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Simulation of Deepwater Horizon Oil Spill using Atmosphere-Ocean General Circulation Model

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Abstract

The Deepwater Horizon accident discharged a staggering amount of oil (about 780,000 *Kl*) into the Gulf of Mexico. In other forecast simulations based on the ocean-only models, spilled oil reach the Atlantic Ocean by the Gulf Stream. In this study, we simulated 3-dimensional movement of oils using the real-time oceanic and atmospheric conditions obtained by the coupled MSSG (Multi-Scale Simulator for the Geoenvironment) model. Our simulation show that the amounts of oil discharge into the Atlantic is very limited due to the trade winds. The atmospheric coupling to the ocean model is essential in the forecast simulation of spilled oils.

Key words : *Oil Spill Simulation, General Circulation Model, Gulf of Mexico*

1. Introduction

The Deepwater Horizon (Hereafter DH) oil spill, caused by a drilling rig explosion on 20 April 2010, is the largest oil spill on the Earth. It had released about 780,000 kl of crude oil from a depth of 1600 m.

Generally, oil-spill modelling in the ocean involves two models: a hydrodynamic model and an oil transport model. Since the oil spill in the ocean is very complicated process of winds, ocean currents and oils' random movements, modeler should consider about the characteristics of oceanic and atmospheric conditions and general circulation models. Most of oil-spill accidents are occurred in the coastal seaway or oil tanks around the coast and many of oil-spill simulation researches used two dimensional ocean circulation model for the hydrodynamic model[1), 2)], or sigma coordinate models which is not suitable for the open ocean circulation with steep topographic slopes[3), 4)]. Choi et al.[5)] showed that high resolution 3-dimensional z-coordinate atmosphere and ocean model is effective for accurate simulation of oil-spill in open ocean. For the transport model, a Lagrangian particle-tracking model which is totally free from the numerical diffusion is established as an effective method because spilled oils in the ocean are treated as passive tracer.

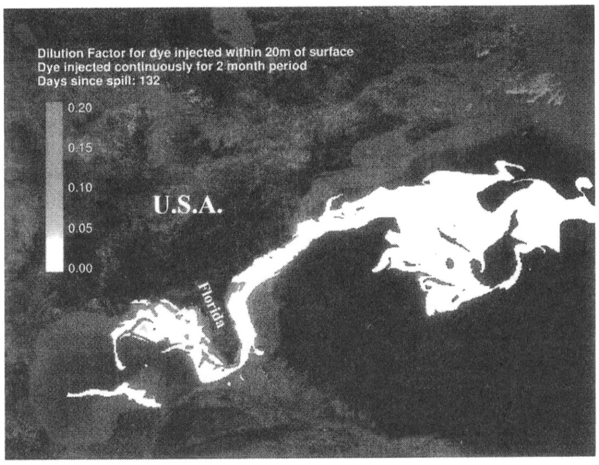

Fig.1 Distribution of the spilled oil from the DH, simulated by NCAR. Light gray shaded indicates oils in the ocean surface.

The National Center for Atmospheric Research (NCAR), which is funded by the US government, conducted a supercomputer simulation about the DH oil spill with 3-dimensional z-coordinate ocean general circulation model (OGCM)[6)](Fig.1). They suggested that Gulf crude oil could discharge into the North Atlantic in about 120 days. Once the oil in the uppermost ocean has become entrained into the LC, it is likely to reach

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Florida's Atlantic coast within weeks. It can then move north as far as about Cape Hatteras, North Carolina, with the Gulf Stream, before turning east.

On the other hand, another possible spread scenario of the Gulf crude oil over one year was studied by a team of researchers from the University of Hawaii. They used the oceanic parameters conducted with the OFES (OGCM for the Earth Simulator) which is provided by Japan Agency for Marine–Earth Science and Technology (JAMSTEC). They also indicated that the oil enters the LC and the GS, and about 150,000 kl of crude oils are transported through the Straits of Florida and finally into the North Atlantic after about 240 days[7)]. However, the previous studies did not considered about the effect of wind on the spilled oils in the ocean surface.

In this study, we investigate the DH oil spill by numerical simulation with high resolution atmosphere and ocean general circulation model. Numerical models are well established in simulating atmosphere and ocean circulations in the regional domain for the GOM. The particle tracking oil spill model is described, followed by applications for the DH accident.

2. Simulation System

2.1 Atmosphere-ocean model

The Multi-Scale Simulator for the Geo-environment (MSSG)[8)] is used for the regional numerical simulation, using the Earth-Simulator II (ES2) provided in JAMSTEC (Japan Agency for Marine-Earth Science and Technology). Both atmospheric and oceanic components are developed based upon the primitive equations.

