OIL SPILL ANALYSIS AND QUICK RESPONSE SYSTEM FOR THE SEA OF JAPAN BASED ON THE SHALLOW WATER CIRCULATION MODEL

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Introduction

Marine oil exploration and transportation of oil by sea cause the permanent risk of such technological disasters as oil spills. The numerical simulation and prediction of oil spill processes is an important tool for the planning of the protection and spill response operations. For the purposes of the long-term spill protection planning the most evident application of the oil spill simulation systems is a risk analysis of environmental pollution from existing and planned potential oil spill sources for most sensitive areas (power station water supply plants, recreation areas, marine farms *etc.*). For organizing of the spill recovery after the accidental marine oil spills and for the short term environment protection planning the prediction of the spill trajectory and oil fate is most important.

The oil spill from the tanker *Nakhodka* in the Sea of Japan in January 1997 caused serious damages to the coastal environment of Japan. It demonstrated the importance of being ready for protection from such technological disasters. In this paper we describe the system developed by authors for the incidental oil spill analysis and prediction in the Research Institute for Applied Mechanics (RIAM), Kyushu University.

The incident mentioned happened in the Sea of Japan, when the tanker was ruptured in a storm about 100 km NNE from the Oki Islands of Shimane prefecture. Approximately 3700 m^3 of oil spilled out. The upturned bow section drifted toward the coast of Japan and January 7, 1997 grounded on the rocks near the Mikuni town, Fukui Prefecture of Japan. The total amount of medium fuel oil released into the sea was estimated as about 5000-6500 m^3. January 9 spilled oil spread to the coasts of Ishikawa, Kyoto and Hyogo prefectures, January 10 oil reached the coast of Tottori prefecture, January 11 – the coasts of Shimane prefecture and January 21 spilled oil spread to the coasts of Niigata prefecture. So wide geographical distribution of spilled oil was one of specific features of the *Nakhodka* incident. Fig. 1 shows the observed distribution of spilled oil in the Sea of Japan for 12th and 19th days after the start date of spilling (for January 14 and 21, 1997 respectively).

Information about the *Nakhodka* oil spill was limited due to the severe weather conditions following the incident. However, the comparison of the model simulation results with the observed features of the *Nakhodka* spill is the only way to test the model's ability to reproduce the drift and the fate of oil spilled in the Sea of Japan.

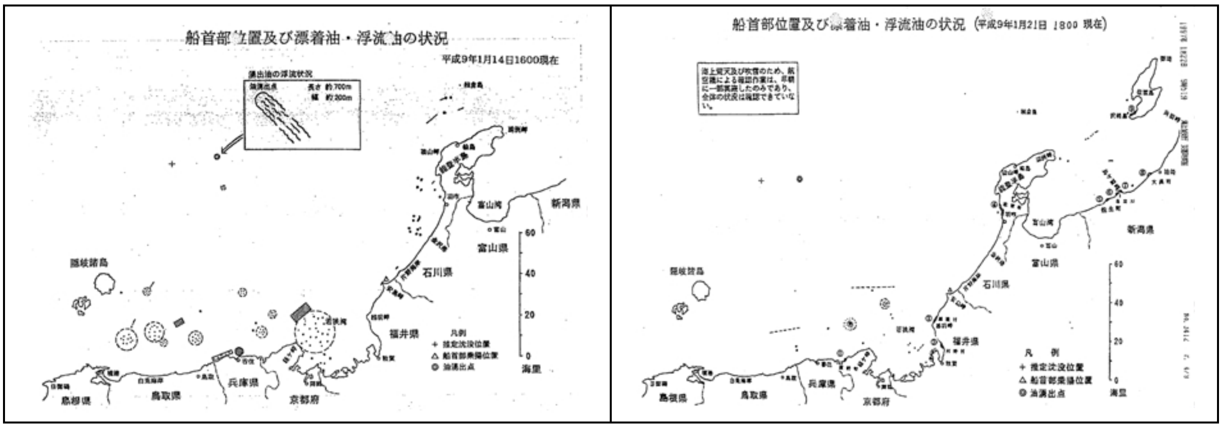

Fig. 1. Observed position of oil compounds in the Sea of Japan for January 14 (left) and January 21, 1997 (right) from the technical reports for the Japanese Oil Spill Disaster Committee prepared by the Japan Maritime Safety Agency

System Structure

The structure of the oil spill analysis and prediction system realized by authors is presented in Fig. 2. The oil spilled in to the sea is transported by a combination of winds, currents and waves; it experiences a weathering and interacts with the coastal area. To implement these effects the system includes the meteorological data processing subsystem, the Japan Sea regional ocean circulation model (OCM), oil spill simulation models and the system's database to keep all required data and simulations results. The system was created as an application for the oil spill analysis and forecasts for the Sea of Japan with the emphasis to the Japanese coastal waters. The oil spill January 1997 was used to verify the model and to select optimal model parameters for the spill simulation in the Sea of Japan (Varlamov *et al.*, 1999; Varlamov *et al.*, 2000).

