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Statmap—a 3-dimensional model for oil spill risk assessment

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Abstract

Stochastic oil spill models have traditionally focussed on the production of statistics for oil on the sea surface and along shorelines. Environmental risk analyses of potential spills therefore have tended to neglect potential risks to organisms in the water column. *StatMap* fills this void, supplying in addition statistics on the spatial distribution of hydrocarbon concentrations in the water column. This paper describes the model concepts and provides examples of model input and output.

Keywords: Oil; Environment; Statistical simulations; Drift; Spreading; Weathering

1. Introduction

Relevant information on possible drift and fate of oil spills is one of the basic requirements in environmental impact assessments related to planned or ongoing offshore petroleum activities. Simulation of drift and spreading of oil forms an important basis for consequence studies, and by running oil drift simulations for a large number of weather situations, one may establish a picture of the possible influence area. Together with knowledge of location of vulnerable resources in time and space, the simulation results may establish a basis for evaluating the damage potential from eventual oil spills from the actual oil field.

Up to recently, the major concern of oil spill environmental risk assessments has been the drift and fate of *surface* oil, and the potential impact on shorelines as well as the threat to seabirds and marine mammals frequenting the sea surface. The *SlikMap* stochastic model was developed in 1984 for this purpose and has been extensively used for consequence studies in Norwegian waters. Throughout the 1990s, the *SlikMap* model has undergone several improvements (Johansen and Skognes, 1994), including oil–ice interactions in arctic regions, adaptation to wind and current grids from the Norwegian Meteorological Institute, exportation of data to GIS-based environmental risk analysis models (MRDB, SIMPACT) and tuning of oil weathering algorithms to results from the SINTEF lab-data-based oil weathering model.

During the last several years of oil exploitation, there has been a trend to use production frames and pipelines situated on the seabed. Consequently, the more "typical" accidental oil spill scenario is now a seabed blowout instead of a surface blowout. A general feature of a seabed blowout is that oil and gas under pressure is released at or near the seabed, where an intense mixing between the oil, gas and the water mass takes place. Depending on the spill conditions, the oil and gas plume may rise to the surface or may be trapped at intermediate water depths. In many situations, very little oil will appear at the surface, and if so, the oil film is much thinner than for a surface blowout, giving cause to more rapid entrainment of oil into the water column. The situation where most of the oil from a seabed blowout is in the water column drastically reduces the oil impact on the sea surface and shorelines. The question however arises: "What environmental threat does the subsurface oil present to marine organisms, such as fish, fish eggs and larvae?".

In 2000, the *StatMap* model replaced the *SlikMap* model, now also accounting for subsurface oil concentrations (in addition to sea surface and shoreline impact), and with directly integrated oil dispersion algorithms

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from the *Sintef Oil Weathering Model*. The *StatMap* model includes export facilities for communicating results on standard NOFO (Norwegian Clean Seas Association for Operating Companies) and OLF (The Norwegian Oil Industry Association) UTM-grids/formats for coupling with GIS-based environmental resource databases and impact assessment models.

2. Model concepts

2.1. Feature overview

To establish oil drift statistics, the *StatMap* model simulates oil spills from a given location for a large number of weather situations (scenarios) extracted from a historical wind database. For Norwegian waters, the model uses a gridded wind hindcast database from *The Norwegian Meteorological Institute (DNMI)*, spanning a period of 27 years.

Oil drift is supposed to be governed by a *local wind-driven surface current* and a seasonal *background current*, which for Norwegian waters is provided by a monthly climatological current grid database from *DNMI*. In ice infested areas, the drift and weathering of the oil is also modified by the local ice coverage, using a gridded hindcast ice archive from *DNMI*.

Oil *weathering* and *natural dispersion* depend on the wind speed during the drift period and on the actual oil type and release conditions (initial film thickness). The amount of oil that eventually reaches a coastal or open water area will vary according to the drift time and the weather situation. For practical reasons, the oil is tracked for a limited time period, i.e. up to 30 days after it is released, and eventual stranding or oil contamination after the limiting tracking time period is not registered.

Statistics may be extracted for specified seasons of the year and the results are presented as a total picture from all the simulated scenarios, i.e. statistics on drift time to the coastline, stranded amount of oil and probability for contamination of surrounding ocean areas both on the sea surface and in the water column. Statistics may be extracted based on either fixed values for spill duration and rate or based on a specified probability distribution.

2.2. Geophysical data input

2.2.1. Winds

The simulations are based on DNMI's wind hindcast database, employing a 75 × 75 - km grid with a time step of 6 h, over 27 years. The start time for each spill (scenario) is drawn randomly within this time span, eventually limited to a specific season of the year.

2.2.2. Currents

The background ocean current is represented on a 20 × 20 km grid and derived from model simulations by the DNMI, but *StatMap* also includes the option of *nested* current grids, i.e. using a higher resolution (e.g. 4 × 4 km) grid in a specified geographical region. The current data are organized as monthly files, i.e. a current field for each month of the year (climatological mean value). The contribution from tidal variations is neglected under the assumption that it has little effect on the *long time transport* of oil.

2.2.3. Sea ice

For northern geographical areas, the DNMI ice coverage database is included, with the same historical time span as the wind data, but with a time step of 24 h and a spatial grid of 20 × 20 - km (the same grid as used for the background current). The ice coverage affects the oil drift speed and direction as well as the evaporation and natural dispersion.

2.2.4. Sea temperatures

To be able to adjust the oil weathering characteristics according to the actual sea temperature (relative to the reference sea temperature used for the oil properties data table), a data set of monthly climatological (average) sea temperatures for the region of concern is used.

