CHARACTERISTICS OF WINTER CURRENT PATTERN IN THE ISHIKARI BAY

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The winter current pattern in 2003 in the Ishikari Bay was investigated by using the Princeton Ocean Model (POM) and field observation data. The model was forced by six hour, spatially distributed wind and open boundary forcing. The later was obtained from larger scale model namely Japan Coastal Ocean Predictability Experiment (JCOPE). Through three numerical experiments with different driving forces the following conclusions have been deduced: (1) the open boundary forcing is the major driving force for current in deep water, the effect of wind in this region is limited in few surface layers (2) the flow along the shelf and current in shallow region are mainly driven by wind forcing (3) circulations occur in the shallow area during strong wind conditions. A comparison between observed and computed current velocities showed that the model is capable to reproduce current pattern in the bay.

Key Words: *Wind forcing, open boundary condition, circulation, POM, Ishikari Bay*

1. INTRODUCTION

The Ishikari Bay is an open coast located in western Hokkaido, in the Japan Sea. The location and topographic characteristics of the bay are shown in Fig.1. The current characteristics in the bay have been studied by some researchers. Yamashita et al. found that wind was an important driving force to generate current in the bay in both winter[1)] and summer[2)]. Wang et al. mentioned sea current as another contribution to current pattern in the bay[3)]. However, in these papers, the roles of wind and sea currents were evaluated very qualitatively; and they could not show the current pattern in the bay in detail. Thus, for a more quantitative and comprehensive understanding of the current pattern in the bay a numerical approach is still needed. The goal of this paper is to investigate the current features in the Ishikari Bay in the winter 2003 by using the Princeton Ocean Model (POM). Observed current velocity at one station in shallow region of the bay is also used to evaluate the model performance.

The paper has following structure: In section 2 general characteristic of wind in study area and a description of observation current velocity are presented. Model configuration, initialization and formulation are described in section 3. In section 4, the results of simulations are presented and analyzed. Section 5 is a summary of the outcomes of this study.

2. WIND AND CURRENT CHARACTERS

(1) Wind characteristics

Six hour interval wind velocity was obtained from Japan Meteorological Agency (JMA) data with about 10x10km resolution in horizontal directions. This was not observed data but the simulated results by JMA's wind model. The wind speed was usually stronger in offshore and weaker near the coast. In the winter, wind was strong and chaotic. For use in

