Modeling of Suspended Particulate Matter in the East China Sea

Jun ONO and Xinyu GUO

Center for Marine Environmental Studies, Ehime University, Bunkyo-cho 2-5, Matsuyama 790-8577, Japan

Received 19 September 2011; accepted 11 October 2011

Abstract—It has been known that suspended particulate matter (SPM) plays an important role in the behavior of persistent organic pollutants (POPs). In the East China Sea (ECS), the Yangtze River (Changjiang) and Yellow River (Huanghe) carry a massive amount of SPM into the ECS. To investigate the SPM dynamics in the ECS, we developed a three-dimensional model for SPM transport in the ECS. The SPM model was coupled with an ocean circulation model that can well reproduce the real flow fields to represent the advection and diffusion. The model also includes processes of tidal currents, river discharge, and resuspension at the seabed. In the present study, we focused on the single-sized cohesive sediment of clay prevailing in the ECS. The model showed a clear seasonal variation with high concentration during the fall and winter months and low concentration during the spring and summer months. High concentrations are mainly formed in coastal regions. These features are qualitatively consistent with results derived from satellite observations. The simulated SPM concentrations also changed with spring-neap tidal cycle and high concentration regions were consistent with areas where tidal currents (bottom stresses) are strong. This study created monthly averaged SPM concentration dataset for the ECS, providing a reliable boundary condition SPM data for our POPs model.

Keywords: numerical model, East China Sea, suspended particulate matter, persistent organic pollutants, seasonal and tidal variations

INTRODUCTION

It has been known that the behavior of suspended particulate matter (hereinafter called SPM) in the marginal sea play an important role in the material transport from land to the oceanic region (e.g., Walsh et al., 1988). The East China Sea (hereinafter called ECS), including the Yellow Sea and Bohai Sea, is one of the larger marginal sea in the world, receiving a massive amount of SPM mainly from Yangtze River (Changjiang) and Yellow River (Huanghe). Since SPM influences the transport process of nutrients, such as phosphorus, nitrogen, and silicate, understanding the SPM dynamics is crucial for maintaining high biological productivity of these seas. One of the impacts of SPM on the nutrients is the shielding effect. Isobe and Matsuno (2008) suggested that nutrients are transported...
over a long distance from the Changjiang River mouth to offshore regions by SPM before nutrients are exhausted.

In the East Asia countries, serious environmental contamination by persistent organic pollutants (hereinafter called POPs) has been of concern over the last decade. In particular, polychlorinated biphenyls (Fung et al., 2004) and dichloro diphenyl trichloroethanes (Hu et al., 2009) are found to be high concentrations in the ECS due to the enhancement of industrialization. POPs are mainly characterized by persistence, long-range transport in the atmosphere and ocean, bioaccumulation, and toxicity. For this reason, we have developed a three-dimensional transport model for POPs in the ECS and applied it to PCB 153 from the atmosphere (Ono et al., 2011). From our simulation results, it was shown that the uptake process of POPs by phytoplankton is important. However, since phytoplankton data used in the model was derived from the satellite, phytoplankton biomass is affected by the shading effect of SPM. In addition, SPM itself influences the POPs transport process in the ocean (Liu et al., 2008). Thus understanding and quantifying the SPM dynamics are important to improve our POPs model.

The objective of this study is to elucidate the SPM dynamics in the ECS, particularly, focusing on the seasonal variability. To this end, we developed a three-dimensional model for SPM transport in the ECS and also created the monthly averaged dataset of SPM concentration for the ecosystem and POPs models in the ECS. In the rest of the paper, Section 2 describes a three-dimensional/high-resolution transport model for SPM in the ECS. In Section 3, we present results from numerical simulations.

