Marine pollution monitoring and prediction

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Abstract

The monitoring and prediction of marine pollution, for which oil spills are a major contributor, is dependent on access to high-quality information on ocean circulation. GODAE ocean assimilation systems are able to provide prognostic data for currents, temperature and salinity in the open ocean, with global coverage, and are now being used in oil spill fate forecasting systems around the world. Examples are given of the different ways that the ocean forcing data are implemented in various oil spill modeling systems, including both direct application and via nesting of local hydrodynamical models. The most important benefits of the GODAE data sets are improved prediction accuracy, global coverage and the availability of alternative data sets for a given area. In addition, the use of GODAE data sets has proven to be a boon to international cooperation on marine pollution response.

Key words: oil spill, ocean, forecast

1 Introduction

Monitoring and forecasting the fate of marine pollution, including oil spill, is one of the most important applications for operational oceanography. Most coastal nations support monitoring and response services for oil spill response inasmuch as the responsibility for preventive and remedial actions is national. Prediction services can play an important role both in decision-making during incidents and in designing response services.

The monitoring, prediction and, to a certain degree, detection of marine pollution are critically dependent on reliable and fast access to environmental data products, observations and predictions. These products provide an overall picture of the present and future status of the meteorological and oceanographic conditions. They may also be used to drive prediction models for pollutant fate, either directly or by providing boundary conditions to high resolution nested models of the local weather and ocean state. There is therefore a need to make access to large geophysical data sets interoperable with regional and sub-regional (national) observing and modeling systems, through the use of standard formats and service specifications. For the global and regional oceans, GODAE has been a major driver in the development and interoperable dissemination of required numerical and observational products, specifically, operational ocean forecast products.

Marine pollution encompasses a range of substances that are put into the ocean by human activity, either accidentally or intentionally. The importance of a pollution incident depends on its detrimental effect on living organisms, e.g., toxicity, (sensitive marine life), smothering (shoreline ecology) or interruption of thermal protection (birds), as well as on the perceived degradation of the environment, e.g., beached oil particularly in sensitive habitats, such as marshes. In all cases, the key factor is the dosage relative to effect, insofar as it is known. Determining the critical doses of a pollutant, and consequently whether a pollution event is in some sense serious, is a complicated matter of science and, to some degree, aesthetics. There are issues of time scale – catastrophic incidents vs. long-term, low-dosage effects – and geographic location. Two extreme examples are a large oil spill from a grounded supertanker (large amount, short time, high concentration, immediate and long-term effects) and the buildup of PCB in marine organisms (low dosage, long-term, complex propagation through the food-chain). Even a small spill as sensitive area (e.g. bird rookery) can have serious consequences. Oil spill at sea has been one of the most studied forms of marine pollution, due to the catastrophic and highly visible character of accidents, as well as its dramatic effects on marine life. Since quick action can reduce the effects of oil spill accidents, the ability to forecast of the drift and fate of spilled oil is needed by coastal societies, and many national services have developed over the last few decades. While oil spilled into the sea in many ways is a special form of pollution, the methods used to predict its fate are much the same as for most other major pollutants. This is certainly the case in the context of GODAE and operational oceanography, which deals with prediction on time-scales up to the order of 10 days. In this paper, we will therefore focus almost exclusively on oil spill as a paradigm for marine pollution.

Oil spill forecasting is typically carried out using a numerical forecast model for the advection and weathering of the oil in the sea. Weathering, which includes the processes evaporation, emulsification and natural dispersion, is determined largely by the chemical properties of the particular oil type under the influence of the ambient environmental conditions. The most common numerical formulation for oil represents the oil mass as a cloud of discrete particles (or super-particles), which are subject to weathering and motion induced by geophysical forces. For an overview of oil spill modeling, see *Galt (1994), Reed et al.* (1999) and *Hackett et al.* (2006). While the formulations of particles and weathering processes may vary considerably between oil models, all are critically dependent on geophysical forcing to determine the fate of the oil spill, in particular its motion. Currents and winds are clearly the most important forces, but models vary widely in the forcing data used. Early oil spill models parameterized all forcing from wind data, which was all that was readily available. More recent models may access external data for surface wave energy, Stokes drift, air temperature, water temperature and salinity, turbulent kinetic energy, depending on the parameterizations employed by the particular model. These geophysical forcing data are usually obtained from numerical models for weather, ocean circulation and waves. In some oil spill forecast services, the forcing data come from operational numerical models, and this trend will increase with further refinement of ocean model prediction capability.

For marine oil spill prediction modeling in the open ocean, it is *ocean circulation* data that is the forcing component with greatest scope for improvement, mainly because ocean forecasting is less mature than weather and wave forecasting. Here, the two main issues are forecast *accuracy* and forecast *reach*, both geographical and temporal. Operational ocean prediction systems emerging from the GODAE program are therefore important developments. These systems offer the promise of better forecast accuracy through the assimilation of available ocean observations, which are also a major GODAE contribution. The geographical reach of the GODAE systems extends from basin-scale to global, thereby facilitating truly global oil spill modeling capabilities. The forecast horizon at these scales is 10-14 days. It should be noted at this point that oil spill model systems may utilize GODAE ocean prediction data in two ways: 1) as direct forcing to the oil drift model and 2) as boundary conditions to higher-resolution local ocean models that, in turn, provide forcing data to the oil drift model. The latter approach – nesting – is often favored since it allows more detailed information (such as coastlines) and exploits local modeling expertise. On the other hand, using the global/basin-scale data sets directly may be the only recourse if the oil spill forecast provider does not have access to high-quality nested local models for a given area.

2 National, regional and global service examples

Over the last few years, a number of oil spill monitoring and prediction providers around the world have implemented GODAE operational ocean data products to improve and enhance their services to authorities, industry and the public. Somewhat different approaches have been taken concerning the implementation of ocean forcing data. In the following sections, some representative examples will be offered, both to show the current state of oil spill monitoring and prediction, and to provide guidance for developing services.

