

SIMULATION OF THE BEHAVIOR OF OXYGEN-DEFICIT WATER IN TOKYO BAY BY THREE-DIMENSIONAL WATER QUALITY MODEL

Nobuo Mimura¹, Member ASCE, Mitsuhiro Tsukada² and Masaharu Suzuki³

ABSTRACT

Semi-enclosed bays have been suffering from eutrophication in many countries. The present study deals with simulation of this problem focusing on Tokyo Bay, Japan. Tokyo Bay faces blue tides and fish death events caused by the oxygen-deficit water formed in the bottom layer during summer. To study the formation of the oxygen-deficit water, a model is developed to simultaneously simulate the flow, density stratification, and the material circulation in the ecosystem. The behavior of oxygen-deficit water, such as formation, growth, and stagnation, in Tokyo Bay is reproduced and examined by the model. The present model is effective in studying the temporal and spatial changes in water quality in a detailed manner. Moreover, countermeasures such as reduction of the land-based pollutant loads and sand capping on the polluted bottom mud are also examined.

1. Introduction

Semi-enclosed bay such as Tokyo Bay, Japan, have been suffering from water pollution. Tokyo Bay is about 65km and 25km long in the longitudinal and transverse directions, and 1,200km² in surface area. The inner part is occupied by shallow sea of less than 20m deep. The bay is surrounded by the Tokyo metropolitan area, where about 30 million people live, and major ports and industrial belts exist. Six major rivers flow into the bay, and the total fresh water inflow is about 325m³/s including these rivers. From these settings, the organic nutrients loads to Tokyo Bay are extremely large(Fig.1).

¹ Professor and ² Graduate Student, Center for Water Environment Studies, Ibaraki University, 4-12-1 Nakanarusawa, Hitachi, Ibaraki 316-8511, Japan

³ Computer Technology Integrator Inc., 1-27-2 Meieki-Minami, Nakamura-ku, Nagoya, Aichi 450-0003, Japan

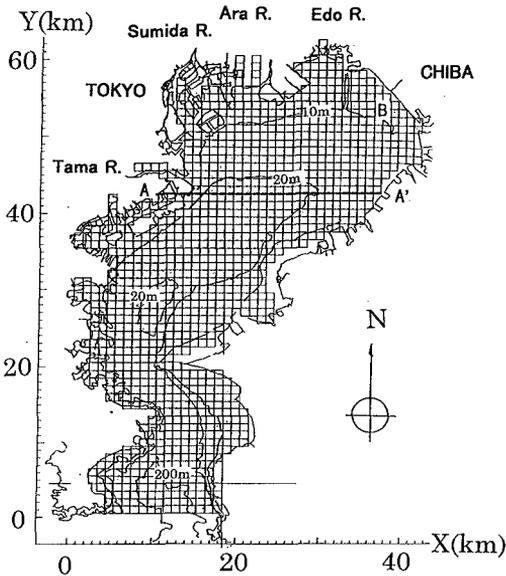


Figure 1 Tokyo Bay and computational grid

One of the major problems in Tokyo Bay is the formation of the oxygen-deficit water in the bottom layer during summer, which often causes blue tides and fish death by suffocation. The oxygen-deficit water is generated under specific combinations of the flow, density stratification, and the material circulation in the ecosystem. Therefore, a model with simultaneous equations for flows, density distribution, and ecosystem is needed to realistically calculate the processes related with water quality.

In this paper, a three-dimensional numerical model is developed to simulate the formation, growth, and stagnation of the oxygen-deficit water in Tokyo Bay. Then the spatial and temporal changes in water quality in 1993 are reproduced to trace the detailed behavior of the oxygen-deficit water mass.

2. Three-Dimensional Water Quality Model

The present model consists of three sub-models for flow field, density field, and material circulation in the ecosystem.

(1) Flow and density fields

The equations of continuity and momentum conservation are discretized by an FDM scheme on a three-dimensional grid system (Mimura et al., 1993; Kobayashi et al., 1995). Since the period of simulation often exceeds a year, an effective and stable method of computation is required. For this purpose, a special scheme to implicitly solve the terms of vertical turbulent transfer of momentum and pressure gradient is used (Sato et al., 1993). As boundary conditions, temporal records of tidal elevation at the bay mouth, wind stresses, and river discharges are given from field observations.