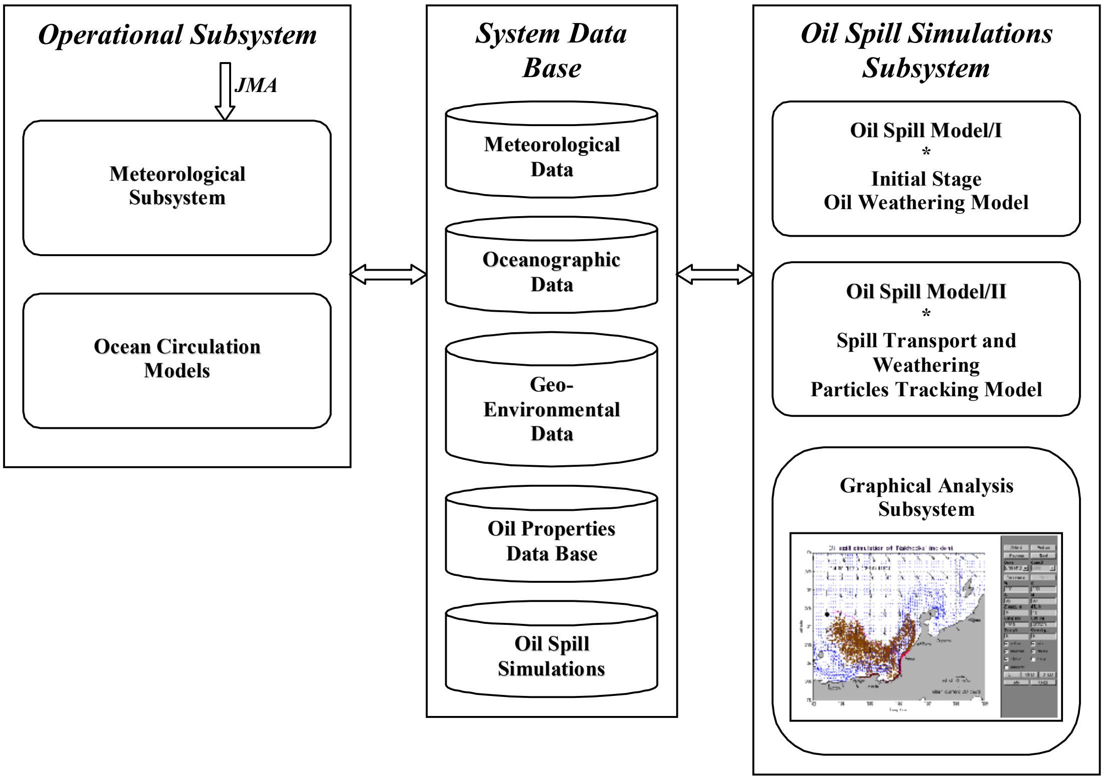

Fig. 2. Schematic structure of the oil spill analysis and quick response system of RIAM, Kyushu University

Meteorological Data Processing Subsystem

Meteorological conditions influence the evolution of spilled oil in many ways. It is the surface wind drift of spilled oil, intrusion of oil in to the seawater due to the surface turbulence generated by overturning wind waves, air temperature influences on the oil weathering processes *etc.* The wind stress defines the sea surface currents and commonly, meteorological forcing defines main features of the global ocean circulation and through it the drift of oil entrained in to the water column. Although the meteorological data from the coastal, island stations and some meteorological buoy stations are most precise, direct meteorological observations in the place of incident are very rare. The same time stations data do not provide predicted values and would create a problem for the wind definition more or less accurately in an arbitrary sea point, especially in the case of spacious Sea of Japan. It explains why we use as a source of regular meteorological data the production of the numerical weather prediction models which is provided in the form of grid point values by main weather prediction centers.

