Norwegian Meteorological Institute
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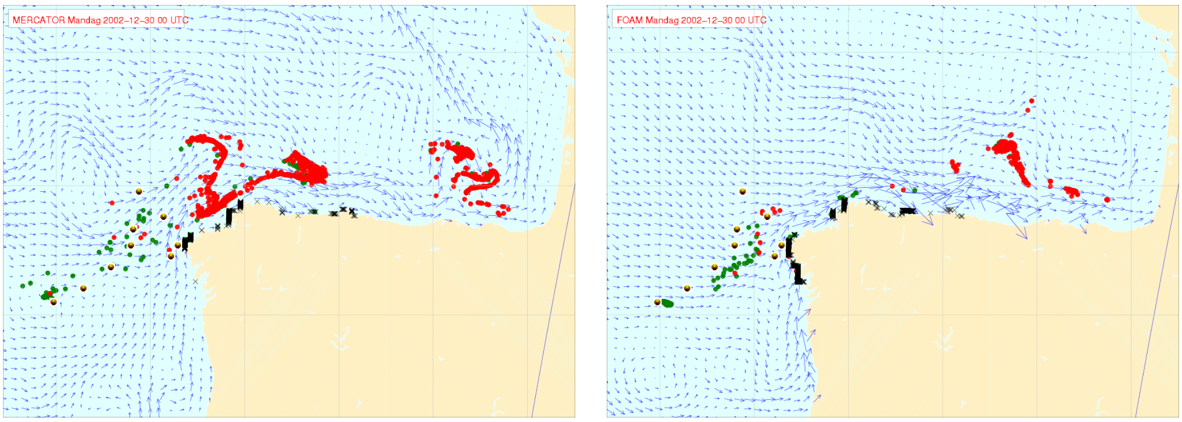
met.no report

Report no. 13/2004
Oceanography
ISSN: 1503-8025
Oslo, 26th October 2004

The impact of global ocean model forcing data on oil spill fate prediction: a comparative study of the “Prestige” accident.

Bruce Hackett



MERSEA Strand 1 Task 5.3

Norwegian
Meteorological Institute
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report

Number	Subject	Date	Classification	ISSN
13/2004	Oceanography	26th October 2004	☒ Open ☐ Restricted ☐ Confidential	1503-8025

Title

The impact of global ocean model forcing data on oil spill fate prediction: a comparative study of the "Prestige" accident.

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Client(s)	Client reference
European Commission, Research Directorate-General	EVK3-CT-2002-00089

Abstract

Numerical simulations of the "Prestige" oil spill accident are performed using the **met.no** oil spill fate model OD3D, comparing the impact of ocean forcing data (currents, temperature and salinity) from two global ocean models: FOAM and Mercator. Also compared are initial simulations, using best available model data at the time of the accident, with refined simulations, using data from dedicated ocean model reruns. The initial simulations, using daily snapshot data from both models, are negatively affected by aliased inertial oscillations. These errors are significantly reduced in the refined simulations, in which daily mean fields, extracted from the reruns, are used. The FOAM- and Mercator-driven simulations both replicate the gross features of the observed oil drift. There remain, however, striking differences in the daily mean current fields, which lead to significant differences in the simulated oil drift, especially near the coast. The report offers a number of recommendations for improving operational oil spill modeling and for implementing a service chain for regional and global oil spill forecasting.

Keywords

Oil spill, Ocean models

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1 Introduction

As part of the MERSEA Strand 1 project (hereafter Mersea.S1), the Norwegian Meteorological Institute (**met.no**) has performed simulations of the oil spill from the tanker "Prestige" in the winter of 2002-03. The purpose of the exercise is to demonstrate the current capabilities of oil spill monitoring and prediction services in Europe, using existing ocean models and observations. It is an element in the overall aim of Mersea.S1, which is to investigate the current state-of-the-art in European operational oceanography and illuminate its strengths and weaknesses.

One of the specific aims of Mersea.S1 is to compare four currently operational basin-scale ocean circulation data assimilation systems in order to elucidate the degree of agreement in their representation of the ocean dynamics and thermodynamics. This type of system is the backbone of the planned pan-European operational oceanography system, and the quality of the ocean predictions is crucial to all downstream applications in the production chain. For oil spill fate prediction, the ocean circulation variables required are 3-dimensional currents and hydrography (temperature and salinity).

In this demonstration, two parallel simulations have been performed in which the only difference is the ocean circulation data used. The two data sources are the Mercator system (*Bahurel et al.* (2002)) run by Mercator Ocean (www.mercator-ocean.com.fr/en/), and the FOAM system (*Bell et al.* (2000), *Bell et al.* (2003)) run by the Met.Office (www.met-office.gov.uk/research/ocean/). In both simulations, the current and hydrographic data from these system are used to force the oil spill fate model directly, i.e., there is no nesting of a high-resolution ocean model to downscale the forcing to local scales. Thus, differences in the resulting oil spill predictions are directly attributable to differences in the Mercator and FOAM forcing data.

2 The "Prestige" accident

On 13 November 2002 off the coast of Galicia (Spain), the Greek-owned tanker "Prestige" suffered hull damage and began leaking oil. It was carrying 77,000 tons of heavy fuel oil. The ship was towed first north and then southwest until 19 November, when it broke in two and sank. The sunken wreck lies just southwest of the Galicia Bank at approximately 3600 m depth. The path of the leaking ship is shown in Fig. 1.

Estimates of the amount of oil leaked are uncertain, but the following are best estimates obtained from CEDRE:

1. During the tow and breakup: 12,000 to 17,000 m^3;
2. During the descent and hitting the sea floor: 5,000 to 10,000 m^3;
3. Leakage on the seabed: 3,000 to 6,000 m^3 @ 125 m^3 per day till end of January 2003.

The oil has been characterized as IFO-650 (*Daling and Moldestad* (2003)): a very heavy fuel oil (burner oil) with a viscosity of 650 cSt at 50^{o}C and a density of 0.995 kg/l.

Figure 1: Map of the Galicia coast and Galicia Bank showing the tow route (red line) of the "Prestige" and where it sank. Also shown is surface oil distribution on 17 November 2003 derived from SAR imagery. [Courtesy UNEP-WCMC 2002]

3 The oil spill fate prediction system at met.no

Simulation of oil spill fate has been an ongoing activity at **met.no** since the 1970's. **met.no**'s Marine Forecasting Centre provides a 24-hour service for the Norwegian National Coastal Administration (KV) and the oil companies operating in the Norwegian sector. The user specifies the simulation on a request form. The response time is maximum 30 minutes. In 2002 the service was extended to simulation of oil drift from oil spills in deep water, using the DeepBlow module developed by SINTEF (Trondheim, Norway).

The oil fate model OD3D can be applied both for instantaneous and continuous releases. The changes in the mass of oil and emulsion as a result of evaporation and emulsion are computed. For oil spill at deep water, hydrate formation and gas dissolution are taken into account. The properties of the oil depend on the oil type, and in the present version 64 different types of oil can be simulated. The drift, dispersion and weathering of the oil are determined by hindcast/forecast data from numerical prediction systems for the atmosphere (surface wind and air temperature), ocean circulation (3-dimensional currents, temperature and salinity) and surface waves (Stokes drift, significant wave height and mean wave period). Surface wind and air temperature are used to estimate evaporation and water uptake exposure, as well as whitecapping effects on mixing. Wave data are applied in calculating turbulent diffusivity and vertical dispersion, and for determining oil droplet size. Temperature and salinity data determine the vertical density stratification which is used to find the rate of rise or sinking for oil particles.

In the operational national service, the oil fate model uses “best available” forcing data from **met.no**’s operational model system. For forecast out to +60 hours, atmosphere data are obtained from HIRLAM, thereafter to +168 hours from the ECMWF. Ocean circulation and wave data are supplied by the MIPOM and WAM models, respectively, both using the atmospheric forcing just described.

The result of the oil drift simulations are plotted on sea charts used for navigation, either as trajectory plots or particle plots showing the situation at a given time, including a budget of oil and emulsion. The results may also be disseminated as data files to be included in the user’s own GIS system.

4 Model setup for the "Prestige" case

The OD3D model is considered well-suited to the “Prestige” case, since it includes facilities for both surface and sub-surface releases. However, a number of modifications were necessary to perform the hindcast simulations. Details of the changes and of the forcing data applied are given in the following.