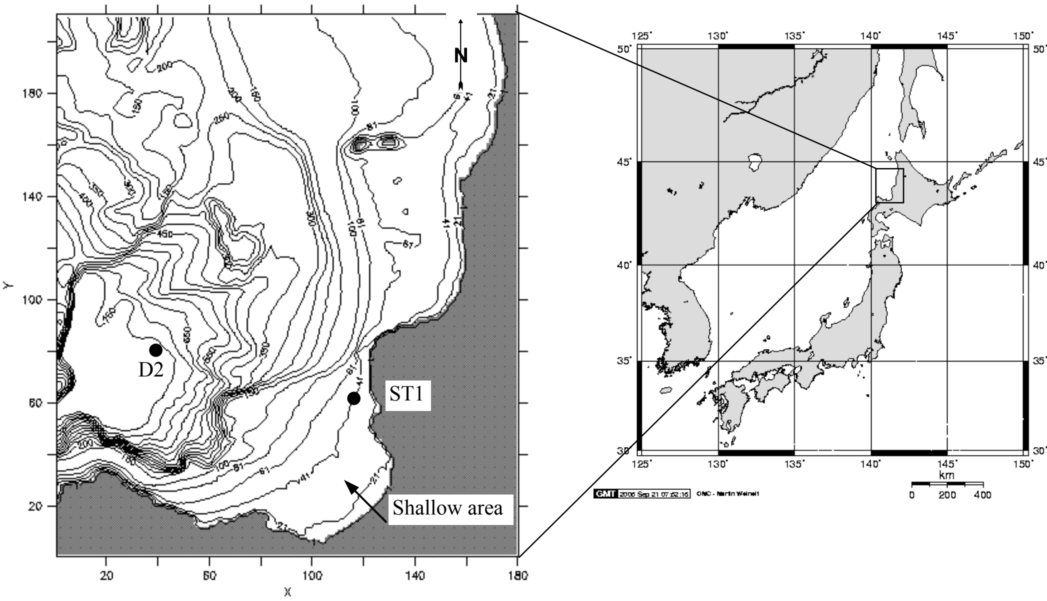

Fig.1 The location of the Ishikari Bay and the bathymetry of the region, contour interval is 20m for the depth less than 100m and 50m for the deeper areas

our computation, wind data was then interpolated into each grid point of the model domain.

(2) Current observation

The location of current velocity observation station (ST1) is shown in Fig.1. The station is in shallow water at 40m depth. Instrument used to observe velocity was Acoustic Doppler Current Profiler (ADCP) mounted in a downward looking configuration. The period of mooring was from Feb 4^{th} to Mar 18^{th} 2003. The ADCP was set up to measure in 1m depth bins and returned good data in the depth range from 3 to 30m. The measurement interval was 20 minutes. The quality of the ADCP data in the upper layers was not good, thus, these data can not be used for analysis. It was found that the current velocity at the observation station was mostly characterized by one layer flow (not shown).

The hourly vertical average of observation current velocity at ST1 during mooring period is presented in Fig.2 along with wind velocity at the same location. The correlation between wind and current velocity is obvious. The higher wind velocity, the stronger current occurs and vice versa. There is only one exception in the period of 4^{th} to 9^{th} Feb, the time that wind was weak but observed current was quite large.

3. MODEL FORMULATION

The Princeton Ocean Model (POM) has been presented in detailed in some where else[4),5)]. It will not be repeated here. This section will briefly describes the model configuration, initialization and treatment of open boundaries

(1) Model configuration and initialization

The POM was configured in a domain shown in Fig.1. The model domain was from $140^{o}20'$ to $141^{o}50'$ in longitude and from $43^{o}06'$ to $44^{o}51'$ in latitude (approximately 120kmx200km). The actual bottom topographic data was taken from the Marine Information Research Center, Japan Hydrographic Association. The horizontal grid scales were both in 30 seconds. Thus, the model consisted of 180x210 grid points in x and y direction, respectively. There were 16 levels in the vertical with finer resolution (log distribution) near the surface and bottom layers.

The simulation period in this study was from January 20^{th} 2003 to the end of March. This period was chosen since the wind speed was rather strong and the discharge from Ishikari River to the bay was relaxed with an average of $300m^3/s$, thus, we neglected the affect of the river flux. The average temperature and salinity in winter, 2003 obtained from JCOPE data were used to initialize model and kept constant throughout simulation period.

(2) Open boundary conditions

The model domain has two open boundaries in the western and northern sides. For external mode, the vertical average velocity component normal to open boundary was estimated by Flather scheme[6)]. For the tangential component of the external velocity and surface water elevation, a gravity wave radiation condition is used[7)]. The formulation of boundary condition for internal mode we apply the Orlanski method in implicit form[7)].

The present model uses data from the larger scale model (JCOPE data) for implementation of the open boundary conditions. The JCOPE data is the simulated results by POM model from larger scale area. This model has a horizontal resolution of 5