2.2.5. Coastlines

For registering stranding of oil, certain cells in the current grid (eventually nested current grids) are marked as *"coastal cells"*. Oil which drifts into these cells is defined as stranded and does not drift any further in the actual scenario. The coastal grid cells are derived from a digital map of the area and are defined as cells crossed by a coastline segment. The StatMap basis geographical digitization of the coastline is thus 20 × 20 km—but higher resolution in specific geographical areas may be achieved by use of *nested* grids (e.g. 4 × 4 km mesh size).

The above described input data are implemented for Norwegian waters, covering a large geographical area, from the North Sea in the south to the Barents Sea in the north.

2.3. Spill conditions and oil properties

In addition to the geophysical data input, a set of information concerning the spill conditions and oil properties must be given:

- Spill location (latitude, longitude)
- Oil type/oil density (kg/m^3)
- Spill rate (m^3/h)
- Spill duration (h)
- Spill situation (surface or seabed blowout)

For seabed blowouts, the following information is also needed for establishing the initial oil film thickness by running the SINTEF *DeepBlow* near field plume model (Johansen, 2000) calculations:

- Water depth at spill site
- Estimated gas to oil ratio (GOR)
- Estimated outlet temperature for oil and gas
- Estimated outlet diameter

If weathering studies have been carried out for the actual oil, results from these studies are utilized to determine the weathering of the oil and changes of oil properties over time (evaporation, water uptake, density, viscosity). If the oil type is not known, or if weathering studies of the actual oil have not been performed, an oil type is used which may be assumed similar to the oil in the actual spill case.

2.4. Particle concept

StatMap represents the oil spill by releasing a specified number of "particles" (small increments of the total spill) in each timestep (e.g. 10 particles per hour) throughout the specified spill duration. Each particle has an assigned set of parameters (particle record) which are updated during the simulation period:

X	*X*-position (grid)	
Y	*Y*-position (grid)	
Z	Mixing depth (m)	
Rdiffus	Horizontal diffusion radius (m)	
Trel	Release time (h)	
Tdrft	Drift time (h)	
Tsubm	Drift time in submerged state (h)	
Tevp	Evaporative exposures (h)	
Temul	Emulsification exposure (h)	
Filmthick	Oil film thickness (mm)	
Qinit	Initial mass (kg)	
Qrest	Actual mass (kg)	
Wcont	Water content (%)	
SolubFrac	Soluble fraction	
IceCov	Ice coverage at particle pos. (%)	
Istate	Particle states	
	SURFACE	Particle on surface
	SUBMERGED	Particle submerged
	STRANDED	Particle on shore
	ONICE	Particle on ice floe
	UNDERICE	Particle under ice floe
	OUTOFAREA	Particle out of area
	TIMEOUT	Particle timeout (time limit)

Some particle parameters are a part of the output data set from the model, while others are internal parameters, used for calculating oil properties during simulation.

2.5. Particle seeding

At each timestep, a specified number of particles are seeded and the particle parameters (particle record) are initialized for the actual particle *"batch"*. The initial mass *Qpart* of a particle is calculated as:

$$Qpart = Qrate\rho_{oil}\Delta t/Npart$$

where *Qrate* is the actual oil spill rate (m^3/timestep), ρ_{oil} is the density (kg/m^3) of the fresh oil, Δt is the length of the timestep (h) and *Npart* is the number of particles seeded per timestep.

The initial values of the oil properties (if available) are acquired from tables of laboratory oil weathering analyses for the actual oil type, while the initial oil film thickness is pre-calculated by gravity spreading algorithms for surface oil leaks, or Sintef *DeepBlow* model runs for seabed blowouts.

In open water, the particle state (SURFACE or SUBMERGED) at the time of seeding is established according to the expected distribution of particles on the sea surface and in the water column. In ice infested areas, the probability of seeding the particle in the ONICE (surface leak) or UNDERICE (subsurface leak) state is proportional to the local ice coverage.

2.6. Particle advection and horizontal diffusion

For *drifting* particles (not STRANDED, OUTOFAREA, TIMEOUT), the drift is governed by a seasonal *background current* and a *local wind-driven surface current*, where the latter is implemented by a drift factor concept—as a sum of Ekman and Stokes drift, modified by local ice coverage:

Ekman drift, open water	1.5% of wind speed, 30° right of wind direction
Ekman drift, 100% ice	2.0% of wind speed, 30° right of wind direction
Stokes drift open water	2.0% of wind speed, along wind direction
Stokes drift, 100% ice	0.0% of wind speed

Depending on particle state, the following drift factor combinations apply:

Processes	Surface particles			SUBMERGED
	SURFACE[a]	ONICE[b]	UNDERICE[b]	
Ekman drift	Yes	Modified	Modified	Yes
Stokes drift	Yes	No	No	No

[a] Drift of particles in SURFACE state is also modified by local ice coverage.
[b] Particle state changes from ONICE/UNDERICE to SURFACE by melting of ice. Ekman drift *on* or *under* ice floes is calculated as for 100% ice coverage. In the case of *fast ice*, no advection of particle takes place.

Horizontal diffusion is calculated according to Okubo's spreading diagram (Csanady, 1980), and is implemented as a random walk added to the advection due to current and wind. The initial spreading radius assigned to a particle is given from the initial film thickness and the volume of oil associated with the particle, and this radius is updated each timestep on the basis of local wind speed (reduced by eventual local ice coverage).

2.7. Oil weathering and dispersion

At each timestep, calculations of evaporation, emulsification and natural dispersion are carried out. A drifting particle will be subject to the various oil weathering processes according to the particle state as follows:

Processes	Surface particles			SUBMERGED
	SURFACE[a]	ONICE[b]	UNDERICE[b]	
Evaporation	Yes	Modified	No	No
Emulsification	Yes	No	No	No
Dispersion	Yes	No	No	No

[a] Note that the weathering of SURFACE particles also is influenced by the ice coverage.
[b] Particle state changes from ONICE/UNDERICE to SURFACE by melting of ice.

