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Discussions

Usefulness of high resolution coastal models for operational oil spill forecast: the Full City accident

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Abstract

Oil spill modeling is considered to be an important decision support system (DeSS) useful for remedial action in case of accidents, as well as for designing the environmental monitoring system that is frequently set up after major accidents. Many accidents take place in coastal areas implying that low resolution basin scale ocean models is of limited use for predicting the trajectories of an oil spill. In this study, we target the oil spill in connection with the Full City accident on the Norwegian south coast and compare three different oil spill models for the area. The result of the analysis is that all models do a satisfactory job. The “standard” operational model for the area is shown to have severe flaws but including an analysis based on a higher resolution model (1.5 km resolution) for the area the model system show results that compare well with observations. The study also shows that an ensemble using three different models is useful when predicting/analyzing oil spill in coastal areas.

1 Introduction

Oil spill models are important tools for predictions of oil spill movement and for evaluating their affect on the environment: an accurate prediction is of tremendous value for the organization that is on standby for the cleaning actions and for setting up environmental monitoring programs. Any comprehensive modeling systems for oil spill are by necessity complex: besides the full three-dimensional velocity, temperature and salinity fields needed for advecting the oil spill, the oil chemistry and its interaction with water, waves, bottom etc must be described (Castanedo et al., 2006; Dick and Müller-Navarra, 2002; Diez et al., 2007; French-McCay, 2004; Reed et al., 1999; Wanga et al., 2008). The complexity of the entire system implies that many simplifications must be introduced and it is not always clear how these simplifications (e.g., considering two-dimensional models only, neglecting wave mixing and drift, etc.) will influence the performance of the model. Most likely, the performance will depend on the exact physical situation during the spill. In any case, it is safe to state that validation of oil spill models are an important ingredient for evaluating the performance of the models and further studies are required for guiding development and testing of model systems.

1.1 Full City accident

On 30 July 2009 at around 12:00 h UTC (we will use UTC throughout this study) the Panama-registered cargo vessel MV Full City anchored on the Norwegian coast about 2 km from the Såstein Island outside Langesund (see Fig. 1) in the Skagerrak area. According to Accident Investigation Board Norway (AIBN) the Full City started to drift toward Såstein Island at about 21:50 due to very strong winds and waves from southwest (AIBN, preliminary report). Both flukes on the anchor broke off and albeit that the engines were turned on the ship remained un-maneuverable and run onto the rocky ground off Såstein Island[1] on 30 July at about 22:25 (Fig. 1). The ship suffered severe damage to her hull and started to leak heavy bunker oil that polluted the sea and the shorelines. The ship carried about 1000 t of heavy bunker oil (IF180 with a density of 994 kg m^{-3}) and 120 t of marine diesels. It is estimated that about 300 t of heavy bunker oil were released; preliminary estimates suggest that 200 t were spilled the first hours, and the remaining 100 t over the next 6–8 h. The accident was reported during the night and the oil spill response action was started next morning, and it was quickly foreseen that it was a significant oil spill in an ecological sensitive area, with several special protected areas and bird sanctuaries. The accident took place in the main holiday season in a popular area for vacation and the spill received major attention in news media.

According to the Norwegian Coastal Authorities (NCA) oil was observed on 2 August in several areas along the coast (see the discussion in Sect. 3). About 70 km of the coastline were directly polluted by the oil spill and oil were observed at about 190 different locations. Some of the affected fjords are protected areas and bird sanctuaries

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[1] Exact position was 9.716° E, 58.9671° N.

and an extensive monitoring of the environmental consequences is still going on. On the days following the incident hundreds of birds covered in oil were considered beyond saving and had to be put to death: totally it is estimated that about 1500–2000 eiders and about 500 additional seabirds were killed during to the accident (Lorentsen et al., 2010).

By 12 August NCA claimed that 860 m^3 of oil were recovered from the ship, 28 m^3 pure oil were recovered from the sea, 74 m^3 from the beaches, and 180 t of oil emulsions had been recovered from the beaches and sea; accordingly, it is estimated that about 190 tons of oil remained in the environment (Lorentsen et al., 2010). About 15 000–18 000 man days were used in the cleaning action: the total cost estimated for the remedial action was about 25 m euros, and up to 2 m euros will be used for environmental monitoring until 2014 (Olsen, 2009).

1.2 Weather conditions during the period

1.2.1 Atmospheric conditions

In Fig. 2 the weather conditions during and immediately after the accident, i.e., on 31 July at 00:00, and 12:00 and on 1 August at 00:00, and 12:00, from the met.no setup of the High Resolution Local Area Modeling (HIRLAM) model (Undén et al., 2002) using a 8 km resolution are shown. We see an intense low pressure system located over the southern Norway at the time of the accident. The low pressure system gave rise to strong gale winds in the Skagerrak area, with wind essentially parallel with the Norwegian coast at the time of the accident. The strong winds prevailed a few hours after the Full City was grounded; however, after this the wind speed decreased rapidly. met.no has an observation stations at Jomfruland (about 30 km southwest from Såstein, Fig. 1) and the wind speed from this station show that the wind speed was about 18 $m\,s^{-1}$ at Jomfruland at the time of the accident (direction about 210 degrees), the wind remain constant for about 5 h, and then it decreased to about to about 7 $m\,s^{-1}$ (and direction 235 degrees) 6 h after the accident. At 31 July 12:00 the wind shifted direction to about

275 degrees) and decreases slowly with time. From about 11:00 at 1 August, the wind speed was about 9 m s^{-1} and had direction 220 degrees, and was constant until 2 August when there was a major shift in wind direction to about 60 degrees from 06:00 in the morning to about 24:00. It should be noted that in a reanalysis of the fate of the oil spill that was carried out by SINTEF, the wind speed observations at Jomfruland were used rather than wind speed from the meteorological models as it produced results in better agreement with observations (M. Reed, personal communication).

1.2.2 Wave conditions

The strong wind directed along the coast on the midnight between 30–31 July gave rise to significant wave heights of order 5–6 m in the central Skagerrak area (according to model analysis) while the significant wave height along the Norwegian coast reached about 4 m (Fig. 3). Waves are known to contribute to particle drift due to the Stokes drift (Phillips, 1977)[2], and there was a significant Stokes drift of order 0.2–0.3 m s^{-1} towards northeast associated with the strong wave field. The wave condition depends essentially on the wind speed and the significant wave height declined rapidly when the wind speed decreased. On 1 August at 06:00 the significant wave height was about 1 m in the central Skagerrak area. It is well known that wave models are accurate for open water conditions and we expect these simulations to be relatively precise (Cavalieri, 2007; Komen et al., 1994). The exact wave height at the coast depends on whether the wind direction was in towards the coast or slightly out from the coast. Local geographic condition with refraction of the waves could also play a role for the exact wave conditions at the accident site, these fine scale structures are not captured by met.no model.