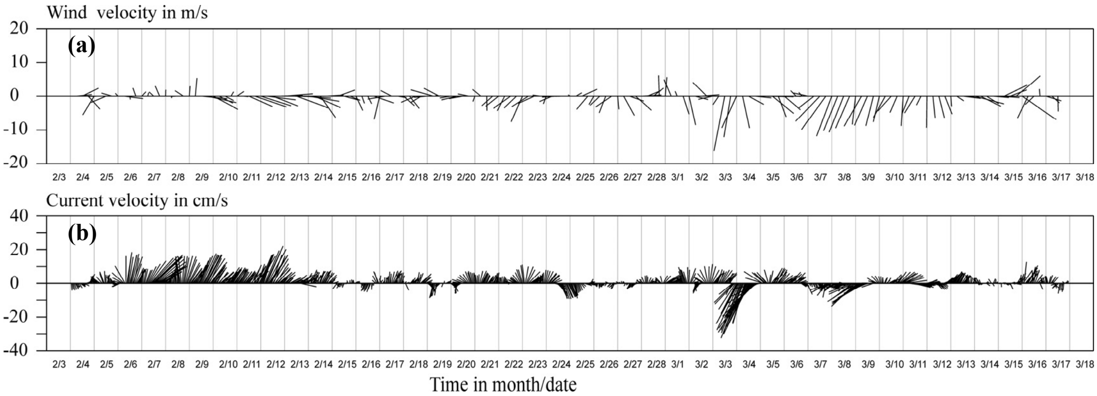

Fig.2 Time series of wind velocity **(a)** and observed current velocity **(b)**. The northward components are plotted along the ordinate as a positive, and the eastward components are plotted from its time origin in the positive direction along abscissa

minutes and 45 vertical sigma levels. The model is driven by wind stresses, and heat and salt fluxes. The data includes sea surface water level, and 45 layer horizontal fluxes, temperature and salinity. All of them are in 48 hour averaged interval.

(3) Model formulation

As presented in section 2 that wind has significant effect on current pattern at the observation station. Moreover, the Ishikari Bay is an open coast thus the far field effect through open boundary may be important. To examine the influence of these forces on the current pattern in the Ishikari Bay, three simulations were tested. In the first experiment, the model was run under open boundary forcing only. The second experiment used the wind stress as the unique driving force. The last experiment combined both wind forcing and open boundary forcing. It is noted that the JCOPE results used in this experiment included the current induced by wind forcing. However, it is assumed that the sea state at the open boundary is governed mainly by phenomena that happen outside the study area; the effect of local wind in the Ishikari Bay to the open boundary is neglected. All experiments were initialized from the rest and the results in the first 10 days were not used for analysis.

4. MODEL SIMULATION RESULTS

The results from experiment 1 showed that the direction of the current pattern in this case is nearly steady throughout simulation period; however its magnitude slightly changes with time. Moreover, the structures of the current patterns in all vertical layers are very similar. Fig.3 presents the time average in the whole simulation period of the vertically integrated horizontal current pattern from this test.

Fig.3 shows that the inflow comes from the lower part of the western boundary and it is separated into two branches. The first one flows in counterclockwise around the deep region and advects

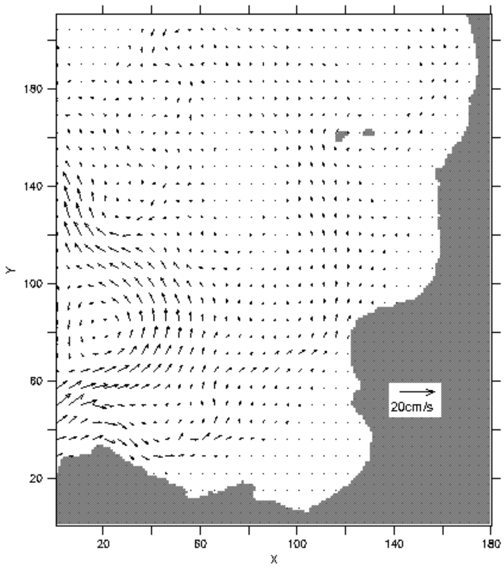

Fig.3 Time average of simulated vertically integrated horizontal current under open boundary forcing only

out of the model domain in the middle part of western boundary. The second branch which has smaller magnitude flows along the shelf and advects out of the domain at the northern boundary. The existence of the first branch in this simulation is consistent with JCOPE model result (not shown). The second branch is not clear in JCOPE model because of too coarse resolution used in this model. The current in the inner shallow region of the bay is very small; the average current at ST1 is 1cm/s in the simulation period. It is about ten times smaller compared with the current magnitude in the deep region. It can be concluded that the open boundary forcing has limited influence in current pattern in the shallow part of Ishikari Bay.

