Chapter 4

SURF - A simulation model for the behaviour of oil slicks at sea

38274

ZHANG Bo and ZHANG Cunshi
Physical Oceanographic Division, Institute of Marine Environmental Protection, SOA, P.O. Box 303, 116023, Dalian, China.

J. OZER
Management Unit of the North Sea and the Scheldt Estuary Mathematical Models, Gulledelle 100, B-1200 Brussels, Belgium.

1. Introduction

This report describes the SURF model, one of the basic models of the OPERA software package, which predicts the fate of oil spilled at sea.

SURF is a fully operational computer model for describing the behaviour of oil slicks at sea. With necessary information, it may be used to simulate or to forecast the transport, the spreading and the aging of oil slicks. The model aims mainly at forecasting the behaviour of a pollution in case of an accident at sea. The information provided by the model (position and extent of the polluted area, oil characteristics) can efficiently help the authorities and the combating teams in making decisions on how to wrestle the pollution. But other model applications can be faced. For instance, knowing the zones where oil is extracted, carried or trans-shiped, the model can be used to investigate, *a priori*, the high risk areas.

During the last decades, a large number of computer models to simulate the behaviour of oil slicks at sea have been developed. Efforts have been devoted to various components of the behaviour : transport, spreading and aging.

Transport is usually considered to be controlled by water current, wind-induced current and wave drift. Water current which contributes 50-100 % to the movement of the slick might be tidal current or residual current depending on the objective of the simulation and the problem at hand. For instance, tidal current might be important when the slick is close to a sensitive area, whereas residual current might be prevailing for longer period. The advection of the slick caused by wind is commonly parameterized with a magnitude of 2-4 % of wind speed and a direction to the right of the wind direction (Northern hemisphere) at a deflection angle of 0-40 degree. Wave-induced transport, generally in the order of magnitude of a few centimeters per second, has been emphasized by Kuipers (1981) and described as a Stokes drift in some models. The accuracy of the simulated transport relies highly on the modelling of meteorological and hydrodynamical conditions.

For the spreading, Fay's theory (Fay *et al.*, 1971) has been widely used because it is based on a rather comprehensive description of the spreading mechanisms and has been calibrated by laboratory experiments and other analytical solutions (Hung *et al.*, 1988). A circular shaped slick with uniform thickness passes through three phases, according to Fay, under the balance of gravity-inertia forces, gravity-viscosity forces and surface tension-viscosity forces respectively for each phase.

Various aging processes (*e.g.*, evaporation, dispersion, dissolution, emulsification, sedimentation, biodegradation and so on) have been investigated and are sometimes incorporated in the models. Evaporation, as main aging process, proves to be responsible for the loss of up to 60 % of the spilled oil. The importance of the interaction between spreading and aging has been realized and the effect on spreading of the modification of oil properties tends to be taken into account. Thorough reviews of the oil spill models can be found in Huang (1983) and Scory (1984).

However, the behaviour of oil slicks at sea is dominated by numerous physical, chemical and biological factors with varying significance as function of time. The complexity and the lack of clear understanding of many processes, especially concerning the aging, results in the difficulty of the formulation. Simplification and empiricism have to be introduced into the modelling. Further experiments and studies are still needed to improve the reliability and accuracy of the expressions used to parameterize various processes. Nevertheless, it seems impractical to deal with all the factors in an oil spill simulation and prediction model. In an emergency situation, when an oil spill incident occurs at sea particularly near the coast, attention will be mostly concentrated on the behaviour of the slick at the early stage after the spillage (*e.g.*, several hours to a few weeks). In that case, it is more reasonable and useful to take into account the factors which are prominent during this period while omitting the others and to use, for these factors, simple formulations able to give, at least, a good order of magnitude using the sparse information available in real time.

The SURF model, based on the work of Scory (1984), deals with the following processes:

(i) transport,
(ii) spreading,
(iii) aging:
- evaporation,
- spray formation,
- emulsification,
- dispersion,
- dissolution,
- mechanical recovery,
- density, surface tension and viscosity changes.

In the model, an extension of Fay's point of view for spreading is used, where the influence of the evolution of the oil properties (density, viscosity and surface tension) on spreading is taken into account. Aging processes are mostly expressed as functions of oil volume, wind speed and wave height, the latter taken as a quantifier of the sea state. Model formulas are summarized in section 2.

The computer program is illustrated in section 3, while section 4 describes an application of the model in a real incident* which occured in the Bohai Sea (China). Some conclusions are drawn in the last section.

2. Model formulation

The purpose of this section is to provide a brief description of the parameterization of the various processes taken into account in the model. Further details on this parameterization can be found in Scory (1984, 1991). The presentation is organized as follows :

(i) Transport : general movement of the slick,
(ii) Spreading : relative movements of elementary particles constituting the slick,
(iii) Aging : modifications of the physical and chemical properties of the oil.

2.1 Transport

The velocity of the gravity center of the slick due to water current and wind is written as a vectorial addition:

$$U_{oil} = U_{water} + \alpha\, \mathbf{D} . U_{air}$$

where

U_{oil}	:	the velocity of the slick center,
U_{water}	:	the water current velocity,
U_{air}	:	the wind speed at 10 meters above sea level,
α	:	the wind drift factor.
D	:	the transformation matrix which allows to introduce a deviation angle :

$$\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

In the applications discussed in section 4, the wind drift factor is set equal to 0.0315 (a value commonly used in this type of models) and the deviation angle is computed according to :

θ : $40° - 8\sqrt{U_{air}}$ when $0 \leq U_{air} \leq 25$ m/s,
0 when $U_{air} > 25$ m/s.

2.2 *Spreading*

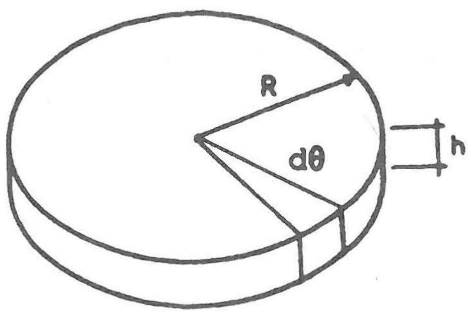


Figure 2.2.1 A schematic slick and an elementary sector.

Assuming that the slick has a circular shape (Fig. 2.2.1), the spreading of the slick is derived from a balance between driving forces (*i.e.*, gravity [F_{gr}] and surface tension [F_{st}]) and retarding forces (*i.e.*, inertia [F_i], viscosity force at the oil-water interface [F_v] and internal viscosity force [F_{iv}]). The balance of forces reads :

$$F_{gr} + F_{st} = F_i + F_v + F_{iv}$$

The expression of the various forces is :

$$F_{gr}=\frac{gV^2\rho_o\Delta}{2\pi^2R^3}d\theta$$

$$F_{st}=\sigma R\ d\theta$$

$$F_i=\frac{\rho_o V}{3\pi}\ddot{R}\ d\theta$$

$$F_v=0.49426\rho_w\sqrt{\frac{v_w}{\pi}}(R\dot{R})^{1.5}d\theta$$

$$F_{iv}=v_o\ \rho_o\frac{V}{\pi}\frac{\dot{R}}{R^2}d\theta$$

where

$$\Delta=\frac{\rho_w-\rho_o}{\rho_w}$$

V :	the volume of oil (m^3),
R :	the radius of the slick (m),
ρ_w and ρ_o :	the density of water and oil respectively (kg/m^3),
σ :	the net surface tension (kg/s^2),
$\dot{R}$:	the spreading rate (m/s),
$\ddot{R}$:	the acceleration of spreading (m/s^2),
v_w and v_o :	the viscosity of water and oil respectively (m^2/s).

By a number of numerical experiments, it has been found that internal viscosity is too weak to exert any noticeable effect on spreading. Therefore it has been decided to neglect this term in the spreading equation used in SURF. Then the equation for spreading under the balance of the other four forces may be written as :

$$\ddot{R}=\frac{3gV\Delta}{2\pi R^3}+\frac{3\pi\sigma R}{\rho_o V}-2.62817\frac{\rho_w\sqrt{v_w}}{\rho_o V}(R\dot{R})^{1.5}$$

Two initial conditions are needed to solve the equation. According to Kuipers (1981), the initial radius of the slick may be set equal to $K\sqrt{V}$ where K is a dimensional factor equal to 1 $m^{-1/2}$.

