Development of oil–spill simulation system based on the global ocean–atmosphere model

Young Jin Choi[1], Akihisa Abe[2], and Keiko Takahashi[3]

[1] *Graduate School of Maritime Sciences, Kobe University, 5-1-1 Fukaeminami-machi, Higashi-Nada-ku, Kobe 658-0022, Japan, E-mail: himrchoi@gmail.com*
[2] *Graduate School of Maritime Sciences, Kobe University, 5-1-1 Fukaeminami-machi, Higashi-Nada-ku, Kobe 658-0022, Japan, E-mail: a-abe@maritime.kobe-u.ac.jp*
[3] *Multi-Scale Simulation Group, Earth Simulator Center, Japan Agency for Marine-Earth Science and Technology, 3173-25 Showa-machi, Kanazawa-ku, Yokohama city, Kanagawa 236-0001, Japan, E-mail: takahasi@jamstec.go.jp*

Abstract. Development of a high–resolution numerical simulation on an oil spill accident was demonstrated. Present study uses the fastest vector supercomputer, the Earth Simulator II (ES2), under the collaboration with JAMSTEC. The adoption of nesting grid system for neighboring Japanese Islands and the global ocean model by means of Yin–Yang grid enables us to realize the quick and accurate response for emergency countermeasures. The hindcast particle tracking experiments for the accident of the Russian tanker “Nakhodka” in the East/Japan Sea (EJS), in January 1997, were conducted to evaluate the oil spill simulation system. The movements of spilled oils are defined by the surface wind drift and ocean currents which are obtained from the general circulation model. As a result, using the simulation with ocean model and ECMWF wind data, improved results compared with a previous simulation based on regional ocean model is obtained. Moreover, in the event of the simulation using both numerical results of ocean current and wind velocity, the numerical evaluation on the amount of drifted ashore oil indicates shows high correlation (0.84) with the field observation.
Key Words: General Circulation Model, Japan Sea, Nakhodka accident, Oil–Spill Simulation

1. Introduction

The graduate school of maritime sciences in Kobe University is granted for the research program “The research for international marine transport system integrating three–principles of transport” supported by MEXT (Ministry of Education, Culture, Sports, Science and Technology of Japan). This project aims to create marine transport system which integrates three principles of transport: confidence/safety, economical efficiency and environmental preservation. In a research division of environmental preservation, preventive technologies and measures on harmful chemicals and creatures discharged from ships have been studying by experimental and numerical methods.

One of the serious ocean environmental problems is an oil spill accident by cargo–ships and tankers. Japan has virtually no domestic oil or natural gas reserves and is the second–largest net importer country of crude oil and the largest net importer of liquefied natural gas in the world. The growing concern over the impact of an accidental oil spill in oil transport routes between Japan and Middle East is a motivating factor for the development of the simulation system to evaluate the oil spill response in the open oceans, to provide the environmental impact assessment and to be used in the contingency planning. Thus, it is necessary to construct the high–accuracy numerical modeling system for oil–spill simulation which covers the global domain. We developed a nested numerical oil–spill model using the Earth–Simulator II (ES2) provided in JAMSTEC (Japan Agency for Marine–Earth Science and Technology). The ES2 is a vector supercomputer that has 160 nodes with 8 processors per node. A peak speed of each vector processor is 100 Gflops. The number of cores of ES2 is smaller than one-tenth of that of scalar supercomputers that have similar performances, i.e., each node is more powerful and amount of data exchange via network interfaces is smaller than scalar machines.

Numerical prediction models have been generally used to solve the movement and diffusion of water-borne pollutants (Reed *et al*. 1999; Montero *et al*. 2003) and regional atmosphere–ocean models are used in most studies in spite of being affected by conditions of open boundaries. In order to accurately evaluate impacts of an oil–spill on local coasts, it is necessary to take into account meso–scale (around 100 km scale) eddy mixing and other phenomena by using a high–resolution ocean model. Our aim is to construct the high–resolution oil–spill forecast simulation system for the whole routes between Japan and Middle East. In this study, as a verification of the performance and accuracy of the simulation system, we conducted a simulation experiment focused on the neighboring Japanese Islands. We examined a high–resolution hindcast oil–spill simulation of the Nakhodka accident in 1997 and compared the simulation results with that of the observation and the previous study.