An atmospheric component of MSSG (MSSG_A) is 3-dimensional non-hydrostatic global and regional atmosphere circulation model. It compromised of fully compressive flux form, Smagorinsky-Lilly type parameterizations for sub-grid scale mixing. In the ocean component (MSSG_O), incompressible and hydrostatic equations with the Boussinesq approximation are adopted.

In both the atmospheric and oceanic components, Arakawa-C grid is used. The atmospheric component utilizes the terrain following vertical coordinate, while the ocean component uses the z-coordinate system for the vertical direction.

In this study, we used 15km resolution horizontal grid, covering North Atlantic (65°N ~ 10°S, 100°W ~ 20°E, Fig.1). For vertical layer, MSSG_A used 32 layers varying from 100 m to 30 km, while MSSG_O used 26 layers varying from 20 m to 5000 m.

The initial temperature and salinity distributions were generated using a combination of the OFES 1/10° climatological product[9)], calculated in the JAMSTEC.

Each component is coupled after spun up for 2 years and 10 years for the atmospheric and ocean components, respectively. Coupled simulation was carried out for 1 year from April 20th, 2009.

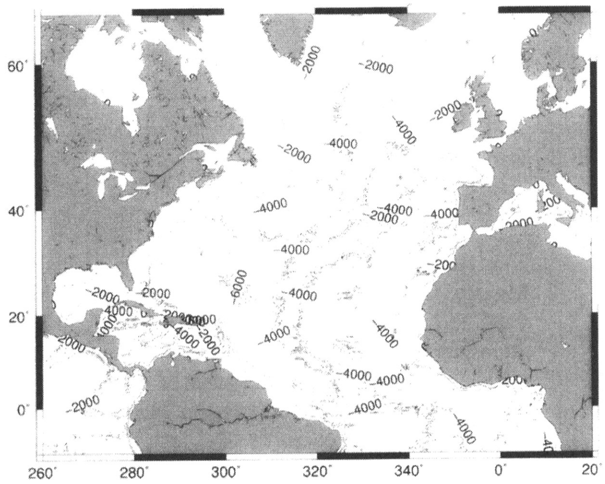

Fig.2 Domain and Topography (ETOPO5) for the GCM simulation

2.2 Simulation results

The monthly mean surface current field in April is shown in Fig.2. The North Equatorial Current and the Gulf Stream (GS) are well reproduced. The separation of the GS around the coast at Cape Hatteras is reasonably simulated.

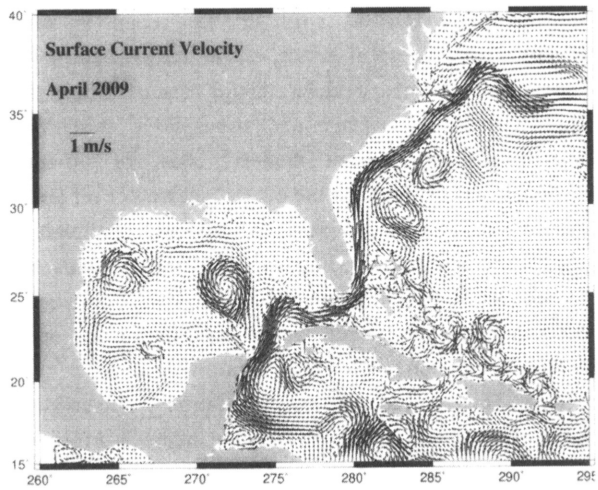

Fig.3 Surface current velocity from the MSSG_O

The ocean circulation in the GOM is characterized by three features like below:

1) The Loop Current (LC) that flows northward

between Cuba and the Yucatan peninsula, moves north into the GOM, loops east and south before exiting to the east through the Florida Straits and joining the GS.

2) The anti-cyclonic warm eddy detached from the LC.

3) Large stationary eddy in the west of the GOM.

Those three features are well reproduced in our simulation (Fig.2). In the simulation results, the horizontal velocity of the GS is up to 15 cm/s above 500 m depth, under which the velocities are only about 0~5 cm/s.

Fig.3 shows the 10-meter wind velocity field above ocean in April. The trade winds blow westward in the tropics, and the wind above 30°N blows southwesterly by the effect of the Westerlies which blow eastward at mid-latitudes. It should be noted that the wind velocities in the GOM is relatively weak compared to the Caribbean Sea.