Another condition is found by assuming that the slick behaves as prescribed by the first Fay's law at the very early stage of its life. In this case, the initial spreading rate is given by:

$$\dot{R}(0) = 0.65\sqrt{g\Delta}$$

Based on field observations, Fay (1971) suggested that changes in slick properties caused by aging may result in the eventual cessation of the mechanical spreading. This idea is adopted in SURF. The simulation of the spreading process is stopped when the radius of the slick reaches a maximum value computed according to :

$$R_{max} = \sqrt{10^5\ V^{0.75}/\pi}$$

2.3 *Aging*

2.3.1 *Evaporation*

The time evolution of the evaporated volume is computed according to :

$$\dot{V}_e = \frac{\pi}{4}\ K_{ev}\ 2^{2-\beta}\ U_{air}^{\alpha}\ C14\ R^{2-\beta}\ PM/60$$

where

V_e : the evaporated oil volume (m^3),
$K_{ev} = 1.2 \times 10^{-8}$ for a neutral atmosphere,
U_{air} : the wind speed (m/s),
PM : the product of the vapour pressure by the molecular weight,
$\alpha = (2 - n)/(2 + n)$,
$\beta = n/(2 + n)$,
n = 0.25, a turbulence parameter,
C14 = 0.02.

The evolution of the parameter PM is expressed by

$$\dot{PM} = -PM(0)\frac{\dot{V}_e}{\phi V_0}$$

where PM(0) is the initial value of PM, ϕ is the evaporable fraction of the oil and V_0 is the initial volume of the oil.

2.3.2 *Spray formation*

It is assumed to be directly proportional to the sea state and the untransformed volume

$$\dot{V}_{sa} = C6\ V_r\ H$$

where

$\dot{V}_{sa}$: the oil volume lost per unit time due to spray formation (m^3/s),
$C6 = 10^{-8}(ms)^{-1}$,
V_r: the untransformed volume of the oil remaining at the surface (m^3),
H : the wave height (m).

2.3.3 *Dispersion*

Similarly to the spray formation, we have:

$$\dot{V}_d = C5\ V_r\ H$$

where

$\dot{V}_d$: the oil volume lost per unit time due to dispersion (m^3/s),

$C5 = 3 \times 10^{-6}\ (ms)^{-1}$.

2.3.4 Dissolution

It is assumed that the rate of dissolution is proportional to the untransformed volume of oil :

$$\dot{V}_{\delta} = C7\ V_r$$

where C7 = 4 x 10^{-10} s^{-1}

2.3.5 Mechanical recovery

Assuming that the oil is recovered at a constant rate, we may write :

$$\dot{V}_{mr} = C17$$

where C17 (m^3/s) is the recovery rate.

2.3.6 Emulsification

The rate of emulsification is taken as proportional to the untransformed volume and sea agitation. Thus, the time evolution of the oil volume in the emulsion is computed according to :

$$\dot{V}_{em} = \frac{K_{em}}{C15} HV_r - C17 \frac{V_{em}}{V_t}$$

The water contents in the emulsion is based on the assumption that the ratio "water in emulsion to total volume of the emulsion" is constant :

$$\dot{V}_w = \frac{C18}{1-C18} \frac{K_{em}}{C15} HV_r - C17 \frac{V_w}{V_t}$$

where,

$\dot{V}_{em}$: the evolution of oil volume in the emulsion (m^3/s),

K_{em} : the ability of oil to form emulsion, varying between 0 and 120,
$C15 = 5 \times 10^7$ (ms),
$V_t = V_r + V_{em} + V_w$: the total volume of the surface slick,

$\dot{V}_w$: the evolution of water volume in the emulsion (m^3/s),
$C18 = V_w/(V_w + V_{em})$: is the "water in emulsion to total volume of the emulsion" ratio.

2.3.7 Slick balance

Based on the mass conservation law, the rate at which the oil "transforms" may be derived :

$$\dot{V}_{r1} = -\left\{ C4\ R^{2-\beta}\ PM + V_{r1} \left[H\ (C6 + C5 + \frac{K_{em}}{C15}) + C7 + \frac{C17}{V_t} \right] \right\}$$

and

$$\dot{V}_{r2} = -\left\{ V_{r2} \left[H \left(C6 + C5 + \frac{K_{em}}{C15} \right) + C7 + \frac{C17}{V_t} \right] \right\}$$

where

$\dot{V}_{r1}$: the time derivative of the evaporable fraction of the oil volume,

$\dot{V}_{r2}$: the time derivative of the "un-evaporable" fraction of the oil volume,

and

$$C4 = \frac{\pi}{4} K_{ev}\ 2^{2-\beta}\ U_a^{\alpha}\ C14/60$$

2.3.8 Property changes

Assuming that the slick is consists of an homogenous oil, its density writes :

$$\rho_o=[\rho_{r1}(V_{r1}+V_{em1})+\rho_{r2}(V_{r2}+V_{em2})+\rho_w V_w)]/V_t$$

with

ρ_w = 1026 (kg/m^3),
ρ_{r2} = 1.85 $\rho_o(0)$-0.00085 $\rho_o^2(0)$ when $\rho_o(0)$ < 1000 kg/m^3,
ρ_{r2} = $\rho_o(0)$ when $\rho_o(0) \geq$ 1000 kg/m^3,
ρ_{r1} = [$\rho_o(0)$ - ρ_{r2} (1 - ϕ)]/ϕ

where $\rho_o(0)$ is the initial density of the spilled oil.

The evolution of surface tension is modelled by the assymptotic expression :

$$\sigma=\sigma(0)\frac{V_r}{(V_r+V_{em})}$$

where $\sigma(0)$ is the initial value of the surface tension.

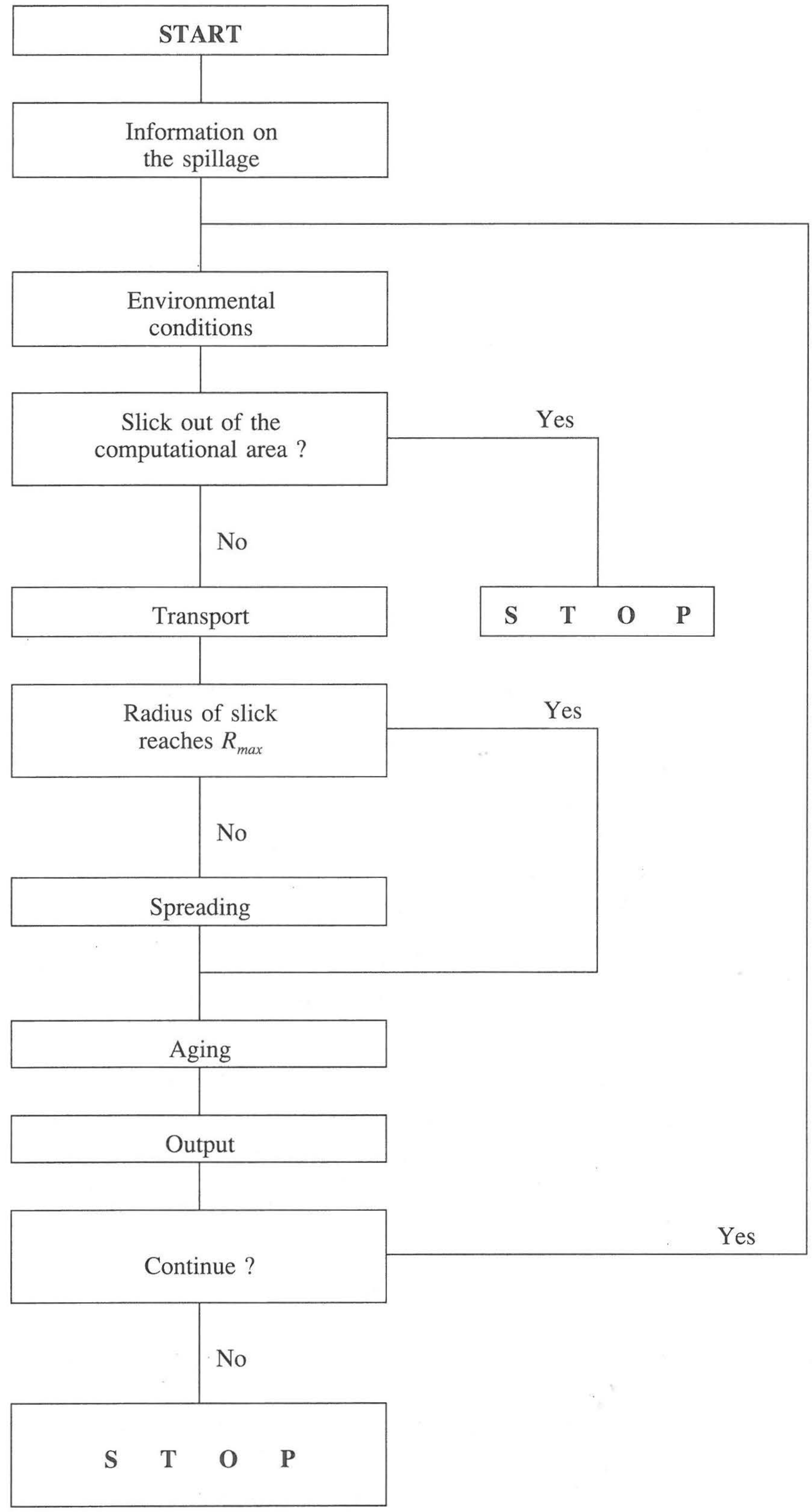
For viscosity evolution :