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[2] see also http://en.wikipedia.org/wiki/Stokes_drift

1.2.3 Current conditions

The ocean current conditions for the period from the met.no ocean model with 1.5 km resolution that focuses on Skagerrak and northern North Sea is outlined in Fig. 4. It should be noted that wind and wave conditions are most likely fairly similar in all models used in this study, the main difference is probably in the ocean models and the various setups of the oil drift models. However, we recapture the situation from the met.no model for the Skagerrak to exemplify typical current patterns for the area. For this period there was a strong cyclonic current system in the Skagerrak (in this model) with inflow in the southern Skagerrak and outflow along the Norwegian coast. At the time of the accident there was a flow of surface water out from the Norwegian coast, this was probably the wind driven Ekman current. It should be noted that there may be a thin north-eastward coastal current at the Norwegian coast, probably forced by the strong wind and the associated upwelling along the coast (the current arrows closest to the coast on 31 July at 00:00 indicate a north-eastward coastal current although it is not very distinguish). Some time after the accident the wind speed decreased reaching essentially calm conditions by 1 August. We thus expect weaker wind driven Ekman currents out from the coast and the north-eastward coastal jet will weaken. Accordingly the coastal current will most likely return to more normal conditions with south-westward buoyancy driven current (i.e., the southward coastal current driven by the steady freshwater output from Baltic Sea and the European rivers and is an stable current system along the coastlines of the northern Skagerrak). We see that this situation occurs in the met.no ocean model. We thus expect that the oil will move northeastwardly initially and outwards from the coast after a few hours; after this we expect that the oil will move southwestwardly with the reappearing coastal current.

The oil drift models in this study are based on super particles that are advected by ocean currents and wind speed, the currents can be taken from ocean models or parameterizations of drift speeds. The super particles also contain descriptions of oil chemistry, horizontal dispersion, and mixing within the water column. Accordingly, we describe the oil drift models and the atmospheric, wave and ocean models that are used the force the oil drift models in Sect. 2. In Sect. 3 we describe observations of the oil spill and discuss how the different oil spill models in this study captures the observations. Given that we only have qualitative observations of the oil spill, we limit the analysis to a simple “show and tell” description. Section 4 is devoted to discussion of the results.

2 Model descriptions

2.1 Norwegian Metrological Institute model system

2.1.1 Atmosphere and wave models

The HIRLAM 8 km model, where 8 km indicates the horizontal resolution, is a hydrostatic grid-point model in which the dynamical core is based on a semi-implicit semi-Lagrangian descretisation, with a hybrid coordinate in the vertical, of the basic dynamical equations. The prognostic variables are horizontal wind components u, v, temperature T, specific humidity q. The linearised geopotential height G are defined at full model levels. Pressure p, geopotential height Φ, and vertical wind velocity are calculated at “half” levels. For the horizontal discretisation, an Arakawa C-grid is used. The equations are written for a general map projection, but in practice normally a rotated lat-lon grid projection is adopted. Turbulence is described using a prognostic Turbulent Kinetic Energy (TKE) scheme (Tijm and Lenderink, 2003). The assimilation of observations is mainly done by variational methods combining 3D-VAR (Unden et al., 2002) and 4D-VAR. Bias corrections are applied to most satellite data. Observation screening involves logical and representivity checks, background quality checks, black-or-white listing, multi-level and station level checks, redundancy checks and moving platform checks.

The wave model is based on the wave analysis model (WAM) that describes the energy in different wave components (Cavalieri, 2007; Komen et al., 1994; Phillips, 1977): WAM belongs to the third generation wave model and accounts for the non-linear interaction between the wave components. The Stokes drift is calculated from an integration over the wave spectrum, the tail in the spectra that is not resolved by the model is calculated using a self-similar spectral shape of the tail (Komen et al., 1994; Phillips, 1977). The Stokes drift is calculated routinely at both met.no and European Centre for Medium Range Weather Forecast (ECMWF) and may be considered as a reliable and well predicted quantity that is important for drifting objects (Broström et al., 2009).

2.1.2 Operational ocean modeling at met.no

The operational ocean model at met.no as of today is based on the Princeton Ocean Model (POM) (Blumberg and Mellor, 1987), which has been modified for operational use at met.no (Engedahl, 1995). The local model has the name MI-POM (Meteorological Institute Princeton Ocean Model) and solves numerically the three-dimensional primitive equations in sigma coordinates (terrain following coordinates) to describe the ocean dynamics. The model uses a 2.5-order turbulent mixing model (Mellor and Yamada, 1982; Melsom, 1996). The heat flux formulations have been adjusted for Norwegian conditions (Røed and Debernard, 2004); the model also includes a simple nudging scheme to assimilate satellite SST products. Tides are included and described by the eight harmonic components (M2, S2, N2, K2, Q1, O1, P1 and K1) taken from a barotropic tidal model. The tidal forcing is applied at the lateral edge of the model. In this study we use two different setups of the model, they are both on a polar stereographic grid and the results must be interpolated onto a regular lat-lon grid before being used in the oil drift model. For this study we interpolate forcing onto a grid that has similar resolution as the underlying ocean model, interpolation/extrapolation to a finer grid may affect the beaching pattern of the oil drift model.

2.1.3 Oil drift modeling

The oil drift model at met.no is based on the Oil Drift 3-Dimensional numerical model (OD3D) that was developed in cooperation with SINTEF[3] (Martinsen et al., 1994; Wettre et al., 2001). OD3D is based on super particles that represent the main characteristics of the oil and is forced by wind, wave (including the Stokes drift), and oceanic currents and stratification; the oil chemistry depends mainly on temperature, wind speed and significant wave height while the drift follows ocean currents and the Stokes drift. The model operates with a 30 min Euler time step and the numerical advection of particles, especially in areas with complex topography, is not very accurate. Furthermore, in the present operational setting the model does not allow for oil particles to be inside the one-half grid point closest to the coast for numerical reasons[4]. The OD3D model (and the other models in this study) predicts the drift oil particles, how they disperse in time, and how much oil has been evaporated, submerged and beached. In this study, we will focus on the advection, dispersion, and beaching.

In the operational setting OD3D uses the 4 km ocean model; however, it is well known that ocean models with 4 km resolution does not perform well in the vicinity of the coast line when the coastline is rugged or/and where there is an archipelago. The oil drift model can be driven using various atmospheric, wave, and ocean models in a non-operational mode (i.e., requires trained staff to extract forcing from these various sources) and in this study we will study the performance of the 4 km standard model and the 1.5 km Skagerrak model for the Full City accident. Notable, OD3D only accepts

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[3] SINTEF is a semi-private non-profitable Norwegian research organisation.

[4] This numerical setting is based on a central differencing scheme that is not adjusted in coastal areas, this is of course unacceptable for reliable tracking of oil in near shore areas; however, this is the way the operational oil drift model was in operation during the Full City accident. While met.no is in the process of changing the operational oil drift model from ODS3D to the SINTEF model OSCAR no attempts to improve the numerical scheme in the oil drift model have been made.

fields in geographic grids, i.e., in standard longitude-latitude grids. Thus in order to generate inputs to OD3D all driving fields must be interpolated to the same latitude-longitude domain.

2.2 BSH model system

The oil spill model of of the German Federal Maritime and Hydrographic Agency (BSH) is an important part of a decision support system (DeSS) for combating marine environmental pollution. The model system consists of a hydrodynamical circulation model for the North Sea and Baltic (BSHcmod) and various drift and dispersion models for different substances or applications. The circulation model is three-dimensional and takes into account meteorological conditions in the North Sea and Baltic Sea area, tides and external surges entering the North Sea from the Atlantic, heat fluxes between atmosphere and ocean as well as river runoff from the major rivers (Dick et al., 2010). The meteorological forecasts are provided by models of the German Weather Service (DWD). The BSH circulation model predicts tidal, wind and density driven motion up to 84 h ahead on two nested grids. Grid resolution is 900 m in the German Bight and western Baltic Sea, while it is approx. 5 km in other parts of the North Sea and Baltic as well as in the Skagerrak area.

A Lagrangian drift and dispersion model (BSHdmod.L) is used primarily to assist the German Central Command for Maritime Emergencies in cases of marine environmental pollution and to support search and rescue operations. Additionally, the model is frequently used to trace back harmful substances and thus has become a valuable tool in the identification of environmental polluters.