2. Numerical simulation of spilled oil

2.1 The grid system

In our simulation, a nesting model based on global grid system was used. The grid dimension of global ocean model is $2170 \times 1085 \times 23$ (longitudinal, latitudinal, and vertical dimension, respectively) and regional ocean model is $1025 \times 792 \times 23$. The 1/20–degree model (NESTED) covering around Japanese

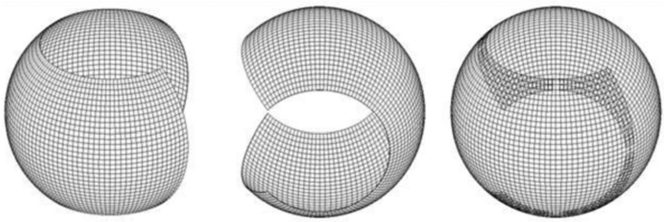

Figure 1 The Yin-Yang grid system: (a) Yang grid, (b) Yin grid, and (c) the combined grid of (a) and (b), data are exchanged and interpolated every time steps.

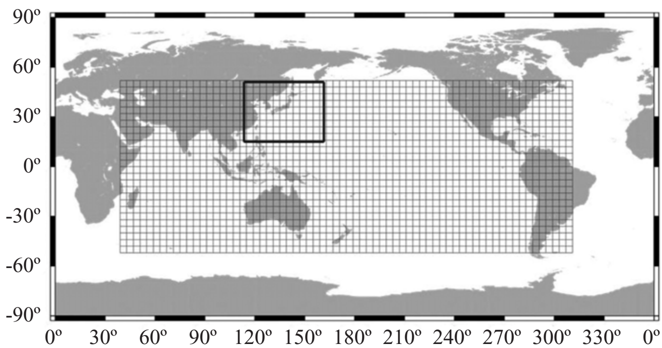

Figure 2 Nested grid around the Japanese Islands on the "Yang" grid

Islands is embedded in a 1/6–degree global model (GLOBAL). For the atmospheric simulation, $954 \times 477 \times 32$ is used. We employed a recently proposed grid system, named "Yin–Yang grid" (Kageyama and Sato 2004) for the global model as shown in Figure 1. The Yin–Yang grid consists of two component grids that have exactly the same shape and size. They partially overlap each other on their boundaries. Data on the overlapped grids are obtained by interpolation. The Yang grid covers from 45 to 315 degrees in longitude and from -52 to 52 degrees in latitude. In the vertical direction 23 levels are assigned and finer grids are used near the sea surface.

We refined the regional ocean circulation model by nested grid method. Variables for the coarse grid are first advanced in time by one integration time step. The coarse grid values at the boundaries of the nested area provide boundary conditions for the nested grid. The nested grid has buffer grids in its boundaries. The boundary values are provided by the coarse grids through the buffer grids. The values in the buffer grids are smoothed by cosine function. Figure 2 shows the nested area on the Yang grid.

2.2 The ocean circulation model

The numerical model used in this study is the three–dimensional, time–dependent, free surface, primitive equation MSSG (Multi–Scale Simulator for the Geoenvironment) model (Takahashi 2005) which was developed at the Earth Simulator Center. The model calculates prognostic variables of the hydrodynamics: velocity, temperature, salinity and surface elevation in the regional small–scale domain in combination of high–resolution regional model and coarse–resolution global model. The bathymetry data used in this study is the ETOPO1 (global relief model with topography and bathymetry) which has one minute resolution (Amante and Eakins 2008). The wind stress fields used in the present hindcast simulation were obtained from the CCMP (Cross-Calibrated Multi-Platform), a global variational analysis of wind speed (Atlas *et al*. 1996) with a resolution of 0.25° for the period 1997. The model sea surface temperature (SST) are restored to monthly average climatology values with a Newtonian restoring time of 7 days. The sea surface temperature was provided by 18 km resolution of AVHRR (Advanced Very High Resolution Radiometer). The model is spun–up for 20 model years on the ES2 which could calculate one model year in 10 hours. The calculation time for 1 year is about 12 hours with 24 nodes of ES2.