2.1 Northern European waters (met.no)

In northern European waters, which include the North Sea, Baltic Sea, Norwegian Sea and Barents Sea, marine oil pollution stems from both ship traffic and from the offshore petroleum industry. While small, illicit spills from ships probably still account for the largest amount of oil spilled into the ocean over time, the large oil industry gets the most attention due to the large potential for damage to the environment from large, catastrophic spills. Industry activities include not only offshore oil production, but also exploration, oil transport, refining and operational support, all of which have the potential for accidental oil spill. With the advent of North Sea oil production in the early 1970's, several bordering countries saw the need for rapid response capabilities in the case of oil spill accidents. In the Norwegian sector of the North Sea, the Bravo

blowout accident in 1977 underscored the seriousness of the problem. Consequently, development of the Norwegian preparedness capability has been mainly focussed on large, accidental spills from offshore installations and associated ship traffic (tankers). This is reflected in the oil spill forecasting tools that have been developed to support the response activities, as will be described below.
Oil and gas production from Norway has risen as fields have been developed in the North Sea and more recently the Norwegian and Barents Seas; presently, Norway is the world's 3rd largest exporter of crude oil. At the same time, oil spill modelling capabilities have been developed, primarily at the Norwegian research establishment SINTEF, and incorporated into a forecasting service at met.no. This service is provided primarily to the Norwegian Coastal Administration (NCA) , which is the government agency responsible for enforcing regulations in all oil spill events, and to the Norwegian Clean Seas Association of Offshore Operators (NOFO), which is an industry body set up to coordinate the operators' regulatory obligation to enact remedial action. The duality of government-industry roles is a result of "the polluter pays" principle in Norwegian pollution regulations. In addition, the service is made available to government agencies and other third parties as needed.

2.1.1 Oil spill forecast system at met.no

The system has been developed by combining the oil chemistry and modelling expertise at SINTEF with the weather and ocean forecasting expertise at met.no into a robust operational service maintained by met.no. As a normal procedure, users contact a duty forecaster at met.no and request an oil spill forecast. By contract with NCS/NOFO, met.no is obligated to return a prognosis in agreed format within 30 minutes of a request and to maintain a duty forecaster available for consultation. Data files are delivered in a format compatible with proprietary visualisation tools at NCS/NOFO. Met.no also maintains a backup visualisation facility that may be employed by the duty forecaster to deliver graphical information on request or as needed.
The oil spill fate forecast system consists of three components: an oil spill fate model, geophysical forcing data and a user interface. At the core is the *oil spill fate model* OD3D, which calculates the 3-dimensional drift and chemical evolution of surface and sub-surface oil in the guise of a number of "superparticles," each of which represents a certain amount of oil or its by-products. Superparticles are seeded at each time step, according to the specified location, duration and rate of release. Approximately 70 different oil types have been implemented, each with laboratory-derived characteristics for evaporation, emulsification and natural dispersion. A novel seeding module for deep sources is included. *Geophysical forcing data* are perhaps the most decisive component of the system and, given the present context, will be discussed more fully in the following. The *user interface* consists of an on-call duty forecaster, available 24/7/365, and an interactive web service, with which a user may order, monitor and visualize a forecast run, as well as download data.

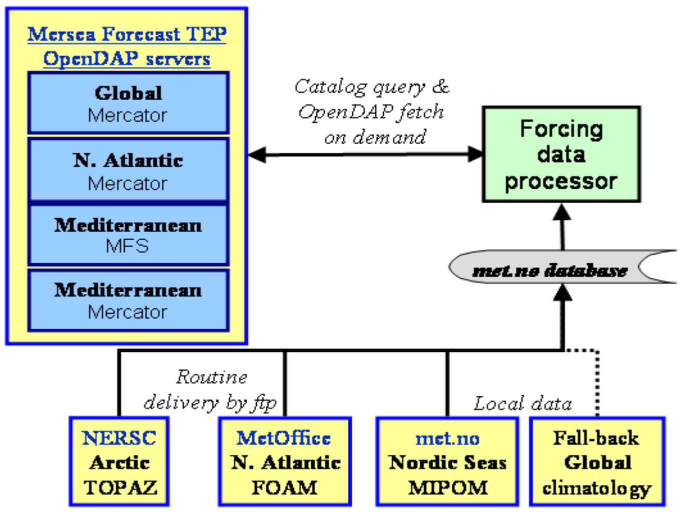

Figure 1: Schematic of met.no forcing data pre-processor access to local and GODAE prognostic ocean data sets. At bottom: data sets that are stored in met.no database; includes all met.no models, routine deliveries by ftp and static data (global climatology from the Met Office FOAM). Upper left: Mersea Thematic Portals (TEP) from which data sets are obtained on demand via queries to THREDDS catalogues and retrieval from OPeNDAP servers..

