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A numerical simulation of oil spill in the Seto-Inland Sea

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Abstract: A 3–D oil spill model is used for simulating the fate of oil spilled from an accident which happened at Mizushima on the Seto-Inland Sea in December 1974. The model calculates time evolution of the partition of spilled oil to surface oil slick, entrainment into the underlying water column and sedimentation on the bottom, with empirical formulae derived from laboratory experiments. The simulated distribution of oil spreading agrees fairly well with visual observations from aircrafts.

1. Introduction

The spilled oil in the sea changes its physicochemical properties with time (MACKAY and MCAULIFFE, 1988). Main processes affecting spilled oil are schematically shown in Fig.1. The oil is weathered with time due to various processes such as evaporation, entrainment, emulsification and biodegradation.

Advection is caused by both wind and water currents. It is calculated as the vector sum of a wind-induced drift and water current-induced drift.

For many years, Fay's three-regime spreading theory (FAY, 1971) has been commonly used for spreading which determines the aerial extent of spilled oil.

Evaporation transfers 20–40% of spilled oil from the sea surface to the atmosphere within several days, depending on the type of oil (REED, 1992). Although highly refined oil loses 75% or more of its volume through evaporation within a matter of days (SHEN *et al.*, 1991), C heavy oil dealt with in the present paper contains it very little, so that no evaporation of it is considered. Subsequent evaporation is treated together with biodegradation. Loss rate due to evaporation and biodegradation is specified as a constant of 10% per day.

Subject to wind and waves, oil on the sea surface is entrained into the underlying water column. Entrainment, strongly dependent on the turbulence and sea state, is described by an equation derived from a mixing length theory and a finite amplitude wave theory. The parameters in that equation are specified with an empirical formula (HORIGUCHI *et al.*, 1991).

The formation of water-in-oil emulsions (or mousse) depends on the oil composition and sea state. Emulsified oil in the form of micrometer-sized dispersed droplets can contain water as much as 80% of its mass. The entrainment rate of water into oil slick is specified with a formula by MACKAY *et al.* (1979). Increase of oil viscosity with time governing the entrainment rate is specified with a relationship between the viscosity and water content by MACKAY *et al.* (1981). The rate of water content increase with time is given by a JOIA report (1988). The oil-in-water emulsification process is ignored because it is not significant for C heavy oil.

These various processes interact with each other in a complex way. The model used here (called SPILOR) is composed of several submodels as shown in Fig. 2. In this model, behavior of oil spill is described by an advection-diffusion equation with processes of floating, sinking, entrainment, emulsification, evaporation and biodegradation. Bond's formula is used for floating process, and Stokes's formula for sinking process (JOIA, 1988). The equations are solved by using finite difference method. Details of the model structure are described in another paper (HORIGUCHI *et al.*, 1991)

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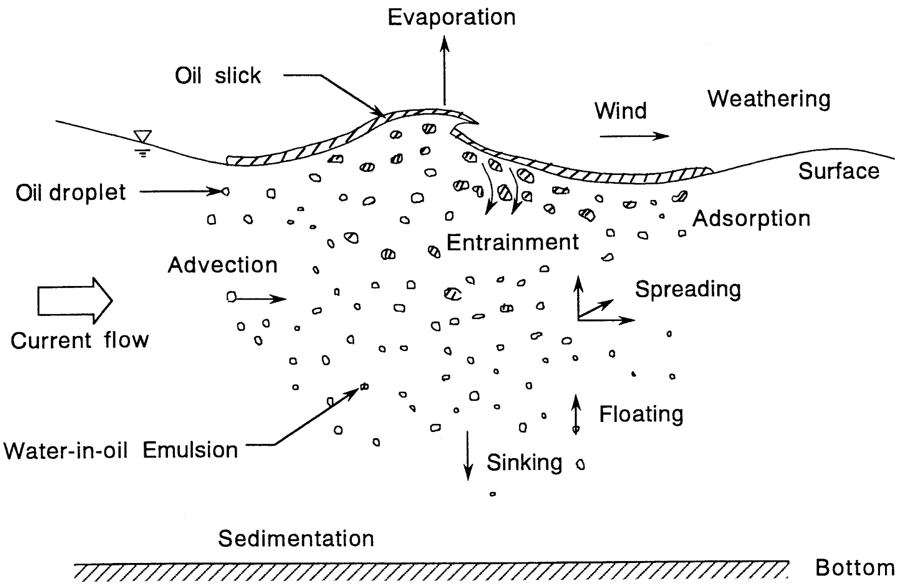


Fig. 1. Oil spill processes.

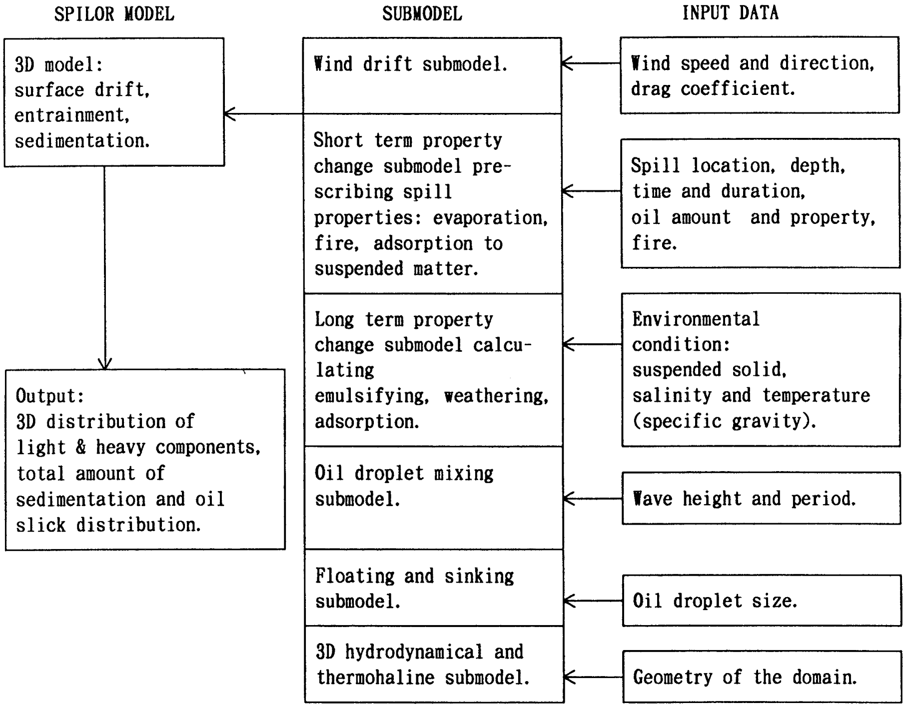


Fig. 2. Structure of the model (SPILOR).