$$\nu_o=\nu_o(0)\ \left[(V_r+V_{em})/(V_w+V_r+V_{em})\right]^{-4}$$

where $\nu_o(0)$ is the initial viscosity of the oil.

3. Computer program

The structure of the program may be illustrated with the following flow chart :



The information on the spillage contains the moment and the location of the spill, the volume and the type of the oil spilled, the starting time and the duration of the simulation to perform. Various kinds of oil are divided into six types with different physical-chemical properties, according to Van Oudenhoven (1983). This information is put in a data bank (Tab. 3.1) for the convenience of the model operator in a emergency situation. Once the type of the oil is determined, its properties are read from the bank by the program itself. The contents of the data bank can be easily modified. It is possible to add other types of oil or to modify the value of some oil properties. It should be noted that, once the type of oil is chosen, the oil characteristics are displayed on the screen and the operator has the possibility to change the default value if he wants.

Characteristics	Heavy fuel	Medium fuel	Light fuel	Kuwait crude	Ekofisk crude	Other
Specific mass	965	950	925	870	820	850
Evaporable fraction	0.1	0.1	0.4	0.4	0.5	0.5
Kinematic viscosity	8.6E-4	2.3E-4	5.0E-6	2.0E-5	1.0E-6	1.0E-6
Net surface tension	0.02	0.02	0.02	0.024	0.025	0.033
Vapour pressure x Molecular weight	300	300	300	1800	2000	2000
Emulsification constant	5	10	1.0E-4	100	20	20

Table 3.1 Default value of the oil characteristics for the various oil kinds as contained in the model data bank.

A continuous spillage may be simulated by assuming that several patches (up to 10 in the actual version of the program, but this number can be easily increased) are released at different moments. All of the information is keyed in by responding the requests displayed on the screen.

The environmental conditions include current fields, wind conditions and wave heights. Current fields are provided by the HYDRO model (see Chapter 2). Wind conditions and wave heights need to be inserted separately depending on the data available. The values of current and wind speeds are specified at nodes of the computational grid and interpolated every time step (10 min) to ensure the precision of the simulation of transport. The equations of spreading and aging are solved by means of a Runge-Kutta method (4th order).

Information on the position of the slick, the radius of the patch, oil properties and oil volumes are issued at regular time intervals (usually one hour) on the screen and stored in a disk file which is used by the graphic software to display the results of the simulation and by DISPER to compute the behaviour of the fraction released in the water column.

4. Application of the model

In this section, an application of SURF to an oil spill accident which happened in the Bohai Strait (China) is presented. Three simulations of the behaviour of the oil slicks, performed after the spillage, are described. All the input data of the modelling are listed and the results are presented and discussed. A more complete presentation of this application can be found in a seperate report (Ozer and Zhang Bo, 1990).

Due to the insufficiency of field observations on the environmental conditions like winds, wave heights and on the evolution of oil properties, it is difficult here to compare all the modelling results with the actual behaviour of the oil.

4.1 The incident

On the 8th of June 1990, two ships collided in the Bohai Strait (38°32'48"N, 120°56'42"E) at 2:00 a.m. (Beijing time) with one seriously damaged and its tank broken. Till the 14th of June, the amount of heavy fuel released continuously from the broken tank was estimated to be of the order of 250-350 t. At the same time, aerial surveys were carried out by a team of Chinese experts and three maps of the distribution of the spilled oil on the sea surface issued (Fig. 4.1.1 - Fig. 4.1.3). Some environmental factors were observed by a monitoring vessel in the wreck site which indicated that the speed of wind, blowing from the south, did not exceed 4 m/s and that the wave height was around 0.5 m during these days. After the 15th of June, the oil spill continued but the survey had to be cancelled due to very bad weather conditions.

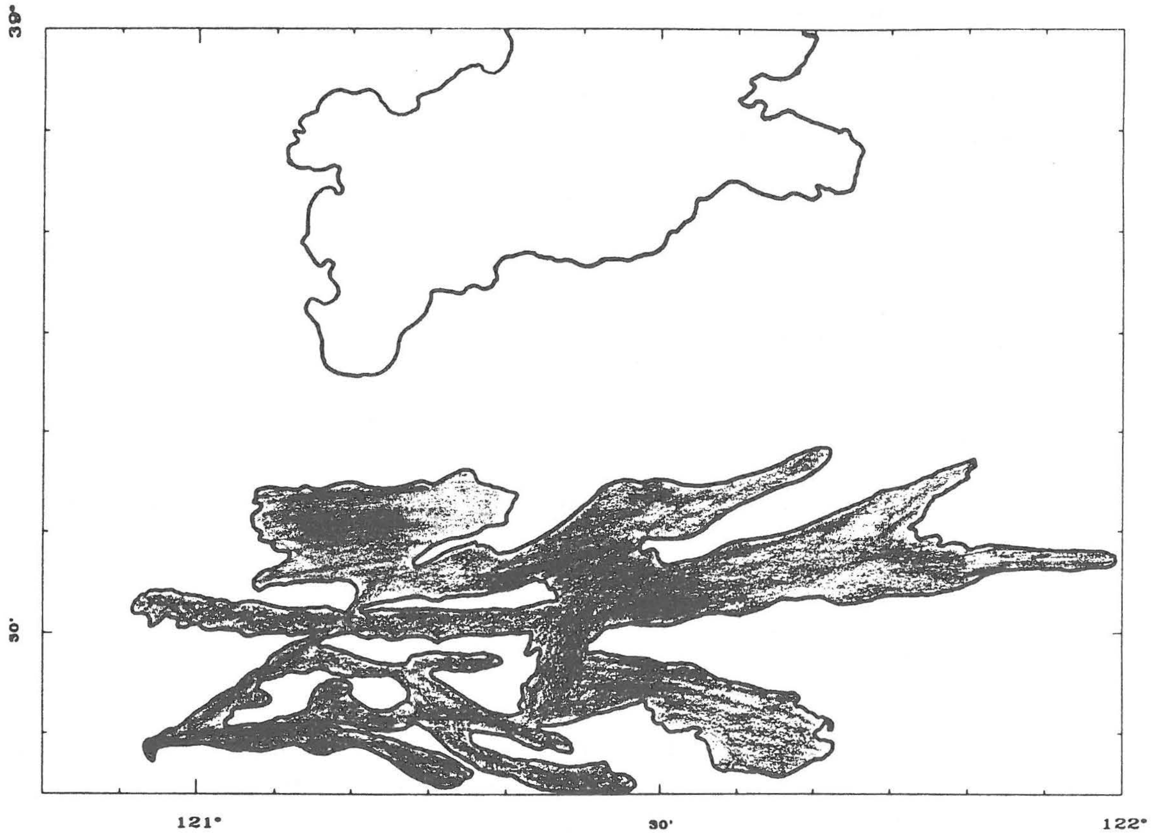


Figure 4.1.1 : Oil pollution observed the 9[th] of June.