2.1.2 Geophysical forcing data

OD3D can utilise prognostic model data for currents, wave height, wave direction, Stoke's drift and winds; 3-dimensional salinity and temperature data are also required for a deep spill source. For meeting national responsibilities in

Norwegian waters, forcing data are taken from met.no's operational models for weather, waves and ocean circulation; at present, these are HIRLAM (12km), WAM (10 km) and MIPOM (4 km), respectively. These data are updated at least twice daily to yield 60-hour forecasts. In addition, analysis fields for the past seven days are retained in a fast archive so that events starting up to a week in the past may be readily simulated.
Experience with this system over many years showed that the most critical component for forecast skill is the accuracy of the ocean current data applied. OD3D is formulated such that the horizontal motion of the oil is determined by the ocean model currents, along with the Stoke's drift from the wave model. There is no direct parameterisation on the wind vector, as in some other systems. Since prognostic ocean models are less mature (and accurate) than atmospheric and wave models, a major effort has been put into obtaining the best possible current data. In the Mersea Integrated Project (www.mersea.eu.org; funded by the European Commission under the Fifth Framework Programme), met.no, together with partners Météo-France and University of Cyprus (OC-UCY), has investigated the benefits of applying global to basin scale ocean model data from the Mersea forecasting centres. Several of the Mersea forecasting systems are major components of GODAE: Mercator (global, North Atlantic; www.mercator-ocean.fr), FOAM (global, North Atlantic; www.metoffice.gov.uk), TOPAZ (Arctic Ocean; topaz.nersc.no), MFS (Mediterranean Sea; www.bo.ingv.it/mfs/). Both direct application of the Mersea data products to OD3D and nesting of met.no's local ocean models in Mersea data have been studied. The implementation consists of a multi-source forcing data pre-processor that facilitates access to ocean model data sets from met.no, Mersea and other providers. This approach has a number of advantages: it allows a global service, when combined with global atmospheric and wave data from the ECMWF; it allows a "mini-ensemble" of forecasts when several data sets cover the area in question; the same pre-processor may be used to force similar drift models for floating objects and ships, and allow consistent coupling of the drift models (e.g., oil spill from a drifting tanker).
As shown in Figure 1, access to external data is either by routine ftp delivery or by OPeNDAP on demand. Routine ftp is necessary for nesting and is potentially more robust, but requires local storage of (mostly unused) data. OPeNDAP allows access to just the required portions of multiple, large data sets, without local storage, but at the cost of real-time data transport.

2.1.3 Case study: Statfjord A accident

During the Mersea project, validation exercises were carried out with the met.no oil spill fate forecasting system and several other systems, using various ocean forcing data sets, including GODAE/Mersea data. A Mediterranean example is described in section 2.2. By happenstance, a real oil spill occurred during the demonstration period, and in Norwegian waters. On 12 December 2007, about 4000 m^3 of crude oil were spilled from a ruptured loading line at the Statfjord field in the northern North Sea. Persistently strong southerly winds combined with the prevailing easterly currents indicated a drift toward NNE. The actual drift is uncertain since the strong winds also led to rapid evaporation and natural dispersion of the oil, and hindered field work. Met.no carried out forecast simulations using met.no forcing data (the national service), as well as alternative simulations using a variety of GODAE/Mersea data sets. Meteo-France also offered alternative forecasts. As shown in Figure 2, there is a sig-

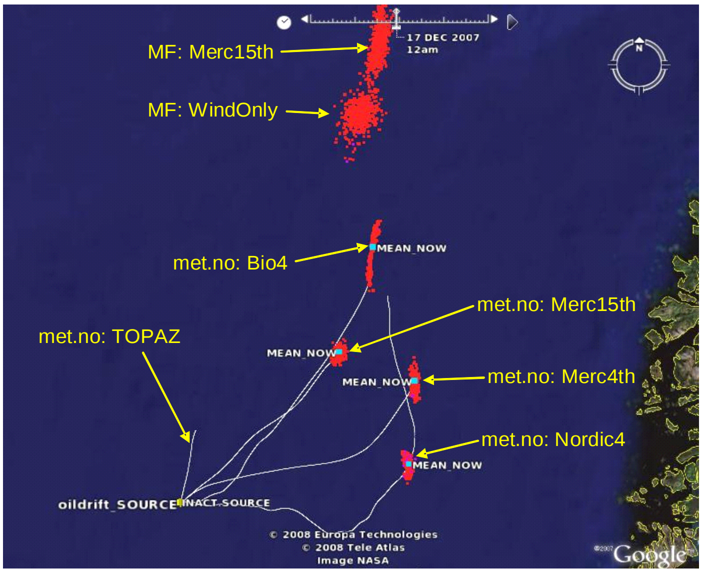

Figure 2: Statfjord A oil spill forecasts overview as rendered in Google Earth. Two Météo-France (MF) and five met.no forecasts, with ocean forcing data indicated, are shown. Merc4th=-Mercator Global; Merc15th=Mercator N.Atl; Nordic4=met.no standard model; Bio4=met.no model nested in FOAM data. The red clusters represent the predicted slicks at 2007-12-17 00 UTC (4.5 days after the spill). Grey lines indicate the trajectory over the forecast duration (met.no Nordic4 extends to 2007-12-19 12 UTC)

nificant spread in the predicted mean trajectories of the oil slick, but the consensus lies in the NE quadrant. Note that the national service (Nordic4 in Figure 2) is at one extreme of the multi-model ensemble. (The first forecasts issued by met.no showed an even more southerly trajectory than shown in Figure 2, due to a bug in the model.) An important conclusion of this case study is that a mini-ensemble approach gives valuable information to the duty forecasters who must assess the quality of their forecasts. The study also supports the finding from the other Mersea demonstrations that the best forecasts tend to come from simulations driven by data from local ocean models nested in basin-scale GODAE/Mersea data sets (see section 2.2.4 below).

2.2 Global and European waters (MF)

Globally, there has been a perceptible decrease in the number and total volume of accidental oil spills since the record 750,000 tonnes in 1979 (http://www.itopf.com/). Thus, after considerable prevention efforts made after the Amoco Cadiz disaster (1978), only four oil spills involving over 1,000 tonnes occurred in France in the 25 years that followed. However, the Erika accident in December 1999 and the Prestige accident in November-December 2002 were reminders that oil spills remain a permanent threat and that they do not respect national boundaries. However, passing ships, such as Erika and Prestige, are not the only problem. Collisions and accidents when approaching harbour are almost as significant in their contribution to world-wide oil spills, while accidents on offshore platforms, as exemplified in the previous section, also contribute to accidental oil spillage. Oil is not the only source of pollution. The collision of the Allegra in the Channel in 1997 caused the spillage of nearly 900 tonnes of palm oil. Again in the Channel in 2000, the wrecking of the chemical tanker the Ievoli Sun highlighted the danger involved in chemical tanker accidents.