The density sub-model consists of the diffusion equations of heat and salinity. At the water surface, heat exchange by solar radiation, long-wave radiation, and sensible and latent heat transfer by evaporation are taken into consideration. Inflows of freshwater by rainfall and river discharge are also included. These terms are calculated by giving the time histories of the observed data for atmospheric temperature, solar radiation, wind etc as mentioned later.

(2) Material circulation in the ecosystem

In this sub-model, ecosystem is represented as a network of material flows among the components of phytoplankton, zooplankton, detritus, dissolved organic matter, phosphate, and inorganic nitrogen as shown in Fig.2. The key elements and nutrients, such as carbon, nitrogen and phosphorus, are stored in these components, and transported among them. As a result of such material flow, water quality changes. Chemical oxygen demand (COD) and dissolved oxygen (DO) are taken as the indices of water quality. The governing equations of the ecosystem sub-model are the diffusion equations with bio-chemical process terms.

$$\frac{\partial B}{\partial t} + U \frac{\partial B}{\partial x} + V \frac{\partial B}{\partial y} + W \frac{\partial B}{\partial z} = \frac{\partial}{\partial x} \left(K_x \frac{\partial B}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial B}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_z \frac{\partial B}{\partial z} \right) + \Delta B$$

where, U , V and W are velocity components, and K_i is diffusion coefficient in x , y , and z directions.

The bio-chemical process term, ΔB , expresses the temporal change in the concentration of each component. In the case of phytoplankton, this term includes photosynthesis, respiration, extracellular release, and grazing by zooplanktons. These processes are modeled by empirical and semi-theoretical relationships obtained in the existing studies. Equations to represent the relationships are shown in Fig.3 in a conceptual manner (Nakata, 1993). The factors controlling the rates of changes are given as empirical equations. Regarding the material flow, changes in carbon (C) flows are calculated first, then the contents of other nutrients, i.e. nitrogen (N) and phosphorus (P),

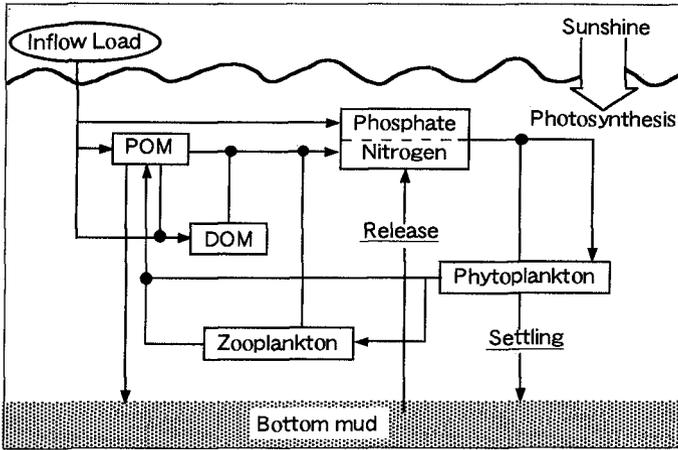


Figure 2 Material flow in the ecosystem

are determined based on the empirical ratios of N/C and P/C. The DO consumption of each bio-chemical reaction is calculated by the ratio between the theoretical oxygen demand and carbon content (TOD/C).

These equations include the terms for release of nutrients from bottom mud and consumption of DO in the bottom. It was pointed out that such exchange between bottom water and mud is very important, for the bottom mud play a role of significant nutrients' stock. These processes are controlled by the concentration difference of each component between bottom water and mud, water temperature and DO concentration. In this model, equations given by Matsunashi(1993) are used to represent these relationships.

3. Simulation for Tokyo Bay

(1) Grid system

Tokyo Bay is about 65 km long and 25 km wide, and the water depth decreases sharply from 200 m at the bay mouth to less than 20 m in the inner half of the bay. A three-dimensional grid was set in Tokyo Bay as shown in Fig.1. The horizontal grid is 1 km \times 1 km, and water depth was divided into 20 layers with variable height. The layer height is 2 m each for the upper layers to reproduce the vertical density distributions precisely, while it is 30 m beyond the depth of 60 m. The time step of the calculation, Δt , is 4 minutes.

