PARTICLE TRACKING EXPERIMENT ON A MODEL OF THE OKHOTSK SEA: SPREADING OF THE AMUR ORIGIN WATER

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INTRODUCTION

In November 2005, the Amur River was severely polluted by the contaminants due to a chemical plant explosion at the upper river in China. If such contaminants flowed out from the mouth of the Amur River and were dissolved or suspended in sea water without removal, they would eventually come to Hokkaido coast via the East Sakhalin Current (ESC). On the other hand, in February and March 2006, thousands of dead seabirds were found in massive amounts of oil on the shores of Hokkaido, including part of a UNESCO World Heritage site. Although the cause of this incident has not been clarified, these birds were likely transported from the north via the ESC. If an oil spill incident occurred around the Sakhalin oil field, spilled oil would be brought southward along the Sakhalin east coast and finally to Hokkaido coast.

It is very important to predict the drifting and spreading of these contaminants or spilled oil. The ocean current is the most important component for their drifting (Varlamov et al., 1999). However, the prediction models that have been developed so far do not include appropriate currents. This is just because the current system in the Sea of Okhotsk had not been well understood before the recent international Japan-Russia-U.S. joint study of the Sea of Okhotsk.

Surface drifter observations (Ohshima et al., 2002) suggested the cyclonic circulation and clearly revealed the existence of the ESC, which is consistent with the schematics of Moroshkin (1966) and Luchin (1998). The ESC is strongly controlled by the bottom topography. Ohshima et al. (2002) showed that the ESC consists of two cores: the nearshore core on the shelf and the offshore core over the shelf slope. Mizuta et al.(2003) clarified the structure and seasonal variations of the ESC based on long-term moored current measurements. They showed that the transport and velocity of the ESC exhibit large seasonal variations with the maximum in winter and minimum in summer. Simizu and Ohshima (2006) showed that the nearshore core (branch) is mainly driven by the alongshore wind stress through the onshore component of Ekman flux trapped over the shelf. On the other hand, Ohshima et al. (2004) showed that the offshore core (branch) of the ESC is regarded as the western boundary current of the cyclonic circulation driven by a positive wind stress curl.

In this study, toward the development of a prediction model for the drift/diffusion of the contaminants or spilled oil, we make a particle tracking experiment using the general circulation ocean model. Specifically, we run an experiment on drifting and spreading of water originating from the Amur mouth. This experiment is also useful for examining the drift and diffusion of suspended and dissolved matters from the Amur, which may be important ingredients for biological productivity (Nakatsuka et al., 2004).

1. MODEL

We used the Okhotsk Sea model of Simizu and Ohshima (2006). The model is a Princeton Ocean Model incorporating the realistic bottom topography and density stratification. Zonal and meridional grid spacings are 1/6 degree. The vertical grid uses 21σ

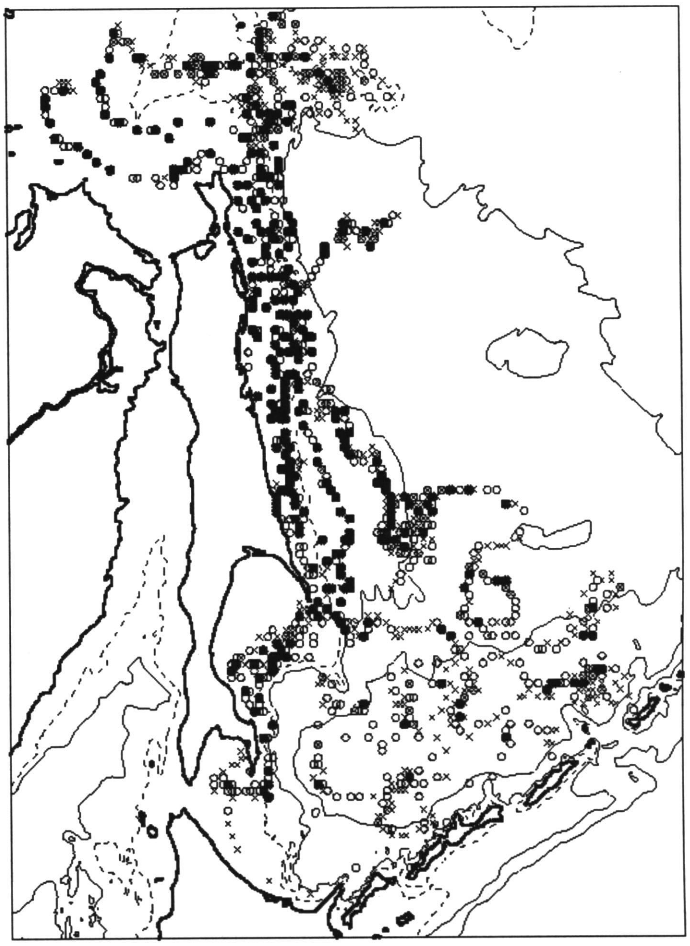

Figure 1: Map of fitting between the model and buoy velocities on 3-day running mean basis. Good fitting (R<0.5: solid circles), moderate fitting (0.5<R<1.0: open circles), and bad fitting (R>1.0: crosses)