Initially, the SINTEF *Oil Weathering Model* (Aamo et al., 1993) is run to calculate a table of evaporated fraction and oil properties as a function of time for the type of oil spilled. This table is established for a specified reference condition, i.e. for a chosen film thickness of the oil slick, and a given wind speed and sea surface temperature, and is used by the *StatMap* model in the following way:

Evaporation is taken into account by accumulating an exposure time for evaporation as a function of the wind variations through the drift period, with resulting reduction of the mass of each oil particle. The evaporated fraction of oil which has drifted a certain time on the sea is calculated from an exposure time for evaporation, $t_{E,}$ as follows:

$$t_E = Tfac\frac{h_{ref}}{h}\sum\frac{U}{U_{ref}}\Delta t$$

where h_{ref} and U_{ref} is the film thickness and wind speed that was used in the calculation of the initial oil properties table, and where h is the initial film thickness for the given spill case, and U is the wind speed at the time step. For *surface spills*, this film thickness is calculated from the spill rate and the specific gravity of the oil. For *sea bed blowouts*, the film thickness is computed by the SINTEF *DeepBlow* model, based on information on spill rate, the volume ratio between gas and oil at atmospheric pressure (GOR) and the sea depth at which the blowouts takes place. In the presence of ice, the evaporation exposure for oil in wakes is reduced in proportion to the ice coverage. For oil on ice floes, the film thickness is increased by a factor of 4 relative to oil on the sea surface.

The evaporation exposure is adjusted by an empirical correction factor, *Tfac*, according to the sea temperature T_{sea}, relative to the temperature T_{ref} by which the initial oil properties table was calculated:

$$Tfac = 2^{((T_{sea}-T_{ref})/8)}$$

The evaporated amount of oil at an exposure time, t_E, is determined by interpolation in the oil properties table calculated for the reference conditions (evaporation tabulated as a function of time t).

Emulsification is taken into account by accumulating an exposure time for water uptake, in the same way as for evaporation, but where the exposure time is proportional to the square of the wind speed:

$$t_W = \sum\left(\frac{U+1}{U_{ref}+1}\right)^2\Delta t$$

The water content of the oil at an exposure time t_W is then determined by interpolation in the oil properties table calculated for the reference conditions (water content tabulated as a function of time t). In the presence of ice, the emulsification exposure of oil in wakes is reduced in proportion to the ice coverage.

Natural dispersion of oil particles is calculated as a function of the *whitecap coverage* (percentage of sea surface with breaking waves) (Marks, 1987) and the *wave energy* (Delvigne and Sweeney, 1988). The whitecap coverage and wave energy is related to *the significant wave height* and *mean wave period* (fully developed sea), both of which again are a function of the actual wind speed (reduced by eventual local ice coverage). According to the emulsion viscosity and density of the actual oil, a *dispersion rate* (mass per unit area and unit time) is calculated. Successively, a probability *Pdisp* for submersion of a particle is calculated as a function of this dispersion rate and the remaining mass of the particle after evaporation. The particles are then submerged by random selection (relative to *Pdisp*), and the submerged particles will then continue to drift in the water column.

The particles that are entrained by breaking waves are assigned an initial mixing of half the significant wave height. The mixing depth for entrained particles will successively increase due to vertical diffusion where Ichiye's approach (Ichiye, 1967) is used for the calculation of the vertical diffusion coefficient.

2.8. Oil dissolution and biodegradation

If data on the soluble fraction of the oil are available, the model also calculates the mass of dissolved hydrocarbons coming from submerged particles. If data on the biodegradation rate are available, the model calculates the mass reduction of submerged particles from this process as well—otherwise, the model assumes zero dissolution and biodegradation.

2.9. Oil concentration calculation

Hydrocarbon concentrations in grid cells are calculated by:

$$C = \sum \frac{Q_i}{\Delta A Z_i}$$

where ΔA is the area of the grid cell, Q_i is the mass of submerged particles in the cell and Z_i is the mixing depth of the individual particles. If the dissolution potential of that type of oil is known, the model distinguishes between total hydrocarbon concentration (THC) and dissolved hydrocarbon concentration (DHC).

2.10. Stranding of oil

A SURFACE particle reaching a coastline grid cell is regarded as stranded. The corresponding stranding position, drift time and remaining oil mass are registered, and the particle is not subject to further tracking, i.e. the model assumes no outwashing of oil from the shore. The particles in other states, e.g. submerged particles, are not regarded as stranded, and will be subject to further drift and tracking.

2.11. Data accumulation and output

During a run, the model accumulates drift times, oil mass and oil concentrations mapped onto output grids (polar sterographic and/or UTM). By the end of a scenario run (a model simulation typically runs several hundreds of scenarios), data sets on particle hits in open water grid cells and possible coastline impact are written to output files for later computation of statistics.

3. Model application example

3.1. Spill scenario description

Location	65°15′24″N, 5°59′32″E (See Fig. 1)
Release situation	Surface blowout
Spill rate	330 m^3/day
Spill duration	5 days
Oil type	Stafjord A, 827 kg/m^3
Initial oil film thickness	0.85 mm
Season	June–August

3.2. Oil properties

The oil property table was established by the SINTEF *Oil Weathering Model* (*OWM*) based on laboratory studies of the *Statfjord A* crude oil and is an input into *StatMap* (Table 1).

H_{ref}, T_{ref} and U_{ref} are the reference values (by which the table is calculated) for film thickness, ambient temperature and wind speed, respectively. Since the biodegradation rate *Biodeg* is unknown, it is set to zero (turned off). The table shows oil properties as function of time. The solubility *Solub* is also unknown and therefore set to zero.

