Precipitation effect on surface salinity and temperature in the Yatsushiro Sea

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Abstract. Field observation was carried out during July 2016 in Minamata Bay of Yatsushiro Sea, measured data of temperature and salinity of five stations has been used for comparing the numerical simulation based on Princeton Ocean Model (POM). Simulation results showed deviations existed between simulated and measured data, especially the salinity field, which was probably caused by the increased precipitation during plum rain season. Therefore, a new precipitation module and modified heat flux forcing for POM were built to present the rainfall effect of salinity and temperature. It is indicated that the accuracy of predicted temperature and salinity was improved to some extent. In contrast with the previous simulation, deviations were reduced significantly. Nevertheless, simulation results of new model under rainy and sunny conditions showed the cooling impact of precipitation was slight, which may be caused by the daytime observation and solar radiation was dominated. However, this study has shown that precipitation effect is an important factor for surface numerical simulation during rainy season.

1. Introduction

The Yatsushiro Sea is situated in the west coast of Kumamoto Prefecture, surrounded by the Kyushu mainland and Amakusa Islands, Japan. In the southeast part of Yatsushiro Sea is the Minamata Bay, known as the Minamata disease caused by wastewater discharge contained mercury from the Chisso factory during 1932 to 1968. The Minamata Bay Pollution Prevention Project (1977-1990) was carried out as a remediation measure to dredge highly contaminated sediment in order to prevent further diffusion of contaminants. After the remediation project, mercury concentration around Minamata Bay has decreased significantly, however, the residual mercury pollution level was still higher than the background value of this area [1]. Our research group has been carrying on a periodic field investigation since several years ago to monitor the different mercury contents of sediment and water column, and other ocean indexes [2]. Three fixed points were chosen for sample collection, station 4 and station 5 were added in recent years (figure 1). In order to provide basic environment for the simulation of sediment and mercury transportation, temperature field and salinity field were simulated first. Simulation results of July 2016 obtained from the previous model showed that the simulated surface temperature was lower than measured data of five observation stations, while the simulated surface salinity was abnormally higher (figure 2). Through consulting historical datum, a large amount
Figure 1. Research region and five sample collection points. Bold lines in the lower left quarter represent the position of open boundary conditions for elevation during simulation.

Figure 2. Comparison of the previous model simulation results and measured data. (Station order is from south side to north side, consistent with the measuring sequence).
of precipitation was found in the research area during the simulation period, which was caused by the plum rain season. The simulation results indicated that precipitation effect on surface salinity and temperature in the Yatsushiro Sea couldn’t be neglected, especially in the rainy season. Ocean researches related to the rainfall impact have been carried out in recent years. Jones et al. presented near surface salinity profile with rainfall events by a rain impact model [3]. Ho et al analyzed the influence of rainfall in different degrees on sea surface salinity based on satellite remote sensing data [4]. Li et al improved the rainfall prediction from the sea surface salinity change by establishing linkage between these two factors [5]. Therefore a precipitation module was added into the Princeton Ocean Model for the first time, which can reflect the real time effect on surface temperature and salinity field of rainfall. Meanwhile, new thermal radiation boundary condition which could change temporally and spatially was adopted for calculating heat fluxes, providing more accurate simulation for the diurnal and regional temperature change compared to the previous constant heat flux forcing.

2. Model description

The three-dimensional Princeton Ocean Model (POM) [6] was used for the simulation of salinity field and temperature field of Yatsushiro Sea. POM consisted of a two-dimensional external mode with a short time step for fast moving external gravity waves and a three-dimensional internal mode for slow moving internal gravity waves. The Arakawa C differencing scheme was used in the horizontal curvilinear orthogonal coordinate and the horizontal diffusivity was calculated by the Smagorinsky diffusion scheme. A σ-coordinate system was adopted in the vertical coordinate for irregular topography and vertical mixing coefficients were provided by the level-2.5 turbulence closure scheme. The basic equations for temperature and salinity of POM are shown in equations (1) and (2).

