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NUMERICAL SIMULATION OF WATER QUALITY STRUCTURE IN ISE BAY AT TOKAI HEAVY RAIN USING ATMOSPHERE-OCEAN-WAVE-WATER QUALITY COUPLED MODEL

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ABSTRACT

Water quality structures in semi-enclosed water areas are influenced by not only meteorological disturbances but also freshwater inflow from rivers. Large floods, in particular, have a great impact on ecosystem. In this paper, an atmosphere-ocean-wave-water quality coupled model is developed so that the primary production of phytoplankton, the decomposition of organic matters and the circulation of nitrogen and phosphorus can be estimated. The coupled model is applied to elucidate water quality structure in Ise Bay at the Tokai heavy rain. As a result, the model is found to be capable of reproducing water quality structure during the Tokai heavy rain. Furthermore, it is revealed that the abrupt change of the water quality structure at large flooding is mainly dominated by inflow load from rivers.

Keywords: atmosphere-ocean-wave-water quality coupled model, Ise Bay, Tokai heavy rain

1. INTRODUCTION

In recent decades, with the rapid growth in economic development and population, eutrophication which promotes algae blooms has strongly been associated with the water environmental problems in semi-enclosed bays such as Tokyo Bay, Osaka Bay and Ise Bay in Japan. Eutrophication depends not only on land-based nutrient loads but also on physical factors of vertical mixing and mass transport dominated by tidal current, density flow, river flow and wind. Excessive phytoplankton growth or red tides, resulting from eutrophication, would cause an increase in detrital flux when the phytoplankton dies. Decaying organic materials are settled to the bottom layer and the subsequent remineralization processes deplete ambient dissolved oxygen (DO). As a result, an oxygen-depleted water mass yields serious problems such as the occurrence of hypoxic and anoxic conditions in the bottom waters. Hypoxia and anoxic conditions have a critical impact on the living marine resources and may cause damage to aquatic environmental system, which is strongly associated with the dissolved oxygen concentration. Moreover, the upwelling of the oxygen-depleted bottom waters along coast, that is, blue tide may take place under a certain wind condition. The occurrence of blue tide also lethally damages shellfish fisheries in shallow areas of the bay and seaweed and clam harvesting on tidal flats.

Many researchers have studied the water quality problem, based on field observation data and have attempted to control and improve the water environment in semi-enclosed bays.

Takahashi et al.(1999) discussed the seasonal variation in intrusion depth of oceanic water and the hypoxia in Ise Bay. Kawasaki et al.(2006) studied density and water quality characteristics in Ise Bay using long-term observation data. These studies have provided some important information for water quality management in the bay. On the other hand, numerous numerical studies have been performed in order to understand water quality structure in semi-enclosed bays. A number of biochemical interaction models coupled with a depth-averaged two-dimensional advection-diffusion model have usually been adopted for coastal region studies (e.g., Chau and Jin, 2002), but could be inadequate when a strong density stratification is present and the vertical structure of the biological system has an important role. For this reason, some water quality models coupled with a three-dimensional hydrodynamic model such as Princeton Ocean Model (POM) and Environmental Fluid Dynamics Computer Code (EFDC; Hamrick, 1992) have been developed. Hydrodynamic-Eutrophication Model (HEM-3D; Park et al., 1995) combined with EFDC has been applied to Kwang-Yang Bay (Park et al., 2005), and Irie et al.(2004) discussed the water quality problems in Osaka Bay by using water quality model coupled with POM-based hydrodynamic model. However, the influences of meteorological disturbance and atmosphere-ocean-wave interaction have not been sufficiently taken into consideration in the existing water quality models.

Since a large amount of contaminants enter bay through rivers especially during a large flooding event, the accurate estimation of freshwater discharge rate flowing into the bay is also of great importance in examining the water quality structure in Ise Bay. However, few studies have numerically been performed in order to examine water quality structure in Ise Bay (e.g., Ukai, 2007). In addition, there have not been studies on water quality structure in Ise Bay under influence of meteorological disturbance or large flooding event.

The main purpose of this study is to develop a highly-accurate water quality model combined with an Atmosphere-Ocean-Wave Coupled Model (Murakami, 2005). An atmosphere-ocean-wave-water quality coupled model developed newly in this study is applied to Ise Bay area during the abnormal event of the Tokai heavy rain in September, 2000 to discuss the sudden change of coastal current and water quality structure induced by large flooding. The validity and applicability of the model are also verified by comparing with the observed field data.