MODEL DESCRIPTION

Ocean Circulation Model

To incorporate effects of advection and diffusion of SPM by current and turbulence, we used a three-dimensional ocean circulation model, which has been based on the Princeton Ocean Model (POM) (Blumberg and Mellor, 1987; Mellor, 2003). This model can well reproduce seasonal variation in physical fields of the ECS (Guo et al., 2003). The model domain is 117.5°–131.5° and 24°–41° (Fig. 1), covering the Bohai, Yellow, and ECSs. The grid in this model has a resolution of $1/18°$ (~5 km on average) horizontally and 21 sigma levels vertically (0.000, –0.002, –0.004, –0.006, –0.010, –0.020, –0.040, –0.060, –0.080, –0.100, –0.120, –0.140, –0.170, –0.200, –0.300, –0.400, –0.500, –0.650, –0.800, –0.900, –0.950, and –1.000), with a fine-scale resolution near the surface and bottom. The external and internal time steps are 6 and 360 s, respectively.

The ocean circulation model runs from December 1st 1986, using the results of the nested model (Guo et al., 2003) as initial conditions. The model is driven by wind stresses, heat fluxes and salt fluxes applied at the sea surface. Along the open boundary, monthly temperature, salinity, subtidal currents and sea level elevation from a nested ocean model (Guo et al., 2003) were used. This model also includes four major constituents ($K_1$, $O_1$, $M_2$, and $S_2$) provided by Matsumoto et al. (2000) and river discharges.
According to Wang (2002), a three-dimensional equation describing SPM transport is given by a partial differential equation;

\[
\frac{\partial C}{\partial t} + \frac{\partial}{\partial x} (uC) + \frac{\partial}{\partial y} (uC) + \frac{\partial}{\partial z} \left[ (w + w_z) C \right] = \frac{\partial}{\partial z} \left( K_a \frac{\partial C}{\partial z} \right) + F_C
\] (1)

Fig. 1. Model domain and bathymetry. Velocity fields at the surface in August were superimposed by vectors. The 20, 50, and 100-m isobaths were also superimposed by thin solid lines. A thick solid line denotes the section along which vertical structures of SPM are presented in Fig. 4. SP and KP denote Shandong and Korean Peninsulas.

**SPM Transport Model**

According to Wang (2002), a three-dimensional equation describing SPM transport is given by a partial differential equation:
where $C$ is the SPM concentration; $t$ is time; $x$, $y$, and $z$ are the zonal, meridional and vertical coordinates; $u$, $v$, and $w$ are their velocity components; $w_s$ represents the sinking velocity of SPM; $K_h$ is the vertical eddy diffusivity coefficient which is calculated by a 2.5 Mellor-Yamada turbulence closure scheme (Mellor and Yamada, 1982); $F_c$ is the horizontal diffusion term parameterized according to the Smagorinsky diffusion scheme (Smagorinsky, 1963). The SPM model numerical scheme is similar to that used for solving variables such as salinity and temperature in POM. The integration of Eq. (1) is carried out by two steps. The first step is to explicitly integrate $C$ for advection and horizontal diffusion. The second step is to implicitly solve $C$ by vertical diffusion. A first-order upstream scheme (Smolarkiewicz, 1984) was used for advection in Eq. (1). Stokes law was used to calculate $w_s$ by

$$w_s = \frac{gd^2}{18 \nu} \left( \frac{\rho_s}{\rho_w} - 1 \right)$$

(2)

where $g = 9.806$ m s$^{-2}$ is gravity acceleration, $d = 20 \mu$m is SPM grain diameter, $\nu = 1.3 \times 10^{-6}$ m$^2$ s$^{-1}$ is the molecular kinematic viscosity, $\rho_w$ is clear seawater density, and $\rho_s = 1100$ kg m$^{-3}$ is density for clay. In this study, the target SPM is lithogenic clay prevailing in the ECS. The SPM inputs from the rivers are given by

$$K_h \frac{\partial C}{\partial z} = F_r \text{ at } z = \eta$$

(3)

where $F_r$ is the monthly averaged SPM concentration from the Yangtze River or Yellow Rivers (not shown). At the seabed, SPM concentration gradient was prescribed according to

$$K_h \frac{\partial C}{\partial z} = E \text{ at } z = -H$$

(4)

where $E$ is the net SPM flux normal to the bottom boundary due to deposition or resuspension at the seabed. Following Wang and Pinardi (2002), the seabed SPM flux $E$ can be formulated as follows:

$$E = \begin{cases} E_0 \left( \frac{\tau_b}{\tau_c} - 1 \right) & (|\tau_b| > \tau_c) \\ C_b w_s \left( \frac{\tau_b}{\tau_c} - 1 \right) & (|\tau_b| < \tau_c) \end{cases}$$