2. Application of the SPILOR to the Seto-Inland Sea

The model is applied to an oil spill accident in the Seto-Inland Sea which occurred at Mizushima oil plant of Mitsubishi Petroleum Corporation at 21:00 on Dec. 18, 1974. The En-

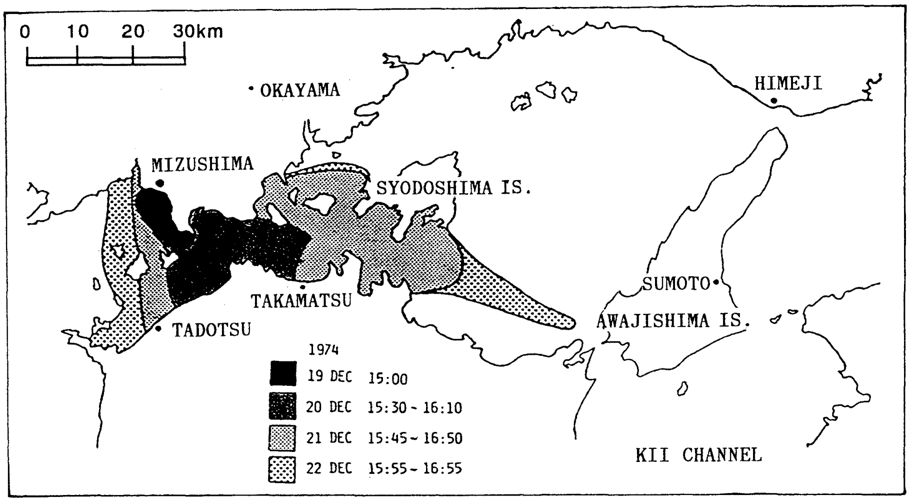


Fig. 3. Transition of oil spreading area visually observed from aircrafts of the 5th and 6th Regional Maritime Safety Headquarters. (YANAGI and OKAMOTO, 1984)

vironment Agency estimates an amount of 7500∼9500kl C heavy oil was spilled (Environment Agency, 1975). The spread of oil from 19 to 22 Dec. 1974 is shown in Fig. 3 (YANAGI and OKAMOTO, 1984), where spreading area is determined with visual data from aircrafts. The oil concentration is not reported, however.

2.1 Circulation calculation

To begin with, the circulation is calculated with a 3-D hydrodynamical and thermohaline submodel (Fig.2). The calculation domain is enclosed by three open boundaries A-A′, B-B′ and C-C′ as shown in Fig. 4. The grid size is variable; the finest one is 1.5 km in the north-south direction at Mizushima area (source area) and the coarsest one is 3.0 km in both east-west and north-south direction at the remote area. Basically five layers are set up in the vertical; 0-2m, 2-5m, 5-10m, 10-20m and 20-201m. The thickness of the lowermost layer varies according to the bottom depth.

Since the M_2 tide is dominant in the Seto-Inland Sea (Oceanogr. Soc., 1985), only the M_2 tide is considered for tidal forcing, and to be a representative of the semidiurnal tides, so that its period is taken to be 12 hours instead of 12.42 hours. The tidal amplitudes and phases are specified by a tidal harmonic constants table (Hydrographic Department, 1989) at A, A′, B, B′, C and C′. Amplitudes and phases along the lines A-A′, B-B′ and C-C′ are determined by interpolation.

The temperature and salinity at the open boundaries are specified with climatological data by past observations in winter (Oceanogr. Soc., 1985). The initial conditions of temperature and salinity for the interior of the domain are specified also with climatological data (Oceanogr. Soc., 1985). The surface salinity flux is neglected. The fresh water supply from rivers is given by monthly data in Dec. 1988 (Ministry of Construction, 1988a). For the surface heat flux, only the solar radiation and cloud cover are considered; latent and sensible heat fluxes, upward and downward long wave radiation are ignored. The temperature of the fluvial fresh water is specified with monthly data (Ministry of Construction, 1988b). The surface wind stress is neglected, so that the wind driven current is neglected.

The coefficient of horizontal eddy diffusion for momentum, heat and salinity is taken to be $50\,\mathrm{m^2/s}$ based on field data of drifting card (NAKATA and HIRANO, 1978). The coefficient of vertical eddy diffusion for momentum, heat and salinity is constant horizontally but variable vertically with the Richardson number which is variable with vertical stability. Although the vertical stability is slightly time-dependent in the course of time integration, it is taken to be a constant in time; $0.3\times10^{-4}\mathrm{m^2/s}$ at the surface