The content of the paper is as follows; Chapter 1 describes the background, motivation and purpose of this study. In Chapter 2, the concept of the atmosphere-ocean-wave-water quality coupled model will first be explained. Then, the numerical procedure of the coupled model will be mentioned. In Chapter 3, the coupled model will be adopted to Ise Bay area at the Tokai heavy rain in order to discuss the abrupt change of coastal current and water quality structure before and after large flooding event. The validity and utility of the coupled model will also be confirmed in comparison with the field data.

2. ATMOSPHERE-OCEAN-WAVE-WATER QUALITY COUPLED MODEL

2.1 Concept of the coupled model

A water quality model combined with an atmosphere-ocean-wave coupled model is developed in this study to understand the water environment more accurately. The atmosphere-ocean-wave-coupled model proposed by Murakami (2005) consists of a 5th generation Mesoscale Model “MM5” (Pennsylvania State University/National Center for Atmosphere Research Mesoscale Model), a Coastal ocean Current Model “CCM” (Murakami, 2005) and a third-generation time-dependent spectral wave model “SWAN” (Simulating. WAves Nearshore) (Delft University of Technology). The concept of the atmosphere-ocean-wave-water quality coupled model is briefly described below and the coupled model framework is demonstrated in a schematic diagram Figure 1.

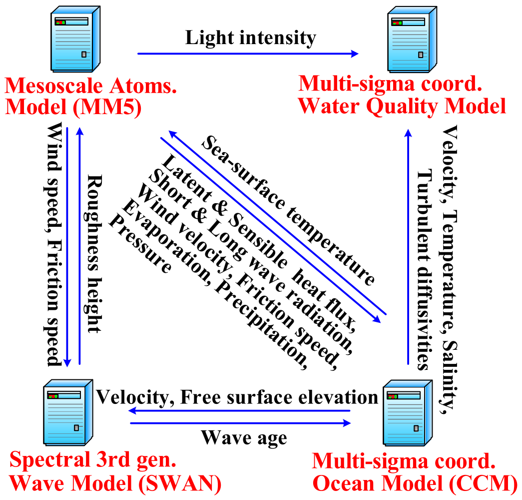


Figure 1 Coupled model framework

Computations with four models of the MM5, the CCM, the SWAN and the water quality model are separately performed as physically-based independent tasks, and a model coupling program known as a model coupler controls these four computations and data exchanges among the models using a message passing interface at a certain time interval. As shown in Figure1, friction velocity, latent and sensible heat fluxes, short and long wave radiations, wind velocity, evaporation, precipitation and sea surface pressure outputted from the MM5 and sea surface temperature from the CCM are exchanged between the two models. The SWAN also have attached to the coupled model with the momentum roughness height and wave age as the data exchange parameters and receives information on the wind speed, friction speed from the MM5 and current velocity and free surface elevation from the CCM, respectively. External variables such as light intensity, current velocity, temperature, salinity and turbulent diffusivities influence the water quality model system. In the water quality model, light intensity at the sea surface is calculated using the MM5, and the information on sea state (current velocity, temperature, salinity and turbulent diffusivities) relating to physical transport process is provided by the CCM.

2.2 Description of water quality model

Phytoplankton growth and the associated nutrient and dissolved oxygen (DO) dynamics are governed by a number of interacting physical and biochemical processes, which vary in time and space, due to river inflows and tidally driven circulation, mass transport by advection and dispersion, organic loads, solar radiation, water temperature, rainfall, nutrient regeneration, deoxygenation and reaeration.

In the present study, we consider a system of eight water quality state variables, which are organic phosphorus (O-P), organic nitrogen (O-N), chemical oxygen demand (COD), inorganic phosphorus (I-P), dissolved oxygen (DO), ammonia nitrogen (NH_4-N), chlorophyll-a (Chl-a), and nitrate state variable (NO_2/NO_3-N). The water quality model developed here uses the same biochemical interaction description and kinetic reaction coefficient as water quality model by Irie et al.(2004). However, their and our water quality models differ significantly in a sigma-coordinate system for the vertical dimension. A POM-based water quality model by Irie et al.(2004) is a single sigma-coordinate system. In contrast, our water quality model is based on a multi-sigma coordinate system to resolve oceanographic phenomena from the bottom to the sea surface more precisely. In addition, the algorithm of the water quality model in this study is integrated directly into the atmosphere-ocean-wave coupled model so that the models share the same computational grids and time steps and simultaneously simulate without any space averaging.

