ASMA
Final report

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Partners:

1. Centre of documentation, research and experimentation on accidental water pollution (CEDRE)
2. Geographic Resource Analysis and Science Ltd. (GRAS)
3. Admiral Danish Fleet (Naval Operational Command-NOC) (provider of data from Danish spills)
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1 GENERAL REMINDER

1.1 Project objective

The overall objective of the project is as follows:

- Identify needs and constraints of techniques and means for locating and quantifying slicks or patches of submerged oil by reviewing past accidents
- Improve capability to locate and quantify submerged oil by testing and refining remote sensing techniques
- Provide real-time means to predict trajectories of submerged oil by improving and testing oil drift models
- Provide input to guidelines for future mapping of submerged oil

1.2 Partnership

The partners comprise:

- DHI, an independent, international consulting and research organisation authorised by the Danish Ministry of Science, Technology and Innovation as an Approved Technological Service Institute.
- CEDRE, Centre of documentation, research and experimentation on accidental water pollution. CEDRE is responsible, at national level in France, for documentation, research and experimentation on pollutants, their effects and the response means and tools to combat them.
- GRAS was created jointly by the University of Copenhagen and DHI – Water & Environment in October 2000. The company has its own permanent staff complemented with the expertise and experience of key personnel from the Institute of Geography, University of Copenhagen. GRAS is a non-profit company and the generated revenue is used for further research and development.
- ADMIRAL DANISH FLEET is the overall responsible for military security and safety in Danish waters, including pollution combating at sea.

1.3 Deliverables

Key deliverables comprise:

- A report presenting an overview of current efforts in detecting and mapping submerged oil and an assessment of the effectiveness of the different approaches
- Short report describing the feasibility of using ocean colour remote sensing data to detect submerged oil
- Demonstration of the potential of acoustic sensors for fine-scale mapping of submerged oil
- Report presenting test of oil spill model applied to Sea Venture II spill (Great Belt, Denmark)
2 SUMMARY OF PROJECT IMPLEMENTATION PROCESS

2.1 Project Rationale

In several recent oil accidents in Europe detection and monitoring of spills have been hampered by fast sinking oil. Noticeable examples include Volgoneft 248 (Sea of Marmara, Turkey 1999), Erika (France, 1999), Prestige (Spain, 2002), Fu Shan Hai (Baltic Sea, 2004) and Sea Venture II (Great Belt, Denmark, 2005). When a larger part of an oil spill sinks below sea surface the magnitude of the spill, the fate (transport and weathering) of oil and the impact on marine life become difficult to estimate and ultimately may remain unnoticed - or the cause of damage to marine life may fail to be identified. In the case of Prestige (November 2002), some of the heavy fuel oil probably have travelled for days below the surface or close to the sea bottom without being detectable by the usual means (e.g. aircraft crew visual observation). Presence of submerged oil was occasionally reported by fishermen, but most of the time, the oil spill could not be quantified nor precisely located. The continuous beaching of tar balls on the French coastline suggested quantities of oil sunken in shallow waters in front of the coastline, however, a sampling campaign based on small trawl nets failed to detect oil. During this process spill questions arose about the sinking of the oil at night and its re-floatation at midday, which was observed from oil recovery vessels. This was in agreement with the fact that aerial surveys proved to be more efficient in the afternoon, whereas for guidance of spill control vessels it would have been better to obtain results from aerial observations at dawn of each day. After the spill from the Sea Venture II (2005) in the Great Belt (Denmark) it was considered that spilled oil may have moved below the sea surface (probably just above the permanent pycnocline located at 8-12 m), as no oil was observed from either air or sea surface, whereas oil and some 4,000 oil-covered diving birds were observed in different places along a 50 km shoreline. The origin of the stranded oil was verified because samples of the stranded oil and the oiled birds proved to match with the oil from the Sea Venture II.

Leaving no trace at the surface the quantification and monitoring of sunken/submerged oil is very difficult and adequate methods are lacking or have not been tested thoroughly. In some cases the monitoring of the submerged oil slicks has been done visually by means of divers when re-oiling problems had occurred (e.g. oil from Erika polluting the Belle-Ile coast) or in rare cases acoustically by means of sonar (e.g. Prestige in Galicia). The lack of adequate methods to detect submerged oil will delay or prevent proper remediation actions that could diminish the risks of environmental impacts.

Thus the aim of the project has been to collect and review existing information from past accidents where submerged oil occurred and to examine and review the feasibility of new techniques to quantify the magnitude, advection and potential impacts of submerged oil spills.

2.2 Time schedule and used resources

In general the project has progressed as planned and according to the initial implementation time schedule. Also the allocated resources have been spent according to the initial staffing and budgets. However, during the project it was decided to reduce the number of project meetings initially planned.
2.3 Expected and actual results

The main findings and conclusions regarding the different project tasks are provided below. A detailed description can be found in the corresponding annexes A through D.

2.3.1 WP 1: Review of existing information from past accidents where submerged oil occurred

With focus on submerged oil this task comprised collection and sorting of data on Heavy Oil (HO) spills recently occurred in European and non-European waters.

For each case the various techniques and means used for detecting of the sunken oils were analyzed and pros and cons have been established regarding the applied methods.

In European waters data have been collected and analyzed for the Erika and Prestige (in French water) based on detailed information available at CEDRE and other French authorities.

Potential links between oiled seabirds arrivals and oil deposits on the shoreline have also been assessed for the Prestige spill.

Subsequently, a worldwide search on accidents reporting submerged oil was carried out.

2.3.2 WP 2.1 Applicability of ocean colour remote sensing to detect submerged oil

The available techniques for detection of surface oil using radar and near infrared are not feasible due to absorption of radiation in the water column.

There is no straightforward way to identify and map submerged oil, however, since the submerged oil do change the optical properties of water, it should in theory be detectable using various change detection techniques. This can be done by monitoring changes against the non polluted background (another date where we know that no oil was present).

In principle the detection of sub-surface oil using ocean colour remote sensing could be feasible using:

1. Optical remote sensing data (Reflected light from the blue, green and to a limited extend the red spectrum)
2. Reflectance and fluorescence in the UV (ultraviolet).

The focus has been aimed at optical remote sensing data since no space born UV images data sources are available at the present.

Based on information about ship positions in relation to the spills from Sea Venture II, Prestige and Erica, a comprehensive study of available satellite data has been carried out.

The quality of the available EO (Earth Observation) data was generally poor. Serious cloud cover has either impeded analysis or simply not allowed acquisitions of data or, when cloud free or partly cloud free data were available, e.g. for the Sea Venture II case, the poor light conditions during winter have not allowed unambiguous analysis and conclusions to be made. A substantial effort has been made carefully analyzing the available images and of the three cases, only the Sea Venture II case was suitable for continued work and has been reported here.
Most likely the present study of the Sea Venture II oil spill accident shows that in winter time with low sun angles and limited reflected radiation, sub surface oil cannot be identified in optical medium resolution EO data. However, features in an MERIS full resolution image from February 1, 2005, indicate possible signs of oil. The following MERIS reduced resolution images from February 2, 2005, could not confirm this, however, small differences in the image may exhibit some of the same features as shown in the February 1 image. In support of the interpretation the oil occurrence on the beaches west of Funen facing Langeland were reported on January 29 and on the island of Agersø on January 31. Reservations against the identification of sub surface oil spill are the limited amount of light reflected from the water body.

The final conclusion must be that further studies are needed and that oil spill cases from the summer period should be used in order to allow the best quality optical EO data to be acquired.

2.3.3 WP 2.2 Refining acoustic methods to detect and quantify sunken oil

The goal of this task has been to select the most adequate survey strategy concerning sunken oil slicks using the most efficient acoustic means presently available (or will be in the near future). Focus has been on reanalysing and updating data from previous experiments carried out by CEDRE and partners (DENIM and EXCAPI projects).

A number of seafloor mapping systems are commercially available, but they have not been used in response to actual oil spills. For this reason CEDRE has been involved in a comprehensive acoustic experiment utilising a large seawater tank in the Navy Base (actually a former dry dock for submarines). Different types of heavy oil patches were used and several sonar systems have been tested with regard to their response and ability to map these oil patches according to their frequency, resolution and type (side scan sonar, multibeam-panoramic sonar and 3D real-time sonar).

Appendix C provides a detailed presentation of test results and the main conclusions.

2.3.4 WP 2.3 Modelling subsurface oil drift and fate following Sea Venture II spill

Oil drift and fate modelling has been carried out for the Sea Venture II oil spill using the MIKE FM ECO Lab. Briefly the model system comprise a 3-dimensional hydrodynamic model, combined with a Lagrange representation of oil particle drift and an open solver (EcoLab) for inclusion of the weathering processes (such as e.g. evaporation, mechanical spreading, dissolution, emulsification and degradation). During the project relevant processes has been further developed and implemented in the ECO- Lab solver.

In the case of Sea Venture II the oil disappeared from the water surface most likely due to a combination of strong winds (and hence vertical mixing) at the time of the release and high oil densities. The quick cooling of the oil due to low winter temperatures increased the density of the oil and combined with the high flow resistance of tiny droplets, the oil could stay submerged for a long time. Weathering of the oil increased the density of the oil further as time went by.

The modelling study of the Sea Venture II spill demonstrated that modelling can be an efficient tool for tracking of sunken oils. In particular it was demonstrated that oil slicks close to the sea surface followed the main wind directions. As the oil sank into deeper layers the movements were primarily in the direction of the currents. This phenomenon was in agreement with observations.
2.3.5 WP 3: Dissemination of results

During the project period the ASMA project has been presented during two workshops. Furthermore, a project web page has been established http://asma.dhigroup.com/ where all reports generated by the project have been published.

In November 2006, the ASMA project and preliminary findings were presented at a workshop in Brest. The workshop was organized by CEDRE and funded by EC in application to the 2005 Calls for Proposals in the field of Community co-operation in the field of accidental or deliberate marine pollution. Various European organizations, among which ITOPF (GB), MUMM (Belgium), SINTEF (Norway), Admiral Danish Fleet HQ (Denmark), etc, attended this workshop entitled “Workshop on heavy fuel oil. What do we know? What do we still ignore? What possible responses?”

In December 2006, CEDRE participated in a specific workshop on heavy fuel oils in Durham (New Hampshire), USA. The theme of the workshop was “Submerged Oil – State of the practice”, organized by the Coastal Response Research Centre (CRRC). Various organisations, mostly from North America, attended this event (example: NOAA, USCG, various universities, U.S. Environmental Protection Agency, Applied Science Associates, Environment Canada…). During the workshop the findings of the ASMA projects was presented. In a similar way the workshop provided input to the ASMA project regarding recent U.S. incidents involving submerged oil spills.
Review existing information from past accidents where submerged oil occurred (WP1)
WP1 / Review existing information from past accidents where submerged oil occurred

SUMMARY

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WP1 (review existing information from past accidents where submerged oil occurred)

INTRODUCTION

In order to identify the actual needs and constraints of use of techniques and means for accurately locate and dimension slicks or patches of sunken oil, precise data on spills of very heavy fuel oil (HFO) needed to be collected and subsequently analysed.

The purpose of this section (WP1) is to carry out such an approach on the spills that occurred recently in European waters as well as outside Europe. The first part of the section is devoted to the French experience with HFO and more particularly on the feedback from the recent Erika and Prestige oil spills, while the second part analyses other spills occurred in and outside Europe.

For achieving the French experience survey, Cedre made use of data available in its archives (already gathering its own Erika’s and Prestige’s data and most of data from the authorities in the frame of its archive mission on accidents specifically requested to Cedre by the French government). Cedre also identified recorded data available either in a specialised organisation like the French meteorological institute MeteoFrance involved, moreover in the weather forecast, in oil spill modelling or in French Navy and in Customs (for aerial surveys), the Maritime affairs (for fishing bans or for alerts on possible sunken oil), as well as, operational teams involved in sunken oil recovery operations (Appendix 1).

The main difficulties for getting external reliable information is that, most of the time, no reports are available since operational teams don’t use to draw detailed report on spill controls as well as on pollution follow up and even less on observations or facts done during them; so, only words have generally been reported several years later when it was possible to contact the people involved who very often moved.

Because one often says that polluted seabirds wash ashore prior the oil deposits, announcing somewhere the coastal oil pollution, potential links between oiled seabirds arrivals and oil deposits on the shoreline have recently been tested through a comparative agenda of oil arrivals and of oiled seabirds in the case of the Prestige spill.

For achieving the worldwide overview, Cedre carried out a literature review and had direct contact, notably via meetings and workshops, for getting complementary information.
Some accidents involving HFO occurred in French waters: the *Tanio* tanker (1980) that sank in the Channel, the *Vista Bella* oil barge (1991) that sank in the Caribbean waters, examples to which can be added the *Gino* tanker (1979) that sank off the western Brittany coast with its cargo of 40,000 tons of Carbon Black Oil. Whenever relevant information is available, the main facts for those past events are summarized in another section -along with other spills occurred in the world (see specific descriptive files in part II).

More recently, the French waters were badly affected by two other accidents involving HFO that submerged under the sea surface before washing ashore and locally sunk: the *Erika* oil spill (Bay of Biscay, France, 1999) and the *Prestige* oil spill (off Galicia coast, Spain, 2002). Hereafter are summarized some problems which emerged during those two recent incidents, regarding fate and behaviour of the oil, as well as various aspects of the response at sea (detection, drift-forecasting…).

### I-1 THE *ERIKA* OIL SPILL

The main points related to the incident, to the detection and tracking of oil at sea, etc., are briefly reported hereafter. For more details, see appendix 2, featuring a chronology of events during the first two weeks after the *Erika* broke in two parts (December 12th, 1999). This chronology is based upon the daily reports drafted by Cedre’s Emergency Department along the crisis.

#### I-1.1) Overview of the incident

On 11th December 1999, the Maltese tanker *Erika*, laden with 31,000 tonnes of heavy fuel no.6, en route from Dunkirk (France) to Livorno (Italy) in very rough sea conditions (westerly wind, force 8 to 9, with 6 m swell), was faced with structural problems off the Bay of Biscay. After sending an alert message, then proceeding to transfer cargo from tank to tank, the captain informed the French authorities that the situation was under control and that he was heading to the port of Donges, at reduced speed. On the 12, at 6:05 am he sent a Mayday: the ship was breaking in two.

A rescue operation was immediately launched and the crew was winched to safety by French Navy helicopters, backed up by Royal Navy reinforcements, in extremely difficult conditions. The *Erika* split in two at 8:15 am (local time) in international waters, about thirty miles south of Penmarc’h (Southern Brittany). The quantity of oil spilled at that time was estimated between 7,000 and 10,000 tonnes.

The bow sank the following night, a small distance away from the place where the ship had broken up. The stern was taken in tow by the salvage tug *Abeille Flandre* on 12 December, at 2:15 pm, to avoid it drifting towards the French island of Belle-Ile, and it sank the following day at 2:50 pm. The two parts of the wreck ended up 10 km apart from each other, 120 m deep.
I-1.2) Detection of oil at sea

Method / technique:
During the Erika spill, the main method used for detection of oil at sea was **aerial surveillance**. Plane surveys were conducted by French Customs and French Navy. Satellite (SAR) images were not suited for detecting oil slicks because of the nature of the pollutant, which did not form an oil film -and thus not dampened capillary waves on the sea surface. Also, the bad weather (clouds) did not allow for slicks observation. Aerial surveys were planned twice daily, in order to provide updated slick location and thus to account for the oil trajectory.

Outcomes:
Floating oil slicks have been located by aerial surveys since the early stages of the spill –that is in the morning of December 12, 1999, when the Erika broke up in two and began to release its cargo. These observations by plane also allowed for **dimensioning** the surface of the slick, a basis for rough estimation of the quantity of released oil (according to different thicknesses hypothesis) on the first day of the spill.
From the day after the Erika broke up, “new” slicks have been detected from one day to another by successive aerial surveys. On several occasions, a given slick -or group of slicks- could be relocated, allowing estimates of their **trajectory**.

Difficulties:
However, relocating oil slicks proved to be impossible other than on a short term (a few days to the best), because of their **fragmentation** in smaller objects (mats, pancakes) in the course of the weathering process, and also most probably because of **submersion** of emulsified heavy fuel oil. It is probable that the latter phenomenon was enhanced by the rough weather conditions at sea (that is, turbulent waters) prevailing in the weeks after the incident.
Fragmentation of the heavy fuel oil slicks was observed since 5 days after the Erika sank, although this phenomenon increased notably on the 2nd week after. As a consequence, several slicks were ‘lost’ from one aerial survey to another (for example between December 23 and 24).
Also, from the third day after the tanker broke, follow-up of groups of oil slicks by aerial surveillance suggested that part of the heavy fuel was submerging. Indeed, this hypothesis was supported by the obvious decrease, noticeable from one overflight to another (for example between the morning and afternoon on December 15th), of the amount of floating oil visible in a given area.
Aerial surveys permitted to cover large areas, and actually provided useful results: for example, they allowed for updated mapping of the pollution –which was useful for the response operations. They also provided input data for modelling (see § I-1.4 and § I-3). Nevertheless, visual detection results were strongly dependant on meteorological conditions, which allowed or not the overflight, and also which dictates the visibility of floating oil. In the case of the Erika spill, bad conditions at sea eventually prevented overflights to be conducted on some days.
As regards to the characteristics and behaviour of the heavy oil at sea, visual detection by plane surveys was impeded by the fragmentation of the slicks (numerous small objects) and, in the same time, of probable submersion of oil thus drifting under the sea surface. As mentioned earlier, these processes were enhanced by rough weather conditions at sea (stormy wind, waves…).

I-1.3) Fate and behaviour of spilled oil
The spilled oil was a heavy fuel oil (similar to HFO N°6), with a density close to that of the sea water, and very viscous (> 20 000 cSt at 10 °C). Regarding response decisions, these characteristics clearly pointed out, in the early stages of the spill, that chemical dispersion was not an option. Also, it indicated that the oil would have low evaporation rate, and low potential for natural dispersion.
<table>
<thead>
<tr>
<th>Heavy Fuel Oil N°6 (Erika)</th>
<th>Initial viscosity (at 10 – 11°C)</th>
<th>43 000 cSt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Density</td>
<td>0.996</td>
</tr>
<tr>
<td></td>
<td>Saturated hydrocarbons</td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td>Aromatic hydrocarbons</td>
<td>48%</td>
</tr>
<tr>
<td></td>
<td>Resins</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td>Asphaltenes</td>
<td>8%</td>
</tr>
</tbody>
</table>

Analysis of the initial characteristics of oil spilled by the *Erika* tanker (performed at Cedre's laboratory).

According to these characteristics, the formation of a thick, viscous, dense water-in-oil emulsion was expected, showing a high specific gravity that could enhance the submersion of the oil. Given the harsh conditions at sea (stormy winds with 6 to 8 meters waves), a fragmentation of slicks into pancakes / mats / pellets, was also expected.

These hypothesis about weathering and behaviour of the spilled oil were tested on samples of the oil transported by the *Erika* at Cedre facilities, from the day after the tanker sank (see appendix 2). An experimentation performed in a flume, starting from December 13th, showed that the heavy fuel oil:
- didn’t disperse naturally in the water mass;
- was forming a very viscous water-in-oil emulsion, containing up to 50 % water and with a viscosity as high as 200 000 cSt after 48 hours;
- in the experimental conditions, oil slicks were floating and showed little fragmentation.

These early statements were coherent with aerial surveys results in the first days of the spill (see above § I-1.3) reporting floating slicks that began to fragment from the 5th day approximately. During the second week after the accident, the then very thick (up to 30-40 cm) emulsion continued fragmenting. The water amount in the emulsion sampled *in situ* was somewhat lower (25 %) than in the emulsion at Cedre’s laboratory.

### I-1.4) Oil drift modelling and forecasts

During the *Erika* spill, the drift of oils slicks was forecasted by using the *Météo-France* (French national weather service) trajectory model MOTHY (“*Modèle Océanique de Transport d’Hydrocarbures*”). Atmospheric input data (winds, sea level pressure…) were provided by an atmospheric model, that could be the IFS model (*European Centre for Medium-Range Weather Forecasts*) or the ARPEGE model (*Météo-France*). Retrospective lessons learnt from the *Erika* spill modelling using this model can be found in § I-3.

The model was run as soon as the *Erika* broke up and began to release its cargo, on December 12, 1999. The starting point used for this first simulation was the position of the wreck. From that day, actual slick locations provided by aerial surveillance were used as input data for running the model on a daily basis.

In the early stages of the spill, some discrepancies were eventually noted between forecasted and later observed oil slicks location at sea especially regarding the longer term predictions (> 3 days). This emphasized the interest to run the model with recalibrated oil slicks location, as much as possible. That was achieved by using the most recent results provided by aerial surveys (twice daily updated observations of slicks location). From December 21 (9 days after the *Erika* broke up), the MOTHY model was run twice daily: in the afternoon and in the evening -respectively using the observations reported on the morning and in the afternoon.

During the first 2 weeks of oil drifting at sea, the forecasts provided on a given day by the MOTHY model were generally coherent with the observed distribution of oil slicks the days after. For example, on the first 3 days of the spill, daily forecasts indicated drift towards East-South East, though no stranding on the shoreline was to be expected at least in the first 5 days after each simulation. These previsions were relatively in accordance with observations provided by aerial surveys.
During the second week of the spill (for example between December 22 and 24), forecasts at a 4 days term were indicating that oil was susceptible to wash ashore in various areas, starting from December 25 and/or 26. Those stranding events were to be confirmed on Belle-Île Island and on the shorelines of Loire-Atlantique district on December 25. Nevertheless, unpredicted arrivals of oil happened two days before (Dec. 23 and 24) on the coastlines of Vendée and south-Finistère. These unexpected events were probably due to oil slicks that could not be visually detected during aerial surveys.

Drift modelling proved to be an interesting tool, providing useful information, such as guiding antipollution vessels on areas with oil slicks concentrations. As a matter of fact, there was a feedback between modelling results and aerial surveys: the first were used to determine the areas to cover during the next plane surveys; the latter provided updated slick locations for running the model.

I-1.5) Sunken oil detection and recovery

After the Erika spill, fishermen stated oiling of fishing devices (traps, nets…) locally, a nuisance then accounted on submerged and/or sunken heavy fuel oil patches. This reportedly occurred close to the shoreline, in waters less than 10 metres depth. However, these sources of information were very often imprecise as regards to the exact location and amount of such suspected sunken oil. In order to verify those assertions, some underwater surveys were eventually conducted by fire fighters-divers. Still, no oil was detected on the sea floor during these operations. Due to continuing reports about sunken patches, Total decided to finance an official survey campaign in-and between- areas that were reportedly polluted by submerged heavy fuel oil. Those surveys were achieved by local professional divers with good knowledge of the surroundings. They were in charge of checking any suspect form/object that was eventually detected on the bottom by means of a subsmerisible remote operated video device. It’s finally turned out that substantial amount of oil effectively deposited locally in shallow water areas surrounding Belle-Île Island.

The accumulations of sunken oil were found near shore in small embayments on sandy substrates at depths ranging from 5 to 12 metres. The weathered fuel oil was recovered mostly manually by divers. For the record, a few tests with a yet experimental air-lifted recovery system were also carried out.

Left: Patches of sunken oil mixed with sandy substrates in the surroundings of Belle-Île Island. Right: manual recovery by divers (Photos: © Yves Gladu)

I-2 THE PRESTIGE OIL SPILL

The main points related to the incident, to the detection and tracking of oil at sea, etc., are briefly reported hereafter. For more details, see appendix 3, featuring a chronology of events (based upon the daily reports drafted by Cedre’s Emergency Department) during the first two weeks after the Prestige began to leak oil.
I-2.1) Overview of the incident

On 13\textsuperscript{th} November 13\textsuperscript{th} 2002, the single-hulled oil tanker \textit{Prestige}, flying the Bahamas flag, sent a distress call offshore in the region of Cape finisterre (Galicia, Spain). The tanker, carrying 77 000 tonnes of heavy fuel oil loaded in St Petersburg (Russia) and Ventspils (Latvia), was heading to Singapore via Gibraltar. The vessel developed a reported 30 degree starboard list whilst on passage in heavy seas and strong winds and hence requested partial evacuation of the crew. The captain, the first mate and the chief mechanic stayed onboard. The engine was damaged and the ship went out of control and drifted according to the weather conditions. Aerial observation revealed a fuel leak at sea. All night long, four tug boats from SASEMAR (\textit{Sociedad de Salvamento y Seguridad Maritima}), the Spanish organization in charge of sea rescue and pollution control, tried to take the oil tanker in tow. The emergency towing system of the ship didn’t work and the different attempts failed. The \textit{Prestige} was taken in tow by a ship from \textit{Smit Salvage} on November 14. It was towed to the north-northwest all day, and then to the south. On the 15\textsuperscript{th}, it was torn over 35 metres on the right side. On the 16th, its towing was turned to the south-west to avoid the Portuguese waters. On the 19th at 9 am, the vessel broke in two, coordinates 42°15N and 12°08W, about 130 nautical miles off the Spanish coasts, west-southwest of Cape Finisterre. At 12 pm, the stern part of the \textit{Prestige} sank at 3 500 metres depth. The bow part followed a few hours later.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{trajectory.png}
\caption{The \textit{Prestige} trajectory while it was towed (Photos: French Customs)}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{sinking.png}
\caption{The stern section of the vessel sinking on December 19\textsuperscript{th}, 1999 (Photo: French Customs)}
\end{figure}

I-2.2) Detection of oil at sea

\textit{Methods / techniques:}

The oil was tracked throughout the entire time it was drifting in and around the Bay of Biscay and at the westernmost reaches of the English Channel, thanks to French and Spanish ship-based and aerial surveys (visual detection). Observed slick locations were then fed, along with floating buoys data, into various slick drift forecast models.