Major accidents generally lead to a review of procedures, techniques, materials and products used for remedial action on a local scale. This reaction generates advances in know-how and response means, as well as national and international measures. For example, the Amoco Cadiz and Erika spills provoked the review and modification of the French national instruction on accidental marine pollution response (Polmar Instruction). The Erika disaster led to measures taken at the European scale (Erika Packets I, II and III).

2.2.1 Oil spill forecast system at Météo-France

France has three seaboards: Channel/North Sea, Atlantic and Mediterranean. The maritime traffic along these coasts is heavy, about 45,000 ships every year in the Channel and 8,000 in the French zone of the Mediterranean. In addition, French overseas territories in the Caribbean, Pacific ocean (French Polynesia, new Caledonia) and Indian Ocean (Réunion, Mayotte) require the use of resources across the Globe. The French response to accidental marine pollution is organised by the Polmar Instruction, applicable to discharges of any substance likely to damage the marine environment. The structure in charge of operations comprises representatives of all the Government Departments concerned and appropriate technical bodies, in particular Cedre (Centre for Documentation, Research and Experimentation on accidental water pollution), IFREMER and Météo-France. Météo-France is in charge of metocean support and slick drift predictions.

The oil spill forecast system has been developed by combining the oil chemistry expertise at Cedre with the weather and ocean forecasting and modelling expertise at Météo-France into a robust operational service maintained by Météo-France. As a normal procedure, users contact a duty forecaster at Météo-France and request an oil spill forecast. By contract with Cedre and under the POLMAR instruction, Météo-France is obligated to return a prognosis in agreed format and to maintain a duty forecaster available for consultation. Data files are delivered in a format compatible with proprietary visualisation tools at Cedre. Météo-France also maintains a backup visualisation facility that may be employed by the duty forecaster to deliver graphical information on request or as needed.

Météo-France's oil spill fate forecast system is quite similar to the system at met.no, as described above. The oil spill drift model is MOTHY, which is also a superparticle type model, but differs from met.no's OD3D in that it relies more heavily in wind-parameterisation of the currents. This and other aspects of the geophysical forcing data are discussed more fully below. The system's user interface consists, similarly, of a 24/7/365duty forecaster and a web service on-line visualisation and data download.

2.2.2 Geophysical forcing data

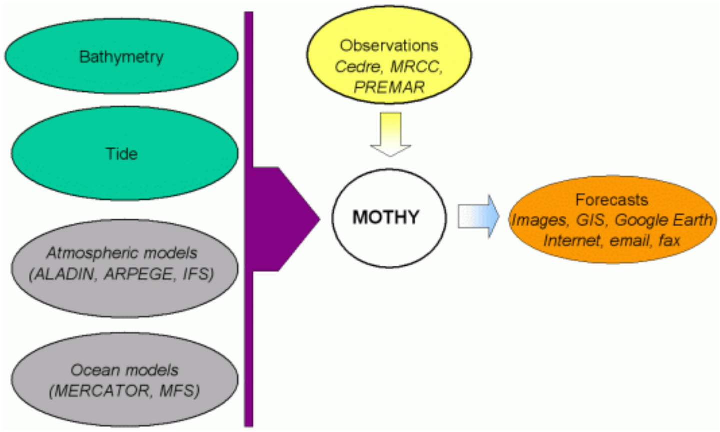

Figure 3: Schematic of Météo-France general framework with access to local and GODAE prognostic ocean data sets. In green: static data. In grey: data sets that are stored in Météo-France database; includes all Météo-France/ECMWF models and routine deliveries by ftp (MFS) and secure copy (Mercator).

MOTHY can utilise prognostic model data for currents and winds. For meeting national responsibilities in French waters, forcing data are taken from Météo-France and ECMWF operational models for weather forecasts; at present, these are ALADIN (10km), ALADIN-Réunion (10 km), ARPEGE (25 km), ARPEGE-Tropiques (50 km) and IFS (25 km). These data are updated twice to four times daily to yield up to 120-hour forecasts. In addition, analysis fields for the past nineteen days are retained in a fast archive so that events starting up to nineteen days in the past may be simulated.
MOTHY only uses ocean model data from a single depth – typically at the base of the Ekman layer – in the place of a climatological background current, and calculates the main drift component from the wind and tide data. It parameterizes the upper ocean drift from wind speed using a sophisticated Ekman type scheme. In the previously described Mersea Integrated Project, Météo-France has participated in the investigation of the benefits of applying ocean model data from the Mersea/GODAE forecasting centres. Implementation of multi-source ocean forcing data, including data sets from Mersea and other providers, provides current data estimates from a range of different depths and models; when combined with global atmospheric data from ARPEGE/IFS models, this allows a “mini-ensemble” of forecasts for both global and national areas. The same implementation is used to force similar drift models for floating objects and ships.
As shown in Figure 3, access to external data is either by secure copy or routine ftp delivery.