The advection-diffusion equations on water quality state variables solved in the model, therefore, are derived in a similar way to the CCM, and the governing equation in time and space with multi-sigma coordinate can be expressed as

$$\frac{\partial C}{\partial t}+\frac{\partial uC}{\partial x}+\frac{\partial vC}{\partial y}+\frac{\partial \omega C}{\partial \sigma}=\frac{\partial}{\partial x}\left(k_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial C}{\partial y}\right)+\frac{1}{D^2}\frac{\partial}{\partial \sigma}\left(k_z\frac{\partial C}{\partial \sigma}\right)+S \qquad (1)$$

where C is the concentration of water quality state variables; D is the total water depth (mean sea level plus free surface elevation); t is the time; u and v are water velocities along the x and y axes, ω is the vertical water velocity along the σ axis; k_x, k_y and k_z are the diffusion coefficients along the x, y and vertical directions; S is time rate of change resulting from internal and external sources and sinks respectively.

Figure 2 shows the biochemical interactions among the eight water quality state variables in water column.

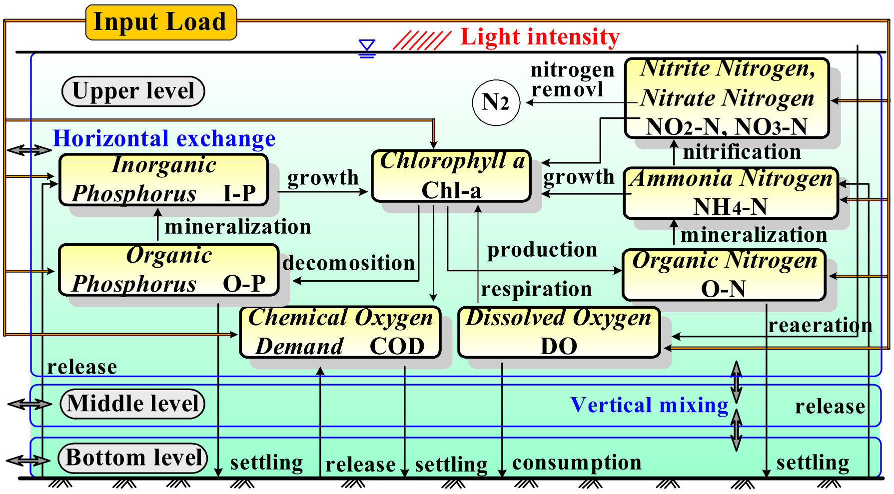


Figure 2 Conceptual diagram of the water quality model

The following processes, as depicted in Figure 2, are simulated in the model. Chl-a is taken as a measure of the gross level of phytoplankton, and primary production by phytoplankton in surface waters is considered as a major source of interactions among different water quality state variables. Phytoplankton decreases due to the overall death or mortality (including the endogenous respiration, zooplankton predation or grazing for diatoms and greens only and non-predatory mortality). On the other hand, phytoplankton increases due to its growth and direct source. During the photosynthesis process, the growth rate of phytoplankton depends highly on three principal components of temperature, solar radiation and nutrients. The light limitation function of Steel and Baird (Thomann and Mueller, 1987), with measured solar radiation intensity by MM5, is employed here. All the individual nutrients are computed by a Michaelis-Menten type expression, and the minimum value is chosen for the nutrient limiting factor.

Regarding the kinetics of the nitrogen species, ammonia and nitrate are used by phytoplankton for growth. During algae endogenous respiration and non-predatory mortality, a fraction of the cellular nitrogen is returned to the dissolved and particulate organic nitrogen pool. The remaining fraction is recycled to the inorganic pool in the form of ammonia nitrogen and readily available for uptake by other viable algae cells. Organic nitrogen is converted to ammonia at a temperature- and phytoplankton-dependent rate, and ammonia is then converted to nitrate via nitrite (nitrification) at a temperature- and oxygen dependent rate. Organic nitrogen decreases as it converts to ammonia nitrogen and settles to the sediment, and increases due to recycling of dead algae and direct sources. Ammonia nitrogen increases from recycling of dead phytoplankton, organic nitrogen heterotrophic decomposition and direct sources and decreases by consumption of phytoplankton, and also due to biological oxidation to nitrate via nitrite nitrogen. Nitrite is generally rapidly converted to nitrate and thus nitrite and nitrate can be combined. Nitrate state variable, which is considered as a sum of nitrate and nitrite nitrogen, is consumed by phytoplankton, denitrification, and increases due to oxidation of ammonia nitrogen and direct sources.