For the model verification we used the data produced by the European Center for Medium Range Weather Forecasts (ECMWF) with spatial resolution 0.5625 degree or less then 64 km and 6 h time interval. The data of the Japan Meteorological Agency (JMA) are utilized in the operational system. Meteorological information includes the surface wind, air temperature, sea level pressure, air humidity *etc.* It is renewed by the JMA twice a day and consists of the analysis of data based on the assimilation of meteorological observations and the forecasts up to five days. The spatial resolution is 1.25 degree and the time step is 6 h between forecasted fields for first 3 days following the analysis time. For the 4th and 5th days the forecasts produced by the meteorological model with 2.5 degrees spatial resolution and with a time step 24 hours are available. Meteorological forecasts are used for the prediction of the sea currents by the OCM and for the evaluation of the expected drift of spilled oil. After receiving more precise meteorological analysis data the predicted currents and oil drift are recalculated with new meteorological forcing from the last saved state corresponding to the analysis time.

The meteorological data processing subsystem of RIAM automatically, once a day or by request, receives by FTP (file transfer protocol) necessary meteorological analysis and forecasts data prepared by the JMA and available for the non-commercial use from the server, supported by the JMA. Data are provided and used by the oil spill and the ocean circulation models in the WMO binary GRIB code format. It means that meteorological information from any other weather prediction center can be used easily. The universal interpolation method is implemented in the system for the interpolation of data from the original meteorological data grid in to the ocean circulation model grid or in to the arbitrary points for the oil spill model. It includes the masking of land points for the interpolation or extrapolation of data over the sea surface only and uses the bicubic spline interpolation method.

Ocean Circulation Model

Modeling of the oil spill in the Sea of Japan using different approaches for the simulation of the transport of spilled oil demonstrated the importance to use for this purposes the sea currents in the upper surface layer defined by the in-time meteorological forcing (Varlamov *et al.*, 1999; Varlamov *et al.*, 2000). The surface floating oil is drifted basically under the wind effect, however, the wind drift does not only explain the observed in the Sea of Japan oil spreading far north to the coast of the Niigata prefecture (see Fig. 3 below for location of mentioned prefectures). In this paper the results for the simulation of oil spill are presented with the sea currents estimated by the high resolution shallow water OCM of the Japan Sea coupled with the local vertical current profile model. Although this model seems to be less suitable for the presentation of currents in the deep sea than 3D models used by us in the previous version of system (Varlamov *et al.*, 1999), it has a small number of parameters and demonstrates results that are in good agreement with the observed spreading of oil spilled in the Sea of Japan in January 1997.

The numerical model of the depth averaging mean currents was adopted from the versions developed by Kim & Yoon (1996) and Hirose & Yoon (1996). It is a finitely different model on the Arakawa C grid and it adopts the Arakawa and Lamb potential enstrophy and energy conserving scheme for the grid in spherical coordinates. The grid step for both the longitudinal and the latitudinal directions was taken as 1/12 degree or 5 minutes. It corresponds to the zonal resolution from about 8 km at 33°N to 6 km at 52°N and the resolution along the meridian is about 9 km. The model area covers all the Japan Sea and includes total 191×228 grid points. Model was integrated with the time step 10 s which satisfy to the CFL criteria.

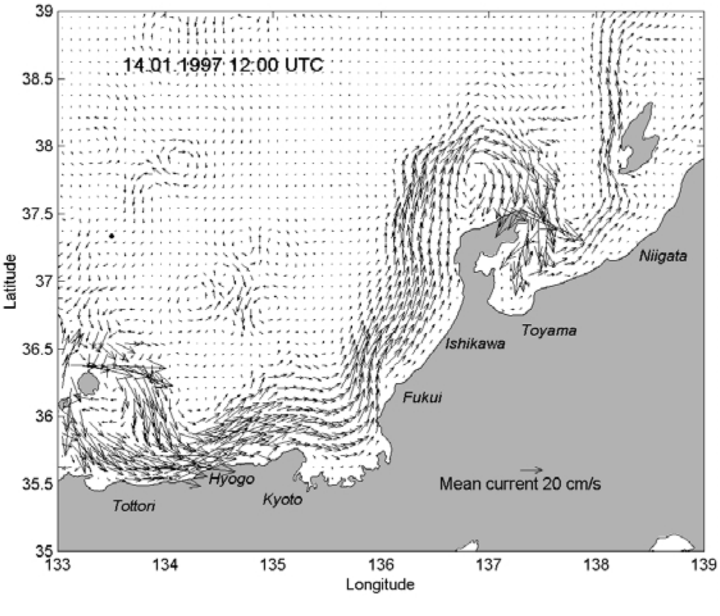

Fig. 3. Depth mean current simulated by shallow water OCM for January 14, 1997, 12:00 UTC