It will become apparent in the following that the simulation setup and the forcing data used are not optimal with respect to what is potentially available. This is partly due to the short timeframe of the project and partly the desire to obtain some results for the “Prestige” case while the accident is still fresh in mind. It is also instructive in relation to the MerseaS1 objectives in that it demonstrates the currently realistic capabilities of interfacing various European components of an oil spill fate service.

4.1 Model domain

The **met.no** operational model setup is focused on Norwegian waters and the service automatically uses **met.no**’s operational ocean circulation model grid as its domain. However, this grid does not extend far enough south to cover the accident area. Thus, there was no option of nesting **met.no**’s model into the Mercator and FOAM grids. Instead, a special horizontal grid covering the area (see Fig. 2) was specified and all forcing data fields were interpolated to it. The grid is polar-stereographic with approximately 10 km grid-spacing; the spacing is about the same as the finest grid in the forcing data. In addition, OD3D is configured to expect all forcing data variables on the same grid points, so there is no staggering of the velocities.

4.2 Current and hydrographic data

4.2.1 Mercator data

The Mercator team ran two dedicated hindcasts to supply data for the demonstration: an initial hindcast for the period 12 November 2002 to 31 January 2003, and a second hindcast for the period 12 November 2002 to 31 March 2003. In both cases, data were obtained from the Mercator North Atlantic system, which is run on a rotated grid with approximately 6 km grid spacing. The model assimilated altimeter data. The model fields were interpolated to a $1/12^o$ ($\approx$ 10 km) grid before transmission to **met.no**.

In the first hindcast run, the data consisted of daily snapshots, i.e, instantaneous fields at 00 utc. Snapshots were extracted because, in the early phase of the project (winter 2002-03), this was the only immediately available type of data. The initial results gave rise to concern that the data might be degraded by aliased inertial oscillations (see discussion in 6). Therefore, in the second hindcast, carried out in the fall 2003, daily mean fields centered at 12 utc were calculated. In both runs, the data were delivered with the u and v variables interpolated to the T and S grid points, and on 43 fixed depths (3.13, 9.765777, 17.01684, 25.08886, 34.14732, 44.3913, 56.05698, 69.42432, 84.82568, 102.6503, 123.3546, 147.4681, 175.6007, 208.448, 246.7941, 291.5095, 343.5449, 403.9166, 473.6866, 553.9279, 645.6872, 749.9391, 867.5318, 999.1409, 1145.225, 1305.993, 1481.394, 1671.114, 1874.604, 2091.114, 2319.739,

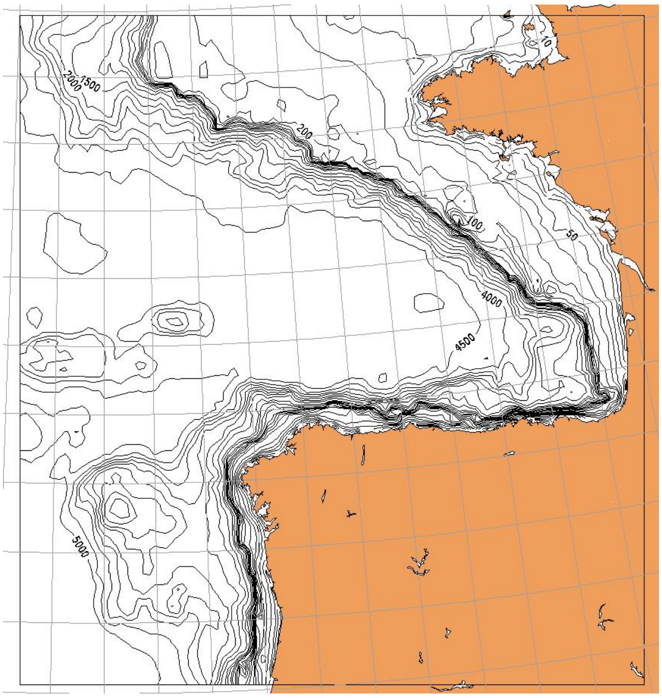

Figure 2: The special oil spill grid used by the oil spill fate model. Contours show the bottom topography (NB! not equidistant contour intervals).

2559.469, 2809.242, 3067.985, 3334.651, 3608.249, 3887.857, 4172.639, 4461.847, 4754.821, 5050.982, 5349.833, 5650.943 m).

4.2.2 FOAM data

Two sets of data were also obtained from the FOAM team. The initial data set, which covered the period 12 November 2002 to 15 January 2003, was obtained from the Live Access Server maintained by the University of Reading (www.nerc-essc.ac.uk/las/main.pl). These data are daily snapshots at 00 utc (analysis time) archived from the daily operational runs of the FOAM system. They were the most quickly available FOAM data early in the project. In the fall of 2003, the FOAM team ran a new hindcast to supply data for the demonstration: for the period 8 November 2002 to 31 March 2003.

In both cases, data were obtained from the FOAM North Atlantic system, which is run on a 1/9^o ($\approx$ 12 km) grid. The 1/9^o grid is nested in a 1/3^o grid of the Atlantic and Arctic, which in turn is nested in a 1^o global grid. The model assimilated altimeter, SST and temperature profile data. Data were delivered with the u, v, T, S data on the model's staggered horizontal grid and on 20 fixed vertical levels (5, 15, 25, 35, 48, 67, 96, 139, 204, 301, 447, 666, 996, 1501, 2116, 2731, 3347, 3962, 4577, 5192 m).

4.3 Atmospheric data

Atmospheric forcing data were obtained from the NWP system at the European Centre for Medium-range Weather Forecasts (ECMWF). The data consist of wind at 10 m height (U10) and air temperature at 2 m height (T2M) extracted from archived 6 hourly operational analyses.

4.4 Surface wave data

Surface wave data were obtained from **met.no**'s regional wave model which is a version of WAM, run at 0.45^o resolution. The data consist of significant wave height (Hs), mean wave period (Tm) and Stokes drift extracted every 6 hours from archived operational model runs. The model is driven by atmospheric fields from **met.no**'s operational NWP model HIRLAM.

4.5 Data preparation

The Mercator and FOAM daily fields were obtained, as described above, as netCDF or GRIB files, which were converted to **met.no**'s internal file format. The fields were then horizontally interpolated to the special grid using a combination of bilinear interpolation, in open water, and “nearest neighbor” replication, near the landmask. In the initial simulations, land and bottom masking of the current and hydrographic fields was derived from the delivered Mercator and FOAM data and was not matched after interpolation. This uncovered some discrepancies between the the land masks that are retained in the initial simulation results. For the final simulations, a common landmask was used in order to give more comparable results, particularly stranding. This landmask was obtained by interpolating the ETOPO5 topographic database to the special grid and manually adjusting the resulting field to better match a coastline database.

The OD3D system requires surface (0m depth) fields of current, temperature and salinity, but these were not available in the Mercator and FOAM deliveries. Therefore, the uppermost fields - 3.3m in Mercator and 5m in FOAM - were simply “moved” to 0m depth. In order to keep memory use manageable for these relatively long simulations, only nine other depths were selected from the original deliveries. Preliminary simulations of the leakage from the sunken wreck indicated that the oil rises quite quickly to the surface. Therefore, the depth levels used are weighted toward the upper 200 m.

The atmosphere and wave fields were interpolated to the special grid using a modified 16-point Bessel algorithm.

The daily ocean data were time interpolated to 3-hourly intervals, while the 6-hourly intervals of the atmosphere and wave data were retained.

4.6 Hindcast simulation

The “Prestige” spill event can be considered in two phases: 1) the surface release, from the time the ship was damaged until it sank, and 2) the bottom release, from the time the wreck reached the bottom. These phases were simulated separately and the results combined to give an overall picture.

