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3D Oil Drift and Fate Forecasts at DMI

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Contents

Summary 1
Introduction 1
About DMI 1
DMI oil drift models 1
Spill condition and oil properties 1
Report content 2
Conclusion 2
1 3D oil drift and fate model application 4
1.1 Fu Shan Hai 4
1.2 Baltic Carrier 8
2 3D ocean drift circulation model system 11
2.1 Operational 3D Ocean Circulation Model 11
2.2 The Operational 3D Drift Model 12
2.3 3D Oil drift and fate modelling 13
3 Weathering Processes 14
3.1 Spreading 14
3.2 Evaporation 15
3.3 Natural dispersion –vertical dispersion 15
3.4 Emulsification 16
3.5 Dissolution 17
3.6 Sedimentation 17
4 Oil types and properties 18
4.1 Crude and refined oils 18
4.1.1 Light Oils 18
4.1.2 Medium Oils 19
4.1.3 Heavy Oils 19
4.1.4 Oil types heavier than water 19
4.2 Oil classification in the model 19
Reference 21

Appendix A Fu Shan Hai - oil drift simulation plots and detailed oil statistics
Appendix B Baltic Carrier - oil drift simulation plots and detailed oil statistics

Summary

Introduction

About DMI

Danish Meteorological Institute (DMI) provides an operational 24 hours standby forecast service for drift of oil spill and floating objects. The maximum forecast length is 54 hours and the backtracking 42 hours back in time. The objective of this standby forecast service is drift forecast calculations and predictions of possible oil spill and floating objects – and in this way be able to make warnings of the magnitude and extent of oil pollution and effects on coastal areas. By the facility of backtracking the model is able to simulate oil spill and drifting objects back in time, with the purpose of detecting likely release sites and originators. Additionally the model can simulate leaking oil from a sailing tanker – both forward and backward in time.

The model applied for this service is constantly updated by the most recent meteorological and hydrodynamic data and forecasts, such that the model always takes into account the current water and air movements. The oil drift model applied cover the entire North Sea, Skagerrak, Kattegat, the Sound, the Belt Sea and the Baltic Sea. The applied meteorological model is DMI's operational weather model; HIRLAM, which is the most detailed weather model for the area.

DMI oil drift models

DMI has in its oil drift forecasting service for a number of years applied the *MIKE 21-SA (2D oil drift model)* – developed by DHI Water & Environment*.* This oil drift model is based on a 2D depth integrated current field.

DMI has now introduced a *new* improved oil drift model based on a 3D current field. The new model calculates the oil transport, drift and fate at *sea surface* and at the *deeper water depths.* The new model is a 3D oil drift and fate model based on a 3D ocean circulation model - developed by BSH (Bundesamt für Seeschiffahrt und Hydrographie) in Germany.

Spill condition and oil properties

In addition to the meteorological and hydrodynamic data input, a set of information's 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/hour] – or instantaneous volume spill
- Spill duration [hours]
- Spill situation (surface or seabed release)
- Water temperature

In case of a seabed release the water depth at the spill is needed.

If the oil type is unknown, or if weathering studies of the actual oil has not been performed, an oil type is selected which is supposed to be representative for the oil in the actual spill case.

Report content

The following report will illustrate the *new* 3D oil drift and fate model applied at DMI. The illustrations are based on the two seriously oil spill accidents; the *Baltic Carrier accident* in 2001 and latest the *Fu Shan Hai accident* in May/June 2003. The model is validated against reported observations from Danish authorities and one satellite image. The improved prediction capacity using the 3D model are demonstrated by comparisons to the MIKE 21-SA 2D oil drift model and will additionally illustrate the advantage of the model to simulate subsurface oil transport.

The 3D oil drift and fate model system at DMI is described in **chapter 2**. As the oil drift model is based on a *3D ocean circulation model*, this model is initially described together with the *3D drift modules* – which include the *3D oil drift and fate model* system. The description will illustrate the forecast abilities of the 3D drift model (floating object, dissolved substance, oil spill and backtracking) and a more detailed presentation of the 3D oil drift and fate model system.

In forecasting drift and fate of *oil* the model need to include the important physical and chemical processes that oil undergo when spilled in seawater. Theses processes are related to the oil types and thus the oil's physical and chemical characteristics together with the so-called weathering processes (spreading, evaporation, emulsification (water-in-oil emulsion), dispersion, dissolution and sedimentation). The weathering processes simulated by the oil drift model are described in **chapter 3**. The oil types and properties are described in **chapter 4**.

Conclusion

DMI has experienced successful oil drift and fate predictions by the use of the *3D oil drift and fate model* - for the latest two oil spill accidents in the Danish waters: the *Fu Shan Hai* and the *Baltic Carrier.*

In the Fu Shan Hai case, the 3D oil drift and fate model predicted very precisely the oil pollution at the coast of Borrby. The model also predicted the later drift of oil from the Swedish coast zone out on the open sea and towards the sensitive Danish island group of Ertholmene. The Fu Shan Hai forecast is an example of the advances of a 3D oil drift model, that takes into account oil spilled below the surface or at the seabed and calculates the oil spreading and movement at subsurface water layers.

In the Baltic Carrier case, the *3D oil drift and fate model* predicted oil drift and spreading through the Grønsund Strait and oil pollution of the south coast of Møn – both in agreement with observations. The constructed dam between Bogø and Møn is not implemented in the model topography, which caused the model to predict oil drift north of the Bogø Island and through the strait between Bogø and Møn. In reality the oil drift was west of the island of Bogø.

In the Fu Shan Hai simulation MIKE 21-SA predicted an oil drift to strand at the coast of Ystad - 25-30 km west of the observed position. The MIKE 21-SA oil drift model did not predict the offshore oil drift towards the Danish island group of Ertholmene. In the Baltic Carrier simulation MIKE 21-SA predicted oil pollution on the coastline of Hesnæs - 3 km south of Grønsund Strait where the oil actually was drifting through and polluted the coastlines of North Falster, Møn and Bogø.

1 3D oil drift and fate model application

The model has been used successfully to predict the drift and dispersion of seriously oil pollutions accidents – such as for example the “Baltic Carrier” accident at the maritime border between Germany and Denmark 29 March 2001 and the Fu Shan Hai collision 4.5 km to the north of the island of Bornholm in the Baltic Sea 31 May 2003. The oil drift and dispersion predicted by the 3D Oil drift Model at DMI will in the following be presented for the “Fu Shan Hai” and “Baltic Carrier accidents.

1.1 Fu Shan Hai

The accident
The Chinese bulk carrier “Fu Shan Hai” collided with the Polish freighter “Gdynia” on Saturday 31 May 2003 about 40 km southwest of Sweden and 4.5 km north of Hammer Odde, Bornholm in the western Baltic Sea. The collision occurred (in nice weather condition with clear skies, calm winds and seas and good visibility) around 12:25 Danish time and at 20:48 Fu Shan Hai sank at 68 meters water depth from where it began to leak oil. Fu Shan Hai was carrying; 66.000 tons of carbonate of potash, 1680 tons of heavy fuel oil, 110 tons of diesel oil and 35 tons of lubricating oil.

Oil slick drift observation
Monday morning 2 June an oil slick of about 12 km long and 3 km wide was observed offshore south of the Swedish coast. The oil was drifting towards the coast of Borrby. On Tuesday morning 3 June the first oil slicks had stranded on the south coast of Sweden –from Borrby to Sandrishamn. At that time the Danish and Swedish authorities had cleaned-up 100 tons of oil that had leaked out of the tanks. Thursday evening 5 June the wind changed to a strong westerly wind, which caused the oil at the Swedish coastline to drift offshore again. During the night the oil drifted towards Christianø, Frederiksø and Græsholmen – the Danish island group of Ertholmene – located northeast of Bornholm. Friday 6 June oil was still leaking from Fu Shan Hai and was also moving towards the Danish island group of Ertholmene. From early Friday morning three Danish oil-combating vessels were trying to prevent the oil drifting into the coast – by dike and collecting of the oil slick. Saturday 7 June oil polluted the shores and cliffs of Christianø.

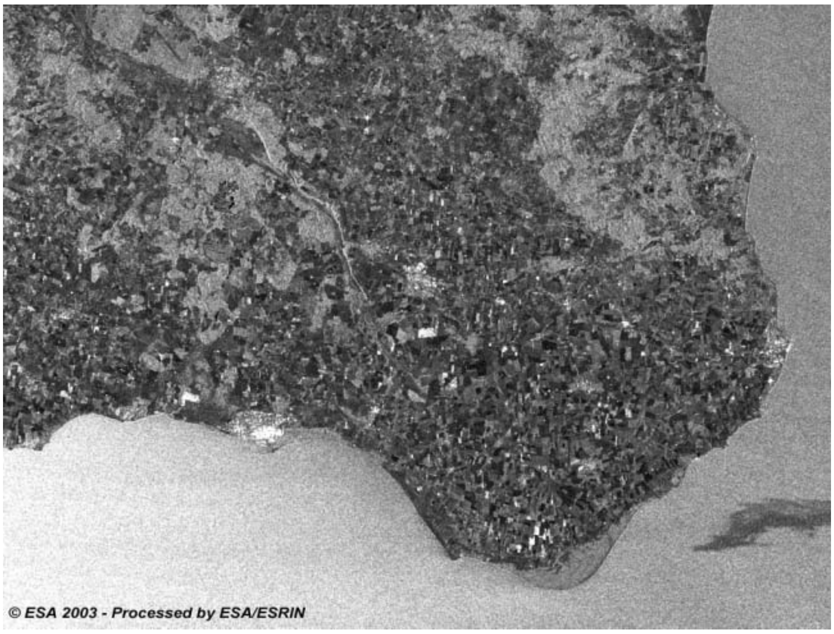


Figure 1. ESA ERS-2 satellite image (orbit 42439 Frame 1107) from 2 June 2003 at 10 p.m., same day as the oil spill approaches the Swedish coast, as seen in the lower right corner. Image acquired from http://earth.esa.int/ew/oil_slicks/sweden-denmark_sea_03/os_sweden_jun_03.htm

3D model result

The drift and spreading of the leaked oil was simulated by the *3D Oil Drift and Fate Model* at DMI and published at the homepage of DMI (www.dmi.dk). The ongoing reporting from the authorities of oil observations the following days, indicate that the oil was discharged discontinuously, in several phases. Due to uncertain information about the oil discharge phases – the oil release was specified as a continuous discharge in the simulations. The discharge was set to 7.2 ton/h from 31 May 2003 at 20:30 UTC to 12 June 2003 at 6 UTC. The applied oil type was heavy fuel oil (Bunker C). The simulation can be considered as "a worse case" – since the amount of oil cleaned-up was not taken into account in the simulation and oil was released continuously in the model. The oil was released at 68 meters water depth.