If aerial surveys were the main tools to detect and track the \textit{Prestige} spill, some attempts were also made at detecting oil slicks by using SAR (Synthetic Aperture Radar) satellite images.

*Visual detection / aerial surveys

Maps reporting the slick locations were established daily from aerial observations made by planes and helicopters, as well as from sea-based observations by response vessels. From the November 14\textsuperscript{th}, 2002 (day after the \textit{Prestige} sent a distress call), French Navy and French Customs planes were collaborating with SASEMAR in the framework of the Biscay Plan (cooperative agreement between Spain and France in case of an oil spill in the Bay of Biscay area).

The first slicks were detected from November 14\textsuperscript{th} (while the \textit{Prestige} was towed), located and dimensioned by plane surveys. From then on, overflights were conducted daily and allowed to (re)locate slicks drifting at sea –either near the coastline or leaking from the distressed vessel.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{sailing.png}
\caption{The \textit{Prestige} trajectory while it was towed (Photos: French Customs)}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{sinking.png}
\caption{The stern section of the vessel sinking on December 19\textsuperscript{th}, 1999 (Photo: French Customs)}
\end{figure}
Aerial surveys allowed detection of slicks ranging from several meters to hundreds of meters (main slicks) in diameter.

However, some difficulties were met as regards to visual detection of the heavy fuel, because the main slicks split up into many smaller ones on account of strong winds and current regimes prevailing in the area since the beginning of the incident. These smaller slicks, patches, etc., became increasingly difficult to see from the air and keep track of for the spotter planes as the tar balls broke down into even smaller tar balls that either floated on the water surface or tended to drift around in the upper layers of the water column throughout the entire Bay of Biscay. On many occasions in the first week of the spill (last days of November), oil slicks that were spotted during the morning overflights could not be relocated in the afternoon, most probably because of submersion due to the density of water-in-oil emulsion. This illustrated the difficulty to track such heavy oil spills by visual surveys (from aircrafts as from ships).

Moreover, as during the *Erika* spill, stormy weather conditions and bad visibility punctually hampered aerial surveillance, and thus impeded tracking slicks trajectory at sea. For example, on November 20th (the day after the *Prestige* sank), oil slicks that had been spotted in the morning could not be located in the afternoon by French Customs plane *Polmar 2*, because of adverse meteorological conditions (winds ranging between 40 to 50 knots, in very rough sea).

Note that, in order to locate drifting slicks to guide response vessels towards the intervention areas, the fishermen’s guild of the Basque Country adapted a method used to locate fishes. A plane covered the area by going back and forth perpendicularly to the coast, pointing out on a GPS system the observed hydrocarbon accumulations. Then the headquarters visualized on a computer screen the different spots observed and the ship location on the scene of the action. Next step was to guide by satellite phone the ships which were the closest from the work areas.

* SAR (*Synthetic Aperture Radar*) satellite images

ERS-2 and *ENVISAT* imagery were made available by ESA (*European Space Agency*) for the clean-up teams in the framework of the International Charter on Space and Major Disasters, which was activated on November 14 by the European Commission's Civil Protection and Environmental Accidents Unit to support local authorities in Spain in monitoring the oil spill. From November till the end of December, about 60 SAR images have been analysed by *Cedre*. However, no information could be retrieved from 21 of them, because of bad weather conditions or no pollution at sea. Amongst the 41 others, 2 were of particular interest, dating from the early stages of the spill while the *Prestige* was towed: November 17th (*Envisat ASAR image showing for the first and only time the oil pollution in its entirety*) and November 18th (*Radarsat*). Slicks due to the leaking wreck were observable on some of the others SAR satellite images (most notably on Nov. 25th then on Dec. 2nd and 9th) (Appendix 4).
Oil spill detection on ASAR Wide Swath image from November 17th 2002, after the Prestige tanker started to leak oil off Galicia coast (Photo courtesy of ESA).

Probable oil slicks (circled) detected on ENVISAT image from December 2nd, near the wreck area and closer to Galicia coastline (Photo courtesy of ESA).

However, observations derived from the analysis of SAR images needed to be cross-checked with data obtained from aerial and sea-based surveys (ships, aircrafts) as to avoid false interpretation due to meteo-oceanic phenomena.

Also, SAR satellite images analysis during the Prestige incident underlined that this method showed limitations as regards to detection and tracking of heavy fuel oil, because slicks tended to fragment and probably to submerge—especially in such harsh meteorological conditions.

I-2.3) Fate and behaviour of spilled oil

The Prestige’s cargo (M-100 according to the Russian terminology) was very similar to the heavy fuel oil spilled during the Baltic Carrier incident (Denmark, March 2001), characterized by an initial density (0.99) close to that of seawater and a high viscosity (615 cSt @ 50 °C). It exhibited a low potential for both evaporation and natural dispersion. In a way that is quite comparable to the Erika case, the heavy fuel was prone, once spilled, to form a very viscous water-in-oil emulsion.

<table>
<thead>
<tr>
<th>Property</th>
<th>Heavy Fuel Oil M-100 (Prestige)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density at 15°C</td>
<td>0.993</td>
</tr>
<tr>
<td>Pour point</td>
<td>+6°C</td>
</tr>
<tr>
<td>Viscosity at 50°C</td>
<td>615 cSt</td>
</tr>
<tr>
<td>Viscosity at 15°C</td>
<td>30,000 cSt</td>
</tr>
<tr>
<td>Flash point</td>
<td>143°C</td>
</tr>
<tr>
<td>Sulphur</td>
<td>2.58%</td>
</tr>
<tr>
<td>Vanadium (ppm)*</td>
<td>76</td>
</tr>
<tr>
<td>Nickel (ppm)*</td>
<td>12</td>
</tr>
<tr>
<td>Asphaltens</td>
<td>12.4%</td>
</tr>
</tbody>
</table>

Analysis of the initial characteristics of oil spilled by the Prestige tanker

On November 22nd, analyses were carried out at Cedre on an oil sample taken at sea by the Ailette response vessel on the 18th of November. The water content of this on-site weathered fuel was then of 45%. With a viscosity of 100 000 cSt at 15°C and a measured density of 1.01, the emulsion remained thick (slicks, plates or oil cakes) at the surface of the water, and under the surface in turbulent waters. Those experimental results strongly supported the hypothesis of submersion of oil slicks in rough sea, as suggested by in situ aerial observations (see § I-2.2). After several days of ageing in Cedre’s “polludrome”, the water content of the emulsion stabilized around 60%.

One of the characteristics of the Prestige spill was the extended stay of the oil at sea. During this considerable period of time, the viscosity of the heavy fuel oil increased steadily as the initial main slicks divided gradually into patches and smaller slicks. As an illustration of this fragmentation, on November 21st (3 days after the Prestige sank), an oil slick estimated to 12 000 m³ (2 nautical miles x
300 metres) was spotted and relocated 24 hours later in the form of a group of hundred smaller patches.
As a result, the spilled oil weathered at sea, fragmented and drifted seemingly forever throughout the entire Bay of Biscay before eventually landing on the beaches in France after a period of steady westerly winds, in the form of patches, small mats, pellets...

I-2.4) Oil drift modelling and forecasts
As for during the *Erika* spill, the drift of oils slicks was forecasted by using the *Météo-France* (French national weather service) trajectory model MOTHY (“*M*Ôdèle *O*céanique de *T*ransport d’*H*ydrocarbures”). Retrospective lessons learnt from both the *Erika* and *Prestige* spills modelling using this model are summarized in § I-3.

* France: setting up of a « National Drift Committee »
From November 13th, *Cedre* activated its cooperation agreement with *Météo France*, and provided drift forecast maps for the Préfet Maritime of the Atlantic, thanks to the MOTHY model. As for the *Erika* spill, oil slicks locations reported by aerial surveys were used as input data for running the model.
On motivation of the French General Secretariat for the sea, and with the addition of representatives of *SHOM* (Oceanographical and Hydrographic Service of the French navy), *IFREMER* (French Research Institute for Exploitation of the Sea) and of the Maritime Prefecture of the Atlantic, this drift forecast unit was soon expanded into a “National Drift Committee” (officially created on Nov. 25). The Committee members met every day at *Cedre* to prepare maps gathering results from the sea-based and aerial surveys (actual locations of oil at sea), as well from the drift forecast available for four days. These maps were produced daily until Mars 23rd, and occasionally beyond. Accepted as a national reference, they were intended to provide expertise about potential slicks trajectories, to anticipate the threat for the coasts in southern reaches of the Bay of Biscay, and to guide response vessels on site.

![Example of daily map (Nov. 25) provided by the French National Drift Committee to the Maritime Prefecture of the Atlantic (source: Cedre)](image)

* Portugal / Spain
On its side, from December 2, the Portuguese Hydrographic Institute produced a drift forecast chart every day. Also, from December 8, AZTI (Spanish Basque Country technology institute for fishing and food resources) provided a daily comprehensive memorandum which covered the northern coast of Spain. It included weather reports and forecasts, updated slicks positions at sea, the French Drift Committee forecast maps, as well as AZTI’s own trajectory forecasts and drift data from buoys dropped in the midst of the main fuel accumulations observed at sea.

Any time discrepancies appeared between the different forecast charts. The used reference data were cross-checked, to produce the best possible information, as a clear-cut demonstration of the advantages of direct cooperation between national institutions.
* Results / difficulties

As much as possible, the numerical drift model was run daily (or twice-daily) during the first weeks of the spill. The most recent observations available from aerial and boat surveys were used as input data.

Practically, rough meteorological conditions prevailing at sea eventually impeded visual detection of the oil, because of submersion of the emulsified heavy fuel oil as well as fragmentation in smaller patches, and/or postponed over-flights. As a result, running the model with daily updated slicks positions was not always feasible. In that case (for example on Nov. 26 and 27), drift forecasts were conducted by using the meteorological data that were recorded since the slicks were lastly spotted.

Global, it was considered that there was a good consistency between forecasted positions and the positions observed a few days later.

During the early stages of the spill (while the Prestige was towed and leaking), oil slicks stranding events along the Spanish shoreline were quite accurately forecasted. On the day the vessel broke up, the wreck position was used as the starting point for modelling the oil trajectory. Given its distance from the coast, those initial drift forecasts indicated that the oil would remain more than 90 nautical miles off the coast in a 72 hours term, and thus were unable to predict precisely where/ when subsequent stranding would occur.

* Tracking of slicks by drifting buoys

In order to complement aerial surveys, oil slicks location maps were also established by monitoring the drift data from surface and subsurface buoys. These satellite-tracked buoys have been implemented directly by SASEMAR, SHOM and AZTI or in the framework of SASEMAR/Cedre and AZTI/Cedre cooperation. On the long-term, one of the interests of using buoys was that, as weeks and months passed by, the spill became so fragmented and scattered on such a broad area that visual detection by planes was not an option anymore. Then, drift modelling results on the long-term were hardly reliable without any update about the location of remaining oil.

From December 3, surface buoys, as well as sub-surface (-15 metres) buoys, were dropped in the midst of oil slicks in various locations, such as above the Prestige wreck site or in the Bay of Biscay. The data were useful to explain how the extended stay of the oil at sea allowed for its drift on a broad geographical scale, before washing ashore -in the form of weathered mats and pellets- in the months following the incident.

I-2.5) Sunken oil detection and recovery

In order to assess the amount of oil in the water column and on the sea floor in the vicinity of the Arcachon basin, fishing boats (trawlers) were requisitioned in the framework of the French Polmar-Sea contingency plan.

Surface and subsurface trawls were conducted in the 20 miles off Cape Ferret, which is at the mouth of the Arcachon basin, a site of great concern as regards to important oyster farming activities. The sea bottoms were investigated in the first mile off coast from Lacanau to Biscarrosse, respectively located on the north and the south sides of Arcachon basin.

After the Prestige incident, the Spanish Navy was responsible for devising a Seabed Cleanup Plan, that was implemented on February 25th, 2003, in the Atlantic Islands National Park (located in Rias Baixas, off Galicia southern coast).

The detection of oil deposits on the seabed was achieved by team divers as well as by ROV directed video surveys from 15 to 30 meters depth. Removal of oil was completed manually, but also with dredgers and air-sucking extraction machinery (Ministerio de Medio Ambiente, 2005).
During the *Erika* (1999) and *Prestige* (2002) oil spills, forecasting the drift of oil slicks was performed by Météo-France (French national weather service) using the trajectory model MOTHY (which stands for “Mo**dèle** Océanique de **Transport** d’HYdrocarbures”). Hereafter are summarized some problems, as well as achievements, that were encountered during those spills as regards to identify the transport of heavy fuel oil by using this model. The main characteristics and chronology of events along the first two weeks of both *Erika* and *Prestige* crisis are summarized in the previous chapter (§ I-1, § I-2; Appendices 2 and 3).

**Main features of the MOTHY model**

The MOTHY model, which is operational since 1998, is an integrated system including hydrodynamic coastal ocean modelling and real time atmospheric forcing from a global meteorological model. According to Daniel et al. (2001; 2004), “the oil slick is modelled as a distribution of independent droplets that move in response to currents, turbulence, and buoyancy. A coupling between a 2-D hydrodynamics, limited area, ocean model and a 1-D eddy viscosity model provides currents (...). The 2-D model is driven by tide components and by winds and sea level pressure forecasts from a global atmospheric model. This atmospheric model can be the IFS model (European Centre for Medium-Range Weather Forecasts) or the ARPEGE model (Météo-France). The 1-D model assumes a bilinear eddy viscosity profile. Turbulent diffusion is modelled with a 3-D random walk technique. The buoyancy force depends on the density and size of the oil droplets (...). In general, 65 to 70 % of the droplets remain on the sea surface. If a droplet is moved on to land, then that droplet is considered beached and no further part of the simulation.”

Given the fact that the motion of an object drifting on the sea water surface is the result of a number of forces acting at the air/water interface (mainly winds and water currents), the immersed part of the floating object is a key parameter in fitness of the forecast. Unfortunately, this parameter is often -if not usually- unknown. This is an important issue when it comes to an oil spill involving heavy products prone to sink and/or to form slicks drifting in subsurface. Indeed, the *Erika* and *Prestige* oil incidents are examples of spills that involved heavy fuel n°6. In both cases, the MOTHY model has been used in order to forecast the transport and fate of oil, with various results—good and less good.

The MOTHY model was used routinely for several weeks after the *Erika* broke up, and for several months in the case of the *Prestige* spill. Daily accurate positioning of the oil slicks was needed as input data for running the MOTHY model. But, during the *Erika* oil spill, satellite (SAR) images proved somewhat inadequate for detecting oil slicks because of the nature of the pollutant, which did not form an oil film on the water, and thus was not cancelling capillary waves on the sea surface (Daniel, 2001). Moreover, the bad weather did not allow for slicks observation. Thus, actual oil slicks locations were provided by over flights. These aerial surveys were performed twice a day by the French Customs service “Polmar” airplane, and the data (location of oil slicks at sea) were transmitted to Météo-France through Cedre. In the case of the *Erika* spill, Météo-France performed simulations of the oil slick trajectory from December 12th to December 25th, 1999. Up to two forecasts per day were performed starting from December 21th; each simulations using as input data the most recent slicks location at sea (aerial surveys).

**I-3.1) An illustration of achievements and gaps**

Two days after the *Erika* broke up in two parts, six long-term MOTHY forecasts (up to 10 days) were carried out using six different atmospheric previsions (provided by the IFS global atmospheric model) as forcing variables, and using the slick position observed on December 13th. These atmospheric previsions were selected from a set of 51 forecasts, because they were considered as the most likely and representative of each alternative scenario. None of the six MOTHY long-term forecasts indicated oil landing for the next 10 days (up to December 23th), an this information proved very useful for response organization (Daniel et al. 2001).
Then, during the two weeks after the spill, forecasts were carried out daily by Météo-France, based on aerial positions transmitted to Cedre. Generally, the oil slick locations reported on a given day by airplane surveys showed a good consistency with the forecasts performed by running the numerical model with the most recent observations at sea (i.e. actual oil slicks locations the previous day).

The MOTHY model predicted that the coastline was at risk and that the beaching of the main slicks released by the Erika would occur after 2 weeks at sea (approximately December 26th). Actually, on December 21st, aerial observations reported a group of 13 slicks, located at 105 km off the coasts of Belle-Île and 72 km off Yeu Island. These locations were transmitted to Cedre, who defined a zone (polygon) including these slicks. The geographical coordinates for the extreme points outlining this polygon were then transmitted to Météo-France to be used as input data for running the MOTHY model. According to this method, impacts on the shoreline of Belle-Île island and on the continent (Loire-Atlantique: Le Croisic and mouth of the Loire River) were then forecasted on the nights of 24-25th and 25-26th December, respectively. Those forecasts were confirmed with first records of landing of heavy fuel slicks in the concerned areas.

However, some stranding occurred that were not forecasted by the model, both in time (1 or 2 days before the main slicks) and space (200 km east of the main beaching locations). This discrepancy was later explained by the fact that, due to bad weather conditions prevailing at sea, a number of oil slicks leaking from the wreck could not previously been spotted by aerial surveys.

Hind cast runs and backwards integration of the model supported the hypothesis of undetected continuous releases from the Erika. This underlined the importance of adequate oil slicks location data, thus the need for efficient slick observation and detection means/techniques.

**I-3.2) Summary of lessons learnt:**

The Erika and Prestige incidents showed the usefulness of a tool allowing forecasts of slick drift, particularly towards the decision-making for the authorities in charge of the response at sea. As a matter of fact, if that tool proved to be quite satisfying, some aspects have been put into light, as regards to the adequacy of input data and the constraints generated by the characteristics of heavy fuel.

* Need for oil slicks observation means/techniques
The Erika and Prestige oil spills underlined the necessity of means and techniques for obtaining and transmitting **accurate and regularly updated information about the actual oil slicks location at sea**. In this case, this point proved crucial to provide relevant data for the numerical model, thus to obtain forecasts of the oil slicks drift that were precise and useful for the response operations, both at sea and on the shoreline.

For example, landing events that were not predicted, due to the fact that some heavy fuel oil slicks were not observed (most probably because of bad weather), emphasizes a need to develop **accurate observation/detection means**.

* Need for accurate forcing variables:
Moreover, both the Erika and Prestige wrecks were quite remote from the shoreline. This increased the duration/exposure of the heavy oil to meteorological parameters at sea, thus the sources of uncertainty in the modelling results (Daniel, 2001), and then again the need for running the drift model with regularly updated slicks locations. The extended stay of the oil at sea also implied that the **accuracy of the forecasts relied heavily on the accuracy of the meteorological/forcing parameters** ran into the model. This applies to the forecasted parameters (wind and sea pressure level, provided by atmospheric models IFS or ARPEGE), as well as the measured parameters (real-time acquisition of on-going conditions at sea).

* Constraints linked with heavy fuel oil characteristics / weathering:
The physical and chemical properties of the pollutant generated some specific constraints, in particular because of its high viscosity and proneness to fragment and to form numerous slicks. Furthermore, this process was enhanced by meteorological conditions. **This fragmentation induced a multiplication of**
the items that needed to be taken into account all along the crisis (i.e. oil slicks to be reported and followed-up from day to day, by airplane surveys in this case) (Daniel, 2001). The same process was also reported during the Prestige incident, when slicks of heavy oil gradually broke into patches, pancakes, pellets, as the product weathered at sea (sometimes for a few months before stranding on remote shorelines).

Thus, one of the lessons learnt from the Erika and Prestige spills was that it seems desirable to develop / improve techniques allowing the follow-up of many heavy fuel slicks at sea.

Also, Erika and Prestige oil spills illustrated the need to detect and monitor submerged oil slicks. It is highly probable that the unexpected arrivals of heavy fuel onshore resulted in part from movements of undetected oil whether deposited on the sea bottom or floating below the seawater surface. Supporting this hypothesis, the great quantity of oil stranded onshore between December 23 and February, after the Erika incident, is difficult to explain only by the quantities observed at the sea surface. This strongly suggests a drifting, underneath the sea surface, of submerged oil slicks. According to Daniel et al. (2002), the heavy fuel spilled by the Erika started to sink a few centimetres under the surface on December 17 (i.e. five days after the vessel broke in two parts).

I-3.3) Overview of improvements:

* ... On the drift model

Since the Erika oil spill, Météo-France, in collaboration with Cedre and IFREMER, has been working on improvements of the MOTHY model, including:

- Comparison with other hydrodynamic models (MARS-3D, OPA…)
- Evaluation of currents from altimetry
- Effects of waves
- Better account for the various meteorological events (e.g. storm) that may occur punctually during the course of the spill

For the Prestige oil spill, a first attempt was also made at taking into account currents at a larger scale that that offered by MOTHY. Then, larger scale currents provided by a 3D ocean general circulation model named MERCATOR were integrated in MOTHY (Daniel et al., 2004; 2006). In short, the simulations were a result of both MOTHY’s surface drift modelling and MERCATOR’s large scale current (103 m depth). Although of relatively low impact during the first days of the Prestige spill, this approach proved useful at refining forecasts on longer-term simulations.

Also, it could be helpful to integrate in numerical models some key parameters about the behaviour of the spilled oil, according to its properties. In particular, evaluation of the weathering processes of heavy fuels may provide useful indications about the fate of oil (sinking, fragmentation…), and could contribute to achieve better forecasts/results. Since the Erika and Prestige spills, studies have been carried out as regards to the inclusion of an oil weathering model into the forecasting system MOTHY (Comerma et al., 2003).

A regards to improving knowledge on the oil behaviour/weathering process, Cedre conducted some tests about the weathering pattern of spilled oil, using its experimental facilities (amongst which a circular hydrodynamic flume –or “Polludrome”). For example, during the Erika crisis, the results showed that after 1 day in seawater, the fuel oil was still floating despite its density, and the slick began to break up and to form a very viscous (70,000 cSt) water-in-oil emulsion with 30 % of water. After 2 days, the emulsion contained 50 % water. Those results, together with analysis of samples of oil in situ, gave indications for the response at sea, as regards to chemical dispersion (which was not an option) or containment and recovery (that was considered feasible, although difficult).

* ... On the organizational level

On an organizational point of view, in case of an accidental marine pollution, improvements in the field of the information/communication technologies are valuable in the transmission of frequently updated data (e.g. aerial surveys, meteorological parameters…). Towards this end, in the eve of the Erika spill, it was suggested that a dedicated network can contribute efficiently to saving time as well
as reducing losses of information. For example, during the *Erika* oil spill, it happened that some predictions maps produced by *Cedre* after the latest MOTHY results could be made available too late to be used for the Navy authorities in charge of planning the observations flights the following day. This was due to excessive delays, both in the transmission of information needed to run a simulation (from French Navy and C.R.O.S.S. to *Cedre*, then to Météo-France) and in the returning of the results. Such a situation can result in collecting incomplete information (aerial surveys missing areas with oil slicks and vice-versa), potentially with dramatic consequences as regards to response options.

During the *Prestige* oil spill, these organizational aspects were addressed by the setting up of a *National Committee for Drift Forecasting*. As described in another section (see § I-2.5), this multi-agencies committee was in charge to provide daily the Préfet Maritime with comprehensive and updated information about both observed and modelled oil drift (*Cedre*, 2004). Daily maps were produced, combining (i) information about the oil drift as forecasted by MOTHY model, (ii) on-site drift monitoring data provided by surface buoys dropped in the oil slicks, and (iii) updated results about actual slicks locations provided by both aerial (planes) and sea based (ships) observations.

Summary

During the *Erika* and *Prestige* spill, the utilization of the model was useful, but not ideal. Firstly, MOTHY -being a 2-D model is probably limited in forecasting the drift of submerged/sunken heavy oil slicks.

Secondly these recent experiences highlighted the need to use regularly updated/validated locations of slicks at sea as input data. In both cases, bad weather conditions added to the difficulty in aerial observations, but the probability for heavy oil drifting in subsurface underlines the need to develop tools and methods to detect and monitor submerged slicks in order to be able to use their accurate positions in drift models.

Also, integration of heavy oil weathering process in drift models seems to be desirable towards enhancing the accuracy of forecasts. In the case of the *Erika*, this remark does not apply only to the
changes in density/emulsification, but also to the ability of the dense slicks to break up into small fragments which behaviour and movements is quite different from the one of large slicks (tens, hundreds meters).

I-4 RELATIONSHIP BETWEEN SEABIRDS AND OIL ARRIVAL ON THE SHORELINE

Because the arrival at shore of materials drifting at the surface (or in the upper layer of the water column) is closely dependant on wind direction and speed, it is often suggested that, in case of an oil spill, stranding events of dead/dying seabirds (or mammals) may be a reliable indicator of the presence of oil slicks drifting offshore (at, or underneath, the surface) and thus of forthcoming oil deposits on the coastline.

To our knowledge, no attempt has been made to test/verify this assertion in the case of the *Erika* oil spill, which was followed by an estimated beaching of 74 000 oiled birds (including dead and live specimens; Cadiou et al., 2004). That being said, during the second week of this spill, arrivals of oiled birds on the shoreline were reported as preceding oil washing ashore.