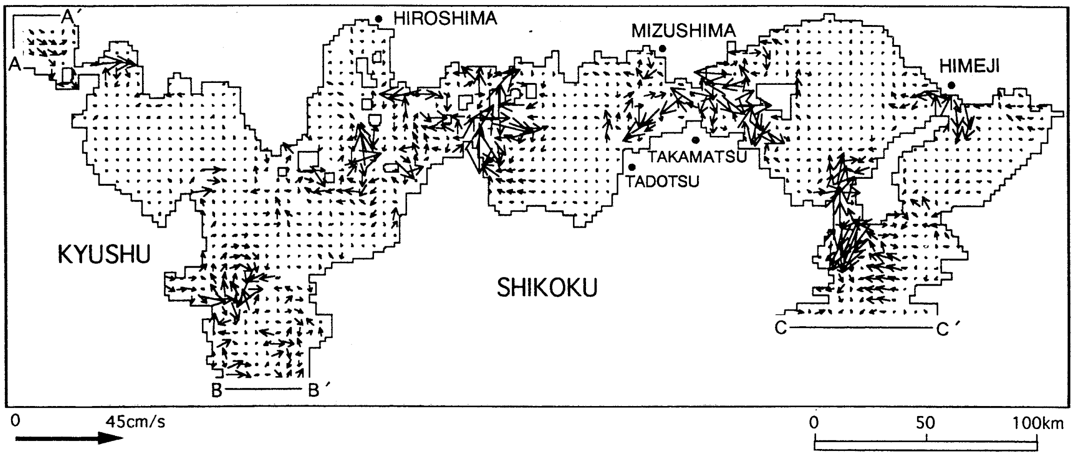


Fig. 4. Distribution of the simulated flow at the first layer. The arrow length is proportional to the speed.

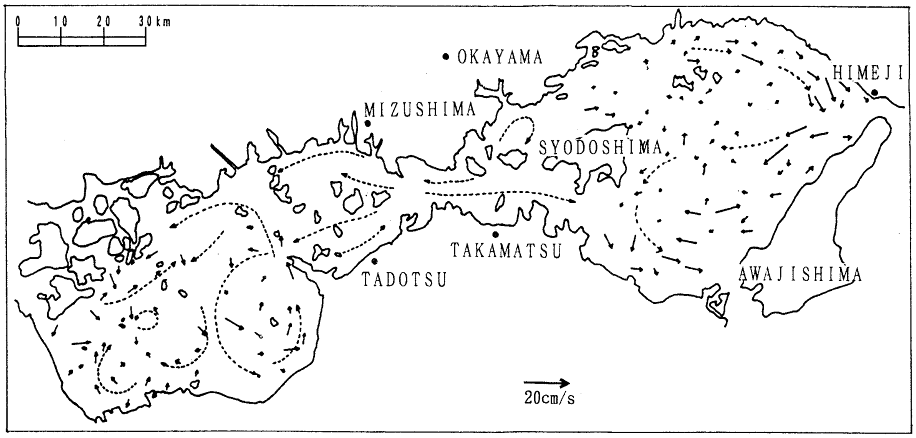


Fig. 5. Distribution of the observed flow at 10m depth. The arrow length is proportional to the speed. Dotted lines show the flow pattern schematically. (Oceanogr. Soc., 1985)

layer and $0.5\times10^{-4}\text{m}^2/\text{s}$ at the deeper layers. The equations for momentum, heat and salinity are integrated for 48 hours with a time step of 30 seconds. The boundary conditions mentioned above are kept constant in time, except for sea levels at the open boundaries.

The distribution of the calculated flow averaged over the last 12 hours is shown in Fig. 4, although a period of 48 hours is obviously too short for the thermohaline flow to reach a statistically almost steady state. Figure 5 schematically shows the flow pattern based on observed data (Oceanogr. Soc., 1985). Figures 4 and 5 are qualitatively similar to each other, though neither longer period tidal currents nor wind-driven currents are taken into account in the calculation. Off Mizushima, the calculated flow is eastward with 3cm/s, while no observed data are available. To the east of Shoudoshima Island the calculated velocity at the 1st layer is generally 1–10cm/s smaller than the observed one. The calculated velocity at the 2nd layer is almost the same as that at the 1st layer.

2.2 Estimation of dispersion

The grid structure is the same as that for the circulation calculation except for adding a very thin sheet over the sea surface. Oil in the surface sheet moves with the water in the first layer without slipping. The surface oil thickness is not explicitly calculated, but only the oil amount in the surface sheet is a prognostic variable. The oil is assumed to be initially spilled into the surface sheet $2.25\text{km} \times 1.5\text{km}$ large on one grid box surface off Mizushima. The oil entrained from the surface into the underlying water column is dispersed by horizontal and vertical subsurface flows, diffusion, sinking and floating due to its density relative to surrounding water density.

The dispersion is calculated for 20 days starting on Dec. 18 for two cases; one is the case of no oil entrainment and the other with oil entrainment. In the former case, there is no adsorption, no sedimentation, either; there is no downward pathway from the surface.

A continuous source, constant in time for 6 hours, is set up off Mizushima. The total amount is 10000 t. The specific gravity of oil is 985kg/m^3, a typical value of C heavy oil. The coefficient of horizontal diffusion is taken to be $20\ \text{m}^2/\text{s}$, which is consistent with the field data cited above. The coefficient of vertical diffusion is taken to be $0.5 \times 10^{-4}\text{m}^2/\text{s}$ in the surface sheet and $1 \times 10^{-4}\text{m}^2/\text{s}$ at the 1st to lowermost layers. The time step is 600 seconds.

Daily mean wind velocity is calculated from data supplied every 3 hours from 18 weather stations around the Seto-Inland Sea (Fig.6a). These data are interpolated by using spline method in space at each grid point. Linear interpolation in time applies at each time step. So far the difference of the wind between at sea and on the land has been discussed (e.g., U.S. Army Coast. Eng. Res. Center, 1966). The offshore wind can reach up to 1.5 times as fast as the wind on land, but offshore increase of wind speed is ignored here. The wind is assumed to bring about an oil advection at a rate of 3% of its speed. Vector diagrams of the wind velocity are shown from Dec. 18, 1974 to Jan. 6, 1975 in Figs. 6b, c. At stations near Mizushima (e.g., Okayama, Takamatsu, and Tadotsu) the wind is dominantly eastward with a speed of about 3 m/s for these days, so that its effect on oil advection is greater than that of water flow with a speed of 3cm/s.