(5)
where $E_0$ is the erosion coefficient, $\tau_b$ is the bottom stress, $\tau_c$ is the critical stress for resuspension and deposition, and $C_b$ is the SPM concentration at the deepest sigma layer. As mentioned by Wang (2002) and Wang and Pinardi (2002), there is considerable uncertainty for choice of $E_0$ and $\tau_c$. In the present study, we used the values of $10^{-9}$ kg m$^{-2}$ s$^{-1}$ and 0.05 N m$^{-2}$ for $E_0$ and $\tau_c$, respectively. The SPM model does not include wind wave interaction mechanism for SPM transport. The SPM model was integrated for 10 years. SPM concentration attains a nearly steady state in about 6–7 years (not shown). This indicates that the spin-up is accomplished in about 6–7 years. In this study, the last year was analyzed as a control run.

Fig. 2. Horizontal distributions of the monthly averaged surface SPM concentration.
RESULTS AND DISCUSSION

To investigate the temporal and spacial variations in SPM, the monthly averaged SPM concentrations at the surface and bottom are shown in Figs. 2 and 3, respectively. The model showed a remarkable seasonal variability in the SPM concentration at the surface and bottom. Concentrations are high in fall and winter (November–March) and low in spring and summer (May–September). This is qualitatively consistent with results from satellite observations. The high concentration area is mainly formed near coastal regions from China to Korean Peninsula. In particular, the concentrations are high around the southern part of the Shangdong Peninsula and in the western coast of Bohai Sea. By contrast, the
surface SPM concentrations are low in the central Yellow Sea. Such spatial variation is partly caused by differences in the resuspension process. Bottom stresses in coastal regions, where the tidal currents are dominant, are stronger than those in offshore regions. As a result, a massive amount of SPM are supplied from the seabed into the water column. The SPM concentrations at the bottom (Fig. 3) are higher than those at the surface (Fig. 2), regardless of seasons, because of the resuspension process at the seabed.

To examine the vertical structure of the SPM concentration along a section of 31°, the vertical distribution of the SPM concentration in February and August are presented in Fig. 4. In February, the SPM concentration is almost vertically uniform over the shelf and its horizontal gradient is large. In contrast, the SPM concentration in August is not so high over the shelf, regardless of the high SPM load from the Yangtze River. It is therefore suggested that the SPM supply from the Yangtze River has no significant impact for the SPM distribution near the river mouth. In addition, the high SPM concentration in February is partly caused by horizontal advection due to the China Coastal Current prevailing in fall and
winter. To confirm this hypothesis, we need further analysis and numerical experiments as future works.

In the present study, we developed a three-dimensional model for the SPM transport in the ECS. From the comparison of the model and satellite data, the model reproduced the temporal and spatial features in SPM to some extent. These dataset of SPM concentration is available for the boundary condition data of the ecosystem and POPs models. Using the SPM model, several numerical experiment will be carried out to elucidate effects on the SPM dynamics of tidal currents and river discharge, and to assess the impacts on the POPs behavior. In addition, our future effort will take account of following effects: (1) wind wave, (2) stratification due to the SPM, and (3) flocculation, which are important processes for SPM.

Acknowledgments—We would like to thank Joji Ishizaka of Nagoya University for providing satellite data. We are also very thankful to one anonymous reviewer for useful comments. This study was supported by a Grant-in-Aid for the Global COE Program in Ehime University (Leader: Prof. Shinsuke Tanabe) from the Japanese Ministry of Education, Culture, Sports, Science and Technology.

REFERENCES


J. Ono (e-mail: jo@sci.ehime-u.ac.jp)