In the model the particular substance is represented by a particle cloud drifting with the current. Sub-scale turbulent motion is simulated by a Monte Carlo method. Substances floating on the surface are additionally driven in direction of the wind with a factor of 2.3 percent of wind velocity. In simulations of oil dispersion, the physical behavior of different oil types on the water surface and in the water column is also taken into account. The BSH's oil drift model simulates wind and current induced drift, spreading, horizontal and vertical dispersion, evaporation, emulsification, sinking, beaching as well as the deposition of oil on the sea bed (Dick and Soetje, 1990). Wave effects on drifting and dispersed oil are parameterized by wind velocity. In the BSH model, a particular oil consists of 7 groups of hydrocarbon compounds and a residuum. Different oil types are described by different composition of the eight compounds. In the past years, the models had been used successfully in several cases of oil pollution (Dick and Müller-Navarra, 2002).

2.3 DAMSA/SMHI model

The DAMSA/SMHI oil drift model is called Seatrack Web, and is regarded as the official HELCOM oil and chemical modeling and drift forecasting system. Seatrack Web covers the Baltic Sea area and the eastern part of the North Sea. The system is available over internet, which enables users to start an oil drift simulation on the server and have the results presented on their local computer. The results of a simulation are typically available within a few minutes.

Seatrack Web consists of three parts. The first part is the operational weather and ocean forecasting system, which provides the necessary wind and current fields. The second part is the drift, spreading and weathering model. The execution of the model is controlled by the third part of the system, which is the client/server web application. It handles the communication and comprises a graphical user interface (GUI) on the client side and a Java Servlet on the server side.

2.3.1 Wind and ocean fields

Wind and ocean forecasts are taken from the Swedish Meteorological and Hydrological (SMHI) forecasting systems; i.e. the SMHI setup of HIRLAM atmospheric model and the High Resolution Operational Model for the Baltic Sea (HIROMB) ocean model, respectively. HIROMB is run four times a day using forcing fields from HIRLAM with 22 km resolution and produces 48-h forecasts of currents, temperature, salinity, and ice conditions for the North Sea–Baltic Sea area. HIROMB calculates current velocities on a regular spherical lat-lon grid with a horizontal resolution of 3 nautical miles (about 5.5 km). In the vertical direction HIROMB uses z-level coordinates with up to 24 layers, ranging from 4 m thick at the surface to 60 m at the deepest parts. Stoke's drift is accounted for in Seatrack Web, and calculated based on the wave spectrum. Currently the wave spectrum is not imported from an operational wave forecast model. Instead, a parameterised wind-dependent spectrum for fetch-limited growth is used. The HIRLAM and HIROMB forecasts are subsequently processed and made available for Seatrack Web, in which simulations 2 days ahead and 30 days back in time are possible.

A particular feature of Seatrack Web is that it uses the map coast line as its boundary rather than the ocean model grid boundary. Consequently, there are areas outside the model grid but inside (or "wetside") the coast line where there is no model calculated ocean forcing. Temperature and salinity in these areas are extrapolated from the closest model grid cells, while a wind driven surface current parameterized as 1 percent of the wind speed in the wind direction is used in the drift calculation.

2.3.2 Oil drift, spreading and weathering

As with the other two models in this study, Seatrack Web uses a particle tracking technique to model the drift and spreading of oil spills. The spill is divided into an ensemble of discrete particles, initially of equal mass. The particles are advected and dispersed in a three-dimensional velocity and turbulence fields, which are discretised in space and time. Algorithms for gravitational surface spreading of buoyant oil and vertical dispersion result in additional particle displacements.

The properties of oil spilled at sea will change owing to weathering processes. Seatrack Web calculates changes in oil density and viscosity. These parameters are important state variables in relation to cleanup operations, but are also mutually connected to the rate of weathering and spreading. Density and viscosity are diagnostic variables and vary as functions of temperature, evaporated fraction and water fraction (in the case of emulsifying oils).

3 The oil drift experiments

The Full City grounded on 30 July at 22:23 (UTC); the discharge was 300 m^3 of IF 180, which is heavy bunker oil, over 8 h; the discharge was probably uneven in time with greater discharge in the early part of the accident with about 100 m^3 in the first hour. However, in this study we simply assume that 300 m^3 was released between 30 July 23:00 and 31 July 07:00 at a constant rate. The exact point of release was very close to the coast, and the release points in the models will to some agree depend on the model formulation.

The release of oil from the ship is fairly well established. However, this was a major release of oil close to the coastline in an area with complex topography. It is likely that a certain amount of the released oil was initially trapped in the vicinity of the accident site, and released to the more open ocean in a later stage. From an oil drift modeling point of view the initial beaching/trapping of oil with a subsequent later release of oil is not described in the model system. Accordingly, it is possible that the modeling of oil spill should have a somewhat different release timeline then the actual release of oil from the ship.

3.1 Observations of the spill

3.1.1 Direct observations

We here give a brief description of the oil spill based on observations recorded by the Norwegian Coastal Administration and oil samples taken during the response action. The times of the records refer to the first reported observations, it might be a time lag from that the oil actually appeared in an area until it was discovered and reported.

Shortly after the grounding, oil slicks drifting northwards were observed. Within few hours oil hit the shore in the area Krogshavn at Langesundtangen (near Langesund). On 31 July around 11:00 oil was observed in the area Mølen in Vestfold (the peninsula on the eastside of the Langesundsfjord, see also http://www.norgeskart.no) and soon also Oddane a little further east was affected by the spill. In the evening (around 19:00–20:00) first indications that oil was drifting southwards from the grounding site were reported.

In the early morning on 1 August observations from the public indicate that smaller amounts of oil were drifting south of the island Jomfruland. In the evening drifting oil was observed in the area outside Risør. Larger amounts were recorded in the Risør area in the morning of the 2 August. In the late afternoon oil has stranded at Ruaker, near Grimstad.

Figure 5 shows all areas were stranded oil has been recorded after shoreline survey and verification of reports from the public, a work that went on for weeks and months. All observations of stranded oil regardless of amount are included in the figure.

3.1.2 Observations by remote sensing

The satellite SAR detection for the oil spill was investigated immediately after the spill by the Nansen Environmental and Remote Sensing Center (NERSC) in Bergen, Norway. However, the impact of the remote sensing capabilities based on SAR images at the time of the accident was reduced due to rough wind and that the spill was close to land or islands. Later, on 4 August, a relatively large area of low backscatter associated with weak winds dominates the image in the central Skagerrak waters. Moving closer to the coast dark elongated features becomes visible. In close proximity of the coast, on the other hand, the spatial backscatter variability is high and without any clear and distinct expressions of possible spills. Only with access to simultaneous airborne over flight with operation of cameras and IR/UV-sensors is it possible to classify the numerous dark features. The Nansen Center has demonstrated this in Fig. 6 in which the airborne photos make clear expression of the film damping induced by the oil spill.

3.1.3 Summary of the observations

We conclude that

- There were significant beaching of oil north-northeast of the accident site (the peninsula south of Langesund) relatively quickly after the accident (within 3 h).
- There were observations of oil east of the accident site (on the southern beaches of the peninsula in Vestfold where Mølen and Nevlunghavn is located). This area received considerable amounts of the spilled oil.
- The area southwest (up to 50 km) of the accident site had significant beaching about 2 days after the time of the accident. The timing of this beaching remains somewhat uncertain but appears to be simultaneous over a large area on 1–2 August (or about 48–60 h after the accident).
- There were some observations further to the southwest but the amount of oil remains unknown. Only minor and scattered beaching was observed southwest of the 50 km limit from the accident site.