Results from experiment 2 showed three significant features for depth averaged current velocities in the bay. The first one is that the current velocity in the deep region is weak in the whole simulation period. Second feature is the occurrence of current in the shallow area of the Ishikari Bay. And lastly both the velocity and direction of currents along the shelf and in the shallow region varies corresponding to wind conditions. The results

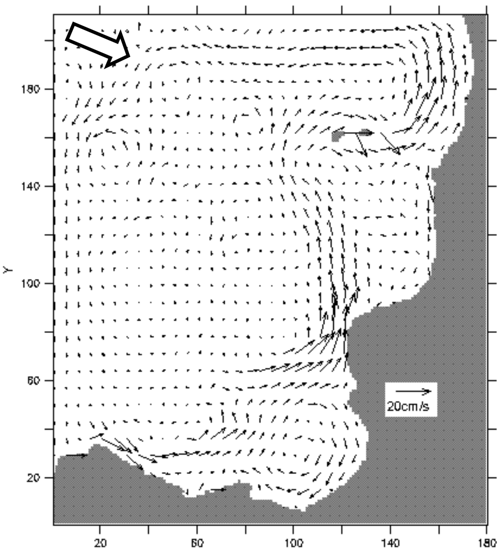

Fig.4 Simulated vertical average horizontal current pattern at 24^{h} Feb 13^{th} 2003 in experiment 2. Wind direction is indicated by block arrow in the top of the figure

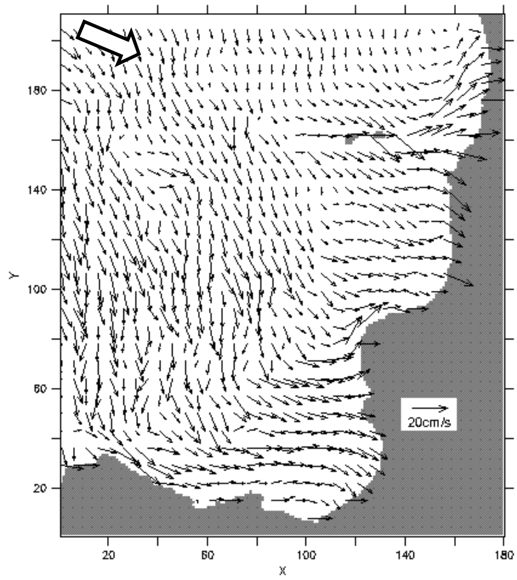

Fig.5 Simulated surface (σ=-0.021) current velocity at 24^{h} Feb 13^{th} 2003 in experiment 2. Wind direction is indicated by block arrow in the top of the figure

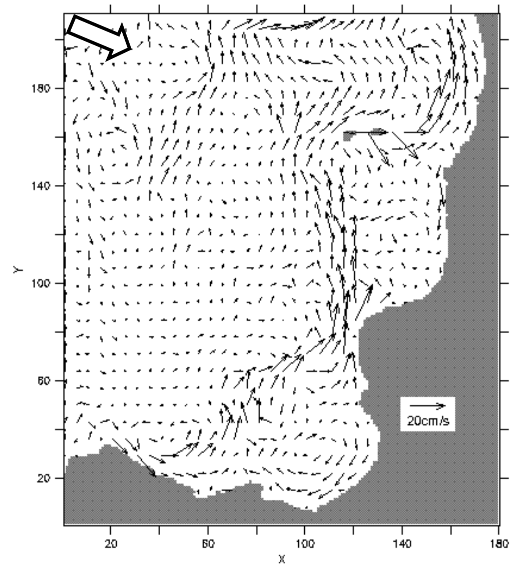

Fig.6 Simulated current velocity at 8^{th} layer (σ=-0.50). Time and wind condition are same as Fig.5

also showed that the vertical distribution of horizontal velocities in the deep and the shallow regions is quite different. While the current velocity focuses in the surface layers in the deep region, the flow presents in all layers in the shallow area.