The model predicted a severe oil pollution at the Swedish southeast coast – from Borrby in the south up to Simrishamn - 3-4 days after the accident. The model prediction turned out to be correct. Tuesday morning 3 June (4 days after the accident) the Swedish coastline was polluted by oil. Additionally the model predicted that the oil along the Swedish coastline would drift offshore again and eastwards towards the Danish island group of Ertholmene. Thursday evening 5 June oil was predicted to drift towards the east and strand on Christiansø. Friday 6 June oil had truly stranded on Christiansø.

Figure 2 shows the predicted position of the oil slick on the 2 June at 10 p.m. - same day and time as the satellite image in figure 1. The prediction is seen to be in good agreement with the satellite observation.

Figure 3-10 below shows the simulation results of the Fu Shan Hai oil spill for the period; 1 June 2003 at 6 UTC to 9 June 2003 at 7 UTC.

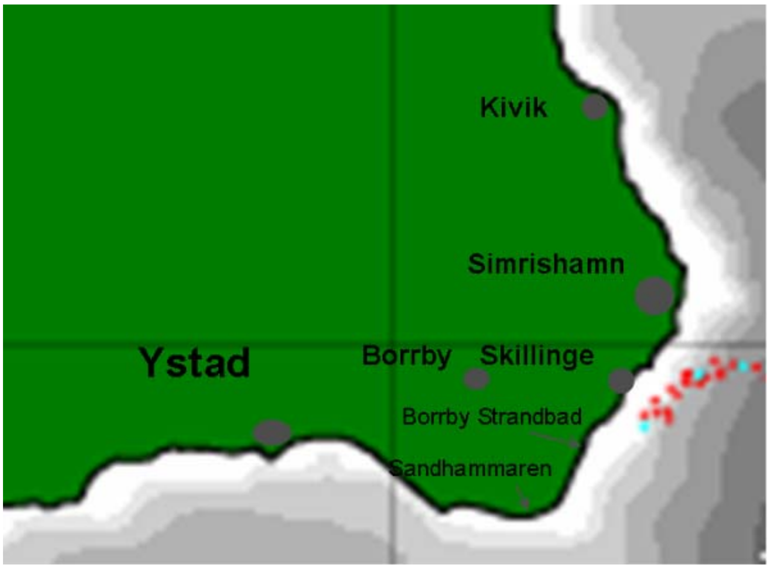


Figure 2. Model prediction of the oil slick position 2 June 2003 at 10 p.m. – the same date and time as the satellite image in figure 1. Red colour indicates oil at the surface and light blue colour dispersed oil.

Simulation series:

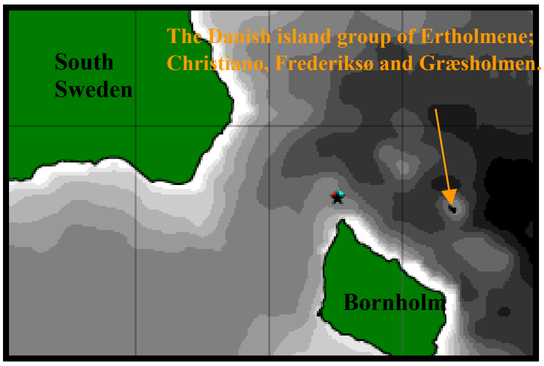


Figure 3. Simulation time: 01.06.03 06:00 UTC. (10 hrs after the oil spill) First sign of oil spill from the ship at 68 m water depths. Light blue dots indicate oil particles that are still in the subsurface water layers whereas red dots indicate oil particles that have reached the sea surface.

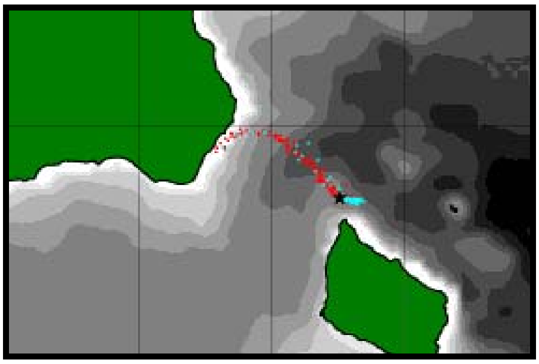


Figure 4. Simulation time: 03.06.03 00:00 UTC. (52 hrs after the oil spill) The oil spill has drifted towards the coastal zones of south Sweden.

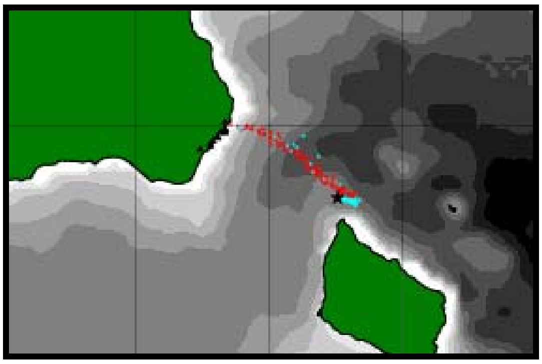


Figure 5. Simulation time: 03.06.03 05:00 UTC. (57 hrs after the oil spill). During the night of 3 June the oil spill polluted the coastline of Sweden from Borrby to Sandrishamn.

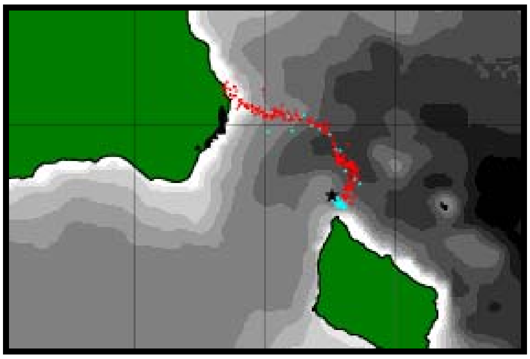


Figure 6. Simulation time: 04.06.03 14:00 UTC. (90 hrs after the oil spill) The oil spill has drifted further northwards to Simrishamn and thus polluted a larger part of the Swedish coastline.

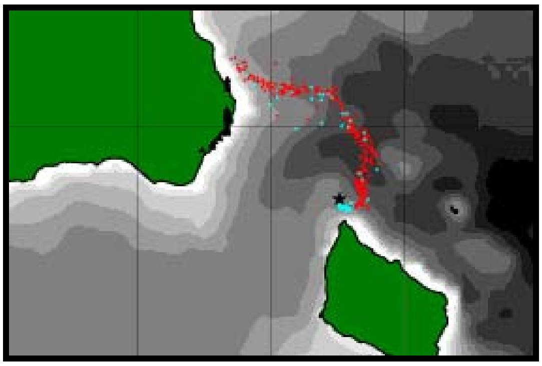


Figure 7. Simulation time: 05.06.03 07:00 UTC. (107 hrs after the oil spill). The oil spill has drifted further northwards.

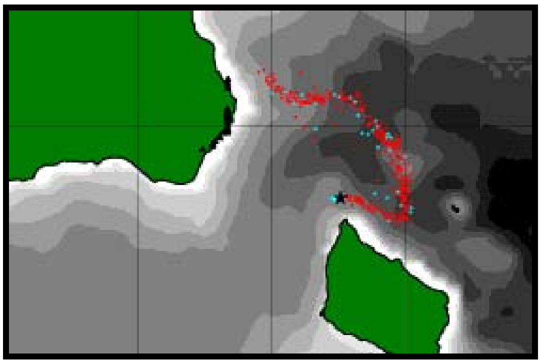


Figure 8. Simulation time: 05.06.03 10:00 UTC. (120 hrs after the oil spill) The oil spill has now drifted offshore towards the Danish island group of Ertholmene –northeast of Bornholm.

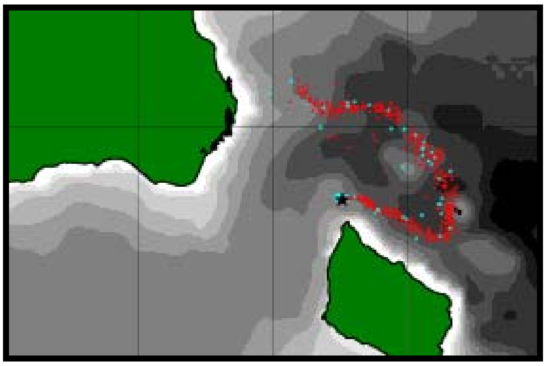


Figure 9. Simulation time: 06.06.03 07:00 UTC. (135 hrs after the oil spill). During the morning of 6 June the oil spill drifted onto the coasts of Ertholmene. In reality the oil first drifted into the island the next morning. However the simulation did not take into account the three oil-combating vessels who early Friday morning were preventing the oil slick to pollute the coastlines.