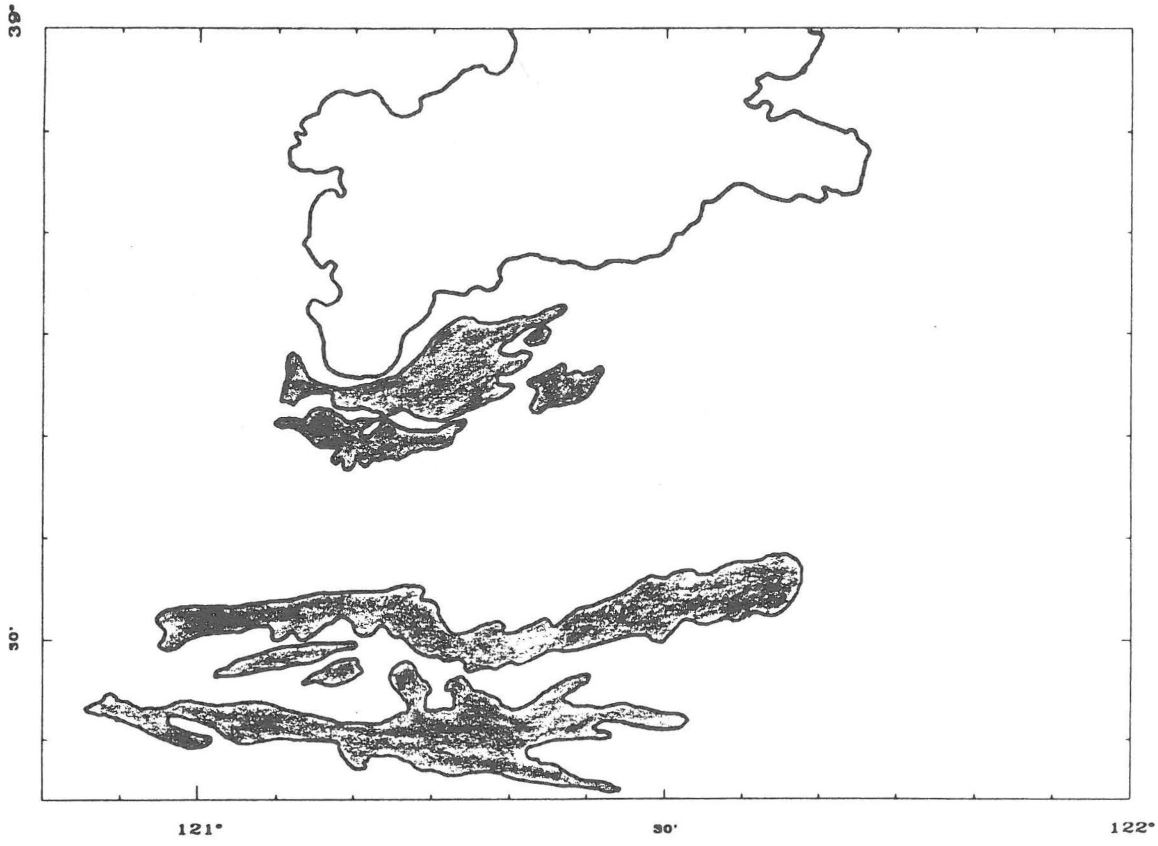


Figure 4.1.2 Oil pollution observed the 12[th] of June.

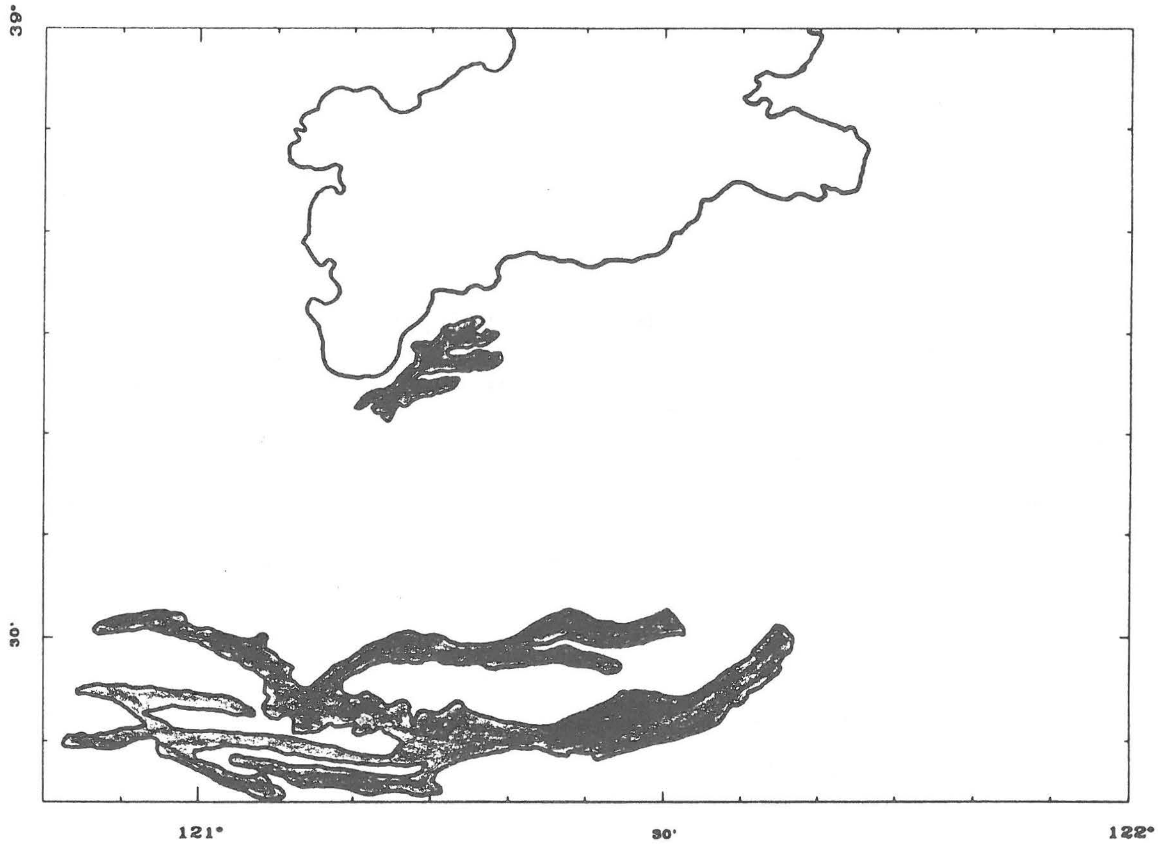


Figure 4.1.3 : Oil pollution observed the 15th of June.

4.2 *Input data*

The duration of the three simulations is equal to five days, starting on the 7th of June 1990 at 17:00 (GMT) when the accident happened. It is assumed from the observations that during this period of time ten patches were released. The time interval between two releases has been set equal to 4 hours.

The input data are summarized in Table 4.2. Current fields (Fig. 4.2.1 - Fig. 4.2.4) are provided by the HYDRO model and are the same for the different simulations performed with SURF.

Parameters	Case I	Case II	Case III
Spill time (GMT)	7th of June 1990 at 17:00		
Spill position	38°32'48"N, 120°56'42"E		
Duration of simulation (d)	5	5	5
Oil type	heavy fuel	(transport only)	(transport only)
Oil volume for one patch (m^3)	30	(transport only)	(transport only)
Current fields	from HYDRO model		
Wind speed (m/s)	3	3	see Fig. 4.2.5
Wind direction	S	SSW	Observations
Wave height (m)	0.5	(transport only)	(transport only)

Table 4.2 Input data used in the three model applications.