In the case of no oil entrainment, Fig. 7 shows the distribution of oil concentration (oil amount divided by a grid box area) in the surface sheet at 1 day, 6 days and 20 days after. Concentration of 100mg/m^2 is colored purple. Very thick oil reaches Awaji Island (90km apart from the source) 20 days after spill, showing an average eastward speed of 5cm/s. This speed is compatible with wind and current speed. The wind speed is much more important than the current speed in the surface dispersion. Figure 3 gives an eastward speed of about 23cm/s averaged over the first 4 days. The simulation gives 12cm/s averaged over the first 6 days (Fig. 7b), which is smaller than the observed speed by a factor of about 2.

Figure 8 shows the distribution in the surface sheet in the case of oil entrainment at 1 day, 6 days and 20 days after. There is no significant difference between Figs. 7a, b and 8a, b, which indicates the oil entrainment is negligibly small

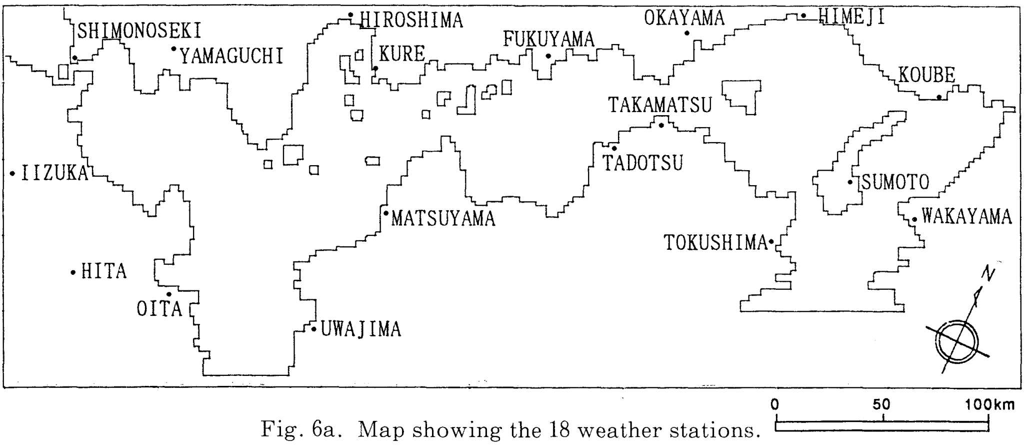


Fig. 6a. Map showing the 18 weather stations.

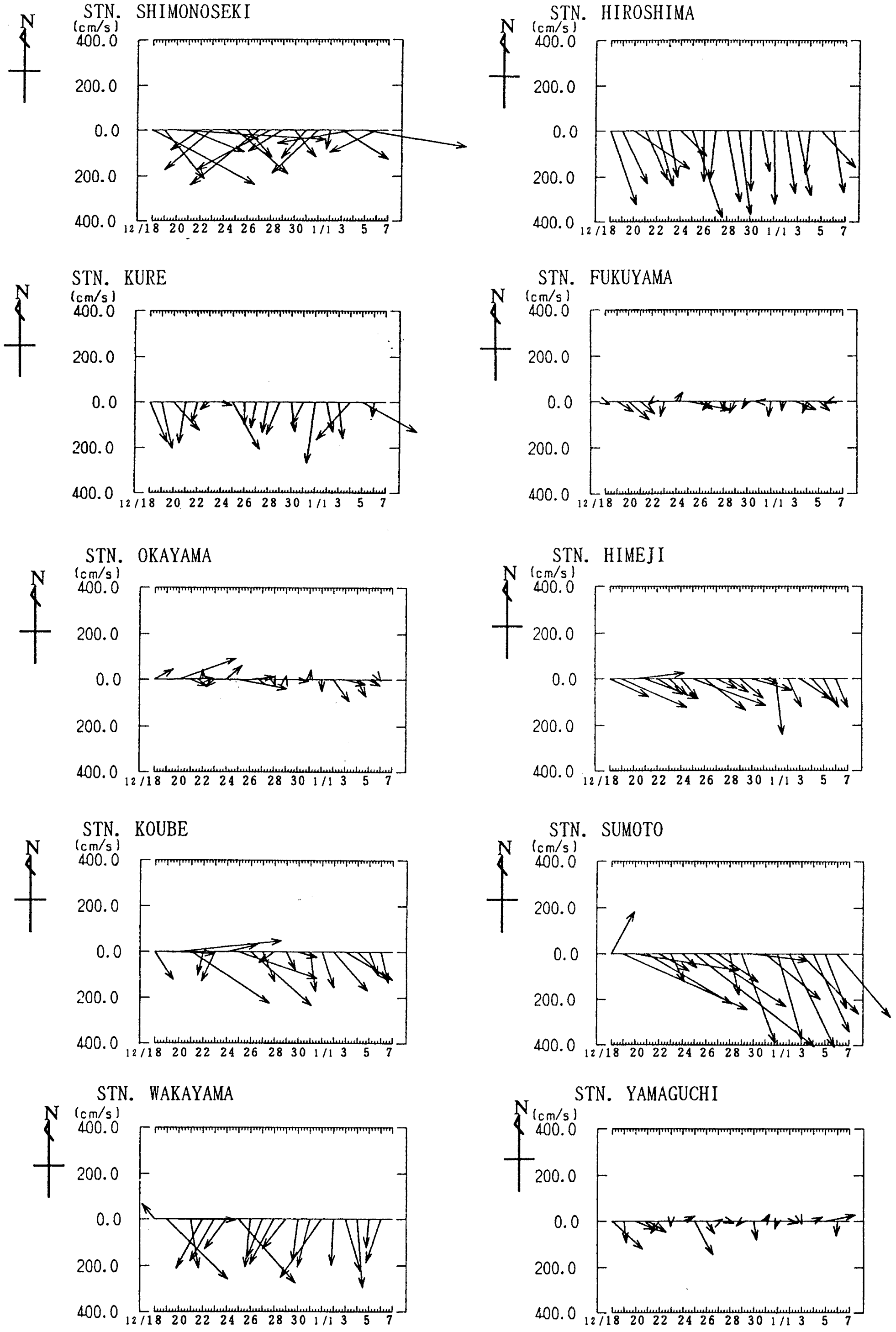


Fig. 6b. Vector diagrams of the wind velocity for Dec. 18, 1974 to Jan. 6, 1975 at 10 weather stations shown in Fig. 6a.

