A PROCESS STUDY OF SUSPENDED SEDIMENT MATERIAL TRANSPORT IN THE ISHIKARI BAY

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プリンストンオーシャンモデル（The Princeton Ocean Model ; POM）に懸濁物質の輸送モデルを結合し、石狩湾における懸濁物質の輸送について調べた．その結果、以下のことが分かった．(1)湾の底面剪断応力は、浅海域の波によって支配されていた．(2)春季における石狩川からの土砂流出は、湾の懸濁物質の主な供給源である．石狩川から流出した細粒懸濁物質（FSM）は北方へ輸送され、浅海域から広がる．一方、粗粒懸濁物質（CSM）のほとんどがこの流出土砂のソースであることが確認された．(3)冬季における懸濁物質量は、波による堆積物の再懸濁量に依存する．FSMおよびCSMの高濃度が浅海域で観測されており、それらは南西方向へ輸送されてた．高濃度のFSMは、CMSフラックスより高いFSMフラックスを引き起こす．

Key Words: *Suspended sediment transport, The Princeton Ocean Model, settling velocity, Ishikari Bay*

1. INTRODUCTION

The transport of suspended sediment matters (SSM) in coastal is important to the marine environment, since many contaminants are transported in an absorbed state[1)]. There are essentially two physical processes that control sediment transport in coastal oceans. The first one is advection which transports suspended sediment materials away from the input sources such as rivers. The other process is sediment resuspension at the sea bottom that provided sediment fluxes into the water column. This vertical sediment transport is controlled by sediment settling and vertical motion of the water particles. It is also governed by vertical diffusivity generated by the turbulence in the boundary layers where shear velocity is strong due to the presence of skin friction. Wave current interaction further enhances the bottom resuspension in the bottom boundary layer (BBL), and can play an important role in the sediment transport in shallow waters.

Yamashita et al.[2)] reported that sediment discharged from the Ishikari River is transported, deposited in a wide area not only by the nearshore current, but also by the strong wind driven current and ocean current outside the breaker zone in the Ishikari Bay. Shimizu et al.[3)] showed that about 80% of the annual sediment discharged from the Ishikari River occurs in the snowmelt season when the direction of current in the Ishikari Bay is dominated to northward[2)]. In winter, sediment is resuspended from the seabed under high wave events. Then, it is transported and redistributed by current induced by wind in the bay. However, the spatial and temporal variations of suspended sediment concentration and flux under different hydrodynamic conditions in the bay have never been reported. The general objective of this paper is to simulate the SSM concentration and flux in the Ishikari Bay considering the above two sediment sources: river source and resuspension from the sea bottom.