2.2.3 Case study: Prestige accident

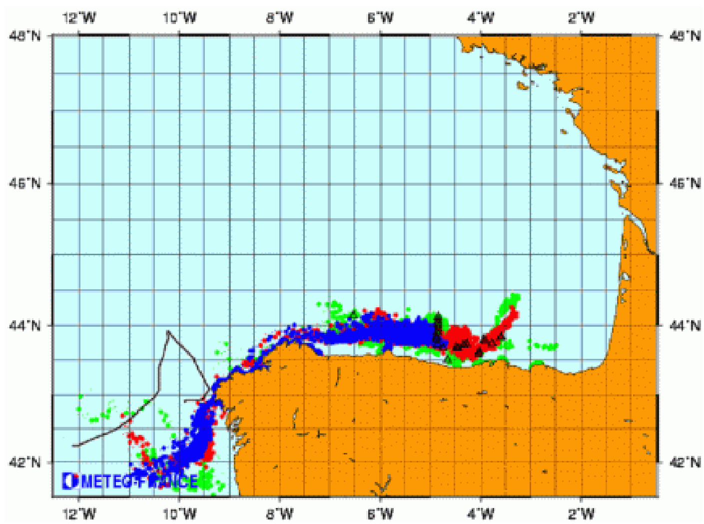

Figure 4: Prestige case snapshot 2002-12-13 12 UTC. Comparison between in situ observations and MOTHY simulations based on a constant leakage along the tanker’s trajectory (black line). MOTHY+climatological currents is in blue, MOTHY+Mercator in green and MOTHY+FOAM in red. Black triangles are the observed slicks.

On 13 November 2002, the tanker Prestige was damaged and came adrift off of Cape Finisterre (Galicia, Spain), leaking oil from a gash in the hull. The tanker was carrying 77,000 tons of heavy fuel oil, was heading to Singapore via Gibraltar. The ship sank on 19 November after being towed in various directions (see Figure 4).
The first slicks reached the coast of Galicia in the morning of 16 November between La Coruña and Cape Finisterre. Oil stranding events followed in late November and in early December, during which the northern coast of Spain was affected from Asturias to the Spanish Basque Country. Stranding included both oil slicks and thick, viscous balls, pancakes and various sized patches. At the beginning of January, the coast of Galicia faced with a fourth massive stranding. The French coast was hit near St Jean de Luz on 31 December, 2003.

Stranding of Prestige oil hit Brittany in May and the coast of the English Channel in September. In France close to 2500 km was affected, the last stranding occurring in October, 11 months after the wreck.
From 13 November, Météo-France started to produce drift forecast charts for the authorities, including simulations using GODAE ocean data sets from Mercator and FOAM. The impact of adding these data was unclear during the first few days of the spill but became useful in the Bay of Biscay for longer simulations (Figure 4). It was concluded that the Mercator and FOAM contribution is visible for long-term simulations in waters where the large-scale circulation has a significant impact. These results were the first use of GODAE/ Mersea data and were most encouraging. However, they revealed large differences between the current data sets (Mercator and FOAM).

2.2.4 Case study: Mersea exercises in the Mediterranean Sea

During the Mersea project, validation exercises were carried out in two areas of the Mediterranean Sea with the oil spill drift forecasting systems of Météo-France, OC-UCY and met.no, using various ocean forcing data sets, including GODAE/Mersea data. Oil-emulating surface drifters were deployed first southwest of Cyprus by OC-UCY and later off the southern coast of France by Cedre (Figure 5).

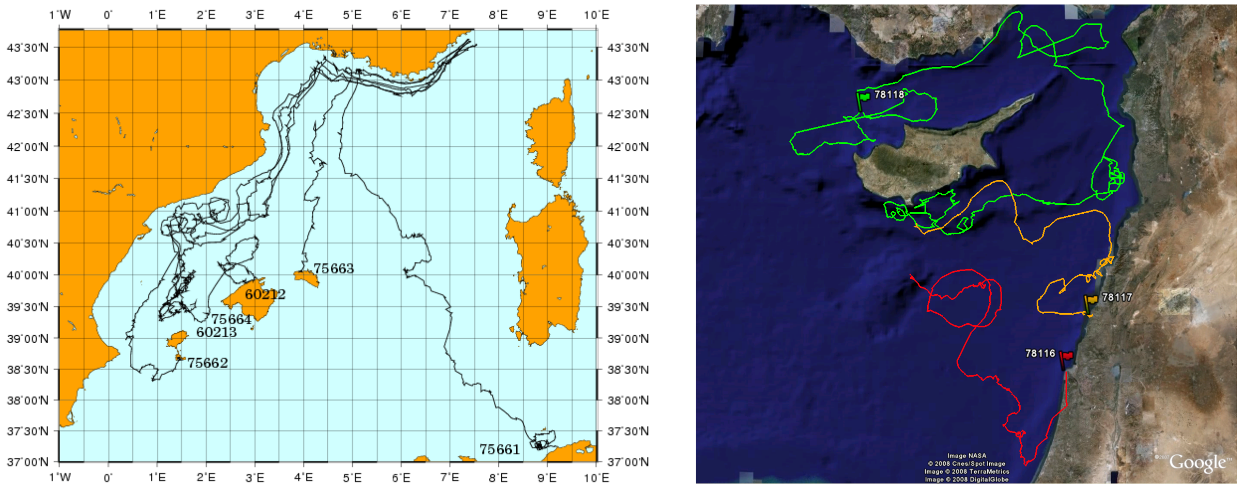

Figure 5: The tracks of the drifters released in the Eastern Mediterranean by OC-UCY (right) and in the Western Mediterranean by Cedre (left), Fall 2007. Both deployments were supported by funding from Mersea.

The partners' oil spill forecast services were applied to these to these "oil spills," facilitating an assessment of model-model forecast comparison and model-data validation. Furthermore, the models were forced by several alternative ocean data sets, including Mersea/GODAE pre-operational products from Mercator (Global ¼° and Med 1/15°) and MFS (1/15°).
The most important findings from the Mediterranean drifter experiments include:

- In the eastern Mediterranean, simulations by OC-UCY indicate that more accurate results are obtained when applying currents from a local, fine-scale ocean model nested in MFS basin-scale data as opposed to applying MFS data directly in the oil spill model.
- In the eastern Mediterranean, the three GODAE/Mersea ocean data sets showed large differences in the predicted current fields. MFS and Mercator Med are both considered eddy-resolving and assimilated the same data, yet the eddy fields they produced south of Cyprus differ considerably. Mercator Global produced much smoother and weaker current fields. The resulting oil drift trajectories vary considerably and often agree poorly with the drifters, especially those produced by met.no's OD3D, which relies heavily on the ocean model currents to calculate the oil drift.
- In the western Mediterranean, the drifters were deployed off Nice in the coastal current, which is a strong, persistent feature of the current field. In this case, simulations using OD3D and MOTHY with Mercator and MFS direct forcing agreed much better, both with observations and with each other, as long

as the drifters remained in the coastal current. The drift direction was generally well reproduced, but the excursion length was underestimated in all simulations.