Fig.4 is the vertically integrated horizontal velocity at 24^{h} Feb 13^{th} 2003 from this experiment. The current pattern at this time is an illustration of response of the bay under strong wind in WNW direction (see Fig.2). It can be seen from Fig.4 that the flow along the shelf is strong and has northward direction. A circulation with clockwise direction exists in the shallow area during this period and its velocity is weaker than the flow along the shelf. The occurrence of a circulation flow in shallow area in this figure is the resultant of the strong E-W wind component when it approaches the shore orthogonally from west to east.

Further considering of the depth averaged current velocities at other times with different wind conditions shows that the current velocity along the shelf is always larger than that in the shallow region. Moreover, both the direction and magnitude of the flow along the shelf and circulation in the shallow area depend on the wind conditions. The occurrence of circulation in the shallow area under strong wind conditions is consistent with the result of Wang et al. (2004)[3)] but in more detail.

For further understanding of current pattern in responding to wind forcing, the vertical distribution of horizontal current velocity is considered. The common structure found in the simulation period is that: in the deep region, the surface current velocity is strong and it decreases rapidly in the lower layers due to the Ekman effect (Fig 5, 6 and Fig.7a, b); in the shallow region, the flow exists in all layers because of topographic and close boundary effects (Fig.5, 6 and Fig.7c, d, e). In addition, a comparison between the current velocities in each layer at any given times showed that both current direction and its magnitude doesn't change much from the 6^{th} layer to the bottom layer (Fig.7d, e). This finding is in agreement with the observed ADCP current velocity at station ST1 discussed in section 2.

The last experiment is implemented by coupling between open boundary and wind forcing. The significant features of hydrodynamic condition in this experiment can be distinguished into two different regions. In the deep region the current pattern is mainly driven by open boundary forcing, the effect of wind is limited in the three surface layers, even though in very strong wind conditions. Along the shelf and in shallow region of Ishikary bay the flow is mainly governed by wind conditions.