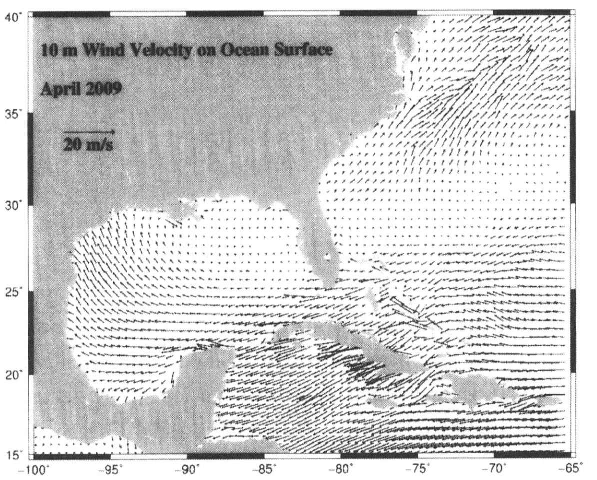

Fig.4 10m wind velocity on ocean surface from the MSSG_A

3. Oil-Spill Simulation Results

The particle tracking (Lagrangian) approach has been adopted for the oil-spill simulation, using the three-dimensional results from the MSSG model simulation.

In the particle tracking method, a spill is considered to be represented by many small discrete quantities, or particles, rather than as a continuous oil body[10]. The method naturally allows advection and diffusion to be separately dealt with. Advection of a particle can be calculated by the following simple equation

$$L = (U_{current} + \alpha U_{wind})\Delta t + L_{random}, \quad (1)$$

where L is the moving distance of a particle, $U_{current}$ is the ocean current velocity at the sea surface, and U_{wind} is the 3% of wind velocities at 10 m above the water surface[11], respectively.

The advection due to turbulent diffusion L_{random} is computed by the random walk method for Gaussian "spillets" as

$$L_{random} = R\sqrt{6D/\Delta t}, \quad (2)$$

where R is the random number between −1 and 1. The empirical horizontal diffusivity coefficient D is taken as 10 m^2/s[12]. For the vertical direction, diffusivity is 1/10 of horizontal value.

The differential equations were solved using a second order Runge–Kutta (R-K) algorithm[13] with a time–step of 60 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

$$x^*_{n+1/2} = x_n + v_n \Delta t/2, \quad x_{n+1} = x_n + v^*_{n+1/2}\Delta t. \quad (3)$$

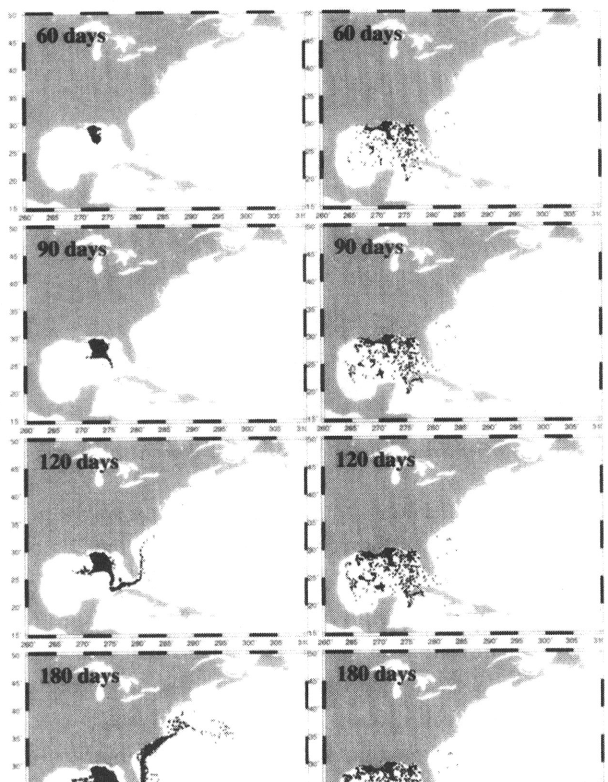

Fig.5 Simulation results of the DH oil spill for CASE1 (Left) and CASE2 (right), respectively.