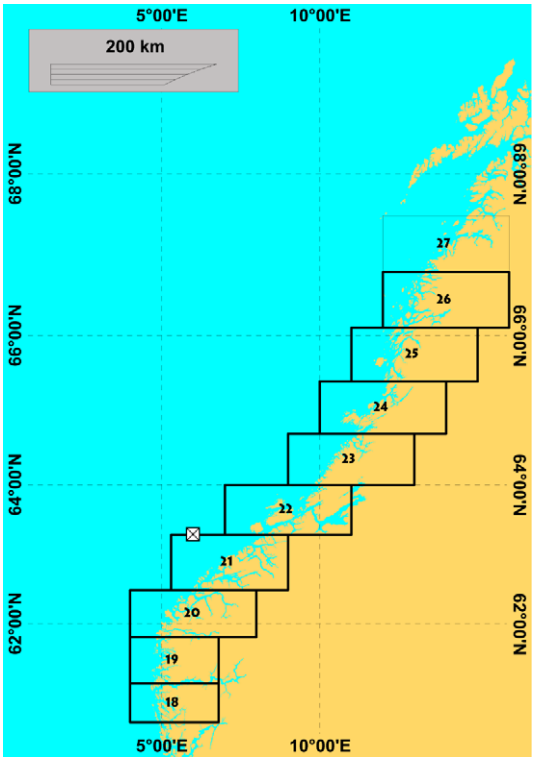

Fig. 1. Spill location ⊠ and numbered coastal zone definitions.

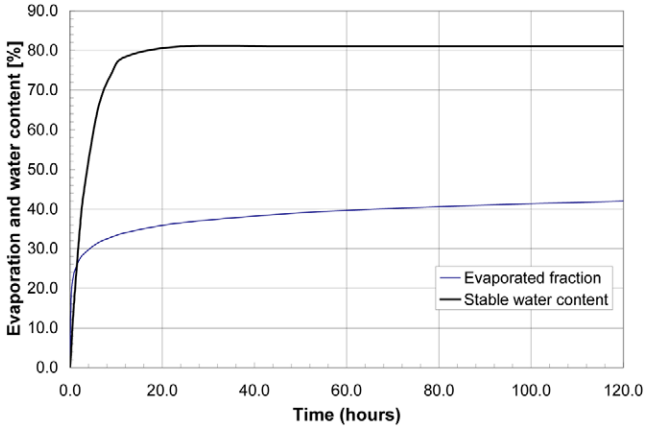

Fig. 2. Evaporated fraction and water content as a function of time.

Evap	Evaporated fraction (%)
Ro	Density of oil (kg/m^3)
We	Unstabilized water content (vol%)
Visco	Viscosity of oil (cP)
WE24	Water content after 24 h settling (vol%)
ViscE24	Viscosity of emulsion after 24 h settling (cP)

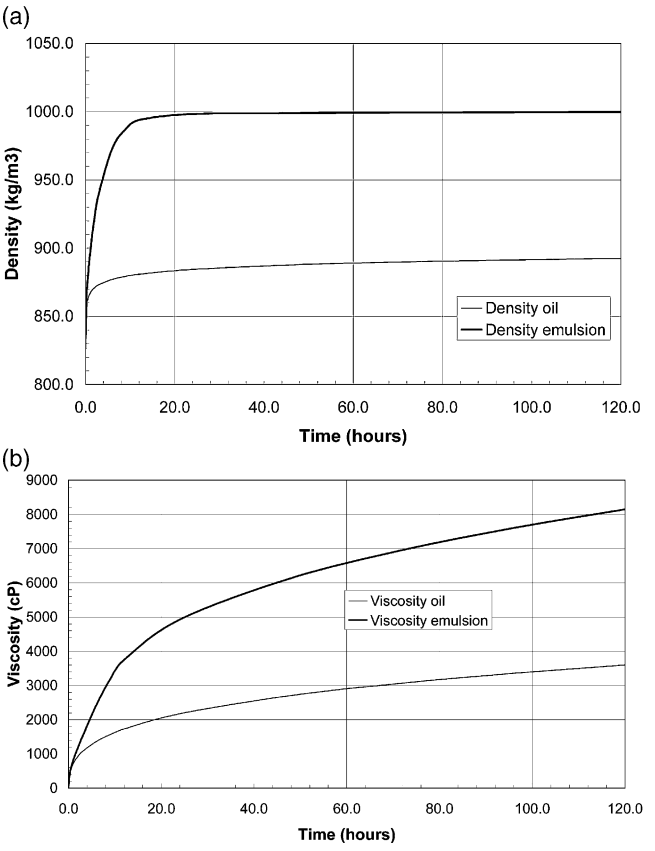

Fig. 3. (a) Density of oil and emulsion as a function of time. (b) Viscosity of oil and emulsion as a function of time.

As we can see from the oil property table, as much as 42% of the oil is expected to be evaporated after 5 days, with a wind speed of 10 m/s, an ambient temperature of 10 °C and an initial oil film thickness of 2 mm. We also notice quite a rapid water uptake and that the Stafjord A crude is able to form a stable emulsion, i.e. has a persistent water content after 24 h of settling. Figs. 2–4 show graphs of oil properties. In *StatMap*, the density of the emulsion is computed as a function of the sea water density ρ_{water} (1025 kg/m^3) and the oil density ρ_{oil}:

$$\rho_{emul} = (\rho_{water} Wc + (100 - Wc)\rho_{oil})/100$$

where Wc is the water content (%) and ρ_{emul} is the emulsion density.

The ability of the *Statfjord A* crude to form a stable emulsion (reaching a stable water content of 80% in shorter than 24 h at the specified reference conditions) indicates that one would expect that an oil slick on the sea surface will have some degree of persistence if the spill takes place under moderate weather conditions.

In situations with wind directions against the shore, one would expect also that some of the oil that "survived" on the sea surface might contaminate the shore.