In case I, a wind speed of 3 m/s from the south is used based on the observations from the vessel in the site. The wave height is assumed to be equal to 0.5 m. The oil type has been chosen as being heavy fuel.

In case II, the wind speed is still equal to 3 m/s but it is assumed that the wind is blowing from SSW.

In case III, the wind data (Fig.4.2.5) observed hourly at the Dalian Weather Station, which is located at about 60 km northeast of the spill site, are used.

For case I, a complete simulation (*i.e.*, including transport, aging and spreading) has been performed while for case II and III, only trajectories of the patches were computed.

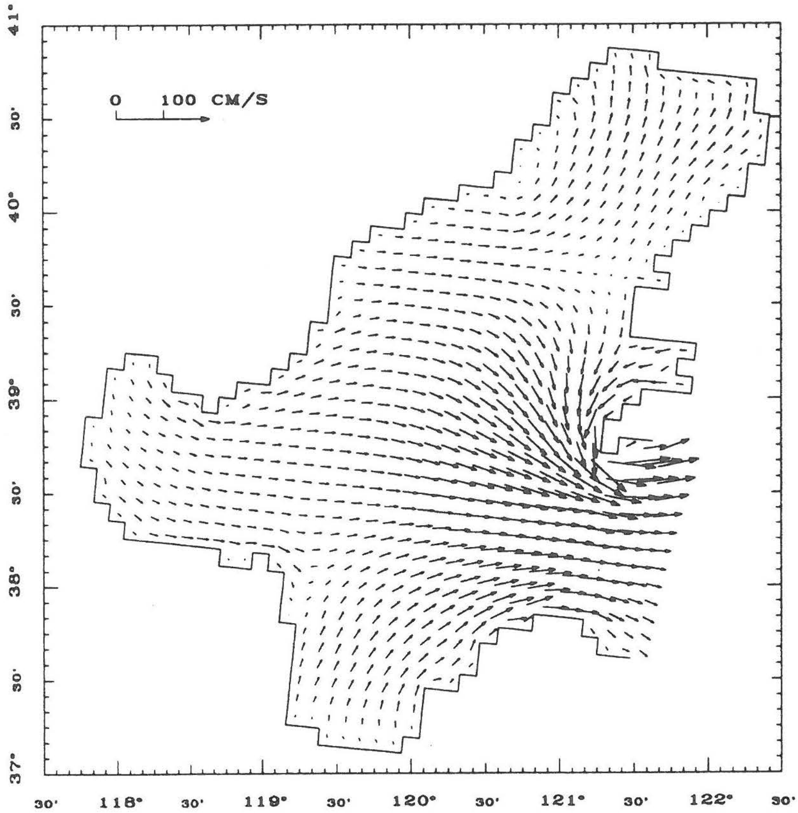


Figure 4.2.1 : Tidal currents on the 10th of June 1990 at 6:00 GMT.

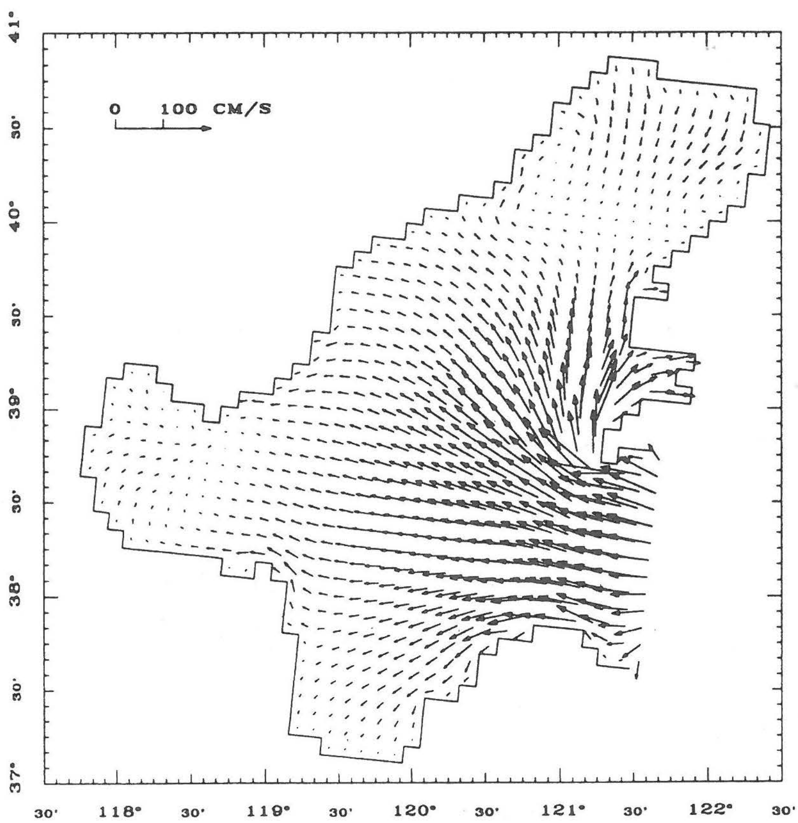


Figure 4.2.2 : Tidal currents on the 10th of June 1990 at 12:00 GMT.

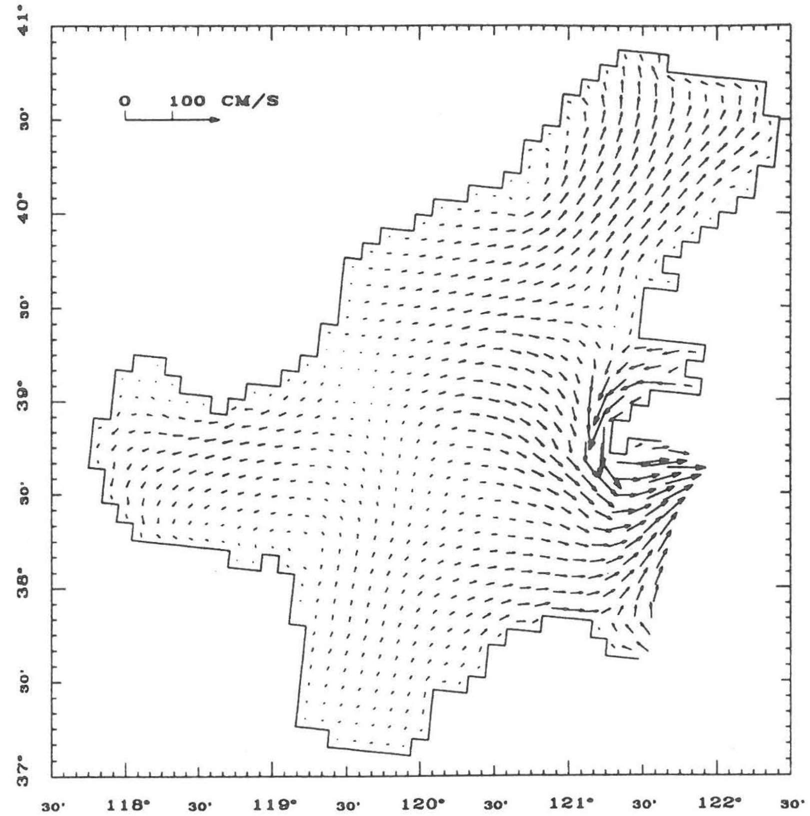


Figure 4.2.3 : Tidal currents on the 10[th] of June 1990 at 18:00 GMT.