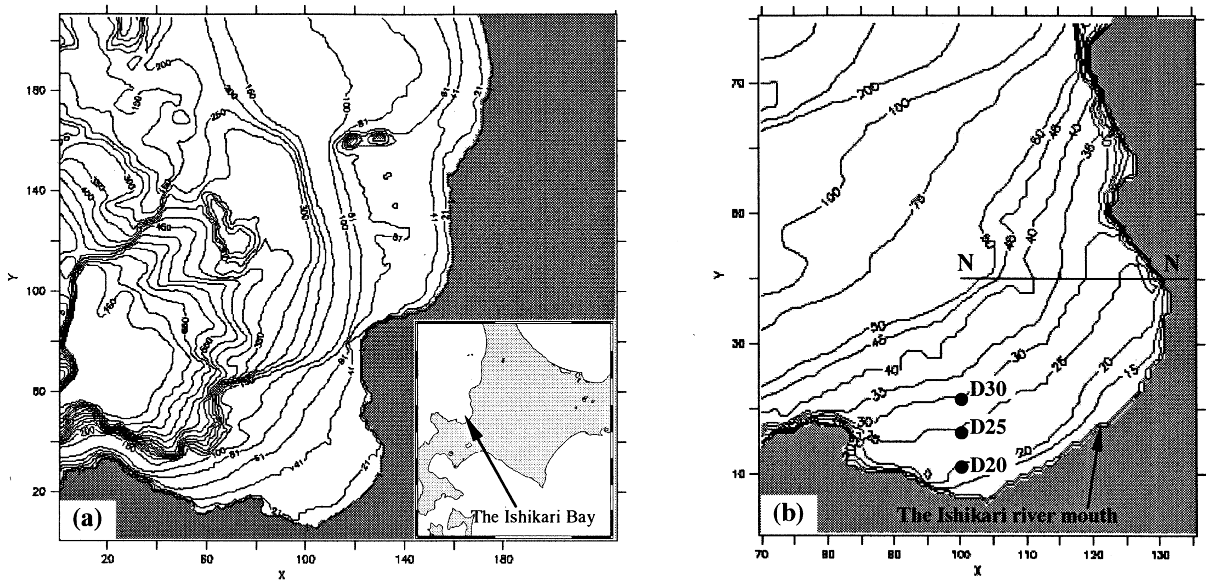

Fig. 1 (a) The hydrodynamic model domain for the Ishiakibay and (b) The inner region of the bay where suspended sediment transport is examined

2. THE MODEL SYSTEM

The study is based on a numerical model system which couples a three-dimensional sediment transport model and a bottom boundary layer (BBL) model into POM. They are briefly described as following.

(1) The sediment transport model

The Princeton Ocean Model (POM) has been presented in detailed in some where else[4]. This section will present the modifications made to include the computation of suspended sediment in POM. The governing equation for suspended sediment transport in sigma coordinate is:

$$\frac{\partial CD}{\partial t}+\frac{\partial CUD}{\partial x}+\frac{\partial CVD}{\partial y}+\frac{\partial C(w-w_s)}{\partial \sigma}=\frac{\partial}{\partial \sigma}\left[\frac{K_H}{D}\frac{\partial C}{\partial \sigma}\right]+\frac{\partial}{\partial x}(K_x H\frac{\partial C}{\partial x})+\frac{\partial}{\partial y}(K_y H\frac{\partial C}{\partial y}) \quad (1)$$

where C is the concentration of the suspended sedimentary material, U, V and w are current velocities in x, y and σ direction respectively, w_s is settling velocity (downward direction) of the considered sediment type; H is the bottom depth; D is total depth; and K_x, K_y, K_H are diffusion coefficients. Here we set K_x=K_y=A_h, where A_h is horizontal eddy diffusivity used in POM. The value of K_H is assumed to be equal to that of heat and salt and computed in POM.

Settling velocities for suspended sediment depend upon many factors such as particle size, shape, composition, ability to aggregate, and the physical environment. Here, the simple formula known as Stokes law is used to determine w_s.

Deposition or resuspension processes are taken into account by the bottom boundary condition.

$$-C w_s-\frac{K_H}{D}\frac{\partial C}{\partial \sigma}=Q_b \quad at\, \sigma=-1 \quad (2)$$

where Q_b is the sediment flux from the bottom describing the quantity of suspension or deposition. The sediment flux depends on the total skin shear stress τ_s and sediment properties and can be formulated as:

$$\begin{aligned} Q_b &= \frac{\tau_s-\tau_d}{\tau_d}(w_s C)_{bottom} && \tau_s \le \tau_d \\ Q_b &= 0 && \tau_d < \tau_s < \tau_e \quad (3) \\ Q_b &= E\frac{\tau_s-\tau_e}{\tau_e} && \tau_s \ge \tau_e \end{aligned}$$

where E is the erosion constant, τ_d and τ_e is the critical shear stress for deposition and resuspension, respectively. Reported values of E, τ_d, and τ_e vary over a significantly wide range due to the site-specific character of sediments. In the absence of both field and laboratory experiments on the deposition and erosion parameters of the sediment in the Ishikari Bay, the values shown in Table 1 were used in this study. These values are in the middle class of the range listed in the literature.

Surface boundary condition:

$$-C w_s-\frac{K_H}{D}\frac{\partial C}{\partial \sigma}=Q_s \quad at\, \sigma=0 \quad (4)$$

where Q_s is sediment flux from the sea surface computed by using the sediment discharge from the Ishikari River.