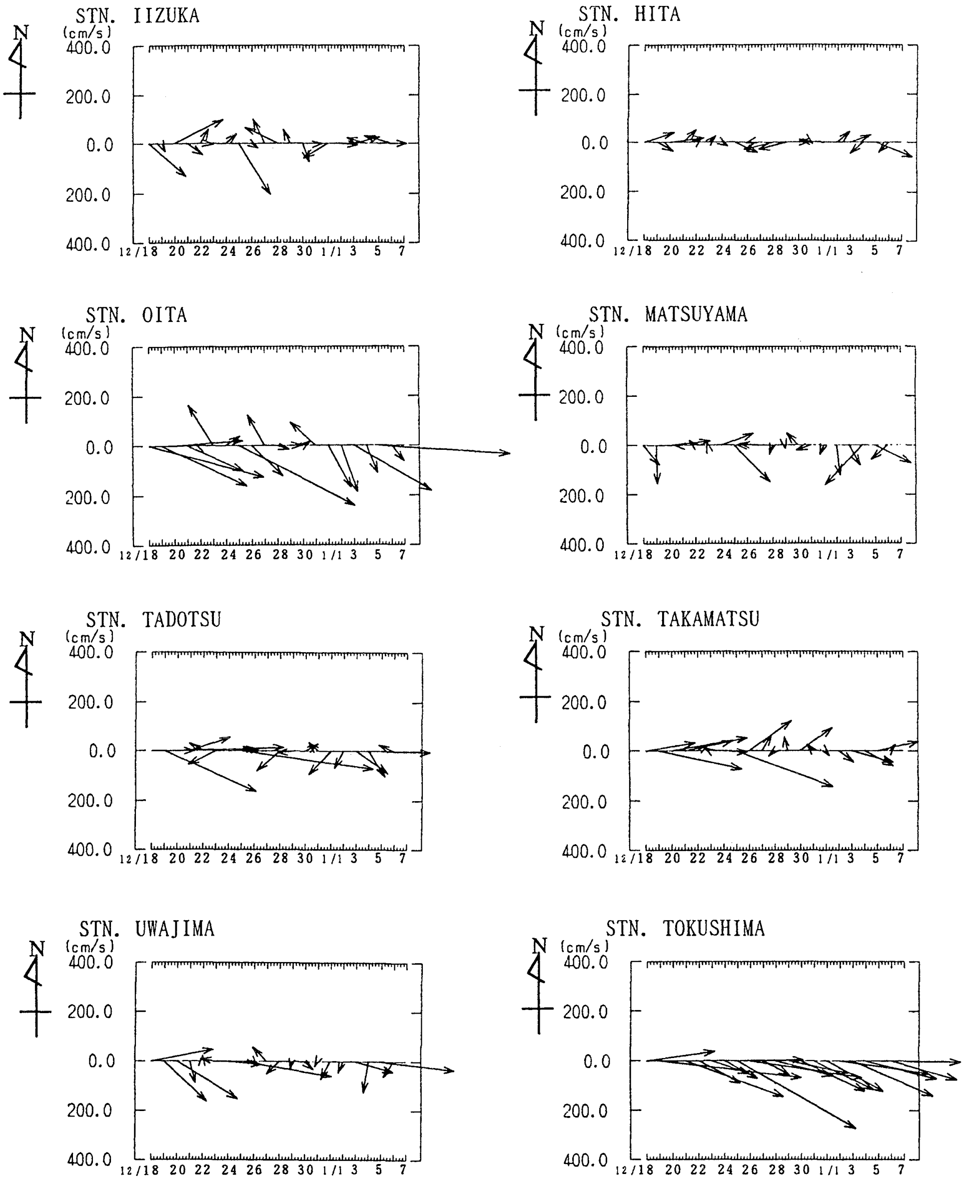


Fig. 6c. Same as Fig. 6b except for stations.

for the first 6 days. The difference is, however, striking between Figs. 7c and 8c 20 days after, probably because of the water content increase in oil droplet with time, which enhances entrainment into deeper layers through the oil density increase. While there is no significant difference in oil extent between days 6 and 20 in the case of entrainment (Figs. 8b, c), there is in the case of no entrainment (Figs. 7b, c); in other words, the expanding speed is very small between days 6 and 20 in the former case but still significant in the latter case because it remains a small amount of oil on .the surface with entrainment, but a large amount of oil on the surface without entrainment.

The distribution of oil concentration at the 1st layer (0–2m depth) is shown in Figs. 9a, b, c. Comparison of Fig.8 with Fig.3 shows that the