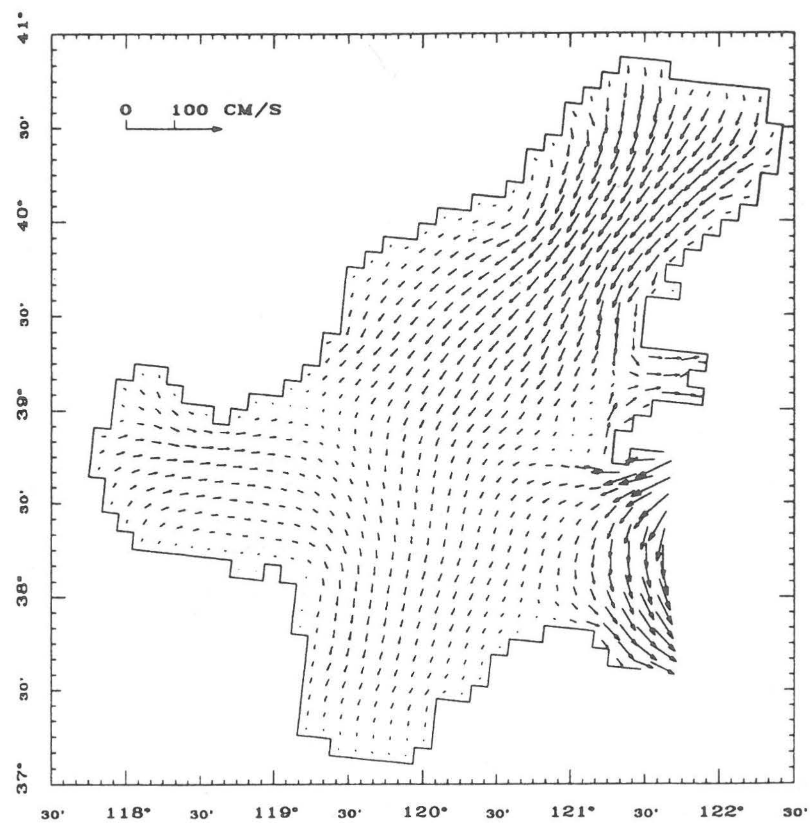


Figure 4.2.4 : Tidal currents on the 11[th] of June 1990 at 0:00 GMT.

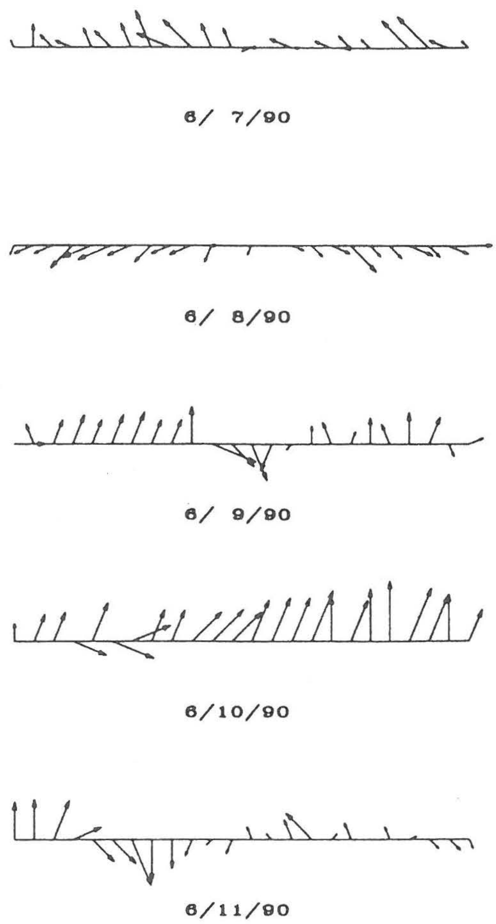


Figure 4.2.5 : The wind data from Dalian Weather Station.

4.3 Results and discussion

To get a better understanding of the results given by the SURF model, it should be mentioned here that the computational grid of HYDRO does not have the resolution required to obtain a fairly good approximation of the tidal currents in the area. The current can not turn smoothly around the land and the water flows too strongly towards the southeast (Fig. 4.2.1 and Fig. 4.2.3). This might have a deleterious effect on the trajectory of the patches computed by SURF. The extent, towards the east, of the polluted area determined by SURF might be underestimated. Moreover, the applications of the OPERA software presented in this chapter have been done in the early stage of the project. At this time, the results of the HYDRO model were not as good as they are now (see chapters 2 and 3). Therefore, the results presented here have to be seen as preliminary results. The discrepancies between model results and observations discussed hereafter cannot be ascribed to the SURF model. Be sure that good model results can be obtained as soon as the information concerning the wind forcing and the water current field is sufficiently reliable.

In case I, the trajectories of the ten patches indicate that the oil slicks drift towards the Dalian peninsula (Fig. 4.3.1). It should be noted that some oil actually reached the coast in that area and that a drift of part of the oil towards the peninsula has been observed during two aerial surveys (see Fig. 4.1.2 and 4.1.3).

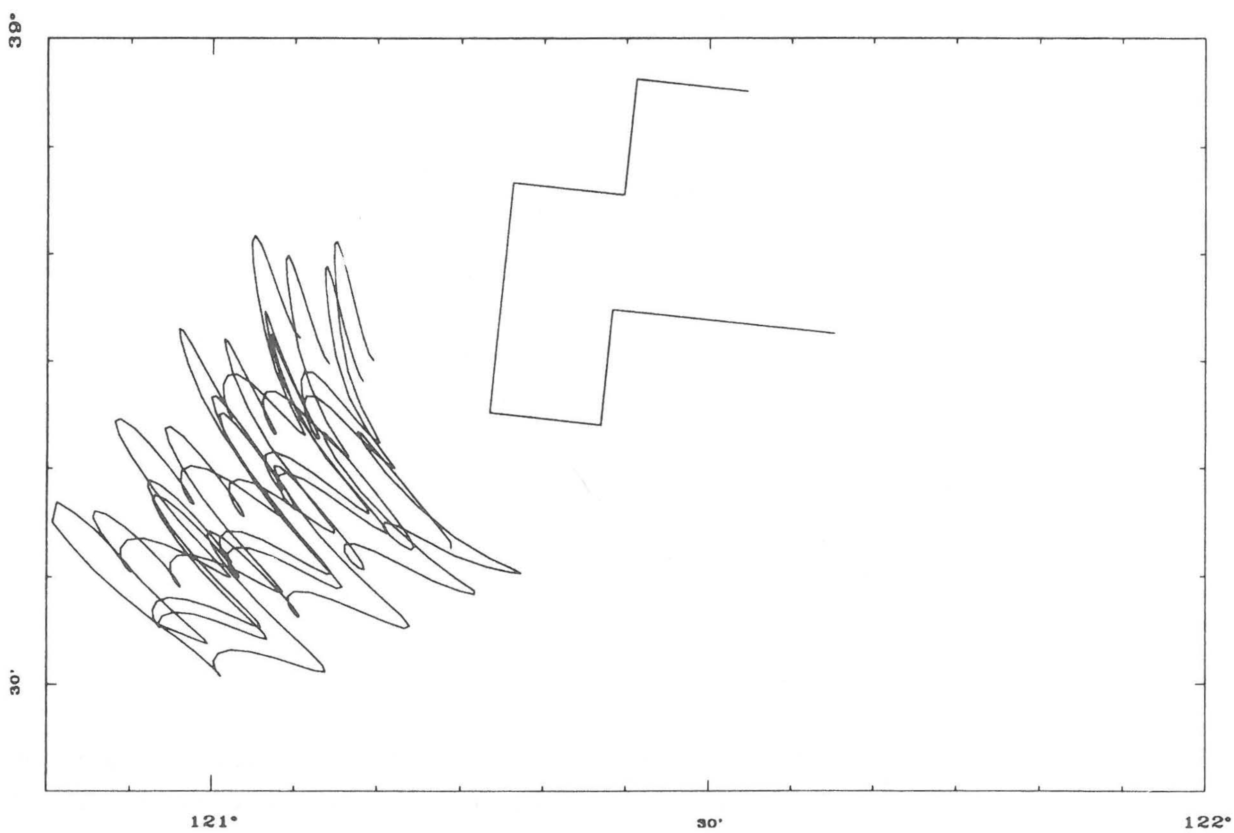


Figure 4.3.1 : Computed trajectories in case I.