4.6.1 Surface release phase (13-19 November 2002)

The OD3D system is currently only able to treat point sources and not moving sources. Thus, the continuous release of oil from the drifting/towed ship had to be approximated. Fig. 3 shows a map of the ship's movements for 13-19 November 2002. From this map and spill amount estimates supplied by CEDRE a timeline for the simulated release of the oil was constructed as follows: The estimated 17,000 m^3 of oil released during the tow is assumed evenly distributed over time (135 m^3 per hour), as a surface spill. At each of nine waypoints along the tow, all the oil estimated to have leaked out in transit from halfway from the previous waypoint to halfway to the next waypoint is released at the current waypoint over the elapsed time period. During the breakup and descent to the bottom, it is believed that 5000-10000 m^3 of oil was released. Thus, at the last waypoint, an additional 5000 m^3 of oil was released at 1000 m depth over a span of 5 hours; the DeepBlow module was invoked for this release. Separate runs of the model system were performed for each waypoint, with oil released for the appropriate time span; each run was thereafter continued up to the end of the simulation period to follow the fate of the released oil.

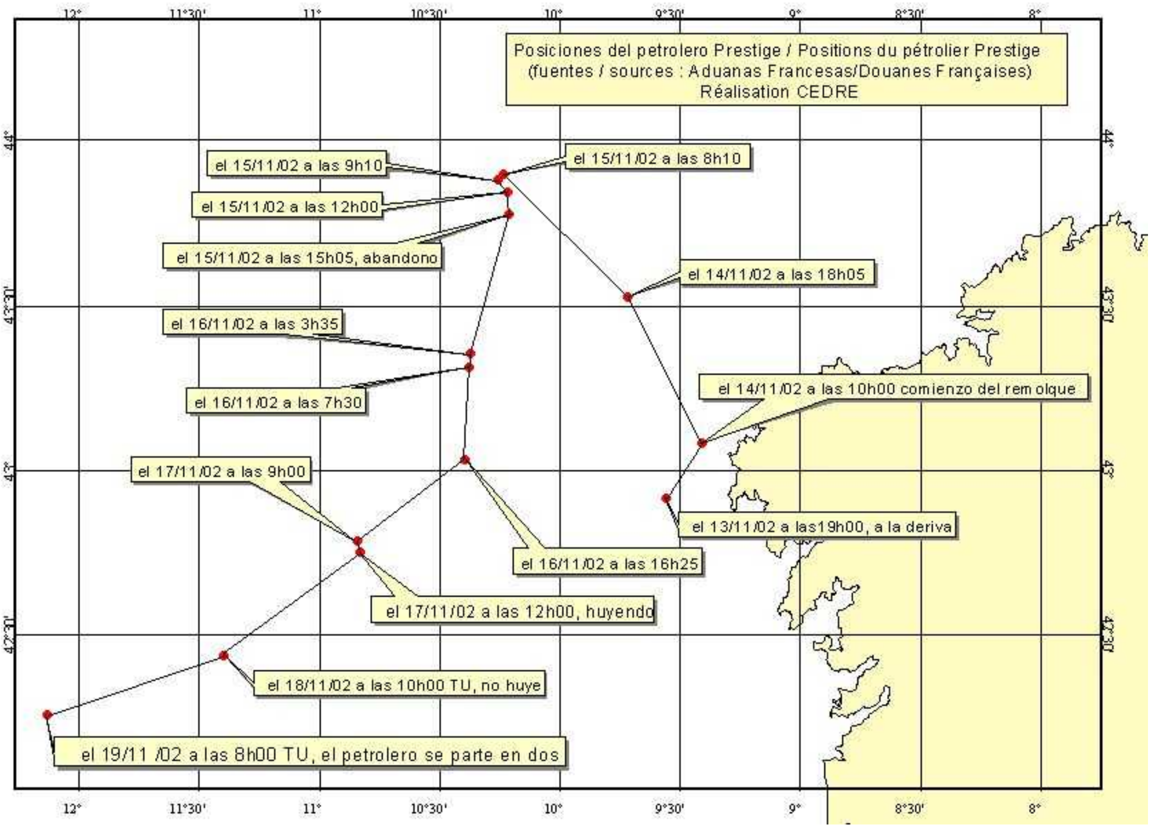

Figure 3: Map showing the tow route and timeline of the "Prestige" accident. Used to determine oil release in the model simulations. [Courtesy CEDRE]

This procedure is certainly a crude approximation, but probably a rather realistic procedure for a real-time simulation of such an incident. In any event, there is no accurate data available on how the oil was in fact released during the event.

4.6.2 Bottom release phase (from 19 November 2002)

A single final run of the OD3D system was performed for the period 12 utc 19 November 2002 to the end of the simulation period. In this case, the DeepBlow module was invoked to handle the evolution of the oil from the bottom to the surface layer. The estimate of 5 m^3 per hour was used for the continuous outflow of oil at the final position shown in Fig. 3. After 31 January 2003 the leakage from the wreck is believed to have been stopped and the simulated outflow was turned off. As with the surface releases, the simulation proceeded with no oil input until the end of the simulation period.

5 Observations of the oil spill

Most of the observations of the oil slick emanating from the Prestige are visual sightings made from ships and aircraft. These are invaluable for showing the evolution of the slick from day to day and for estimating the amount of oil, but it can be difficult to construct an overall distribution map. The best data for mapping the surface oil distribution are satellite SAR imagery and aircraft SLAR imagery.

ITOPF (International Tanker Owners Pollution Federation) constructed situation maps using available information from ships in the area and aircraft overflights (see www.itopf.com/-prestige.html). Three of these maps are shown in Fig. 4. They show that 1) oil stranded on the Spanish coast from Cape Finisterre to La Coruna before 18 November; 2) there was no significant extension of stranding eastward along the northern coast from 18-24 November; and 3) that there was some new stranding to the east on 24-25 November. The maps also show the oil slick as a filament stretching eastward from the tanker and following the shelf break along the northern coast.

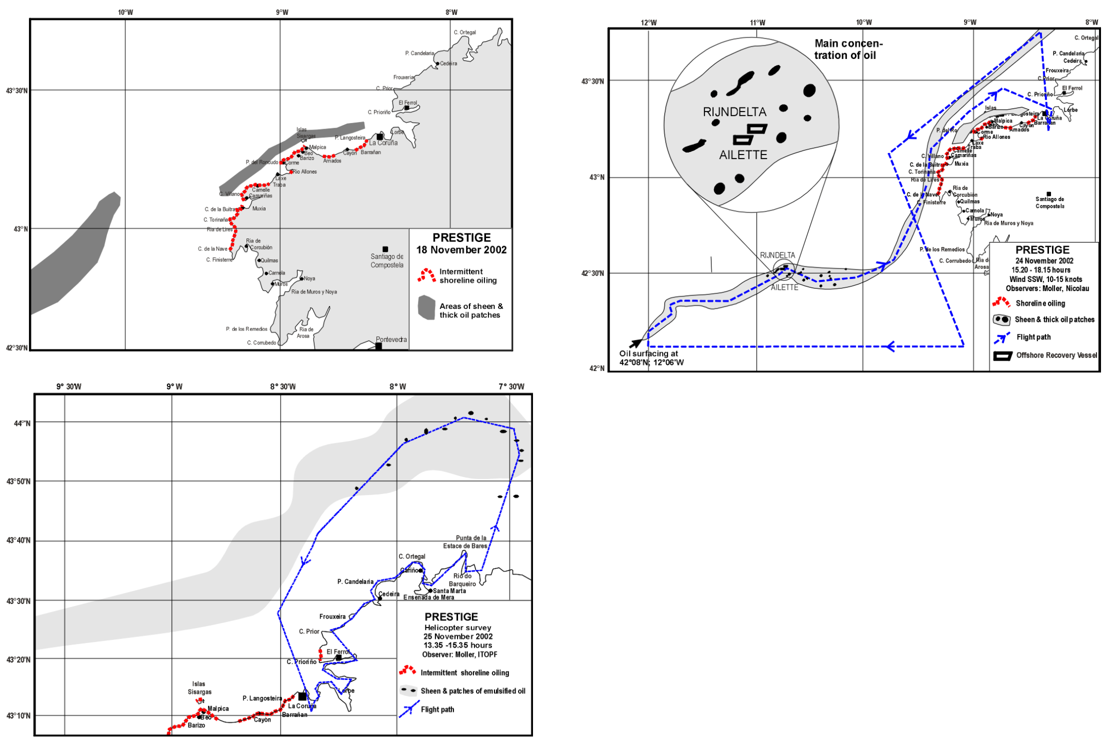

Figure 4: Situation maps of the “Prestige” oil spill on 18, 24 and 25 November 2002. [Courtesy ITOPF (International Tanker Owners Pollution Federation)]

Fig. 5 shows the oil slick on 17 November 2002, two days before the ship sank. The plume from the towed tanker separates into two filaments that are convoluted by the drift history. The broader (southern) filament appears to be connected with oil stranding on the coast, while the thinner (northern) filament seems to be associated with the tow trajectory (see Fig. 1). There are also likely large patches of oil south of Cape Finisterre. However, it is not possible to reconstruct how the oil was released from this picture alone. Note that, according to ESA (earth.esa.int/ew/oil_slicks/galicia_sp_02/), this image was generated on 20 November, i.e., three days after the satellite overpass.