- A common result from both experiments is that the drifter trajectories are better reproduced in areas where the ocean model data are most accurate, i.e., along coasts and in other areas where topographical steering is important. The often large model-model and model-data discrepancies found in open sea areas, are due to unstable mesoscale dynamics (eddies, meanders), which are difficult to predict.
- The Mediterranean experiments demonstrate the importance of *how* the forcing data – currents, wind and waves – are applied in different oil spill model systems.

2.3 Western Pacific waters (JMA)

To support the processing activities in case of a large-scale marine pollution accident, the 11th Committee for Marine Meteorology (CMM) of World Meteorological Organization (WMO) proposed the Marine Pollution Emergency Response Support System (MPERSS) in April 1993. In this framework, Japan Meteorological agency (JMA), as an Area Meteorological Coordinator (AMC), was going to provide meteorological and oceanographic information, when a serious oil spill accident would occur in the northwest Pacific Ocean.

In 1997, there were several major oil spill accidents, the case by the Russian tanker 'Nakhodka' was especially serious. It brought heavy damage to the environment along the western coastline of the Japanese major island Honshu. The importance of oil spill prediction accompanied by information on meteorological and oceanographic conditions was recognized in particular.

2.3.1 Oil Spill Prediction Model at JMA

This led JMA to the development of an oil spill prediction model for an additional supply of oil spill information. The oil spill model was newly developed and has been put into operation in JMA since 1998. Afterwards, the model accuracy has been improved, by revising input (forcing) data according to improvements of JMA's meteorological and/or ocean operational models.

The specifications are shown as follows:

Type of model		particle diffusion model
Applicable area		10°S-65°N, 120°E-180°E
Domain of calculation		Variable (0.8×0.8 -- 12×12 degrees)
Grid spacing		Variable (2-30 km), according to the domain of calculation
Number of grids		41×41
Prediction period		192 hours
Physical and chemical process	Advection	surface flow(estimated from wind field of Global Spectrum Model) Stokes drift (estimated from wave field of Global/Coastal Wave Models) Ocean current (Ocean Comprehensive Analysis System)
	Diffusion	Elliott (1986) etc.
	Evaporation	Fingas (1997)
	Emulsification	Reed (1989)

These specifications are published at www.jma.go.jp/jma/jma-eng/jma-center/nwp/outline-nwp/index.htm.

2.3.2 Improvement of ocean current data in MOVE-WNP - the benefit of GODAE

JMA develops and operates an ocean model and assimilation system, in order to provide the oceanographic information such as sea surface temperature (SST) and ocean current. This assimilation system, which is a GODAE contribution, was recently (March 2008) upgraded from COMPASS-K to MOVE-WNP.

In MOVE-WNP, a new assimilation scheme was introduced, in which the EOF analyses of the vertical profiles of temperature and salinity are correlated with altimeter data. This scheme has a good ability to correct physical values appropriately, keeping the dynamical balance as much as possible, and it only

requires small computation time though it still possesses nonlinearity. As a community for lively technical discussion, GODAE played an important role in developing this scheme.
MOVE-WNP gives much improved simulation of the Kuroshio route, on the continental shelf slope in East China Sea, the coast of Tokai region of Honshu Island, and in the Tocharian Strait. The expression of small scale meanders, that propagate westward around the sea south of Shikoku Island and east of Kyushu Island, is also improved. Moreover, the model produces warm and cold eddies propagating westward south of Japan, as well as weak currents such as the Tsushima stream and the currents in several small straits.
GODAE also contributes in the international exchange of oceanographic data. At JMA, most of the observational data available are reports from research vessels in Japanese coastal seas and ARGO float data in the deep ocean. This came from ARGO/GODAE.

2.3.3 Impact of the ocean current data from MOVE-WNP on oil spill prediction

JMA have never run the oil spill model officially, since no serious oil spill accident has occurred after JMA developed the system. Therefore model validation was only carried out by drifting buoys (hereafter referred to as oil pursuit buoy), which were built to move like spilled oil and were put in several areas to get real wandering data in the past.
We here show the result of a case in East China Sea in November, 2001. Figure 5 shows the 12-hourly points of the oil pursuit buoy and simulated positions (centre of spilled area) at the same valid time, from 17th to 24th of November. It should be mentioned that the other input data, such as surface winds, ocean waves, and SST, were those from the results of operational models at that time, which means resolution and expression could be rougher than those of present models.
It is obvious that the simulated track by MOVE-WNP is favorably compared with the oil pursuit buoy track, than that by COMPASS-K. Moreover, the turning point of oil pursuit buoy track was quite reasonably simulated in the case of MOVE-WNP.
Figure 6 shows sequence of the simulated error every 12 hours. For the first 72 hours, the error was at most 20km for MOVE-WNP, while the error increased to about 60km in the case of COMPASS-K. The further investigation on the other cases and the case of "Nakhodka" confirmed the superiority of MOVE-WNP data.
It could be said that the new ocean model of JMA, based on the results of GODAE, has also improved the performance of the oil spill model.