Table 1
Oil property table

STATFJORD A							
H_{ref} (mm) 2.0		T_{ref} (C) 10.0		U_{ref} (m/s) 10.0		Biodeg (%/h) 0.0	
Time (h)	Evap (%)	Ro (kg/m^3)	We (%)	Visco (cP)	WE24 (%)	ViscE24 (cP)	Solub
0.0	0.0	827.0	0.0	48.4	0.0	48.4	0.0
0.25	18.1	857.9	5.1	407.9	4.4	418.9	0.0
0.5	21.3	862.5	9.8	545.0	9.5	578.8	0.0
1.0	24.3	866.9	18.5	717.4	18.5	810.5	0.0
2.0	27.1	871.0	33.0	927.8	33.0	1176.1	0.0
3.0	28.7	873.3	44.3	1073.0	44.3	1510.2	0.0
6.0	31.4	877.1	64.9	1366.9	64.9	2431.5	0.0
9.0	32.9	879.4	74.2	1571.7	74.2	3190.5	0.0
12.0	34.0	880.9	78.4	1732.1	78.4	3755.3	0.0
24.0	36.5	884.5	81.0	2176.5	81.0	4927.8	0.0
48.0	38.9	888.0	81.0	2712.4	81.0	6141.0	0.0
72.0	40.2	890.0	81.0	3073.2	81.0	6957.8	0.0
96.0	41.2	891.4	81.0	3359.1	81.0	7605.1	0.0
120.0	42.0	892.5	81.0	3599.7	81.0	8149.9	0.0

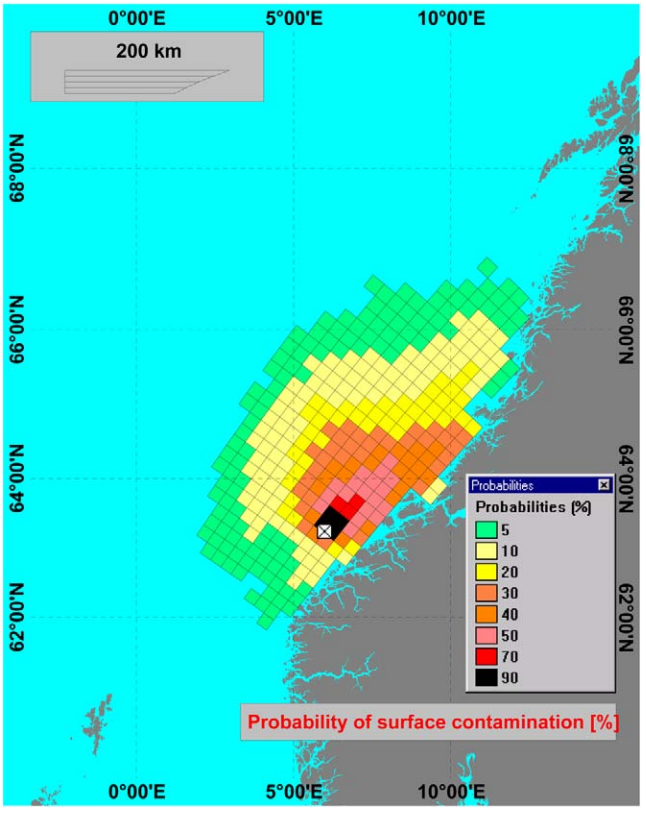

Fig. 4. Probability (%) of surface contamination from a spill initiated at ⊠.

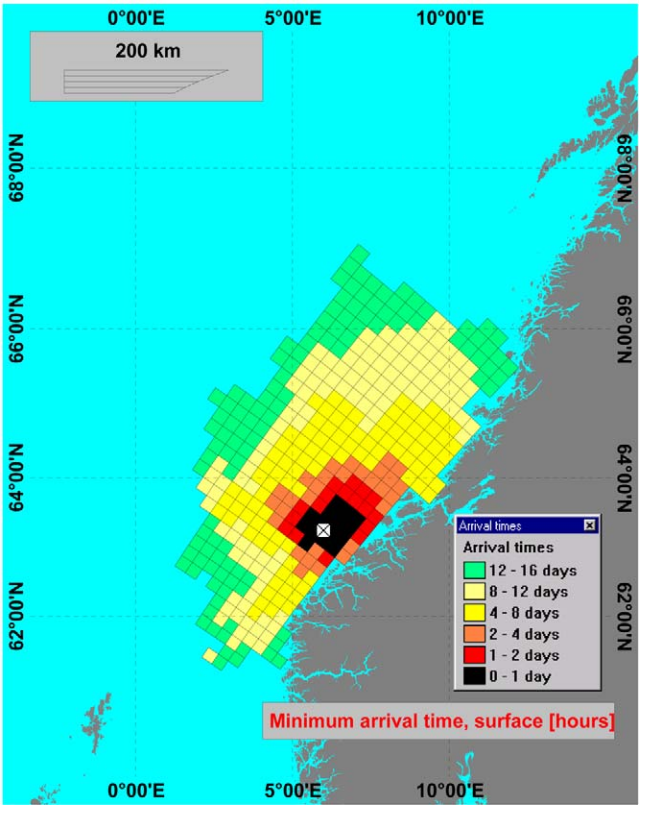

Fig. 5. Minimum arrival times (days) to surface areas from a spill initiated at ⊠.

3.3. *Influence area on the sea surface*

Figs. 4 and 5 show the *sea surface* contamination probability and the shortest arrival time of oil in areas surrounding the spill site. As we can see, the influence area on the sea surface has an extension typically elongated along the coastline, due to the coastal current in this area. Also, there is a likelihood of oil contact to the

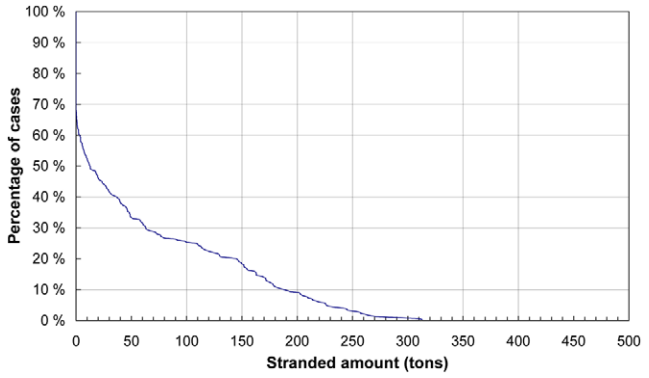

Fig. 6. Cumulative probability distribution of the amount of stranded oil on the coastline as a whole.

shoreline—as high as about 50% at some points, with a shortest arrival time of about 1–2 days.