3.2 Met.no OD3D simulations

For met.no oil drift model we will consider two model simulation, one based on the standard 4 km ocean model, and one based on a 1.5 km resolution ocean model for the North Sea area. The first 24 h of the OD3D simulation based on the met.no 1.5 km simulation is shown in Fig. 7. Initially the particles move north-northeast into the fjord at Langesund; and in this scenario this movement is mainly due to the Stokes drift; there is also near-shore northeastern costal current but this is relatively weak. There is significant beaching south of Langesund near the southern tip of the peninsula in this simulations (although it should be remembered that the model system do not describe the fine details in the topography). The wind changes direction from southwest wind to more northern winds after a few hours and the drift direction changes from north-northeast to almost southwards; accordingly, 12 h after the accident the oil comes very close to the shore on the other side of the fjord (i.e., the peninsula east of the accident site) but in this simulation the oil does not touch the coastline. Observations show that oil actually beached on this shoreline, and also on the shore on the peninsula east of the accident site. We know that the OD3D seem to have less dispersion (i.e., the numerical description of horizontal dispersion is perhaps too weak) than other similar models, and this may be one of the reasons that particles do not beach over a large area as seen in observations, the other reason is of course that currents may not be accurate for this area for this period. We simply state that the met.no model system do not describe the (i) the large beaching in the vicinity of the accident site, and (ii) the advection of oil particles east-northeast during these conditions and that this is in conflict with observations, and we postpone further discussion to the results and discussion section.

After 15 h the wave field and thus also the Stokes drift declines rapidly and the oil moves essentially with the Eulerian ocean currents. The oil accordingly moves out from the coastal area and gets caught up by the coastal current at some distance out from land. Here we find a rapid movement of particles southwards: this is further highlighted in Fig. 8. The oil spreads quickly south-westwards the following 12 h; at model hour 20–30 the wind increases in strength it also changes direction and becomes toward the Norwegian coast. The oil starts to drift toward the coast and hits the coast over a large area at around model hour 36 (Fig. 8). The dates of oil arrival to the coast given by the coastal authorities only give information about the days of detection but it appears that the oil hit a large portion of the coast southwest of the accident site on 1–2 August, and we conclude that the simulation is accurate for oil beaching in these areas. There were observations of oil further to the south and this is also well described by the model; notably, the model only predicts minor beaching after 2 August.

Figure 8 also shows simulations based on the 4 km ocean model available at met.no (blue dots); it should be noted that the 4 km model is the standard (only) option for the

24-7 operational oil drift model. Due to inaccurate numerics in the oil drift model, the oil drift using this model has to be started at a location out in the Skagerrak. The oil particles are released directly into the southward going coastal current and this model simulation has a much stronger drift south-westward along the coast than the 1.5 km model. Another peculiar feature of the 4 km model run is that the oil particles strands on the coastline of the 4 km grid (i.e., one half gridpoint out from the coast due to the difference scheme for advection). We conclude that within this setup of the model, the oil drift simulation based on the 4 km model do not describe observations particularly well. It is possible to improve the performance of the model by interpolating the ocean fields to a finer grid (which reduce the problems with the advection scheme) but it is likely that the final simulations will not describe observations in the same detail as the model runs based on the 1.5 km model.

3.3 BSH oil drift simulation

Oil drift simulation by the Federal Maritime and Hydrographic Agency (BSH) using wind forecasts of the German Weather Service (DWD) is shown in Fig. 9. The oil particles initially move north-eastwards. Within the first 24 h some particles strand at the coast both north and northeast of the accident site. This agrees well with observations although it is likely that the particles move slightly too slow in this model simulation as compared to observations; furthermore, the model does not predict the extent of the beaching east of the accident site. The oil particles start to move southwards after 30–36 h reaching the coast west and southwest of the accident site after 2 days. After 3 days all the particles are stranded at the coast over distance of approximately 45 km. The beaching of particles takes place at the boundaries of grid cells having a resolution of 5 km in this area. As observations show more beaching over a larger area, the BSH oil drift model underestimates the southward drift of oil. In spite of the rather coarse resolution in the Skagerrak area the main characteristics of the oil spill are well described within the model.

Compared to the 1.5 km met.no model, the BSH model computes weaker south-westward coastal current causing also slower drift velocities. Additionally, the slowness of the oil particles movement in the model is most likely due to the fact that the particles remain close to the coast at all times where current velocities are weak. It should be noted that even with this coarse resolution the model captures the oil stranding in a better way than the met.no 4 km model in the sense that the oil gets to the north-east entrance of the fjord and the stranding times and locations match the observations in a better way.

3.4 DAMSA oil drift simulation

The oil drift simulation from the DAMSA setup of the Seatrack Web is shown in Fig. 10. Initially we have a slow north-eastward drift of oil and there is some beaching northeast of the accident site. Approximately 10 h after the accident the oil drift changes direction and becomes essentially out from the coast. The oil comes close to the peninsula where Nevlunghavn is located but there is no beaching on this side; however, there is some beaching on the southern tip of the peninsula east of the accident site. Some oil particles can also be found close to land eastwards of the accident site but again there is no beaching. The oil particles remains well collected at all times as a result of small dispersion in the model. It is likely that we would have larger amount of beaching if the role of dispersion were increased in the model (which appears to be very small, as compared to OD3D and BSH model, given that all particles are well collected in a streak).

After 10 h there is a swift drift out from the coast, and similar to the met.no system the particles get caught up in a swift coastal current that moves oil quickly southwards along the coast. There is some beaching on the coast southwest of the accident site but not in the same amount as was observed. However, in a model run allowing for a release longer than 8 h, as suggested above with initial beaching/trapping of oil with a subsequent later release, there is increased beaching on the south-western coast. The south-westward movement in the coastal current is somewhat faster then was observed, but, in general it may be stated that the predictions of a south-eastward transport of oil is well captured in the model.

4 Discussion and conclusions

4.1 Accuracy of the simulations

As stated earlier the estimates of the timing and amount of oil beaching in the Full City accident could be more precise. However, there are nevertheless some clear conclusions on the oil spill movements (i) the coastal area northeast of the grounding site was immediately hit with large amounts of oil, (ii) the area east of the accident (up to 1 km east of the accident site) was affected by the oil spill, (iii) the area southwest of the grounding site (up to 60 km from the site of the accident) was also hit by oil, and it appears that the beaching in this area took place about 1–2 days after the accident. This scenario is well presented in the model runs although there are some glitches.

4.2 Beaching of oil

4.2.1 First 24 h

The positions where the oil beaches is an important output parameter and the beaching positions from the models are shown in Fig. 11. First of all we see that all models predict that there was beaching of oil on the peninsula north-northeast of the grounding site within the first 6 h. After this initial movement the oil started to move more or less eastwards: the BSHdmod.L has some beaching on the shore east of the accident site, in agreement with observations, while the oil particles in OD3D and Seatrack Web comes close to the coast but does not actually have any beaching on this shore. However, in both OD3D and Seatrack Web there is a movement of oil east-north-eastwards in the initial part of the simulation, the oil gets very close to the coast but no particles are beached. It is likely that increasing the number of oil super-particles and increasing the (numerical) dispersion rate will increase the number of beached particles in this area. The dispersion in OD3D and Seatrack Web is smaller than the dispersion in the BSH model; furthermore, model inter-comparison studies reveals that OD3D has less dispersion than e.g., Meteó France oil drift model (Broström et al., 2010). If the dispersion rates are increased in OD3D and Seatrack Web we probably get more realistic beaching in vicinity of the accident site.