Next, phosphorus circulation is explained. Dissolved inorganic phosphorus is utilized by phytoplankton for growth. A fraction of the phosphorus released during phytoplankton respiration and non-predatory mortality is in the inorganic form and is readily available for uptake by viable algae cells. The remaining fraction is in the organic form and must undergo mineralization or bacterial decomposition into inorganic phosphorus before utilization by phytoplankton. Organic phosphorus decreases because of conversion to inorganic phosphorus and settling to the sediment, and increases due to recycling of dead phytoplankton and direct sources. A saturating recycle equation is used for hydrolysis and bacterial decomposition of organic nitrogen to ammonia and the mineralization of organic phosphorus to inorganic phosphorus.

The production of DO is a by-product of photosynthetic carbon fixation. An additional source of oxygen from algal growth occurs when the available ammonia nutrient source is exhausted and the phytoplankton begins to utilize the available nitrate. The initial step for nitrate uptake is the reduction to ammonia with the production of oxygen. Owing to the deficit from the saturation concentration, DO increases by reaeration from the atmospheric, photosynthetic oxygen production and its direct source and so one.

The above interactions among different state variables are represented by numerical equations and a number of kinetic parameters are used in this water quality model combined with atmosphere-ocean-wave coupled model.

3. NUMERICAL SIMULATION OF WATER QUALITY STRUCTURE IN ISE BAY

3.1 Computational domain

The coupled model was applied to Ise Bay area located on the south coast of central Japan shown in Figure 3. There are large flows of fresh water in the northern head of the bay throughout Kiso, Nagara and Ibi rivers know as the Kiso Three Rivers, which accounts for 80% of the annual fresh water input volume of 20km^3. The bay opens to the Pacific Ocean in south, and to relatively shallow Mikawa Bay (9.2m average depth) to the south-east. Ise Bay covers a surface area of 1738km^2 and has a mean depth of 20m. Water exchange between Ise Bay and the Pacific Ocean takes place mainly through Irago channel.

In the MM5, it is necessary to take a larger computational domain in comparison with a target water area in order to reproduce cloud and precipitation processes with high accuracy (Ohsawa et al., 200). The MM5 is, therefore, configured with three computational domains as shown in Figure 3. The outermost nest (domain I) covers the main island of Japan, whereas middle (domain II) and innermost nests (domain III) cover the central Japan and Ise Bay, respectively. The MM5 allows the use of nested grids. A dynamically consistent two-way nesting method was used to nest the numerical results among the three domains. Other models of the CCM, the SWAN and the water quality model are coupled with the innermost nest domain III of the MM5.

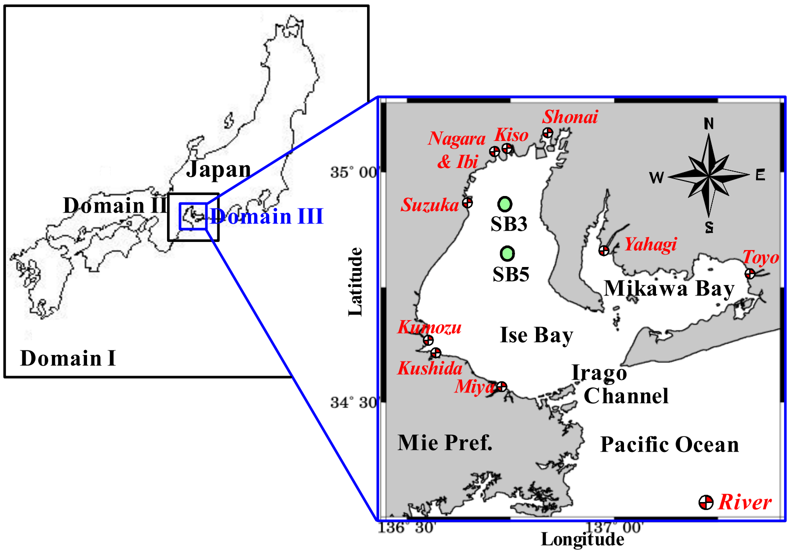


Figure 3 Location of Ise Bay, three computational domains and main ten rivers in Ise Bay

