DEVELOPMENT OF A CONCEPTUAL MODEL FOR DISSOLVED OXYGEN CONCENTRATIONS CONSIDERING FLOOD EVENT EFFECTS IN TOKYO BAY

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This paper proposes a method to evaluate the occurrence of anoxic water in Tokyo Bay, which is a typical enclosed bay in Japan. In Tokyo Bay, seawater exchange with the ocean is revealed to be dominantly controlled by estuarine circulation. Dissolved oxygen (DO) concentrations in the bay head are, thus, expected to be influenced by estuarine circulation. The strength of estuarine circulation changes owing to wind and inflow from rivers. Therefore, we investigated the influence of inflow from rivers on DO concentration around the bay head by using a three-dimensional ecological model. To evaluate the occurrence of anoxic water, we developed a conceptual DO model which was verified through good agreement with the results from a three-dimensional ecological model. As a result, the conceptual DO model has potential in the evaluation of the occurrence of anoxic water around the head of Tokyo Bay.

Key Words: *dissolved oxygen, estuarine circulation, wind, inflow, river, seawater exchange*

1. INTRODUCTION

In a lake or an enclosed bay, vertical mass transport is likely to be suppressed by the stratification effect, which is due to strong radiation and large inflow from rivers during summer. The suppression of vertical mass transport may lead to the appearance of anoxic water adjacent to the seabed as dissolved oxygen is consumed due to the accumulation and decomposition of particulate organic matter (POM). Since anoxic water may severely impact aquatic biota, it is important to understand where anoxic water appears and how it is transported.

Tokyo Bay, one of the three major bays in Japan, is considered to be a typical enclosed bay. Around the bay, significant development has occurred and shallow water areas have been reclaimed along the coastal margin. This has greatly influenced the ecological system of the bay. For example, increased nutrient loads reaching the bay from inland areas have accelerated the accumulation of POM around the bay head[1)]. The decomposition of the accumulated POM leads to consumption of dissolved oxygen (DO) near the seabed and results in the formation of an anoxic water mass in the bottom layer when stratification is strong from spring to summer. It is well-known that anoxic water has influenced water quality and the ecological system of Tokyo Bay and investigating the mechanism of its occurrence is important[2), 3), 4), 5), 6), 7)].

In Tokyo Bay, seawater exchange with the ocean has been revealed to be dominantly controlled by estuarine circulation. Since DO concentrations outside of the bay are higher than those inside, deepwater intrusion due to estuarine circulation is expected to be a major factor governing changes in DO concentration around the bay head. In previous studies, seawater exchange, which is mainly controlled by estuarine circulation, has been revealed to be about 30 days during summer in Tokyo Bay[8), 9), 10), 11)]. Furthermore, it has been inferred that inflow from rivers enhances estuarine circulation, and the resultant intrusion of deepwater with high DO concentration, during flood events. Therefore, it may be important to clarify the influence of inflow from rivers on changes in DO concentration inside the bay.

In this study, we thus aim to investigate changes in DO concentrations around the bay head during summer, taking into account the effect of rivers. To clarify the role of inflow from rivers, a three-dimensional numerical computation[12), 13)] was carried out from May to August, 2003. Finally, we developed a conceptual DO model which may enable us to analyze the river effect theoretically.

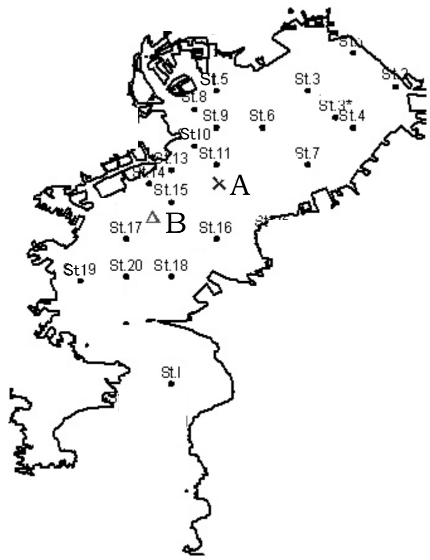


Fig. 1 Tokyo Bay indicating field observation stations. At station A, DO concentration was observed form May to August, 2003. At station B, ADCP measurement was conducted from 13th May to 12th June, 2003. Dots denote stations where salinity and water temperature were observed every month from May to August, 2003.