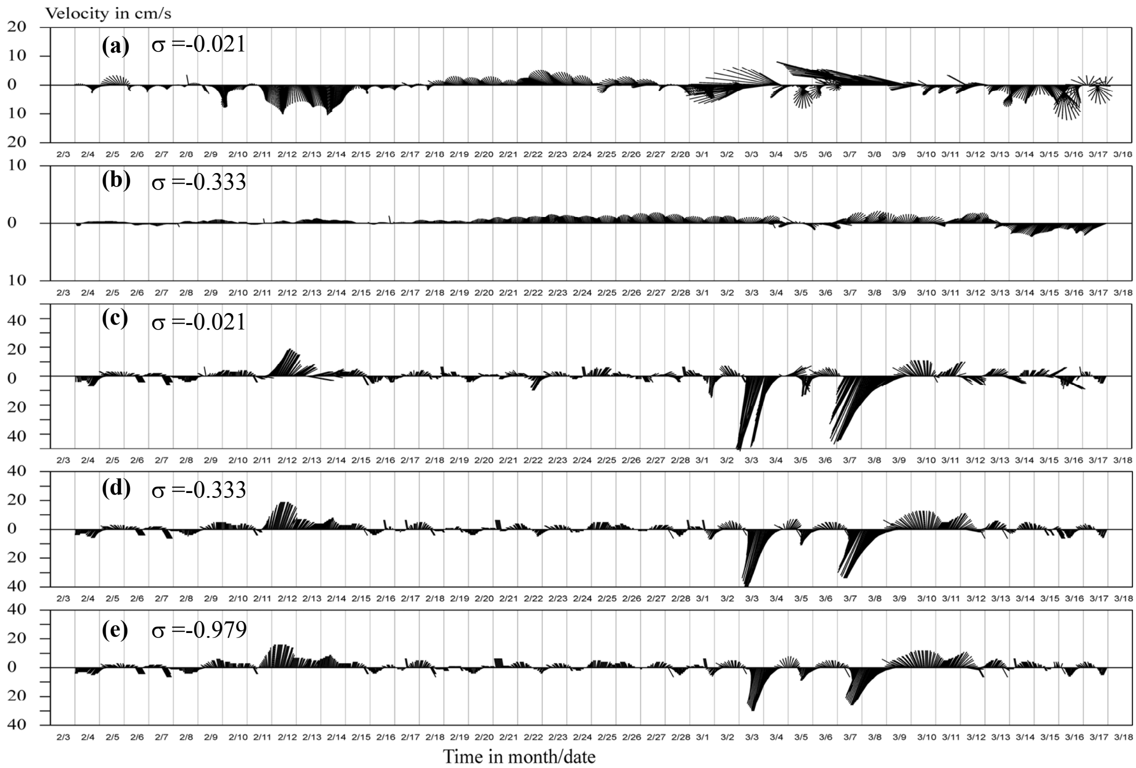

Fig.7 24h moving average current velocity at D2 at surface (a) and 6th layer (b). Hourly average current velocity at ST1 at surface (c), 6th layer (d) and 15th layer (e). The D2 is at 750m depth with the location shown in Fig.1. Please note the vertical scales

The simulated current velocity structures along the shelf and in the shallow area in this experiment are very similar with those in experiment 2. Fig.8 is an example of the vertical average current pattern in this experiment at the time indicated in Fig.4. As can be seen in Fig.8 that the current in the deep area is similar with those shown in Fig.3 and the current along the shelf and in the shallow region is similar with the current structure shown in Fig.4.

Next, the simulated current velocity at ST1 in experiment 3 is compared with observation data. As mentioned in section 2, there was problem with observed surface current velocity at ST1. Thus, only data from middle to bottom layer are considered here. Moreover, as indicated previously, both the observed and simulated current velocities in the shallow area are almost vertically uniform. Thus, the hourly vertical average time series of computed current velocity at station ST1 from the 5th layer to the 13th layer (about 3 to 30m from bottom) during the mooring period is plotted along with those of the observation in the equivalent depth range in Fig.9. The agreement between observed and simulated current velocity is obvious. The strong current velocity in both observed and simulated time series occurs at the times of strong wind conditions. To quantify the relation between observed and computed current velocities, the complex correlation coefficient, ρ, and angular displacement, θ, are used[8)]. The optimal value of ρ is unity and θ is zero, respectively. Excluding the data from the initial to the end of 9th Feb 2003, the values of these parameters were found with ρ=0.51 and θ=34°. A small value of θ and fairly high value of ρ means that in overall, both the direction and magnitude of current velocities are reproduced by the model. In addition, if only strong wind periods are considered, the results of these parameter are ρ=0.65 and θ=36°. The model gives a better performance in strong wind conditions.

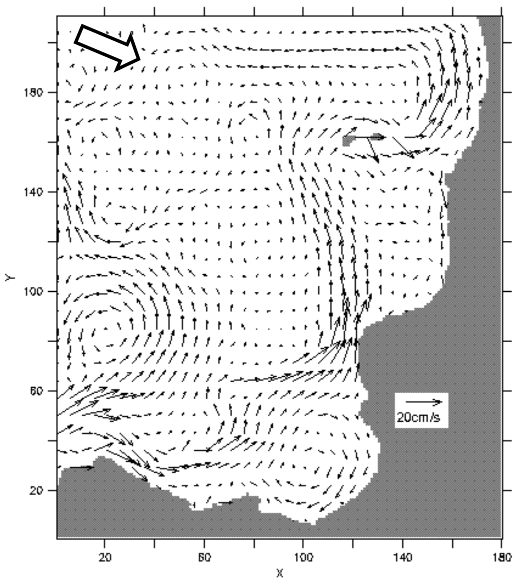

Fig.8 Same as Fig. 4 but for experiment 3

Although the model is capable to reproduce the general current patterns in the bay, there is still one feature should be noted here. During the period from 6th to 10th of February the simulated flow is