(2) Bottom boundary layer model

As shown in the sediment transport model, in order to estimate the amount of erosion or deposition the shear stress on the seabed need to be known. In the shallow region of the Ishikari Bay this shear stress is the result of the wave-current interaction within the BBL layer. The BBL process is usually not resolved in the circulation model because of too coarse resolution in the vertical direction. Therefore, a specific boundary layer model component has been introduced which involves the interactions between waves, currents and seabed properties. The current induced bottom shear stress is calculated using current velocity from the near bottom layer in the circulation model.

Wave-current interaction in this study is solved following the well known concept introduced by Grant and Madsen (1979)[5]. The total bottom shear stress caused by currents and waves is defined by:

$$\tau_{cw} = \rho u_{*cw}^{2} = \rho(u_{*c}^{2} + u_{*w}^{2}) \qquad (5)$$

in which ρ is the sea water density, u_{*c} is the bottom shear velocity caused by currents, u_{*w} is bottom shear velocity caused by waves.

The total bed shear stress consists of two components: skin friction shear stress, corresponding to the force acting on the individual grains, and form drag, which is generated by larger structures of the seabed. The skin friction shear stress controlling resuspension and deposition is the relevant component for the sediment transport and can be computed by:

$$\tau_{s} = \rho u_{*s}^{2} = \rho(u_{*sc}^{2} + u_{*sw}^{2}) \qquad (6)$$

where u_{*sc} is current skin friction velocity, u_{*sw} is wave skin friction velocity.

To solve for the stresses in the above equations the method introduced Kuhrts et al.[6] is used in this study. In this theory, the bottom shear stresses not only depend on wave and current conditions but also the roughness of the sea bottom. We use the data shown in Fig. 2 to determine the roughness of the seabed in the inner of Ishikari Bay.

3. MODEL SIMULATION

The model domain and setting used in this study are the same as those used by Le et al.[7] shown in Fig.1. In this paper, it has been concluded that the wind stress is the major driving force for winter current pattern in the inner of the Ishikari Bay, the far field effect through open boundary can be neglected[7]. In spring and summer when the river discharge is high, the density driven current should be taken into account. Therefore, both wind stress and Ishikari River discharge are used to force the circulation model in this study.

The source for SSM in the Ishikari Bay is either from the river or resuspension from the seabed or a combination of them. Thus, for the computation of SSM transport, the following numerical process experiments will be formulated: (1) Spreading of SSM from the Ishikari River mouth under a typical spring wind event (2) Resuspension and transport of suspended sediment from seabed under a combination of wave and a dominated wind event in winter and (3) repeating the experiment 1 by adding spring wave event. In each experiment two types of sediment are considered: fine sediment matters (FSM) and coarse sediment matters (CSM). Their sedimentological characteristics are listed in Table 1. The analysis of sediment transport results will be only done for the inner region of the Ishikari Bay shown in Fig.1b.

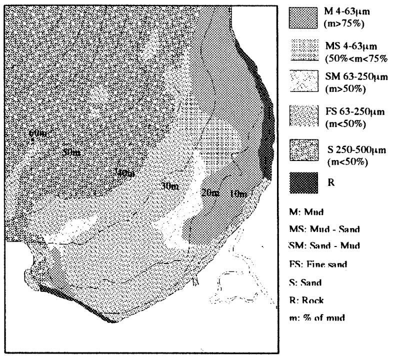

Fig.2 Distribution of sediment types in the inner Ishikari Bay

The formulations of the open boundaries for current velocities are the same as shown in Le et al.[7]. An advection scheme is used for temperature and salinity. For the sediment concentration, a zero concentration value is used at the western boundary, no gradient scheme is used at the northern boundary and a zero flux condition is applied at close boundaries.

The initial conditions for temperature and salinity were derived from seasonal climatology data in 2001. All other variables were initialized from the rest.

To start simulation of sediment transport model, some important parameters are needed to be determined and they are shown in Table 1.