2. FIELD OBSERVATION FROM MAY TO AUGUST, 2003 IN TOKYO BAY

DO concentrations were measured at a depth of 20 m at Station A in **Fig. 1**, from May to August, 2003 (**Fig. 2a**). DO concentrations gradually decreased to almost zero from the beginning of May to the middle of June, and then recovered slightly for about one month. However, DO concentrations again decreased from the end of July to 10th of August, at which time there was a sudden increase.

In general, stratification becomes stronger from spring to summer and vertical mixing is suppressed, leading to easy formation of anoxic water. However, the recovery of DO concentrations observed during summer when stratification was still present suggests that stable pycnoclines due to strong stratification are not the only factor controlling the appearance of anoxic water in Tokyo Bay.

The main purpose of this study was to statistically investigate the influence of inflow from rivers on DO concentration around the bay head. Therefore, collection of as detailed inflow data as possible is needed. However, in general, the accuracy and availability of inflow data is lower than that of rainfall intensity data. Therefore, in order to analyze the results theoretically, we decided to attempt to use rainfall intensity data to estimate inflow of rivers by using a simple model.

A kinematic wave model was used in this study to estimate inflow from rivers, which may be easily combined with a conceptual DO model. The kinematic wave model used in this study is as follows[14)]. A linearized kinematic wave model was used to analyze the model theoretically.

$$\frac{dS}{dt} = A_S R - q \tag{1}$$

$$q = B_S S \tag{2}$$

where, S is the specific storage [mm hr^{-1}], t is the time [hr], A_S is 0.6, R is the rainfall intensity [mm hr^{-1}], q is the specific discharge [mm hr^{-1}], B_S is 0.018[hr^{-1}].

Rainfall intensity was evaluated by using meteorological observation stations, AMeDAS, in the watershed from which rivers flow into Tokyo Bay. The AMeDAS stations used in the study were Ebina, Fuchu, Hachioji, Kisaradzu, Konosu, Okawachi, Oume, Sagamihara, Saitama, Sakabatake, Sakuma, Shinkiba, Chiba, Chichibu, Tokyo, Ushiku, Yokohama, and Yorii stations. Inflow from rivers was larger from July to August, 2003 (**Fig. 2b**). It was found from the comparisons of **Figs. 2a** and **2b** that the increase in DO concentration corresponds to the occurrence of peak discharge.

In addition to inflow, estuarine circulation is expected to be influenced by wind. Thus, we computed the wind speed with positive direction defined as Northeast to Southwest (**Fig. 2c**). Positive wind speed enhances estuarine circulation and was dominant in July. DO concentrations were observed to recover in July, which may correspond to the enhancement of estuarine circulation due to positive winds. Therefore, it may be that the wind effect has a large influence on changes in the strength of estuarine circulation.

To consider the relationship between inflow

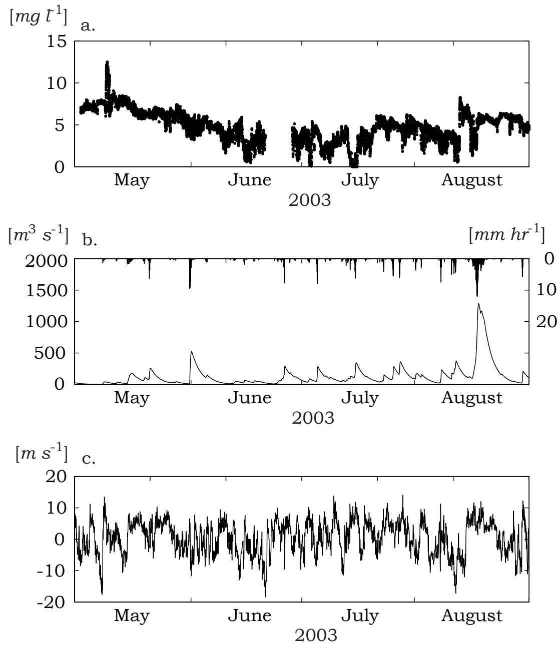


Fig. 2 Time series of **(a)** DO concentration at a depth of 20 m at Station A, **(b)** Hydrograph, and **(c)** Wind speed with positive direction defined as Northeast to Southwest, from May to August, 2003.