3.2 Computational conditions

The MM5 is initialized with re-analysis of upper air and surface data from the European Center for Medium Range Weather Forecasts (ECMWF). Sea surface elevations calculated by tidal prediction model NAO.99JP (National Astronomical Observatory, Japan; Matsumoto et al., 2000) were employed in the CCM as a open boundary condition at every time step. In addition, hourly-observed freshwater discharge rates of the main ten rivers including Kiso Three Rivers shown in Figure 3 are prescribed at the inflow boundaries. Figure 4 shows the time variations of freshwater discharge rate at Kiso Three Rivers during the Tokai heavy rain. The inflow concentrations of all water quality variables, except for Chl-a concentration are specified as a times of measured freshwater discharge rate at each river. Because Chl-a concentration has been observed only at the Nagara river, the concentration of Chl-a for other rivers was used as the same value at the Nagara river. Based on in-situ field study (Kawasaki et al., 2006), water temperature, salinity and water quality data are interpolated onto the model grids and were employed as initial condition.

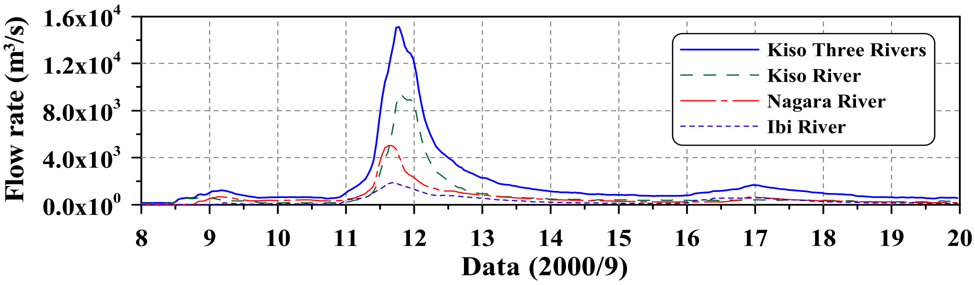


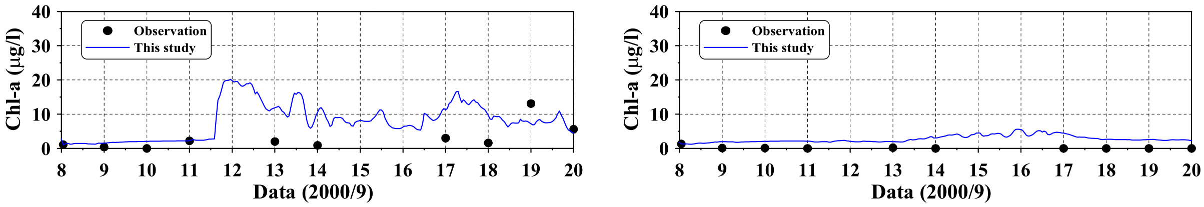
Figure 4 Flow rates of the Kiso Three Rivers during the Tokai heavy rain

3.3 Accuracy verification of the coupled model

To verify the water quality model combined with atmosphere-ocean-wave couple model, the simulated results for the Chl-a and DO in Ise Bay at the Tokai heavy rain were compared to the observed ones at the monitoring stations of SB3 and SB5 indicated in Figure 3.

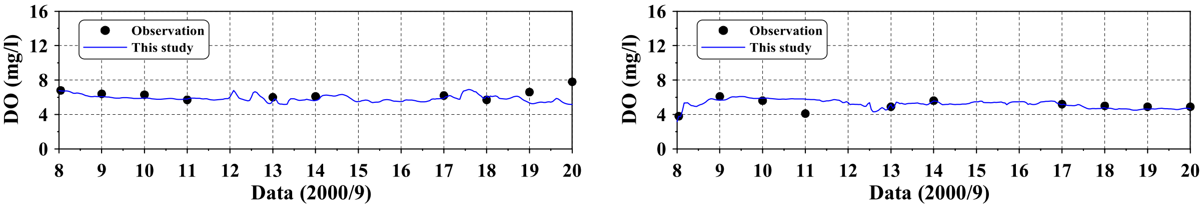
Figure 5 shows the comparisons of the daily variations between computed Chl-a and observed ones at the monitoring station of SB3. It is found that the model results tend to overestimate for both the surface and bottom Chl-a. The difference of the calculation and observation results might be due to the Chl-a inflow concentration taken as the same values in each river because of no field data except for Nagara river. Nevertheless, the calculation result mostly corresponds with the observation one. If the actual Chl-a loading from all the river outlets can be obtained, it would be thought that much better simulations is performed and the accuracy of the results is improved. Both the computed and observed results of DO at the monitoring station of SB5 are shown in Figure 6. It can be seen from this figures that the comparison shows a good agreement between the calculated and the observed results at both the upper and lower layers.