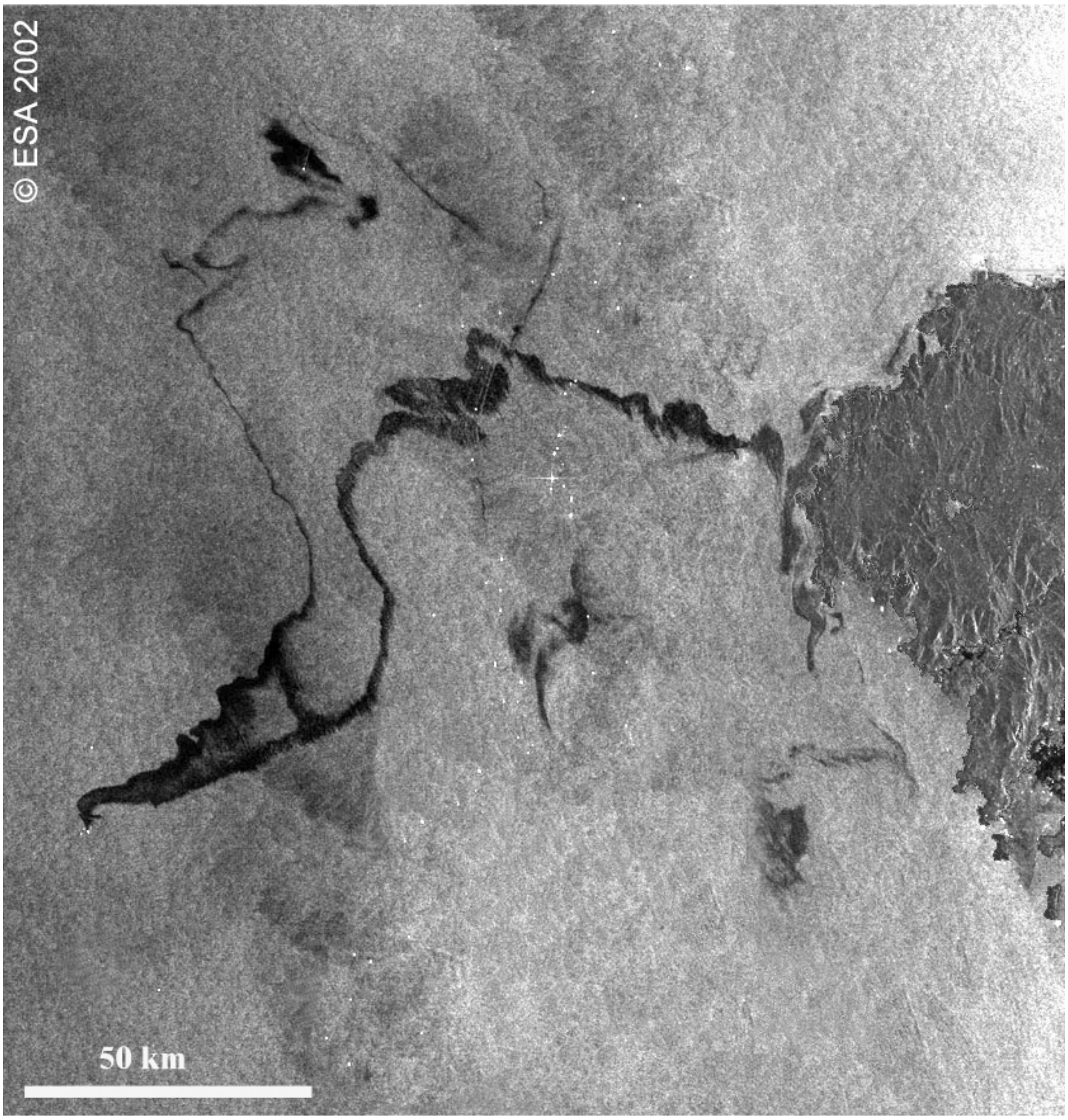

Figure 5: Envisat ASAR image showing the distribution of the surface oil slick at 10:45 utc on 17 November 2002. The dark areas indicate surface oil, and the Galicia coast is at the right. [Courtesy ESA]

The only other readily available SAR image is a RADARSAT image showing the oil along the northern coast on 18 November 2002 (Fig. 6). The image indicates oil lying close to the coast and probably stranding at several places. This may be contrasted with the map drawn by ITOPF for the same day (Fig. 4 left-hand panel), which shows the slick lying offshore.

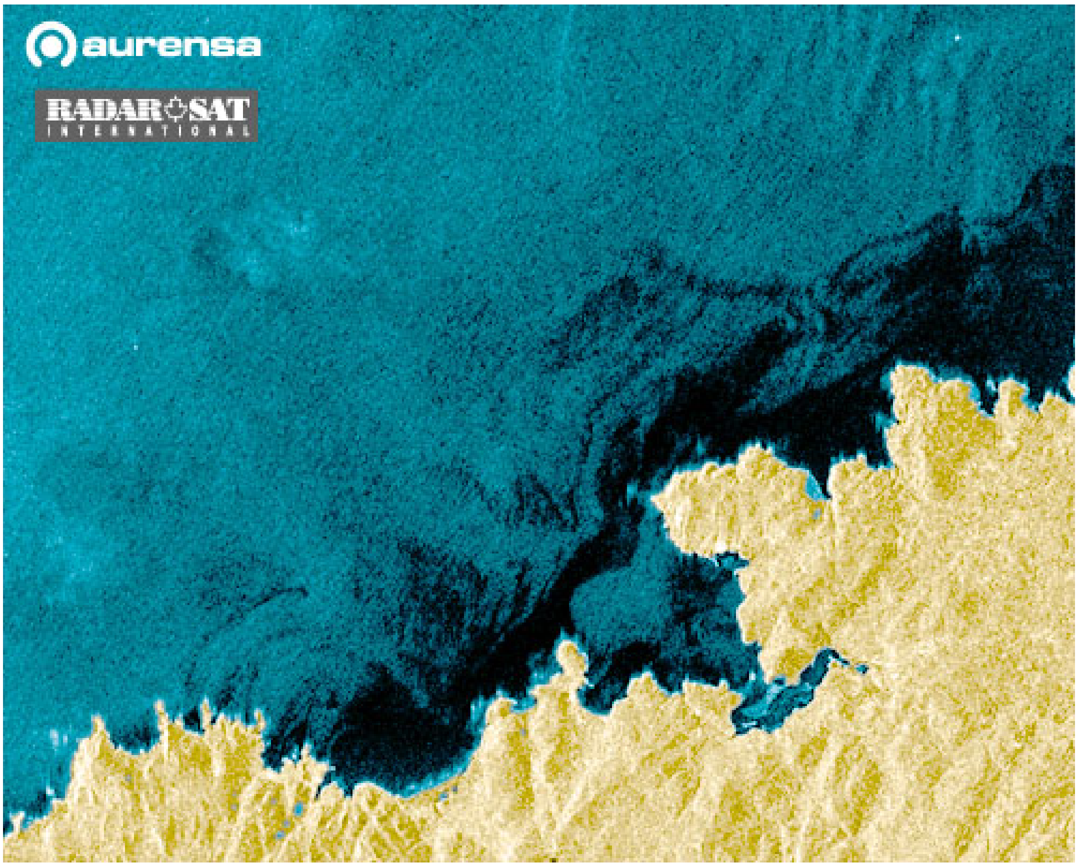

Figure 6: RADARSAT image showing the distribution of surface oil at the north coast of Galicia on 18 November 2002. P. del Roncudo is at right center. The dark areas indicate surface oil. [Courtesy RADARSAT International, Aurensa S.A]

6 Initial simulations - daily snapshot ocean fields

In the initial simulations, the Mercator and FOAM current data were daily snapshots. In general, the current fields exhibit similarities in the coastal currents and the slope current along the shelf break, but significant differences are also evident, especially in the deep water areas. This is exemplified in Fig. 7. At this time, which is 2 days into the spill, there are large differences in the current direction and strength in the deeper regions and especially in the vicinity of the oil spill. There is better agreement nearer the coast, where both models show southward surface flow. Note also the strong northwestward current in the Bay of Biscay in Mercator; this is a persistent feature that is not seen in the FOAM fields. The most striking feature of both data sets, however, is the large day-to-day current variability, leading to the suspicion that there is significant sub-diurnal variability in the model currents. Since there are no tides in either model, a likely candidate is inertial oscillations induced by strong wind events during the period. If this is the case, aliasing of the sub-diurnal currents would be an important source of error in the drift calculations, especially in the deep areas. In addition, it could also explain much of the difference in the models' current fields, since the models almost certainly produce inertial oscillations differently.