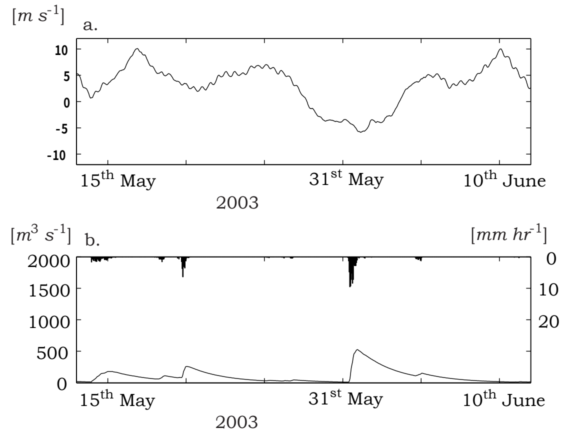


Fig. 3 Time series of **(a)** Velocity averaged for a depth of 10 m above the bottom along a Northeast to Southwest direction, and **(b)** Hydrograph, from 12th of May to 13th of June, 2003.

from the rivers and the estuarine circulation, current measurements were conducted using ADCP at Station B (**Fig. 1**). Bottom currents, with positive direction defined as Southwest to Northeast, and a hydrograph are shown in **Fig. 3**. The bottom current shown in **Fig. 3a** is the current averaged for the 10 m from the sea bottom. The depth of 10m from the sea bottom is equal to the measurements depth of DO concentration (**Fig. 2a**). Because the representative timescale of the specific discharge q from the equation (1) is about 2.3days, high frequency data with periods less than three days was eliminated from the current data to capture the inflow effect. The bottom current in **Fig. 3a** is three days averaged residual flow, which consists of tide-induced residual currents, wind-driven current and density-driven current. It is clear that the bottom current increased during flood events, leading us to conclude that the enhancement of estuarine circulation may result from the inflow effect.

3. THREE-DIMENSIONAL ECOLOGICAL MODEL

The main purpose of this study was to develop a conceptual DO model which enables us to evaluate the influence of flood events on DO concentrations. The conceptual DO model aims to reproduce DO concentrations averaged across the lower layer around the head of Tokyo Bay. However, there are very high costs associated with conducting field experiments in order to obtain a time series of DO concentrations averaged across the lower layer. Therefore, in this study, a three-dimensional ecological model was applied to numerically reproduce the flow field and to obtain the DO concentrations averaged across the lower layer from May to August, 2003.

The three-dimensional ecological model ELCOM&CAEDYM consists of ELCOM combined with CAEDYM, which is the module for ecological modeling. The features of ELCOM are: hydrostatic three-dimensional model; implicit scheme for water surface computation to use larger time step; partial cell method to represent topography smoothly; ultimate scheme for adjective terms; a mixed-layer turbulence closer model scheme; a mixing-model to directly compute vertical turbulent transport; and z coordinate system to inhibit numerical diffusion.

The numbers of meshes used in this study were: 60 and 45 (horizontal) with 1 km interval and 50 (vertical) with 1.5 m to 3.9 m interval (**Fig. 4**). Meteorological data at Tokyo station was used in the computation as boundary conditions. Wind data used in the computation was magnified two times from observed data by referring Igarashi et. al[15]. Tides measured at the mouth of Tokyo Bay at Mera obtained by Japan Oceanographic Data Center were given in the computation. With regard to the river, four main rivers, Ara River, Tama River, Edo River and Tsurumi River, were included. In CAEDYM, Phytoplankton, Ammonium, Nitrate, Filterable reactive phosphorus, Particulate organic carbon, Particulate organic nitrogen, Particulate organic phosphorus, Dissolved organic carbon, Dissolved organic nitrogen, Dissolved organic phosphorus, Silica and Dissolved oxygen were included. The sediment oxygen flux is a function of the overlaying water temperature and dissolved oxygen. The sediment nutrient fluxes are regulated the dissolved oxygen concentration in the bottom layer.