The comparisons indicate that the present atmosphere-ocean-wave-water quality coupled model can simulate the variation of water quality state variables resulting from interaction of atmosphere, ocean and wave with the acceptable accuracy.



(a) upper layer (0.1m) (b) lower layer (15m)

Figure 5 Comparisons of computed and observed Chl-a at SB3



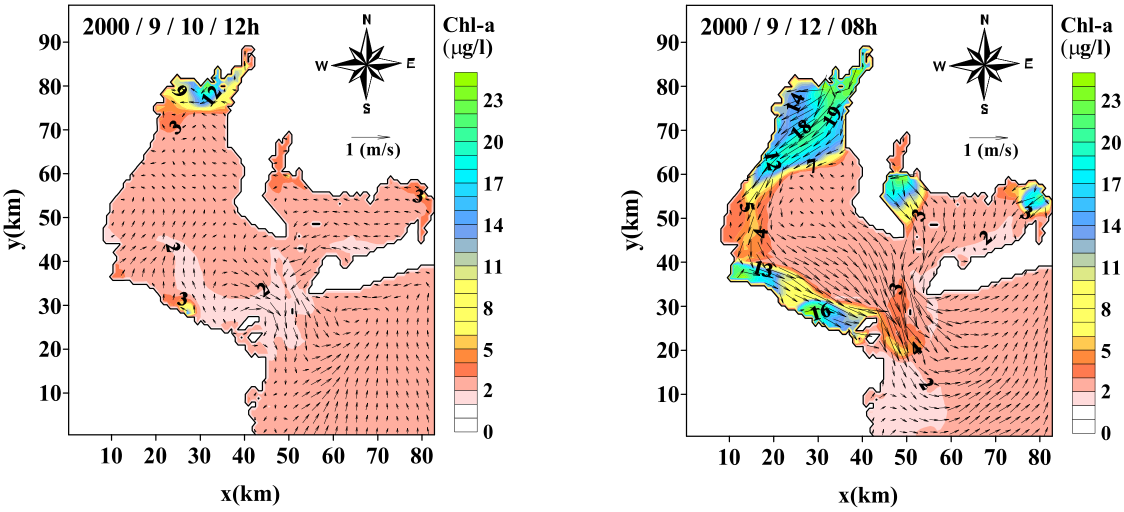
(a) upper layer (0.1m) (b) lower layer (15m)

Figure 6 Comparisons of computed and observed DO at SB5

3.4 Water quality structures induced by large flooding event

The surface distributions of tidal current velocity and Chl-a before and after the flood are shown in Figure 7. The effect of river plume before and after large flooding on the tidal current velocity and Chl-a variations can be clearly seen in the figure. From the comparisons of Figures 7(a) and 7(b), it can be found that the strong current velocities develop toward the bay mouth from the head of the bay at the western shore of Ise Bay after large flooding. The spatial distribution of Chl-a in Figure 7(b) became higher than that in the Figure 7(a). In particular, higher Chl-a was recorded in the vicinity of the mouths of the rivers, and the highest

Chl-a was observed near the head of the bay because of the existence of Kiso Three Rivers. Moreover, it is also found from the computational results that the spatial distribution of Chl-a after large flooding has an almost similar trend to that of surface density after large flooding revealed by Murakami et al.(2007).