Phytoplankton (**Phy**)

$$\frac{\partial \text{Phy}}{\partial t} = \text{Photosynthesis} - \text{Extracellular Release} - \text{Respiration} \\ - \text{Grazing by Zoop.} - \text{Death} - \text{Settling}$$

Zooplankton (**Zoo**)

$$\frac{\partial \text{Zoo}}{\partial t} = \text{Grazing of Phyt.} - \text{Egestion} - \text{Respiration} - \text{Death}$$

Detritus (**POM**)

$$\frac{\partial \text{POM}}{\partial t} = \text{Death of Phyt.} + \text{Egestion of Zoop.} + \text{Death of Zoop.} \\ - \text{Biodegradation} - \text{Settling}$$

Dissolved Organic Matter (**DOM**)

$$\frac{\partial \text{DOM}}{\partial t} = \text{Extracellular Release of Phyt.} + \text{Biodegradation of POM} \\ - \text{Oxidation}$$

Dissolved Inorganic Nitrogen (NH_4 , NO_2 , NO_3 ; **DIN**)

$$\frac{\partial \text{DIN}}{\partial t} = -\text{Uptake by Phyt.} + \text{Respiration of Phyt.} + \text{Egestion of Zoop.} \\ + \text{Decomposition of POM} + \text{Oxidation of DOM} + \text{Release from Mud}$$

Dissolved Inorganic Phosphorus (**DIP**)

$$\frac{\partial \text{DIP}}{\partial t} = -\text{Uptake by Phyt.} + \text{Respiration of Phyt.} + \text{Egestion of Zoop.} \\ + \text{Decomposition of POM} + \text{Oxidation of DOM} + \text{Release from Mud}$$

Dissolved Oxygen (**DO**)

$$\frac{\partial \text{DO}}{\partial t} = \text{Photosynthesis} - \text{Respiration of Phyt.} - \text{Respiration of Zoop.} \\ - \text{Oxidation of DOM} - \text{Oxidation of POM} - \text{Consumption by Mud} \\ + \text{Reaeration}$$

Chemical Oxygen Demand (**COD**)

$$\frac{\partial \text{COD}}{\partial t} = \text{Temporal changes in COD components of Phyt.}, \text{Zoop.}, \\ \text{POM, and DOM}$$

Figure 3 Conceptual relationships of the bio-chemical processes

(2) Target year and field data

A serious problem which we faced during the study was lack of observed data. Though the present model can calculate the temporal and spatial changes very in detail, it is difficult to find data obtained in a similar manner for the calibration of the model. After gathering as much data as possible, the data set in 1993 was found to be relatively complete, then 1993 was chosen as the target for the calculation. In 1993, the oxygen-deficit water began to form in the middle of May, and seven blue tide events were recorded from June to September. Therefore, it was tried to hindcast the temporal change of water quality from April to September in 1993.

Initial and boundary conditions used for this calculation were as follows.

- 1) Water density: Salinity and water temperature were set as 34.3‰ and 14°C respectively, uniform for all grid points.
- 2) Tide: Observed tidal elevation was given along the boundary of the bay mouth.
- 3) Climate: Rainfall, solar radiation, cloudiness, direction and speed of wind observed hourly in Tokyo were used.
- 4) River discharge: Daily records of the discharges were given for six major rivers (Edo R., Arakawa R., Tone R., Sagami R., Sagami R., Sagami R.; Japan River Association, 1995). The salinity of the discharge was assumed 0 ‰, and the concentration of COD and other nutrients were set to be the yearly mean values, i.e. constant.
- 5) Bio-chemical terms: The bio-chemical components were set as the data observed on March 23, 1993.

4. Comparison of Simulation and Field Data

As mentioned above, there are no data set of water quality obtained continuously for a sufficiently long period of time. The longest record for salinity, water temperature, and DO was found for a month, from August 30 to September 28 in 1993. In order to verify the present model, the simulated results were compared with the observed data. The point of the comparison was Point B in Fig.1.