Table 1 Sediment types and parameters

Sediment type	d_{50} (μm)	E $(kg/m^2/s)$	w_s (m/s)	τ_d (N/m^2)	τ_e (N/m^2)
FSM	35	5×10^{-5}	5×10^{-5}	0.06	0.20
CSM	125	5×10^{-5}	4×10^{-4}	0.08	0.20

* *d_{50} is the median diameter of suspended sediment*

(1) Spreading of material from river mouth

This experiment considers how different types of materials are distributed in the Ishikari Bay from a point source which is continuously supplied with constant rates of sediment. We study the transport pattern of two types of materials: FSM and CSM. The effect of wave on sediment transport is switched off. An idealized wind event with southeast direction, that is the dominant wind in spring, and seasonal river flux of 1000m^3/s in spring are used to drive current pattern in the bay. It is noted that, wind velocity is not uniform in the bay because the effect

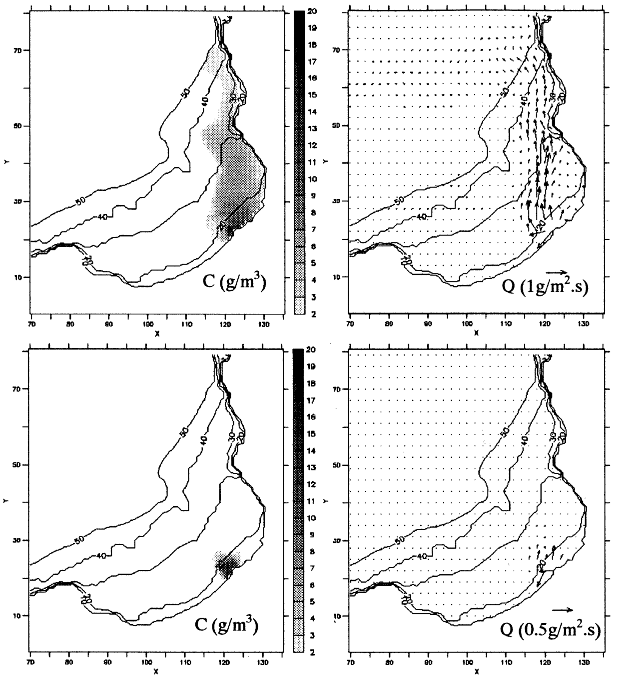

Fig. 3 Simulated depth averaged sediment concentrations and fluxes for FSM (top) and CSM (bottom) at day 30

of the Shakotan peninsula. Wind is usually stronger in offshore and weaker nearshore. Therefore, in this experiment a steady but non-uniform wind event that occurred in May 25 2003 is used to take into account the spatial variation of wind in the bay. Wind velocity in offshore at this time is about 9m/s.

The hydrodynamic model is run continuously for 10 days, and then sediment discharge from river is added. The results of current pattern can be characterized by Ekman transport in the deep region and topographic guided in the shallow area of the model domain (not shown). The simulated skin friction shear stress in this experiment is relatively small (not shown) and it does not exceed a maximum value of $0.01N/m^2$. It means that the contribution of current to skin friction stress is too weak to resuspend bottom sediments.

According to Shimizu et al.[3], the annual sediment discharge from the Ishikari River is about 0.8 million m^3, 80% of which is reported to occur in the snowmelt season. Therefore, the net sediment flux at sea surface in spring can be computed with a value of $Q_s=48x10^{-6}kg/m^2/s$. This flux is presented at four coastal grid cells. It was also found that 62% of sediment from the Ishikari River is fine grained sediment with grain size less than 75μm, and the remaining is for coarse sediment[2].