The resulting oil distributions also show both similarities and differences. In the surface release phase, shown in Fig. 8, the simulations agree fairly well for the first few days. Both result in oil moving toward the coast, but stranding occurs much sooner in the Mercator-driven simulation. on the coast north of Cape Finisterre. Later, when the tanker was towed away from the coast, larger differences develop. This corresponds to moving the oil source from the slope current area, where the two models agree fairly well, to the deep ocean, where they differ more.

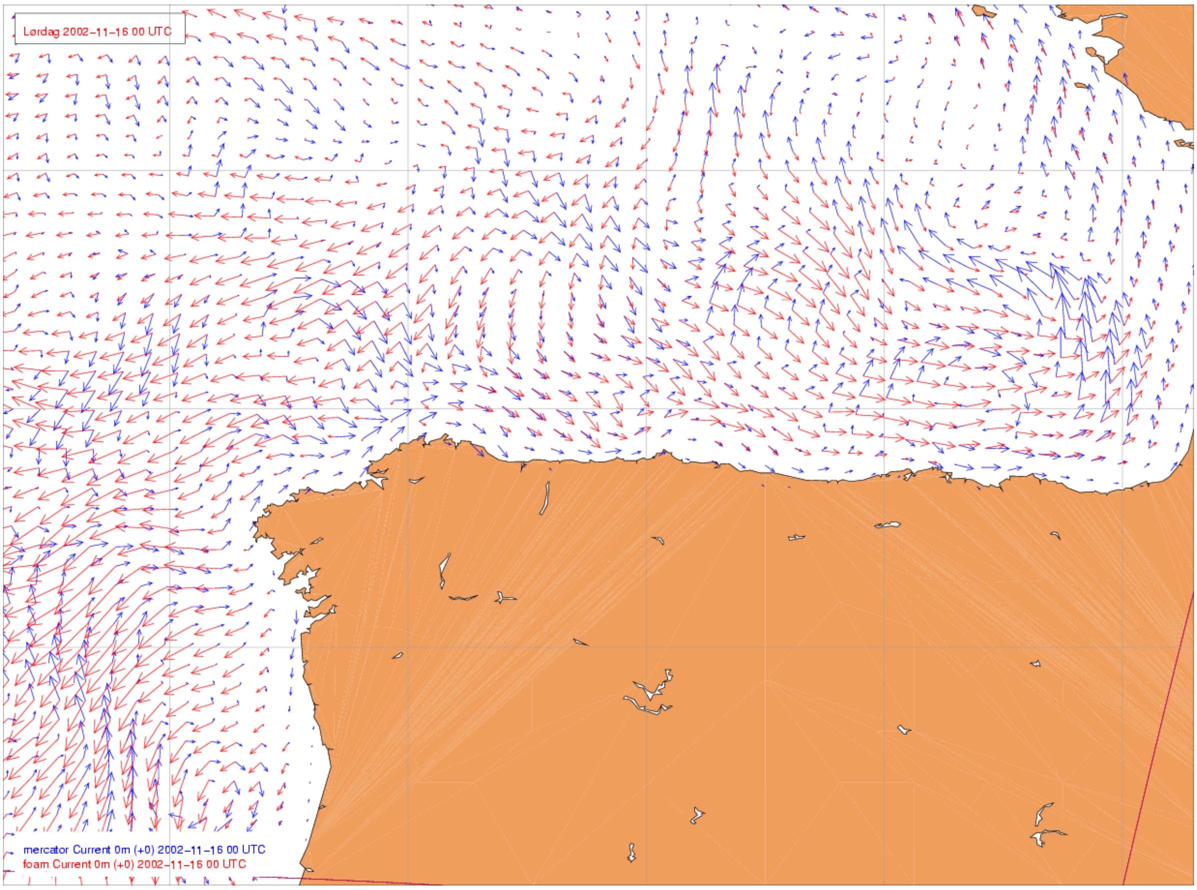

Figure 7: Comparison of snapshot surface current fields on 16.11.2002 00 utc. Blue = Mercator, Red = FOAM. Current fields have been interpolated to the special grid. Every second current vector is shown.

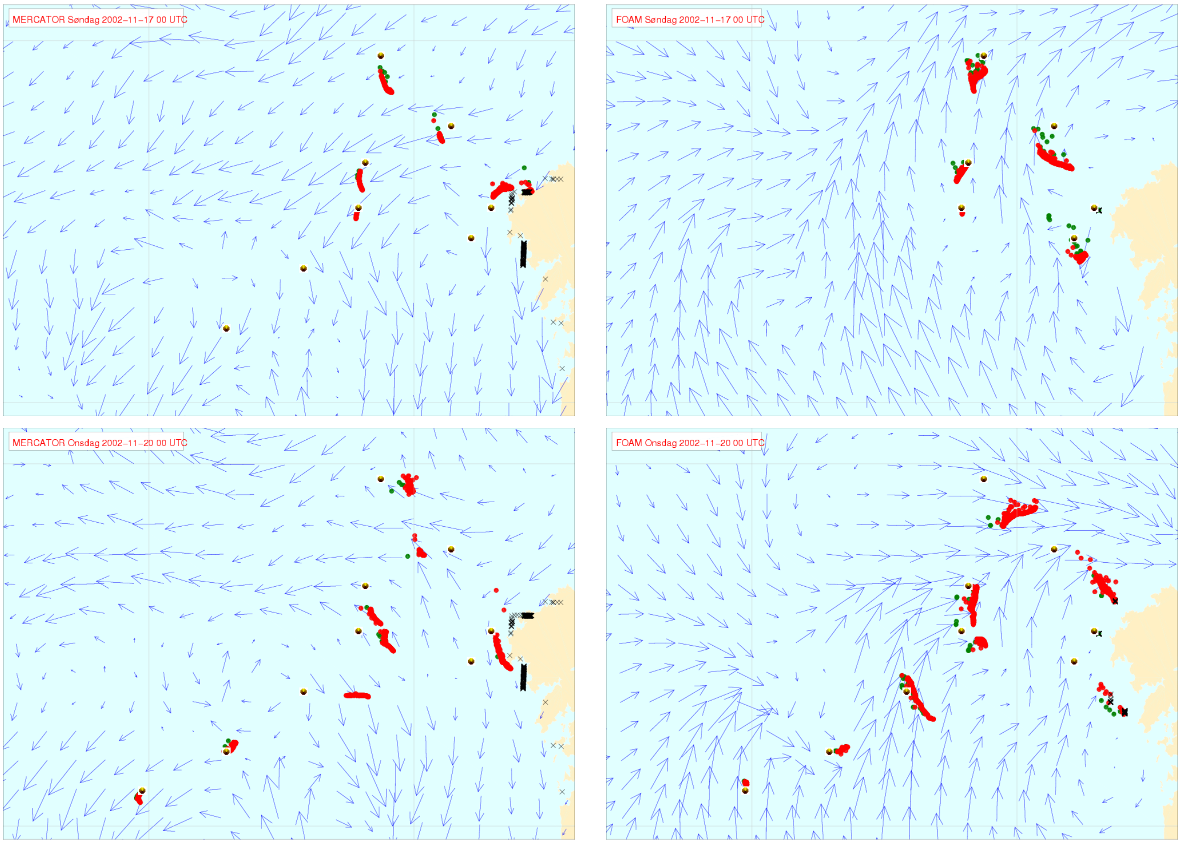

Figure 8: Distribution of oil from Prestige spill on 17.11.2002 00 utc (upper) and 20.11.2002 00 utc (lower), simulated by OD3D with Mercator (left) and FOAM (right) snapshot current fields. Colored dots represent oil super-particles; blue = surface, green = subsurface. “X” represents oil stranded on coast. Gold symbols indicate waypoints along the ship’s drift/tow path where oil is released in the simulation (see text).