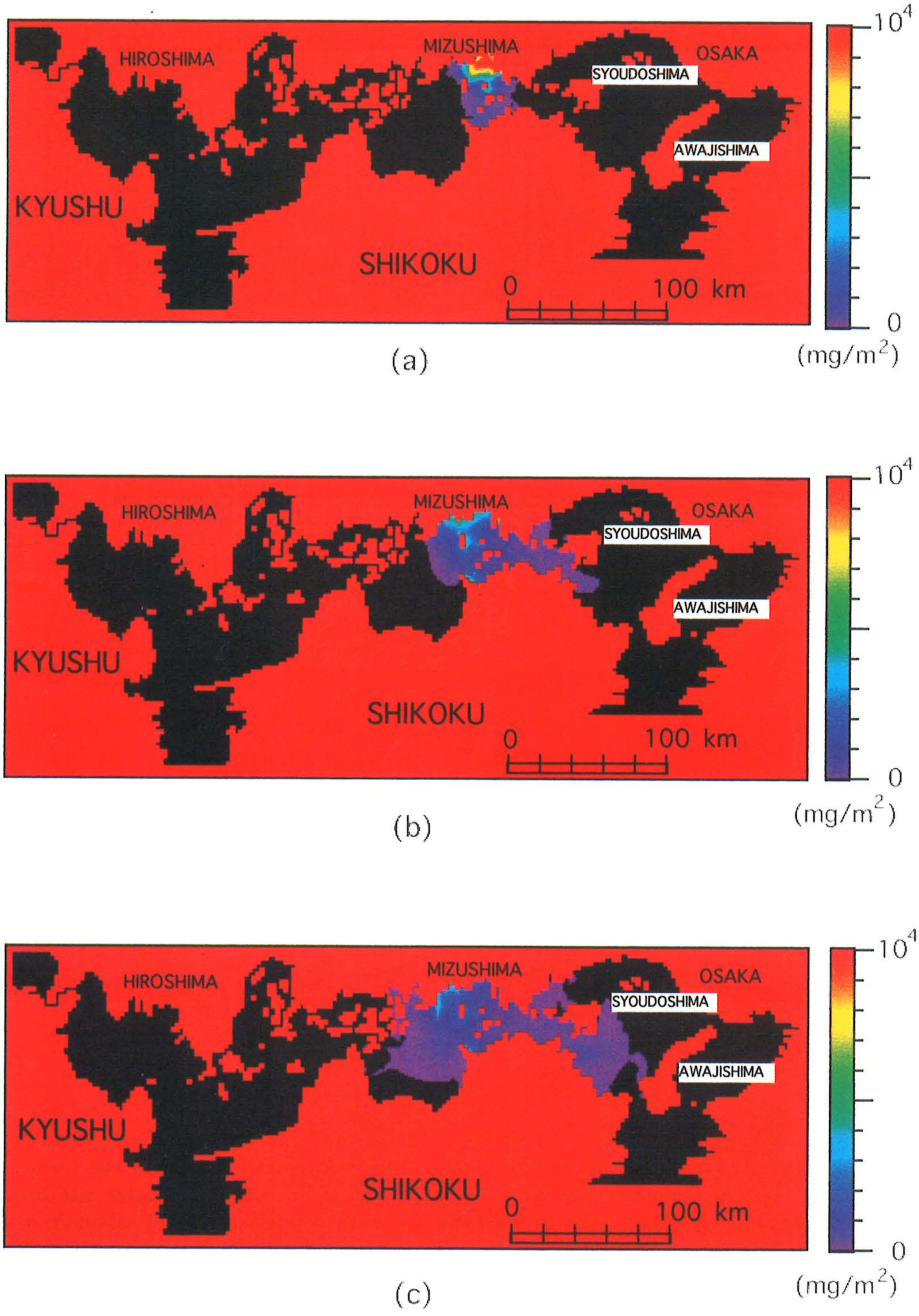
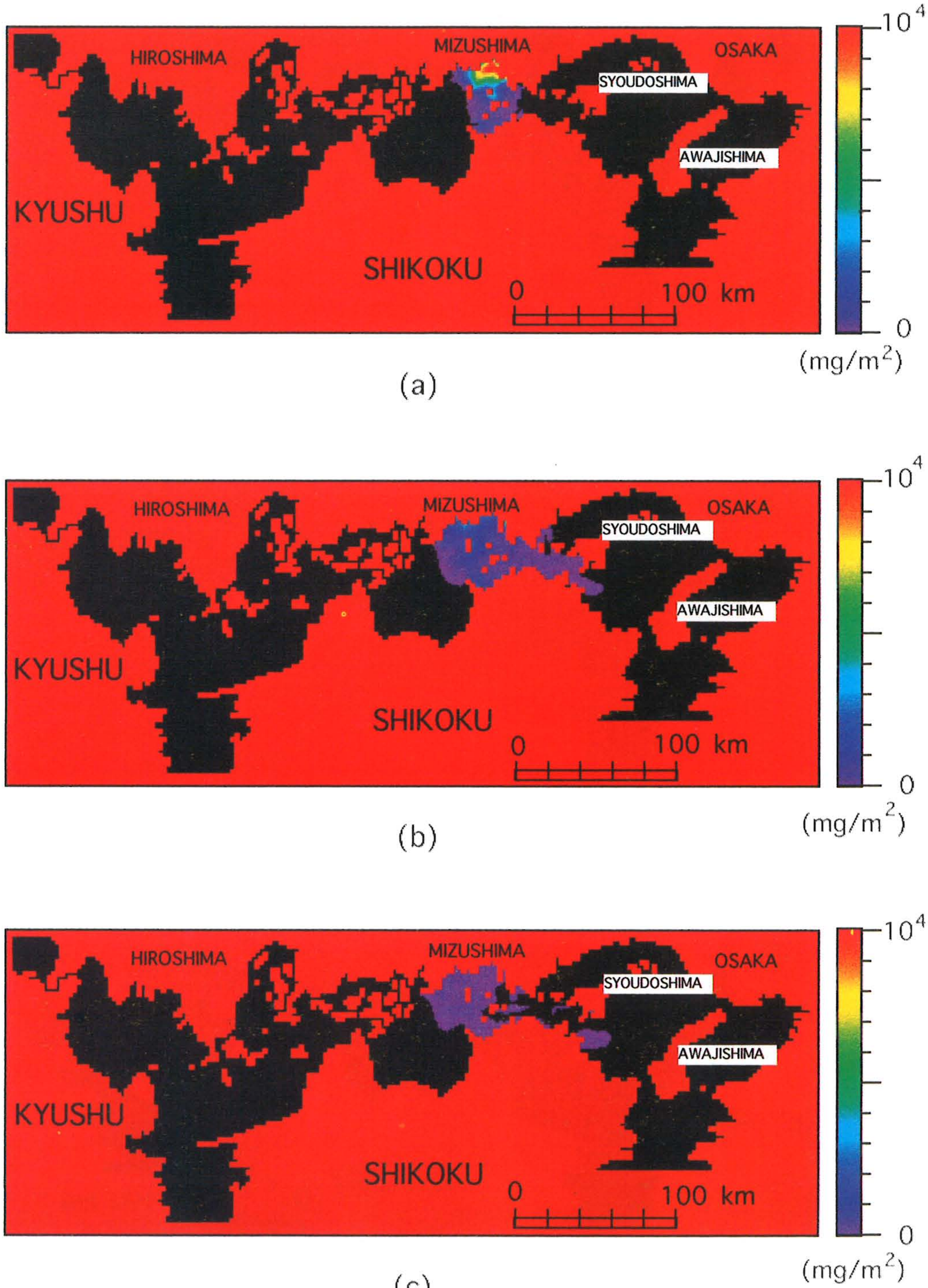


Fig. 7. Distribution of the oil concentration in the surface sheet. (a) one day, (b) 6 days and (c) 20 days after oil spill without oil entrainment.