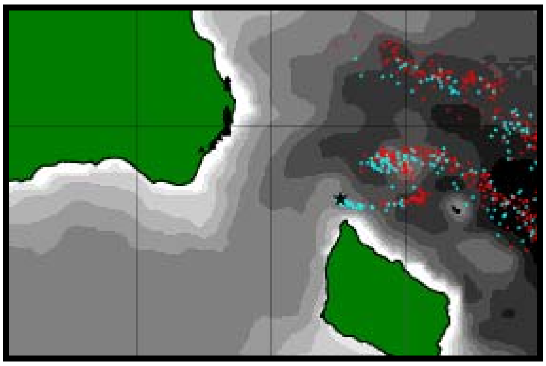


Figure 10. Simulation time: 09.06.03 10:00 UTC. (206 hrs after the oil spill). Oil release and oil slick distribution 8-9 days after the accident indicate approximately 58% oil floating at the sea surface and approximately 22% oil drifting in the waters below the surface, see appendix A. From the release point – at 68-meter depth the simulation indicates an easterly oil drift under the surface – making the oil spill first to become visible at the sea surface a distance from the sunken ship.

In appendix A more detailed statistic of the oil drift simulation is shown which includes in addition to the simulation plots of the oil drift – an overview over the wind speed and direction, the quantum of oil released as time passes and an oil statistics of the percentages of oil at sea surface, oil at subsurface water layers, oil deposited at sea bed or beaches, the expected evaporation and water content in the oil slicks.

2D model result

The oil drift was also simulated by use of the MIKE 21-SA 2D oil drift model at DMI. The predicted oil slick drifted northwest and stranded on the Swedish south coast of Ystad approximately 25-30 km west of where the oil was observed to strand.

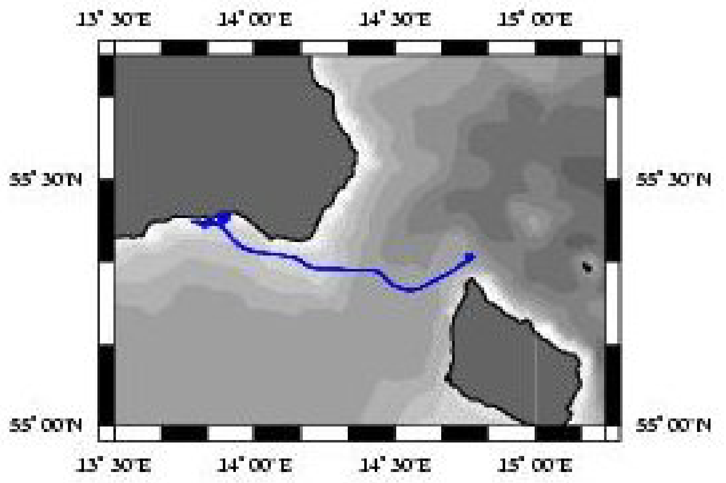


Figure 11. Simulated oil drift by MIKE 21-SA. The plot is a mean track of the oil drift.

The model simulated the released "oil particles" to strand and deposit on the coastline. Particles reaching the coast are considered "stranded" and are not considered in subsequently calculations. The model was therefore not able to simulate that the oil drifted offshore and out on the open sea again and further eastwards and towards the island group of Ertholmene.

The better performance of the 3D-model versus the 2D-model is clearly illustrated by this demonstration case. This is primarily because of the 3D-models ability to simulate the below-surface movements and weathering processes.

1.2 Baltic Carrier

The accident

The sugar freighter " Tern" and the tanker "Baltic Carrier" collided 29 March 2001 at 1:30 MESZ (Danish summer time) in the Baltic Sea at the position 54º 43´ 36´´ N and 12º 30´ 12 ´´E (in Kadetrenden - east of Falster). The Baltic Carrier tanker was carrying 30.000 tons of Heavy Fuel Oil 380.

Oil slick drift observation

Release of Heavy Fuel 380 began immediately from a hole in the starboard side of the tanker Baltic Carrier. This tank contained approximately 2.700 tons of oil. Due to the sea condition (~2,5m waves) and the extent of the boat damages, attempt failed to control the release of oil. The oil spill drifted northwest towards the Danish coastlines – and reached the Grønsund Strait 17:00 – 18:00 MESZ the same day. The oil continued to the coast of Bogø, Nordfalster and the south point of Møn. The total affected coastline has been estimated to about 30 – 50 km.

3D model result

The drift and spreading of the oil pollution was simulated by the *3D Oil Drift and Fate Model* at DMI. In the model the oil release was specified by an instantaneous release of 1000 tons oil and the applied oil type was heavy Intermediate Fuel Oil, IFO 450, which is the oil type, most alike IFO 380, which is available in the model and contain a high fraction of residual fuels. The model predicted oil drift and spreading through the Grønsund Strait between Falster and Møn and an oil pollution of the south coast of Møn, at 17:00 MESZ in agreement with observations. The model predicted oil to drift through the strait between Bogø and Møn. In reality a dam is built between Bogø and Møn, which forces the oil to drift past instead of through – in consistency with the observations.

Figure 12-15 below, shows the simulation results of the Baltic Carrier oil spill. The blue star indicates the oil spill release position. Red colour indicates oil at the surface, light blue colour dispersed oil and dark blue colour oil deposited at either sea bottom or coastlines.

Simulation series:

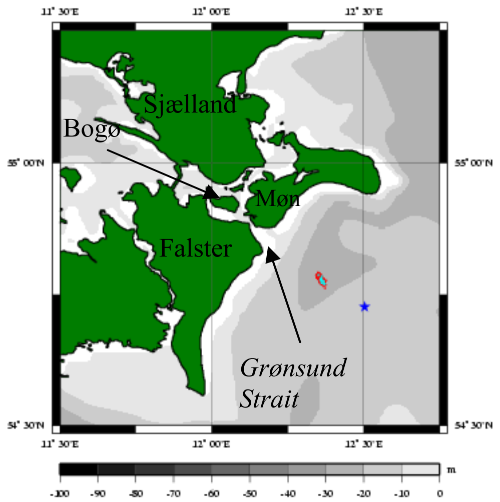


Figure 12. Simulation time: 29.03.01 13:00 MESZ. (12 hrs after the oil spill). The oil spill drifted towards the Grønsund Strait of Denmark. The oil spill is both drifting at the sea surface and in the deeper water layers.

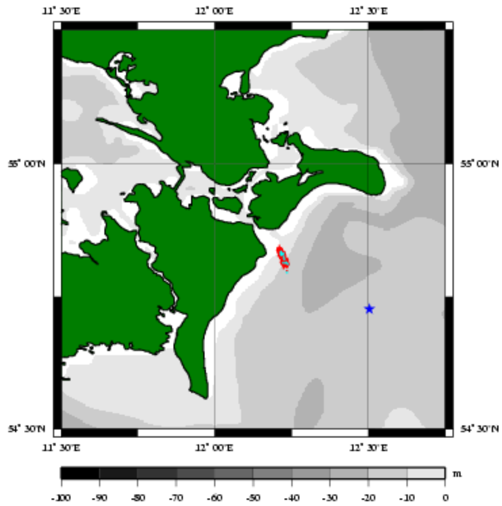


Figure 13. Simulation time: 29.03.01 17:00 MESZ. (16 hrs after the oil spill). The oil slick has reached the mouth of Grønsund Strait.

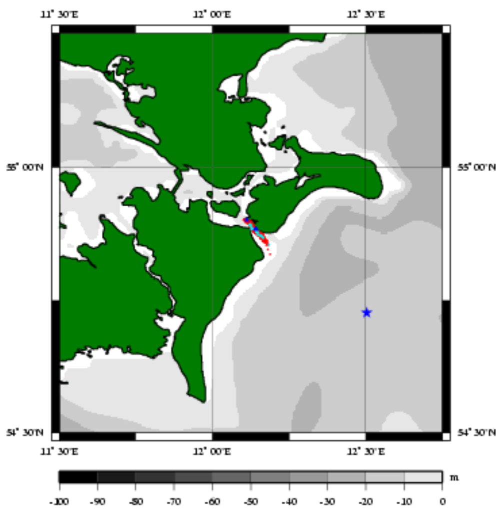


Figure 14. Simulation time: 29.03.01 19:00 MESZ. (18 hrs after the oil spill). The oil has polluted the south point of Møn.

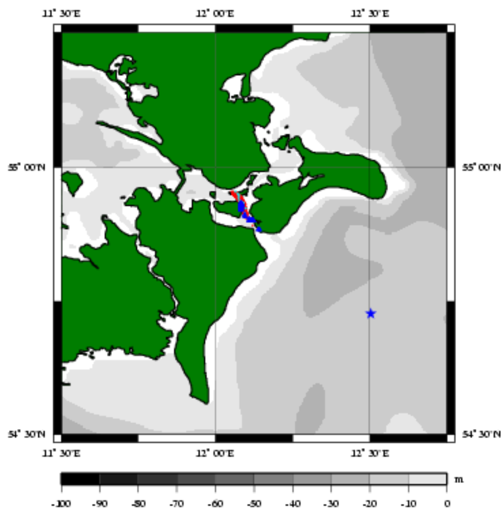


Figure 15. Simulation time: 29.03.01 21:00 MESZ. (20 hrs after the oil spill). The oil spill drifted through the strait between Bogø and Møn – which is a result of the missing constructed dam in the model topography. As indicated by the dark blue colour oil has stranded both on the sea bottom and coastlines.