7 Final simulations - daily mean ocean fields

The results of the initial experiments raised the concern that the differences seen in the oil drift patterns were more an artifice of the temporal sampling of the model fields than a reflection of fundamental differences in the ocean model dynamics. To come to grips with this, the second set of simulations applied daily mean fields from Mercator and FOAM, as opposed to the daily snapshots used in the initial simulations. The daily mean data sets were calculated from new hindcast runs of the Mercator and FOAM systems performed in the Fall of 2003.

The mean surface current fields differ significantly from the snapshot fields, as exemplified in Fig. 9 compared with Fig. 8) for the surface release phase. Furthermore, the Mercator and FOAM mean fields are overall in rather better agreement with each other than are their snapshot fields. In the area of the oil release, both models produce a general southward flow and, in particular, a southward current near the west coast. The main differences are: a) FOAM has stronger southward flow at the coast; b) Mercator has an anticyclonic eddy in the tow area, probably connected with the Galicia Bank, while FOAM does not; c) on 20 November, the FOAM currents turn more easterly, notably at the north coast. It is also evident that Mercator generally produces a more textured eddy field than FOAM, which is likely attributable the finer grid-spacing used in Mercator - 6 km compared to 12 km in FOAM. These differences result in significant differences in the simulated oil drift and stranding. The Mercator-driven simulation has oil stranding north of Cape Finisterre by 17 November, and more yet by 20 November. In the FOAM-driven simulation, no drifting oil has yet stranded by 20 November, but oil has drifted further south near the coast. It is also evident that the eddy in Mercator is moving some of the offshore oil southward, while the FOAM currents are moving the oil more toward the Bay of Biscay.

As the simulations progress through December 2002 and January 2003, the two current models agree well on the gross features of the oil distributions (see Fig. 10): both models predict oil from the surface release phase moving into the Bay of Biscay and stranding along the north coast of Spain and west coast of France; and both agree that nearly all oil from the bottom release phase remains at sea. Yet, there are significant differences, the most striking of which is the amount of drifting oil visible. Much more of the FOAM-driven oil has stranded, and did so on more limited stretches of coast. Note that an “x” symbol is drawn for each oil superparticle when it advects onto the landmask, and it is retained throughout the rest of the simulation. With the large number of particles used in these simulations, many symbols are overlaid and it is not possible to “see” the amount of stranded oil. The particle budget in Fig. 11 shows that, during the first week after the accident, there is considerable stranding in the Mercator case and very little in the FOAM case. This is oil that is spilled early in the surface release phase and strands quickly on the west coast. Thereafter, stranding in the FOAM simulation increases and surpasses that in the Mercator simulation. This is oil from later in the surface release phase that has drifted along the coast and strands on the north coast. In both simulations, the stranding increases episodically in time, reflecting on-shore advection events. From about day 35 (18 December 2002) and onward, there are twice as many stranded particles in the FOAM case. Since the amount of sub-surface oil is the same in the two simulations, the amount of surface oil in the FOAM case is much less than for Mercator. With more oil on the surface, and exposed to weathering processes, the Mercator

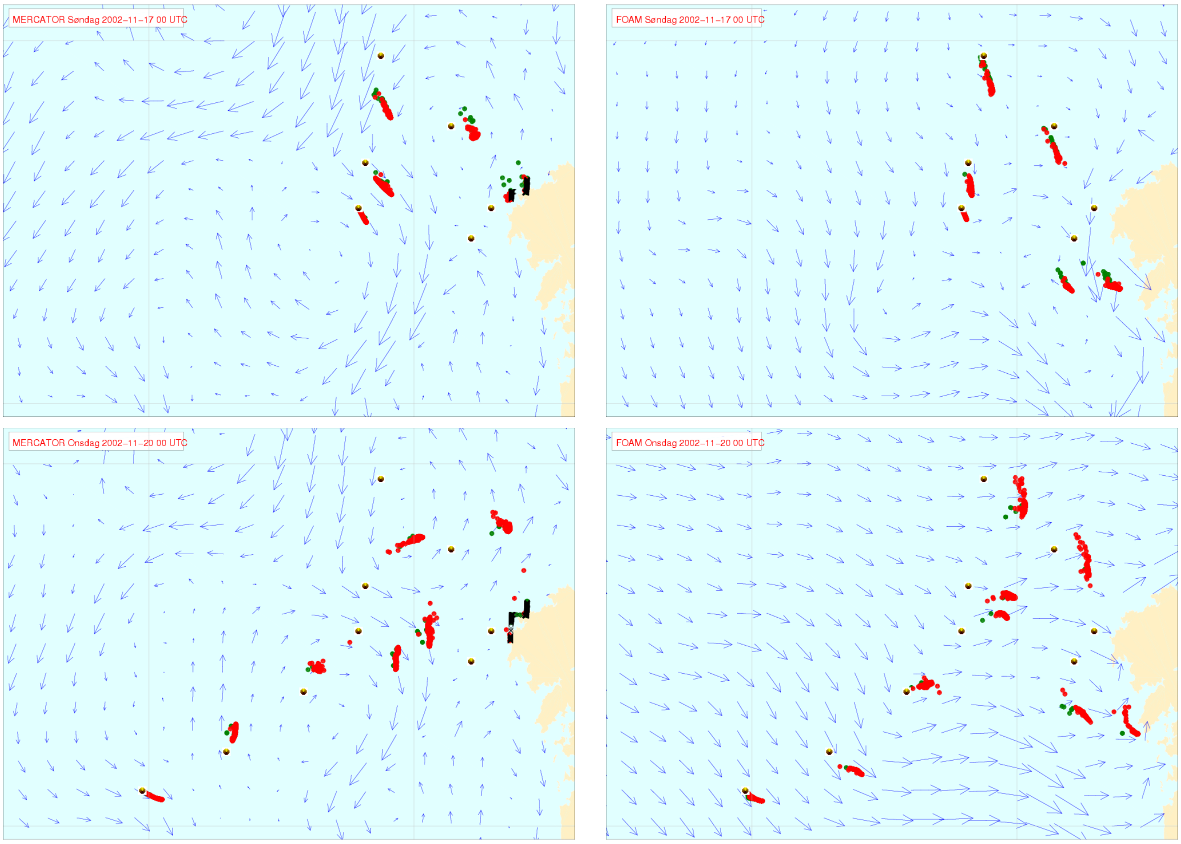

Figure 9: Distribution of oil from Prestige spill on 17.11.2002 00 utc (upper) and 20.11.2002 00 utc (lower), simulated by OD3D with Mercator (left) and FOAM (right) mean current fields. See caption for Fig. 8.

case also loses more oil particles in total.

Other striking differences between the simulations include: a) the FOAM-driven simulation shows oil stranding south of Cape Finisterre; this is oil from the early release that initially advected southward with the coastal flow (cf. Fig. 9); b) the Mercator-driven oil strands along most of the northern coast of Spain, while in the FOAM simulation stranding is limited to the western part; c) at the end of January 2003, there is much more oil drifting northward in the Bay of Biscay in the Mercator simulation, while the FOAM-driven oil tends more to strand on the coast of France; d) a small amount of oil from the bottom release phase reaches the Spanish coast in the FOAM simulation, but none does so in the Mercator simulation; this is largely due to the eddy at Galicia Bank in Mercator.