On the other hand, studies have been carried out in retrospect of the *Prestige* incident (Castege et al., 2005), a spill during which more than 23 000 oiled birds have been collected (with more than 2 800 in France).

This study aimed at assessing the relationship between:
- meteorological data (provided by *Météo-France*) such as wind (speed, direction) and swell (height, mean period, direction) parameters;
- amounts of hydrocarbons collected daily along the coastline (provided by *Cedre*);
- daily records of oiled beached birds – dead and live (provided by DIREN Aquitaine);

The correlation between oiled birds beaching and heavy fuel oil arrivals was examined by conducting Principal Components Analyses (PCA), applied to the abovementioned data from 1st January to 31st March 2003 along the Aquitaine coast (south of France). This 3 months period runs from the first records of oiled birds on this section of the coast to the closing down of rehabilitation centres. Daily variations of some of these data are represented below.

In short, the main results regarding this analysis were that:
- Wind descriptive variables (speed and direction) were strongly correlated with arrivals of both oil and birds on the coastline, while swell variables explained a lesser part of the total variance.
- On a given day, beached birds were significantly related with the wind measured the very same day. Oil arrivals were significantly correlated with wind data cumulated over the 7 previous days; Patterns of daily arrivals of oiled birds were significantly related to those of oil deposited onshore 8 days later.

It was then concluded that the beaching of oiled birds preceded the stranding of oil by 8 days, from January to March 2003 in south of France during the Prestige spill. As often observed and stated in previous spills, the authors suggest that these results confirm that beached birds can be used as indicators of the presence of oil drifting offshore (eventually washing ashore –depending on the wind regimes during a more or less important time scale).
WP1.II – ANALYSIS AND FEEDBACK OF INCIDENTS INVOLVING SUBMERGED OIL OCCURRED IN THE WORLD

II-1 INCIDENTS THAT INVOLVED SUNKEN/SUBMERGED OIL: FILES

A literature review has enabled to sort out 21 incidents involving submerged/sunken heavy fuel oil (HFO). These accidents are presented in this section, in the form of individual files summing up the main facts describing the conditions of the accidents as well as the operations carried out for monitoring and detecting the non-floating oil (sunken as well as submerged oil), and eventually the recovery methods.

As previously stated by various authors (for example Michel et al., 1995), very little information is available regarding response to oils that sink or remain neutrally buoyant in the water column. Thus, the spills reported in this section do not constitute an exhaustive review of incidents that involved submerged oil, but rather examples that were documented enough as regards to various topics such as the circumstances of the spill, fate of the oil, submerged / sunken oil detection, recovery methods…

Note also that some spills that occurred in freshwaters have been included here, provided sufficient information was available. Indeed, if the processes by which the oil may submerge or sink may differ between freshwater and seawater spills, it appeared that the problematic and methods as regards to detection and recovery methods are very close, if not identical.

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**SS Sansinena**

- **Date of incident:** December 17, 1976
- **Location:** San Pedro Harbour, Los Angeles, California, USA.
- **Type of oil:** Bunker C
- **Amount of spilled oil:** 1,260,000 gallons
- **Event:** While refuelling, berthed in LA harbour, the vessel suffered an explosion, caught fire and sank -loaded with 22,000 barrels of bunker oil. The explosion occurred after explosive vapours were emitted from the cargo tank vents, in a still-air situation. A pipeline was also wrecked during the incident, thus contributing to the spill.
- **Spill features:** A part of the oil burned after the incident, and the residue deposited on the bottom at a 50 feet depth. Reportedly, the majority of the spilled oil -heavier than water- sank right after the vessel’s tanks were damaged. Heavy oil formed pools into crevices and depressions on the bottom.

**TECHNOLOGIES / METHODS FOR SUBMERGED OIL DETECTION & MONITORING:**

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diving visual surveys</td>
<td>- Allowed assessment of the extent and form of deposited oil.</td>
</tr>
</tbody>
</table>

**DRIFT ASSESSMENT / FORECAST:**

Modelling of the drift: **NO**

**SUBMERGED OIL RECOVERY METHODS / TECHNOLOGIES:**

- Mechanical recovery: Divers directed pumping device, connected to a barge (a suction head with an hydraulically driven screw-type progressive cavity pump mounted on top of it).

**REFERENCES:**

NOAA’s website at: [http://old.incidentnews.gov/incidents/history.htm](http://old.incidentnews.gov/incidents/history.htm)  
### Eleni V

- **Name:** Eleni V
- **Vessel:** Tanker ship
- **Date of incident:** May 6, 1978
- **Location:** North Sea, off Norfolk, UK
- **Type of oil:** Heavy fuel oil
- **Amount of spilled oil:**
- **Event:** The oil tanker *Eleni V* was sailing in thick fog from Rotterdam to Grangemouth with a load of 12,000 tonnes of heavy fuel oil. The French bulk carrier *Roseline* ran into her about 10 km off Norfolk coast in the North Sea. The bow section of the *Eleni V* was punctured and subsequently released about 5,000 tonnes of heavy fuel oil. The stern was successfully towed to Rotterdam where the remaining cargo was lightered.

- **Spill features:** The spilled oil was very viscous, and initially formed huge slicks that fragmented and drifted at sea, under the water surface as it weathered. It ultimately stranded on English and Dutch coastlines as thick pancakes (sized up to 12 inches in diameter) and/or globules of viscous “mousse”. Also, it was later suggested that some stranding events on Dutch shores came from the bow of the *Eleni V*, which had been towed several miles offshore to be blown up 24 days after the incident.

### Technologies / Methods for Submerged Oil Detection & Monitoring:

[No information found about detection & tracking of submerged oil]

### Drift Assessment / Forecast:

**Modelling of the drift:** YES. Trajectory models (most probably 2D) were used in order to help identifying the origin of the oil that washed ashore on Dutch coastline.

### Submerged Oil Recovery Methods / Technologies:

- No information

### References:


*NOAA’s website at: [http://old.incidentnews.gov/incidents/history.htm](http://old.incidentnews.gov/incidents/history.htm)
**GINO**

- **Name:** Gino
- **Vessel:** oil tanker
- **Date of incident:** April 28, 1979.
- **Location:** Off Ouessant island, Brittany, France
- **Type of oil:** Carbon black oil
- **Amount of spilled oil:** 32 000 tons
- **Event:** The Liberian oil tanker Gino, loaded with 40 000 tonnes of carbon black, was en route from Port Arthur (Texas) to Le Havre, when it collided with the Norwegian oil tanker Team Castor in foggy conditions. The Gino sank with its cargo at 120 metres depth while an estimated 1 000 tonnes of oil were spilled from a damaged tank on the Team Castor. Investigations were subsequently conducted as regards to the amount of remaining cargo in the Gino tanks.

- **Spill features:** Carbon black oil is a refined product 1.09 times denser than water, which thus spread in very viscous slicks on the sea bottom in the vicinity of the wreck, not reaching the surface. Side-scan sonar surveys and visual surveys were conducted by French Navy, as well as wreck inspections. It was estimated that about 75 % of the cargo had leaked from the tanks.

**TECHNOLOGIES / METHODS FOR SUBMERGED OIL DETECTION & MONITORING:**

<table>
<thead>
<tr>
<th></th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side-Scan sonar</td>
<td>Allowed for detection and tracking of the oil slicks movement and fragmentation on the bottom. Conducted bimonthly.</td>
<td></td>
</tr>
<tr>
<td>Trawled underwater camera</td>
<td>Allowed for visual confirmation/completion of results provided by the side-scan sonar method.</td>
<td></td>
</tr>
<tr>
<td>Underwater video surveys with submersibles</td>
<td>- Allowed identification of leaks from the tanks, and of thickness of oil on the bottom</td>
<td>- Operations relying on weather conditions - Costly. One-off operations rather than a ‘survey’.</td>
</tr>
<tr>
<td>Grab samples</td>
<td>- First rough identification of the slick.</td>
<td>- Limited outcomes when patchy distribution of oil</td>
</tr>
</tbody>
</table>

**DRIFT ASSESSMENT / FORECAST:**

*Modelling of the drift:* NO

**SUBMERGED OIL RECOVERY METHODS / TECHNOLOGIES:**

None

**REFERENCES:**


**M/V Alvenus**

The M/V Alvenus leaking oil in Cameron, Louisiana, July 1984 (Photo credit: NOAA).

- Name: M/V Alvenus
- Vessel: Tank vessel
- Date of incident: July 30, 1984
- Location: Calcasieu River Bar Channel, Cameron, Louisiana, USA
- Type of oil: Venezuelan Merey (medium crude) and Pilon Crude (heavy crude)
- Amount of spilled oil: approx. 2.7 M gallons
- Event: Grounding and hull rupture near tanks. The resulting spill was pushed ashore by strong winds.
- Spill features: An amount of oil estimated between 1 000 and 1 500 tons adsorbed onto suspended sediments nearshore, and then sank in the surf zone where it was trapped between successive sandbars and trenches.

### Technologies / Methods for Submerged Oil Detection & Monitoring:

<table>
<thead>
<tr>
<th></th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerial Surveys</td>
<td>- Provided actual oil slick positions.</td>
<td>- Efficient for floating oil only</td>
</tr>
<tr>
<td>Diving surveys</td>
<td>- Allowed for identification of the extent, form and approximate quantity of nearshore submerged oil.</td>
<td>- Time costly (low area coverage)</td>
</tr>
</tbody>
</table>

### Drift Assessment / Forecast:

**Modelling of the drift:** YES. Use of both existing and forecast weather and current conditions as input data for a trajectory model (processed by NOAA’s Scientific Support Coordinator).

### Submerged Oil Recovery Methods / Technologies:

- Mesh screening
- Pumping (high capacity vacuum truck)

**Remark:** none of these techniques proved effective. Submerged oil progressively moved onshore within a two weeks. An unknown quantity mixed with sand and remained buried in sediments.

### References:


**NESTUCCA**

- **Name:** Nestucca
- **Vessel:** Tank barge
- **Date of incident:** December 23, 1988.
- **Location:** 3 km off the coast of Grays Harbor, Washington, USA
- **Type of oil:** Heavy Fuel N°6 (Bunker C)
- **Amount of spilled oil:** 231,000 gallons
- **Event:** During replacement of a broken tow line, the barge Nestucca collided with its tug. Heavy Fuel spilled from a barge’s damaged tank.

- **Spill features:** The heavy oil formed tar balls / mats that drifted below the water surface thus could not be tracked visually. During the first days after the incident, initial estimates underrated the amount of oil spilled, as only sheens and small globules could be detected at sea. Nevertheless, 2 weeks after the spill, weathered fuel stranded as far as Vancouver Island (British Columbia, Canada), 175 kilometres north of the release site. These events were unexpected since there was no tracking means as regards to submerged oil slicks. Up to 10,300 oiled wintering birds were collected dead or alive in Grays Harbor area.

**TECHNOLOGIES / METHODS FOR SUBMERGED OIL DETECTION & MONITORING:**

[No information found about detection & tracking of submerged oil.]

**Remarks:**
- Aerial surveys of the surface were conducted, but they proved unable to visually detect submerged oil, which remained mostly unsuspected until it washed ashore in Canada.
- This incident demonstrated the importance of early and accurate detection and tracking of the oil at sea. In this case, incorrect / insufficient assessments hampered response operations, and the need for a better and early detection of the slicks was one of the lessons learned.

**DRIFT ASSESSMENT / FORECAST:**

- **Modelling of the drift:** NO.

**SUBMERGED OIL RECOVERY METHODS / TECHNOLOGIES:**

- None

**REFERENCES:**

**T/V Presidente Rivera**

- Name: Presidente Rivera
- Vessel: 749 ft. tank vessel
- Date of incident: June 24, 1989
- Location: Delaware River, south of Marcus Hook, Pennsylvania, USA.
- Type of oil: Heavy Fuel Oil #6
- Amount of spilled oil: > 300,000 gallons
- Event: The Uruguayan tanker Presidente Rivera ran aground in the Delaware River while preparing to dock at a refinery. Four of its 17 tanks opened and released approximately 306,000 gallons of highly viscous oil. The tanker was later refloated and unloaded.

- Spill features: The N°6 fuel oil spilled formed a thick coating upon contact with the shoreline, sticking in globs rather than forming extensive slicks, and a part of it eventually sank after having picked up sediments. Also, due to low water temperature (< oil pour point) and a high density, the spilled oil drifted as large masses in the water column, maintained under the surface by eddies, and later surfacing as tar balls. Only 10% of the oil was visible at the surface. Note that some large patches of oil collected sand by rolling on the bottom, thus penetrated into the substrate, becoming difficult to recover.

### Technologies / Methods for Submerged Oil Detection & Monitoring:

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trawled nets (in water column)</td>
<td>Nets rapidly clogged up with oil and debris, and could not be used twice</td>
</tr>
</tbody>
</table>

Remarks:

- Not much detailed info was available about submerged oil detection in this case

### Drift Assessment / Forecast:

- Modelling of the drift: NO

### References:

**T/V HAVEN**

- **Name:** T/V Haven
- **Vessel:** 1,096 ft. supertanker
- **Date of incident:** April 11, 1991
- **Location:** Genoa, Italy
- **Type of oil:** Iranian Heavy Crude Oil
- **Amount of spilled oil:** approx. 144,000 tons
- **Event:** The Haven underwent a series of explosions while anchored 7 miles off of Genoa. It broke into three parts, all of which sank.

- **Spill features:** Because of an increased density due to burning, oil residues (between 10,000 – 50,000 tons) sunk under the track of the vessel. Also, a part of the fresh heavy oil that initially floated stranded on sand beaches before being transported by wave actions and ultimately sank in the form of tar mats in near shore areas.

### TECHNOLOGIES / METHODS FOR SUBMERGED OIL DETECTION & MONITORING:

<table>
<thead>
<tr>
<th>Method</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side-scan sonar</td>
<td>[No feedback information. Reportedly limited results as regards to quantification]</td>
<td></td>
</tr>
<tr>
<td>Sub bottom profiler</td>
<td>[No feedback information]</td>
<td></td>
</tr>
<tr>
<td>Remotely operated underwater video (ROV)</td>
<td>- Allowed mapping submerged oil areas in shallow water along the shoreline.</td>
<td>- Provided limited results as regards to quantification of sunken oil</td>
</tr>
<tr>
<td>Trawls</td>
<td>- Series of 1-hour trawls allowed for detection of submerged oil areas within 10 km off the coast (depth range: 500-800 meters).</td>
<td>- Scope of operations was limited by submerged objects (debris, wrecks...)</td>
</tr>
<tr>
<td>Bathyscaphe based visual inspections</td>
<td>- Allowed identification of the extent of the spill, as well as the form of the residue (mats, tarballs...)</td>
<td>[No feedback information]</td>
</tr>
<tr>
<td>Remote sensing data from high resolution sensors (Landsat Thematic Mapper and SPOT High Resolution Visible)</td>
<td>- Used for monitoring locations/movements of oil slicks and the extent of the spill.</td>
<td>Detection of surface oil only (floating slicks).</td>
</tr>
</tbody>
</table>

### DRIFT ASSESSMENT / FORECAST:

**Modelling of the drift:** YES, as regards to floating oil slicks. Both remote sensing (see above) and acquisition of sea surface circulation by high frequency sensors (NOAA AVHRR -Advanced Very High Resolution Radiometer) provided input data for a pollution dispersion model (ESA).

### SUBMERGED OIL RECOVERY METHODS / TECHNOLOGIES:

- Manual recovery by divers of the oil residues detected on the seafloor at 10 m depth.
- Divers-guided vacuum systems

### REFERENCES:


**T/B BOUCHARD B-155**

- **Name:** Bouchard B-155  
- **Vessel:** tank barge  
- **Date of incident:** August 10, 1993  
- **Location:** Tampa Bay, Florida, USA  
- **Type of oil:** Heavy Fuel Oil N°6  
- **Amount of spilled oil:** 336,000 gallons  
- **Event:** Three ships collided in Tampa Bay: the Bouchard B-155 barge, the freighter BALSA 37, and the barge OCEAN 255. The B-155, punctured on the port bow, spilled approximately 336,000 gallons of its cargo in Tampa Bay.

- **Spill features:** A part of the spilled oil sank, due to mixing up with sediment in the water column or after stranding in the surf zone. These patches of increased density tar mats submerged and deposited in low energy areas such as shallow flats around mangrove islands. Several mats were also located offshore, at 6 to 20 feet depth.

**TECHNOLOGIES / METHODS FOR SUBMERGED OIL DETECTION & MONITORING:**

[No detailed information found about detection and/or tracking of submerged oil]

**Remarks:**
- Aerial surveys of floating slicks were conducted, and buoys were used to assess the drift at the water surface.

**DRIFT ASSESSMENT / FORECAST:**

*Modelling of the drift:* YES. Drift forecasts were provided, based on daily weather data, tides, currents, trajectory updates.

**SUBMERGED OIL RECOVERY METHODS / TECHNOLOGIES:**

- Vacuum transfer units on barges in mangrove shallow areas.  
- Buckets and shovels in very shallow areas.  
- **Note:** Mapping of sunken tar mats offshore was reportedly planned, as well as an evaluation of recovery procedures.

**REFERENCES:**

NOAA’s website at: [http://old.incidentnews.gov/incidents/history.htm](http://old.incidentnews.gov/incidents/history.htm)
- **Name:** T/B Morris J. Berman
- **Vessel:** 302 ft. tank-barge
- **Date of incident:** January 7, 1994
- **Location:** Escambron Beach, San Juan, Puerto Rico
- **Type of oil:** Heavy N°6 Fuel Oil
- **Amount of spilled oil:** 800,000 gallons
- **Event:** Barge grounded on hard bottom (rocky substrates and corals), and drifted ashore after towing cable parted from its tug boat. Eventually the barge was re-floated, and then towed 20 miles offshore to be scuttled and sunk into 6,000 ft. of water.

- **Spill features:** The grounded barge leaked oil, and booming was not an option because of waves. Lightering operations were hampered as heavy oil quickly became very viscous. Slicks of spilled oil initially floated then sank without stranding, after picking up suspended sediment in near shore areas—a process enhanced by wave action. Two percent sand by weight was enough to cause the oil to sink. Submerged oil accumulated on the bottoms of two lagoons, in the vicinity of the grounding site, in the form of large mats, patches, clumps and tar balls. Refloating of submerged oil in small globules was observed daily in these shallow waters. Three mechanisms were hypothesized to explain this resurfacing phenomenon: sand migration through the oil; solar heating and water turbulence.

### TECHNOLOGIES / METHODS FOR SUBMERGED OIL DETECTION & MONITORING:

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection and monitoring of offshore slicks twice daily</td>
<td>Detection of floating oil only (surface).</td>
</tr>
<tr>
<td>Overview of the spill</td>
<td>Limited success because the oil formed scattered tarballs and pancakes ⇒ low IR signal</td>
</tr>
<tr>
<td>Identifying oceanographic features that might affect distribution and movement of oil (e.g. convergence zones)</td>
<td></td>
</tr>
<tr>
<td><strong>Side Looking Airborne Radar (SLAR) AN/APS 131 coupled with IRS-18 C infrared/ultraviolet line scanner (IR/UV LS)</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Helicopter based infrared imaging</strong></td>
<td>Detection of floating oil only (surface).</td>
</tr>
<tr>
<td>Monitoring of the oil at night</td>
<td>Limited success because the oil formed scattered tarballs and pancakes ⇒ low IR signal</td>
</tr>
<tr>
<td><strong>Aerial Surveys / observations</strong></td>
<td>Aerial observation of submerged oil in lagoons was possible because of shallow and clear seawater.</td>
</tr>
<tr>
<td>Provided actual oil slick positions for mapping purposes.</td>
<td></td>
</tr>
<tr>
<td><strong>Divers directed video surveys</strong></td>
<td></td>
</tr>
<tr>
<td>Verification of “suspect” sites</td>
<td></td>
</tr>
<tr>
<td><strong>Side-scan sonar</strong></td>
<td>[Reportedly used to map submerged oil, but no feedback information found]</td>
</tr>
</tbody>
</table>

### DRIFT ASSESSMENT / FORECAST:

**Modelling of the drift:** YES (on-scene spill model processed by NOAA experts team), but at sea-surface (floating oil slicks).

**Forcing data:** wind (weather forecast and real time observations), surface currents.

**Other methods:** Actual positions of slicks, provided twice daily by overflights, were positioned using a hand-held GPS then reported on maps used to forecast oil movements (in the first two weeks of the spill). Also, satellite-tracked surface buoys technique was implemented to provide test-data for oil spill trajectory model.

### SUBMERGED OIL RECOVERY METHODS / TECHNOLOGIES:

- Manual removal by divers
- Divers directed pumping of heavy concentrations: various vacuum/suction devices, archimedian screw pumps, positive displacement pumps.
- Submersible dredges for small or scattered concentrations of oil.

### REFERENCES:


**T/B Apex 3512**

- **Name:** T/B Apex 3512  
- **Vessel:** 297 ft. tank barge  
- **Date of incident:** October 11, 1995  
- **Location:** Above Head Of Passes, Mississippi River, Louisiana, USA.  
- **Type of oil:** Slurry oil  
- **Amount of spilled oil:** 194,500 gallons  
- **Event:** Collision between the tows of two motor vessels, each one pushing barges. Amongst the latter, the T/B Apex 3512 suffered damages on one tank that discharged almost its entire content in the Mississippi.

- **Spill features:** Soon after the incident, on scene personnel and Coast Guard helicopter overflight reported nothing but sheening, indicating that all of the spilled oil sank on the bottom. Locating the oil on the river bottom was the primary difficulty encountered.

**Technologies / Methods for Submerged Oil Detection & Monitoring:**

<table>
<thead>
<tr>
<th>Sorbent pads (sorbent around heavy chain)</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
</table>
| - Low tech., using material readily available  
- Allowed a rough cartography of the spill extent | - Exact locations of pockets of oil were difficult to document when no GPS system was used.  
- Limitation of the technique because of patchiness of oil.  
- Time consuming.  
| Diving surveys | - Personal protection / safety  
- Poor visibility, high currents | |
| Side-scan sonar | - Effectiveness was inconclusive.  
- The sonar should have been calibrated over areas over known oil | |

**Drift Assessment / Forecast:**

*Modelling of the drift:* NO

**Submerged Oil Recovery Methods / Technologies:**

- Crane (on a deck barge)  
- Divers directed pumping devices (hydraulic Marflex pump)

**References:**

NAKHODKA

Leak from the punctured starboard tank N°4. (Video-taped by "Dolphin-3k" on February 23, 1997) (Photo credit: http://www.jamstec.go.jp/)

- **Name:** Nakhodka
- **Vessel:** Tanker vessel
- **Date of incident:** January 2, 1997.
- **Location:** Off Oki Islands, Japan Sea.
- **Type of oil:** Medium Oil Fuel
- **Amount of spilled oil:** 6 200 tons.
- **Event:** The tanker broke up in two parts, during stormy conditions at sea, 110 km off Oki Islands. The stern sank with its 10 000 tons of cargo at a depth of 2 500 meters, leaking oil up to 15 m³ per day. Due to severe weather, attempts at towing the upturned (and leaking) bow section failed. It grounded on the shoreline where it caused the most important pollution ever recorded in Japan.
- **Spill features:** The heavy fuel oil leaking from the stern drifted submerged in the water column, on a distance of at least 2 km around the wreck before reaching the surface.

**TECHNOLOGIES / METHODS FOR SUBMERGED OIL DETECTION & MONITORING:**

[No information found about detection & tracking of submerged oil]

**Remarks:**
- In order to confirm the situation of the stern section of the tanker and the presence of leaking oil, the Science and Technology Agency (STA) and the Japan Marine Science and Technology Center (JAMSTEC) carried out an underwater survey by using a towed device equipped with a video camera and a sonar capable at the depth up to 4 000 meters. It allowed the visualisation of leaking oil from punctured tanks, though no further attempts at tracking submerged oil were carried out.

**DRIFT ASSESSMENT / FORECAST:**

**Modelling of the drift:** YES. A simulation/forecast of the drift was performed according to a 2D oil spill drift model for the Sea of Japan operated in the Research Institute for Applied Mechanics, at Kyushu University. More info on http://nmg.riam.kyushu-u.ac.jp/~vsm/html/oil_spill.htm.

**REFERENCES:**

Japan Marine Science and Technology Center (Jamstec) website: http://www.jamstec.go.jp/jamstec/PR/NAHOTOKA/


M/V Kuroshima

- Name: M/V Kuroshima
- Vessel: 368 ft. freighter
- Date of incident: November 26, 1997
- Location: Summer Bay, Dutch Harbor, Unalaska Island, Alaska (USA).
- Type of oil: Bunker C
- Amount of spilled oil: 39,000 gallons
- Event: The vessel was dislodged from its anchorage during a severe windstorm and subsequently went aground, releasing heavy fuel oil in the intertidal zone. A part of the spill flowed into Summer Bay Lake, under the action of strong winds and high tides.
- Spill features: Soon after the incident, there were concerns about the heavy oil submerging and sinking on the bottom of Summer Bay Lake. Oil density increased because of previous mixing with sediments in the surf zone on the shoreline. Thus as part of the cleanup operations, an underwater survey was conducted, in order to locate, quantify and evaluate the quality of the sunken oil.