Appendix B contains information of the simulated oil statistics. 16 hours after the oil spill the model predicted 9.6% oil evaporation and 1.5% oil dispersed to deeper water layers – i.e. 88.6% oil was left at sea surface. In agreement with the observations only a small percentage was evaporated and removed naturally. The main part of the spilled oil polluted the coasts of Denmark – in agreement with observations.

2D model result

Using the MIKE 21-SA 2D oil drift model the oil slick was predicted to drift northwest with a southern deflection – causing the main oil spill to strand on the coastline of Hesnæs (Falster) approximately 3 km south of the mouth of Grønsund Strait – in disagreement with the observations.

Comparison of 3D model and 2D model

Figure 16 shows the simulation by the 3D Oil Drift and Fate Model and MIKE 21-SA, respectively. The MIKE 21-SA drift simulation (blue line) deviates from the observations of the oil drift and the oil drift simulated by 3D Drift model (red line). The most likely explanation to this deviation between the two models is the differences in current fields of the models. The 3D drift model applies a 3D current field, while the 2D drift model applies a 2D depth-integrated current field.

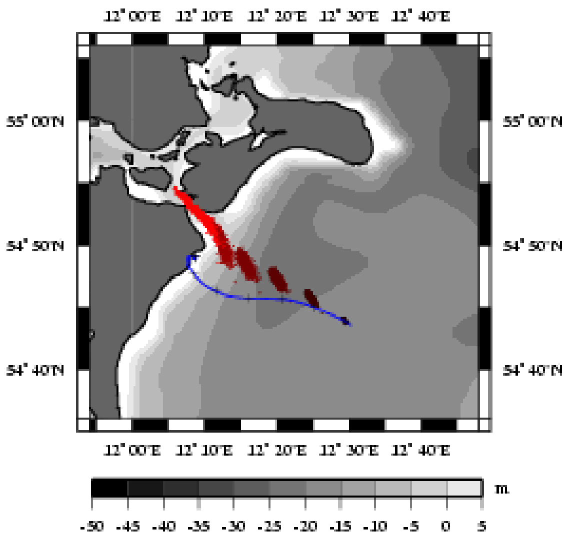


Figure 16. Simulated oil drift by the "3D drift and fate model" (red signature) and "MIKE21-SA" (blue line), respectively. Result from the 3D drift and fate model is plotted for each 3-hour and oil drift result by MIKE 21-SA is plotted as a mean track each hour.

2 3D ocean drift circulation model system

DMI is today operating a *3D Oil Drift and Fate Model* with focus on oil pollution accidents. The model is an extended module of the operational *3D Ocean Circulation Model* developed by the BSH (Bundesamt für Seeschiffahrt und Hydrographie).

The advantage of the *3D drift model* compared to a drift model based on a 2D (i.e. depth-integrated) ocean model is the inclusion of density driven (baroclinic) currents – generated by temperature and salinities gradients in the ocean – vertical as well as horizontal. These baroclinic currents are especially significant in the Baltic Sea where the water exchange is dominated by brackish water from river run offs in the northern part of the Baltic Sea and more saline water from the North Sea entering the Baltic Sea though the Danish water straits.

The model simulates, besides wind and current induced drift, spreading, horizontal and vertical dispersion, evaporation, emulsification, sinking, beaching and deposition of oil on the sea bed, collectively termed "weathering processes". The weathering processes depend among others on the characteristic of the oil type. The model includes at present 8 different pre-coded oil types.

The *3D Oil Drift and Fate Model* is able to simulate not only the drift and fate of oil at sea surface but also oil at the greater water depths where the transport and fate of the oil often differ significantly from the oil at the surface. This is a significant advantage of an oil drift model since the oil – as described in the weathering processes chapter 3 - seldom is only kept at the sea surface. Oil slicks at the surface drift faster and in a different direction than the oil droplets entrained in the water column. This is a significant mechanism of spreading and dilution of oil, which only can be predicted by use of 3D hydrodynamics oil drift models, which takes into account the velocity distribution in the water column.

The ability for the model to take into account the actual water depth has become important during the last years, due to the trend that oil exploitation is carried out by production frames and pipelines situated on the seabed, leading to a more typical accidental oil spill scenario will take place at the seabed rather than on the surface.

2.1 Operational 3D Ocean Circulation Model

The *3D Ocean Circulation Model* predicts water level, 3D ocean currents (barotrope currents from sea level gradients and baroclinic currents from density gradients), water temperature and salinity distributions and sea ice cover, concentration and thickness in the North Sea- Baltic Sea system.

The model is a finite difference ocean model and solves the 3D hydrodynamic equations and coupled thermodynamic ice equations. Meteorological conditions in the North Sea and Baltic Sea is taken into account by the use of DMI's numerical weather prediction model; HIRLAM, which provides cloud covers, wind stress and pressure at the ocean surface, and net heat and freshwater fluxes through the ocean surface. A 24nm resolution 2D surge model – covering the northeast Atlantic area – provide the sea level at the open boundaries in the northern North Sea and at the entrance to the English Channel (see figure 17). The applied temperature and salinity at the open boundaries are "nudged" towards monthly climatological values. The model includes furthermore freshwater input from 65 rivers of which 60 rivers are based climatology and 5 German rivers (Rhine, Weser, Ems, Elben and Oder) on daily observations. In case of missing observations or connections inability climatologic values are applied.

The model consists of two nested and interactively coupled grids (indicated by the black lines in figure 17).

- **The North Sea – Baltic Sea regional model area** (30N-75N, 69W-30Ø) has a horizontal grid resolution of 6nm.
- **The Coastal local model area** which cover the Inner Danish Waters (except Kattegat-Skagerrak), German Bight and western Baltic Sea has a horizontal grid resolution of 1nm.

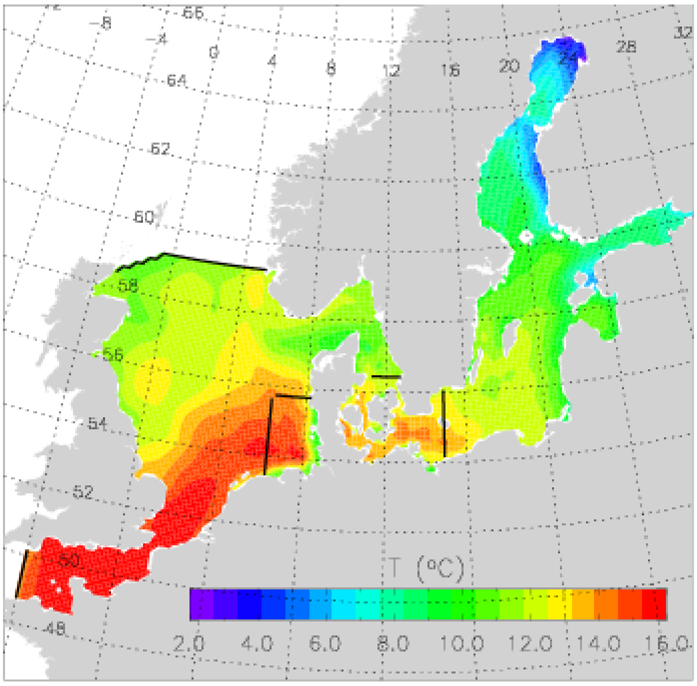


Figure 17. Drift and 3D Ocean model calculations areas. The black lines indicate the model nesting areas. The colour contour is mean water temperature in October 2002.

The model contains a maximum of 14 vertical layers with a grid resolution or thickness varying from a few meters in the upper layers to several hundreds meters in the lower layers (in deep waters areas). The thickness of the deepest grid cell is adapted to the bottom topography.

2.2 The Operational 3D Drift Model

The *3D Drift Model* is an extended module of the above described ocean circulation model and run decoupled. The *3D Drift Model* and *3D Ocean Circulation Model* domain areas are identical and showed in Figure 17.

The *3D Drift Model* predicts drift and dispersion processes at sea applying the Lagrangian dispersion formulation. The model apply water level and 3D current field simulated by the *3D Ocean Circulation Model*. The applied current field include both wind-induced motion, contribution from density-driven motion, tidal current and turbulences motion.

Four types of drifts can be considered and simulated by the model:

- Floating object
- Dissolved substance

- Oil spill
- Backtracking

The drift of a *floating object* can for example be a “man-over-board”, a container or a ship without a steering ability. The objects are drifting under influence of winds and currents.

The drift and dispersion of “*Dissolved substance”* and *“oil spill”* are represented by a particle cloud drifting with the current. The particle cloud can either be released instantaneously or continuously. For substances and oil floating on the surface 3% of the wind speed is added to the drift. Turbulence induced motion is taken into account and described by the Monte Carlo method.

In the simulation of *oil drift and dispersion*, the model includes the so-called; “weathering processes”, which is the collectively term for; oil spreading, evaporation, dispersion (vertical and horizontal), emulsification and dissolution. As the weathering processes depend on the oil types (oil’s chemical compounds and physical properties as: density, viscosity, maximum evaporation and pour point) – the model also takes into account different oil types. In the model the oil types are defined by 7 groups of hydrocarbon compounds and by a residuum. 8 different oil types are defined in the model at present, 4 crude oils and 4 fuel oil types.

The so-called *“backtracking”* is a simulation back in time to trace the source of pollution or where an object came from.

2.3 3D Oil drift and fate modelling

Oil drift, dispersion and oil fate simulation conducted by the *3D oil drift and fate model* include, as described above, all physical and chemical processes which are the most important ones in the first days after an oil spill accident. Sinking and sedimentation on the sea bottom and the coastline are included in the simulation as well. Processes such as oxidation and biodegradation are not included in the drift model but these processes become important later on and determine the ultimate fate of the oil.