Next, the vertically integrated sediment concentrations and fluxes for FSM and CSM are considered. Their values at the end of day 30 are shown in Fig.3. Owning to a faster settling velocity, the CSM was mostly confined to the sediment source. The value of CSM concentration and flux are high near the river mouth and they rapidly

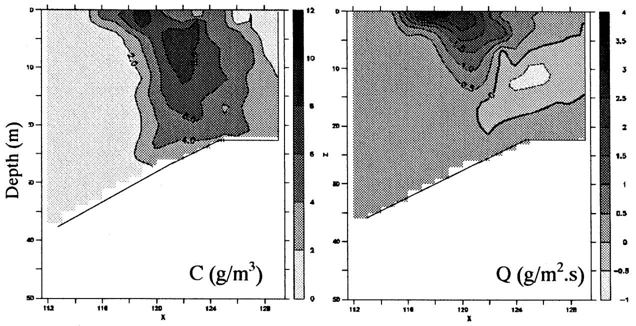

Fig. 4 Vertical distribution of sediment concentration and flux for FSM at cross section N-N at day 30

diminish in surrounding area. For FSM, due to the strong northward surface current velocity and small settling velocity, northward transport of FSM was evident near Ishikari coast. The concentration and flux of FSM are extended in northern direction beyond the shallow area of the bay. The spreading of FSM in east-west direction is also significant to a water depth of 30m or more.

The vertical structures of sediment concentrations and fluxes for FSM at section N-N, which is about 15km northward from Ishikari River mouth, are shown in Fig.4. High FSM concentration was observed at the surface near the shore. The FSM concentration gradually decreases in the subsurface layers. This pattern is a vertical display of a slowly sinking of sediment supplied to water column from the sea surface. Since the sediment flux is the production of horizontal velocity and sediment concentration, high surface FSM concentration leads to high sediment flux at the surface of section N-N. Moreover, at cross section N-N the sediment flux is in northward direction in almost the whole section. This is the resultant of the one layer flow occurred at this cross section under the above wind condition. Both the concentration and flux of CSM at the N-N cross section are negligible, and they are not shown here.

(2) Resuspension under uniform wave in winter

In this experiment, hydrodynamic condition in the Ishikari Bay is driven by an ideal northwest wind event that is the typical storm wind in winter. Similar to experiment 1, we take into account for the spatial variation of wind characteristic, thus, the wind event that occurred in March 13 2003 is used as steady wind in this experiment. Wind velocity during this storm in the offshore reaches more than 13m/s. The winter river discharge is rather small (less than $300m^3/s$) and it is neglected

Wave is usually high in winter, especially in storm condition. Wave events with a significant height of 3m or more and period of 7 second were observed about three to four times in normal years in the winter. The above uniform wave is applied for entitle area of the model domain. The hydrodynamic model is run continuously for 20 days; wave forcing is

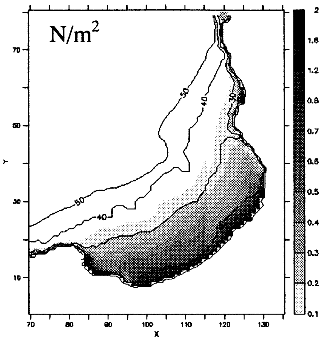

Fig. 5 Simulated bottom skin stress by wave-current interaction

added from day 11. The same wave condition remains for 1 day and it is stopped from day 12. The surface sediment flux from the Ishikari River in winter is so small that can be neglected in this experiment. Thus, sediment source in this experiment is purely by resuspesion from the seabed.

Similar to the first experiment, the contribution of current to bottom shear stress is very limited. However, the simulated bottom skin friction shear stress is significantly high during the times with the presence of wave (day 11) as shown in Fig.5. High shear stresses are found in shallow areas near the coast and its magnitude decreases significantly with increasing depth. The maximum value of skin friction shear stress reaches to $2N/m^2$ in the most shallow waters. With the critical erosion shear stress of $0.2N/m^2$, the depth at which erosion occurs is less than 30m. An important feature should be noted is that at the same depth, the shear stress in the northeast part of the bay is smaller than in the southwest area. For example, with the above wave condition, skin friction shear stresses at 30m depth are about 0.1 and $0.2N/m^2$ in the northeast and southwest areas, respectively. This is the result of the finer seabed material located in the northeast area shown in Fig. 2. Therefore, it is expected that the erosion rate in the former area is less than in the later.