The probability of reaching a grid cell is calculated as the ratio between the number of scenarios that have particle contact to this cell divided by the total number of scenarios simulated. The shortest arrival time is the shortest registered time from the start of the spill until oil has reached that grid cell throughout all the simulated scenarios.

3.4. Stranding of oil

Surface oil reaching coastal areas represents a contamination risk to shorelines, and from Figs. 4 and 5 above, such a risk is evident in the oil spill simulations performed. The simulations make it possible to give a detailed statistical estimate of shoreline impact.

Fig. 6 shows cumulative probabilities for amounts of stranded oil on the coastline as a whole. We see that the total probability of stranding any amount of oil is close to 70%, while, for example, the probability of stranding more than 200 tons (equivalent to 15% of total spilled amount) is approximately 10%. The largest expected amount stranded is around 315 tons, equivalent to about 23% of the total spilled amount.

Fig. 7 shows cumulative probabilities for arrival times

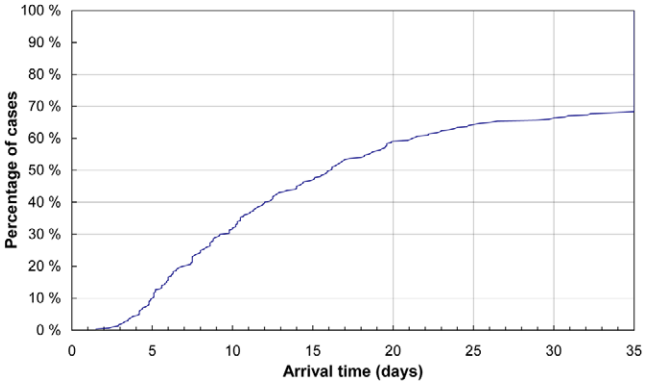

Fig. 7. Cumulative probability distribution of the arrival times to the coastline as a whole.

to the coastline as a whole, where an arrival time is the time from the start of the spill until oil reaches the shore. The probability of arrival times shorter than 5 days is about 10%, while the shortest arrival time is about 1.5 days.

Table 2a shows the statistical distribution of amounts of stranded oil in the defined coastal zones (Fig. 1). We see that zones 21–24 are the most exposed regions. Zone 22 has a probability of being contaminated of 44%, and a maximum amount of stranded oil of approximately 300 tons. The probability of stranding more than 200 tons of oil in this zone, however, is just 2%, while the average amount stranded is about 52 tons.

Table 2b shows the statistical distribution of arrival times to the defined coastal zones. We, for example, see that the shortest arrival time to zone 22 is 2.5 days, while the probability of reaching this zone in shorter time than 5 days after spill start is 6.7%. The average arrival time to zone 22 is 10.6 days.

3.5. Subsurface influence area and hydrocarbon concentrations

Figs. 8 and 9 show the *subsurface* contamination probabilities and the shortest arrival times of oil in areas surrounding the spill site.

If we compare Figs. 4 and 8, we notice higher probabilities for subsurface than for surface oil contamination in areas surrounding the spill site. The explanation for this is of course the process of natural dispersion of oil by wave action, downmixing oil particles into the water column, and decreasing the oil on the sea surface. The downmixed particles will continue to drift in the water masses, although with increasing mixing depth due to vertical diffusion. The submerged particles will not be subject to evaporation or stranding, and, as dissolution and biodegradation may be very slow processes, this implies that the downmixed oil particles may “live” for a long time—resulting in a larger subsurface than surface influence area. In the actual simulations, the dissolution and biodegradation are set to zero.

If we compare Figs. 5 and 9, we observe that the statistics on minimum arrival times are not so very different. This is what would be expected, as the minimum arrival time in a grid cell is the “extreme value” through all simulated scenarios, and relatively independent of the probability of reaching this cell.

An important question now is what environmental threat the submerged oil may present to subsurface marine life (fish, fish egg and larvae, plankton, etc.). The essential parameter in connection with such environmental risks, of course, will be the hydrocarbon concentration levels in the water column.

Fig. 10 shows the average total hydrocarbon concentration (THC), which, in some regions, goes up to 5–10 ppb. If data on dissolution potential of the oil are avail-

able, the *StatMap* model also calculates dissolved hydrocarbon concentrations (DHC).

In environmental risk assessments, some critical concentration levels with respect to specific marine organisms may be defined, and the risk of exceeding such concentration levels may be essential information. Fig. 11 shows the probability of the average THC exceeding 1 ppb, with a much reduced "influence area".

4. Export of data to environmental effects models

To calculate the effects of oil contamination on marine organisms, a coupling of the results from oil drift simulations with data on the marine organisms living in the region of influence, including their vulnerabilities to exposure of oil is essential.

The *StatMap* model includes export facilities for communicating results on standard NOFO (Norwegian Clean Seas Association for Operating Companies) and OLF (The Norwegian Oil Industry Association) UTM-grids/formats for coupling with GIS-based environmental resource databases and impact assessment models.