It is necessary to know how weathering processes interact to understand how different oils changes over time whilst at sea. *The 3D oil drift and fate model* takes into account the dissimilarity of different oil types – regarding their physical and chemical properties. The *weathering processes* and *oil type and properties* are therefore described in the following two chapters: 3 and 4, respectively.

3 Weathering Processes

Due to atmosphere and ocean processes as well as the oil's physical and chemical characteristics a number of different processes occur when oil spills into the marine environment. Theses processes are collectively referred to as "oil weathering". Although the individual processes may act simultaneously, their relative importance varies with time and oil type. Together they affect the behaviour of the oil and determine its ultimate fate. The processes of spreading, evaporation, emulsification (water-in-oil emulsion), dispersion and dissolution are most important during the early stages of a spill – whilst oxidation, sedimentation and biodegradation are more important later on and determine the ultimate fate of the oil. The different oil weathering processes are illustrated in Figure 18.

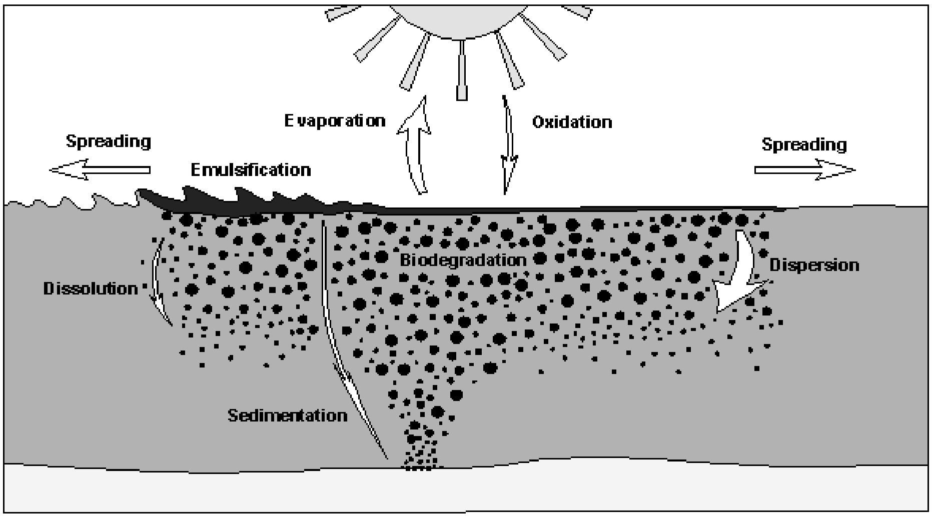


Figure 18. Weathering of an oil spill. Source: http://www.itopf.com/fate.html

For oil spill forecasts the important weathering processes are spreading, evaporation, emulsification (water-in-oil emulsion), dispersion, dissolution and sedimentation. These processes are included in the 3D oil drift and fate model and briefly outlined in the following sections.

3.1 Spreading

The early behaviour of oil when spilled on sea is dominated by its spreading behaviour. A balance between gravity and interfacial forces as well as a resistance provided by inertia and viscosity controls the spreading process. Gravity force and surface tension causes increasing oil spreading, while inertia and viscous forces retard it. The spreading process forms a thin layer – "slick" – which will drift under the influence of wind and currents. Initially the oil spread as a coherent slick, after which the oil may begin to break up or fragment. Solid or highly viscous oils (heavy oil types) have a tendency to fragment rather than spread to thin layers. In general the rate of spreading depends on the viscosity of the oil and the volume spilled. Fluid, low viscosity oils (light oil types) spread more quickly than those with a high viscosity. The rate at which the oil spreads is also determined by the environmental conditions such as temperature, water currents, tidal streams and wind speeds. In general the more severe the conditions are, the more rapid is the spreading and breaking up of oil.

If the oil types and thereby the oil density, viscosity, and interfacial tensions (oil-air, oil-water and air-water) are known, it is possible to characterize the spreading behaviour by numerical ocean-oil drift models. In the *3D oil drift and fate model* at DMI the spreading is simulated according to Fay's equations (1969, 1971) – which takes into account three different regimes of the spreading process.

In the first phase of spreading, the change of the oil spill radius is determined mainly by gravity and inertia. In the intermediate phase gravity and viscous forces will dominate and in the final phase viscous forces balance the surface tension.

3.2 Evaporation

Evaporation to the atmosphere is one of the most important of the weathering processes and plays a significant role during the early stages of an oil spill. The rate and degree of evaporation of an oil type depends on the oil vapour pressure, which is influenced by the mixture of components in the oil, size of the spill, temperature, solar radiation, wind speed and sea conditions. Oil with a large percentage of light and volatile compounds will evaporate more than one with a larger amount of heavier compounds. In general, oil components with a boiling point below 200 °C will evaporate within a period of 24 hours in temperate conditions. The more components with low boiling points the oil contains, the more will the oil evaporate. Initially, the more volatile components of the oil evaporate and, to a lesser extent, some fraction of the oil will dissolve into the water column. This process will continue and for a very light crude and light refined oil types, it may eventually account for the loss of a major fraction of the oil pollutant. Strong winds, rough seas and high air temperature increase the rate of evaporation. The evaporation rate will furthermore increase as the oil spreads, due to the increased surface area of the oil slick.

The evaporation is not limited to the oils at the sea surface but also from oil droplets entrained into water layers below the surface. The amounts of oil evaporated will enter the sea again and not necessarily as hydrocarbon. The gas is most likely oxidized photochemical of OH- compounds in the air and converted into CO, CO_2 and oxygen organically materials.

The density and viscosity of the remained oil increases as part of the oil slick evaporates. This affects the subsequently weathering processes and the effectiveness of clean-up techniques. The remaining oil properties will change significantly due to the large percentage of heavier compounds left.

Light crude oils can lose up to 75% of their initial volume by evaporation and medium crude oils up to 40% within a few days following a spill. In contrast, heavy or residual oils will evaporate less than 10% of their volume. Refined products such as kerosene and gasoline may evaporate completely within a few hours.

3.3 Natural dispersion –vertical dispersion

The oil content at the surface decreases rapidly due to evaporation in the first stage of the oil spill. Next after the oil evaporation the other important process that removes oil from the sea surface is the vertical dispersion caused by turbulence (primary generated by wind waves) and buoyancy. The dispersion is a break-up of the oil into small droplets that are mixed down into the water column. If the droplets are small enough, they are kept in suspension by the turbulent motion of the sea and in this way kept in the water column, while larger oil droplets will rise back to the surface, where they either coalesce with other droplets to reform a slick or spread out in a very thin film. Dependent on the droplets size and turbulence it may also entrain further down into the water column. Remained oil suspended in the water has a greater surface area than before dispersion occurred. This promotes other natural processes such as dissolution, biodegradation and sedimentation.

The speed at which oil disperse is largely dependent upon the nature of the oil and the sea state. Breaking waves are needed for a significant rate of natural dispersion, and occurs most quickly if the oil is light and of low viscosity and if the sea is very rough. In the initial stages of weathering the rate of natural dispersion can be relatively high. But the natural dispersion will rapidly be reduced due to oil slick viscosity increase caused by the evaporation and emulsification processes.

3.4 Emulsification

Emulsification is the combination of oil and water – one suspended in the other (without separation of oil and water). The emulsion can be either oil-in-water or water-in-oil. Both types of emulsification require wave action and occur only for specific oil compositions. When the oil take up water droplets and form water-in-oil emulsion the volume of the oil slick can increase by a factor of up to four. The emulsion formed is usually very viscous and more persistent than the original oil and is often referred to as chocolate mousse because of its appearance. The water-in-oil emulsion formation can lead to a water-in-oil mixture that often reaches 50-75% water content. As the amount of water absorbed increases, the density of the emulsion approaches that of seawater.

The oil properties to form emulsion depend on the presence of asphaltenes and resins (and waxes) – as the water is stabilized in the oil by two forces: viscous and elastic forces resulting from the interfacial action of resins and asphaltenes. Asphaltenes and resins accumulate at the oil-water interface and form a barrier to recoalescence. Asphaltenes form more stable emulsions than those stabilized by resins alone. The presence of theses compounds and the sea state determine the rate of which emulsion form. Emulsion stability and water-in-oil states can be classified in four states:

- Stable emulsion
- Meso-stable emulsion
- Unstable emulsion
- Entrained water

Stable emulsion is often formed when the oil type spilled has asphaltene content greater than 0.5%. This formation may persist for many months after the initial spill has occurred. *Meso-stable emulsion* lack sufficient asphaltenes to render them completely stable. However the viscosity of the oil is high enough to stabilize some water droplets for a period of time. Less stable emulsions may separate out into oil and water if heated by sunlight under calm conditions or when stranded on shorelines. *Unstable emulsions* are those that largely decompose to water and oil after mixing, generally within a few hours. However oil may not always form emulsion. Water can be "*entrained*" by the oil due to viscous forces, without forming a stable emulsion. The *entrained state* has a short life span, but residual water, typically about 10%, may persist longer.

The viscosity increases as a result of the emulsification process (and as the lighter components of oil evaporate) – which subsequently increases the stability of the emulsion since the water droplets' ability to break away from oil is reduced. The formation of water-in-oil emulsion is the main reason for the persistency of light and medium crude oils on the sea surface. It can cause the oil to sink, which give the false impression that the oil has disappeared and that there is no longer a threat to the marine environment. Furthermore the increase of the oil viscosity and the subsequently emulsification will affect the success of clean up operation since very viscous oils are difficult to skim and pump.

The formation of water-in-oil emulsion reduces the rate of other weathering processes.