The monthly average of surface velocity field from the global simulation is shown in Figure 3. The major ocean currents are well reproduced – the Equatorial Current Current around the Equator, the Gulf Stream in the east of North America, the Kuroshio in the southeast of Japan, and the Antarctic Circumpolar Current. However, the global model could not successfully resolve the regional circulation. Figure 4 shows the comparison of the Kuroshio circulation from the global (left) and regional (right) models by using the ocean component of the MSSG (MSSG_O). In the global model result, the Kuroshio overshoots over 40°N. On the other

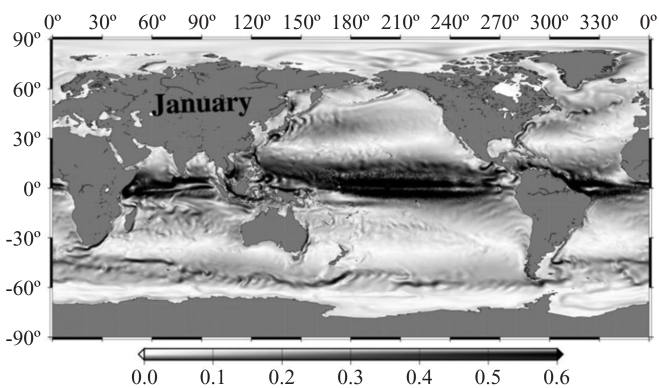

Figure 3 The ocean current velocity field simulated by the global MSSG_O model.

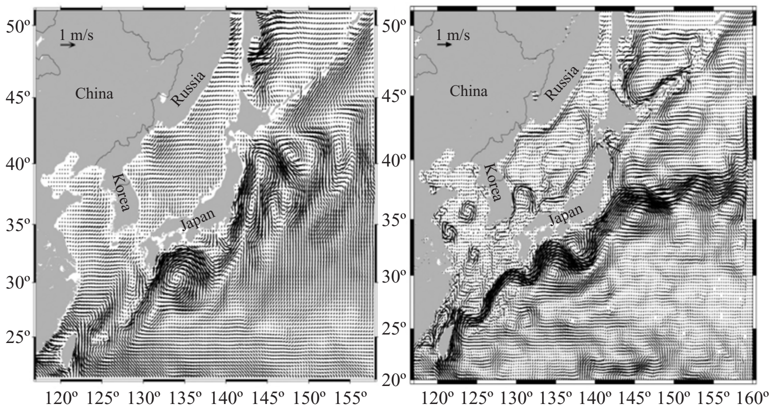

Figure 4 The regional ocean surface current fields around Japanese Islands from the global model (left) and the regional nested model (right), respectively.

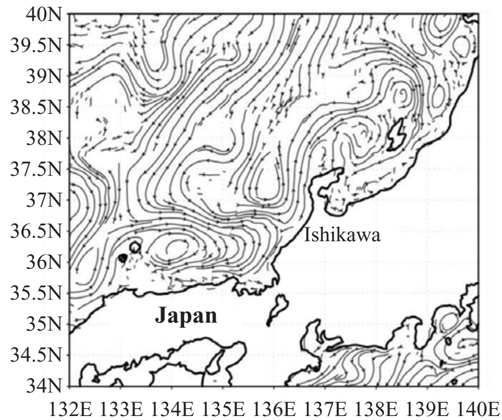

Figure 5. The monthly averaged (January) surface current field around the west coast of Japan, where the "Nakhodka" accident had been occured.

hand, in the nested simulation, the western boundary current of the Kuroshio Extention and the East Korea Warm Current (EKWC) are separated around 37ºN and 38ºN, respectively. The cold currents of the Oyashio and Riman are clearly reproduced as well. These features agrees well with the previous studies about the EJS (Seung and Kim 1993) and Kuroshio (Yasuda 2003). Moreover, the nested simulation reproduced many meso–scale eddies of which diameters are in the range of 30 to 100 km.

The current speed in the East/Japan Sea (EJS) is about 10 to 30 cm/s, which is much smaller than the Kuroshio (up to 200 cm/s). The result implies that the effect of winds (up to 2 m/s) on oil movements is important, as well as ocean currents in the EJS. Figure 5 shows that a strong current are bifurcated around the coast of Ishikawa prefecture (136ºE, 36.5ºN) and narrow onshore northeasterly flow branch along Japan coasts are observed while another branch flows into southwestern direction.