Observations tell us that there was also some beaching on the shores that is located up to 10 km east of the accident site. This is not captured in any of the models and requires some analysis. We have stated that there is a strong wind blowing along the coast, if this wind blow long enough there will be an Ekman transport out from the coast and there will be some upwelling of deep dense water along the coast, accordingly, general theoretical arguments tells us that this may trigger a narrow coastal current in the direction of the wind (Gill, 1982; Pedlosky, 1987). The width of the coastal current is given by the internal radius of deformation (or internal Rossby radius), $R = \sqrt{gh_0\Delta\rho/\rho_0}/f$ where g is gravity, $\Delta\rho$ is the density difference between the upper layer and the lower layer, ρ_0 is the reference density, and h_0 is the thickness of the upper layer. Using $f = 1.2 \times 10^{-4}\,\mathrm{s}^{-1}$, $h_0 = 10\,\mathrm{m}$, $\rho_0 = 2\,\mathrm{kg\,m}^{-3}$, and $\Delta\rho = 2\,\mathrm{kg\,m}^{-3}$ (10 °C between upper and lower layer) the internal radius of deformation is 3.7 km; also considering an salinity difference of 2 psu between the upper and the lower layer the internal radius of deformation becomes 5.2 km. It is clear that the low resolution models (for this particular area) used by met.no (4 km in the standard model), 5 km in the BSH model, and 5 km in DAMSA/SMHI model cannot describe the width and strength (which is coupled to the width) of the wind driven coastal jet. In principle, the 1.5 km model could produce a solution that resembles the foreseen jet along the coast; however, in the area around the grounding site the coastline is very complex and it is likely that the model do not describe a narrow strong current particularly well. However, more detailed studies are needed before we can make conclusive arguments about the existence and strength of a north-eastward coastal jet driven by the wind, and if this is the main explanation of the eastward drift of oil in the Full City accident. Another speculation is that wave forced flow may be responsible for the eastward (or alongshore) drift of oil particles, it is well known that waves may force a very near coast jet (with width less that 100 m) when impinging on a gently sloping beach (Longuet-Higgins, 1970; Nielsen, 1992). The physics behind the generation of this current is transformation of wave momentum to Eulerian mean momentum when the waves decay at shallow water. It is possible that some kind of wave forced flow close to the coast is also responsible for the movement of particles along the shore.

4.2.2 Oil drift between 24–72 h

After the initial north-eastwards movement the wind change direction and became directed out from the coast, OD3D and Seatrack Web predicted that oil particles start to move out from the coast and well into the coastal current outside the Norwegian coast, while BSHdmod.L had some movement out from the coast but not as distinct as in the other two models. Accordingly, in OD3D and Seatrack Web the oil spill starts to move south-westwards rapidly when reaching the coastal current. The oil particles in Seatrack Web reach the southern tip of Norway by 3 August; OD3D runs based on the 4 km ocean model has a similar development while the run based on the 1.5 km model is somewhat slower. The oil particles in the BSHdmod.L never reach out in the coastal current and stay relatively close to the coast; accordingly, the particles stay closer to the accident site than the particles in the OD3D and Seatrack Web.

At about 40–48 h the wind again changes direction in become inwards toward the coast. The models respond by moving particles closer to the coast and there is significant beaching of oil particles southwest of the accident site in all models. We have not been able to verify that this is an accurate description of the oil spill movements but it is clear that there were many observations of oil spill south-westward from the grounding site about 1–2 days after the accident and we concluded that all models give an accurate description of this feature. However, there are some differences between the models:

- BSHdmod.L has beaching relatively close to the accident site, and it takes place on 2 August (approximately at midday)
- The oil particles in OD3D using the 1.5 km model reach about 60 km southwest from the accident site and has beaching over a very large area at the same time (essentially 32 h after the accident, i.e., at 2 August at about 06:00). The simulation based on the 4 km grid has beaching at about the same time but over a much larger area.
- Seatrack Web predicts that there will be beaching of particles after about 48 h, and the beaching takes place over a wide area almost down to the southern tip of Norway.

There are uncertainties regarding the beaching of oil southwest of the accident site but it appears that OD3D describes the beaching in this area correctly.

OD3D and Seatrack Web both predict that there are oil particles that move southwestwards with time. It is unclear if there were observations of oil south of the area indicated in Fig. 2 (i.e., southern tip of Norway); in any case, we conclude that there was not any major beaching of oil in these areas. Furthermore, as far as we know, there has not been any detection of oil by flight in this area and we consider it unlikely that large amounts of oil moved this far south along the coast. However, there were scattered observations along the coast giving some credit to the simulations.

4.3 Land masks

We see large differences in the way coastlines are treated. In OD3D and BSH model the oil is beached on the side of the numerical grid while the oil is beached on the land mask in the Seatrack Web. In the OD3D model, the main part of the particles based on the 4 km model is beached well out in the ocean, this is mainly due to an inappropriate numerical scheme that do not allow for advection of particles in the one half grid-point closest to the coast. The situation becomes much better with the 1.5 km model than the 4 km model. The beaching in the BSH model is better described although it is obvious that particles are beached at sides of grid point, and that these do not represent the coastline very accurately. Seatrack Web follows another strategy and uses high-resolution coastlines to track beaching.

In fact, although the beaching is a very important parameter in most models the physics of beaching is described in a very simple way. Furthermore, although tracking of high resolution coastlines are enabled in Seatrack Web, the actual physical properties that are responsible for beaching at a coastline is not fully described. If no direct wind drift would affect particle transport it may be noted that beaching would not occur in an ocean model with accurate numerical schemes simple because no water particles are beached within a model due to the continuity equation in combination with impermeable walls. Accordingly we conclude that in the model beaching is the result of (i) direct drift by wind or waves, (ii) numerical dispersion of particles (i.e., most oil spill models rely on a simple random walk description of particles), or (iii) inaccurate numerical schemes. In reality, the beaching is probably very complex and depends on processes with strong vertical shear due to (i) wind drift, and (ii) Stokes drift that are not described within the models. The representation of beaching in a complex geometry and the amount of oil that is passing through is a challenge for the future but is much needed for more accurate forecast of oil spill in areas with complex geometry (see e.g., Fig. 12).

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Fig. 1. **(a)** Location of the Island Såstein in Skagerrak area where the ship Full City grounded. **(b)** Picture of the MV Full City outside Såstein on 2 August (photo: NCA).