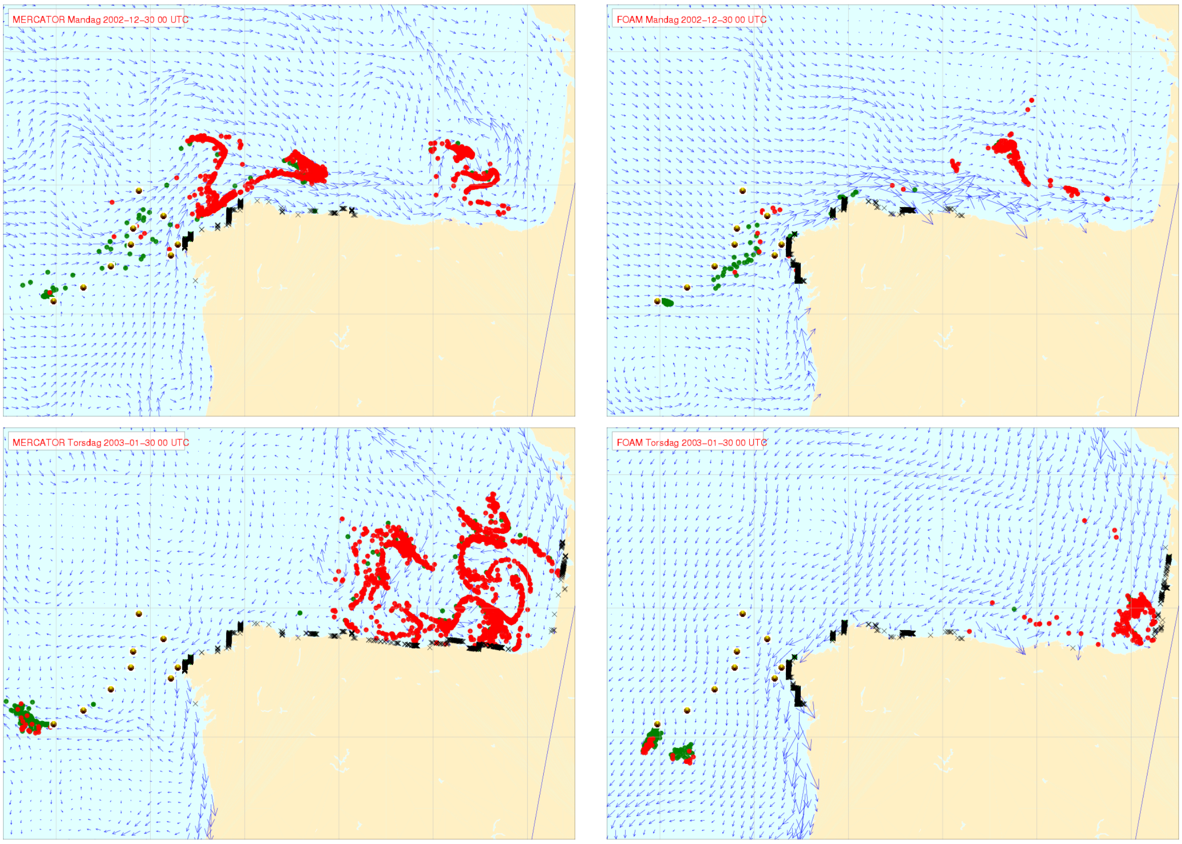

Figure 10: Distribution of oil from Prestige spill on 30.12.2002 00 utc (upper) and 30.01.2003 00 utc (lower), simulated by OD3D with Mercator (left) and FOAM (right) mean current fields. See caption for Fig. 8.

8 Comparison with observations

The observations available indicate stranding of oil on the coast north of Cape Finisterre by 17 November (Fig. 5), and extending northward to La Coruna by 18 November (cf. Figs. 6 and 4). Also, there are no observations of oil stranding on the coast south of Cape Finisterre during

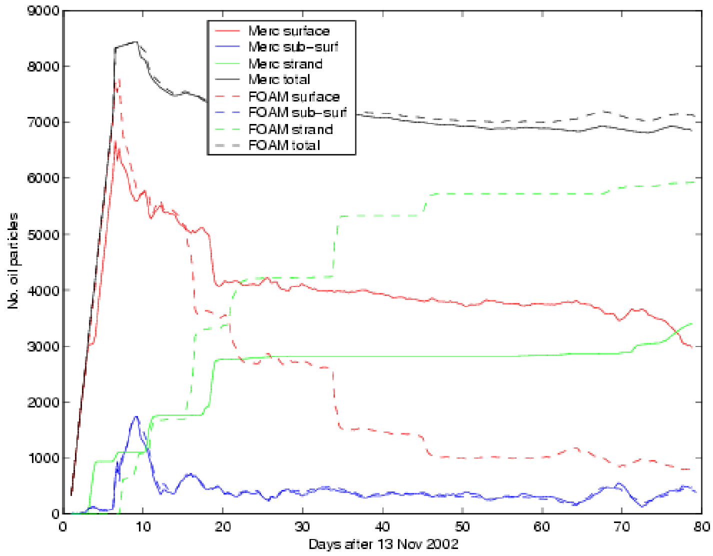

Figure 11: Time series of number of oil superparticles for two Prestige simulations: Mercator-forced (solid lines) and FOAM-forced (dashed lines). Three classes of particles are shown: surface (red), sub-surface (blue) and stranded (green); the total is shown in black).

this phase of the release and up to 25 November. Compared with Fig. 9, it appears that the Mercator-driven simulation gives better agreement than the FOAM-driven one for the surface release phase. It seems that the southward coastal flow in FOAM is too strong in the area of the initial release. On the other hand, both model simulations show oil moving eastward toward the north coast of Spain, which is in gross agreement with the offshore slick shown in Fig. 4.

9 Discussion and conclusions

Two sets of twin numerical simulations of the “Prestige” accident have been performed in order to illustrate the current state-of-the-art in operational oil spill fate prediction in Europe. The twin simulations consist of runs of the **met.no** oil spill fate model OD3D in which the only difference is ocean forcing data provided by the two leading North Atlantic ocean circulation models FOAM and Mercator. In the first (“initial”) set, the most readily available data products from two ocean models at the time of the accident are used; for both models, the data are daily instantaneous fields (*snapshots*). These data are not optimal for the purpose, but numerical forecasting models are still expected to be superior to the available alternatives, i.e., climatological background currents. In the second (“final”) set, the FOAM and Mercator models were rerun in hindcast mode and produced daily *mean* fields, which are expected to be more suitable than the daily snapshots.

The motivation for applying two competing ocean models is to demonstrate the sensitivity of oil drift prediction to “best available” ocean model forcing data, and thereby shed light on the reliability of the predictions. The motivation for running the second set of simulations is to elucidate the improvement possible when targeted data products are extracted from the ocean models.

The initial data sets from FOAM and Mercator showed considerable differences in the current fields, which, in turn, led to more striking differences in the oil drift, especially for the important issue of oil stranding. It was also evident that both models exhibited large day-to-day variability, leading to the suspicion that much of the difference was due to aliasing of inertial oscillations, which is an error source in its own right. The daily mean fields used in the final simulations showed better agreement between the models for large-scale currents, although there were still significant differences. The most important differences for oil drift are the opposing near shore currents during the early stage of the oil spill and the persistent eddy near the Galicia Bank in the Mercator fields. Causes of these differences are most likely to be found in the model setups, rather than the numerical codes: a) Filtering out the inertial oscillations revealed that there is generally more mesoscale texture in the Mercator fields, a result attributable to the fact that Mercator was run at higher horizontal resolution than FOAM. This can explain the more persistent anticyclone near Galicia Bank in Mercator, with corresponding ramifications for oil drift. b) The two model systems assimilated different observations. Most notable is the lack of altimeter assimilation in the FOAM runs. c) Atmospheric forcing data differed; FOAM used Met Office Unified Model data while Mercator used ECMWF analyses.