\[
\frac{\partial TD}{\partial t} + \frac{\partial TUD}{\partial x} + \frac{\partial TVD}{\partial y} + \frac{\partial T\omega}{\partial z} = \frac{\partial}{\partial \sigma} \left( \frac{K_H}{D} \frac{\partial T}{\partial \sigma} \right) + F_T - \frac{\partial R}{\partial z} \tag{1}
\]

\[
\frac{\partial SD}{\partial t} + \frac{\partial SUD}{\partial x} + \frac{\partial SVD}{\partial y} + \frac{\partial S\omega}{\partial z} = \frac{\partial}{\partial \sigma} \left( \frac{K_H}{D} \frac{\partial S}{\partial \sigma} \right) + F_S \tag{2}
\]

where \( U, V, \omega \) represent the velocity components along horizontal and vertical directions, respectively; \( T \) is water temperature and \( S \) is salinity; \( D=H+\eta \), sum of bottom topography depth and free surface elevation, \( K_H \) is the vertical eddy diffusivity coefficient of temperature and salinity, \( F_T \) and \( F_S \) are the horizontal diffusion terms for temperature and salinity, \( \partial R/\partial z \) is the heat radiation forcing term.

2.1. Model domain

The simulation domain covering all the Yatsushiro Sea is shown in figure 1. Grid arrangement of 119 \( \times \) 119 was taken and horizontal resolution was about 500 m in both longitude and latitude directions. Time intervals were 1 s and 5 s for external and internal modes, respectively. σ-coordinate system discretized the vertical domain into 10 layers. The surface elevation was chosen as the tidal forcing on the west and south open boundaries. Due to the lack of tidal gauge data, a tidal prediction method based on historical data was applied to obtain the harmonic constants of four tidal constituents (\( M_2, S_2, K_1, O_1 \)) and the predicted harmonic constants were interpolated to two open boundaries. Temporally changed surface wind stress was added into model step by a linear interpolation. Total simulation duration was from July 5\(^{th}\), 2016 to July 20\(^{th}\), 2016. Five stations’ measured temperature and salinity data on July 5\(^{th}\) were interpolated to the whole simulation domain as initial conditions. Field observation was carried out 5 times to collect the salinity and temperature data during the simulation period, which were used for comparing the simulated data.

2.2. Precipitation and river inflows forcing

Origin POM applied the river discharge to represent the rainfall effect on salinity field simulation, while previous researches on the Yatsushiro Sea showed the river discharge influence was only around the river mouse areas, especially for B-class river. Among these five observation stations, station 5
which located on the Komenotsu River mouth was significantly affected by the river inflow, however, this effect on other four stations was relatively weaker. Simulation results in figure 2 showed the necessity of adding the rainfall precipitation effect into the model in rainy season. Precipitation data were treated as vertical velocity on surface ocean layer during the simulation period, surface salinity flux between ocean and atmosphere was calculated by equation (3).

\[ W_s = v_{fl} \times (S_A - S_{surf}) \]  \( (3) \)

where \( W_s \) is surface salinity flux, \( v_{fl} \) is the volume flux through water column surface and specified as surface layer velocity, \( S_A \) is atmosphere salinity and \( S_{surf} \) is ocean surface salinity.

Three rivers exist in the simulation domain, Kuma River and two B-class rivers, the Minamata River and Komenotsu River. There are no river discharge records for B-class river, therefore two B-class rivers’ discharge was set to a constant value of 70 m³ s⁻¹ and doubled if the rain rate was larger than 4 mm after calibration. Recorded daily discharge of A-class Kuma River was used in simulation. Surface salinity and temperature flux boundary condition for river inflows is shown in equation (4).

\[ \left( \frac{\partial S}{\partial A}, \frac{\partial T}{\partial A} \right) = \left( \frac{SR}{A}, \frac{TR}{A} \right) \]  \( (4) \)

where \( K_H \) is the vertical turbulent diffusivity coefficient, \( S \) is salinity, \( T \) is temperature, \( R \) is river discharge and \( A \) is grid area where the river locates.