TECHNOLOGIES / METHODS FOR SUBMERGED OIL DETECTION & MONITORING:

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Underwater video surveys</td>
<td>- Surveys were conducted along transects using a modified SCAT procedure (semi-quantitative estimations of oil patches) - Mapping of submerged oil was allowed by use of a differential GPS device.</td>
</tr>
</tbody>
</table>

DRIFT ASSESSMENT / FORECAST:

Modelling of the drift: YES, but for floating oil. NOAA’s support team provided maps of floating oil as well as trajectories based on several wind conditions.

SUBMERGED OIL RECOVERY METHODS / TECHNOLOGIES:

- Manual recovery by divers. Tar balls, tar patties and tar mats were placed in plastic bags and lifted to the surface, to a barge.

REFERENCES:


### Evoikos

- **Name:** Evoikos  
- **Vessel:** Tank vessel  
- **Date of incident:** October 15, 1997  
- **Location:** Strait of Singapore, Singapore.  
- **Type of oil:** Heavy fuel oil  
- **Amount of spilled oil:** 29 000 tonnes  
- **Event:** Two tankers, the Evoikos and the Orapin Global, collided in the Strait of Singapore. The former suffered damage on three tanks, which leaked very quickly approximately 29 000 tons, while the latter was in ballast and thus did not spill any oil.  
- **Spill features:** In a few days, the oil viscosity increased due to weathering process. The slicks fragmented, drifted partially submerged and spread unevenly towards Malacca Strait. The slicks drifted during several weeks before finally hitting the Malaysian coastline. At this time after the incident, it was suggested that a part of the weathered oil had begun to sink.

### Technologies / Methods for Submerged Oil Detection & Monitoring:

[No information found about detection & tracking of submerged oil]

### Remarks:
- Aerial and boat surveys of surface slicks were conducted.  
- SAR satellite images were also reportedly used to monitor the drift of the Evoikos oil residues

### Drift Assessment / Forecast:

- **Modelling of the drift:** YES. Reportedly, a spill prediction model has been used in order to help identifying critical oil slicks that should be given priority to disperse.

### Submerged Oil Recovery Methods / Technologies:

- None

### References:

- **Name:** M/T Volgoneft 248  
- **Vessel:** tanker  
- **Date of incident:** December 29, 1999  
- **Location:** Off the coast of Istanbul, Sea of Marmara, Turkey  
- **Type of oil:** Heavy Fuel Oil  
- **Amount of spilled oil:** 1,578 tons  
- **Event:** During heavy storms, the Russian tanker Volgoneft 248 broke in two parts off Istanbul, releasing 1,280 tons from 2 of its damaged tanks. The stern section was then driven aground by winds, later to be refloated and discharged ashore without further spillage. The bow section sank in shallow water, and most of its cargo was ultimately recovered.

- **Spill features:** The spilled heavy fuel oil was thick and viscous, with a specific gravity close to that of seawater. A substantial amount of the spilled oil mixed up with sediments and sank on the sea bottom in shallow water areas near the shoreline, where it formed deposits up to 20 centimetres thick. These sunken patches were eventually resuspended due to strong winds, and washed ashore.

---

### TECHNOLOGIES / METHODS FOR SUBMERGED OIL DETECTION & MONITORING:

<table>
<thead>
<tr>
<th></th>
<th><strong>Pros</strong></th>
<th><strong>Cons</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Diving surveys</td>
<td>- Performed at depths of 1 to 15 meters, it allowed identification of oil deposit zones (between rocks, buried under sand…)</td>
<td>- Not possible to quantify precisely the amount of sunken oil</td>
</tr>
</tbody>
</table>

---

### DRIFT ASSESSMENT / FORECAST:

- **Modelling of the drift:** NO

### SUBMERGED OIL RECOVERY METHODS / TECHNOLOGIES:

- Manual recovery by divers (1-15 m depth). Oil placed in plastic bags and lifted to the surface, to a boat.  
- In shallow nearshore areas, manual recovery with spades, by wading to the patches of sunken oil.

### REFERENCES:

**BALTIC CARRIER**

**The damaged tank (number 6) on the starboard side of the Baltic Carrier (Photo credit: DR)**

- **Name:** Baltic Carrier  
- **Vessel:** double-hull tanker  
- **Date of incident:** March 29, 2001  
- **Location:** Kadetrenden, Baltic Sea, Denmark  
- **Type of oil:** IFO 380  
- **Amount of spilled oil:** 2,700 tons  
- **Event:** Suffering a steering failure, the oil tanker *Baltic Carrier* collided with the bulk carrier *Tern* in the western Baltic Sea, leaking some 2,700 tons of heavy fuel oil in open sea. Because of bad weather conditions, the response operations at sea could not be initiated in the first days after the spill.

- **Spill features:** Some slicks submerged in shallow areas, near shore, after picking up sediment.

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**TECHNOLOGIES / METHODS FOR SUBMERGED OIL DETECTION & MONITORING:**

In this case, information about submerged oil detection technique is scarce. It seems that near shore areas with patches of submerged oil in shallow waters were visually located during surveys along the coastline.

**DRIFT ASSESSMENT / FORECAST:**

**Modelling of the drift:** YES.  

The drift of the spill was simulated by 3D *Oil Drift and Fate Model*, run at the Danish Meteorological Institute. This model included weathering processes of the oil (physical and chemical changes), as well as sinking and sedimentation processes. The oil leakage was simulated as a single release of 1,000 tons of IFO 450 (available in the model) from the incident location. The results were consistent with observations. On the contrary, the drift forecasts provided by a 2D model (MIKE 21-SA) showed discrepancies when compared to *in situ* observations about oil slick locations.

**SUBMERGED OIL RECOVERY METHODS / TECHNOLOGIES:**

- Grab buckets (shallow-water areas)

**REFERENCES:**

**FU SHAN HAI**

The *Fu Shan Hai* sinking after collision with the container vessel *Gdynia*, May 31, 2003 (Photo credit: Admiral Danish Fleet)

<table>
<thead>
<tr>
<th>Name: <em>Fu Shan Hai</em></th>
<th>Vessel: 738 ft. bulk carrier</th>
<th>Date of incident: May 31, 2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location: Off the coast of Bornhom, Denmark, Baltic Sea</td>
<td>Type of oil: IFO 380.</td>
<td>Amount of spilled oil: # 1 200 tons</td>
</tr>
<tr>
<td>Event: The <em>Fu Shan Hai</em> collided with a Cypriot container vessel, then began leaking oil soon after the collision, and sank in the evening.</td>
<td>Spill features: Released from the wreck at a 68 meters water depth, emulsified IFO 380 tended to submerge because of its density (0.992-0.995 kg.l(^{-1})) which was actually quite close to that of the seawater (# 1.005 kg.l(^{-1})). As a result, a part of the oil drifted several kilometres below the surface before reaching the sea surface.</td>
<td></td>
</tr>
</tbody>
</table>

**TECHNOLOGIES / METHODS FOR SUBMERGED OIL DETECTION & MONITORING:**

- **Side-scan sonar**
  Used primarily for mapping of the wreck and the bottom surroundings. No feedback info found as regards to efficacy at detecting submerged oil.

- **ROV video survey**
  Used for inspection of the wreck and detection of potential leaks in the surroundings. No feedback information found as regards to efficiency and/or outcomes at detecting submerged spilled oil.

**DRIFT ASSESSMENT / FORECAST:**

**Modelling of the drift:** YES.

Released at 68 meters depth and prone to submerge, the oil eventually drifted in subsurface by different current speed and directions than if it had been transported at the sea surface. Thus, a 3D model was run by DMI (Danish Meteorological Institute) from May 31 to June 12, in which the leak was considered as a continuous release (because of uncertainty as actual discharge events), at 68 meters water depth. The input oil type was heavy fuel oil (*Bunker C*). The model included weathering processes of the oil (physical and chemical changes), as well as sinking and sedimentation processes.

The model predictions were generally in agreement with the oil slick observations (ESA ERS-2 satellite images). The 3D model also took into account the oil weathering process. Its performance (results) was compared with a 2D model (MIKE 21-SA), and proved to be the closest to actual oil locations at sea (aerial surveys and satellite images) and on the shoreline (stranding events).

**SUBMERGED OIL RECOVERY METHODS / TECHNOLOGIES:**

- Submerged pumping operations were carried out, addressing the oil contained in the fuel tanks of the *Fu Shan Hai* wreck.

**REFERENCES:**

**M/T ATHOS I**

- **Name:** M/T Athos I
- **Vessel:** 750 ft. single-bottom, double-sided tanker
- **Date of incident:** November 26, 2004
- **Location:** Delaware River (Pennsylvania)
- **Type of oil:** Venezuelan Bachaquero heavy crude oil
- **Amount of spilled oil:** 265 000 gallons (# 1 000 cubic meters)
- **Event:** collision with a submerged anchor.

- **Spill features:** Two types of submerged oil were noticed: (1) pooled oil accumulated in depressions on the bottom at the collision site and (2) mobile oil that picked up sand after stranding, became negatively buoyant, re-suspended and submerged (transported by underwater currents).

**TECHNOLOGIES / METHODS FOR SUBMERGED OIL DETECTION & MONITORING:**

<table>
<thead>
<tr>
<th></th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Side-scan sonar</strong></td>
<td>- Good spatial coverage</td>
<td>- Could not detect oil but the trench that contained pooled oil (thus, effectiveness was inconclusive)</td>
</tr>
<tr>
<td>(different systems)</td>
<td>- Not affected by poor visibility</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Can be used to identify areas of potential accumulations</td>
<td></td>
</tr>
<tr>
<td><strong>Sorbent drops</strong></td>
<td>- Immediate results: useful to revise search areas</td>
<td>- Ineffective for oil suspended in water column</td>
</tr>
<tr>
<td></td>
<td>- Low tech</td>
<td>- Slow and labour intensive</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Restricted deployment under rough weather conditions</td>
</tr>
</tbody>
</table>

*“Vessel-Submerged Oil Recovery System” (used for recovery as well)*

- Can detect both pool and mobile oil above the bottom
- Provide spatial data on extent of submerged oil
- Relatively efficient for large areas surveys
- Good positioning capability with onboard positioning system while trawling
- Time and labour intensive (deployment, inspection, replacement)
- Snagging on the bottom (e.g. pipes)
- Cannot detect where the oil occurred among the trawl
- Requires a vessel with adequate deck space for operations

*“Snare Samplers (= anchor + 15 m of snare on a rope + float) NOTE: water column*  

- Effective at detecting oil at various depths in the water column
- Provide spatial data on extent of submerged oil
- Time-series data proved useful to track trends
- Time and labour intensive (deployment, inspection, replacement)
- High loss rates
- No calibration of efficacy of sampling
- Not to be deployed in active vessel traffic area.

**Field fluorimetry**

- Allowed for transect sampling
- Proved ineffective, because of low soluble fraction in heavy oils.

**DRIFT ASSESSMENT / FORECAST:**

*Modelling of the drift: NO*

**SUBMERGED OIL RECOVERY METHODS / TECHNOLOGIES:**

- Diver-directed pumping
- V-SORS
- Sorbent barrier/fence

**REFERENCES:**

Lehman S., 2006. Case studies in submerged oil spill. Presentation for the Coastal Response Research Center’s Submerged Oil Workshop, December, 2006, Durham (New Hampshire), USA.

- Name: unspecified
- Vessel: inland barge
- Date of incident: January, 2005
- Location: Chicago Ship & Sanitary Canal, Stickney, Illinois, USA
- Type of oil: CSO (Clarified Slurry Oil)
- Amount of spilled oil: not known
- Event: The inland barge suffered explosion and partially sank (in approx 20 ft. depth). Three cargo tanks tops were blown off. Part of the cargo leaked and sank on the bottom in the vicinity of the wreck.
- Spill features: CSO, which is transported in heated conditions, cooled once spilled in the river. Thus, the oil that leaked out turned quickly into a very viscous and heavy material, sinking in fresh water.

TECHNOLOGIES / METHODS FOR SUBMERGED OIL DETECTION & MONITORING:

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diving surveys</td>
<td>- Allowed for identification of the spill extent, form, and approximate quantity.</td>
</tr>
<tr>
<td>Side-Scan sonar</td>
<td>[No detailed information found]</td>
</tr>
</tbody>
</table>

DRIFT ASSESSMENT / FORECAST:

Modelling of the drift: NO

SUBMERGED OIL RECOVERY METHODS / TECHNOLOGIES:

- Clamshell dredge/bucket unit (operated via a crane housed on a barge)

REFERENCES:

**CANADIAN NATIONAL RAILWAY INCIDENT**

- **Name:** Canadian National Railway
- **Vessel:** freight train
- **Date of incident:** August 3, 2005
- **Location:** Lake Wabamun, Alberta, Canada
- **Type of oil:** Bunker C
- **Amount of spilled oil:** approx. 200,000 gallons
- **Event:** Forty-three cars of the CNR freight train derailed on the shore of the lake, spilling heavy fuel oil which rapidly flowed in the water where it formed a slick affecting 12 km of shoreline.

- **Spill features:** Because of its density close from that of freshwater, and also after picking up sediments, a part of the spilled oil sunk on the bottom. Sunken oil eventually re-floated in the form of small tar-balls, sometimes coalescing then stranding on the shores. Although probably related to changes in temperature, the mechanisms and dynamics underlying this phenomenon are not well understood.

### TECHNOLOGIES / METHODS FOR SUBMERGED OIL DETECTION & MONITORING:

<table>
<thead>
<tr>
<th>Method</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual detection w/ underwater viewing tubes</td>
<td>- Can be operated from small boats, kayaks in shallow waters.</td>
<td>- Need to be validated by samples. - Efficiency relies on turbidity, depth…</td>
</tr>
<tr>
<td>Trawled nets (both in water column and on the bottom)</td>
<td>[No detailed information found]</td>
<td></td>
</tr>
<tr>
<td>Sorbent pads (on long poles)</td>
<td>- Low tech., using material readily available</td>
<td>- Ineffective because oil formed a layer which didn’t adhere to the sorbent</td>
</tr>
<tr>
<td>Sediment sampling (Eckman grab)</td>
<td>[No detailed information found]</td>
<td>- Limited outcomes because of patchiness of oil on the bottom</td>
</tr>
<tr>
<td>Underwater video surveys</td>
<td>[No detailed information found]</td>
<td>- Some attempts were carried out: apart for some shallow areas, the spill was too dispersed to allow efficient results</td>
</tr>
</tbody>
</table>

**Remarks:**
- Both acoustic and fluorosensor techniques were considered for detection of oil in the water column. Nevertheless, none of these approaches were implemented because it was thought that: (i) density of oil particles in the water were below sensitivity limits of acoustic sensors; (ii) the low soluble/fluorescing content in bunker oil would not allow for detection in fluorimetry.

### DRIFT ASSESSMENT / FORECAST:

**Modelling of the drift:** NO

### SUBMERGED OIL RECOVERY METHODS / TECHNOLOGIES:
- Trawled nets (effective in collecting suspended oil particles, but rapidly clogged up)
- Lacking detailed information

### REFERENCES:


**Containment boom around the capsized DBL-152 barge; Nov. 14, 2005 (Photo credit: U.S. Coast Guard).**

**TECHNOLOGIES / METHODS FOR SUBMERGED OIL DETECTION & MONITORING:**

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
</table>
| **Side-scan sonar** *(Edgetech Model 272 analog sonar + Klein Model 3 000 side-scan sonar)* | - Good spatial coverage  
- Not affected by poor visibility  
- Good visualization of large oil accumulations and other debris |
| - Reduced efficacy as the spill spread out (low density patches)  
- Long delays (days) in data processing / obtaining results  
- Needs validation of oil presence (divers)  
- Operations limited by sea conditions |
| **RoxAnn™ seabed classification system** | - Signal is interpreted by the program |
| - Vary the height to adjust coverage and/or improve visibility  
- Could be directed towards edges of accumulation to estimate area/volume and frequency of patches (semi-quantitative estimates) |
| - Limited results when sediment roughness comes close from the oil (less accuracy in soft/muddy substrates)  
- Narrow swath (1-2 m) vs. oil patchy oil distribution  
- Results need validation |
| **Remotely operated underwater video (ROV)** | - Able to cover large distances  
- Can vary the length of the trawl to refine spatial extent |
| - Cannot locate where oil occurred along the trawl  
- Qualitative data only  
- Snagging on the bottom (e.g. pipes)  
- Make sure it maintains bottom contact along the trawl  
- Information decreases with patchiness |
| **“Vessel-Submerged Oil Recovery System”** (used for recovery as well) | - Effective at detecting oil at various depths in the water column  
- Time-series allow to track trends |
| - Time and labour intensive (deployment, inspection, replacement)  
- High loss rates  
- No calibration of efficacy of sampling |
| **“Snare Samplers”** (= anchor + 15 m of snare on a rope + float) **NOTE:** water column | |
| DRIFT ASSESSMENT / FORECAST: |
| - Modelling of the drift: NO |
| - Other methods: Attempts were made at predicting oil drift on the bottom, by placing a Texas Automatic Buoy System (TABS) on site, equipped with a downward looking acoustic doppler current profiler (ACDP). Some processing was needed because of spurious readings near the bottom. |
| SUBMERGED OIL RECOVERY METHODS / TECHNOLOGIES |
| - Diver-directed pumping  
- Vacuum transfer units  
- Dredge  
- V-SORS |
| REFERENCES |
The asphalt barge MM-53 immobilized on its port side against the K&I RR bridge, Ohio River (Photo credit: USCG)

- **Name:** MM-53  
- **Vessel:** 297 ft barge  
- **Date of incident:** January 26, 2006  
- **Location:** Ohio river, near Louisville, Kentucky, USA.  
- **Type of oil:** Liquid asphalt  
- **Amount of spilled oil:** 220,000 gallons  
- **Event:** The barge broke loose from its towboat after the tow struck a dike in a canal. The MM-53 drifted downriver until it hit two piers of a bridge, flipped onto its port side and remained immobilized against the bridge, losing part of its cargo.

- **Spill features:** Asphalt rapidly sank after it was released. Deposited on the bottom in the form of large “pancakes” (very high viscosity, as the asphalt cooled after leaking out of the barge heated tanks). Submerged asphalt was difficult to locate because of very poor visibility (high water turbidity). Moreover, response operations were impeded by high velocity currents.

**TECHNOLOGIES / METHODS FOR SUBMERGED OIL DETECTION & MONITORING:**

<table>
<thead>
<tr>
<th>Visual detection</th>
</tr>
</thead>
</table>
| - Impeded by very poor visibility (< 1 ft).  
| - High pour point (> 200 °F) made it difficult to discriminate from sediment. |

**Remarks:**  
- No information found about implementation of other techniques

**DRIFT ASSESSMENT / FORECAST:**

**Modelling of the drift:** NO  

**SUBMERGED OIL RECOVERY METHODS / TECHNOLOGIES:**

Mechanical recovery of taller accumulations (mech. shovels). The more finely distributed patches were difficult to locate, and thus have not been recovered.

**REFERENCES:**

Lehman S., 2006. Case studies in submerged oil spill. Presentation for the Coastal Response Research Center’s Submerged Oil Workshop, December, 2006, Durham (New Hampshire), USA.  
Another presentation downloadable on Internet:  

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**II-2 OVERVIEW /SYNTHESIS OF THE IDENTIFIED OIL SPILLS**

A short synthesis of the main results can be thematically presented as follows.

**II-2.1) Type of oil involved**

Amongst the 21 incidents considered, 18 involved heavy residual products, while 3 cases only involved heavy crude oils and/or medium crude (Alvenus, 1984; Haven, 1991; Athos I, 2004) (table 1). The most frequently involved HFO is HFO N°6, also referred to as Bunker C. A few incidents involved intermediate fuel oils such as IFO 380. Others spills involved heavy refined products, such as slurry oils, and more rarely liquid asphalt (barge MM-53) or carbon black oil (Gino, 1979).

**II-2.2) Type and conditions of events vs. fate and behaviour of spilled oil**

If causes of the incidents are generally well documented, weather conditions at sea during the spill are not always precisely documented. Nevertheless, in the vast majority of the spills presented here, harsh weather conditions were prevailing during the spill (and were in some cases at the origin of the incident. See -amongst other examples- the Kuroshima case). According to different processes, these adverse conditions (winds, currents) enhance the submersion/sinking process of the spilled products, most notably because of highly turbulent waters. Indeed, because of their high specific gravity, heavy fuel oils show little buoyancy and are prone to be swamped by waves in rough sea conditions (Ansell
Moreover, the environmental parameters act in synergy with the processes of transport and weathering of the oil (formation of a water-in-oil emulsion, loss by evaporation…).

The conditions inducing the increase of density of the oil, which eventually become denser than water, have previously been reported in literature (see for example Michel and Galt, 1995; Michel et al., 1995; National Research Council, 1999).

<table>
<thead>
<tr>
<th>Year</th>
<th>Type of oil</th>
<th>Fresh / Sea water</th>
<th>Behaviour / Fate</th>
<th>Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>SANSINENA</td>
<td>1976</td>
<td>Bunker C / HFO #6</td>
<td>Seawater</td>
<td>Sank</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Heavier than water emulsion (note: part of the HFO burned)</td>
</tr>
<tr>
<td>NESTUCCA</td>
<td>1988</td>
<td>Bunker C / HFO #6</td>
<td>Seawater</td>
<td>Submerged then washed ashore / sank</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Neutrally buoyant emulsion</td>
</tr>
<tr>
<td>PRESIDENTE RIVERA</td>
<td>1989</td>
<td>Bunker C / HFO #6</td>
<td>Freshwater</td>
<td>Submerged then washed ashore / sank</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Neutrally buoyant emulsion</td>
</tr>
<tr>
<td>BOUCHARD B-155</td>
<td>1993</td>
<td>Bunker C / HFO #6</td>
<td>Seawater</td>
<td>Initially floated then sank</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Adsorption of suspended particulate matter + Mixed with sediments once stranded, then resuspended and sank</td>
</tr>
<tr>
<td>MORRIS J Berman</td>
<td>1994</td>
<td>Bunker C / HFO #6</td>
<td>Seawater</td>
<td>Initially floated then sank</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Adsorption of suspended particulate matter</td>
</tr>
<tr>
<td>KUROSHIMA</td>
<td>1997</td>
<td>Bunker C / HFO #6</td>
<td>Sea- and fresh-water</td>
<td>Initially floated then sank</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mixed with sediments once stranded, then resuspended and sank</td>
</tr>
<tr>
<td>LAKE WABAMUN</td>
<td>2005</td>
<td>Bunker C / HFO #6</td>
<td>Freshwater</td>
<td>Initially floated then submerged / sank</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Neutrally buoyant emulsion + Adsorption of suspended particulate matter</td>
</tr>
<tr>
<td>ELENI V</td>
<td>1978</td>
<td>HFO</td>
<td>Seawater</td>
<td>Submerged then washed ashore</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Neutrally buoyant emulsion</td>
</tr>
<tr>
<td>EVOIKOS</td>
<td>1997</td>
<td>HFO</td>
<td>Seawater</td>
<td>Submerged then washed ashore</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Neutrally buoyant emulsion</td>
</tr>
<tr>
<td>VOLGONEFT 248</td>
<td>1999</td>
<td>HFO</td>
<td>Seawater</td>
<td>Initially floated then sank</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mixed with sediments once stranded, then resuspended and sank</td>
</tr>
<tr>
<td>BALTIC CARRIER</td>
<td>2001</td>
<td>IFO 380</td>
<td>Seawater</td>
<td>Initially floated then sank</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Adsorption of suspended particulate matter</td>
</tr>
<tr>
<td>FU SHAN HAI</td>
<td>2003</td>
<td>IFO 380</td>
<td>Seawater</td>
<td>Submerged then washed ashore</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Neutrally buoyant emulsion</td>
</tr>
<tr>
<td>NAKHODKA</td>
<td>1997</td>
<td>Medium Fuel Oil</td>
<td>Seawater</td>
<td>A part of the spill submerged</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Neutrally buoyant emulsion</td>
</tr>
<tr>
<td>APEX 3512</td>
<td>1995</td>
<td>Slurry oil</td>
<td>Freshwater</td>
<td>Sank</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Heavier than water emulsion</td>
</tr>
<tr>
<td>DBL 152</td>
<td>2005</td>
<td>Slurry oil</td>
<td>Seawater</td>
<td>Sank</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Heavier than water emulsion</td>
</tr>
<tr>
<td>INLAND BARGE</td>
<td>2005</td>
<td>Slurry oil</td>
<td>Freshwater</td>
<td>Sank</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Heavier than water emulsion</td>
</tr>
<tr>
<td>GINO</td>
<td>1979</td>
<td>Carbon Black Oil</td>
<td>Seawater</td>
<td>Sank</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Heavier than water</td>
</tr>
<tr>
<td>MM-53</td>
<td>2006</td>
<td>Liquid asphalt</td>
<td>Freshwater</td>
<td>Sank</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Heavier than water</td>
</tr>
<tr>
<td>HAVEN</td>
<td>1991</td>
<td>Crude (heavy)</td>
<td>Seawater</td>
<td>Burned residues / A part of fresh oil initially floated then sank</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Heavier than water after burning + Mixed with sediments once stranded, then resuspended and sank</td>
</tr>
<tr>
<td>ATHOS I</td>
<td>2004</td>
<td>Crude (Heavy)</td>
<td>Freshwater</td>
<td>A part of the spill / sank</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Heavier than water after burning + Mixed with sediments once stranded, then resuspended and sank</td>
</tr>
<tr>
<td>ALVENUS</td>
<td>1984</td>
<td>Crude (Medium + Heavy)</td>
<td>Seawater</td>
<td>Initially floated then sank</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Adsorption of suspended particulate matter + Mixed with sediments once stranded, then resuspended and sank</td>
</tr>
</tbody>
</table>

Table 1. Fate / behaviour of oil in the various considered spills.
In 10 of the 21 spills considered in this report, a part of the oil sank after picking up sediments, either by stranding on the beach or by mixing with particulate matter suspended in the water column (table 3).