The information provided by the StatMap model for this purpose is:

Id	UTM-grid cell id
Qavr	Average amount of oil (kg)
PQ1∗	Probability (%) of oil amount in interval 1
PQ2∗	Probability (%) of oil amount in interval 2
⋮	
PQN∗	Probability (%) of oil amount in interval N
Prob	Probability (%) of contamination
RnhitAvr	Average number of particle hits
Tdmin	Shortest particle drift time (h)
TdrftAvr	Average particle drift time (h)
Tarrmin	Shortest particle arrival time (h)
TarrAvr	Average particle arrival time (h)
TexpMax	Maximum exposure time in cell (h)
TexpAver	Average exposure time in cell (h)
CtotAvr	Average total hydrocarbon concentration (ppb)
CtotMax	Maximum total hydrocarbon concentration (ppb)
CdissAvr	Average dissolved hydrocarbon concentration (ppb)
CdissMax	Maximum dissolved hydrocarbon concentration (ppb)

Table 2
Stranded oil in the coastal zones

	Coastal zones										
	19	20	21	22	23	24	25	26	27	28	
(a) Cumulative probability distribution (% of cases) of arrival times (h)											
Days											
<5	–	–	5.3	6.7	–	–	–	–	–	–	%
<10	–	0.3	23.7	24.3	5.0	0.3	–	–	–	–	%
<15	–	3.0	29.7	34.7	15.7	7.0	0.7	–	–	–	%
<20	0.7	5.0	33.0	41.7	21.0	15.0	2.0	–	–	–	%
<30	0.7	7.0	34.3	43.7	30.3	25.0	9.3	3.0	0.3	0.3	%
<35	0.7	7.3	35.0	44.0	31.0	26.7	10.7	4.0	0.7	0.3	%
Minimum	15.4	9.8	1.5	2.5	6.9	9.0	13.6	22.7	29.7	29.9	Days
Average	15.5	17.6	9.5	10.6	16.5	19.8	23.9	27.9	30.4	29.9	Days
(b) Cumulative probability distribution (% of cases) of amounts (tons) of stranded oil											
Tons											
>0	0.7	7.3	35.0	44.0	31.0	26.7	10.7	4.0	0.7	0.3	%
>1	0.3	5.7	31.0	41.7	26.3	22.0	7.0	2.3	0.3	0.3	%
>2	0.3	4.3	29.0	38.7	22.7	17.7	5.3	1.0	–	–	%
>5	–	3.7	25.3	34.7	19.3	15.0	3.7	0.3	–	–	%
>10	–	1.7	22.3	28.3	14.7	11.7	2.0	0.3	–	–	%
>20	–	0.3	18.3	20.7	10.3	8.0	1.0	–	–	–	%
>40	–	0.3	14.7	16.0	7.7	3.7	0.3	–	–	–	%
>80	–	–	10.3	10.7	3.0	1.0	–	–	–	–	%
>100	–	–	8.7	9.0	2.7	1.0	–	–	–	–	%
>200	–	–	2.0	2.0	–	–	–	–	–	–	%
Maximum	2.4	44.3	246.3	296.1	152.1	153.8	46.8	14.2	1.1	1.1	Tons
Average	1.5	7.5	56.4	51.7	28.3	18.4	6.7	2.3	0.8	1.1	Tons

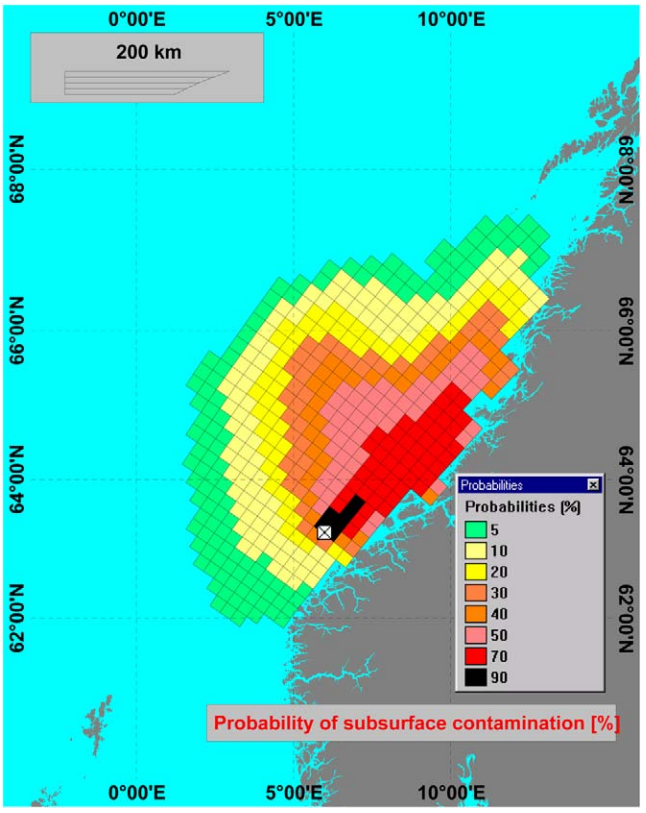

Fig. 8. Probability (%) of subsurface contamination from a spill initiated at ⊠.

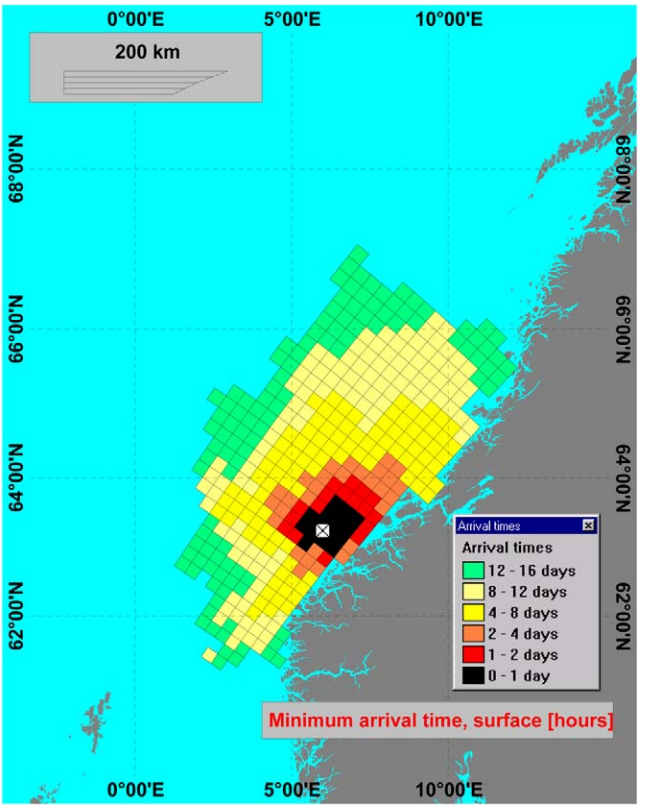

Fig. 9. Minimum arrival times (days) to subsurface areas from a spill initiated at ⊠.