In case II (wind blowing from SSW), an eastward movement of the oil is observed (Fig. 4.3.2) which agrees with the tendency of the main part of the slick in the real situation displayed in Fig. 4.1.1 - 4.1.3.

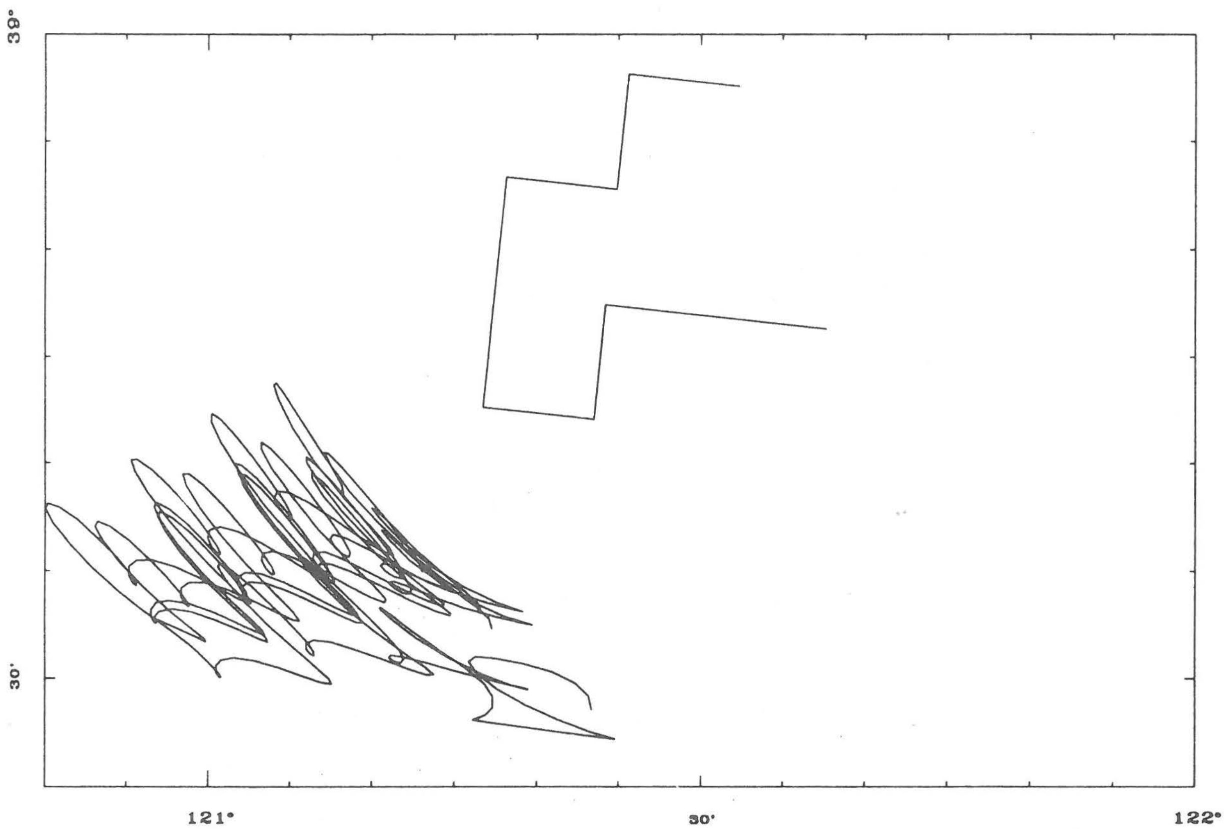


Figure 4.3.2 : Computed trajectories in case II.

For case III, the extent of the oil slick (Fig. 4.3.3) is smaller as compared to the observations. It is probably caused by the discrepancies between winds blowing over the spill area and those observed at the weather station.

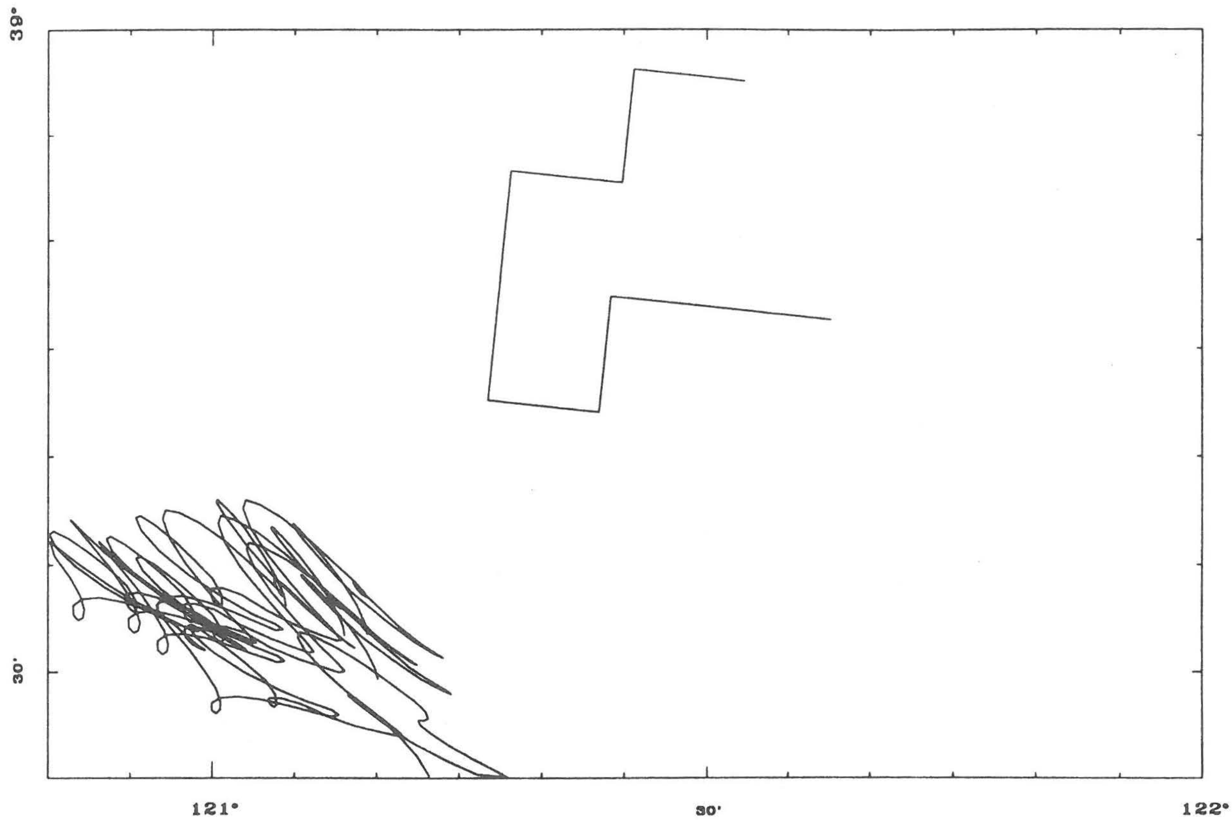


Figure 4.3.3 : Computed trajectories in case III.

From these results it can be concluded that it is quite possible to predict the transport of the oil slick on the sea surface with this model. Even when rather poor information about wind conditions is provided, it can still give, at least, a first order approximation of the slick displacement. With the improvement of the reliability of external information such as wind conditions, better results may be achieved.

The time evolution of the radius for patch 1 and patch 2 is displayed in Fig. 4.3.4. The radii increase and reach their maximum limit (638.8 m) about seven hours and a half after the discharge. In Fig. 4.3.5, the evolution, within one day, of the oil volumes lost through the various aging processes for one patch are shown. From this figure it can be seen that evaporation and dispersion are dominant. More then 90 percent of the volume loss is caused by these two processes.

Because of the lack of observation, it is difficult to discuss the accuracy of the model results concerning spreading and aging. What can be said is that the tendencies of these processes presented in Fig. 4.3.4 and Fig. 4.3.5 look realistic.