Fig. 6 is the vertical average of sediment concentrations and fluxes for FSM and CSM at the end of the wave event (day 11). High concentrations are observed for both FSM and CSM under wave resuspension. The concentrations of both FSM and CSM are higher in nearshore and rapidly decrease in offshore direction. Under the wind condition mentioned previously, the current pattern in the inner of the Ishikari Bay has southwest direction (not shown). This characteristic of the current was also mentioned in Yamashita et al.[2] and Le et al.[7]. As the sediment flux is the production of SSM concentration and current velocity, the sediment fluxes are also in the southwest direction. A high FSM concentration in water column has led to a stronger FSM flux than that of CSM (Fig. 6). Moreover, the simulated SSM concentrations in this experiment are about one order higher than that in

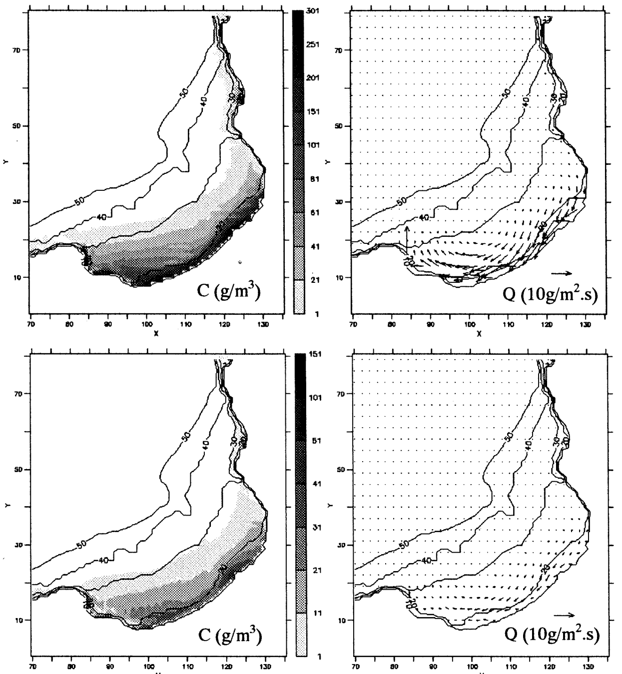

Fig. 6 Simulated depth averaged sediment concentrations and fluxes for FSM (top) and CSM (bottom) at day 11

experiment 1. This result shows the seasonal variation of SSM concentration in the bay: the concentration is higher in winter than in spring.

After the wave event stopped, the sediment concentrations and fluxes gradually decrease. CSM stays in water column for a short time period (about 2 days). On the other hand, the FSM remains for longer time (about 6 days).

Fig. 7 shows the vertical distributions of sediment concentrations for FSM and CSM at day 11 at locations D20, D25, D30 (see Fig. 1). The sediment concentrations decrease from bottom layer to top layer. The variation of sediment concentrations in vertical direction is more significant in nearshore than in the offshore. Fig. 7 again shows a strong variation of suspended sediment concentration in the horizontal direction from onshore to offshore. In addition, at the

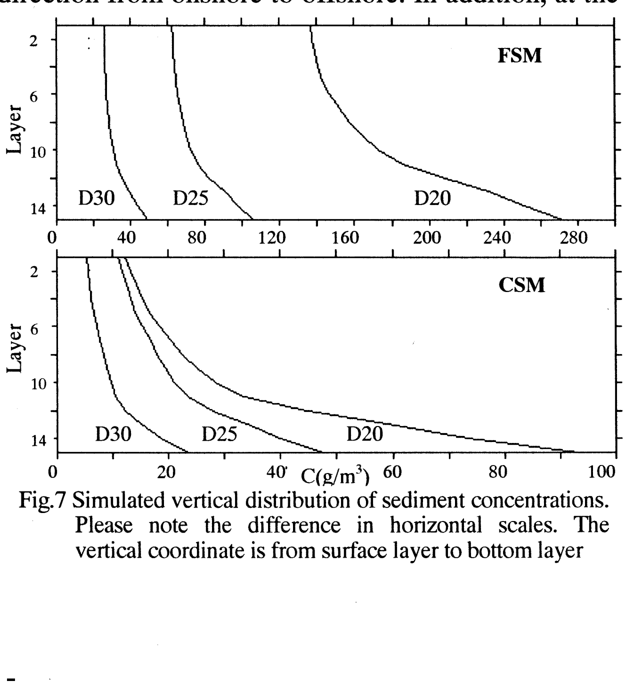

Fig.7 Simulated vertical distribution of sediment concentrations. Please note the difference in horizontal scales. The vertical coordinate is from surface layer to bottom layer