At the closed lateral boundaries no slip boundary conditions for mean velocities were realized. For the open boundary at the Tsushima strait the forced inflow current speed normal to boundary line was defined. It was fixed constant and uniform in all boundary points so that the total volume transport through the strait counted as 2.2 Sv ($1 Sv = 10^6 m^3s^{-1}$). For the open boundaries at the Tsugaru and Soya straits the long gravitational wave radiation conditions were applied for the normal to boundary current component, $u = \sqrt{g/H} \cdot \eta$. The sea level for all open boundary segments and the tangential current components were defined from the zero normal gradient conditions and were taken from the closest model internal grid points. Zero initial conditions were applied for all modeled fields. Wind forcing used for the simulations was discussed above.

Fig. 3 demonstrates the depth mean current field for some local part of the Japan Sea close to the place of spill incident estimated for January 14, 1997 at 12 UTC. The coastal branch of the Tsushima current with the mean current speed exceeding 20-40 *cm per second* along the coast of Japan is well reproduced by these results.

Local Wind Drift Model

The vertical current shear is important for the correct drift simulation of the dispersed oil. However the depth averaged by shallow water ocean circulation model does not provide this information. To estimate it we used the local linear model with bilinear vertical turbulent viscosity profile and assumption that depth integrated mean current must be equal to that estimated from nonlinear shallow water model of the Japan Sea discussed above (Varlamov *et al.*, 1999). In addition, for the oil drifting at the sea surface (0.1 m depth layer) the vector sum of surface modeled current with empirical wind drift was applied. The drift factor for the presented below simulation results was taken as 5% from the surface wind and zero degree right turn angle was assumed.

The numerical realization of the vertical current shear model uses the variable vertical grid step with fixed value of 1 m in upper 40 m and lowest 20 m and larger step in the intermediate layer so that total number of grid points did not exceeded 80. Calculated depth averaged currents differ from the supposed values taken from the nonlinear model not more than by 8%. The surface current turns to the wind direction and for the case of shallow water more strongly follows to the mean current. The example of subsurface current at the 3 m depth is demonstrated in Fig. 4 together with corresponding wind field. It clearly shows that the subsurface current is regulated by both the wind and by coastal gradient current. Despite that such combined model has a lot of disadvantages like lack of mass conservation for resulting current, not accounting for the baroclinic effects *etc.*, it is quite simple and produces reasonable results for simulation of oil transport processes in the surface sea layer.

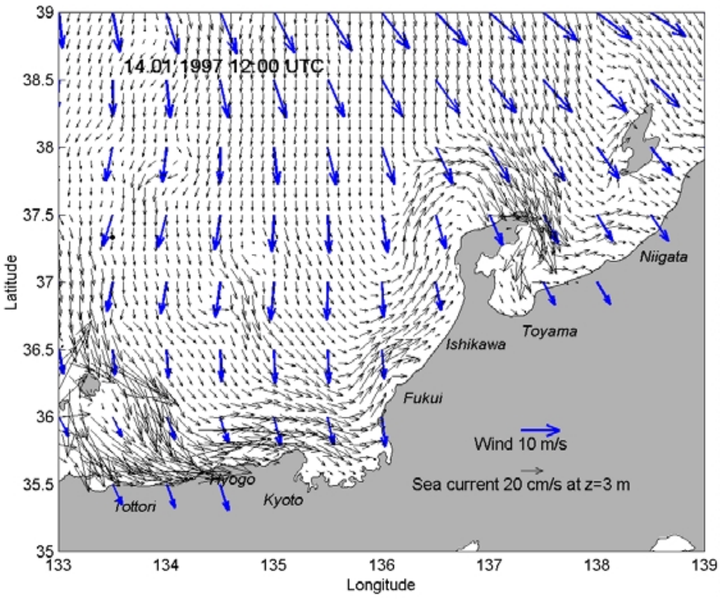

Fig. 4. Wind (thick arrows) and sea current at 3 m depth (thin arrows) estimated by local wind drift model for January 14, 1997, 12:00 UTC