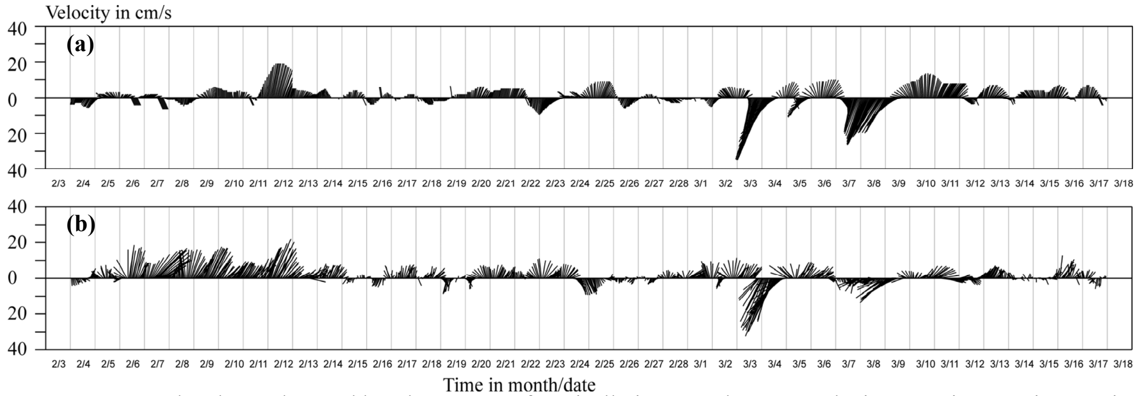

Fig.9 (a) Computed and **(b)** Observed hourly average of vertically integrated current velocity at station ST1 in experiment 3

weak due to small wind velocity but the observation current velocity in this period is quite large. The reason for this phenomenon may lie in the following classes: the effects of other driving forces such as wave, tide that were not included in this model; or there were errors in the wind model.

5. CONCLUSION

The Princeton Ocean Model was applied to simulate current pattern in the Ishikari Bay in Feb to Mar 2003 under open boundary and wind stress forcing. Three numerical experiments with different driving forces have been tested. In the first experiment, the model was forced by open boundary condition only. The current pattern in the study area in this case is nearly steady: the inflow starts at the lower part of the western boundary, and then it is separated into two branches: one concentrates in the deep region and the other weaker branch flows along the shelf. The current velocity in shallow region is so small that can be neglected.

The second experiment used distributed wind as the unique force to the model. The results showed that the depth averaged current velocity in the deep region is quite weak regardless of wind conditions; velocity and direction of currents along the shelf and in the shallow region varies corresponding to wind conditions. During strong wind conditions a circulation occurs in the shallow region of the bay. Moreover, the vertical distribution of horizontal velocities in the deep and the shallow regions is quite different. While the current velocity concentrates in the surface layers in the deep region, the flow presents in all layers in the shallow area and it doesn't change much from the middle to the bottom layers.

The last experiment combined both open boundary and wind stress to force the model. The result of this experiment is a full picture of current pattern in the study area and can be characterized into two different regions. The deep region is mainly influenced by open boundary forcing; the flows along the shelf and in the shallow region are driven by wind. The computed vertical average current velocity at station ST1 in this simulation is compared with those of observation. It was found that there was a good agreement between observed and simulated current velocities. The current at the observation station was stronger at the times of strong wind conditions. It means that wind plays an important role in current pattern in the shallow region of the Ishikari Bay.

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