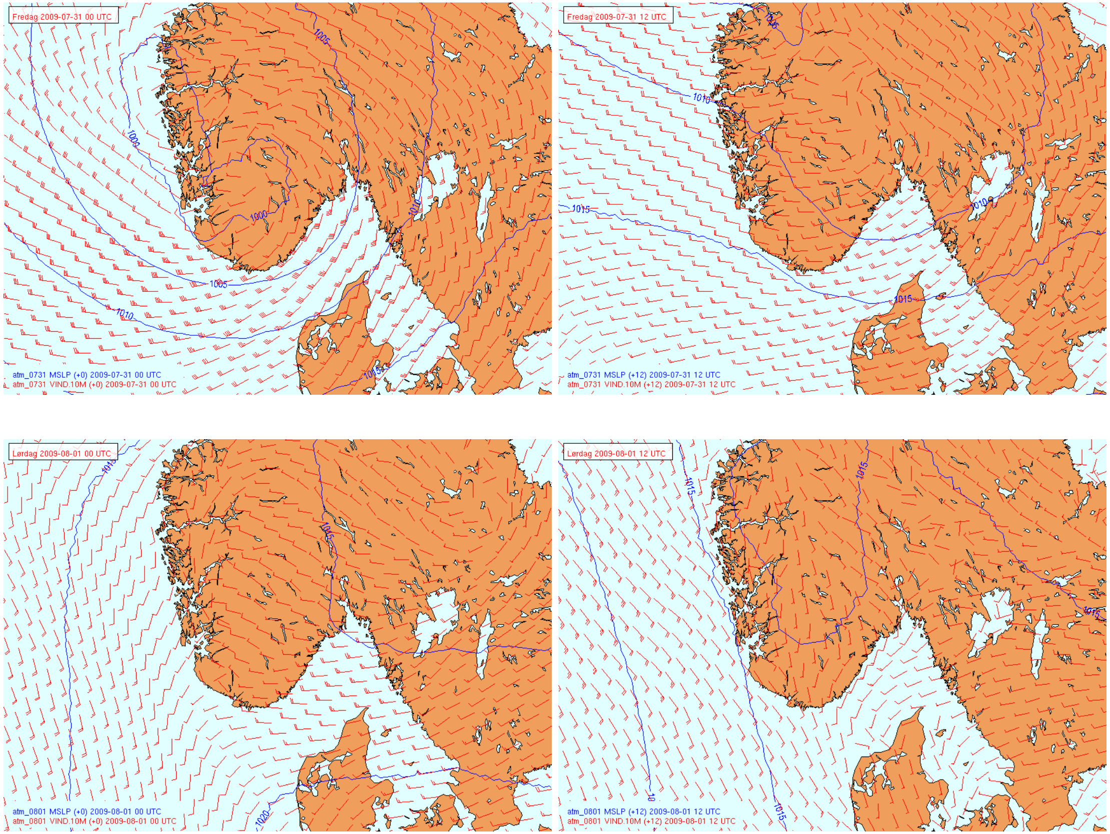

Fig. 2. The sea level pressure and the wind at the surface from met.no. The fields are from the operational HIRLAM model running with 8 km resolution. Upper left panel is from 31 July at 00:00; upper right panel is from 31 July at 12:00; lower left panel is from 1 August at 00:00; and lower right panel is from 1 August at 12:00.

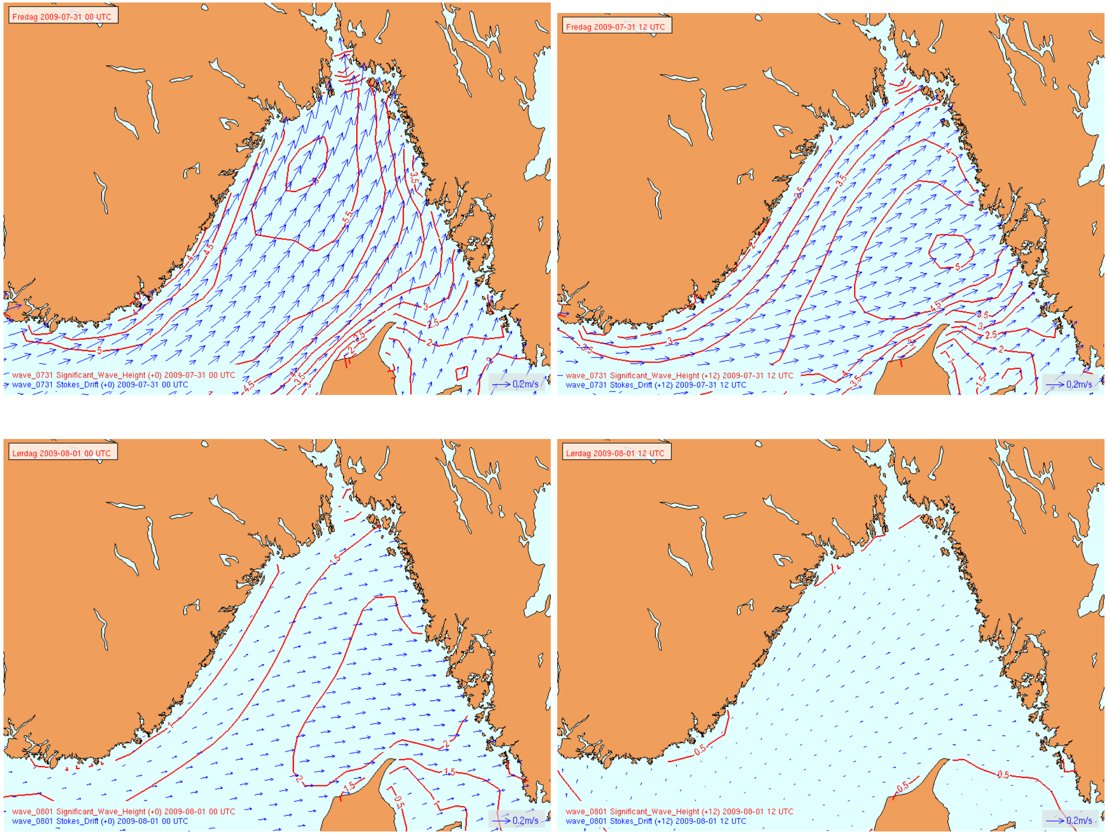

Fig. 3. Significant wave height (red contours) and Stokes drift velocity vector (blue arrows), from the model WAM4km. Upper left panel is from 31 July at 00:00; upper right panel is from 31 July at 12:00; lower left panel is from 1 August at 00:00; lower right panel is from 1 August at 12:00.