(a)

(b)

(c)

Fig. 8. Same as Fig. 7 except for the case of oil entrainment.

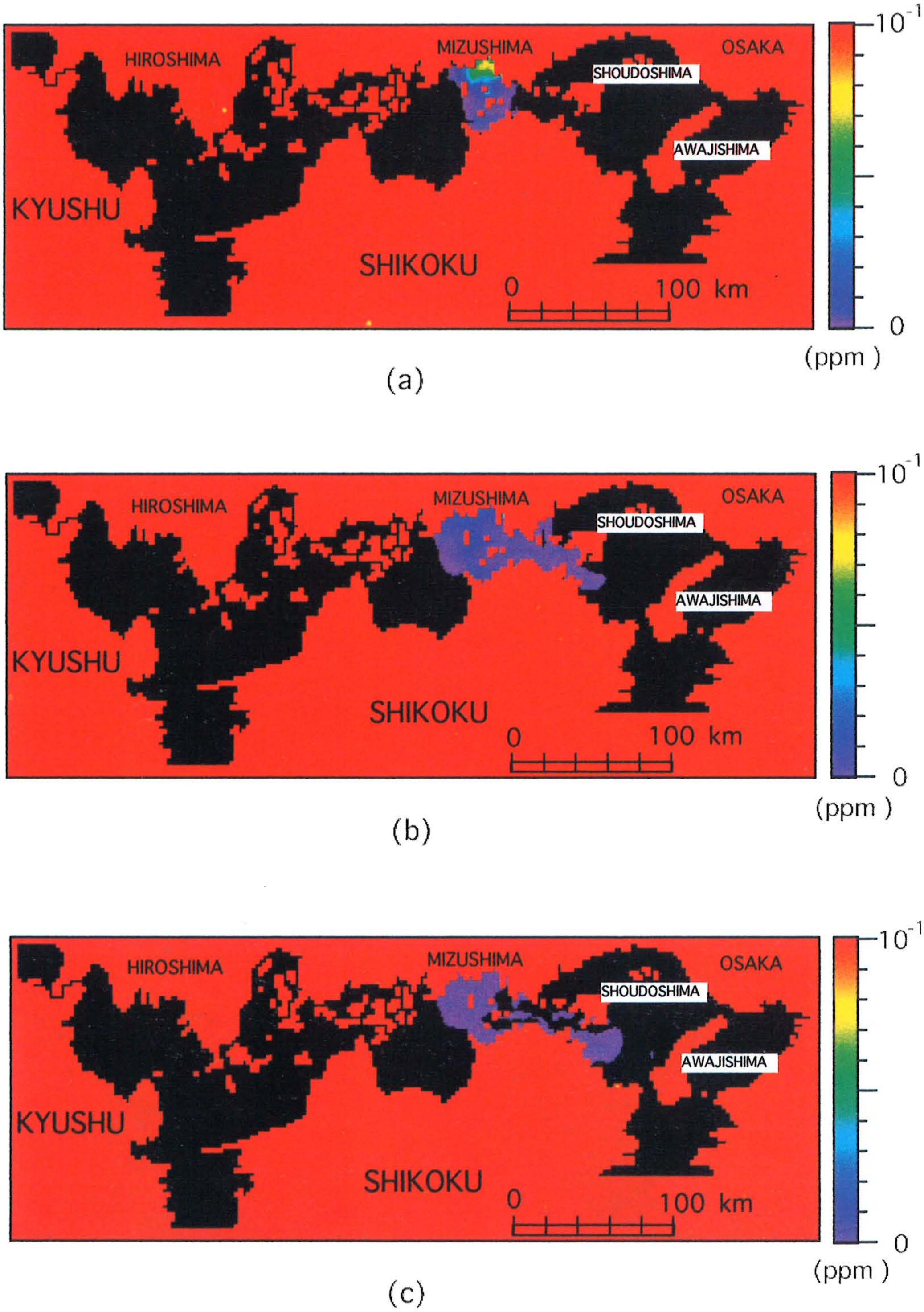


Fig. 9. Same as Fig. 8 except for the 1st layer.

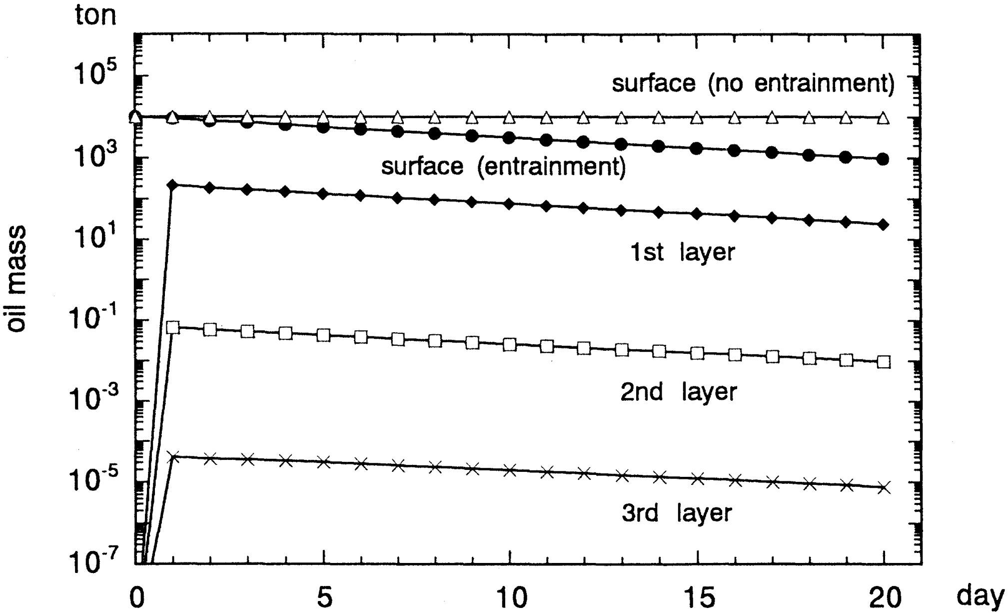


Fig. 10. Time variations of the oil amount in the surface sheet and the 1st to 3rd layers.