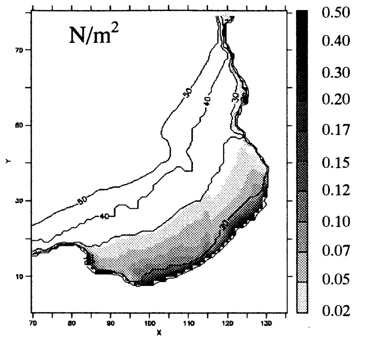

Fig. 8 Simulated bottom skin shear stress in experiment 3

same location the concentration of FSM is much higher than that of CSM.

(3) River sediment discharge and spring wave

In this experiment we extend the experiment 1 by adding a spring wave event to include the sediment resuspension. A typical wave with significant wave height of 1.5m and period of 6s is used. Wave effect is added to the hydrodynamic model from day 30 and it is stopped after 1 day. Fig. 8 shows bottom skin friction shear stress in the inner Ishikari Bay in this experiment at the end of day 30. The depth at which the bottom skin shear stress is greater than critical shear stress for resupension ($0.2N/m^2$) is less than 20m. Thus, the erosion process can only occur in a very limited area of the bay.

The depth averaged sediment concentration and flux for FSM are shown in Fig. 9. It can be seen from this figure that the sediment transport in this experiment is dominated by sediment discharged from the Ishikari River. Fig. 9 is similar to Fig. 3, however, due to the wave resuspension, sediment concentration and flux along the coast is fairly high. For a more quantitative assessment of the effect of the wave resuspesion to sediment transport, the total flux of FSM at cross section N-N in experiment 3 is compared with those of experiment 1. The value for each experiment is 81 and 75kg/s, respectively. Roughly, sediment flux increase 8 percent due to the wave resuspension. The sediment concentration and flux of CSM are not shown because there is no significant difference of the results in this experiment with those in experiment 1 presented in Fig. 3.

4. CONCLUSIONS

The present paper couple sediment transport and bottom boundary layer models into the Princeton Ocean Model to study the dynamic of suspended sediment transport in the inner of Ishikari Bay. The results of three numerical experiments presented and discussed in Section 3 can be summarized as follows:

(1) The bottom shear stress in the study area is dominated by the wave contribution in the shallow area; the contribution of current is very limited.

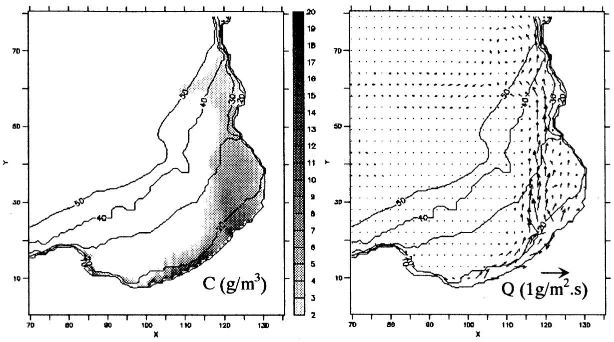

Fig. 9 Simulated depth averaged sediment concentration and flux for FSM at day 30 in experiment 3

(2) In spring when wave height is low, the sediment discharged from the Ishikari River is the primary source for sediment transport in the bay. Under the southeast wind condition, the FSM from the Ishikari Bay is transported in northward direction and spreads out of the shallow area. For CSM, owning to a larger settling velocity, the CSM was mostly confined to the sediment source.

(3) In winter, suspended sediment transport is dominated by wave resuspension. High concentrations are observed for both FSM and CSM in water depth less than 30m. Under northwest wind condition, that is the dominated wind in winter, both FSM and CSM are transported in southwest direction. A higher FSM concentration in water column has led to a stronger FSM flux than that of CSM.

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