levels. The model was spun up for 11 years with the climatological monthly mean wind stress, and subsequently run by the daily wind forcing from ERA-40 and by the monthly heat flux from Ohshima et al., (2003). The effects of sea ice and salt/fresh water flux were not included in the model. A second-moment turbulent closure scheme is adopted to calculate the vertical eddy viscosity and diffusivity. At initial state the ocean is at rest and density stratification is horizontally uniform. The initial profiles of temperature and salinity are typical values of the Okhotsk Sea. All straits are closed and thus inflow and outflow are neglected.

To examine the reproducibility of the model, we compare the model velocity at a depth of 15m with the velocity of the Argos drifting buoys deployed in 1999 (Ohshima et al., 2002): the buoys have large holey sock drogue centered at 15 m depth. Figure 1 is a map of fitting between the model and buoy velocities on 3-day running mean basis. The difference between the two velocity vectors are calculated and categorized into three classes using a ratio of the difference to the buoy velocity (R): good fitting (R<0.5: indicated by solid circles), moderate fitting (0.5<R<1.0: indicated by open circles), and bad fitting (R>1.0: indicated by crosses). The figure shows that the model can roughly reproduce the buoy velocity in the shelf and slope regions with water depths shallower than 1000m, while cannot reproduce it at all in the deep basin.

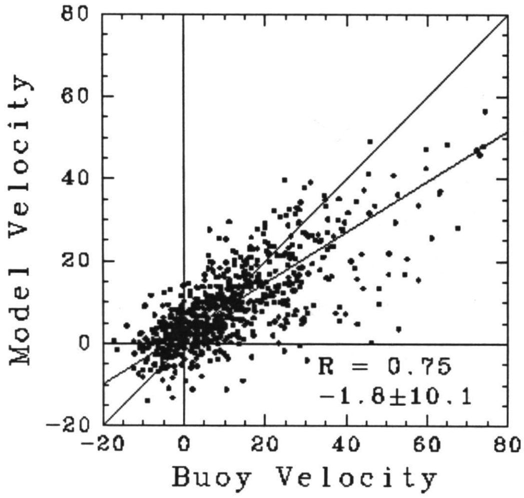

Figure 2: Comparison between the buoy and model north-south velocities in 3-day running mean over the east and north Sakhalin shelves with a water depth shallower than 1000m. Southward direction is taken positive.

Figure 2 shows the comparison between the buoy and model velocities (north-south component) in 3-day running mean over the east and north Sakhalin shelves with a water depth shallower than 1000m. The model velocity is smaller by ~2 cm s^{-1} on average, and the standard deviation of the difference between them is ~10 cm s^{-1}. The correlation coefficient between them is 0.75. Although the principal component line shows some bias (see thick line in Fig.2), the agreement between them is overall good. As long as the simulation of the ESC, the model can work to some degree.

The particle tracking method in the model is similar to that of Awaji (1982). Labeled particles are tracked by the interpolated velocity of the model result. The turbulent velocities caused by tidal currents etc. are incorporated using random-walk on the assumption of a Markov-chain model, where the horizontal turbulent diffusivity and the integral time scale are set to 10^6 cm^2 s^{-1} and 1 day, respectively.

2. RESULTS

In this study, we present the results of the particle tracking experiment in the case of 1998 as an example. 8 particles have been released from the Amur mouth every day from May to October, when the Amur discharge is large (Ogi et al., 2001). Contaminants or spilled oil would usually drift within the upper 0-15 m layer of the sea. Thus we make the particle tracking at the surface and a depth of 15 m.

Figure 3 shows the simulated time series of the particle distribution at a depth of 15 m. At that depth, the current is hardly affected by the wind and the movement of a particle is mostly determined by the ocean current, specifically the ESC in this case. Since the ESC is very weak during May-September, most of the particles are stagnant around the Amur mouth and move southward only slightly during summer. They start to move swiftly southward after October in accordance with the abrupt intensification of the ESC, and finally reach offshore of Hokkaido in December. The particle can reach offshore of Hokkaido in a similar time, regardless of the deployment month.

Figure 4 shows the simulated time series of the particle distribution at the surface. Movement of a particle at the surface is partly affected by the wind drift in addition to the ocean current. During May-September when the ESC is very weak, the particles are diffused offshore due to the wind drift. The particles that were deployed in May-July have been diffused and out of the ESC mainstream before the onset of the ESC intensification, and thus most of them can not be transported to offshore of Hokkaido. While, the particles that were deployed in August and September remain in the ESC mainstream and move swiftly southward after October in accordance with the intensification of the ESC, finally reaching offshore of Hokkaido in December. Dominance of northwesterly wind in fall makes the surface particles drifted offshore. Thereby, the particle distribution at the surface is shifted offshoreward when compared to that at a depth of 15 m (compare Fig. 3d with Fig. 4d).