The improved agreement in the ocean forcing fields led to somewhat better agreement in the simulated oil distributions. There are, however, still significant differences between the simulations and these differences are of the same type as in the initial simulations. Most important is the difference in stranding: its amount, timing and location. Removing the aliasing of high-frequency variability does not remove these differences, so there are other aspects of the model data and the interfacing to OD3D that play significant roles. It has been clearly shown here that there are still differences in the mean current fields, and especially in the near-shore currents in the critical first days of the incident. This is certainly the main reason why, for example, FOAM yielded stranding south of Cape Finisterre and Mercator did not. On the other hand, there is the interpolation of the FOAM and Mercator current data to the special grid which, like any interpolation, is also a potential source of error. It was quite clear that the FOAM and Mercator data were delivered on grids in which the land-masks differed considerably from each other and, of course, both differed to a degree from the land-mask of the special grid to which the data were interpolated. Compared with the coastline contour used at **met.no**, the FOAM land-mask extends further offshore (less wet area), while the land-mask of Mercator lies further onshore (less wet area). The latter may be due to the interpolation from the native Mercator grid to a regular geographic grid prior to delivery to **met.no** (cf. Section 4.2.1). In either case, interpolation (and partly extrapolation) to the near-coastal wet points in the special grid is difficult and carries with it an inevitable degradation of the data. Unfortunately, stranding in the oil drift model is very sensitive to the currents in just this area where the interpolation is most suspect. How much the data interpolation might have to say for oil stranding in these simulations has not been investigated rigorous in this study. Addressing the issue would require adapting OD3D (and the wind and wave data) to the native grids of FOAM and Mercator; this is outside the scope of the Mersea Strand 1 project.

A major weakness of these simulations is that the ocean forcing fields do not include tides, which are well known to be considerable along the Iberian coast (see e.g., www.oce.orst.edu/-po/research/tide/). Neither FOAM nor Mercator include tides and tidal currents were not added in any form. In normal operations in Norwegian waters, OD3D is forced by **met.no**'s operational ocean models which do include tides. The impact of added tidal currents on the drift and stranding in the simulations can only be speculated upon. At the least, it is likely that the oscillating tidal flow along the coast would tend to spread the oil in the along-isobath direction. However, the full effect of the tides can only be estimated through comparative simulations, e.g., using a nested hydrodynamic model with tidal forcing added at its lateral boundaries.

The main conclusions and recommendations (in italics) of this study are summarized in the following. Conclusions concerning the service chain for oil spill fate forecasting:

- The currently running European global ocean forecast models FOAM and Mercator can deliver ocean data to drive oil spill fate models in a crisis situation. In the present case, this means 3-dimensional fields of currents, temperature and salinity. However, as the sole source of ocean currents, the data used here were not optimal for the task. For one thing, neither model directly produces currents at the surface, which presently is a requirement for OD3D. In addition, the most readily available data from both FOAM and Mercator at the time of the "Prestige" accident were daily snapshots, which were most likely degraded by aliased inertial oscillations, leading to large discrepancies.

- Spatial interfacing of the FOAM and Mercator data sets to the OD3D oil fate model was not optimal. Horizontal interpolation was necessary in order to comply with the OD3D system. This inevitably led to a degradation of the current data near land in the oil model grid, which, in turn, influenced how the oil stranded at the ocean-land boundary.

- The usefulness of satellite imagery, chiefly SAR, for monitoring the "Prestige" oil slick and assessing the drift forecasting has been limited. During this study, only two useful SAR images were found during the crisis period 13-20 November 2002. In addition, the better of the two images was apparently not generated until three days after data acquisition. This unexpected scarcity is unfortunate inasmuch as there were three SAR instruments in operation at the time of the accident and the information they can provide is potentially excellent. To be fair, two of the SAR instruments are carried on satellites - ERS2 and ENVISAT - that are not classified as operational.

Recommendations concerning the oil spill fate prediction service chain:

- *Global ocean data sets must be tuned to the specific oil fate application with respect to spatial coverage, temporal frequency and filtering, timeliness and forecast length. This is especially true if they are used to drive the oil drift model directly, e.g., in remote ocean areas.*

- *The problems of grid interfacing between the global ocean data and the oil spill model may be ameliorated either by improving the grid interpolation or by dynamical downscaling, i.e., driving the oil drift model with a compatible hydrodynamic model nested within the global models (recommended where possible). In either case, it is essential that the issue of grid compatibility with the oil drift model be resolved optimally as part of an operational implementation.*

- *Downscaling of the global ocean data requires setting up and maintaining local nested hydrodynamic models ready for oil spill incidents. This can, in some cases, be done by spinning up a new nested model grid as part of the initialization procedure at the onset of a spill event. However, the recommended solution is using an operational local model that is integrated into a nested global-to-local production chain.*

- *A global response capability will still require the ability to apply the global ocean model data directly in the oil drift model, as was done here. Therefore, optimal methods for grid interpolation and/or accommodation of the oil drift model to the global ocean data are needed.*

- *The oil spill fate service chain should have assured real-time access to analyzed SAR imagery, both for routine monitoring and detection in critical regions and for emergency response globally.*

- *The conclusions and recommendations above point to a need for a structured and integrated operational service chain for oceanographic model and observation products covering global down to local scales.*

Conclusions concerning the quality of the oil spill fate simulations:

- The oil drift simulations show fairly good qualitative agreement with the observations of oil drift and stranding. Both FOAM and Mercator drive the oil onto the coast near the accident site, and they advect the oil eastward into the Bay of Biscay, with stranding along the north coast of Spain. There are, however, significant differences in the location, timing and amount of oil that is stranded and oil that remains afloat; the differences are excessive in relation to the needs of coastal oil pollution combatment. In the final simulations, the Mercator-driven simulation appears to replicate the early oil stranding better than the FOAM-driven simulation. There are also differences in stranding and transport of floating oil in the Bay of Biscay, but it is not known how well the simulations agree with observations.

- The discrepancies in oil drift in the two simulations are directly related to the current fields from FOAM and Mercator, which show disturbingly large differences, even in the daily means. Direct current measurements are not available to shed light on the differences. The most likely causes of the differences are thought to be lack of altimeter assimilation in FOAM and higher horizontal resolution in Mercator. Within the Mersea.S1 project, a comparison is presently being performed, but the focus is not on high-frequency shelf and coastal currents.

- The simulations do not include the effects of tides on the oil drift, since the global ocean data used do not include tides and it was not feasible, within the operational constraints of the project, to implement an independent source of tidal forcing. This is a potentially serious deficiency, the ramifications of which can only be assessed through further comparative simulations.

- Met.no's OD3D oil spill fate model currently requires data on a specific type of grid, which in the present simulations necessitated interpolation of all forcing fields to that grid. Interpolation degrades the data, and the problem is especially acute for the ocean model data, since a) interpolation at the land-sea boundary is particularly difficult, and b) stranding of oil in the oil drift model is sensitive to the near-shore currents.

- Detailed local topography (bottom depth and coastline) is important for providing the best possible forecasts of oil drift, especially stranding location.

- The OD3D model system does not have the capability of simulating a continuous, moving oil source, as is the case for the surface release phase of the "Prestige" accident. This type of oil spill accident is not unusual. In these simulations, the continuous release has been approximated by a series of point releases along the ship's track. The resulting oil particle distributions are thus not able to replicate well the continuous filaments of oil seen in satellite and aircraft imagery.

Recommendations concerning the quality of the oil spill fate simulations:

- *A careful comparative validation of the FOAM and Mercator products used for oil fate modeling is needed. More generally, any global ocean model used in the oil spill service chain must be supported by updated measures of accuracy.*

- *Tidal currents must be included in the current forcing fields. This may be done in two ways: a) add independent tidal data to the global ocean data; b) use a high-resolution hydrodynamic model, nested in the global data, that includes tidal forcing, to supply currents to the oil drift model. The second solution is recommended since it allows for greater resolution of the near-coastal tidal currents. What is more, adding tides to the global models is not feasible and probably not desirable.*

- *Nesting of a local, high-resolution hydrodynamic model in the global ocean data (downscaling) to provide forcing data to the oil spill fate model is recommended, if possible, since: a) higher resolution allows more accurate definition of local topography and coastline, as well as better representation of mesoscale dynamics; b) tides are facilitated; c) grid-interfacing problems are moved away from the area of interest; d) the local model will often be tuned to the needs of the oil spill model Note that downscaling of the ocean fields must be accompanied by corresponding downscaling of the atmosphere and wave model data.*

- *A moving source capability is a recommended enhancement of the OD3D oil spill fate model.*

ACKNOWLEDGMENT. Thanks to Arnhild Lunde, Harald Engedahl and Cecilie Wettre for adapting the oil drift model code to the task, and to Lisbeth Bergholt for help with presentation graphics. A special thanks to Marit H. Jensen for stepping in on short notice to take over the main job of preparing the forcing data, performing the simulation runs and preparing the graphic presentation; this work could not have been completed without her timely efforts.

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