Oil Spill Model

After the spilling in to the sea the oil and other hydrocarbons are involved in a number of complicated processes, discussed in reviews of Reed *et al.* (1999), Fingas (1999) *etc.* As an initial stage spill model we realized a kind of *oil weathering model* (OWM) which is widely used for estimations of the oil spill fate (Daling & Strøm, 1999; NOAA: ADIOST^{TM}, 1994; Sebastiãno & Guedes Soares, 1995; *etc).* This model is referred to as Oil Spill Model/I in the Fig. 1 and it is applicable to the simulation of the initial stage of oil spill evolution processes, which could last from some hours to 1-2 days. Mainly physical and chemical processes immediately following the spill regulate oil weathering. At that stage the intensive evaporation, emulsion formation, modification of spilled oil viscosity and density take place and the oil spreading in calm weather can be treated as gravity-viscous spreading. When the slick is broken up (usually during the first day after the spill) and the oil is dispersed into different types of structures such as dispersion, emulsion, floating bolls, *etc*, the representation of spilled oil by particles is very appropriate. This approach was realized for the general spill transport and fate model, referred to as Oil Spill Model/II in Fig. 1, and was described in (Varlamov *et al.*, 1999). In the current version of system the OWM (Model/I) is used to provide initial estimations for the oil properties used by the main spill model (Model/II). In the next versions of system we are planning to include more detailed description of physical processes from Model/I in general spill transport and fate model (Model/II).

The initial stage spill fate model incorporates the relations and rules for simulation of next physical and chemical processes: evaporation, emulsification, spilled oil viscosity and density modification and gravity-viscose spill spreading (Fay's spreading). Evaporation of spilled oil is estimated by empirical relations proposed by Fingas (1999), although the pseudo-component approach was also realized and cold be used. The start of emulsion formation is estimated by empirical data of Fingas *et al.* (1999; Fingas, 1999) or by evaporation rate from the ADIOS™ data base (NOAA: ADIOS™., 1994), depending on what information is available. After emulsification started, relation of Mackay *et al.* (1980) estimates its rate. Relations proposed by Mackay *et al.* (1980) are used to estimate the viscosity modification due to evaporation and emulsification as well as Fay's slick spreading rate. Oil spill density changes due to evaporation and inclusion of water into the emulsion is estimated by relation of Buchanan & Hurford (1988).

Model was verified for some available experimental data (Buchanan & Hurford, 1988) and it shows good agreement between observed and simulated oil spill properties as demonstrated in Fig. 5. However, the results are very sensitive to the oil type information, taken from available references (NOAA: ADIOS™, 1994, Jokuty *et al.*, 1999) or from the oil providers, so if no detailed information is available for the type of spilled oil, estimated results can significantly differ from the real situation.

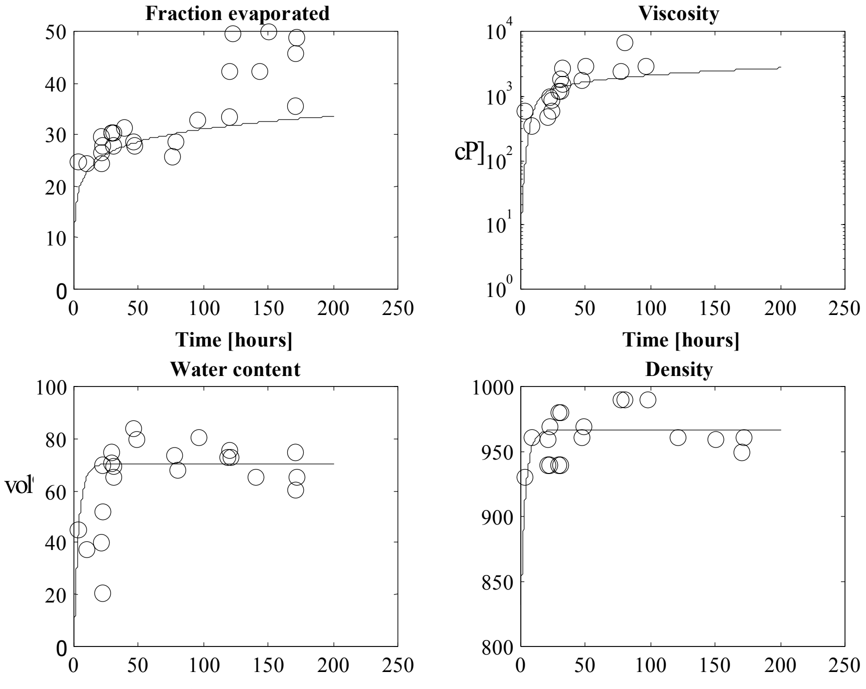

Fig. 5. Simulated by Oil Spill Model/I oil properties (lines) for the Statfjord crude oil compared with experimental oil spill data from Buchanan & Hurford (1988) (circles)