To understand the influence of inflow from rivers

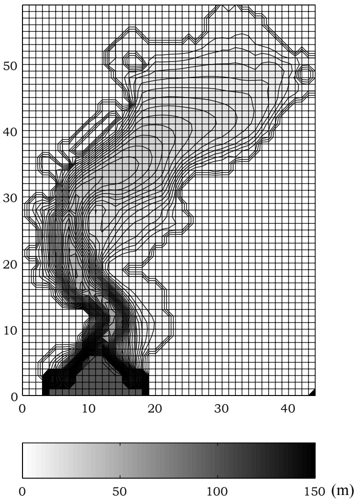


Fig. 4 Bathymetry (m) of Tokyo Bay.

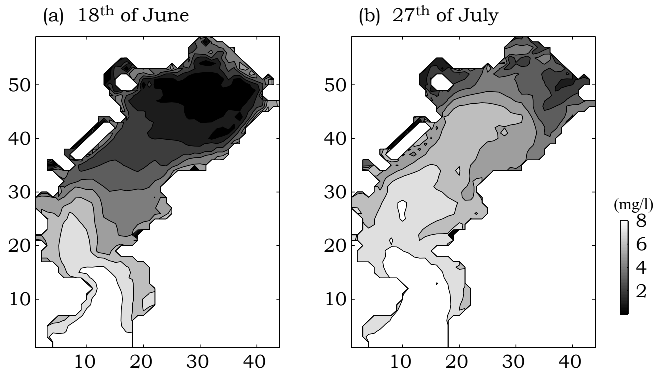
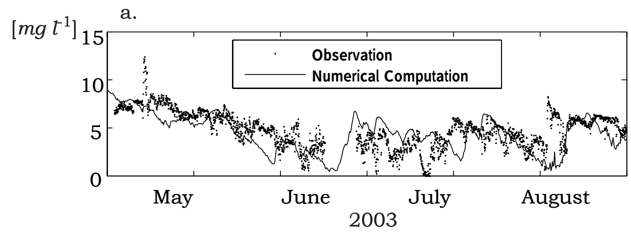


Fig.5 (a) The calculated DO (mg/l) concentration at sea bottom on 18th of June. **(b)** The calculated DO (mg/l) concentration at sea bottom on 27th of July.



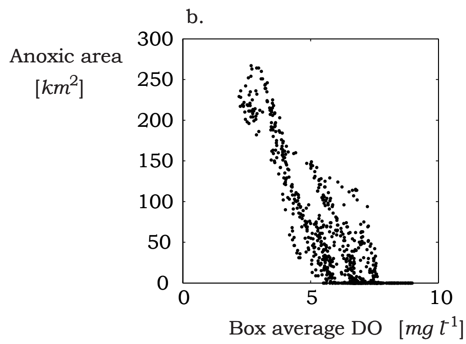


Fig. 6 (a) Field observation results and numerical computation results. **(b)** Box average DO and anoxic area at sea bottom.

and wind, the calculated DO concentration at the sea bottom on 18th of June and 27th of July were shown in **Fig. 5**. Since larger discharge were given and Northeast wind dominated during the period between **Fig. 5a** and **Fig. 5b**, the DO concentration was higher around the bay head due to the enhancement of estuarine circulation. The news of anoxic water mass in Tokyo Bay is published by Chiba Prefectural Fisheries Research Center. The comparison of anoxic water mass news between June 17, 2003 and July 28, 2003 indicated that the anoxic water mass at the bottom layer in July 28, 2003 decreased.