2.3 The wind velocity fields

A high–resolution wind velocity data is needed for the spilled oil drift simulation. We used the atmospheric component of the MSSG model (MSSG_A) and observational data for comparison. We conducted two case of oil–spill simulation: CASE1 uses observational wind velocity, and CASE2 uses the atmospheric simulation result (See Table 1). The 1.5º resolution climatology of surface fluxes from the 6 hours forecasts provided by the ECMWF (European Centre for Medium–Range Weather Forecasts) re–analysis (ERA–Interim) (Simmons *et al*. 2006) is adopted for CASE1. The spatial resolution of the data is interpolated with the bilinear method to the fine resolution mesh (same with NESTED ocean model grid), and the temporal interval of the data is also adjusted to the NESTED model time step. Figure 6 shows the ECMWF wind (left) and the MSSG_A result (right) on January 2nd in 1997. Both data show strong East Asian

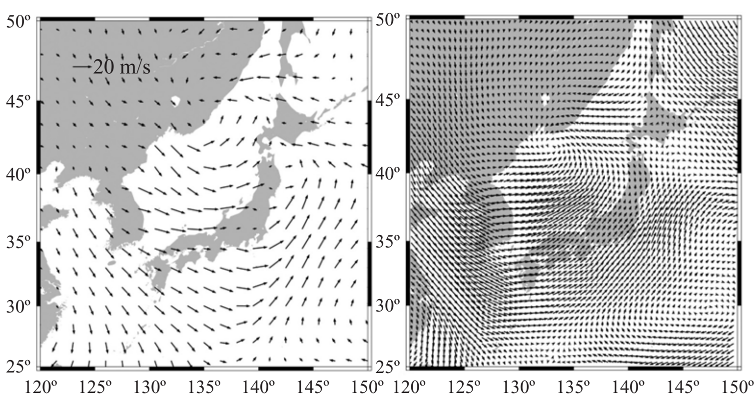

Figure 6 The wind velocity field at 10 m above the sea surface on 2nd January 1997 from the reanalyzed 1.5º resolution ECMWF (left) and the MSSG_A simulation (right), respectively.

Table 1 Summary of data used in the oil–spill simulation cases.

	CASE1	CASE2
Ocean current	MSSG_O	
Wind velocity	ECMWF data	MSSG_A model

winter monsoon which are generated by the impact of the Siberian High.

2.4 The oil spill model

The advection–diffusion equation is a very common mathematical model used to simulate oil transported on the sea surface. Its general formulation is:

$$\frac{\partial C}{\partial t}+U\nabla C=\nabla(D\nabla C)+S\,, \tag{1}$$

where C is the concentration (or density) of oil, U is the velocity vector, D is the diffusivity coefficient, and S is external fluxes. The general Eulerian equation (1) is calculated in Lagrangian formula as follows:

$$L=(U_{curent}+\alpha U_{wind})\Delta t+L_{random}\,. \tag{2}$$

The Lagrangian equation (2) regards spilled oil as a set of floating individual particles. It gives many advantages, e.g. numerical stability, short process time, handling of fluxes, etc. Here, L is the moving distance of each particle during Δt, α is the wind drift factor, usually taken as 0.03 (Stolzenbach *et al*. 1977), $U_{current}$ is the ocean current velocity at the sea surface, and U_{wind} is the wind velocities at 10 m above the water surface, respectively. The advection due to turbulent diffusion L_{random} is computed by the random walk method for Gaussian "spillets" as

$$L_{random}=R\sqrt{6D/\Delta t}\,, \tag{3}$$

where R is the random number between -1 and 1. The empirical diffusivity coefficient D is taken as 10 m^2/s (Okubo 1971). The oil–spill model (2) calculates oil transportation.

The differential equations were solved using a 2nd order Runge–Kutta (R-K) algorithm (Abramowitz and Stegun 1964) with a time–step of 20 min, since time–centering in the method is approximately achieved by anticipating an average force acting between two successive time steps. For Lagrangian equation the usual 2nd order R-K algorithm gives

$$x^{*}_{n+1/2}=x_n+v_n\frac{\Delta t}{2} \tag{4}$$

$$x_{n+1}=x_n+v^{*}_{n+1/2}\Delta t\,. \tag{5}$$

3. Application to the Nakhodka accident

On January 2nd, 1997, the Russian tanker "Nakhodka" carrying 19,000 kl of heavy oil was sunk off Oki Island. Five days later, the leaked oil with the ship