We conducted two case of oil-spill simulation: CASE1 uses only ocean currents for the advection velocity, while CASE2 uses both atmospheric and ocean simulation results. Fig.5 shows the comparison of the simulation results of CASE1 (left) and CASE2 (right). In

CASE1, the ocean current is the only external velocity for the Lagrangian equation, and consequently, the movements of the oils determined by the ocean current. After 30 days from the spill, oil moves mainly into southerly, under the effect of ocean currents. After 90 days, the front edge of the simulated oil slick flows into the LC after 90 days, and they reach Florida's Atlantic coast in 120 days. The oil slicks then move northerly as far as about Cape Hatteras with the GS, before turning east. In the simulations by NCAR and University of Hawaii, it takes about 120 days and 240 days for the oils to reach the North Atlantic. CASE1 shows 180 days to reach the North Atlantic, which agrees with previous studies. On the other hand, CASE2 shows different trajectories from CASE1. Most of the oils are trapped and mooring in the GOM, and very limited oils are passed through the Strait of Florida.

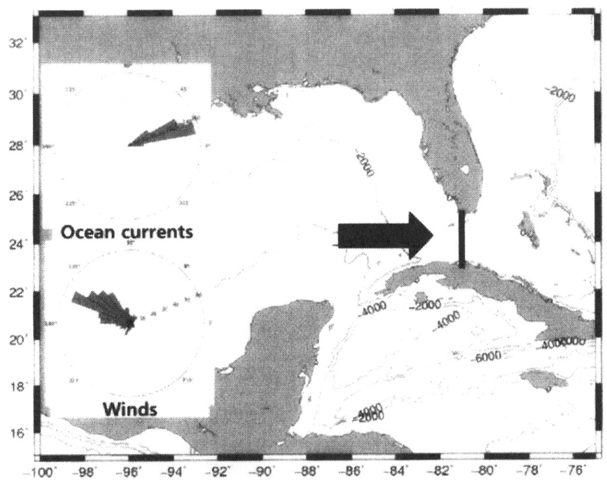

Fig.6 Rose diagrams for the ocean currents and winds through the Florida Strait for 6 months after the DH oil spill.

The directions of ocean currents and winds through the Florida Strait are illustrated by rose diagrams in Fig.6. The ocean currents are apparently directed to the east-northeast direction, which indicates the outflow of the LC into the GS. On the other hand, the rose diagram for the winds through the Florida Strait clearly indicates easterly winds. It should be noted that the direction of the winds in the rose diagram is shifted 30° to the right due to the Ekman effect. The rose diagrams suggest that the easterly blow trade winds keep out the outflow of the oil slicks into the GOM. In CASE2, The oils are widely drifted ashore from the Florida to Louisiana (about 1000 km), which is quite different from CASE1. The combination of west-northwestward forcing due to the winds is effective in the ashore of spilled oils.

Compared with the satellite-observed surface oil locations (Fig.7)[14], observations show that a lot of oils drifted ashore from Florida to Louisiana, which is similar with CASE2. However, In CASE1, oils are hardly drifted ashore. Note that the oil distributions in the southern regions of DH oil spill source, in Fig.6, is similar with neither CASE2 nor CASE1, because of artificial actions by humans – fencing, filtering, and collecting, etc.

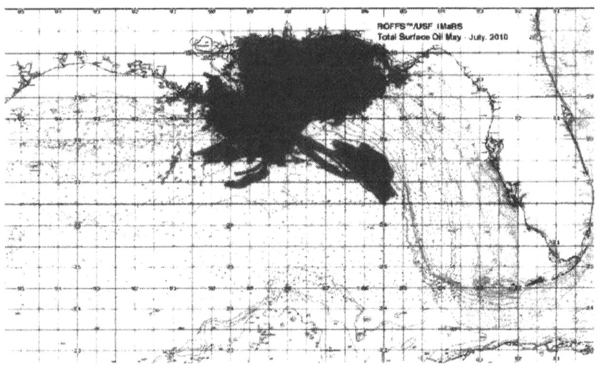

Fig.7 Cumulative Oil Slick Footprint of the DH oil spill, April 25 - July 16, 2010

4. Summary and Conclusion

We conducted oil spill simulation using a general atmosphere and ocean circulation model. The realistic wind and ocean current fields are reproduced by general circulation models. Also, three-dimensional Lagrangian particle tracking method is applied for the oil spill simulations of CASE1 and CASE2. CASE1 shows similar distributions with previous studies, which indicates the ocean current field reproduced in this study is well agreed with high resolution models of NCAR and JAMSTEC.

After the DH oil spill accident, many scientists are concerned about the discharge of oils into the LC, which could transport oils to the North Atlantic. However, our results indicate that the oil movements are largely influenced by wind drift, and spilled oils hardly discharge into the North Atlantic, even if the oils flow into the LC.

Further advances will require the 3-dimensional oil-spill model which includes the chemical changes such as emulsion, dissolution, and deposition on the bottom sediments.

Acknowledgement

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