The comparisons are shown in Fig.4, 5 and 6 for salinity, water temperature, and DO, respectively. Overall agreements between the simulation and observed data are good, indicating that the present model could reproduce the real changes in water quality.

The observation of salinity and water temperature shows that strong density stratification formed in this period, while the difference of salinity and temperature between the surface and bottom layer disappeared on September 4, 13, 17, and 23. This indicates that strong vertical mixing took place during these days. This disruption of the

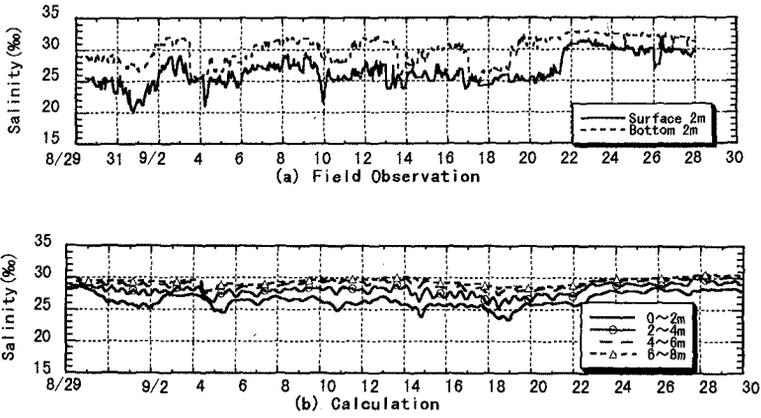


Figure 4 Comparison between observed and calculated results (Salinity)

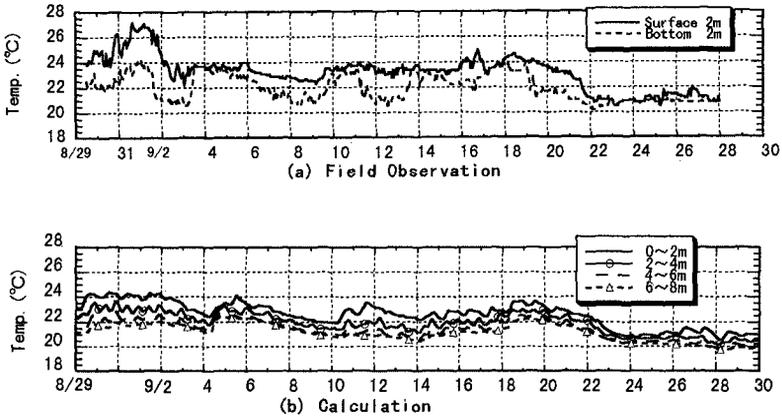


Figure 5 Comparison between observed and calculated results (Water temperature)

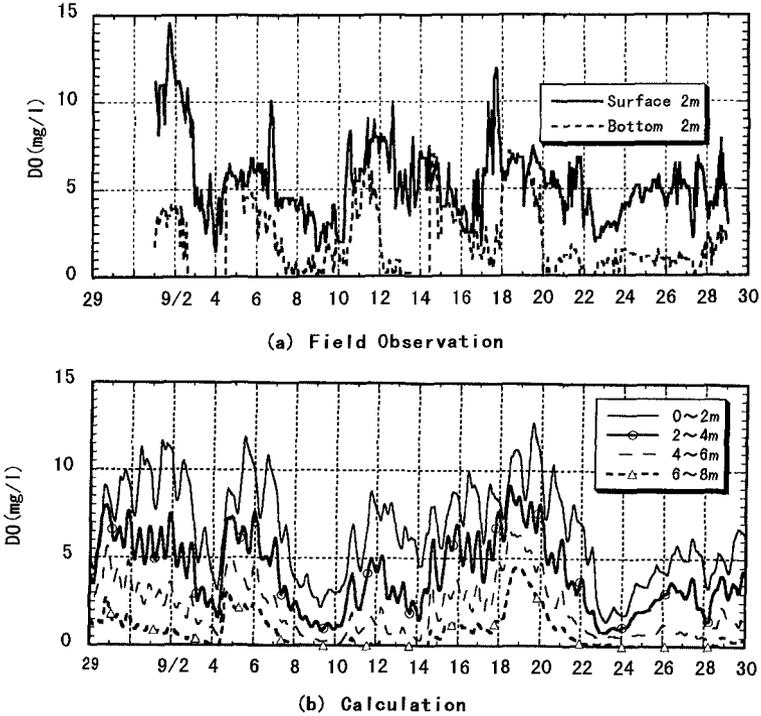


Figure 6 Comparison between observed and calculated results (Dissolved Oxygen)