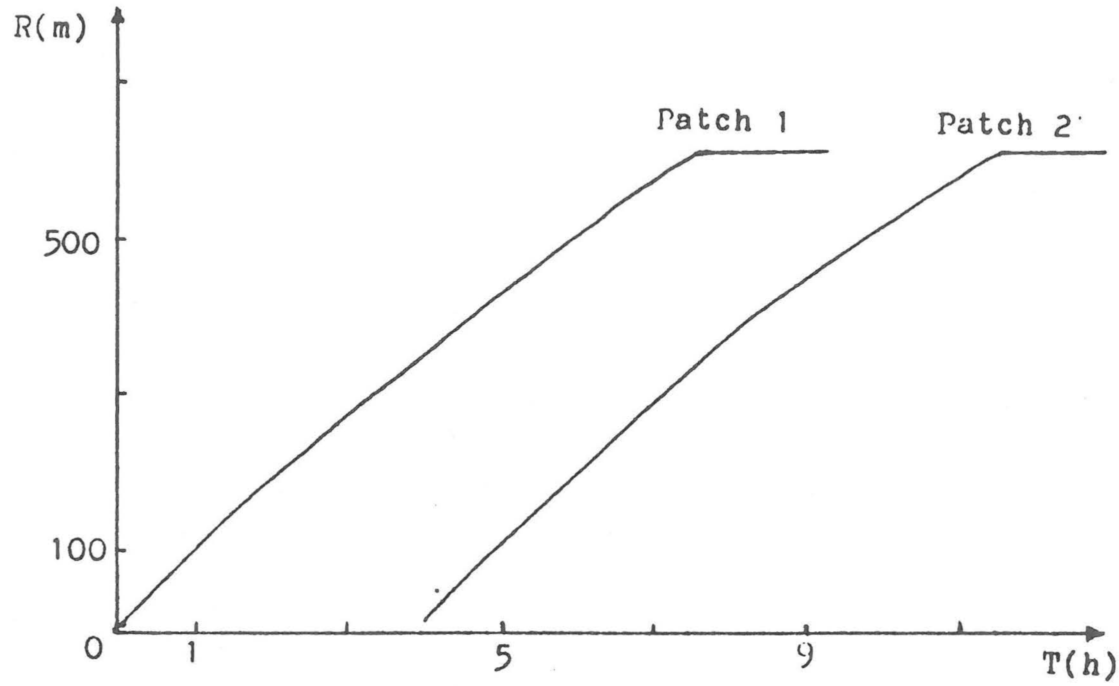


Figure 4.3.4 : Time variation of the radius of patch 1 and 2.

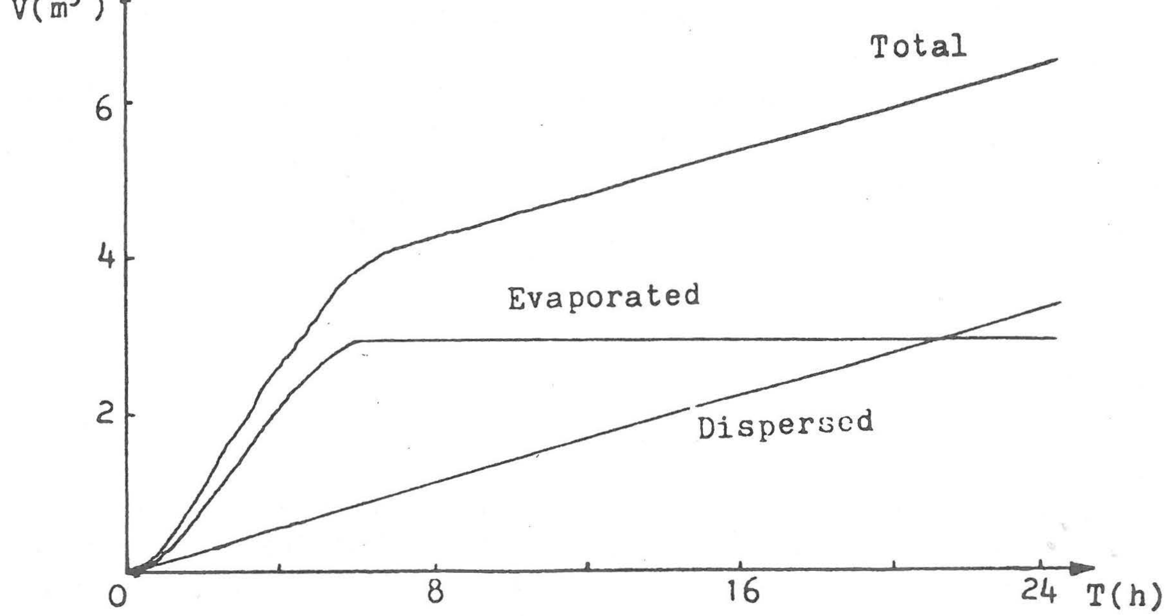


Figure 4.3.5 : Oil volumes lost through different aging processes.

5. Conclusion

The SURF model presents a fully operational computer model for simulating or forecasting the fate of oil slicks spilled at sea. Emphasis is laid upon the behaviour during the early life stage of the slick. The transport of the slick is considered to be controlled by water current and wind-induced current. The interaction between spreading and aging is taken into account by using an extension of Fay's theory for spreading. Aging processes are mainly taken as functions of wind speed, wave height and oil volume remaining at sea.

The computer program is designed for the convenience of the operator in real-time situation. Necessary information such as the time and location of the spillage or the volume of the spilled oil is provided interactively to the computer. When the type of the oil is chosen, its characteristics are read from a data bank by the program automatically.

The model has been applied to an oil spill incident which happened in the Bohai Strait (China). Three simulations of the trajectories of the slick with different environmental conditions were performed, including a numerical test for spreading and aging. Observed moving tendency of the slick was reproduced although rather poor wind data were available. Better results may be expected with the improvement of the accuracy of environmental data. The validation of the model results for spreading and aging were restricted by the lack of observation. Results from the numerical test look realistic. Most of the oil is lost through evaporation and dispersion processes.

The accuracy of environmental conditions provided to the model is essential for the success of modelling the fate of oil slicks with SURF. Further studies are needed to better understand various mechanisms dominating the behaviour of the spilled oil, and to work out more realistic expressions for different factors which influence the behaviour. A new spreading model ought to be developed so that the extent of the oil slick after a longer time of the spillage can be predicted.

6. References

Fay, J. A. and D.P. Hoult, 1971, "Physical processes in the spread of oil on a water surface." Proc. of the Joint Conference on Prevention and Control of Oil Spills, sponsored by API, EPA, and USCG, Washington, D.C., American Petroleum Inst., Washington D.C., pp. 463-467.

Huang, J. C., and F. C. Monastero, 1982. Review of the state-of-the-art of oil spill simulation models. Final Report submitted to the American Petroleum Institute, by Raytheon Ocean Systems Co., East Providence, R.I.

Hung, T.S., and P.D. Yapa, 1988. Oil Slick Transport In Rivers. Journal of Hydraulic Engineering, Vol. 114, No. 5, pp. 529-543.

Kuipers, H. D., 1984. A Simulation Model for Oil Slick at Sea. Delft University of Technology.

Ozer, J., Li Longzhang, Dou Zhenxing, Yang Lianwu and Gong Cheng, 1989. Summary of the work done within the frame of the exchange of hydrodynamic models and of their validation. IMEP's and MUMM's participation to the OPERA project, Joint Activity Report No. JAR01.

Ozer, J. and Zhang Bo, 1990. Oil pollution in the Bohai Sea: Results of a first application of the OPERA software. IMEP's and MUMM's participation to the OPERA, Joint Activity Report No. JAR03.

Scory, S., 1984. Oil spill modelling. Lecture given at the University of Liège, intensive course on modelling and management of marine system, Sep. 3-22, 1984.

Scory, S., 1991. The MU-SLICK model. Management Unit of the North Sea and Scheldt Estuary Mathematical Models, Report CAMME/91/03, Brussels, Belgium.

Van Oudenhoven, J.A.C.M., V. Draper, G.P. Ebbon, P.D. Holmes, and J.L. Nooyen, 1983. Characteristics of petroleum and its behavour at sea. CONCAWE, Den Haag.