In 7 of the cases, oil formed a water-in-oil emulsion with a specific gravity close to that of water, thus becoming neutrally buoyant and submerging, drifting underneath the water surface before washing ashore.

In 6 of the cases, the spilled oil sank directly without stranding, because heavier than water. These spills all involved very heavy refined products, such as slurry oil (ex: *Apex 3512*, barge *DBL 152*), carbon black oil (*Gino*) and liquid asphalt (barge *MM-53*). It must be noted that 3 of these occurred in fresh water—a fact that facilitated sinking (less dense than sea water). In 2 (*Gino* and *DBL-152*) of the 3 marine incidents when the oil sank without floating, the sunken slicks / patches showed ability to more-or-less re-suspend and to move above the sea-bed.

In 2 cases, the increase in density of the oil, causing its sinking, was partly due to the fact that it burned during the incident. That was the case after the explosion of the *Sansenina* (1976), but also during the *Haven* spill (1991) which involved a crude oil (Iranian Heavy).

### II-2.3) Tools used and main facts regarding the oil drift forecasting

Amongst the 15 marine spills considered here, oil drift was forecasted in 10 cases using trajectory numerical models. Details about limitations and characteristics of these models are not always well documented but, in 8 of these cases, it seems that simulation of the drift is achieved by using trajectory models in the upper layer of the water column (if not at the surface). According to literature on similar topics, most of oil spill models focus on the transport and fate of surface oil slicks. The use of three dimensional models to forecast spills has been quite limited. Reasons for such a lack of 3D models include the difficulty to obtain the current data that are necessary for modelling subsurface drift, and also gaps in understanding of the variety of processes controlling the sinking of the oil (National Research Council, 1999; Michel and Galt, 1995).

However, from the examples considered here, surface drift modelling may at least allow to estimate general sense of the trends/trajectories and areas affected by heavy oils spills, whenever submersion and/or sinking phenomenon occurs.

Three-dimensional models were used in 2 of the marine spills considered, the *Baltic Carrier* and the *Fu Shan Hai* ones, that both happened in Denmark (see related files). In the first case, the spill was simulated as a single release, while in the *Fu Shan Hai* incident it was simulated as a continuous release. In both cases, the forecasted transport of the spill by the 3D model (conducted by the *Danish Meteorological Institute*) proved consistent with the observations made at sea (aerial surveys and eventually SAR satellite images) and on the shoreline (stranding events).

No drift modelling was conducted in 5 of the marine spills, including the 3 incidents during which heavy refined products sank directly on the bottom (*Sansenina*, *Gino*, and most recently the *DBL 152* incidents). Nevertheless, in the *DBL-152* case, attempts were made to predict oil movements above the sea-bed by measuring currents in the water column (including lower levels) using a downward looking Doppler current profiler mounted on a buoy (see related file).

### II-2.4) Methods regarding the submerged oil detection

*Visual detection*

Visual detection is probably the most frequently implemented technique as regards to detection of submerged oil (table 2).

- **Aerial surveillance** (from planes, helicopters…) is used in most of the incidents reported here (table 4). It allows to cover large areas, but this technique is limited by both clarity of waters and the depth at which the oil is located -whether sunken on the bottom or submerged in the water column. For example, in the *Morris J. Berman* case, this method was efficient because spilled oil was located in clear and shallow water areas (1994, see related file). In most incidents, aerial surveys allowed for detection of oil in the upper layer of the water column (if not at the surface).
<table>
<thead>
<tr>
<th>SUBMERGED OIL DETECTION TECHNIQUES</th>
<th>Oil suspended in the water column</th>
<th>Oil deposited on the bottom</th>
<th>Other techniques (in red: for floating oil)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Freshwater spill</em></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>SUBMERGED OIL DETECTION TECHNIQUES</strong></td>
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<tr>
<td>Stationary sorbent systems</td>
<td>- Visual detection</td>
<td>Diver observations / video</td>
<td>- Sub-bottom profiler</td>
</tr>
<tr>
<td>Trawl detection devices</td>
<td>- Remotely operated video camera</td>
<td>Sorbent drops</td>
<td>- Remote sensing (satellite)</td>
</tr>
<tr>
<td>Field fluorimetry</td>
<td>- Sediment cores / grabs</td>
<td>Bottom trawl nets</td>
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<tr>
<td><strong>TABLE 2. SUBMERGED OIL DETECTION TECHNIQUES USED IN THE OIL SPILL CASES CONSIDERED.</strong></td>
<td></td>
<td>Chain drags / V-SORS</td>
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<td></td>
<td></td>
<td>Side-scan sonar</td>
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<tr>
<td>Sansinena</td>
<td></td>
<td>X</td>
<td>X Sub-bottom profiler</td>
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<tr>
<td>Eleni V</td>
<td>- Aerial surveys</td>
<td>- Aerial surveys</td>
<td>X Remote sensing (satellite)</td>
</tr>
<tr>
<td>Gino</td>
<td>- Submersible</td>
<td>X</td>
<td></td>
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<tr>
<td>T/V Alvenus</td>
<td>- Aerial surveys</td>
<td>X</td>
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<tr>
<td>Nestucca</td>
<td></td>
<td>X</td>
<td>X Sub-bottom profiler</td>
</tr>
<tr>
<td>Presidente Rivera*</td>
<td></td>
<td>X</td>
<td>X Remote sensing (satellite)</td>
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<tr>
<td>T/V Haven</td>
<td>- Aerial surveys</td>
<td>X</td>
<td>X Sub-bottom profiler</td>
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<td></td>
<td>- Bathyscap</td>
<td>X</td>
<td>X Remote sensing (satellite)</td>
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<tr>
<td>Bouchard-155</td>
<td>- Aerial surveys</td>
<td>X</td>
<td>X Remote sensing (satellite)</td>
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<tr>
<td>Morris Berman</td>
<td>- Aerial surveys</td>
<td>X</td>
<td>X Remote sensing (satellite)</td>
</tr>
<tr>
<td>Apex 3512*</td>
<td></td>
<td>X</td>
<td>X Remote sensing (satellite)</td>
</tr>
<tr>
<td>Nakhodka</td>
<td>- Aerial surveys</td>
<td>X</td>
<td>X Remote sensing (satellite)</td>
</tr>
<tr>
<td>Kuroshima</td>
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<td>X</td>
<td>X Remote sensing (satellite)</td>
</tr>
<tr>
<td>Evoikos</td>
<td>- Aerial surveys</td>
<td>X</td>
<td>X Remote sensing (satellite)</td>
</tr>
<tr>
<td>Volgoneft 248</td>
<td>- Aerial surveys</td>
<td>X</td>
<td>X Remote sensing (satellite)</td>
</tr>
<tr>
<td>Baltic Carrier</td>
<td>- Aerial surveys</td>
<td>X</td>
<td>X Remote sensing (satellite)</td>
</tr>
<tr>
<td>Fu Shan Hai</td>
<td>- Aerial surveys</td>
<td>X</td>
<td>X Remote sensing (satellite)</td>
</tr>
<tr>
<td>M/T Athos I*</td>
<td>X</td>
<td>X</td>
<td>X Remote sensing (satellite)</td>
</tr>
<tr>
<td>Inland barge*</td>
<td>X</td>
<td>X</td>
<td>X Remote sensing (satellite)</td>
</tr>
<tr>
<td>Lake Wabamun*</td>
<td>X</td>
<td>- Aerial surveys</td>
<td>X Remote sensing (satellite)</td>
</tr>
<tr>
<td></td>
<td>- Viewing tubes</td>
<td>Sorbent pads on long poles</td>
<td>X Remote sensing (satellite)</td>
</tr>
<tr>
<td>DBL-152</td>
<td>X</td>
<td>X</td>
<td>X Remote sensing (satellite)</td>
</tr>
<tr>
<td>MM-52*</td>
<td>X</td>
<td>X</td>
<td>X Remote sensing (satellite)</td>
</tr>
</tbody>
</table>

Table 2. Submerged oil detection techniques used in the oil spill cases considered.
In some cases, visual surveys of sunken oil were conducted at important depths by using submersibles or bathyscaphs (ex: Gino, Haven). This technique can be useful to identify the aspect of the oil on the sea-bottom, as well as the extent of the deposits, but as stated in the Gino incident, such operations are quite costly and rely heavily on the weather conditions (one-offs operations rather than “surveys”).

In one incident, where the spill occurred in shallow waters (Lake Wabamun pollution), viewing tubes were used from small boats in order to detect and locate sunken oil patches. Nevertheless, the efficiency of that technique proved to be somewhat limited in turbid waters, and results needed to be validated by samples.

In many cases, diver observations and diver-directed video/photographs were useful at detecting the presence of oil on the bottom. Then again, this method can allow assessment of the extent and form (thickness, distribution in patches, mats, balls…) of the deposited oil in several incidents, but results may sometimes be impeded by poor visibility in turbid waters (example: the Sansinena and the barge Apex 3512). In one of the cases (Alvenus spill), diver surveys were reported to have helped in roughly estimating the quantities of sunken oil. Nevertheless, this method does not always allow precise quantification of the amount of deposits (ex: Volgoneft 248 incident). In some cases the use of a GPS system, to record the oil locations on the bottom, allowed mapping of submerged oil, as for example during the Kuroshima spill when diver-directed video surveys were conducted along transects.

It should be noted that, as diving surveys are conducted on limited areas, estimating the extent, form and amount of sunken oil may become difficult whenever the spill is spread on a broad scale and exhibits a patchy distribution.

Remotely operated underwater video surveys have also been implemented, but provided limited results as regards to quantification of sunken oil (such as for example in the Haven spill case). After the barge DBL-152 incident, it helped in semi-quantitative estimates (area, volume and frequency of deposits), but positioning the results was uneasy, and the coverage was limited by poor visibility.

Generally, it is reported that the data provided from visual surveys should ideally be confirmed validated by in situ samplings.

* Sampling
Detection of the oil by direct sampling, in the water column and/or on the bottom, has been carried out in most of the accidents, although according to different methods.

Water column:

- As regards to the water column, stationary sorbent devices have been used to detect submerged heavy oil in the Athos I and DBL-152 spills. These devices consisted of sorbent snares on a rope attached to an anchor and a float (eventually added with fishing pots stuffed with sorbent). They were effective at detecting oil at various depths, but were time consuming regarding their deployment, inspection and replacement, especially if time-series are needed. Moreover, the feasibility of this technique relies on environmental parameters such as current speed.

- Trawled nets have been used in 2 of the spills that occurred in freshwater (Presidente Rivera spill and Lake Wabamun pollution) but, although being able to detect the presence of suspended oil, nets rapidly clogged up with both oil and debris (Note that sampling by trawl nets have also been implemented to detect sunken oil on the bottom of Lake Wabamun, though we didn’t find much information about efficiency of this method).

- Note also that fluoro-sensing techniques have rarely been used in non-floating oil spills. A field fluorimetry approach has been tested in the Athos I case, but it was relatively inefficient at detecting oil in the water column, because of the low amount of soluble compounds in the spilled heavy crude.

This is particularly true in the case of the heavy to very heavy fuel oils involved in most of the incidents reported here.
Amongst the spills considered here, detection by sampling of oil deposited on the bottom was generally attempted via 3 methods: sorbent drops, sediment core (or grab) sampling, or sorbent dragged on the bottom (chain drags).

- **Sorbent drops** usually consist of sorbent attached to a weight (at the end of chains or ropes) bounced on the bottom. In the barge *Apex 3512* incident, sorbent drops allowed a rough cartography of the sunken oil extent, but this quite simple method is time-consuming, as well as of limited efficiency when the spill is patchy and scattered. The same conclusions were drawn after the *Athos I* spill where, despite being low-tech and providing immediate results, deployment of this technique was impeded by weather conditions. During the pollution of Lake Wabamun, this method was tested, but proved inefficient because oil didn’t adhere on sorbent pads.

- **Sediment grab samples** were useful to provide rough estimates of sunken slicks locations in the case of the *Gino* spill. Nevertheless, the results were limited because of the patchy distribution of the oil. A similar statement was made about sediment **core samples** on the bottom of the Wabamun Lake.

- **Chain drags** have been used in the *Athos I* and *DBL-152* spills. These devices (called V-SORS for *Vessel-Submerged Oil recovery System*) consist in sorbent (snares) on chains that are dragged on the bottom. In both cases, this method allowed to cover large distances, but has some limitations as regards to quantifying the oil as well as to locate it precisely (see related files). Results provided by this detection technique also rely on the patchiness of the oil deposits.

* **Side-scan sonar**
Side-scan sonar systems have been used in several accidents, in order to detect and map oil deposits on the seabed, from the *Gino* spill in 1979 to the barge *DBL-152* incident in 2005 (table 2). Amongst other advantages, this method allows for obtaining geo-referenced data on large areas, and its efficiency is not affected by visibility (contrary to visual surveys). However, data provided by acoustic methods ideally need to be validated, for example by divers or ROV directed observations.

In some cases, these systems were useful at providing data related to the bottom topographic features (such as depressions, for example), hence at giving clues about potential areas for oil accumulations, as reported during the *Athos I* and the *DBL-152* spills (see related files). This technique allowed visualization of large oil accumulations on the seafloor in some spills (*Gino, DBL-152*), but its effectiveness at detecting oil patches proved to be inconclusive in other cases. For example, in the *Athos I* case, side-scan sonar detection allowed to locate *trenches that contained pooled oil* rather than the oil itself. During the spills of the *Apex 3512* and of the inland barge in Illinois (2005), this method was quite ineffective for oil detection.

On quite homogeneous bottoms, as in the *Gino* spill case, repeated side-scan sonar surveys allowed for monitoring oil patches movements above the seafloor as they fragmented in smaller pieces. However, in other spills (*DBL-152*), detection became less efficient over time as the spill spread out in low density patches.

Also, as reported in the case of the *DBL-152* spill (see related file), using side-scan sonar systems to locate and track sunken oil can be time-consuming, because the delay required for data processing (which must be performed by skilled operators).

According to reviews addressing the topic of submerged oil detection (e.g. NRC, 1999), acoustic systems such as side-scan sonar can provide useful results but their performances still need to be evaluated.
REFERENCES:


## APPENDIX 1

*Cedre* archives about drift and behaviour at sea of the *Erika* and the *Prestige* fuel oils

<table>
<thead>
<tr>
<th>Archives</th>
<th>Item</th>
<th>Data / information</th>
<th>Period</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>*<em>GIS (Geomédia <em>.gws)</em></em> + <strong>Access format</strong></td>
<td>Wreck location</td>
<td>3 data : hour, latitude, longitude</td>
<td>12/12/99</td>
<td></td>
</tr>
</tbody>
</table>
| **Oil Drift modelling** | MOTHY model (Météo France, F) | 39 simulations :  
• Date/hour (start – end)  
• Location ( latitude, longitude) and duration | 12/12/99 – 30/12/99 | Raw data available at Météo France |
| | OILMAP model (ASA¹) | 1 simulation (12/12/99) : | 99/12/12 – 99/12/16 | |
| | OSIS Model (BMT²) | 1 simulation (99/12/12) : | 99/12/12 – 99/12/16 | |
| **Aerial survey** | French Customs and French Navy | 512 records of oil slicks  
• Latitude, longitude, date/time  
• Source, characteristics, details. | 99/12/12 – 2000/01/10 | |
| **Oil arrivals on the shoreline** | | 190 records :  
• Date  
• Latitude, Longitude | 25/12/99 – 13/01/2000 | |
| **Oiled birds washed ashore** | | a synthesis of records (17 sites in total) :  
date of arrivals / numbers / species | | partial data, not easy to use, low reliability |
| **computerized files (Excel format)** | Weather Conditions | Météo France | Not available at Cedre (but recorded and probably available via Météo France) | All along the crisis time | Raw data available at Météo France |

Table 1. *Erika* oil spill: computerized archives available from *Cedre* (or at Meteo France)

¹ Applied Science Associates  
² British Maritime Technologies
<table>
<thead>
<tr>
<th>Archives</th>
<th>Item</th>
<th>Data / information</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maps on oil arrivals on</td>
<td>Maps based on <em>Cedre</em> shoreline survey</td>
<td>level of contamination / department (Finistère, Morbihan, Loire-Atlantique, Vendée)</td>
<td>Only maps (without any possibility for extraction of numerical data)</td>
</tr>
<tr>
<td>the shoreline</td>
<td>reports (from 25 December to 13 January):</td>
<td>• affected areas are represented with dots.</td>
<td></td>
</tr>
<tr>
<td>Synthetic maps</td>
<td>Maps on oil drift</td>
<td>detailed oil slicks drift forecasting</td>
<td></td>
</tr>
<tr>
<td>(format *.JPG)</td>
<td></td>
<td>• comparison between MOTHY, OSIS and OILMAP simulations</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>• comparison of actual drift with drift forecasting (MOTHY model)</td>
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<tr>
<td></td>
<td></td>
<td>• oil drift simulation for eventual leakages from the wreck (MOTHY)</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>• oil drift simulation for a continuous leakage from the tanker when en route before she sank (MOTHY)</td>
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<tr>
<td></td>
<td></td>
<td>• backtracking : from two locations on the shoreline : Le Guilvinec and Le Croizic</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(MOTHY)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aerial survey reports</td>
<td>from 12/12/99 to 10/01/2000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>miscellaneous</td>
<td>the first days of the event : the ship route, the event location, the main slick drift</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>the ship route : detailed chronology</td>
<td></td>
</tr>
<tr>
<td>Cedre reports</td>
<td>news</td>
<td>data on response at sea, on the shoreline and other operational facts  (among which possible information or event about oil drift or behaviour (to be analysed)</td>
<td></td>
</tr>
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<td>(format *.doc)</td>
<td></td>
<td>• 126 reports in total:</td>
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<td></td>
<td></td>
<td>- approx. daily from 12/12/99 to 31/01/2000</td>
<td></td>
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<tr>
<td></td>
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<td>- approx. 2 per week from 01/02/2000 to 27/04/2000</td>
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<td>- approx. weekly from 04/05/2000 to 26/12/2000</td>
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<tr>
<td></td>
<td></td>
<td>- approx. 2 per month from January to April 2001</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>- 7 from may to November 2001 and 2 in 2002 (January and July)</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. *Erika* oil spill: computerized files available from *Cedre* archives

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3 daily or weekly synthetic report for the French ministries and services + partners
<table>
<thead>
<tr>
<th>Archives</th>
<th>Item</th>
<th>Data / information</th>
<th>Remarks</th>
</tr>
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<tbody>
<tr>
<td>format *.dbf (table)</td>
<td>Oil Drift</td>
<td>Monitoring of 10 drifting buoys, equipped with Argos system, launched in the Biscay Bay: 10 drifts (6 records per day): date / hour / location (latitude, longitude)</td>
<td>Corresponding weather data is not available at Cedre but possibly via Meteo France.</td>
</tr>
<tr>
<td>format Access and/or GIS (Geomédia)</td>
<td>Oil observation at sea</td>
<td>4996 records (from ship, aircrafts, etc.): date, heure, latitude, longitude</td>
<td>12/2002 – 12/2003</td>
</tr>
<tr>
<td>GIS (Geomédia)</td>
<td>Oil arrivals on the shoreline</td>
<td>3121 records: date / location (latitude, longitude); type of arrivals (tar balls, patties, slicks, etc.); level of contamination (low, mean, high)</td>
<td>01/03/2003 - 01/01/2004</td>
</tr>
</tbody>
</table>
| Format .JPEG | Remote sensing Satellite imagery | • ENVISAT: Nov (17, 23, 26, 27), Dec. (2, 3, 6, 9, 12, 13, 15, 16, 18, 19, 22, 25, 26, 28, 31), Jan (3, 6, 7, 13, 16, 23, 25, 26, 27), Feb (4, 7, 8, 11, 12, 13, 23, 26, 27), Mar (1, 2, 5, 6, 8), Apr (9, 10)  
• ERS 2: Nov (16, 20, 23, 26, 29), Dec. (2, 3, 6, 9, 12, 13, 15, 16, 19, 22, 26), Jan (1, 7, 16, 17, 20, 26), Feb (1, 11, 17, 21), Mar (1, 8, 24, 27)  
• RADARSAT: Nov (17, 18, 21, 25) | Satellite imageries along and off Galician coast |
| format *.doc | ‘Cedre reports 4 | • data on response at sea, on the shoreline and other operational facts (among which possible information or event about oil drift or behaviour (to be analysed)  
• 141 reports in total: daily from 15/11/02 to 28/02/03  
- 3 per week from 01/03/03 to 31/03/03  
- weekly from 01/04/03 to 30/09/03  
- 5 from oct.03 to January 2004 | |

Table 3. The Prestige oil spill: computerized files available from Cedre (or at Meteo France).

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4 daily or weekly synthetic operational emergency report for the French ministries and services + partners
APPENDIX 2
Chronology of events during the first two weeks of the *Erika* spill: main facts regarding detection and monitoring of the oil

**DETECTION / MONITORING OF THE OIL:**
**MAIN FACTS FOR THE 1ST WEEK OF THE *ERIKA* SPILL**

1. **Déroulement de l’accident et observations aériennes des nappes de pollution**

Le pétrolier *Erika* signalait dans la journée du 11 décembre 1999 des difficultés (gîte anormale) durant sa navigation depuis le port de Dunkerque en direction de Gibraltar. Le navire se dirigeait alors vers Donges en Loire Atlantique pour se mettre en relâche. Le capitaine du navire indiquait qu’il contrôlait la situation. Le *Cedre* était mis au courant de la situation et prenait contact avec la Préfecture maritime de Brest (AEM) et TOTAL FINA (propriétaire de la cargaison). L’*Erika* est un pétrolier de 180 mètres de long, construit en 1975 au Japon. Il bat pavillon maltais et transporte pour le compte de TOTAL FINA (affréteur) 31 000 m³ de fuel n°2, cargaison ayant été chargée à la raffinerie des Flandres à Dunkerque.

**Jour de l’accident (J0):** Le 12 décembre à 5h30, le navire lançait un message de détresse. **Vers 7h, le navire faisait naufrage** et le CROSS Etel engageait les moyens aériens et nautiques pour réaliser les opérations de sauvetage de l’équipage. A 8h, le *Cedre* était alerté par la Préfecture maritime de Brest de la situation du navire et était mandaté pour **recueillir les informations concernant les conséquences d’un éventuel déversement en mer**. Le navire était positionné au 47°13’N – 004°34’W, environ à 40 milles au sud de Penmarch. En latitude, le navire se trouvait à environ 80 milles de la côte, sensiblement au niveau de St Nazaire. Le PC de crise du *Cedre* était armé le 12 décembre à partir de 9h30.

A 11h, les informations en provenance de la PREMAR Brest (COM) faisaient état de la rupture du navire en deux tronçons, sans savoir exactement à quel niveau se situait la rupture. La partie arrière du navire (environ 100 m de long) était positionnée au 47°13’N – 04°28’W et la partie avant au 47°14’N – 04°31’W. Le survol aérien indiquait une pollution par hydrocarbures, la nappe observée étant estimée à une longueur de 1,5 km et 200 m de large. L’estimation quantitative d’une telle nappe se situe entre 300 tonnes (pour une épaisseur de 1 mm) et 3 000 tonnes (pour une épaisseur de 1 cm).

Dans l’après-midi, les informations indiquaient que la partie arrière du navire, fuyarde, flottait en position horizontale, permettant une approche pour une manœuvre de remorquage. L’Abeille Flandre réussissait la manœuvre et prenait en remorque cette partie du navire, en direction du large à la vitesse d’un nœud. La partie avant du navire, d’environ 60 m de long et flottant en position verticale, est peu favorable à une prise en remorque.

Selon les dernières informations recueillies en fin d’après-midi du 12 décembre, les hypothèses de travail les plus pessimistes font état d’un contenu d’environ 10 000 m³ d’hydrocarbures dans la partie arrière, 10 000 m³ dans la partie avant et de 10 000 m³ de produit déversé en mer.

Les observations de l’avion Polmar effectuées entre 16h et 17h (heure locale) indiquent une nappe de 50 m de large sur 15 km de long, localisée dans un secteur situé entre le 47°10’N et 47°11’N en latitude et 04°14’W et 04°25’W en longitude.

A 18h, le plan Polmar mer est déclenché par le Préfet Maritime de l’Atlantique.

**J+1 (13/12/99):** La partie avant du navire a sombré durant la nuit du 12 au 13, sans que sa position exacte soit connue. A 14 H, une observation aérienne fait état d’une **nouvelle nappe** d’hydrocarbure en mer qui pourrait correspondre à des remontées d’hydrocarbure en provenance de cette partie du navire, mais ceci reste à l’état d’hypothèse et nécessite une confirmation ultérieure.

La partie arrière du pétrolier, prise en remorque par l’Abeille Flandre, prévue pour se diriger vers une direction sud-ouest, a également coulé à 14H50 au 47°09’N-04°15’W, par 110 à 120 m de fond. Un **heure plus tard, une nappe d’hydrocarbure était observée sur le secteur**, dimensionné dans un triangle de 700 m de côté et de 200 m de base.