2.3. Surface heat fluxes forcing

Field measurements for the heat fluxes are difficult and these values are generally parameterized by using the commonly available hydro-meteorological data. In the present simulation, surface heat fluxes consist of four major heat flux components and the net heat flux \( Q \) on ocean surface is represented by

\[ Q = Q_S - (Q_L + Q_{se} + Q_{la}) \]  \( (5) \)

where \( Q_S \) is the short wave solar radiation flux reaches on ocean surface, \( Q_L \) is the net long wave radiation which emitted from the ocean surface, \( Q_{se} \) is the sensible heat flux and \( Q_{la} \) is latent heat flux. Following Rosati and Miyakoda [7], a series of formulas have been adopted for the calculation of \( Q_S \), \( Q_L \) and \( Q_{la} \).

2.3.1. Short wave solar radiation flux

\[ Q_S = Q_T (1 - 0.62C + 0.0019\phi)(1 - \alpha) \]  \( (6) \)

\[ Q_T = Q_o \tau + \frac{[(1 - A_o)Q_o - Q_o \tau]}{2} \]  \( (7) \)

\[ Q_o = \frac{cosz \times D \times J_o}{a^2} \]  \( (8) \)

where \( Q_T \) is total solar radiation reaching on ocean surface under clear sky, \( C \) is fraction of cloud cover, \( \phi \) is solar noon altitude and \( \alpha \) is ocean surface albedo [8]. \( Q_o \) is solar radiation at top of atmosphere, \( \tau \) is atmospheric transmission coefficient and \( A_o \) is ozone absorption coefficient, \( z \) is zenith angle, \( D \) is daylight fraction, \( J_o \) is solar constant and \( a \) is the radius of earth.

2.3.2. Net long wave radiation flux

\[ Q_L = \varepsilon S_B T_s^4 (0.39 - 0.05E_v^{1/2})(1 - BC) + 4\varepsilon S_B T_s^4 (T_s - T_a) \]  \( (9) \)

where \( \varepsilon \) is ocean emissivity, \( S_B \) is the Stefan- Boltzmann constant, \( E_v \) is vapor pressure and computed by a polynomial approximation from Lowe [9], \( (1 - BC) \) is the cloudiness correction fraction and \( B \) is a latitude varying constant [10], \( T_s \) and \( T_a \) are temperature of ocean and atmosphere.
2.3.3. Latent heat flux

\[ Q_{Ld} = \rho_a L C_v V_w (E_O - r E_d)(0.622 / P) \]  

(10)

where \( \rho_a \) is air density, \( L \) is latent heat of vaporization of water, \( C_v \) is the turbulent exchange coefficient, \( V_w \) is the wind velocity, \( r \) is relative humidity, \( E_O \) and \( E_d \) are the saturation vapor pressure at ocean and atmosphere temperature. \( P \) is the surface air pressure.

2.3.4. Sensible heat flux

Gosnell et al [11] used theoretical models to calculate the sensible heat flux into ocean induced by precipitation. Fairall et al [12] analyzed the bulk variables related to air-sea fluxes and the algorithm was used in the Finite Volume Community Ocean Model (FVCOM) which coupled with the MM5 model [13] for the calculation of precipitation fields to drive simulation. To simulate the precipitation effect on the temperature field, sensible heat flux was separated into two parts in the new improved POM, heat conduction by turbulent transfer from ocean surface to the atmosphere and the cooling of precipitation.

\[ Q_{SE} = Q_{TU} + Q_P \]  

(11)

where \( Q_{TU} \) is the turbulent transfer heat flux calculated by

\[ Q_{TU} = \rho_a C_A V_w (T_S - T_A) \]  

(12)

where \( C_A \) is the specific heat capacity of air. \( Q_P \) is the sensible heat flux caused by precipitation, formulas are given as

\[ Q_P = -RC_w \beta (T_S - T_A)(I + B^{-1}) \]  

(13)

\[ \beta = (1 + (L_d/C_A \frac{dq_s}{dT}))^{-1} \]  

(14)

\[ B = \frac{C_A (T_S - T_A)}{L(q_O - q_A)} \]  

(15)

where \( R \) is rainfall rate, \( C_w \) is water heat capacity, \( \beta \) is the Clausius-Clapeyron wet bulb factor which uses the Clausius-Clapeyron relation for solving \( dq_s/dT \) [14]. \( d_c \) and \( d_b \) are diffusivities of water vapor and heat, \( B \) is bulk Bowen ratio, \( q_O \) and \( q_A \) are specific saturation humidity of ocean and atmosphere.