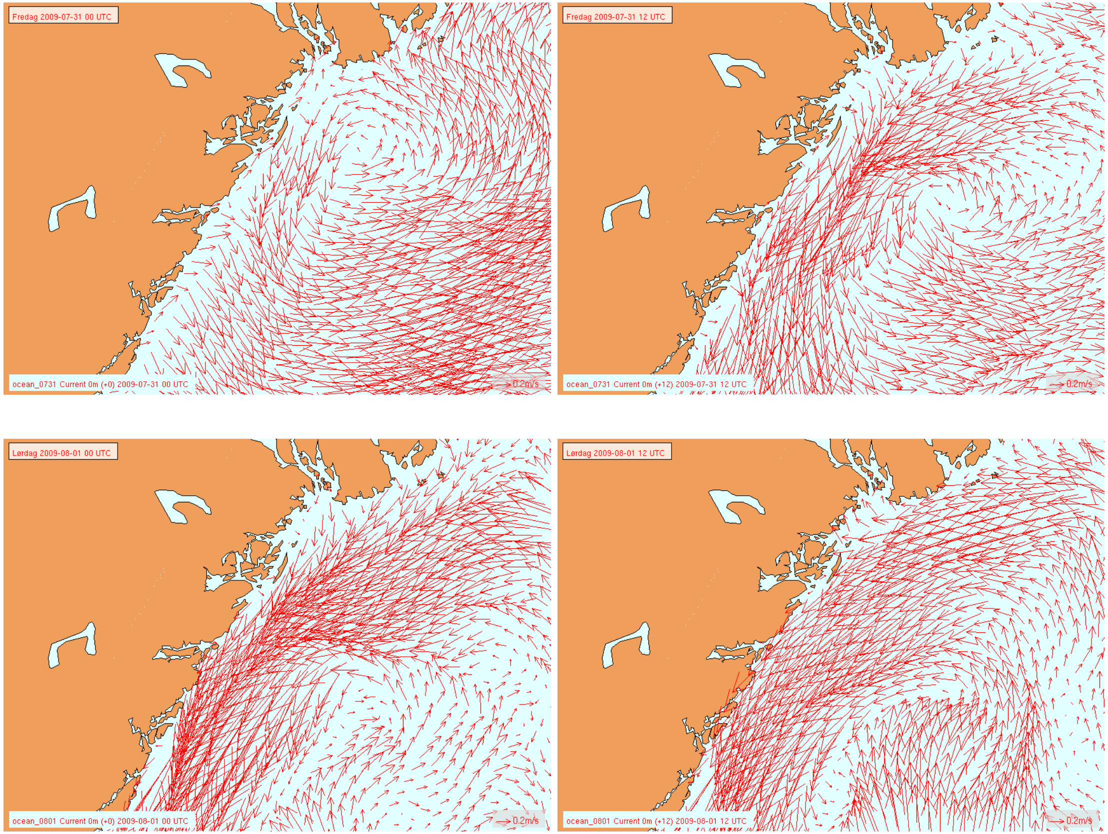

Fig. 4. Velocity vectors of surface currents in the ocean from the met.no 1.5 km ocean model. Upper left panel is from 31 July at 00:00; upper right panel is from 31 July at 12:00; lower left panel is from 1 August at 00:00; lower right panel is from 1 August at 12:00.

Fig. 5. Observations of the spreading of oil after the full city incident. All records regardless of amount of oil are included.

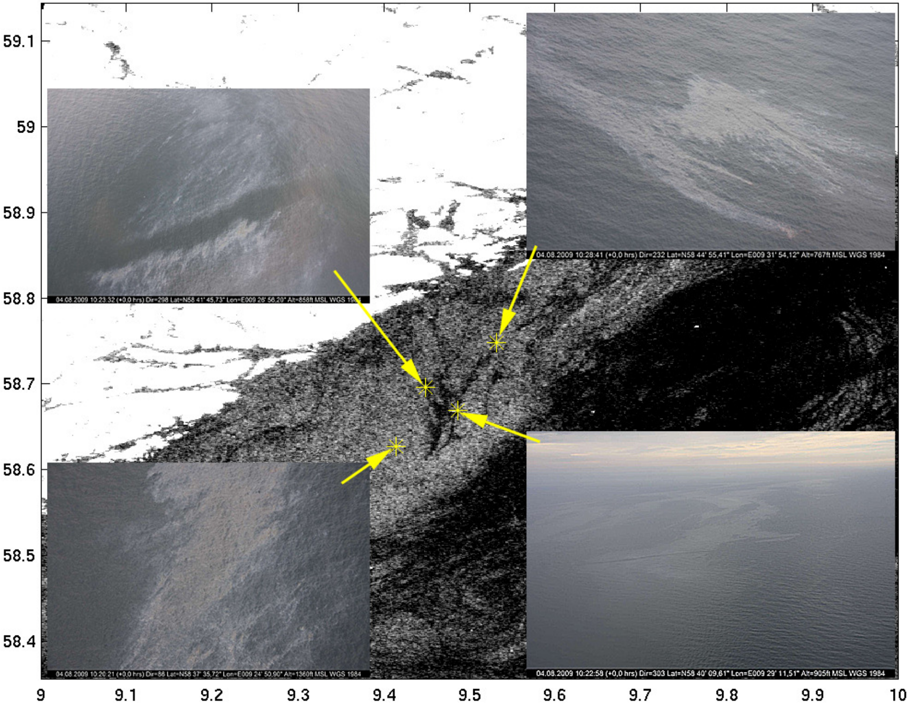

Fig. 6. Contrast enhanced Envisat ASAR image on 4 August after the Full City accident, superimposed geolocated aerial photos from NCA. Courtesies; Press release as of 4 August 2009 from Nansen Environmental and Remote Sensing Center, Bergen, Norway. Envisat ASAR; © ESA. Aerial photos: http://www.kystverket.no.

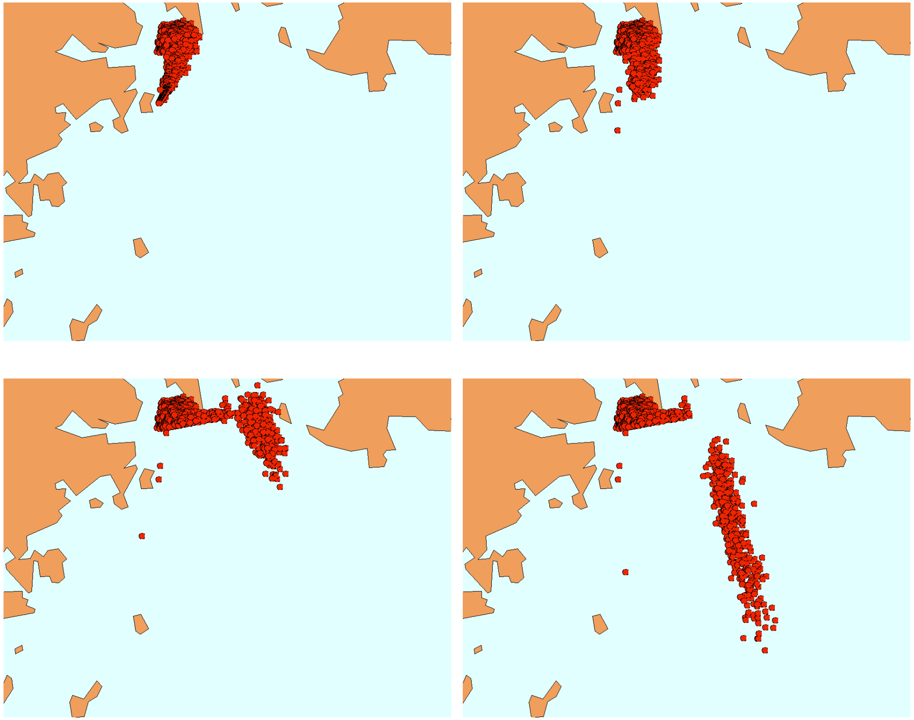

Fig. 7. First 24 h of the OD3D simulation with Skagerrak 1.5 km forcing (i.e. the oil after 6, 12, 18, and 24 h after the accident). The red dots represent oil particles. The particles left behind very close to the land mask represent stranded oil.