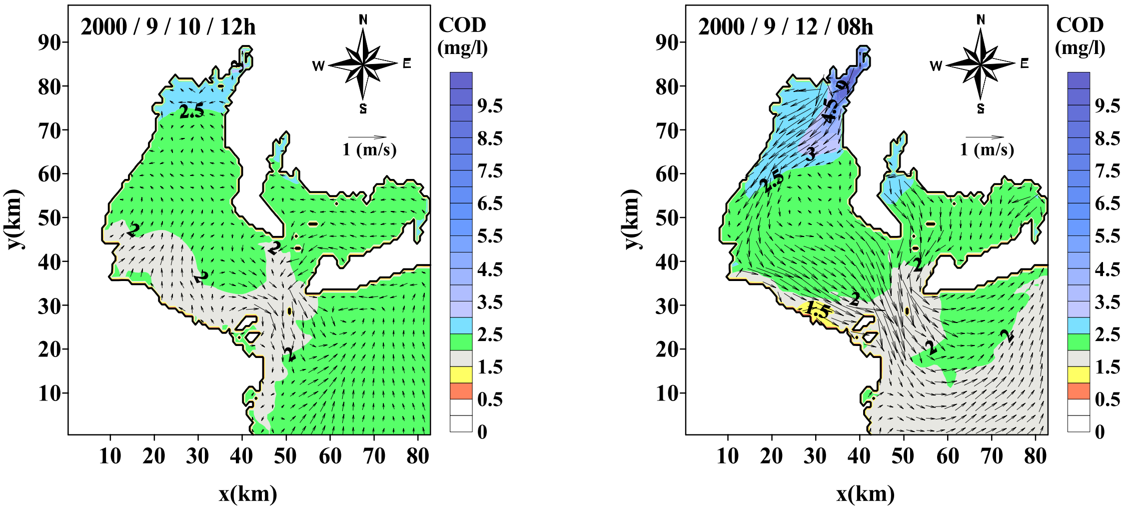


(a) before flooding (b) after flooding

Figure 7 Spatial distributions of Chl-a and coastal current at the surface water layer

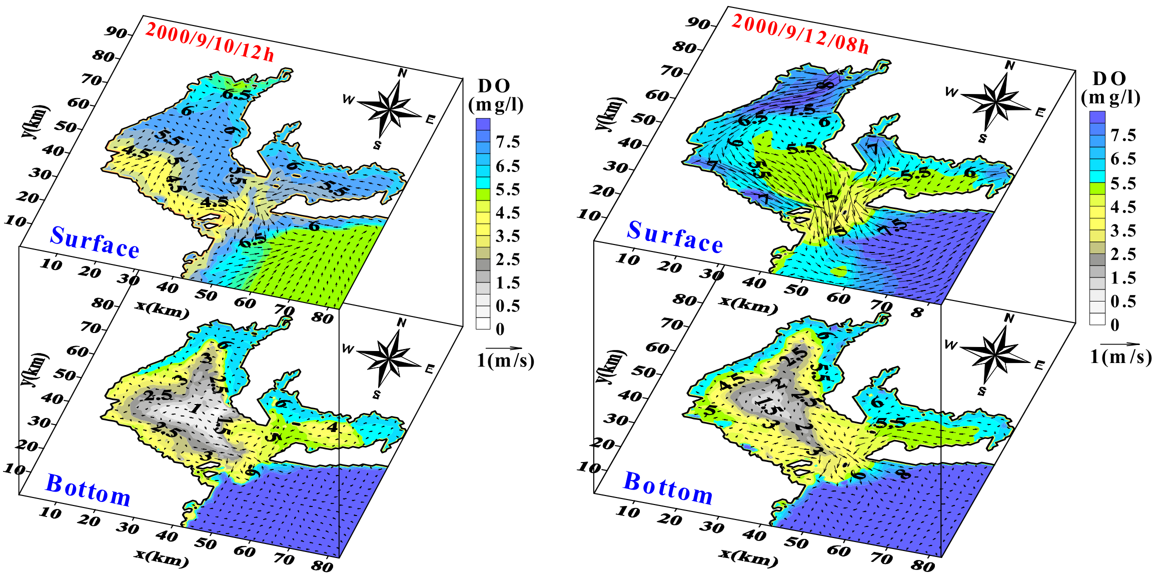
Figure 8 shows COD distribution at the surface water layer. It is shown that the concentration of COD before large flooding is almost uniform values in the whole area of the bay, except the near head of bay. On the other hand, the concentration of COD after large flooding increase toward the bay mouth from the head of the bay in a similar tendency to Chl-a distributions in the bay after large flooding. Especially, the value of COD in the vicinity of the Nagoya Port is more than 9mg/l because the inflow of COD from Shonai river to the bay is higher as compared with other rivers. A similar tendency of COD distribution with high concentration near the Nagoya Port is be also found in the study based on the field observation data by Kawasaki et al.(2006).

The distributions of DO before and after large flooding are shown in Figure 9. DO is one of the most important variables in water quality problems. In general, when DO drops to about 4mg/l, most marine biota would begin to feel stressed and move away from the area. In the DO condition below 3mg/l, mortality of fish will occur and shellfish will begin to shut down. Therefore, DO is said to be a sensitive indicator of health of the aquatic system. From Figure 9, DO is high at the surface water layer, while bottom DO is low. After large flooding, DO increases due to the influences of reaeration from the atmosphere, direct source from rivers and so on. It is, in particular, shown that DO near Kiso Three Rivers are more than 8~9mg/l after large flooding. In spite of flooding, DO values at the surface water layer, which are more than 4.5mg/l, remain adequate. On the other hand, an oxygen-depleted water mass with DO less than 2.0mg/l are formed at the deep water area in the central part of bottom water layer. But, bottom DO on western coast of Ise Bay increases due to the influence of the large flooding from the Kiso Three Rivers and the rivers in Mie Prefecture, as shown in Figure 9(b). Therefore, the central part of bottom water layer is found to become anoxic or hypoxic. The reason for this is that the weak turbulent mixing and the steep temperature and salinity stratification in the water column prevent vertical mixing and replenishment of oxygen from the well aerated surface water layer to the bottom in summer.