![Figure 3. Comparison of elevation for model verification at station 3.](image-url)
3. Results and discussion

3.1. Elevation verification
Simulated tidal elevation was used for the verification of model results. Due to the lack of actual measured data, Japan Meteorological Agency predicted elevation (minus the datum surface value) was adopted as the contrasted data. Based on the predicted location provided by the Meteorological Agency, simulated elevation of station 3 was chosen for comparison. As shown in figure 3, simulated elevation obtained from the tidal prediction method matched well with the official predicted data.

3.2. Surface Salinity simulation
Figure 4 shows the comparison of simulated and measured surface salinity during five times’ field observation and the simulation results of previous model were also presented. The new model was carried out with and without rainfall, separately. Under the circumstance of no precipitation, the new model had a slight decrease in the surface salinity simulation after amending the freshwater boundary condition. Two simulated data of the new model overlapped on July 7th because no rainfall happened. Simulation results showed significant improvement under the precipitation condition which caused 2-7 psu reduction of five stations’ salinity in comparison with the previous model, especially on the last two observation days. The abnormal simulated data of station 5 on July 7th was caused by the constant setting of river discharge which had obvious impact on the river mouse area, where station 5 located.

Figure 4. Comparison of simulated and measured salinity at five stations.  
Figure 5. Rainfall and simulated temporal variation of surface salinity at five stations.

Figure 5 shows the temporal variation of surface salinity and precipitation data during the simulation period. The salinity changing tendency of station 1, 2 and 3 basically kept consistent due to the relatively close position, all the three station were located in the Minamata Bay. In the mid-term simulation of station 3, slight difference was shown and this may be caused by the discharge of Minamata River, station 3 located near to the estuary boundary based on the research of Lou et al [15]. Simulation results of station 5 presented an apparent response to the discharge of Komenotsu River,
the special river mouth location kept surface salinity in a low level during the calibration phase. Five stations' surface salinity increased on July 15th because no rain happened.

3.3. Surface Temperature simulation
Comparison data of surface temperature at five observation points are shown in figure 6. The modification of heat flux module caused about 2-3 degrees increase of temperature. The promotion was more visible in the middle and late stage of simulation. Small error of station 5 was caused by lack of the accurate temperature boundary condition for river inflow. Precipitation impact to the surface temperature field is about 0.2 degrees, the small scale cooling was probably due to the daylight field observation when short wave solar radiation heat flux dominated, while the turbulent sensible heat flux is about an order of magnitude less than the latent heat flux and solar radiation flux. Figure 7 shows the temporally changing surface temperature and averaged solar radiation reaching on ocean surface of five stations. The increase and decrease of temperature roughly corresponded with the variation of radiation.

Figure 6. Comparison of simulated and measured temperature at five stations.

Figure 7. Average solar radiation on ocean surface and simulated temporal variation of surface temperature at five stations.

4. Conclusion
A new precipitation module has been constructed and added into the Princeton Ocean Model with modified heat flux forcing which varied temporally and spatially, several different simulations were carried out for comparing the precipitation effect to surface salinity and temperature. The addition of precipitation reduced the surface salinity of five observation stations in some extent and made the simulated results closer to measured data. Because of the special location of station 5, river discharge of B-class River was set to different values under the case of rainy and sunny day after calibration, while the discharge of Minamata River may have a small effect on the simulation of station 3. Compared with the previous constant heat boundary condition, new heat flux forcing can reproduced
surface temperature well and the numerical results showed good agreement with measured data. Although precipitation has a significant impact to the sensible heat, it is still a small magnitude comparing with the short wave solar radiation heat flux in daytime. This study indicates that the effect of precipitation on rainy season’s numerical simulation, especially for the salinity field, shouldn’t be neglected. The precision of simulation will be higher if a more accurate river inflow boundary condition could be provided. Further researches still need to be continued for optimizing the simulating environment of sediment and mercury transportation.

Acknowledgments
Changlu Zhou was financially supported by the China Scholarship Council 201608050022.

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