density stratification corresponded to the wind condition; it occurred when the speed of southerly or south-westerly wind exceeded 5m/s. This means that such strong vertical mixing might be induced by the breaking of wind waves. On the other hand, the vertical mixing are relatively weak in the simulated results. In the model, the vertical mixing is expressed by the eddy viscosity and diffusivity, and the density effect is represented by a stratification function based on the Richardson Number. Therefore, the mixing term of the present model cannot represent the effect of turbulent mixing from water surface caused by wave breaking.

Regarding DO, the concentration over 10mg/l were observed on September 1, 6, 12, and 17. These events are considered to be supersaturation caused by the blooming of phytoplanktons. During the disruption of the density stratification on September 4, 14, and 18, DO also became uniform in the vertical direction. Though such vertical uniformity was not reproduced, the overall temporal change of DO shows good

agreement with the observed data. The blue tide occurrence corresponded to the upwelling of the oxygen-deficit water from the bottom layer to the shore along Chiba Coast.

5. Behavior of the Oxygen-Deficit Water

(1) Formation and expansion of oxygen-deficit water

From the simulation by the present model, the behavior of the oxygen-deficit water in Tokyo Bay can be examined. Figure 7 shows two different distributions of DO in Tokyo Bay; one is the planar distribution in the bottom layer and the other is the vertical distribution along the A-A' section indicated in Fig.3. The period is from early May to mid June. There have been several definitions of the oxygen-deficit water depending

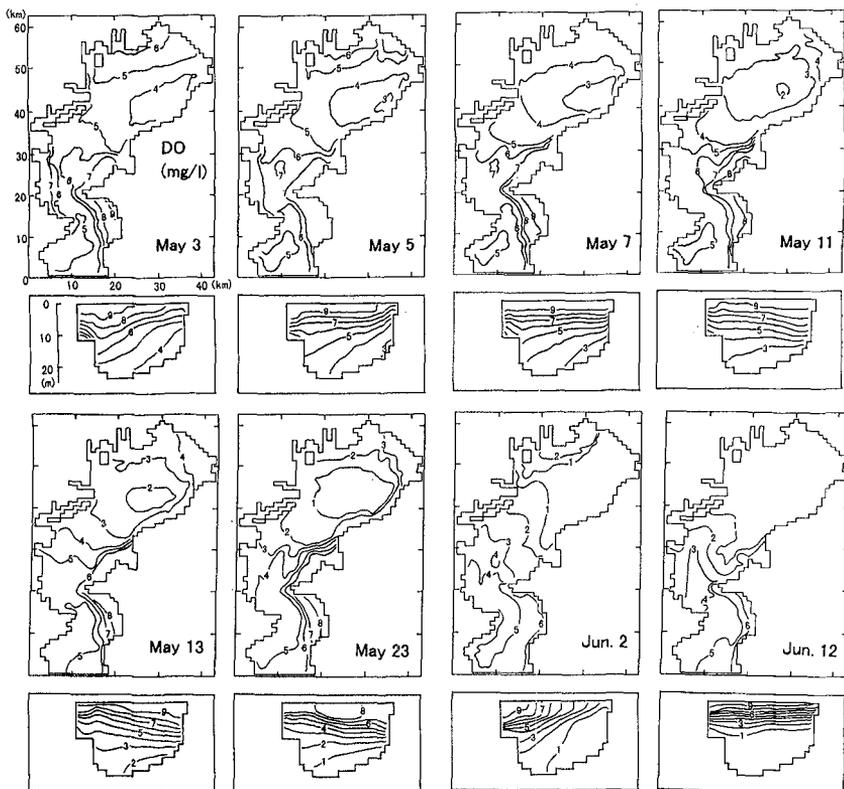


Figure 7 Formation and growth of the oxygen-deficit water

on the degree of harmfulness to the marine organisms. In the present study, DO of less than 3mg/l was taken as the criterion for the oxygen-deficit water.