3.5 Dissolution

Dissolution occurs when water-soluble compounds in oil break down into the surrounding water. The rate and extent to which oil dissolves depends on the composition, spreading, water temperature, turbulence, and degree of evaporation and dispersion of the oil. Compounds that are most soluble in seawater are the light aromatic hydrocarbons compounds such as benzene and toluene. However, these compounds are also the most volatile and are the first to be lost through evaporations – which is 10-100 times faster than dissolution. The dissolution process is the one of less important weathering process since only a very small percentage of oil is lost through oil dissolution. In general the concentrations of dissolved hydrocarbons in seawater rarely exceed 1 ppm and dissolution does not make a significant contribution to the oil removal from the sea surface.

3.6 Sedimentation

The force of gravity will cause some of the oil to sink through the water and settle on the sea bottom. Dispersed oil droplets can interact with sediment particles suspended in the water column and thus become heavier and sink. However, adhesion to heavier particles most often takes place when oil strand on beaches. Particles reaching the coast or seabed are considered “ stranded” and are not considered in the subsequent model drift calculations.

4 Oil types and properties

Characterization of oil type; i.e. *crude oils* and *refined oil products*, in an oil spill accident at sea, is one of the earliest information that is needed for a proper simulation of the oil spill behaviour, persistence and propagation.

The way an oil slick breaks up and dissipates will for example depend largely on how persistent the oil is. Light products such as kerosene tend to evaporate and dissipate quickly and naturally and rarely needs clean up. These are called *"non-persistent oils"*. In contrast, *"persistent oils"*, such as many crude oils, break up and dissipate more slowly and usually require a clean-up response.

The main physical properties which affect the behaviour and persistence of an oil spilled at sea are *specific gravity*, *distillation characteristics, viscosity* and *pour point*. These depend on the chemical composition of the oil such as the amount of asphaltenes, resins and waxes. The *specific gravity* of oil is its density in relation to pure water. Oils with a low specific gravity tend to contain a high proportion of volatile components and to be of low viscosity. The *viscosity* refers to oil's resistance to flow and *distillation characteristics* of oil describe its volatility – i.e. how easily and quickly the oil evaporates into the air. As the temperature of oil is raised, different components reach their boiling point one after another and evaporate, i.e. are distilled. Some oils contain bituminous, waxes or asphaltenic residues, which do not readily distil, even at high temperature – and thus persist in the environment. *The pour point* is the temperature below which oil will not flow. The pour point is a function of the wax and asphaltene content of the oil.

4.1 Crude and refined oils

The chemical composition of crude oils and refined oil products consist of a large quantity of hydrocarbons that range from light gasses to heavier tars and waxes. *Refined products* are derived from crude oils through processes such as catalytic cracking (breaking of molecule) and fractional distillation. These products have physical and chemical characteristics that differ according to the type of crude oil and subsequent refining processes. *Crude oils* contain hundreds of different hydrocarbons and other organic and inorganic substances. All crude oils contain lighter fractions similar to gasoline and heavier tar and wax constituents. Crude oils are often characterized according to their geographical source. For responses and modelling of oil at sea it is more useful to classify the oil types by their characteristica and changes when spilled at seawater. Oils are therefore also often classified into four groups; light, medium, heavy oils and oils heavier than seawater.

Examples of refined products are; Gasoline (very light), Kerosene (light), No.2 Fuel Oil (light), No.4 Fuel Oil (medium light), No.5 Fuel Oil also called Bunker B (medium to heavy), No.6 Fuel Oil also called Bunker C (heavy) and Lubrication Oil (medium).

4.1.1 Light Oils

Gasoline and *Kerosene* are categorised as light refined products. These oil types have typically very high evaporation rates and may evaporate completely in a few hours under temperate conditions. They flow easily and spread very quickly. Gasoline and kerosene poses a risk of fire and explosion because of their high volatility and flammability.

No.2 Fuel Oil is also a light oil type. It has a low viscosity, which causes the oil to flow easily. It spreads very quickly and disperses quickly. The oil rarely form emulsion, and is relatively non-persistent in the environment.

4.1.2 Medium Oils

Most crude oil are medium oils. Medium oils typically evaporate about one-third during the first 24 hours after an oil spill.

4.1.3 Heavy Oils

Heavy oils have almost no evaporation or dissolution, but will typically undergo an emulsification process – i.e. form a water-in-oil emulsion. During the emulsification process the viscosity of the oil-water mixture will increase rapidly and the black colour of the oil slick will turn into a more brown –orange colour. Emulsification can result in water-in-oil mixture with up to 75 percent water content and thereby increase the size of the spill area and volume significant.

Bunker C and *IFO (intermediate fuel oil)* are categorised as heavy refined products. Both Bunker C and IFO contain high concentrations of residual fuels. These oil types often spread up into smaller "pancakes"[1] and then "tarballs", rather than spread into thin films. As the properties of these oil types only change very little – they can cause quite persistent floating-pollutant problems. They do not rapidly form sheens and the resulting tarball fields are very difficult to observe using visual and remote sensing observation techniques. Combined with the persistence of the tarballs, oil spills with these types of oil can cause long-range and unexpected beach impacts.

4.1.4 Oil types heavier than water

A few crude oils and heavy fuel oils are heavier than water and will thus sink. Observations of sinking/submerged oil require very clear and shallow water. Close to the position where the oil has sunk, a light sheen will usually appear on the water surface.

4.2 Oil classification in the model

Table 1 shows the classification of the 8 different oil types pre-coded in the *3D oil drift and fate model* applied at DMI. Furthermore is the maximum evaporation percentage as well as the approximately density indicated for the different oil types.

[1] Oil that fragment into smaller patches of oil - with diameters varying from one meter to hundreds of meters are called **Pancakes.** Oil patches with diameters less than one meter is referred as **tarballs**

Oil nr.	Oil name	Oil calssification	Max. Evaporation approx.	Density approx. [kg/m^3]
1	Fuel N2	Light refined fuel oil	40%	850
2	Bunker C	Heavy refined oil	< 30 %	900
3	Crude Nigeria	Crude oil Africa, the Near East	20-40 %	850
4	Crude Statfjord	Crude oil, North Sea	30-50 %	850
5	Crude Ekofisk	Crude oil	> 50 %	800
6	Kerosene	Light volatile refined oil	Very high evaporation	-
7	Crude Venezuela	Crude oil	20-50 %	high setting point
8	IFO 450	Tough heavy refined oil	< 10 %	high setting point

Table 1. Classification of the oil types included in the 3D oil drift and fate model and their typical evaporation percentages and approximately density.

The properties of each oil type are divided into eight fractions adding up to 100%, defined by their distillation properties and chemical structure. A fraction is determined by its: density, molar weight, saturation vapour pressure, reference viscosity (at 20°C), viscosity constant c_3 (after Mackay et al, 1980) and viscosity constant c_4 (after Mackay et al, 1980). In table 2 below is entered the fractions of the different compounds for each of the pre-coded oil types in the model.

Fraction	Description	Fuel N2	Bunker C	Crude Nigeria	Crude Statfjord	Crude Ekofisk	Kerosene	Crude Venezuela	IFO 450
1	**C_6-C_{12} (Paraffin)**	0.10	0.00	0.15	0.15	0.20	0.15	0.10	0.05
2	**C_{13}-C_{25} (Paraffin)**	0.25	0.01	0.15	0.13	0.15	0.20	0.08	0.05
3	**C_6-C_{12} (Cycloparaffin)**	0.15	0.05	0.20	0.14	0.20	0.20	0.15	0.01
4	**C_{13}-C_{23} (Cycloparaffin)**	0.15	0.01	0.20	0.12	0.20	0.20	0.20	0.01
5	**C_6-C_{11} (Aromatic)**	0.15	0.05	0.05	0.07	0.07	0.15	0.05	0.01
6	**C_{12}-C_{18} (Aromatic)**	0.05	0.01	0.03	0.035	0.04	0.02	0.02	0.01
7	**C_9-C_{25} (Naphtheno-aromatic)**	0.15	0.01	0.07	0.035	0.04	0.08	0.15	0.01
8	**Residual (Incl. Heterocycles)**	0.00	0.86	0.15	0.32	0.10	0.00	0.25	0.85

Table 2 Fraction of different compounds for each of the pre-coded oil types in the model.

Reference

Audunson, T., 1980: The fate and weathering of surface oil from Bravo blowout. Marine Environ. Res. Vol. 3, pp.35-61.

Blumer, M., 1969: Oil Pollution of the ocean, in: *Oil on the Sea, ed. D. P. Hoult, Plenum Press, New York – London 1969*, pp. 5-13.

Børresen, J. A., 1993: Olje på havet. AD Notam Gyldendal 1993.

Cooke, R. F., 1969: Oil Transportation by Sea, in: *Oil on the Sea, ed. D. P. Hoult, Plenum Press, New York – London 1969*, pp. 93-102.

Dick S., Kleine E., Müller-Navarra S. H., Klein H. and Komo H., 2001: The Operational circulation Model of BSH (BSHcmod). Model description and validation. Berichte des Bundesamtes für Seeschiffahrt und Hydrographie. Nr. 29/2001.

Dick, S. und Soetje K. C. 1990: Ein operationelles Ölausbreitungsmodell für die Deutsche Bucht. Berichte des Bundesamtes für Seeschiffahrt und Hydrographie. Ergänzungsheft Reihe A, Nr. 16, 1990.

Dick S. and Müller-Navarra S. H: An operational oil spill model for the North Sea and the Baltic Sea – model feature and applications. Berichte des Bundesamtes für Seeschiffahrt und Hydrographie.