La nappe d’hydrocarbure observée la veille (J0 entre 16H et 17H), était à nouveau localisée dans la matinée du J+1 (# 10H), apparemment scindée en deux nappes. Une nouvelle observation à 16H actualisait la position de la nappe, dont la vitesse de déplacement vers l’Est était estimée à 1,2 nœud.
J+2 (14/12/99) : Des observations de nappes en mer par les avions des Douanes et de la Marine ont eu lieu en matinée (# 10h, heure locale) et dans l’après-midi.

J+3 (15/12/99) : Des observations aériennes d’hydrocarbures en mer (avion Polmar) ont eu lieu en matinée et dans l’après-midi.
- En matinée, il apparaissait que la pollution de surface devenait insignifiante autour de la zone de naufrage de la partie avant du navire. Au niveau de la partie arrière, une pollution continue mais de peu d’importance était observée sur une zone de 400 m x 30m. Plus à l’Est, sur un front orienté Sud Est, 3 zones polluées étaient repérées, comportant de nombreuses plaques (plusieurs dizaines à une centaine de plaques de 5 à 8 cm d’épaisseur).
- Dans l’après-midi, les survols ont permis d’actualiser les positions des plaques observées en matinée.

Selon les reconnaissances aériennes, la densité de plaques d’hydrocarbures semblait moins importante que la veille (J+2). **À ce stade précoce de la crise, cette observation soulève l’hypothèse d’une dérive de plaques d’hydrocarbures en sub-surface.**
La dérive des hydrocarbures observés la veille (J+2) correspondrait à un déplacement moyen dans une direction Sud-Est d’environ 42 km.

J+4 (16/12/99) : Les observations du 16 décembre permettent d’identifier un déplacement des nappes vers le sud d’environ 30 à 40 km depuis la veille.

J+5 (17/12/99) : Les observations aériennes ont permis d’identifier et de suivre l’évolution :
- de deux séries de nappes dans le secteur de l’île d’Yeu
- de nappes de faible épaisseur s’échappant des parties avant et arrière du navire

Ces observations ont permis de constater que les nappes semblaient plus petites (30 à 50 m de diamètre) et moins nombreuses que la veille. Leur fragmentation est favorisée par les conditions météo océaniques, ce qui les rend plus difficiles à observer au moins pour les plus petites d’entre elles.
Les mauvaises conditions de visibilité sur zone ont empêché une reconnaissance plus large.
Des images satellitaires radar sont attendues de l’agence spatiale européenne (ESA). Il n’est pas certain qu’elles donnent des informations utilisables, compte tenu des conditions de mer.

J+6 (18/12/99) : Les survols de 10h et 16h30 ont permis de suivre la distribution de neuf nappes (d’un diamètre de 100 à 180 m) repérées l’après-midi de la veille. Un autre groupe de nappes repérées le matin de J+5 ne semble plus observable. Les prévisions météorologiques à 24 heures indiquent des vents de force 5 à 6, voire 7, qui devraient continuer à morceler les nappes.

J+7 (19/12/99) : L’observation du matin (10h30) a révélé la présence d’un ensemble de 11 nappes de diamètres compris entre 10 et 150 m, qui s’est déplacé d’environ 35 km vers l’est par rapport à sa position de la veille (J+6) au matin. Il est à nouveau repéré à 16h00, un peu plus au sud (95 km de Belle Ille, 50 km de l’île d’Yeu, 107 km d’Oléron et 19 km du plateau de Rochebonne).
Les prévisions météorologiques pour J+8 indiquent des vents de force 4 à 5, voire 6, de direction SE, mer agitée à peu agitée, qui devraient continuer à morceler les nappes en les écartant de la côte.

2. **Les prévisions de dérive : utilisation de l’outil modèle numérique**

12/12/99, jour de l’accident (J0) :
Une prévision de dérive de nappe était demandée le matin du 12 décembre à Météo France. Elle indiquait que le fuel resterait au large, subissant une dérive sur un secteur E à SE. Les projections à 5 jours (16 décembre) indiquaient une localisation de la nappe aux alentours de 46°50’N – 04°00’W.

En liaison avec Météo-France, le Cedre continuera d’étudier les prévisions de dérive de la pollution en fonction de l’évolution des conditions météorologiques.

**J+1 (13/12/99) :** Le 13 décembre, une prévision de dérive de la nappe d’hydrocarbure a été effectuée à partir de la position réelle (observations aériennes) de la nappe la veille (J0) à 16H. Le modèle de dérive MOTHY (Météo France) prévoit une dérive dans une direction ESE. Les observations aériennes in situ à J+1 valident ce calcul en ce qui concerne la latitude ; par contre il existe un décalage d’environ 6 milles vers l’Est entre les simulations et les observations.

Les prévisions MOTHY à 3 jours (échéance 16 décembre vers midi, soit J+4) situerait la nappe au niveau de l’île d’Yeu en latitude et à une distance d’environ 60 milles à l’ouest. 

Le modèle américain Oilmap, dont les prévisions n’ont pas été vérifiées sur zone, donne une position au voisinage de l’île d’Yeu le 17 décembre (soit à J+5).

En conclusion, les résultats produits par les divers modèles numériques de dérive (MOTHY et Oilmap) suggèrent que des arrivées d’hydrocarbure sur le littoral dans les prochains jours ne sont pas à exclure, sans toutefois permettre d’en préciser le lieu et le moment.

**J+2 (14/12/99) :** Le 14 décembre, sur la base des dernières observations aériennes de la veille (J+1), Météo France a fourni une prévision de dérive à 5 jours :

- Les prévisions de dérive et les observations aériennes sont assez cohérentes pour J+2 (avec toutefois une dérive calculée un peu plus Est que la position réelle de la pollution).
- Les projections à J+6 (18 décembre) indiquent des nappes qui restent au large, sensiblement à la hauteur (latitude) de l’île d’Yeu et à une distance d’environ 60 milles de l’île.

Compte tenu de l’importance de l’information prévisionnelle sur le déplacement des nappes en mer, précisons que Météo France fait tourner son modèle de simulation (MOTHY) à l’aide des différentes prévisions météorologiques disponibles : modèle français Arpège, modèles européens et modèle européen à longue échéance (prévision d’ensemble à 10 jours).

**J+3 (15/12/99) :** Pour la période [J+2 ⇒ J+3], la prévision de dérive de nappe du modèle MOTHY est cohérente avec la trajectoire des nappes in situ (déduite des reconnaissances aériennes). Un hiatus est cependant noté en terme de vitesse de déplacement.

Les projections à 4 jours (re-calées à partir de la situation au 15/12, soit à échéance du 19/12) indiquent que une position des nappes sur un secteur au large de l’île d’Yeu.

**J+4 à J+7 (16 au 19/12/99) :** Les prévisions de dérive MOTHY1 (direction et vitesse) sont relativement cohérentes avec les positions relevées quotidiennement lors des observations aériennes.

3. **Un intérêt à étudier le comportement du produit apparu tôt au cours de la crise**

Dès le 12 décembre, la fiche d’analyse du produit Fuel lourd n°2 était obtenue de TOTAL FINA en provenance de la Raffinerie des Flandres. Le produit transporté est un produit raffiné lourd (densité : 1,00) et très visqueux (viscosité d’environ 20 000 cSt à 10°C).

Premier constat : il n’est par conséquent pas dispersible chimiquement par des produits dispersants en cas de déversement en mer. La limite de dispersibilité est en effet donnée à 2 000, voire 5 000 cSt.

Deuxième constat : Le comportement du produit laisse supposer, compte tenu de ses caractéristiques initiales, de très faibles taux d’évaporation, de dispersion dans la colonne d’eau et de formation d’émulsion. Par conséquent, il est vraisemblable que l’état de la mer (très forte avec des creux de 6 à 8

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1 Chaque jour, les simulations sont réalisées à partir des positions réelles les plus récentes relevées par les observations aériennes.
mètres) entraîne une **fragmentation du produit à la surface** et une **dérive à terme de produit sous forme de plaques, galette et boulettes**.

Dès le 12 décembre, et afin de vérifier ces hypothèses de comportement du produit, le **Cedre** a proposé à TOTAL FINA d’expérimenter directement dans son anneau d’essai (polludrome) le comportement du produit transporté par le pétrolier **Erika**. Un échantillon du produit (100 litres) a été envoyé par la Raffinerie des Flandres et est attendu au **Cedre** en fin de soirée.

<table>
<thead>
<tr>
<th>Fuel lourd FO2 (Erika)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Teneur maximale en eau</td>
<td>Environ 51%</td>
</tr>
<tr>
<td>Viscosité initiale (10 – 11°C)</td>
<td>43 000 cSt</td>
</tr>
<tr>
<td>Densité</td>
<td>0,996</td>
</tr>
<tr>
<td>Hydrocarbures saturés</td>
<td>30%</td>
</tr>
<tr>
<td>Hydrocarbures aromatiques</td>
<td>48 %</td>
</tr>
<tr>
<td>Résines</td>
<td>15%</td>
</tr>
<tr>
<td>Asphaltenes</td>
<td>8%</td>
</tr>
</tbody>
</table>

Analyse physico-chimique de la cargaison de l’Erika.

Le 13 décembre, le **Cedre** a procédé à une expérimentation en polludrome, dont les premiers résultats suggèrent que le produit ne se disperse pas naturellement dans la masse d’eau. Il reste flottant et se fragmente peu. Le produit a tendance à **former des émulsions atteignant 30% puis 50 % d’eau au maximum** (en 24 et 48h respectivement). La viscosité du produit atteint respectivement des valeurs de 70 000 cSt et 200 000 cSt.

Ces premières constatations en milieu expérimental sont **cohérentes avec les observations aériennes in situ** qui signalent des nappes dérivantes non fragmentées. Ceci indiquerait une forte probabilité d’arrivées de **nappes** à la côte et non à des arrivées d’éléments fragmentés (plaques, boulettes,…).

Outre les aspects techniques (viscosité élevée), le taux d’émulsion important –avec un volume multiplié par 2- peut poser des **problèmes en termes de logistique de stockage** du produit récupéré. Une suggestion est émise le 14 décembre par le **Cedre** : ce taux d’émulsion aurait pour autre conséquence de diminuer la capacité d’adhérence et de faciliter la capacité de pompage pour la récupération du produit en mer.

Un nouveau résultat : l’émulsion du produit « vieilli » apparaît **très stable**, n’étant pas cassée par un échauffement à 40°C. La fraction des hydrocarbures saturés est située dans une gamme du n-C16 au n-C28. La **toxicité du produit est probablement réduite, compte tenu de son insolubilité**. Les effets à craindre sur la faune et la flore sont donc essentiellement *physiques* (englue).

**J+4 (16/12/99)** : Un échantillon d’émulsion prélevé en mer contient 30% d’eau et présente une viscosité de 250 000 cSt. Le produit apparaît plus collant que le produit suivi dans le polludrome, lequel est émulsionné à 54% d’eau, pour une viscosité d’environ 500 000 cSt et une densité de 1,015 (légèrement plus importante que la densité initiale).

**J+5 (17/12/99)** : Des expérimentations menées sur l’échantillon prélevé en mer ont montré qu’il était possible de faire descendre la viscosité du produit par chauffage. L’action combinée de chauffage et de dés-émulsifiants permet de faire ramener la proportion d’eau de 30 % à 20 %. Ces éléments sont pris en compte dans la stratégie de lutte.

**J+6 (18/12/99)** : L’échantillon prélevé en mer évolue très lentement. L’émulsion se dirige probablement très lentement vers un taux d’eau de 50 %.
1. Déroulement de l’accident et observations aériennes des nappes de pollution

Du 20 au 22/12/99 : Les observations biquotidiennes ont permis de positionner (coordonnées géographiques) et de suivre le déplacement de nappes ou d’ensembles de nappes de fuel lourd de dimensions variables : depuis une dizaine de mètres de diamètre jusqu’à plusieurs centaines de mètres de long (ex : 30x300m ; 150x200m…).

Du 23 au 24/12/99 : Les nappes semblent se fragmenter en mer au long de cette 2ème semaine de crise : de l’ordre de la dizaine le 20/12, elles passent à environ une trentaine le 23/12 dont les dimensions n’excèdent pas 10mx10m. Les suivis des nappes par l’avion Polmar semblent confirmer cet éparpillement des galettes compactes -de 2 à 10 m de diamètre- plus nombreuses mais plus petites d’un jour sur l’autre.

Consequences : au fil des observations, certaines nappes -ou groupes de nappes- sont parfois « perdues » sous l’effet du morcellement induit par les conditions hydro climatiques.

Par ailleurs, le 22, le morcellement d’une nappe du fait d’opérations de récupération en mer est visible lors des survols de reconnaissance de l’après-midi.

Le 24 (soit J+12), le survol de la zone des épaves de l’Erika par un avion Atlantique n’a pas permis de déceler de traces d’hydrocarbures en surface autour de cette position. Une nappe de 300mx1000m était observée le 26, dans la phase d’arrivages croissants sur le littoral. Durant cette phase (fin de semaine 2), de nombreuses nappes sont observables à proximité des côtes polluées (centaines de mètres, dizaines de kilomètres) lors des reconnaissances aériennes.

2. Comportement du fuel lourd (FO2) in situ

Du 20 au 22/12/99 : Les nappes en mer atteignent des épaisseurs de 30 à 40 cm, ce qui porte à croire que leur volume a peu diminué depuis le déversement. Cet épaississement des nappes fait que la proportion d’eau dans l’émulsion in situ est inférieure à celle prévue (i.e. résultats du laboratoire du Cedre). Un échantillon prélevé dans l’une des nappes contenait 25 % d’eau (Note : Ceci pourrait faciliter le traitement des déchets à terre (stockage)).

Les équipages des navires opérant en mer remarquent que le centre des nappes semble moins éмуlsionné que les bords (ce qui pourrait expliquer les différences entre les teneurs en eau prévues par les expérimentations en polludrome et observées réellement en mer).

3. Modélisation de la dérive

Du 20 au 22/12/99 : Globalement et quotidiennement, les observations aériennes des nappes en mer ont souligné la cohérence, au moins sur 24 heures, des prévisions de dérive réalisées par Météo France (lesquelles comportaient éventuellement de légers décalages). Il faut noter que les modélisations étaient chaque jour recalées, sur la base des positions des nappes en mer les plus récemment fournies par les survols.

Des prévisions quant aux arrivages à la côte, à échéance de 4 jours généralement, sont également permises par la modélisation de la dérive. Les prévisions quotidiennes pour la semaine 2 sont résumées dans le tableau ci-dessous.

J+8 (20/12/99) : Tentative d’affiner les prévisions L’Ifremer examine les complémentarités qu’il pourrait apporter par sa connaissance des courants côtiers et les modélisations dont il dispose dans la région.

Du 20 au 26, les prévisions météorologiques indiquent des vents et une mer agitée à forte, voire de très forte à grosse. Cette situation se confirme de jour en jour, s’aggrave même, entravant - voire interdisant les opérations en mer.

<table>
<thead>
<tr>
<th>Date de la simulation</th>
<th>Prévisions à 4 jours issues de la modélisation MOTHY (impact / arrivées à terre)</th>
<th>Observations (arrivées à terre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20/12/99</td>
<td>Pas d'arrivages à la côte au 24/12.</td>
<td>Aucune</td>
</tr>
<tr>
<td>21/12/99</td>
<td>Impact île d'Yeu dans la nuit du 24-25/12/99</td>
<td>Aucune</td>
</tr>
<tr>
<td>22/12/99</td>
<td>Impact île d'Yeu dans la nuit du 25-26/12/99 + second impact sur le continent (lieu et date imprécis)</td>
<td>Aucune</td>
</tr>
<tr>
<td>23/12/99</td>
<td>Pas d'impact île d'Yeu sous 4 jours. Impact prévu sur Noirmoutier le 26-27/12/99.</td>
<td>Arrivages en Vendée et Sud-Finistère (soit échéances à J+11 non prévues par les modèles)</td>
</tr>
<tr>
<td>24/12/99</td>
<td>Arrivées le 24 au soir à Belle-Île, et le 25 en Loire-Atlantique (Croisic)</td>
<td>Arrivages en Vendée et sud Finistère</td>
</tr>
<tr>
<td>25/12/99</td>
<td>Arrivées sur Belle-Île ce jour, risque entre le Morbihan et la Loire-Atlantique le 26, Île d'Yeu et Noirmoutier dans 3 à 4 jours.</td>
<td>Confirmation des arrivages prévus sur Belle-Île et en Loire Atlantique (prévisions Météo France du 24/12)</td>
</tr>
</tbody>
</table>

Premières prévisions d’arrivages de polluant à la côte (résultats produits par le modèle numérique de dérive MOTHY - Météo France) au cours lors de la semaine 2 (20-26/12/99)

4. **Arrivées de polluant à terre**

Des arrivées de galettes et plaques d’hydrocarbure sont signalées pour la première fois à J+11 (soit 4 jours après les premiers reports d’oiseaux mazoutés) sur les littoraux de Vendée (Île d’Yeu, Notre-Dame-de-Monts) et du Sud-Finistère (Penmarch). Les plans Polmar-Terre du Finistère et du Morbihan ont été déclenchés à J+12, rejoignant ainsi les départements de Loire Atlantique, Vendée et Charente maritime.

**Principales caractéristiques (aspect, physique…) des arrivages :**
Les arrivages se présentent sous la forme de boulettes et de plaques de taille variable, atteignant plusieurs dizaines de cm de large et quelques m de long, pour 5 mm à 1 cm d’épaisseur.
Sous l’action des tempêtes, les dépôts se produisent en hauts de plage, voire au dessus en étage supra littoral.
Le polluant ne percole pas dans les sédiments, mais les conditions météorologiques en favorisent l’enfouissement dans les plages (apports de sable) et les laisses de mer.
En zone rocheuse, le polluant adhère aux substrats.

**Phénomènes notables :**
Localement, l’hydrodynamisme permet une remobilisation spectaculaire des accumulations de FO2 constatées la veille (ex : Belle-Île entre le 25 et 26/12).
APPENDIX 3
Chronology of events during the first two weeks of the Prestige spill: main facts regarding detection and monitoring of the oil

DETECTION / MONITORING OF THE OIL:
MAIN FACTS FOR THE 1ST WEEK OF THE PRESTIGE SPILL

1. Déroulement de l’accident et observations aériennes des nappes de pollution

Jour de l’avarie (J0) : 13/11/02
Le mercredi 13 novembre 2002 à 14h50 TU, le pétrolier Prestige (243 mètres, 81 564 tonnes de jauge, battant pavillon des Bahamas) est en avarie machine et émet un MayDay au large du cap Finisterre (Galice, Espagne). Le navire accuse une gîte de 30° et les 27 membres d’équipage sont évacués par hélicoptère, excepté le Capitaine, son second et le chef mécanicien. Le navire dérive au gré des conditions météo-oceániques.

Le navire a chargé 77 000 tonnes de Fuel Oil M-100 (terminologie russe) au terminal de Ventspils, Lettonie se rend à Singapour. A 17h00 locale, une observation aérienne met en évidence une fuite de fuel en mer. L’hydrocarbure Fuel Oil M-100, est identique à celui déversé par le Baltic Carrier en mars 2001 au Danemark, et se caractérise par une densité relativement élevée proche de celle de l’eau (0.99) et une forte viscosité initiale de 615 cSt à 50°C. Il montre, par ailleurs, une très faible tendance à l’évaporation et à la dispersion naturelle, de plus, à l’instar du FO2 de l’Erika et du M-100 du Baltic Carrier, il tend à se mélanger avec l’eau de mer pour former une émulsion extrêmement visqueuse.

J+1 (14/11/02) : Après plusieurs tentatives infructueuses dans la nuit du 13 au 14 novembre les remorqueurs espagnols de SASEMAR1 réussissent à prendre le pétrolier en remorque dans la matinée du 14/11. Du fuel déversé à partir du pétrolier forme un chapelet de nappes de tailles variables (5 mètres de diamètre à 2 milles nautiques de longueur) s’étendant sur 20 milles nautiques de long.
Le « Biscay Plan », accord bilatéral de coopération entre la France et l’Espagne en matière de lutte contre les pollutions accidentelles dans le golfe de Gascogne, est déclenché à midi le 14 novembre. Les moyens nautiques et aériens de la Marine Nationale et des Douanes sont mis immédiatement à disposition de SASEMAR. Le remorqueur de haute mer de la Marine, AILETTE appareille le jeudi 14 novembre à 20 heures et se dirige vers le cap Finisterre. Un officier de la CEPPOL2 et un ingénieur du Cedre participent à la mission.

J+2 (15/11/02) : Le 15 au en soirée le PRESTIGE fait route au Sud sous remorque. Le navire aurait une déchirure de 35 mètres de long sous la ligne de flottaison. La société Smit Salvage pressentie pour le sauvetage du navire est sur place. Des observations aériennes sont lancées.

1 Societad de Salvamento y Securitad Maritima.
2 CEPPOL. Commission d’Etudes Pratiques de Lutte Antipollution
J+3 (16/11/02) : Une nappe a été repérée par l’avion Polmar 2 des Douanes Françaises, dérivant à 10 nautiques à l’ouest du Cap Finisterre.

J+4 (17/11/02) : Le navire se trouve à la position 42°47’ N / 10°50,5’ W, soit à environ 75 milles à l’ouest du cap Finisterre. L’avion Polmar 2 de la Brigade de Surveillance Aéro-maritime de Hyères (Douanes françaises) a effectué un survol le matin et observé deux nappes : l’une de 5 m de diamètre, l’autre de 20 m de diamètre. De façon générale, les différentes reconnaissances aériennes indiquent la présence d’un chapelet de nappes qui coïncide avec la route suivie par le Prestige. A 12h00 UTC, l’équipage de l’avion Polmar 2 signale des fuites abondantes au niveau du navire, stoppé alors à 42°45’N / 10°50’W.

L’hélicoptère Helimer Galicia a également survolé la zone (09h00), et permis d’observer plusieurs nappes à proximité des côtes.


J+6 (19/11/02) : Vers 08 h 00 TU, le Prestige s’est cassé en deux parties à la position 42°15,6 N et 012°08,3 W soit à plus de 130 nautiques dans le 255 du Cap Finisterre. La partie arrière sombre vers 12heures par 42°12’N/12°03W, suivie vers 16 heures de la partie avant. Les fonds à cette position sont de 3 500 m. Les nappes observées lors des survols aériens s’avèrent proches du littoral et devraient s’échouer dans les jours qui viennent.
Cinq hélicoptères et 3 avions assurent la surveillance aérienne. Un avion Polmar des Douanes françaises survole les zones affectées par le naufrage, tandis qu’un Falcon 50 de la Marine surveille les zones à l’ouvert du golfe de Gascogne.

**J+7 (20/11/02) :** Un avion des Douanes françaises survole deux fois par jour la zone des épaves et ouest cap Finisterre. Plusieurs séries de nappes sont repérées. Au dessus des épaves, on remarque une zone polluée de cinq nautiques carrés, deux nappes importantes (200 x 80 mètres et 90 x 49 mètres) à 28 nautiques dans le 240 du cap Finisterre, et enfin, une autre zone de 10 nautiques de longueur, riche en galettes de quelques mètres de diamètre, dont le centre est localisé à 10 nautiques au sud du Cap Finisterre.

Dans la matinée, l’avion Polmar 2 a confirmé la pollution sur la zone du naufrage mais il n’a pas pu relocaliser de manière précise les nappes à la dérive. La dégradation des conditions météo n’a pas permis de faire des observations efficaces (vent de 40 à 50 nœuds sur zone).

2. **Les prévisions de dérive : utilisation de l’outil modèle numérique**

**13/11/02, jour de l’accident (J0) :** Des prévisions de dérive initiales sont activées par Météo France dès le 13/11/02 (19h00). Elles prévoient l’arrivée du fuel à la côte dans l’après midi du 15/11/02 au nord du cap Finisterre (Espagne). Elles sont confirmées par les prévisions de dérive émises le 14/11/02, pour ce qui concerne l’extrémité Nord Est de la nappe de 20 nautiques.

**J+3 (16/11/02) :** Une simulation de dérive réalisée par Météo France montre une dérive de la nappe observée par l’avion Polmar au sud puis nord à partir du 17 novembre en soirée.

**J+4 (17/11/02) :** Les prévisions de dérive effectuées par Météo France sur les deux nappes (43°07’ N / 009°20’ W et 42°32’ N / 009°24’ W) indiquent qu’elles vont tendre à dériver vers le N-NE dans les prochaines 72 heures, rabattues sur le littoral galicien suite à la renverse des vents du SW vers le NW à partir de la matinée de mardi. La nappe la plus nord, 6 milles dans le sud-ouest du cap Villano (nord de la ria de Camariñas), pourrait toucher la côte sous 24 à 48 heures, tandis que la nappe la plus sud, localisée 14 milles dans l’ouest du cap Corrubedo, ne devrait pas toucher la côte avant 3 à 4 jours.

**J+5 (18/11/02) :** Une prévision de dérive à trois jours (21/11/2002 à 18 heures TU), montre que les nappes observées ce jour se trouveront à environ une dizaine de nautiques dans le sud-ouest du Cap Finisterre.