(a) before flooding (b) after flooding

Figure 8 Spatial distributions of COD and coastal current at the surface water layer



(a) before flooding (b) after flooding

Figure 9 Spatial distributions of DO and coastal current at surface and bottom layers

4. CONCLUSIONS

In the present study, the atmosphere-ocean-wave-water quality coupled model has newly been developed based on the multi-sigma coordinate system and the highly-accurate water quality model with biochemical interactions of water quality items. The coupled model was applied to elucidate water quality structure in Ise Bay area at Tokai heavy rain in September 2000. The validity of the coupled model was verified by comparing with the observation data at Tokai heavy rain. The numerical results, furthermore, revealed that the large flooding has significant effects on the water quality structure as well as flow and density structures. The atmosphere-ocean-wave-water quality coupled model developed here could become one of the useful and high-accurate tools for simulating the water quality structure and taking countermeasures against water quality problems.

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REFERENCES

Chau, K. W. and Jin, H. (2002), Two-layered, 2D unsteady eutrophication model in boundary-fitted coordinate system: *Marine Pollution Bulletin*, 45, pp.300-310.

Hamrick, J. M. (1992), A three-dimensional environmental fluid dynamics computer code: theoretical and computational aspects: *Special Report in Applied Marine Science and Ocean Engineering*, 317, VIMS, VA.

Irie, M., Nakatsuji, K. and Nishida, S. (2004), Numerical simulation of dynamics of anoxic water in Osaka Bay: *Ann. J. Coastal Eng., JSCE*, 51, pp.926-930. (in Japanese)

Kawasaki, K., Murakami, T. and Okubo, Y. (2006), Density and water quality structures in Ise Bay based on field observation data: *Ann. J. Coastal Eng., JSCE*, 53, pp.946-950. (in Japanese)

Matsumoto, K., Takanezawa, T. and Ooe, M. (2000), Ocean tide models developed by assimilating TOPEX/POSEIDON altimeter data into hydro-dynamical model; A global model and a regional model around Japan: *J. Oceanography*, 56, pp.567-581.

Murakami, T. (2005), Study on coastal current affected by meteorological disturbances and its modelling: *Doctor thesis, Gifu University*, 154pp. (in Japanese)

Murakami, T., Kawasaki, K., Okubo, Y. and Kim, J. H. (2007), Numerical analysis of flow and density structures in Ise Bay area at Tokai heavy rain: *Ann. J. Coastal Eng., JSCE*, 54, pp.371-375. (in Japanese)

Ohsawa, T., Fukao, K. and Yasuda, T. (2002), Numerical simulation of accurate meteorological fields in the Ise Bay area and its validation: *Ann. J. Coastal Eng., JSCE*, 49, pp.181-185. (in Japanese)

Park, K., Jung, H. S., Kim, H. S. and Ahn, S. M. (2005), Three-dimensional hydrodynamic-eutrophication model (HEM-3D): application to Kwang-Yang Bay, Korea: *Marine Environmental Research*, 60, pp.171-193.

Park, K., Kuo, A. Y., Shen, J. and Hamrick, J. M. (1995), A three-dimensional hydrodynamic-eutrophication model HEM-3D: Description of water quality and sediment process submodels: *Special Report in Applied Marine Science and Ocean Engineering*, 327, VIMS, VA.

Takahashi, T., Fujiwara, T., Kuno, M. and Sugiyama, Y. (1999), Seasonal variation in intrusion depth of oceanic water and the hypoxia in Ise Bay: *Oceanography in Japan*, 9(5), pp.265-271. (in Japanese)

Thomann, R. V. and Mueller, J. A. (1987), Principles of surface water quality modelling and c ontrol: *Harper and Row Publishers*, NewYork.

Ukai, A. (2007), Study on the behaviors of oxygen-deficient water mass in Ise bay and Mikawa bay and the effecs of meteorological disturbances on them: *Doctor thesis, Gifu University*, 108pp. (in Japanese)