The particle tracking method adopted for the general spill transport and fate model (Varlamov *et al.*, 1999) took in to account the effects of oil transport by sea currents, buoyancy and random diffusion, oil evaporation, biochemical decay and the interaction of the oil particles with the coastal line. Random diffusion caused by the vertical and the horizontal turbulent mixing depends from diffusion coefficients which were defined at the sea surface by empirical relations of Morales *et al.* (1997) for the mixing of tracers in the upper sea layer. Thus the rate for the oil droplets penetration in to the water column depends on the surface wind and current values, counting for more large rate in the stormy weather, when in calm weather oil particles will resurface under the buoyancy effect. Last one depends on the oil and the seawater physical properties (density and viscosity) and is influenced by the size of modeled oil particles. Due to the balance between the vertical turbulent mixing and the size-dependant buoyancy effect the modeled particles size strongly effects the processes of vertical oil distribution in the seawater. If the surface oil slick drifts mainly under the wind effect, the subsurface dispersed oil experiences the drift by shear sea current. It could result in wider oil redistribution and later in calm weather the subsurface dispersed oil could reappear at the sea surface due to the buoyancy effect. It is also known as “resurfacing” effect that was observed in many cases of oil spills. The Delvigne & Sweeney (1988) droplets size distribution was used in reported experiments, and the droplet diameters ranged between 25 and 250 μm.

The losses of spilled oil were parameterized in a frame of random processes. For any unit of oil at the sea surface the total probability to be evaporated was defined as function of the oil droplet age. As evaporative decay parameter the evaporative half-life time T_{evp} was used, which is the time when one half of the oil spilled at the sea surface evaporates. The evaporation effects only the oil particles in the upper sea layer (0.1 m in model). Similar approach with the corresponding half-lifetime was used for the parameterization of biochemical losses of oil in the water column. Besides that the oil evaporation stopped after the droplets age exceeded $3 \cdot T_{evp}$, in this way taking in to account the modification of oil properties with time due to losses of light fractions *etc.*

If an oil droplet reached the coastal line, with the given probability (70% in reported experiments) it was marked as beached and was removed from following simulation. In other cases droplet was reflected back to the sea.

Simulation Results for the *Nakhodka* Oil Spill

As was noted above, the detailed information on the spill intensity following the tanker *Nakhodka* incident and during the drift of tanker's bow section is not available due to the storm. For modeling of the *Nakhodka* spill in the Sea of Japan we assumed that oil was spilled continuously and uniformly as the bow section of tanker drifts from the initial incident point to the grounding point where the spilling terminated. The density of spilled medium fuel oil was assumed to be 925 $kg \cdot m^{-3}$. Consistent with the cold winter conditions, the corresponding evaporative and biochemical half-live times were put to 50 and 500 hours respectively. A total of 10000 droplets were used for the simulations. Other parameters were discussed above.

In Fig. 6 the simulated distribution of oil particles is presented for January 9, 14, 21 and 26. Only the particles located in the upper 5 m layer are plotted, because mainly the surface oil is observed and reported during the spill. Beached oil particles are plotted by larger points and they form the thick line along the coastal line taken as an ocean circulation model's boundary. Arrows correspond to wind vectors. These Figures as well as next ones were plotted from the graphical analysis subsystem, realized as MATLAB application with interactive graphical user interface (GUI). As result, the graphical subsystem could run at different computer systems with MATLAB installed. In RIAM it is used both from Windows and LINUX systems. Standalone application also could be generated compiling the MATLAB code with graphical libraries on any supported by MATLAB platforms.

Particles position well marks the oil spreading, however to estimate the pollution rate the concentration of spilled oil seems to be more suitable. Fig. 7 shows the oil concentration in the upper 5 m layer, calculated from the modeled distribution of oil particles for same dates as droplet positions in Fig. 6. Concentration was calculated in 1/12 degree to 1/12 degree cells.