Dippner, J. W. 1984: Ein Strömungs – und Öldriftnodell für die Deutsche Bucht. Verôffentlichung Institut für Meeresforschung Bremerhaven, Supl. B. 8, p.188.

Eley, W. David, 2000: Needs Assessment for a Major Fuel Oil Spill, Glacier Bay National Park and Preserve, May 2000. Cape Decision International Services, 3300 Foster Avenue, Juneau, Alaska 99801.

Fay, J.A., 1969: The spread of oil slicks on a calm sea, in: Oil on the Sea, ed. D. P. Hoult, pp. 53-63.

Fay, J.A., 1971: Physical Processes in the spread of oil on a water surface. Proc. Of Joint Conf. on Prevent. and control of Oil Spills, USA-Washington, D. C., June 15-17, 1971, pp. 463-467.

Mackay, D., W., S. Paterson, and K. Trudel. 1980: A Mathematical Model of Oil Spill Behaviour. Report EE-7. Environmental Protection Service, Fisheries and Environment Canada, Ottawa, Ontario.

Mackay, D., W. Stiver, and P. A. Tebeau, 1983: Testing of crude oils and petroleum products for environmental purposes. Proc. 1983 Oil Spill conf., pp. 331-337.

Michel, Jacqueline; Oil Behavior and Toxicity. Inc.,P.O. Box 328, Columbia, South Carolina 29202.

Vincent, G., S.Le Floch, B. Le Guen, 2001: Accident of the oil tanker “Baltic Carrier” off the Danish coastlines. Final Report, European Task Force in Denmark, p.10

Yang, W. C. and H. Wang, 1976: Modelling of oil evaporation in aqueous environment. Water Research Vol. 11, pp. 879-887.

Arial observations of oil at sea, Hazmat Report 96-7, April 1996.

Physical processes affecting the movement and spreading of oils in inland aters. Hazmat Report 95-7. September 1995.

List of URL's

/1/ Pressemeddelelse fra Cosco Agency, Denmark. http://www.sok.dk/pr/olie/Cosco.htm

/2/ www.ystad.se

/3/ ESA's homepage: http://earth.esa.int/ew/oil_slicks/sweden-denmark_sea_03/os_sweden:jun_03.htm

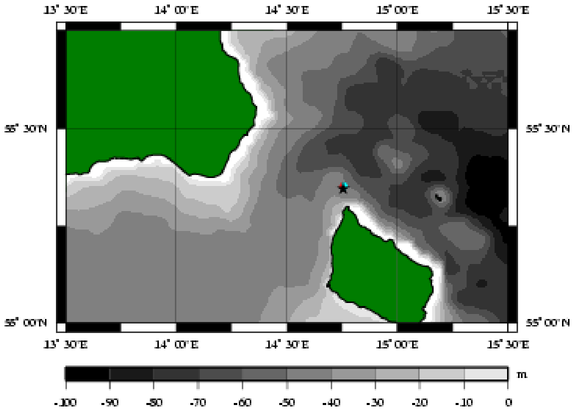
/4/ http://politikken.dk

/5/ *http://www.sintef.no/units/chem/environment/oil_weathering_model.htm#Prediction_sheet*

/6/ http://www.bunkerworld.com/technical/

/7/ http://www.kittiwake.com/knowledge_base/training_anual/articles2.asp

/8/ http://www.itopf.com/fate.thml



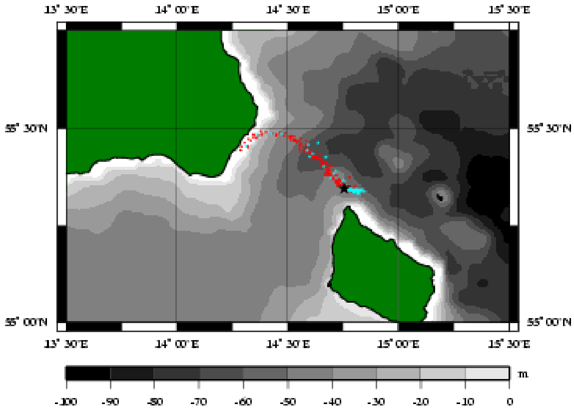
Spill extent 01.06.2003 06:00 UTC

Time of report: 31-05-2003 20:30 UTC
Time elapsed: +010 h
Oil type: Bunker C
Quantum: 70.2 t

Oil statistics:

Surface: 10.2 %
Disperged: 89.6 %
Bottom: 0.0 %
Evaporated: 0.1 %
Water content: 1.7 %
(for oil at surface)

Wind at slick centre:
4.7 m/s 43 deg.T



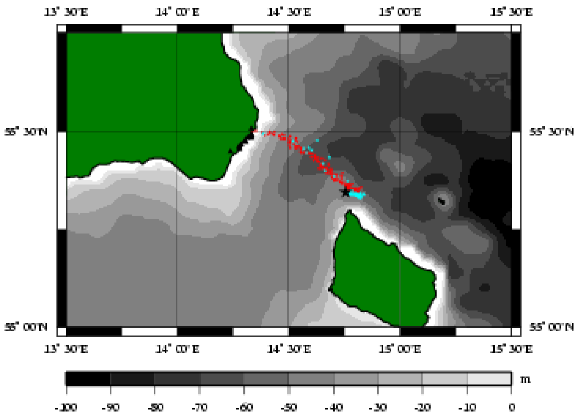
Spill extent 03.06.2003 00:00 UTC

Time of report: 31-05-2003 20:30 UTC
Time elapsed: +052 h
Oil type: Bunker C
Quantum: 372.6 t

Oil statistics:

Surface: 63.8 %
Disperged: 30.5 %
Bottom: 0.0 %
Evaporated: 5.7 %
Water content: 47.4 %
(for oil at surface)

Wind at slick centre:
8.0 m/s 101 deg.T



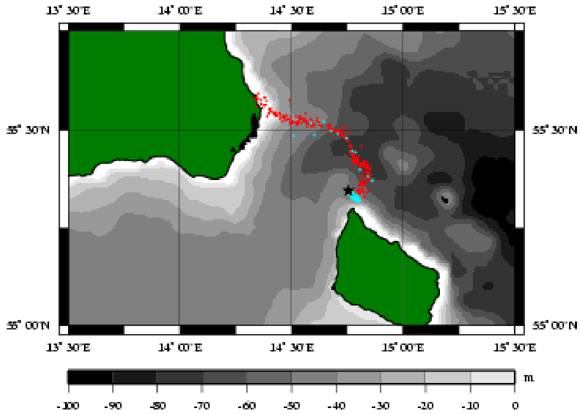
Spill extent 03.06.2003 05:00 UTC

Time of report: 31-05-2003 20:30 UTC
Time elapsed: +057 h
Oil type: Bunker C
Quantum: 408.6 t

Oil statistics:

Surface: 65.2 %
Disperged: 22.4 %
Bottom: 6.6 %
Evaporated: 5.8 %
Water content: 49.2 %
(for oil at surface)

Wind at slick centre:
6.6 m/s 118 deg.T



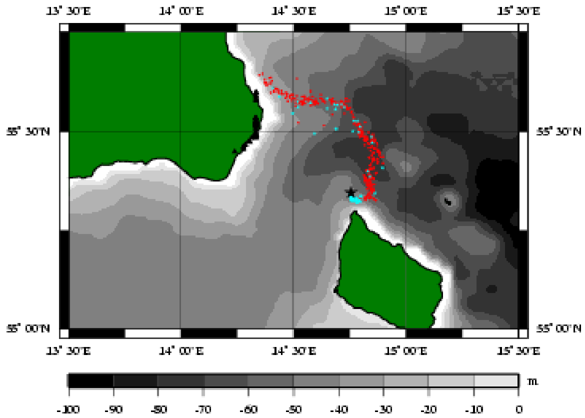
Spill extent 04.06.2003 14:00 UTC

Time of report: 31-05-2003 20:30 UTC
Time elapsed: +090 h
Oil type: Bunker C
Quantum: 646.2 t

Oil statistics:

Surface: 69.0 %
Disperged: 13.6 %
Bottom: 11.2 %
Evaporated: 6.3 %
Water content: 53.6 %
(for oil at surface)

Wind at slick centre:
5.6 m/s 172 deg.T



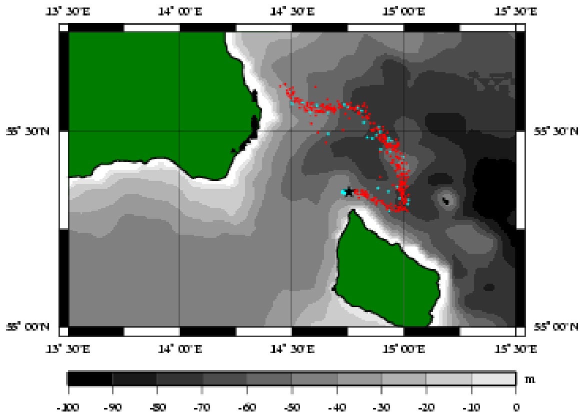
Spill extent 05.06.2003 07:00 UTC

Time of report: 31-05-2003 20:30 UTC
Time elapsed: +107 h
Oil type: Bunker C
Quantum: 768.6 t

Oil statistics:

Surface: ● 68.4 %
Dispersed: ★ 13.7 %
Bottom: ▲ 11.2 %
Evaporated: 6.7 %
Water content: 56.2 %
(for oil at surface)