**J+6 (19/11/02) :** Après rupture du navire, une prévision de dérive est réalisée sur une période de 72 heures à partir de la zone de l’épave. Elle indique une dérive des nappes en direction des côtes occidentales de la péninsule ibérique. Etant donné la distance entre le point de naufrage et la côte, il n’est pas possible de localiser précisément des zones potentielles d’arrivages. La prévision de la dérive positionne les nappes après 72 heures, à plus de 90 milles nautiques dans l’ouest du Cap Finisterre.
3. **Un intérêt à étudier le comportement du produit apparu tôt au cours de la crise J+7 (20/11/02) :** Des échantillons prélevés en mer par l’*Ailette* sont acheminés au *Cedre* pour étudier la signature chimique du produit. Il est prévu que le *Cedre* répartisse cet échantillon vers ses partenaires du LASEM et de l’IFREMER. D’autre part, Sasemar s’efforce d’obtenir un fût de produit d’origine, en provenance de Saint-Pétersbourg, pour permettre d’en évaluer le comportement dans les enceintes expérimentales du *Cedre* (notamment le polludrome).
Détection / Monitoring of the Oil: Main Facts for the 2nd Week of the Prestige Spill

1. Observations aériennes des nappes de pollution : principaux points durant la deuxième semaine de crise :

* Secteur Ouest de la Galice

Les observations aériennes ont permis de suivre un certain nombre de nappes de dimensions importantes à proximité de l’épave. Comme dans le cas de l’Erika, un phénomène de morcellement des nappes de fuel lourd a été observé. Ce processus est probablement appuyé par l’hydro climat (forts vents, mer agitée). Par exemple, le 21, une nappe qui s’étend sur 2 milles de long et 300 mètres de large (estimée à un volume supérieur à 12 000 m³) se présentait 24 heures plus tard sous la forme d’une centaine de tâches formant un triangle de près de 15 nautiques de côté, dérivant vers l’est-nord-est.

Un certain nombre d’ensembles de nappes sont détectés à proximité de l’épave au cours des jours suivants l’accident. Ils sont constitués d’unités atteignant de l’ordre de la dizaine de km², pour des volumes de l’ordre d’1 à plusieurs centaines de m³. Autant que les conditions le permettent, les ensembles de nappes les plus importants sont suivis quotidiennement par les avions de reconnaissance, dont l’avion Polmar 2. Néanmoins, durant les deux premières semaines de la crise, si certains vols ont ainsi permis de re-localiser les plus importantes zones de pollution, d’autres reconnaissances aériennes ont dû être annulées à cause de conditions météorologiques défavorables sur la zone où la pollution était la plus concentrée (zone de travail des navires).

Il est par ailleurs à noter que si SASEMAR coordonne les navires en mer, chaque aéronef est contrôlé par son autorité nationale : les aéronefs français par la France, les portugais par le Portugal et les espagnols par la Xunta de Galicia. En définitive, plusieurs survols sont programmés sur les mêmes zones aux mêmes heures, ce qui ralentit l’acquisition d’informations et pose le risque que certaines zones ne soient pas survolées pendant plusieurs jours en cas de dégradation météo en cours de journée.

[Au vu des données disponibles quant au chargement du navire, les volumes déversés à la date du 22/11 sont estimés à au moins 16 000 m³ (volume des capacités supposément endommagées : une citerne centrale et une citerne latérale de faible capacité). A ce volume il convient d’ajouter ce qui est remonté suite au naufrage, constitué notamment les 2 nappes observées le 22/11 (72 heures après le naufrage) à proximité de la verticale des épaves. Le volume déversé est donc au moins du même ordre que dans le cas de l’Erika (20 000 m³).]

* Secteur Nord : Golfe de Gascogne

Le 24/11, une vingtaine de taches de 1 à 5 mètres de diamètre est détectée par un hélicoptère de surveillance des pêches espagnol à 5 milles nautiques du cap Ortegal, point le plus nord de la Galice. Cela signifie que les hydrocarbures ont atteint l’entrée du golfe de Gascogne, en quantité inférieure toutefois par rapport aux nappes qui dérivent à l’ouest-sud-ouest du cap Finisterre. L’avion Falcon 50 (Marine Nationale) survole le sud du golfe de Gascogne et repère 4 accumulations de nappes (irisations et plaques d’émulsion) se trouvant d’ores et déjà dans le golfe. Les nappes les plus à l’est se trouvaient dans un ensemble centré sur la position 44°15’N / 06°58’W ; les plus au nord dans un ensemble centré sur la position 44°31’N / 07°20’W.

En raison de conditions météorologiques adverses, certains vols de reconnaissance ont par la suite dû être annulés dans cette zone (par exemple le 26/11), ce qui a entravé la détection le suivi et la simulation des dérives des nappes de fuel.

On note que, par exemple durant les derniers jours de novembre, des observations de nappes ont été faites par des avions lors des premiers vols de la journée (matinée), mais celles-ci n’ont pu être re-localisées lors des survols ultérieurs (après-midi). Ceci est venu illustrer les difficultés d’assurer, dans la durée, le suivi des nappes par reconnaissances aériennes. Ces observations, déjà tributaires des aléas météorologiques, sont probablement entravées en raison du comportement du fuel lourd – notamment d’une dérive possible des nappes d’émulsion submergées.
Le problème de la submersion des nappes et de leur suivi s’est posé relativement tôt, environ une semaine après le naufrage du *Prestige*. L’hypothèse d’une dérive des nappes en dessous de la surface est étayée par les résultats produits au *Cedre* lors de l’étude du vieillissement du fuel lourd (émulsion chargée en eau, atteignant une densité proche de celle de l’eau de mer).

De fait, ces problèmes ont jeté un certain doute quant à la présence et à la position de nappes dans la zone nord-Galice. L’une des solutions alors envisagées a été de doubler les observations aériennes d’observations par navire. A cet effet, un avis a été lancé à tous les navires croisant sur cette zone le 27/11. Toutefois les informations recueillies ne concernent, là encore, que des nappes de surface. Malgré la présence très probable de plaques submergées, il arrive que des nappes observées à quelques jours d’intervalle semblent correspondre, si l’on se réfère aux prévisions Mothy. Par exemple, des nappes épaisse observées le 25/11 à l’entrée du golfe de Gascogne ont été re-localisées le 1er décembre dans une zone correspondant aux prévisions du modèle. La cellule observations/prévisions estime qu’il existe une assez bonne cohérence entre prévisions et observations, ce qui permet de continuer à se fier aux prévisions Mothy.

* Tentative d’exploitation de données satellites :* Les images satellites prises le 27/11 ne fournissent pas d’informations exploitables. L’exploitation d’images satellites prises le 2/12 par ERS et Envisat laisse supposer des remontées par « bouffées » depuis les épaves dans la mesure où apparaissent deux paquets de nappes bien distincts, l’une à environ 20 km au SSE des épaves (5 x 3 km) et l’autre dans le Sud Est de l’épave à environ 50 kms. Cette hypothèse est confirmée par les observations aériennes figurant sur les cartes de synthèse jointes établies par SASEMAR.

2. *Modélisation de la dérive : principaux points durant la deuxième semaine de crise :* Comité de dérive et suivi des nappes anciennes.

Afin de tenir compte de la dérive des nappes repérées tout au long du cheminement du navire alors qu’il était en remorque, le Secrétariat Général de la Mer demande la mise en œuvre d’un groupe de travail le 21 novembre. Officiellement créé le 25, ce comité « Dérive des nappes du *Prestige* » intègre les spécialistes de la dérive de Météo-France, de la Marine Nationale et du *Cedre*. Il s’agit de répertorier les nappes dont la présence a été attestée, et de simuler leur dérive en se basant sur les conditions météorologiques réellement observées, et non plus calculées, comme c’est le cas avec MOHY.

Le but de cette étude est d’apprécier la dérive de nappes susceptibles de pénétrer au sud du golfe de Gascogne et de pouvoir guider les aéronefs de surveillance. Un comité d’experts, placé sous l’autorité du Secrétariat général à la mer pour fournir quotidiennement des éléments cohérents et pertinents sur la dérive des nappes. Ce comité regroupe des experts de Météo France, le SHOM, l’IFREMER et le *Cedre*.

Exemple de carte fournie par le comité de dérive des nappes du Prestige à la Préfecture Maritime (source : Cedre)

Durant les premières semaines de crise, les prévisions de dérive sont réalisées quotidiennement, voire bi quotidiennement, en utilisant les plus récentes positions des nappes pour faire tourner le modèle. Durant les 2 premières semaines suivant le naufrage, la difficulté observer les nappes, liée à des conditions météo océaniques interdisant éventuellement les vols, mais aussi au comportement du polluant (submersion), a entraîné une difficulté à modéliser leur dérive en utilisant des positions régulièrement validées. Néanmoins, comme il l’a été signalé dans la partie ‘observations des nappes’, des positions de tâches de pollutions importantes se sont avérées coincider avec des prévisions de dérive lancées quelques jours auparavant sur des nappes également importantes, mais entre-temps « perdues ». Sur la base de cette constatation, il a été considéré raisonnable par la cellule observations/prévisions de dérive de continuer à se fier aux prévisions du modèle de dérive MOTHY.

En cas d’impossibilité de positionner les nappes lors de survols en raison des conditions météorologiques (par exemple les 26 et 27 dans le cas des nappes au sud du golfe de Gascogne), les simulations sont réalisées à partir des dernières positions avérées des nappes de fuel en intégrant toutefois les données météorologiques réelles durant le laps de temps depuis lequel la nappe est « perdue ».

Le 3 décembre, sur les recommandations de la cellule observations/prévisions, plusieurs bouées flottantes de type IESM – PTR (6) et de type Surdrift (2) munie d’une chaussette de 15 mètres ont été mouillées au niveau d’une zone contaminée par des nappes de diamètre compris entre 4 et 8 m et d’épaisseur allant de 0,5 à 1,2 m, soit des volumes unitaires de l’ordre de 10 à 50 m3. La cellule avait recommandé de larguer 2 bouées de surface et une de sub-surface par nappe, et suggéré de tailler une traîne dans un filet à civelle pour rendre les bouées de surface solides de nappes. Ces différentes bouées sont suivies en temps réel au Cedre ce qui permet d’en obtenir la dérive effective et estimer ainsi la dérive des nappes « marquées », et de pallier aux problèmes de détection aérienne.

Les conditions météorologiques en mer sont relativement difficiles, avec une mer grosse du 21 jusqu’au 24/11. Au-delà, la mer reste agitée au moins jusqu’au 26 malgré des vents passagèrement en baisse.

Durant la deuxième semaine de crise (soit au cours de la semaine succédant au naufrage du navire), les vents sont gross pour les secteurs ouest-est et sud-ouest, oscillant entre sud-ouest et nord-ouest, soit vers le continent. Les 25 et 26, les vents sont d’environ 20 nœuds, et selon les zones virent de sud ou sud-ouest à sud-ouest et ouest respectivement.

3. **Etude du comportement du fuel lourd (FO2) au laboratoire**

**Du 21 au 22/12/99 :** Le laboratoire du Cedre a effectué les premières analyses sur les échantillons reçus le 22/11, en provenance de l’Ailette. Le produit, récupéré après plusieurs jours de dérive en mer, est comparable à celui transporté par l’Erika. Bien qu’un peu plus visqueux, la distribution des
hydrocarbures est comparable. La signature du produit est très bien caractérisée. C’est un fuel lourd M-100 selon la terminologie russe. Par ses caractéristiques, c’est un fuel lourd n°2 comparable à celui de l’Erika. La composition globale, comparée à celle de l’Erika fait apparaître sensiblement moins de composés aromatiques, ce qui laisse présager une toxicité moindre.

<table>
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<th>saturés</th>
<th>aromatiques</th>
<th>résines</th>
<th>asphaltènes</th>
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<tr>
<td>Prestige</td>
<td>48.4 ± 1.0</td>
<td>37.6 ± 1.9</td>
<td>8.3 ± 0.8</td>
<td>5.6 ± 0.6</td>
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</table>

Depuis le 25/11/99, du fuel issu du Prestige a été placé dans le polludrome du Cedre, dans le but d’étudier son vieillissement. En début décembre (2/12), il est établi que le fuel a la capacité de se charger en eau de mer à hauteur de 61%, ce qui a plusieurs conséquences : les volumes à récupérer seront 2,5 fois plus importants que les volumes déversés ; la densité calculée de l’émulsion est de l’ordre de 1,01 c’est-à-dire moins de 1% inférieure à la densité de l’eau de mer. De ce fait, sous l’effet d’une agitation de surface (vagues, clapot), le polluant aura tendance à passer en sub-surface. D’autre part, à l’approche des côtes, le polluant coulera probablement si l’il rencontre des eaux saumâtres (estuaires).

Une autre expérimentation a été initiée le 26/11/99 dans le banc à essai du Cedre, pour déterminer les possibilités de nettoyage par la mer (auto nettoyage) du fuel du Prestige. Il s’agit de plaques de granite polluées par du fuel du Prestige placées dans une enceinte expérimentale simulant les mouvements de l’eau. En parallèle, des plaques identiques ont été installées dans un site expérimental in situ (l’Ile des Morts, rade de Brest) pour évaluer l’importance du nettoyage naturel en conditions réelles.

4. **Arrivées de polluant à terre**

**J+8 (21/11/02) :** Des arrivées de galettes et plaques d’hydrocarbure sont signalées. Le 24/11, des reconnaissances du littoral sont menées sur les zones de Malpica et Corme (à 100-150 km environ à l’ouest de la Corogne) par des experts du Cedre, dans le but d’estimer l’importance de la pollution et de préconiser des techniques de nettoyage ainsi que les équipements à mettre en œuvre. Sur cette zone, le polluant arrive à terre sous une forme très émulsionnée, avec un aspect et une consistance proches de ceux observés suite à l’accident de l’Erika.

**Phénomènes notables :** En certains endroits, les nappes s’échouant au cours des premiers jours après que le navire se soit brisé (19/11) tendent à être enfouies sous le sable (jusqu’à 40 cm de profondeur au bout d’une durée de l’ordre de 10 jours après échouage). Des pollutions en « mille-feuilles » sont aussi présentes sur quelques sites, ce qui correspond à une situation rencontrée lors de la pollution de l’Erika.
APPENDIX 4

SAR satellite images (courtesy of ESA) analyzed in order to detect the *Prestige* oil spill

**SATELLITE SURVEY OF THE *PRESTIGE* OIL SPILL**

Contained in the table below is an overview of the satellite images available at Cedre, from 2002 November 17th to December 26th.

Please note that these pictures should be credited as follows: *courtesy of ESA*.

With each photograph comes information including: date/hour; source (satellite), pictured global area, wind direction and speed (in knots).

Some pictures may be hardly exploitable because of bad weather in the spill area and/or poor resolution.

<table>
<thead>
<tr>
<th>Date</th>
<th>Hour</th>
<th>Satellite</th>
<th>Global Area</th>
<th>Source</th>
<th>Area (km)</th>
<th>Orbite</th>
<th>Area (km)</th>
<th>Orbite</th>
<th>Area (km)</th>
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<td>orbite 3741</td>
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<td></td>
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<td>2002-11-18</td>
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<td>RADARSAT-SAR</td>
<td>Standard S3 100 x 100 km</td>
<td>orbite 36747</td>
<td>From Cap de San Adrián to Porto do Son (Galicia)</td>
<td>Wind: SW; 20 knots</td>
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<td></td>
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<td>2002-11-20</td>
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<td>100 x 100 km chacun</td>
<td>orbite 39656</td>
<td>From NE of Coruña to Cap Mondego (Portugal)</td>
<td>Wind: S/SW; 30 knots</td>
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<td>2002-11-21</td>
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<td>Standard S7 3 standart</td>
<td>orbite</td>
<td>From NW of Coruña to N of Cap Mondego (Portugal)</td>
<td>Wind: W/SW; 30 knots</td>
<td></td>
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ASMA project.
Content: *Satellite survey (Photographs courtesy of ESA) of the Prestige oil spill.*

*Cedre.*
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<td>RADARSAT</td>
<td>Scan SAR Narrow 300 x 300 km</td>
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<td>From Cape Ortegal to Cape Mondego (Portugal)</td>
<td>W/SW; 25 knots</td>
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<td>NW Coruña – Cap Finistere to W Coruña</td>
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ASMA project.
Content: Satellite survey (Photographs courtesy of ESA) of the Prestige oil spill.  
Cedre.
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<td>405 x ? km, orbite 3963</td>
<td>W/NW</td>
<td>10 knots</td>
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**Scan SAR Narrow**
- (300 x 300 km)
- orbite 36847
- From NE Coruña to Cap Mondego (Portugal)
- Wind: S/SW; 15 knots

**Wide Swath**
- (405 x 405 km)
- orbite 3670
- W Coruña
- Wind: S/SW; 15 knots

**SAR**
- 100 x 100 km chacun
- orbite 39749
- 855-837-819
- W coast of Spain and Portugal
- Wind: S/SW; 20 knots

**100 x 100 km chacun**
- orbite 39742
- 2745-2763
- East of the Prestige wreck
- Wind: S/SW; 20 knots

Content: *Satellite survey (Photographs courtesy of ESA) of the Prestige oil spill.*

*Cedre.*
ASMA project.
Content: Satellite survey (Photographs courtesy of ESA) of the Prestige oil spill.

Cedre.
### Satellite Survey of the Prestige Oil Spill

#### Photos courtesy of ESA

**Date:** 2002-12-09 11:21

- **3 ERS-2 SAR**
  - 100 x 100 km
  - **orbite 39928-2709**
  - 🏝 NW Coruña

**Date:** 2002-12-09 11:21

- **3 ERS-2 SAR**
  - 100 x 100 km
  - **orbite 39928-2727**
  - 🏝 NW Coruña

**Date:** 2002-12-09 10:52

- **ENVISAT QL ASAR**
  - 405 x 7 km
  - **orbite 4056**
  - 🏝 NW Coruña to W from Portuguese Coast

**Wind:**
- Coastal zone: S/SE; 30 knots, changing to NE; 30 knots towards northern zone
- Open sea: NW; 10 knots

**Date:** 2002-12-09 22:10

- **ENVISAT QL ASAR**
  - 405 x 405 km
  - **orbite 4063**
  - 🏝 Cantabrian Coast

**Wind:**
- E/SE; 5 knots near Cap de Peñas and SE 10 knots near Santander.

**Date:** 2002-12-12 22:45

- **2 ERS SAR**
  - 100 x 100 km
  - **orbite 39971-2745**
  - 🏝 W and SW Coruña

**Wind:**
- W/SW; 15 knots

**Date:** 2002-12-13 10:26

- **ENVISAT QL ASAR**
  - 405 x 7 km
  - **orbite 4113**
  - 🏝 From Cap de Peñas (Basque country) to the mouth of Gironde river (France)

**Wind:**
- E; 15 knots (S; 10 knots towards Santander)
ASMA project.

Content: Satellite survey (Photographs courtesy of ESA) of the Prestige oil spill.

Cedre.
Content: Satellite survey (Photographs courtesy of ESA) of the Prestige oil spill.
APPENDIX B

Remote Sensing Assessment of Sub-surface Oil (WP2.1)
Remote Sensing Assessment of Sub-surface Oil

**Sea Venture II**

The oil spill accident was observed on January 21, 2005 in the morning at ca 7:00. The route the past 24 hours is known and given within these coordinates: Lat 55 38.94, Lon 10 47.12 to Lat 55 42.97; Lon 10 58.39. The geographical area of interest is the entire neighbourhood from January 20 to February 4th including the Great Belt region from the northern point of Langeland to Sejrø in the north.

The following remote sensing data were available for the Sea Venture II oil spill incident and covering the area of interest:

**MERIS Full Resolution (FR) 300 x 300 m pixels**
- February 1: excellent quality
- February 7 and 9: clouded and not useful

**MERIS Reduced Resolution (RR) 1 x 1 km pixels**
- January 21: acceptable, some clouds in the central Great Belt area
- January 22: excellent quality
- January 25: clouded, however, the Southern part of the Great Belt area can be seen
- February 1: excellent quality
- February 2: excellent quality

**MODIS**
- January 21, 22, 23, 24, 25, 28 and 31. Only January 25 allows identifying the area, but the quality of all data are not useful and clouded.

**High resolution data**
- No QuickBird, Ikonos, SPOT or Landsat data were available.

**Image processing**

The data used are the standard MERIS RR/FR level 2 products. BEAM 3.5, the VISAT module, was used to convert the N1 format to Geotiff in order to allow further processing in ENVI. BEAM was used to project data to UTM.
Analysis
Initially the MERIS FR data were analyzed and the MERIS FR image from February 1 showed some interesting structures in the water between Funen and Langeland, east of Langeland, in the bay of Kalundborg and between Kalundborg and Sjællands Odde. Figure 1 below shows a close up of the area of interest and figure 2 shows the larger region.

Figure 1. Close up of the area of interest. MERIS FR image from February 1, 2005 with band 4 (510 nm), 5 (560 nm) and 6 (620 nm) in RGB. Bay of Kalundborg indicated in the northern part of the image. See text for comments and analysis.
Figure 2. This is the same image as shown in figure 1, however, the larger region is shown, where the general dark areas to the east can be seen.

When analysing the individual bands as well as colour composites, the most contrast in the water is obtained using band 2, 3, 4, 5, 6 and 7. The contrast is weaker in band 8 and in band 9 noise begins to appear. The preferred bands are 4 (510 nm), 5 (560 nm) and 6 (620 nm); however, using band 4, 3 and 2 also provided a useful composition and were used. Given the time of the year and the high latitude, there is not much light being reflected from the water body. It is clear that towards the east the light is graduate being reduced both as a consequence of the longitude but equally because of the progressive low sun angle. Consequently are the structures observed around Langeland and at Kalundborg not necessary due to the presence of sub surface oil, but can equally be an effect of the low light situation.

Additional MERIS RR were acquired and analyzed. Especially the image from February 2 was of interest. If substantial areas with su surface oil could be observed on February 1, it would be expected to see some of the same features on the following day. On the image from February 2, two weak features may be seen in the Great Belt area East and West from the island of Langeland, however, this is very uncertain, see figure 3. Observing other parts of the image from the second of February 2, the same dark features can be seen, e.g. east of Funen (blue arrow in figure 3).

The MERIS RR images from January 22 and 21 were used to cross check if the same two dark features around Langeland could be seen. Figure 4 shows these two images and some shades may be visible on January 22nd, but not in the January 21st image, however, the image from January 21 is obscured by clouds.
Figure 3. MERIS RR February 2, band 3,4 and 2 in red, green and blue.

Figure 4. To the left a MERIS RR from January 21, with band 3,4 and 2 in r,g,b. To the right a MERIS RR from January 22, with the same band combination.
Reservations against the identification of sub surface oil spill are:

- The limited amount of light being reflected from the water body
  - A multitude of effects can cause the dark features

In favour of an interpretation of the sub-surface oil detection are the following observations:

- January 29, oil is observed in the counties of Gudme and Ørbæk, south of Nyborg.
  - This is an exact match with the presence of the dark feature on the east coast of Funen.
- January 31, oil is observed at the island of Agersø, south of Korsør
  - A dark feature east of Langeland has it’s northern point 5 to 10 km south of Agersø
- There may be some indications in the images from the following day on February 2 that shows the same features.

**Prestige and Erica oil accidents**

Regarding the oil catastrophe with Prestige November 2002, eight MERIS and 10 MODIS images were acquired. However, no images were suitable for analysis due to severe cloud cover for the entire period.

With respect to the Erica incident in December 1999, eight SeaWiFS scenes were identified; however, only two scenes appeared to be useful and they were from the 9th of January 2000 and January 15th. The accident took place on the 12th of December and with close to one month to the first useful image, further analysis was abandoned.

**Conclusion**

Investigating the three oil spill accidents from Erica, Prestige and Sea Venture II has been a challenge because of the quality of the available EO data. This was known from the start. Either serious cloud cover has impeded analysis or simply not allowed acquisitions of data or secondly, when cloud free or partly cloud free data have been available, e.g. for the Sea Venture II case, the poor light conditions during winter have not allow unambiguous analysis and conclusions to be made. A substantial effort has been made carefully analyzing the available images and of the three cases, only the Sea Venture II case was suitable for continued work and has been reported here.

Most likely the present study of the Sea Venture II oil spill accident show that in winter time with low sun angles and limited reflected radiation, sub surface oil can not be identified in optical medium resolution EO data. However, features in an MERIS full resolution image from February 1, 2005, indicate possible signs of oil. The following MERIS reduced resolution images from February 2, 2005, could not confirm this, however, small differences in the image may exhibit some of the same features as shown in the February 1 image. In support of the interpretation is that oil occurrence on the beaches west of Funen facing Langeland were reported on January 29 and on the
island of Agersø on January 31. Reservations against the identification of sub surface oil spill are the limited amount of light reflected from the water body. The final conclusion must be that further studies are needed and that oil spill cases from the summer period should be used in order to allow the best quality optical EO data to be acquired.
APPENDIX C

Refining acoustic methods to detect and quantify sunken oil (WP2.2)
Introduction
During the last twenty years there have been several important spills involving heavy fuel oil in the world including North America and Europe. In many of these accidents, part of the heavy fuel has sunk and produced a threat to the environment that has been difficult to evaluate because of the lack of means of detection and monitoring. A number of acoustic seafloor mapping systems are commercially available but they have not been used or correctly used in monitoring actual oil spills. For this reason a comprehensive study of the available acoustic sensors is very necessary to help the selection of the most appropriate sensors and methods in case of an accidental oil pollution incident involving heavy fuel oil. The goal is to identify and monitor the possible accumulation areas in the most efficient way according to the local sea bottom conditions.