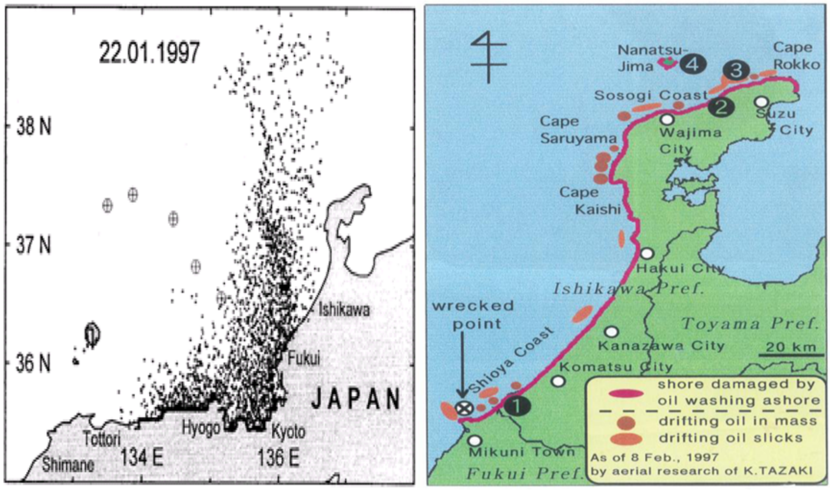

Figure 7 Oil distributions from the regional simulation (Varlamov *et al*. 1999, left) and the observation (Tazaki 2003, right), respectively.

reached Fukui prefecture in Japan while a part of leaked oil reached Niigata 20 days after the accident.

In the previous numerical work by Varlamov *et al*. (1999), they had simulated the Nakhodka accident using 1/6° regional ocean model. Their estimation on the drifted time of spilled oil to Fukui prefecture was eight days (=192 hours), and besides, the spilled oil did not reach Niigata prefecture. Their numerical result was different from the actual fact because the resolution of the ocean model was not high enough to simulate meso–scale eddies and narrow currents circulate around the Noto peninsular in Ishikawa prefecture. Figure 7 show the distributions of spilled oil from the previous regional simulation (Varlamov *et al*. 1999) and observation (Tazaki 2003). In the observation, spilled oil had drifted ashore and widely distributed along the almost whole western and northern coastlines of Ishikawa prefecture. However, in the Varlamov *et al*. (1999), the spilled oils flow northerly from the Fukui prefecture.

Our oil-spill simulation has been performed for 30 days with 20 min time step. The amount of immediately spilled heavy oil was considered to be 50% of total mass of oil. Figure 8 shows the simulation results of oil particles distribution after 20 days from January 2nd by CASE1 and CASE2. The scene of the Nakhodka accident is indicated by a star mark and a dot represents 10 kl of an oil particle. From the both results, the immediately spilled oil particles moved rapidly towards Fukui prefecture, along the winter monsoon wind and ocean surface currents. It is trivially accepted that southerly flow is mainly due to wind drift and easterly flow is due to ocean surface current from Figure 6 and Figure 5. Winter monsoon also