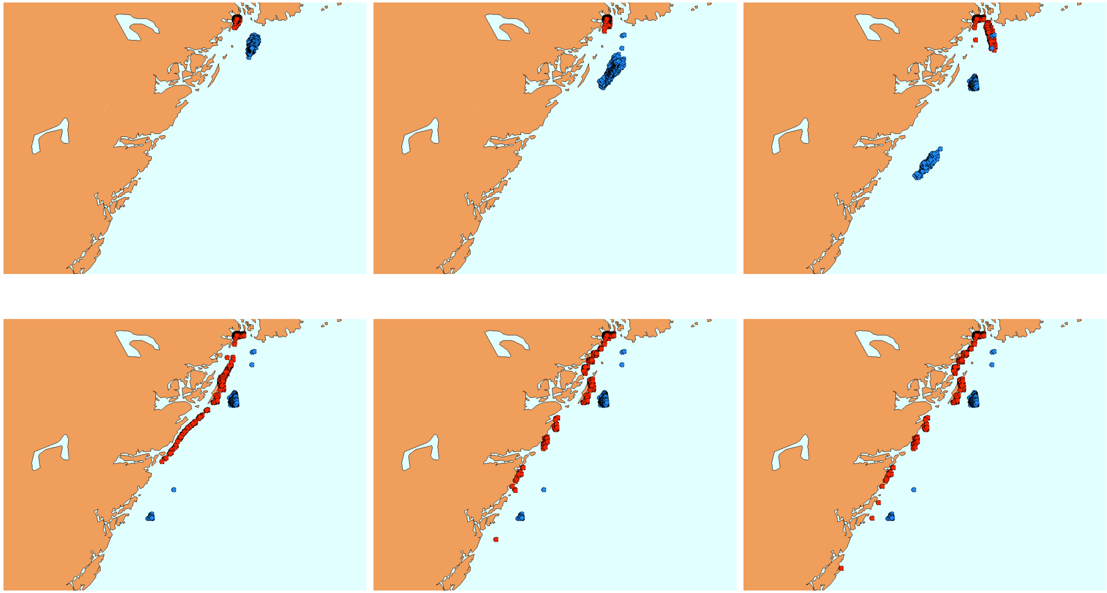

Fig. 8. The oil drift simulations using two different ocean models: red is for a 1.5 km model and blue is for a 4 km model. The figure show the output 6, 12, 24, 36, 48, 60 h after the initial release of oil. Note that the 4 km (blue) model oil particles are stranded well out into the sea due to low resolution: the model simulation also had to be initiated well out into the sea.

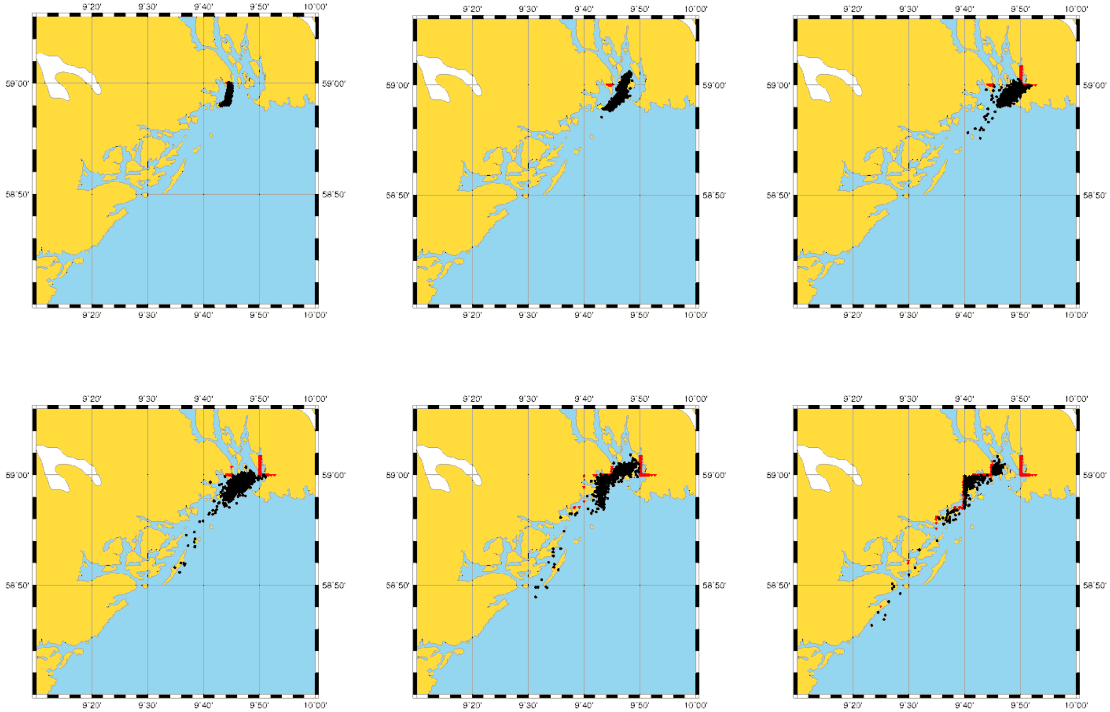

Fig. 9. Simulation of the Full City accident using the BSHdmod.L. The figure shows the output 6, 12, 24, 36, 48, 60 h after the initial release of oil.

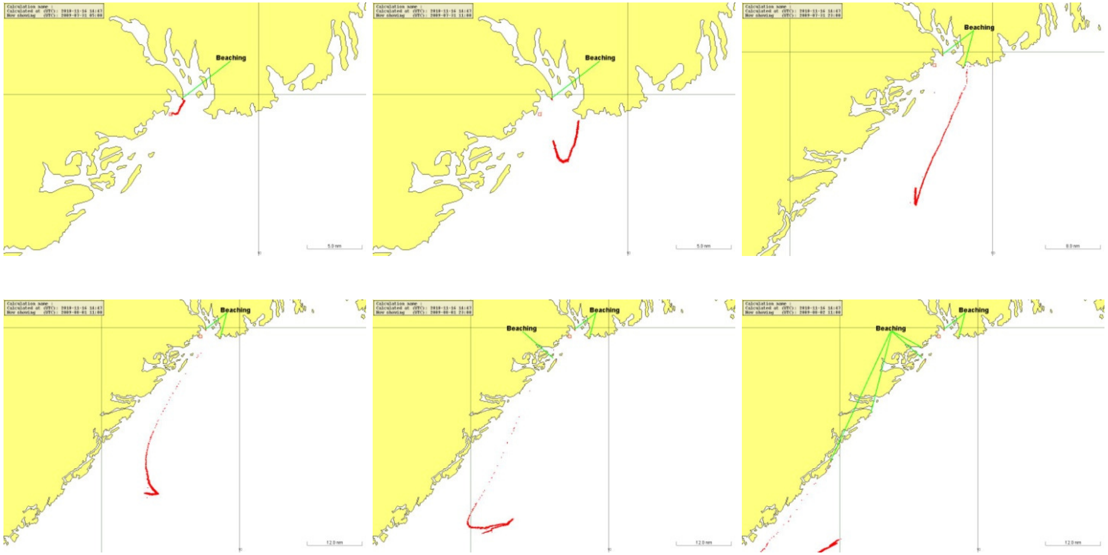

Fig. 10. The Seatrack Web oil drift simulation performed by DAMSA. The figure show the output, 6, 12, 24, 36, 48, 60 h after the initial release of oil.

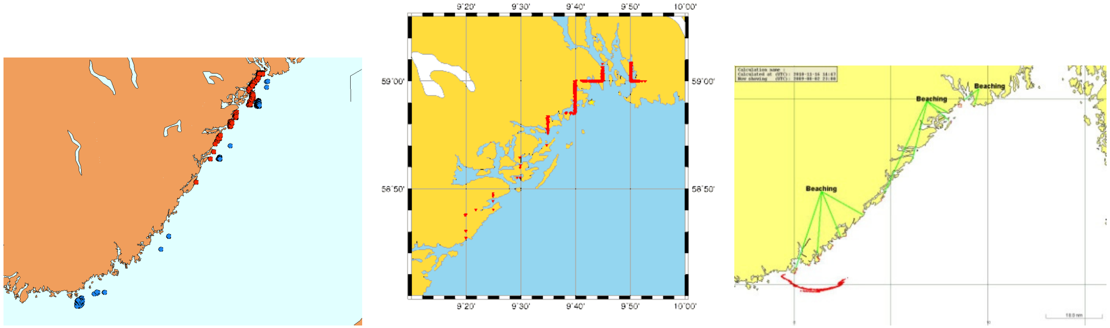

Fig. 11. Example of oil that is advected through a very complex topography (photo: NCA).

Fig. 12. Positions of the beaching of oil in the simulations presented in this study. The figure represents the oil after 72 h the initial release of oil.