We also made experiments for other years. For the case of a depth of 15m, the results are insensitive to year. Most of the deployed particles finally reach offshore of Hokkaido via the ESC. For the case of the surface, the results are somewhat different from year to year, due to the effect of the wind drift. In some years, most of the particles were out of the mainstream of the ESC due to the strong offshore-ward wind drift and the only small portion is transported to offshore of Hokkaido.

Watanabe (1963) and Itoh and Ohshima (2000) showed that low salinity water originating from the Amur River is advected to offshore of Hokkaido in the upper 50 m in November or December via the ESC. The particle distribution shown in Figs. 3d and 4d and the timing of the arrival at offshore of Hokkaido are roughly consistent with these previous observations except that the timing of the arrival in the model is delayed slightly, by about 0.5-1.0 month. This suggests that the water originating from the Amur mouth is transported southward mostly by the wind-driven component and that the density driven component is not large. The delay of 0.5-1.0 month is likely due to the lack of density current due to the Amur River flux in the model.

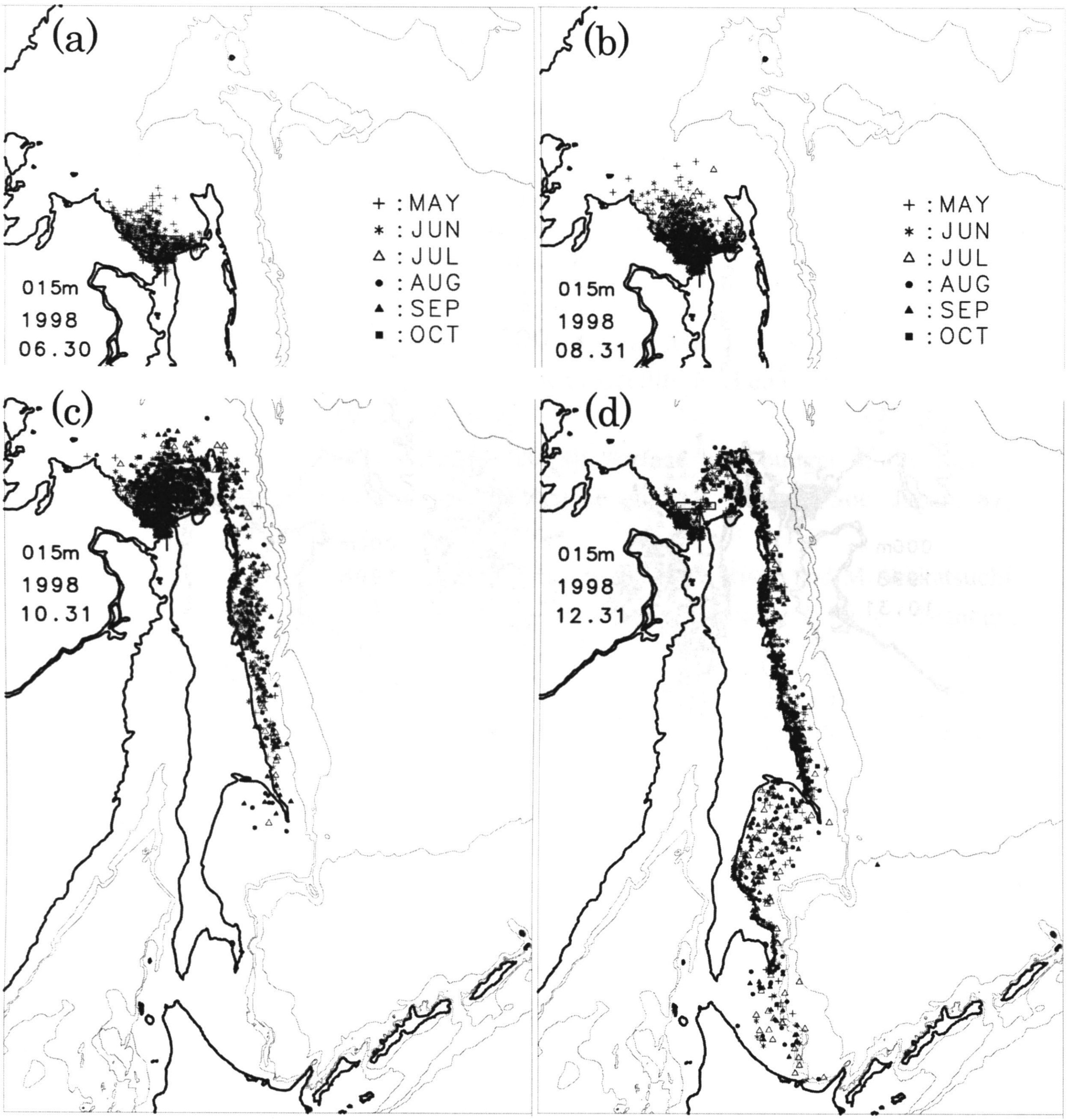

Figure. 3: Simulated time series of the particle distribution at a depth of 15 m at intervals of two months, when 8 particles have been released from the Amur mouth (designated by the rectangular and arrow) every day from 1 May to 31 October, 1998: (a) June 30, (b) August 31, (c) October 31, and (d) December 31. Deployment month of each particle is discriminated by the symbol.

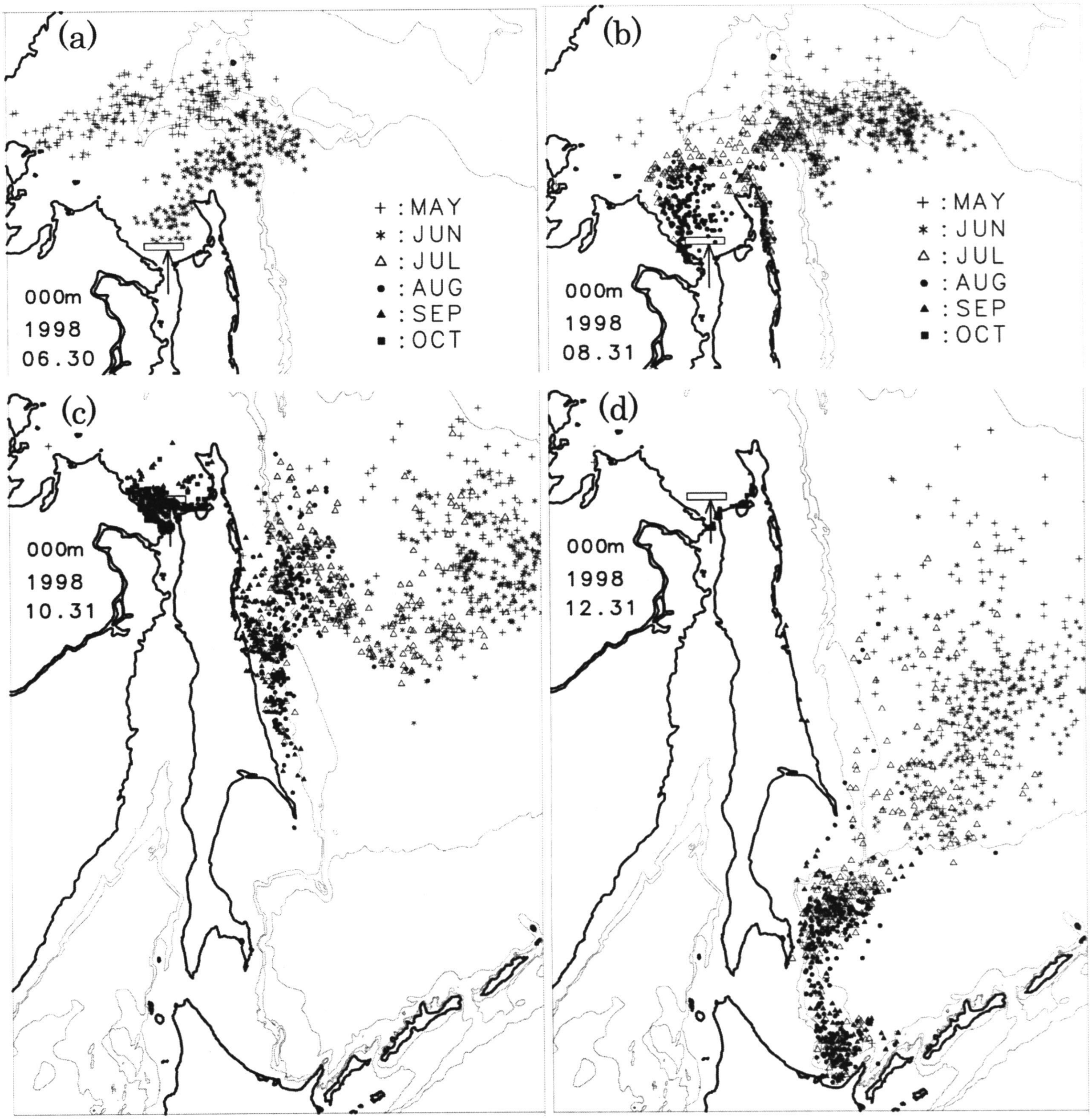

Figure. 4: The same as Fig. 3 except for the distribution at the surface.

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