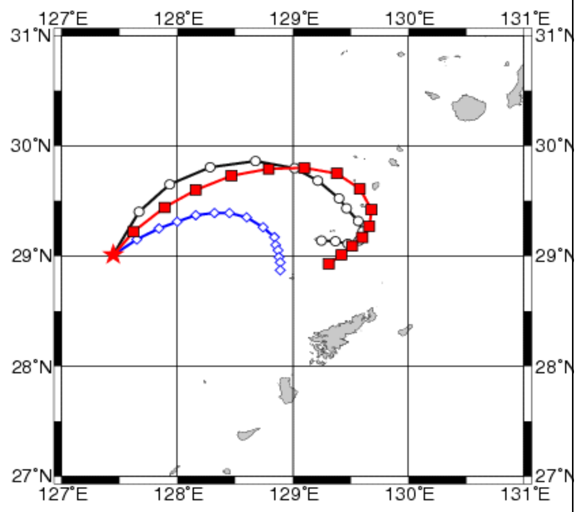

Figure 5: Track of oil pursuit buoy (black circles), simulation of COMPASS-K (blue diamonds), and MOVE-WNP (red squares).

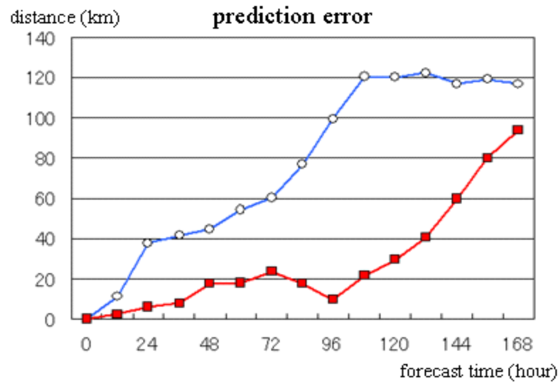

Figure 6: Prediction error simulation of COMPASS-K (blue line), and MOVE-WNP (red line)

2.4 North and South American waters (ASA)

In North and South America, national organizations mandated to respond to oil spill events use a variety of modeling technology ranging from custom or commercial applications, to good will access to scientific expertise through international cooperation. Most modern oil spill models can use imported circulation and wind nowcast/forecast data to calculate trajectory predictions, taking into account chemical weathering of the spilled oil. GODAE products can play a key role in assisting responders in rapidly assessing the fate and transport of spilled oil. Rapid access to trajectory predictions allows responders to plan ahead of the spills movement to allocate personnel and resources (boom, skimmers, dispersants) to adequately respond to the oil spill. Quick response from a trajectory modeler's perspective is obtaining custom subset and temporally aggregated wind and current predictions in order to meet the response team's needs for predictions *now or even sooner* (Beegle-Krause 2003).

Two case studies will be presented, highlighting the need for the availability of GODAE fields for a variety of applications, and the need for tools to facilitate the rapid ingest of global data products when local sources are offline or non-existing. Quality control and extensive verification of predictions using observations are also required for robust utilization of these data fields.

2.4.1 Case Study – In the Wake of Hurricane Katrina, USA 2005

On November 11, 2005, the tank barge DBL-152 collided with a sunken drilling rig about 56 km offshore of the Texas - Louisiana border. The rig sank during the passage of Hurricane Rita earlier that year. As a result of the collision, the barge spilled an estimated 70,000 bbl (>11,000 m^3) of "slurry oil", an oil with the unusual properties of high density and low viscosity. The slurry oil primarily sank, and was easily broken and moved within the environment with storm passage (Beegle-Krause *et al* 2006). Unable to see the oil at the surface, spill responders relied on modeling and Remotely Operated Vehicle (ROV) surveys of the area to determine and location and verify the trajectory of the oil. The puddles of heavy oil broke into pieces with storm passage and traveled roughly along bathymetry lines down the Texas-Louisiana Shelf.

In the USA, the National Oceanic and Atmospheric Administration Office of Response and Restoration (NOAA/OR&R) has the responsibility to provide 24/7/365 scientific support to the US Coast Guard during spill events. Responding to over 120 spills events each year within the US and abroad, NOAA spill trajectory modeling is required in about 5% of incidents. Generally diagnostic rather than prognostic circulation models are used to represent the trajectory modeler's circulation forecast, then combined with a site specific forecast from the NOAA National Weather Service, and chemical weathering predictions to create a trajectory forecast. However, prognostic circulation models become necessary during offshore spills or when the spilled oil is submerged and difficult to visualize (e.g. dense oil and deepwater well).

Trajectory modelers with the NOAA/OR&R wanted to use the NOAA Coast Survey Development Laboratory (CDSL) Gulf of Mexico model, a Princeton Ocean Model (POM) implementation. However, the NOAA model output fields were unavailable at the time: the passage of Hurricane Katrina earlier in the season had led to evacuation and damage of the Naval Oceanographic Office at Stennis Space Center in Mississippi. The wind boundary conditions for the NOAA model were not available, so the model was offline. The trajectory modelers looked to the Texas A&M University oceanographic modelers for access to their Gulf of Mexico model, an implementation of the Regional Ocean Modeling System (ROMS).

Though the staff at Texas A&M was stressed from recovery from Hurricane Rita, the group worked to provide model nowcast and forecast fields formatted for the NOAA trajectory model. The process took weeks, but the Texas A&M model fields were made available to NOAA modelers. Eventually the NOAA CSDL model came back online, currently using NOAA wind fields at boundary conditions. With two circulation nowcast/forecast models to compare, the trajectory modelers noted that the two forecasts agreed well whether the coastal circulation was upcoast or downcoast, but each model frequently transitioned in the opposite direction to the other.

The ability to switch circulation model input (from POM to ROMS) and source location (NOAA, Silver Spring, Maryland to College Station, Texas), though nascent, was key in supporting the trajectory modeling efforts during the incident, and in reassuring the responders, trustees and public that the oil did not pose a risk to Texas beaches (Beegle-Krause *et al* 2006).