calculated extent of oil at the 6th day agrees fairly well with the observed one at the 4th day (22 Dec.). But the calculated extent is much wider to the west of Mizushima, probably due to the underestimated wind speed and wind drift factor. Results of previous studies on the drift factor range from 2.5% to 5.3% (REED, 1992). If it is specified as 5–6% instead of 3% with the wind speed used above, or if it is about 4% with the wind speed intensified above the sea surface by about 50%, the calculated extent will be wider to the east and narrower to the west than that calculated above, and agree better with the observed one. As to the westward dispersion, Fig. 3 gives 4.3 cm/s (mean distance 15km divided by 4 days) and the simulation gives 7.7 cm/s averaged over the first 6 days. If the wind factor is assumed to be 6%, the simulated speed will be about 3.8cm/s, which fairly agrees with the observed speed.

Time variations of the oil amount in the surface sheet with and without entrainment, and in the 1st to 3rd layers with entrainment are shown in Fig.10. The oil amount at the 4th, 5th layers and on the bottom are less than 10^{-5}t. At the end of time integration (day 20) in the case of entrainment, the oil amount is 1079t (10.8% of the initial amount) in the surface sheet and about 27t in the underlying layers. In the case of no entrainment, it is 9996t (99% of the initial amount) in the surface sheet. Most of oil in the surface sheet and in the underlying layers is decreased by weathering: evaporation and biodegradation in the surface sheet, and biodegradation in the underlying layers.

3. Concluding remarks

A 3-D oil dispersion model (SPILOR) is applied to the oil spill accident happened at Mizushima in Dec. 1974 in the two cases; with and without oil entrainment.

The striking difference between the results in the two cases emphasizes importance of the oil entrainment in predicting the oil extent for time scales longer than several days.

The simulated extent agrees fairly well with observation, but improvements are needed to correctly imbed the processes of concern in the model. For the present, the model validation is not easy because very few data are available on the concentration and property change of spilled oil. Only a limited amount of data are available from laboratory experiments. In the meantime, more numerical experiments are useful for understanding how sensitive the model is to various processes and parameters such as the wind drift factor, weathering, entrainment, emulsion formation. In addition, the oil thickness should be explicitly dealt with as a prognostic variable, and the biodegradation should be properly modeled, though it is treated together with evaporation in the present study. While these problems are approached with numerical and/or laboratory experiments, carefully designed field experiments are crucial for the model validation and improvement.

References

Environment Agency (1975): Oil spill accident at Mizushima: pollution survey. Rept. No.6, Environ. Agency, Tokyo. (in Japanese)

Fay, J. A. (1971): Physical processes in the spread of oil on a water surface. Proc. Joint Conf. on the Prevention and Control of Oil Spills, API, 463–467.

Horiguchi, F., K. Nakata, T. Kojima, S. Kanamaki and S. Sugioka (1991): Fate of oil spill in the Persian Gulf. Pollution Control, **26** (4), 39–62. (in Japanese)

Hydrographic Department (1989): Tidal harmonic constants table. 42–78. Hydrogr. Dept., Tokyo.

JOIA (Japan Ocean Development Industry Association) (1988): Technical report on the environmental impact assessment associated with oil development in the sea. JOIA, Tokyo, 310pp. (in Japanese)

Mackay, D. and C. D. McAuliffe (1988): Fate of hydrocarbons discharged at sea. Oil & Chemical Pollution, **5**, 1–20.

Mackay, D., I. Buist, R. Mascarenhas and S. Paterson (1979): Experimental studies of dispersion and emulsion formation from oil slicks. Workshop on phys. behavior of oil in the mar. environ. Princeton Univ., National Weather Service, Silver Spring, Maryland, **1**, 17–40.

Mackay, D., S. Paterson, P. D. Boehm and P. L. Fiest (1981): Physical-chemical weathering of petroleum hydrocarbons from the Ixtoc I blowout. Chemical measurements and a weathering model. Proc. 1981 Oil Spill Conf., 453–460.

Ministry of Construction (1988a): Annual report of fluvial discharge. Japan River Association, Tokyo. (in Japanese)

Ministry of Construction (1988b): Annual report of water quality. Kanto Kensetu Kouseikai Publ., Tokyo. (in Japanese)

Nakata, H. and T. Hirano (1978): On the dispersion and convergence of properties in straits and approaches. Bull. Coast. Oceanogr., **16**, 31–42.

Oceanographical Society of Japan (1985): Coastal Oceanography of Japanese Islands. 694–698. Tokai Univ. Press, Tokyo. (in Japanese)

Reed, M. (1992): Modeling of physical and chemical process governing fate of spilled oil. ASCE Workshop on oil spill modeling, Charleston, South Carolina, 26pp.

Shen, H. T., P. D. Yapa, D. S. Wang, and X. Q. Yang (1991): A mathematical model for oil slick transport and mixing in rivers. Dept. Civil and Environ. Eng., Clarkson Univ., Rept. 91–1, 118pp.

U.S. Army Coastal Engineering Research Center (1966): Shore protection, planning and design. Tech. Rept. No.4.

Yanagi, T. and Y. Okamoto (1984): A numerical simulation of oil spreading on the sea surface. La mer, **22**, 137–146.