On May 3, no significant oxygen-deficit water formed, though there was a water mass with 4mg/l of DO off Chiba Coast. Water mass with 3mg/l of DO appeared for the first time on May 5. It expanded on May 7, and the water mass with 4mg/l of DO covered a large portion of the inner bay surrounding the oxygen-deficit water. On May 11, the water mass with 3mg/l of DO expanded in the inner bay, and water mass with 2mg/l of DO appeared in the middle of it. Until June 12, such expansion of the oxygen-deficit water continued, and the bottom layer of the inner bay was finally covered by strong oxygen-deficit water with less than 1mg/l of DO. After this period, the oxygen-deficit water has been stagnant until September, the end of the computation.

The history of the vertical distribution also shows the formation and growth of the oxygen-deficit water very clearly. It was produced around the innermost place of 10 to 20m deep off Chiba Coast. The expansion of the oxygen deficit water was very quick. After May 5, the density stratification started to be intensified. This is due to the climatic conditions; the atmospheric temperature suddenly increased to 24°C on May 11, and it kept above 20°C during the daytime after then. This climatic condition is the major cause for the rapid formation and stagnation of the oxygen-deficit water in the inner part of Tokyo Bay.

Figure 8 shows the changes in the total volume of the oxygen deficit water mass for the complete period of the simulation. The volume of the oxygen deficit water mass was defined as the volume of water in which DO concentration is less than 3mg/l. The history of the atmospheric temperature for the same period is shown in Fig.9. From these figures, the history of the oxygen-deficit water formation can be understood again. As the water temperature increases in May, the oxygen-deficit water started to form. The volume reached its maximum in early July, then tended to decrease with fluctuation. Amazing thing is that the water mass still exist even at the end of September. These tendency is similar with the real situation qualitatively. However, more accurate quantitative verification needs more data densely measured both in time and space.

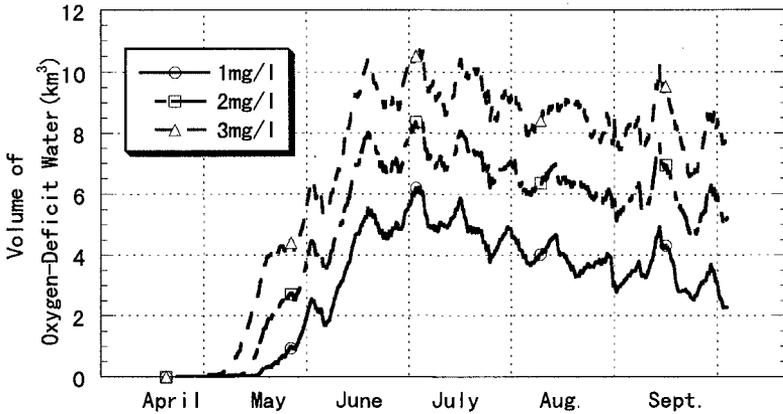


Figure 8 Changes in the total volume of the oxygen-deficit water (from April to September, 1993)

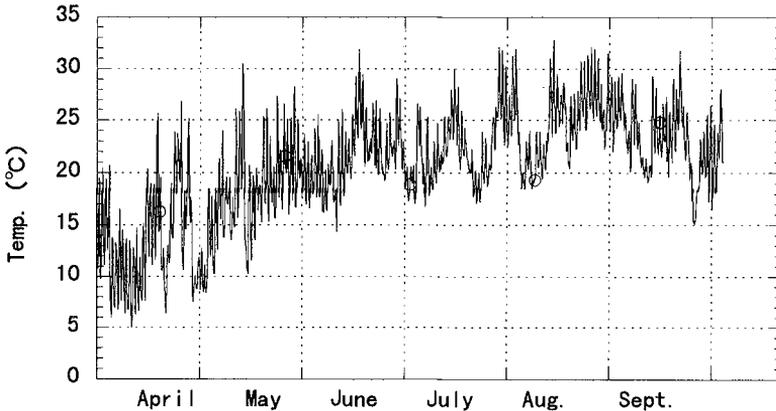


Figure 9 Changes in atmospheric temperature (from April to September, 1993)