2.4.2 Activities in South America

During the last five years, the oil industry has experienced significant growth in South America. In Brazilian waters, improvements in the exploration and drilling techniques has lead to the discovery of previously inaccessible oil deposits, in some cases one mile or deeper below the ocean floor. The drilling and extraction

processes are becoming more complex, making the integrity of wells harder to maintain. Hence, the exploration and production activities in these new oil fields may pose a bigger threat to the environment.
This rapid growth of the oil and gas sector has promoted the development of specific environmental regulations to protect the marine environment. The Brazilian National Oil Company (Petrobras) and several other international oil companies are collaborating with the Brazilian Environmental Agency (IBAMA) to develop such environmental regulation framework.
Within this context, oil spill modeling plays an important role, helping during the prevention/contingency planning phase and also as part of a decision support framework in the case of an actual oil spill. One of the events that heightened awareness in the region was a significant oil spill that occurred in January 2000, when more than 1.3 million liters of heavy oil leaked from a refinery pipeline on the Guanabara Bay in Rio de Janeiro. This led to a series of extensive oil spill modeling studies that looked at potential spills from several refineries along the Brazilian coast.
In addition, Petrobras initiated projects to provide high resolution forecasting services connected to a dedicated operational oil spill modeling system focused on Bacia de Campos, in the Rio de Janeiro state. The operational forecasting system integrates and simulates three components, atmosphere, ocean currents and potential oil spills, and covers Petrobras areas of operations. *In-situ* and altimetry data are fed into the hydrodynamic model, forced by the inputs of the atmospheric model and a large scale circulation model.
The operational hydrodynamic model implemented by the ASA South-America modeling group is based on the Princeton Ocean Model (POM2K). The hydrodynamic model is typically initialized (*spin-up*) with climatological output from a large scale model that supplies an initial 3D thermohaline field, supplying the spatial and seasonal variability of the region. One of the biggest challenges in implementing an operational hydrodynamic model in the South Atlantic region is the scarcity of data to calibrate and validate the model. The South Atlantic does not have exhaustive oceanic data coverage. In that sense, GODAE provides a unique framework of oceanic datasets, providing information at different scales, regional to global.
Over the extensive list of GODAE products, the HYCOM consortium (HYbrid Coordinate Ocean Model) is operationally running a data-assimilative hybrid isopycnal sigma-pressure (generalized) coordinate ocean model that covers the area of interest. This operational modeling effort makes available trusted and extensively validated model results, and has a key role in the implementation of operational hydrodynamic models at a regional level. The recent improvement in the HYCOM data service and the start in September 2008 of its global forecast experiment operationally run by the US Naval Oceanographic Office (NAVOCEANO) will promote the use of global data products as boundary conditions for regional models, resulting in better regional solutions than the use of solely climatological forcing conditions.

2.4.3 Data Distribution & Management services

Global and regional data products are increasingly made available, many of them through large initiatives like GODAE, and are used extensively by scientists around the world who are familiar with the data standards and transport protocols. However, these data need to be readily available directly to the non-scientist community, including marine emergency responders. The role of the “middle user” bridges the gap between the data providers and the data consumers and allows users to access data with commonly used software tools and web-enabled applications. In that sense, ASA has implemented several methods in collaboration with the US Coast Guard, Navy, NOAA, and industry to allow the rapid distribution of global and regional data products for operational purposes. Measures of uncertainty in the data are also essential for practical uses of the data and allow emergency managers to evaluate the confidence in the predictions.
An example of this system that connects data providers and end-users is the implementation of the Environmental Data Server (EDS) within the COASTMAP data services umbrella. EDS provides global, national, and regional observation and model data in support of operational missions, like the US Coast Guard’s Search & Rescue missions. This framework uses a web services architecture and standard data formats such as NetCDF, GIS formats, and OGC standards to share data across applications.

3 International collaboration and future perspectives

The benefits of GODAE data sets and products were clearly demonstrated in the previous paragraphs. GODAE prognostic data have been shown to provide improved current predictions and facilitate alternative and mini-ensemble forecasts to support marine pollution monitoring and response. This is to a large degree thanks to the efforts made to make the data sets more easily accessible to users across national boundaries. The examples also point out the primary future challenge for post-GODAE data providers, which is improving forecast accuracy for currents. Therefore, international collaboration should continue to consolidate work on validation metrics and model intercomparisons to make sure a minimum set of metrics is internationally implemented. In particular, there is a need for more extensive metadata and the inclusion of spatially explicit uncertainty estimates, both for the forcing data and the oil spill model output. The Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM) can be a vector for product standardisation to be developed and interoperability between systems ensured. JCOMM also promote full implementation of operational ocean observing systems, including long-term maintenance of *in situ* systems and key ocean satellite missions.

The transition from demonstration to operational systems is an important issue. Examples of transition to operations for the different nations are numerous. Mercator in France, NCOF in the UK, MyOcean in Europe, NOPP projects in the USA (e.g., HYCOM, ECCO), BlueLink in Australia and COMPASS-K/MOVE-WNP in Japan are now preparing the transition to operational status.

JCOMM recently established an expert team for Operational Oceanographic Forecasting Systems (ETOOFS) in order to provide advice on operational ocean forecasting system requirements and outputs, and on the standards and nomenclature used by operational ocean forecasting systems. As a focal point and JCOMM representative at GODAE meetings, the ETOOFS chair will advise on the limitations and strengths of operational ocean forecasting systems. JCOMM also recommended (JCOMM Management Committee, 6th session) that ETOOFS establish a collaboration with the European Union MyOcean project, Australian BLUELink and other national and regional integrated (*in situ*, satellite, model and data management) operational ocean forecasting systems.

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