where separate data sets for stranded and unstranded surface and subsurface oil contamination are produced.

∗PQN denotes the probability of contaminating a grid cell with oil within a given mass interval. For coastal grid cells, this is the probability of the *accumulated amount* of oil reaching the cell within a defined interval (e.g. 100–500 tons). For open water grid cells, this is the equivalent probability of the *average amount* of oil contacting the grid cell during a timestep.

5. Summary and conclusions

The *StatMap* model comprises tools for the statistical analysis of oil drift, spreading and weathering with respect to sea surface impact and eventual shoreline impact, and also with respect to subsurface oil concentrations.

Results from the statistical simulations are made available in the form of graphs, tables and maps of the geographical and statistical distribution of oil impact, also accompanied by data sets in digital form for use by GIS environmental effect assessment models.

The *StatMap* model is implemented for Norwegian waters using geophysical data sets available from The Norwegian Meteorological Institute and oil properties data from the Sintef laboratory data based *Oil Weathering Model*.

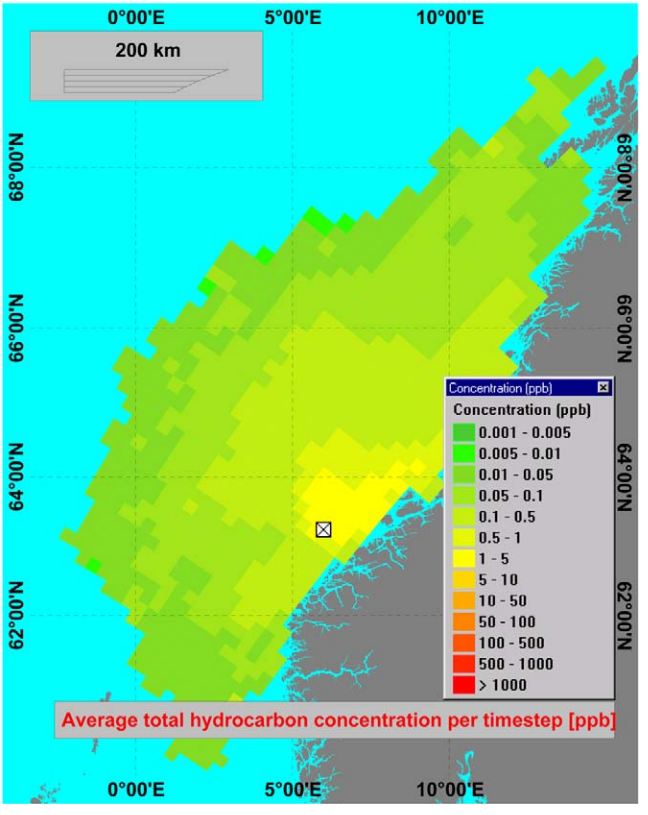

Fig. 10. Average subsurface THC (ppb) from a spill initiated at ⊠.

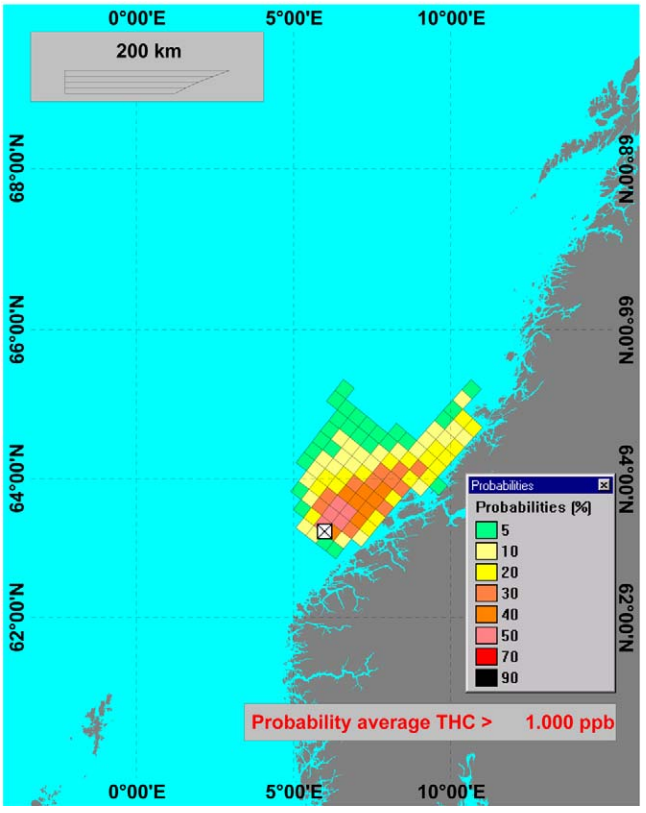

Fig. 11. Probability of THC greater than 1 ppb from a spill initiated at ☒.

Digital output data sets from *StatMap* comply with standard GIS formats defined by NOFO (Norwegian Clean Seas Association for Operating Companies) and OLF (The Norwegian Oil Industry Association) UTM-grids/formats for coupling with GIS-based environmental resource data bases and impact assessment models.

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