(2) Up-welling of the bottom water and formation of blue tide

Figure 10 shows the temporal changes of the DO distribution in the surface and bottom layers during 22 to 30 in September. Throughout this period, the bottom layer of the inner bay was covered by strong oxygen-deficit water, while the appearance of the oxygen-deficit water in the surface layer was intermittent. Though DO was almost saturated on September 22, strong oxygen-deficit water suddenly appeared on the next

day, September 23. This is because wind changed to northerly on September 23, then up-welling was brought about by this wind in front of the north-east coast of Tokyo Bay. Actually blue tide occurred in the same area on September 23.

(3) Effect of countermeasures

The usefulness of such model is that it enables to examine the effects of countermeasures. The possible countermeasures for improving the water quality in Tokyo Bay are reduction of the inflow loads and sand capping over to depress oxygen consumption and nutrients release by bottom mud. In the present study, two trials were made for 50% reduction of the inflow loads and sand capping on the area shallower than 10m. Both countermeasures were not effective to improve the formation of oxygen-deficit water. However, they may be effective if the calculation is continued for several years. Since complete boundary conditions for climate, river discharge, tide, etc. are needed for longer simulation, such attempts are left for future studies.

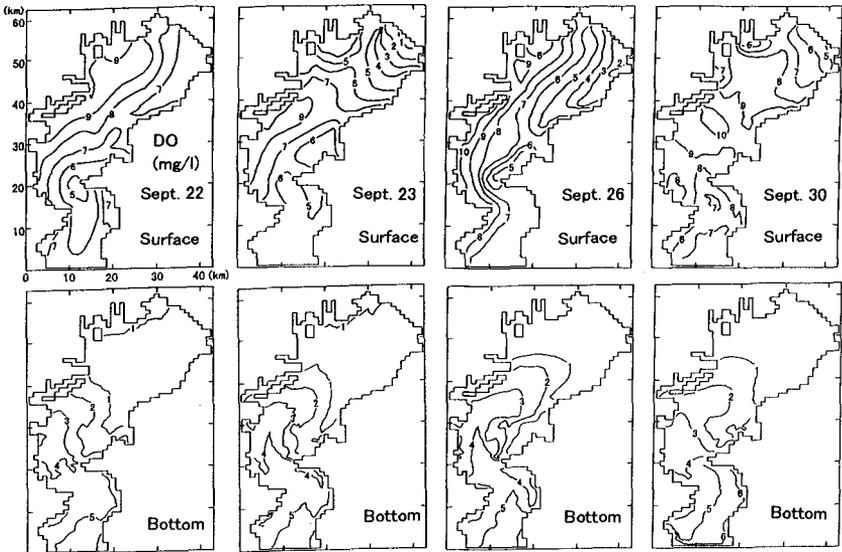


Figure 10 Up-welling of the oxygen-deficit water by wind

6. Conclusions

It is proved that the present model can reproduce the observed spatial and temporal changes in water temperature, salinity and DO rather well. The tendencies of the temporal changes in these parameters are quite similar between calculation and field data through the simulation period of 6 months.

In Tokyo Bay, oxygen-deficit water is generated even in early May in the bottom layer. Once a small mass of the oxygen-deficit water is generated, it expands very quickly to cover the wide area of the innermost part of the bay. During mid-summer, the bottom layer of a half of the bay is covered by strong oxygen-deficit water with DO concentration of less than 1 mg/l. Up-welling of such water occurs when north winds are strong, which in turn brings about blue tide along the north coasts of Tokyo Bay.

When the pollutants discharged from rivers is reduced by 50%, the concentration of nutrients such as phosphate and nitrogen decreases apparently, while the oxygen-deficit water continues to take place. Same tendency was observed, when the effects of sand capping work on the bottom mud was calculated. This indicates the difficulty to improve water quality in Tokyo Bay in a short time. For assessing the effects of such countermeasures, the present model is expected to be useful.

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