The DO concentrations reproduced at Station A agreed well with the observed values (**Fig. 6a**). The predicted DO concentration exhibits differences from observations in the middle of May, in the beginning of June and in the latter part of July. The reason why the model results and observation compare poorly in such periods is the uniform wind condition, whereas in reality the wind speed and direction has horizontal distribution.

Hereafter, this computational result is called Case A. In particular, the decrease in DO concentrations from the beginning of May and the subsequent recovery agreed very well, which may provide evidence that the numerical computation successfully reproduced the stratification processes due to radiation and inflow from rivers by taking into account the wind effect.

Since the conceptual DO model represents concentrations averaged in the lower layer, the DO concentration averaged from the seabed to a depth of 15 m was computed around the bay head using the three-dimensional numerical computation results. Hereafter, this averaged DO concentration is called box average DO. To evaluate the occurrence of anoxic water in the lower layer in Tokyo Bay, we computed the area where anoxic water appears at the seabed below a depth of 15 m around the bay head (**Fig. 6b**). It is obvious that the anoxic area is a function of the box average DO, which provides for the possibility that the box average DO can be applied to evaluate the occurrence of anoxic water.

4. CONCEPTUAL DO MODEL

The box average DO and anoxic area were revealed to have strong correlation in the previous chapter. Thus, we made an attempt to develop a conceptual DO model in order to evaluate the occurrence of anoxic water in Tokyo Bay. In the conceptual model, only the following four components were included, so that the model results are analyzed theoretically:

(1) DO consumption at sea bottom;
(2) Estuarine circulation due to stratification;
(3) Change in estuarine circulation due to wind; and
(4) Change in estuarine circulation due to inflow

from rivers.

DO consumption due to marine diatoms was neglected since the target area is in the lower layer. Furthermore, the second spectrum peak of DO concentration whose period is about 6 days was found to correspond to the spectrum peak of wind speed. This indicates the importance of wind effect on DO concentrations. A conceptual DO model was proposed as follows:

$$\frac{dDO}{dt} = (A_{DO}q + X_{DO}wind + C_{DO})(8 - DO) - Y_{DO} \tag{3}$$

$$\begin{cases} DO < 0 & Y_{DO} = 0 \\ DO \geq 0 & Y_{DO} = D_{DO} \end{cases}$$

$$\begin{cases} DO < 0 \ \& \ wind < 0 & X_{DO} = 0 \\ elsewhere & X_{DO} = B_{DO} \end{cases}$$

where, DO is the box average DO [mg l^{-1}], A_{DO} is the coefficient for estuarine circulation regarding inflow from rivers [mm^{-1} hr^{-2}], B_{DO} is the coefficient for estuarine circulation regarding wind [s m^{-1} hr^{-1}], C_{DO} is the coefficient for estuarine circulation due to stratification [hr^{-1}], D_{DO} is the DO consumption rate at the sea bottom (0.0125 [mg l^{-1} hr^{-1}]).

DO consumption at the seabed was evaluated through sediment sampling observations. The coefficient for estuarine circulation due to stratification can be obtained by using residence time, which is about 30 days averaged from May to August, 2003 as follows[5)].

$$C_{DO} = \frac{1}{30 \times 24} \tag{4}$$

Furthermore, the influence of river effect on estuarine circulation can be obtained using river discharge and the volume of the lower layer as follows:

$$A_{DO} = \frac{A_{WSX}}{1000 V_{BOX}} = 0.0045 \tag{5}$$

where, A_{WSX} is the area of watershed from which rivers flow into Tokyo Bay [m^2], V_{BOX} is the volume of the lower layer [m^3], A_{DO} is the size of the lower layer [m^3].

To evaluate the coefficient for estuarine circulation due to wind effect, box average DO was computed using the results from the three-dimensional ecological model without including inflow from rivers (**Fig. 7b**). We call this Case B. Then, the verification was conducted for the case when river effect is included in the numerical computation (**Fig. 7a**).