Wind at slick centre:
7.8 m/s 257 deg.T



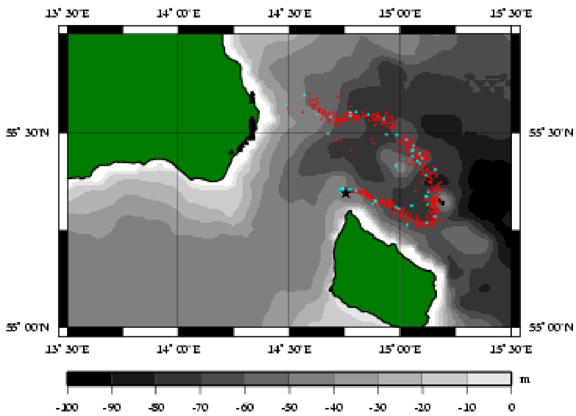
Spill extent 05.06.2003 20:00 UTC

Time of report: 31-05-2003 20:30 UTC
Time elapsed: +120 h
Oil type: Bunker C
Quantum: 862.2 t

Oil statistics:

Surface: ● 69.3 %
Dispersed: ★ 12.5 %
Bottom: ▲ 11.2 %
Evaporated: 7.0 %
Water content: 57.1 %
(for oil at surface)

Wind at slick centre:
6.5 m/s 263 deg.T



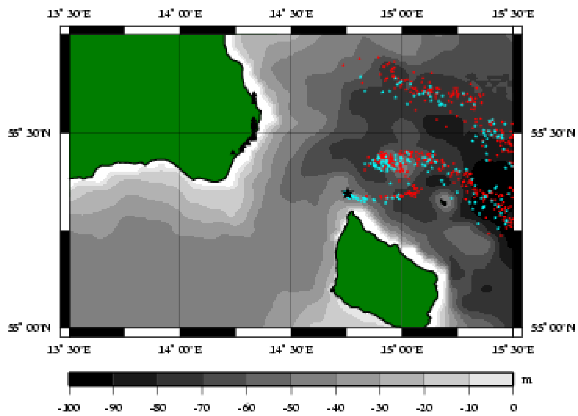
Spill extent 06.06.2003 11:00 UTC

Time of report: 31-05-2003 20:30 UTC
Time elapsed: +135 h
Oil type: Bunker C
Quantum: 970.2 t

Oil statistics:

Surface: ● 69.1 %
Dispersed: ★ 12.4 %
Bottom: ▲ 11.2 %
Evaporated: 7.3 %
Water content: 58.5 %
(for oil at surface)

Wind at slick centre:
7.3 m/s 268 deg.T



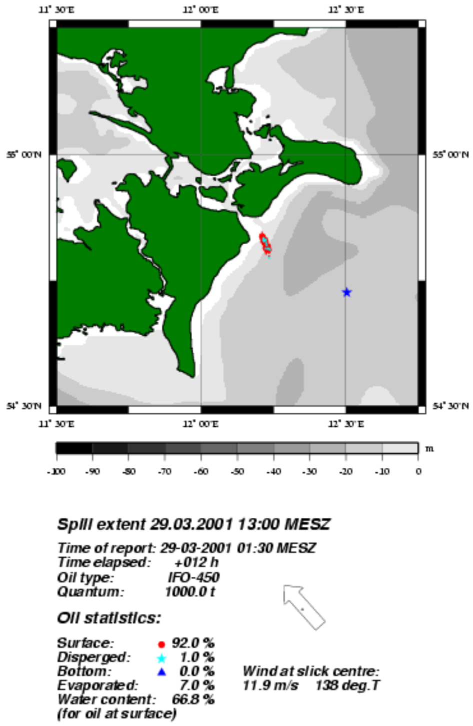
Spill extent 09.06.2003 10:00 UTC

Time of report: 31-05-2003 20:30 UTC
Time elapsed: +206 h
Oil type: Bunker C
Quantum: 1481.4 t

Oil statistics:

Surface: ● 58.4 %
Dispersed: ★ 22.2 %
Bottom: ▲ 11.2 %
Evaporated: 8.2 %
Water content: 61.6 %
(for oil at surface)

Wind at slick centre:
16.0 m/s 246 deg.T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12° 00'E
12° 30'E
55° 00'N
54° 30'N
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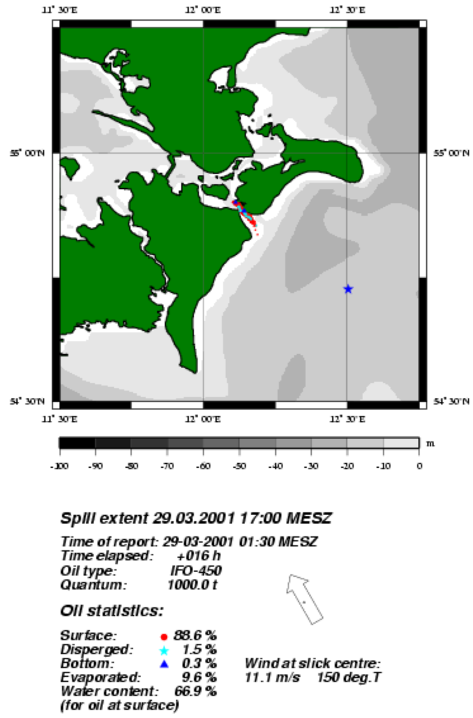
Time of report: 29-03-2001 01:30 MESZ
Time elapsed: +012 h
Oil type: IFO-450
Quantum: 1000.0 t
Oil statistics:
Surface: 92.0 %
Dispersed: 1.0 %
Bottom: 0.0 %
Evaporated: 7.0 %
Water content: 66.8 %
(for oil at surface)
Wind at slick centre:
11.9 m/s 138 deg.T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12° 00'E
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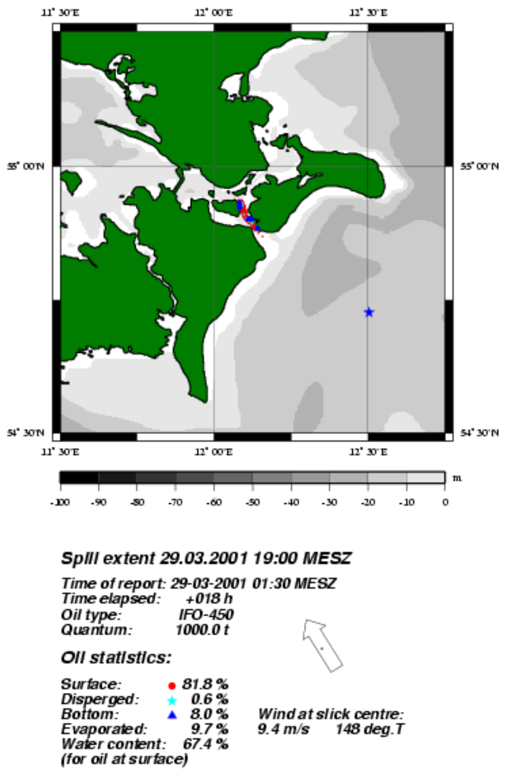
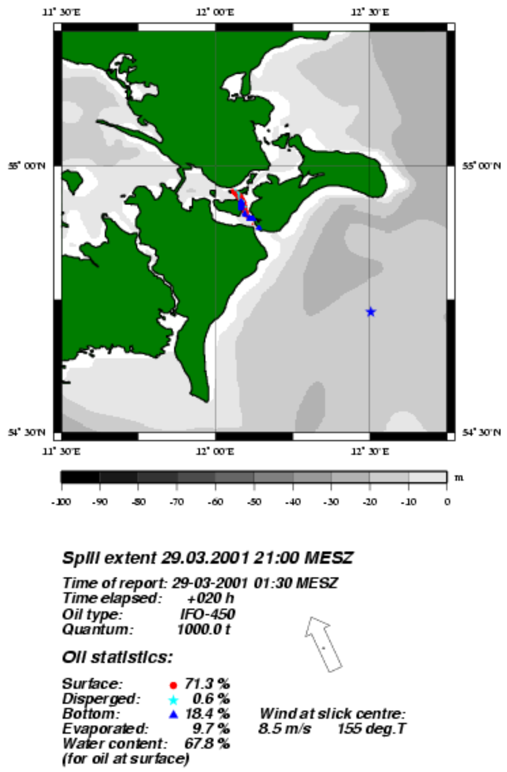
Spill extent 29.03.2001 17:00 MESZ
Time of report: 29-03-2001 01:30 MESZ
Time elapsed: +016 h
Oil type: IFO-450
Quantum: 1000.0 t
Oil statistics:
Surface: 88.6 %
Dispersed: 1.5 %
Bottom: 0.3 %
Evaporated: 9.6 %
Water content: 66.9 %
(for oil at surface)
Wind at slick centre:
11.1 m/s 150 deg.T


11° 30'E
12° 00'E
12° 30'E
55° 00'N
54° 30'N
m
-100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0
Spill extent 29.03.2001 19:00 MESZ
Time of report: 29-03-2001 01:30 MESZ
Time elapsed: +018 h
Oil type: IFO-450
Quantum: 1000.0 t
Oil statistics:
Surface: 81.8 %
Dispersed: 0.6 %
Bottom: 8.0 %
Evaporated: 9.7 %
Water content: 67.4 %
(for oil at surface)
Wind at slick centre:
9.4 m/s 148 deg.T


11° 30'E
12° 00'E
12° 30'E
55° 00'N
54° 30'N
m
-100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0
Spill extent 29.03.2001 21:00 MESZ
Time of report: 29-03-2001 01:30 MESZ
Time elapsed: +020 h
Oil type: IFO-450
Quantum: 1000.0 t
Oil statistics:
Surface: 71.3 %
Dispersed: 0.6 %
Bottom: 18.4 %
Evaporated: 9.7 %
Water content: 67.8 %
(for oil at surface)
Wind at slick centre:
8.5 m/s 155 deg.T