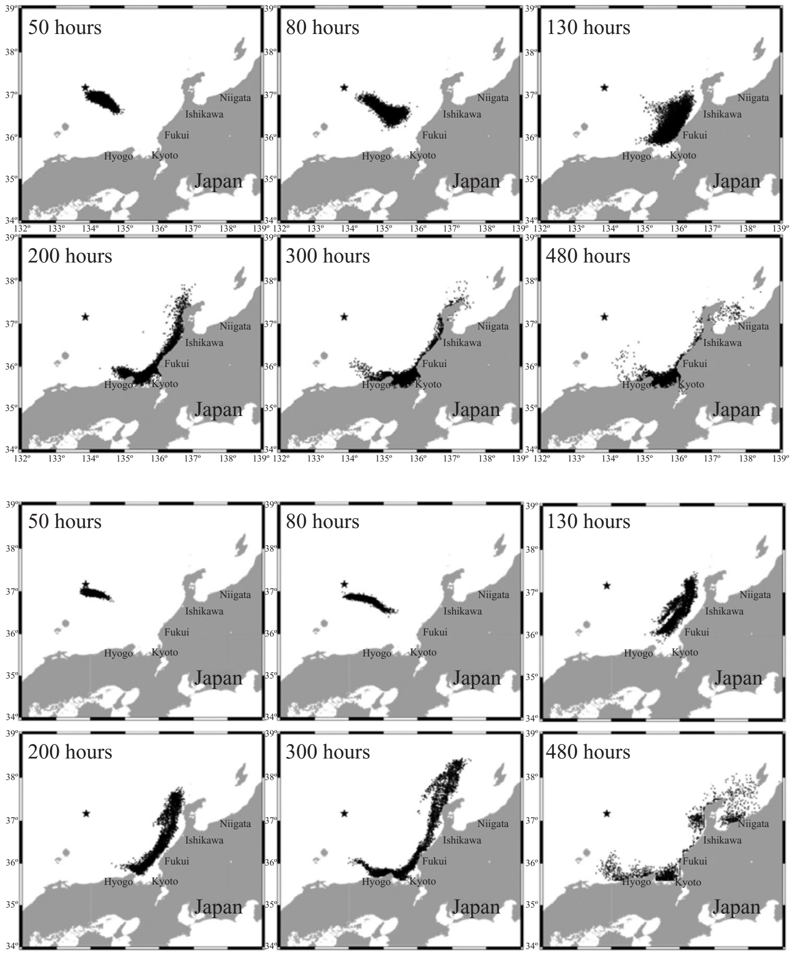

Figure 8 Distribution of drifted oils during 480 hours for the CASE1 (upper) and CASE2 (lower) simulations, respectively.

drifts oil particles to the southeastern direction. After arriving in Fukui prefecture, the oil particles are divided into two parts; the one flows northeasterly, and the other flows southwesterly. Note that this separation of oil particles corresponds to the bifurcation of ocean surface currents mentioned above. Thus the oil particles are widely distributed from the Hyogo to Niigata prefecture. The approximate arrival time of spilled oil in Fukui and Niigata prefecture are 130 hours (＝about 5 days) and 480 hours (＝20 days), respectively. These results of our high–resolution NESTED model agreed very well with observations (Tazaki 2003; Fukui Prefecture 2000). In the CASE2 simulation, amount of drifted oils in the

Fukui and Kyoto prefectures, while more oils are northeasterly flowed into the Niigata and Ishikawa prefectures. The comparisons of the distributions of drifted oils between the observation (Naito 1998) and the each simulation are presented in Table 2. The distributions of drifted oils indicate that more oils flowed from the southwestern regions into the northeastern regions. The correlation between the observation (Tazaki 2003) and the simulation results is 0.84 in the CASE2 and 0. 40 in the CASE1. Therefore, it is found that the high–resolution NESTED model by MSSG_O with MSSG_A (CASE2) is more effective in the Nakhodka oil–spill accident.

4. Conclusions

As a part of a research program "The research for international marine transport system integrating three–principles of transport" carried out in the faculty of maritime sciences, Kobe University, we developed an oil spill simulation system based on a three–dimensional ocean model of the MSSG model that incorporates ECMWF reanalysis wind velocity data and the oil transportation model. Our system is based on the global domain, as well as including real–time nesting scheme for the ocean model. Thus, our oil–spill simulation system has two benefits compared to other systems: for the first, it can be adapted instantly for accidents occurred anywhere in the world. For the second, global domain based modeling system is not affected by open boundary conditions. The most important part of the oil spill simulation is the representation of the ocean currentsin the upper layer (shallower than 30~50 m). A high–resolution regional model is strongly controlled by the boundaries, whereas a global model could not resolve the regional circulation accurately. The nested simulation in this study gives us benefits that could simulate the global oceanic features as well as small–scale variations in the regional circulation.

Accuracy of our simulation was investigated from comparison with the fact of the Nakhodka accident in 1997. The calculated arrival time of spilled oil to Fukui and Niigata prefectures indicated good agreement with the observation data because the high–resolution NESTED ocean model succeeded in simulation of meso–scale eddies and narrow currents circulate around the Noto peninsular in Ishikawa prefecture. In addition, it was found that the essential parameter in the determination of oil motion is the wind speed and sea surface currents. Thus, the use of reliable velocity field is crucial to predict accurately oil spill trajectories. The high–resolution model result of the wind drift velocity induced more realistic oil-spill simulation results (CASE2) compared with the CASE1, which indicate that the resolution of the velocity field is important as well as reproducibility.

For further simulation, we are going to combine nested grid on the

Table 2 The distributions of drifted oils for each prefecture after 20 days from the accident.

	Distribution (%)		
	Observation	CASE1	CASE2
Niigata	7.6	2.5	7.6
Ishikawa	44.3	11.0	36.0
Fukui	37.3	40.1	24.8
Kyoto	7.3	33.6	25.2
Hyogo	2.9	8.1	3.5
Etc.	0.6	4.8	2.9
Correlation	1	0.40	0.84

atmospheric model, and it is expected to enhance the accuracy of oil trajectory simulation. Also, the improvement of the dispersion formation algorithm which represents randomness is important for the realistic simulation of oil movements.

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