The three-dimensional ecological model reproduced the large recovery in DO concentrations around the middles of June and August, but this was not evident in the results from the conceptual DO model. To clarify differences in the models, we

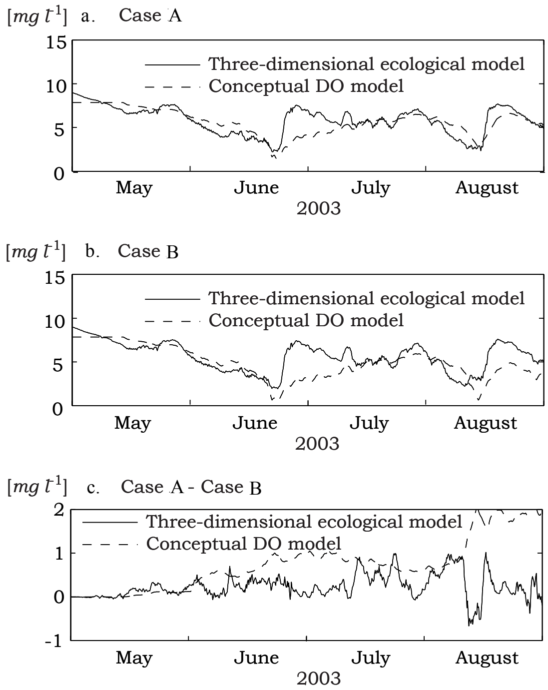


Fig. 7 (a) Case A: Box average DO from ELCOM&CAEDYM and conceptual DO model with including inflow from rivers and wind effect. **(b)** Case B: Box average DO from ELCOM&CAEDYM and conceptual DO model excluding river inflow effect. **(c)** Case A–Case B: Box average DO from ELCOM&CAEDYM and conceptual DO model. This figure indicates the effect for estuarine circulation due to inflow from rivers.

investigated wind speed during the middles of July and August, which revealed that south-southwest winds with speeds of about 20 [ms^{-1}] were prevalent. Therefore, less dense water in the upper layer was accumulated around the bay head during these periods, which resulted in the recovery of the box average DO due to internal seiche effects in the three-dimensional ecological model. Since the accumulation effect of less dense water around the bay head due to strong winds is not included in the conceptual DO model, applicability of the model may be lower during periods of south-southwest winds such as occurred during the middle of June and August. However, excluding those two periods, the two models agreed very well, which may provide evidence of the high applicability of the conceptual DO model into the reproduction of DO concentrations in Tokyo Bay.

To clarify the role of inflow from rivers, the difference of box average DO between Cases A and B was computed using the results of both the three-dimensional ecological model and the conceptual DO model (**Fig. 7c**). Both models revealed that inflow from rivers increases box average DO due to the enhancement of estuarine circulation. However, in the middle of August, there is different response between both models. This reason is a change in stratification strength expressed by three - dimensional ecological model. In the middle of August, there is the recovery of the box average DO due to accumulation effect of less dense water. The weakening of stratification due to the accumulation effect enhances this recovery mechanism. On the other hand, the accumulation effect of less dense water and a change in stratification strength are not included in the conceptual DO model. These differences between both models cause the different responses.

5. CONCLUSIONS

A conceptual DO model was developed to evaluate the occurrence of anoxic water in the lower layer around the head of Tokyo Bay. The meaning of conceptual model is to specify the factor of the recovery of DO, and to verify the contribution of each factor. The following results were obtained in the study:

(1) It is found from field observation results that DO concentration near the sea bottom recovers when winds are dominantly from the Northeast to Southwest. ADCP measurements revealed that estuarine circulation is also enhanced during flood events.

(2) The DO concentration reproduced by a three-dimensional ecological model was confirmed to agree with the field observation results. Box average DO was found to have strong relation with the anoxic area around the bay head.

(3) A conceptual DO model was developed with good agreements with the results obtained from the three-dimensional ecological model.

(4) The DO concentration in the lower layer around the head of Tokyo Bay is much influenced to the deep-water intrusion due to the estuarine circulation. The strength of the estuarine circulation is decided by the wind effects and the inflow from rivers in Tokyo Bay.

(5) When the south-southwest wind with speeds of about 20[ms^{-1}] was prevalent, the DO concentration has recovered by the accumulation of upper layer water not the estuarine circulation.

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