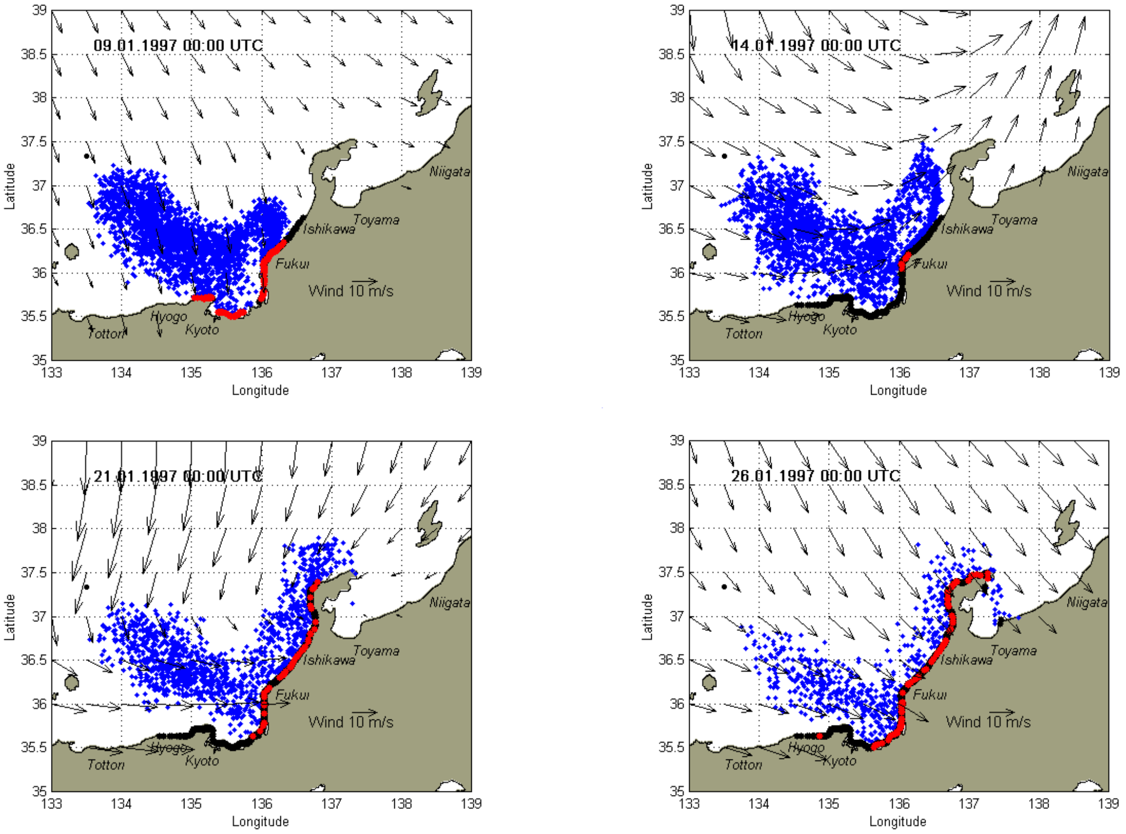

Fig. 6. Modeled distribution of oil particles in upper 5 m sea layer

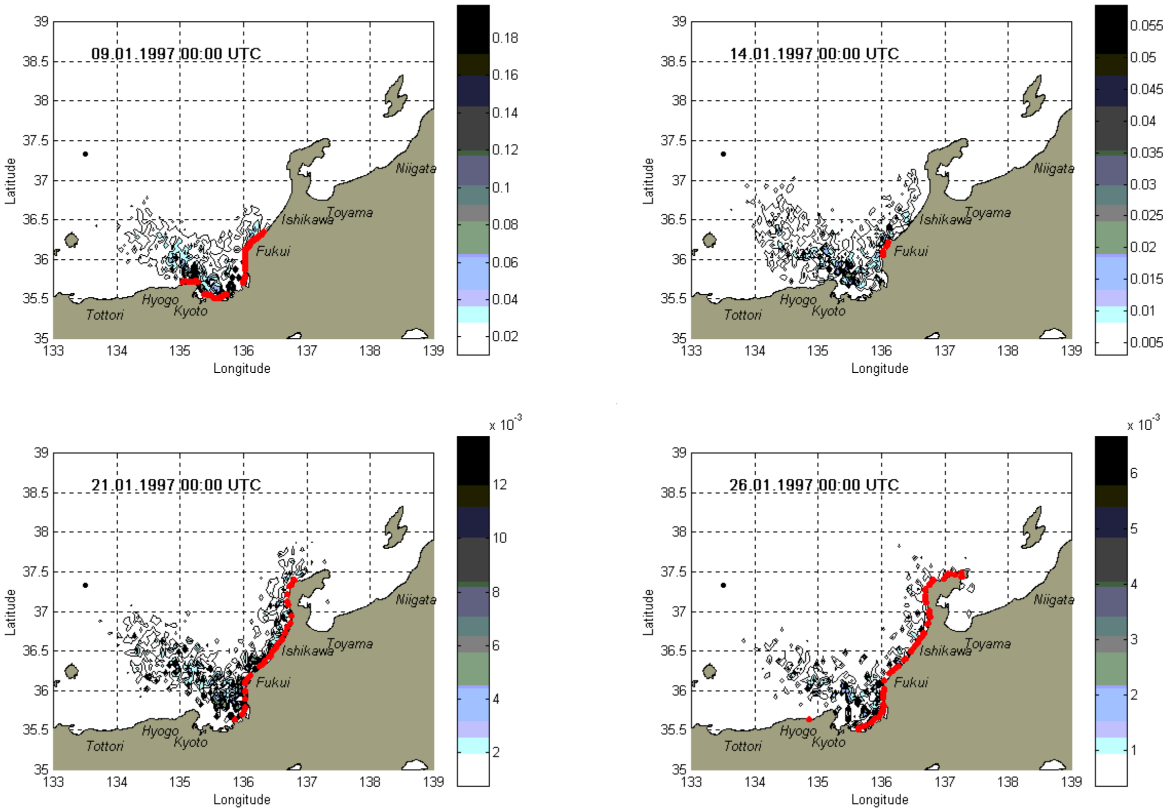

Fig. 7. Modeled concentration (mg/m^3) of spilled oil in upper 5 m sea layer

These results show a good correspondence with observed features of the *Nakhodka* oil spill in the Sea of Japan, reported in Introduction. Chronology of the oil spreading along the coast of Japan is well reproduced by oil beaching features represented in Fig. 6. Simulated oil concentration field reflects the main features in distribution of observed oil in Fig. 1 as a number of random slicks widely distributed along the Japanese coast. Model reproduces the oil spreading to the north along the Japanese coast, although underestimate the speed of coastal current: simulated oil particles enter the Toyama bay east from Noto peninsula not January 20-21 as were observed, but January 25-26.

The main factor supposed to be responsible for the wide oil spreading after the incident was the sea currents that transported the spilled oil. It was confirmed by our experiments with single wind drift model. The wind drift current transported the main part of oil spilled in to the sea southeast and south to the coast of Japan. Largest oil particles, that tend to stay at the sea surface, were transported more quickly and were beached along the coast of Fukui, Hyogo, Tottori and Kyoto prefectures. Smaller particles mixed in to the water column were drifted more slowly by wind induced current which decay almost exponentially with depth. Spilled oil almost did not spread to the north along the Japanese coast and the coastal line of Ichikawa prefecture remained almost did not polluted in this case. The oil drift to the Niigata prefecture was not reproduced by model with the assumption of local wind drift current only.

Conclusion

The simulation and prediction of the oil spill evolution plays an important role for the planning of protection and spill response operations. In this sense the main conclusion after the oil spill incident in the Sea of Japan January 1997 was our understanding that to respond for incidental oil spills we have to create and routinely use the specialized informational and prediction system. As one of solutions the operational system for the incidental oil spill simulation and prediction in the Sea of Japan was created and is run in the RIAM, Kyushu University. Currently it is based on meteorological forecasts provided twice daily by the Japan Meteorological Agency, Japan Sea currents simulated by high resolution shallow water ocean circulation model in RIAM and the spill model which would be run by demand.

Simulation results for the Japan Sea oil spill January 1997 demonstrated that the oil spill system reproduces main features of observed oil spreading after the incident. Results showed that correct representation of the Japan Sea currents together with the high quality meteorological wind data were most important effects for the realistic simulation of wide oil spreading after the incident in the Sea of Japan January 1997. It will define the main efforts for the oil spill analysis and prediction system improvement.

Acknowledgments

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