the oxygen consumption term on the DO model as a factor of the DO fluctuation was large, and the influence of the tidal current was underestimated. In this study, the oxygen consumption rate was set by the month, but it is known that the actual oxygen consumption rate significantly fluctuates hourly or daily. For this reason, different trends were detected, such as a sharp decrease in the DO at the beginning of the month when the value of the oxygen consumption rate changed. It can be estimated that short-term DO fluctuations can be reproduced by improving the method of determining the oxygen consumption rate, considering the tidal current and short-term fluctuations. On the other hand, the long-term variation in the DO could be well reproduced. Moreover, by introducing the turbulent diffusion equations on salinity and water temperature, it was possible to consider the suppression of vertical mixing due to density stratification; thus, the model could also capture the variation in the vertical distribution of the DO. Therefore, the DO model developed in this study is an effective method for analyzing the dynamics of anoxic water masses in the Ariake Sea.

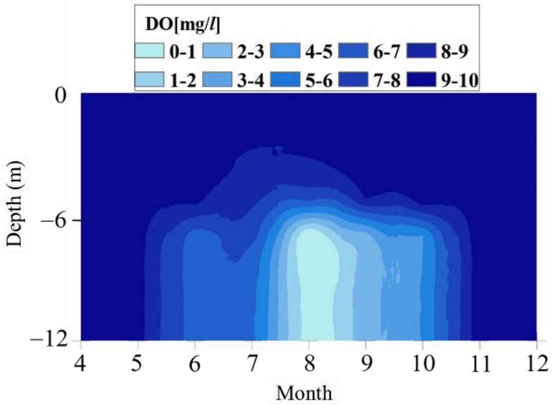

Fig. 3 Seasonal change and the vertical distribution of DO at station 20 (Fig. 1) in the Ariake Sea.

Conclusions

In this study, a three-dimensional DO model was developed, and the dynamics of the anoxic water mass in the Ariake Sea was analyzed. The DO model treats the increase/decrease in the biochemical oxygen production/consumption as a net oxygen consumption in a simple way. Different from previous studies, it considered the seasonal and locational changes in the oxygen consumption rate when determining the oxygen consumption rate. The seasonal change was modeled by the sine curve of the annual cycle with the peak in summer, assuming the temperature dependence of the phenomenon related to the increase and decrease in oxygen. The locational change was considered simply from the ratio of the COD in each sea area by using the results of a cluster analysis. In addition, the turbulent flow diffusion equations of salinity and water temperature were introduced, and the effect of suppressing the vertical mixing was considered. The model had a high reproducibility of the three-dimensional flow field in the Ariake Sea. The secular change and the vertical distribution of salinity and water temperature were also reproduced well. In addition, the calculated result of the seasonal change of the DO agreed with the observations. For this reason, it was found that a method of locally changing the oxygen consumption rate according to the COD value was effective. On the other hand, in this study the DO model was combined with a three-dimensional flow model, but it could not capture the short-term DO fluctuations due to the tidal current and wind. This is because the influence of the oxygen consumption term in the DO model was large, and the influence of the tidal current had not been reflected. It was indicated that further improvements in the accuracy of DO fluctuations and a short-term DO dynamics analysis are possible by improving the method determining the changes in oxygen consumption, tidal current, and wind over time. For these reasons, the DO model developed in this study can be an effective method for analyzing the dynamics of anoxic water masses in coastal areas

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