The first step is the review of the main types of acoustic sensors to estimate their capacity to detect heavy oil slicks on the sea floor. For this purpose a first selection of sonar was conducted and then a realistic detection experiment was performed in a large seawater tank, the bottom of which has been partially filled with medium- to coarse-grain sand and heavy oil slicks laid over. Indeed if there is an accumulation of oil on the seafloor it means that the heavier material like sand has also been trapped there given the fact that sand has a much greater density than any oil mixture.

The result of this experiment allows emphasis to be put on the most pertinent sensors and methods that could be efficient in terms of area coverage and oil discrimination. In addition other operational aspects are also of real importance because of the often bad meteorological conditions and the urgent need for a complete and efficient survey. This is a real challenge when considering the often inconclusive acoustic survey campaigns during the recent oil pollution incidents involving sunken oil.

Finally the operational constraints are taken into account regarding the complete process from the deployment of the acoustic system to the final map of the potentially polluted area.
ACOUSTIC EXPERIMENT AND RESULTS

Introduction
A wide set of acoustic sensors was selected according to their availability and characteristics so that all kinds of sonar could be tested in a large sea water tank on faked oil slicks laying on top of a sandy bottom.

Three different heavy oils were laid on top of sand in patches of two sizes and three thicknesses. In fact these oil patches were contained in flexible round skirts of two different diameters with porous mesh bottoms so as to avoid air bubbles underneath. But as the fuel oil was laid when still warm enough to easily spread there was some leakage around the containment skirt through the porous bottom. This led to additional patterns of patches and not only round patches as initially scheduled. Such irregular patterns are quite an interesting feature that gives good indication as to the ability to detect various sizes of oil patch.

In this facility, commonly used sonars (sidescan sonars, multibeam echosounders, front-looking sonar, 3-D acoustic camera) were tested for their response and ability to map oil patches according to their frequency, resolution. Prior to the testing, the heavy fuel oils used to simulate the actual stranded fuel oil were studied so as to determine their acoustical properties: density, attenuation and sound speed in a range of frequencies from 150 to 500 kHz.

Testing facilities
After preliminary tests concerning the buoyancy and the long term “stability” of various mixtures of fuel oil n°6 with kaolin, Cedre decided to select the following products for these acoustic experiments:
- mixture A: 70% fuel oil n°6 + 30% kaolin,
- mixture B: mixture A emulsified with 30% of fresh water,
- mixture C: mixture B with sand similar to the bottom sand layer.

The natural process of fuel ageing at the ocean surface after the spill has occurred, called weathering, is not quite similar since it first involves emulsification and then possibly mixing with silt sediment that can lead to sinking to the seafloor.
Figure 1: Layout of the various oil patches on the sand floor over the dry dock bottom.

Figure 2: (left) The ten patches on the sand floor, before oil filling and water flooding. (right) Filling of an oil patch.

The sonar head was mounted onto a deployment trolley fully equipped with dual-axis motorization, a small control cabin and the necessary electric power. The trolley could be moved over the sand tank at slow speed and the operating depth was adjustable; for each one of the surveys, the sonar head was kept approximately 5 m above the oil patches.
Acoustical parameters of the fuel oils

Samples of the fuel oil used in the experiment were measured by L.M.A. in order to obtain the relevant acoustical parameters (density, velocity, absorption coefficient). The two samples measured were found to have densities of 1280 and 1109 kg/m³ respectively, and velocities of 1492-1520 m/s and 1500-1515 m/s respectively (varying with frequency inside the range 140-500 kHz). Hence the acoustical impedance is similar to that of seawater. The absorption coefficient values were found to be around 1.0 and 0.6 dB/wavelength respectively, hence quite high values (about 10 times what is typically expected in soft sediments with similar impedance). These heavy fuels are thus essentially characterised by a high attenuation.
Characteristics of the operated sonars

The main characteristics of the tested systems are given in Table 1: namely the sonar type (sidescan sonar, multibeam echosounder, front-looking sonar, 3D acoustic camera), the nominal frequency, the across track resolution (given by the transmitted pulse length), the along track resolution at a 50 m range (given by the along track angular aperture for swath sonars), the number of beams and their across track width (for multibeams), the total angular aperture, and the maximum swath width. All of these characteristics are nominal values available from the suppliers.

<table>
<thead>
<tr>
<th>Type</th>
<th>Nominal Frequency (kHz)</th>
<th>Across track resolution (cm)</th>
<th>Alongtrack aperture (°) / resolut.(cm) @50 m</th>
<th>Beam number &amp; width (°)</th>
<th>Total apert. (°)</th>
<th>Max. swath (m)</th>
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</thead>
<tbody>
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<td>Reson Seabat 8101</td>
<td>MBES</td>
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<td>1.25</td>
<td>1.5° / 130</td>
<td>101 / 1.5°</td>
<td>150°</td>
</tr>
<tr>
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<td>FLS</td>
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<td>/</td>
</tr>
<tr>
<td>Klein 5500B</td>
<td>SSS</td>
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<td>3.75</td>
<td>0.15° / 12</td>
<td>/</td>
<td>/</td>
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<td>2.5°-1.3°-0.6°</td>
<td>4096</td>
<td>90°-50°-25°</td>
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</tbody>
</table>

Table 1: Main acoustic characteristics of the tested sonars, based upon their respective commercial documentation (MBES=multibeam echosounder; SSS=sidescan sonar; FLS=front-looking sonar; 3DAC = three-dimensional acoustic camera).
Selected Sonar images

Klein 5500B: this high-resolution side scan sonar was operated along a series of 11 measurement lines, at various sonar-target distances. The image presented here (Fig. 4) corresponds to a range of 5.2 m between the sonar and the closest sand tank edge. The sonar data was projected over a horizontal grid, the bin size of which was set relatively high (10 cm) in order to allow comparisons with other systems (multibeams); indeed it must be emphasised that the actual resolution of individual sonar images by Klein 5500 systems is clearly much better than the one in Fig. 4. The resulting image gives a very good contrast between the sand and the oil patches. Data recorded at longer ranges were often smeared by unwanted reflections from the water surface, and hence were found to be of lower quality.

Figure 4: Reflectivity map obtained with sidescan sonar Klein 5500B
**DF1000:** This bi-frequency side scan sonar was operated in the same geometry as Klein-5500. The two images presented here were respectively obtained at 400 and 100 kHz, with a 6.6 m range between the sonar and the closest wall of the sand tank; this geometrical configuration gave the best results. The high frequency image is very well defined and contrasted, and provides an excellent detection of the oil patches. On the other hand, the 100-kHz image is poorly contrasted, and is smeared by many echoes from the water surface.

*Figure 5: Sonar image obtained with Edgetech DF-1000 at 400 kHz (upper image) and 100 kHz (lower image).*
**Seabat 8101, multibeam echosounder mode:** This 240-kHz sonar was operated successively along three lines parallel to the sand tank length, at various distances from the longitudinal axis. Each obtained map of backscattered echo intensities (e.g. Fig. 6) gives a clear image of the sand floor with oil patches distinctly visible (contrast around 10 dB). Finally the three maps were averaged over a 0.1-m grid of the horizontal plane, providing an excellent reflectivity image (Fig. 7).

*Figure 6: Echo intensity level obtained with the Seabat 8101 multibeam echosounder operated along a line exactly in the middle of the sand tank.*

*Figure 7: Backscattered level, averaged from three acquisition lines with Seabat 8101.*
Seabat 8125: This high-frequency (455 kHz) and high-resolution (1° x 0.5°) echosounder was operated on the same three tracks as Seabat 8101, parallel to the sand tank length. Compared to the Seabat 8101 results, as expected the image resolution is bettered, while the interpretation is different in terms of reflectivity measurement. On one hand, the echoes are more sensitive to the sand micro-roughness, due to the higher frequency and resolution; on the other hand, echoes from oil patch with various thickness are less differentiated, since the high-frequency signal echo is due to the water-oil interface rather than the oil patch volume and underlying sand.

Figure 8: Reflectivity map recorded with Reson Seabat 8125, with an offset of 0 m (upper) and 2.5 m (lower) from the sand tank longitudinal axis.

Figure 9: Backscattered level, averaged from the three acquisition lines with Seabat 8125.
Seabat 8101, front-looking mode: The 240-kHz echosounder was operated along the longitudinal axis of the sand tank. Four images, extracted from the whole sequence, are presented here, making clear the various targets appearing each in turn.

Figure 10: Successive images obtained with the Seabat 8101 sonar operated in front-looking mode. The oil patches appear as the sonar proceeds along the sand tank axis.
EchoScope 1600: This multi-frequency 3D real time acoustic camera, developed in Norway, was operated in such a way to obtain: echo strength analysis when scanning frequency (100-900 kHz); echo strength analysis as a function of angle; survey of the sand tank in order to build 3D elevation and reflectivity maps. Although this version is not designed for providing as high-quality images as sidescan sonars, the EchoScope gave very interesting results in volume imaging of the targets and reflectivity mapping (see fig.12). It has the capability to provide large snapshots of the seafloor and to allow for making in situ mosaicing. It is a tool that is efficient for a quick ROV survey of polluted areas. The three frequencies allow to adjust the best trade off between maximum range and resolution according to the local conditions for the security of the survey system.

Figure 11: Typical snapshot obtained with Echoscope 3D-Acoustic Camera (left); averaged reflectivity measurement over the targets (right: note the difference between the nominal and the actual location of some oil patches)
Experiment main results

The results derived from the analysis of all the data recorded during these experiments are the following:

- High frequency sonar systems (200-500 kHz), commonly used at sea (side scan sonar, multibeam echo-sounder, front-looking sonar and acoustic camera) should efficiently enable to detect oil patches laying on a sand sediment floor because of the low reflectivity of the oil patches due to their high attenuation property. However the contrast depends on the altitude over the sea floor, on the system type and the corresponding geometry of the beams.

- For any sonar type the contrast that has been obtained in comparison with the surrounding sand, and for all three pollutant type (A/B/C), is in the order of 10-15 dB within the frequency range of 240-460 kHz for the three thickness (3/8/20 cm). Around 100 kHz the contrast is never more than 5 dB and logically varies with the thickness (the thinner the oil patch, the lower the contrast).

- For the multibeam echo-sounder and near the nadir (+/- 10°) when the frequency is increased from 240 kHz to 455 kHz the contrast derived is significantly less. However in this case the bathymetry data clearly gives the thickness of the oil patches although they are not visible on the acoustic image.

- The side scan sonar systems are working away from the vertical (around 25° to 80°) and in such conditions the oil-sand contrast is rather high (around 15 dB). As they have to be operated at a given altitude above the seafloor, these systems would either have to be towed (in water deeper than 15m) or to be hull mounted in shallower waters. Thus they would provide good surveillance achieving a wide swath with good resolution and contrast, however near nadir there is no valuable imaging.

Actually it can be concluded that side scan sonar (SSS) working at frequencies between 200 and 500 kHz could be valuably deployed for mapping large areas so as to quickly assess where there could be trapped heavy oil on the seafloor. Then in the case of detected possible oil patches, a more precise survey could be undertaken with the use of a multibeam echo-sounder (MBES), or a front-looking sonar (FLS). However one of these sensors may be used simultaneously during the initial survey as explained below.

But none of the acoustic means will be able to directly quantify the thickness of the slicks nor the volume. On the other hand it must be emphasised that the above results only concern sandy seafloors and that on very soft sediment, with low backscatter level, the ability to obtain enough contrast is not clear and it will depend on the actual parameters of both the seafloor and the heavy oil.
The list below presents the most widely used acoustic sensors and in addition some new sensors with increased possibility (SAS and 3D-AC) that should be available and operational in the short term. This list is intended for facilitating initial selection and another table gives the dimensions and weight of the selected SSS in the paragraph concerning their deployment.

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<tr>
<th>Type</th>
<th>Nominal Frequency (kHz)</th>
<th>Across track resolution (cm)</th>
<th>Alongtrack aperture (*) / resol.(cm) @50 m dist.</th>
<th>Beam number &amp; width (*)</th>
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<td>48 / 0.8°</td>
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<td>20°</td>
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</table>

Table 2: Main characteristics of the tested sonars, based upon their respective commercial documentation (MBES=multibeam echosounder; SSS=sidescan sonar; FLS=front-looking sonar; AC = acoustic camera).

**OPTIMISING SSS OPERATION**

**Introduction**

The final goal of the SSS imagery is to detect all possible oil slicks among the seabed features, to know their exact position and to classify them according to their size and aspect.

Most of the time this is performed on raw data images that are called “waterfall” but to correctly achieve our goal this should be done on accurately geo-referenced maps.

As the goal is to obtain a quick and complete assessment by imaging and mapping the whole area that has been targeted, the actual drawbacks of the SSS systems have to be analysed accordingly and whenever possible fixed in the best way.

The overall quality of the global assessment depends on the following parameters:

- survey productivity
- data quality
The main limitations of SSS systems are reviewed here, before examining the possibilities for overcoming these limitations.

**Actual SSS limitations**

Concerning the *survey productivity* and completeness, the main limitation derives from the gap at nadir and the decreasing resolution with range.

The *data quality* is hampered by this decreasing resolution but also by the sonar unavoidable rotations (roll, pitch and yaw) if they are not compensated for. The roll will transform straight features such as pipes into curved ones. Pitch and yaw could lead to the accumulation of ping pixels in some places while leaving other places blank but without knowing it.

The *geo-referencing accuracy* depends on the sonar position and attitude knowledge (micro-navigation). Most of the time the position of the sonar on a towfish is either estimated deriving a layback from the actual cable length or measured using an external positioning system. In the first case the accuracy is rather poor and prevents good mapping through a mosaicing process. In the second case the position file has to be fed into the mosaicing software in a post-processing mode which is time-consuming and *considerably reduces the data exploitation productivity*.

Concerning *user-friendliness*, an important parameter for good productivity, the ideal is to have an integrated and optimised system delivered as a turn key system by a single supplier.

**Improving SSS operations**

*Comprehensive software suite*

In addition to having a single supplier providing a system-level support, a comprehensive software suite should be implemented covering the whole chain from survey preparation to final mosaic and analysis export. This kind of software is important from an operational point of view and it provides flexibility during the survey if any change in the survey lines happens to be necessary.

*Synthetic aperture sonar technology*

The SAS technology is an innovative image-building technique that relies on single-target multi-ping correlation rather than on single-ping beam focus. This technology takes advantage of an embedded INS which provides accurate micro-navigation of the antennas and the ability to build an image featuring a high and constant resolution over the whole range. Thus it eliminates low-resolution remote zones encountered with traditional SSS technology and provides a more homogenous high resolution image mosaic (cf. figure 12).
Figure 12: constant resolution so that the 6 pods are seen the same way across and along track
Central gap filler

As the SSS is blind near the vertical (nadir), it is necessary to envisage a complementary sensor. A multi-beam echo-sounder, or a front-looking sonar, depending on their availability, integrated in the same body will illuminate the nadir sector hence filling the gap at nadir. However to maintain good productivity the related data have to be taken into account by the near real-time and/or the post-processing software.

Figure 13: example of an SAS system with a complementary FLS to fill the gap at nadir

When the integration of such a multi-beam echo-sounder (or front-looking sonar) is not feasible, an interesting alternative solution is to install a single beam scientific echo-sounder (such as an ES 60) on the towing vessel that could cover the gap (cf. fig.14). In addition it can eventually provide information on the sediment nature by means of a proper acoustic signal processing (for instance specific signal processing allows acoustic signature differentiation among different bottom types).
Though the latter solution is not an integrated one and the resolution is not of the same level, it can be of great value for the analysis of the final sonar imagery (cf fig. 15 and 17) to obtain information concerning the sea floor nature at nadir of the survey lines.

**Sonar positioning**

Accurate fish positioning not only improves the mosaicing process and results but also allows automatic geo-referencing thanks to automatic position data feeding into the data files. It simplifies and speeds up the individual line mosaics merging into a global mosaic thanks to excellent position accuracy of each pixel (cf. fig.16). In the case of an SAS system the embedded INS will provide a major improvement even in the case of an external positioning system (either a USBL or a LBL)
Figure 16: accurate geo-referencing enables a perfect match between image strips
Real time capability

The real time mosaic production (cf. fig.17) allows the necessary survey lines control and optimisation aiming at avoiding any blank zone so that an additional survey will not be necessary later on. This is a very important feature knowing that the survey time is limited due to operational and sea condition constraints.

Figure 17: final sonar mosaic together with sea bottom classes derived from the vertical ES signal.
Deployment options
The deployment options are to be selected according to sensors and support vehicle availability and to
the specific constraints of the surveyed area. An additional concern is how to get a reliable and precise
acoustic positioning of the underwater towfish or vehicle.

**SSS deployment from a support vessel**

There are three possibilities when using a support vessel:
- a towed fish
- an over-the-side mounted sonar
- a hull-mounted sonar

In the first case the SSS is embedded in a streamlined towfish with an umbilical cable used both for
signal and power transmission and the towing of the body up to 5 m/s. This is the most common
method of deployment and it can be selected when the depth is more than 15m. The other possibilities
have to be considered whenever the depth is less than 15m so as to have enough range and the right
grazing angles and also to avoid any collision with the bottom. These solutions are convenient except
if the support vessel is at risk. If the vessel is at risk when performing the survey then an Autonomous
Underwater Vehicle (AUV) has to be considered, though this vehicle may be somewhat at risk too.
(The towing vessel may be at risk if the targeted area is close to rocky shores and shoals or in the surf
zone.)

Small sized sonar are less costly and readily available; in addition they are very flexible when
intending to operate them onboard vessels of opportunity. This vessel can be quite small for usual
SSSs are quite light (weight between 15 and 70 kg, cf. table 3) and thus are easily handled over board.
In the case of a heavier SSS, notably with the SAS “Shadows”, it would require adjustment of the type
of vessel taking into account the sonar weight in air and its overall dimensions (fig.13 shows the
deployment of the Shadows).

In any case the support vessel has to be accurately positioned through an adequate GPS receiver such
as a GPS RTK. In addition the towfish has to be tracked by a USBL whenever possible (in shallow
waters special caution has to be given to the ability to continuously track the fish).

<table>
<thead>
<tr>
<th>Type</th>
<th>Nominal Frequency (kHz)</th>
<th>Max. Depth (m)</th>
<th>Length (m)</th>
<th>Diam (cm)</th>
<th>Weight in air (kg)</th>
<th>I.N.S. (MRU)</th>
<th>max. range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edgetech DF-1000</td>
<td>100 / 400</td>
<td>1000</td>
<td>1.58</td>
<td>11.4</td>
<td>30</td>
<td>None</td>
<td>500/200</td>
</tr>
<tr>
<td>Edgetech 4200</td>
<td>100 / 400</td>
<td>300</td>
<td>1.25</td>
<td>11.4</td>
<td>48</td>
<td>H+R+P</td>
<td>500/150</td>
</tr>
<tr>
<td>Edgetech 4200</td>
<td>300 / 600</td>
<td>2000</td>
<td>1.25</td>
<td>11.4</td>
<td>30</td>
<td>Idem</td>
<td>230/120</td>
</tr>
<tr>
<td>C-MAX CM2</td>
<td>100/325</td>
<td>150?</td>
<td>?</td>
<td>?</td>
<td>8.9</td>
<td>29</td>
<td>500/150</td>
</tr>
<tr>
<td>Ixsea Shadows</td>
<td>SAS</td>
<td>105 FLS/400</td>
<td>300</td>
<td>2.2</td>
<td>450</td>
<td>FOG INS</td>
<td>300</td>
</tr>
<tr>
<td>Klein 3000</td>
<td>SSS</td>
<td>100/500 ?</td>
<td>1.22</td>
<td>8.9</td>
<td>29</td>
<td>H+R+P</td>
<td>450</td>
</tr>
<tr>
<td>Klein 5500B</td>
<td>SSS</td>
<td>455 ?</td>
<td>1.94</td>
<td>15.2</td>
<td>70</td>
<td>OPTION</td>
<td>300</td>
</tr>
<tr>
<td>Imagenex Yellowfin</td>
<td>SSS</td>
<td>260/330/770</td>
<td>300</td>
<td>0.84</td>
<td>5.4</td>
<td>None?</td>
<td>200</td>
</tr>
</tbody>
</table>

*Table 3: Main characteristics of the SSS body; attitude measurements: H = heading; R = roll; P = pitch.*

**SSS deployment onboard AUVs**

In cases where the support vessel is at risk when towing the sonar fish, the use of an AUV will
improve the capability of operating closer to the shore or to shoals, knowing that the support vessel
may stay away from the surveyed zone.

The availability of an equipped AUV is less probable than that of a normal SSS but it could be
valuable if the survey productivity is improved or the grounding risks are reduced.
The AUV payload and its dimensions and endurance are the main features to consider to select the most adequate system. The payload should at least include a classic SSS but optional sensors should be added as discussed above, such as a complementary sounder (MBES) and an external positioning system in addition to an INS.

The dimensions and weight of AUVs mainly depend on the payload and endurance. The required flexibility of the system utilisation implies selecting a rather light weight vehicle of limited length. Experience suggests that the weight in the air should not exceed 800 kg and the length 4.5m so as to be handled onboard vessel less than 25m long.

In any case the AUV has to be accurately positioned by means of an integrated INS possibly complemented by an acoustic system such a USBL or a LBL whenever possible (in shallow waters special caution has to be given to the ability to continuously track the AUV by an acoustic mean)

The following table gives the main characteristics of the most documented AUVs.
<table>
<thead>
<tr>
<th>Depth</th>
<th>Diam (cm)</th>
<th>Length (m)</th>
<th>Weight (kg)</th>
<th>Energy (kWh)</th>
<th>INS + GPS LBL/USBL</th>
<th>Standard sensors</th>
<th>Optional sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remus 100</td>
<td>100</td>
<td>19</td>
<td>39</td>
<td>1.0</td>
<td>Yes</td>
<td>Yes</td>
<td>DVL+INS</td>
</tr>
<tr>
<td>Remus 600</td>
<td>300</td>
<td>32.4</td>
<td>240</td>
<td>5.2</td>
<td>Yes</td>
<td>Yes</td>
<td>SSS+ADCP</td>
</tr>
<tr>
<td>GAVIA</td>
<td>200</td>
<td>29</td>
<td>50+</td>
<td>?</td>
<td>Yes</td>
<td>Yes</td>
<td>idem</td>
</tr>
<tr>
<td>ODISSEY III</td>
<td>200</td>
<td>53</td>
<td>410</td>
<td>4.0</td>
<td>Yes</td>
<td>Yes</td>
<td>idem</td>
</tr>
<tr>
<td>HUGIN 1000</td>
<td>1000</td>
<td>75</td>
<td>650</td>
<td>3-15</td>
<td>idem (no SSS)</td>
<td>+GeoSwath FLS</td>
<td>idem</td>
</tr>
<tr>
<td>ASTER X</td>
<td>3000</td>
<td>4.5</td>
<td>800</td>
<td></td>
<td>Yes</td>
<td>Yes</td>
<td>+MBES EM 2000</td>
</tr>
</tbody>
</table>

Table 4: Main characteristics of current AUV, based upon their respective commercial documentation. 

(DVL = Doppler Velocity Log; MBES = multibeam echosounder; SSS = sidescan sonar; SAS = Synthetic Aperture Sonar; FLS = front-looking sonar; AC = acoustic camera).

Complementary surveys

Although the initial survey should be complete and may include sea bottom classification whenever possible, confirmation of the detected possible slicks as being real oil slick could be necessary before deciding on any costly recovery action for those oil slicks. The response team may therefore decide to conduct bottom sampling by means of divers and/or close video shots to obtain confirmation and an estimation of the thickness of the main slicks. These actions could be performed immediately after the mapping survey, provided that the mosaic sonar image is produced in near real time as previously mentioned. These types of actions are rather trivial and are therefore not developed here, however it must be underlined that close video shots may be difficult to interpret.
CONCLUSION

Acoustic sensors provide good visualisation of seafloor contours and help to identify potential accumulation areas, but will not provide any estimation of the thickness of the possible slicks. Many sensors are available at short notice and the present report should allow the selection of the most adequate method.

Side scan sonar (SSS) working at frequencies between 200 and 500 kHz could be valuably deployed for mapping large areas so as to rapidly assess where there could be trapped oil pollution on the seafloor. Then in case of detected “possible oil patches” a more precise survey could be undertaken with the use of a multi-beam echo-sounder (MBES), or a front-looking sonar (FLS). However one of these sensors may be used simultaneously during the initial survey as explained below.

The following possibilities are proposed, from the most flexible but less efficient to the most advanced:
- combined use of a light high resolution SSS complemented with a “scientific” vertical single beam echosounder to fill the central gap and possibly classify the nature of the sea bottom. This solution may be implemented onboard, or towed from, a light craft and is considered as the most flexible option.
- use of more heavy SSS providing high quality data over a wide swath such as an SAS complemented with an FLS or preferably an MBES to fill the gap and possibly to classify the sea bottom at nadir. This solution is more efficient due to constant resolution images over the entire swath and to improved positioning data, an INS being part of the sonar array. However the support vessel must be able to handle a heavier towed body.
- combined use of both an SSS and a multibeam echosounder onboard a small or medium size AUV to avoid the risk of grounding for the support vessel. The size of the support vessel will depend on the weight (from 40 kg to 800 kg) and length (from 1.6 to 4.5 m) of the AUV. The heavier the AUV the more it will withstand strong currents but the more costly it will be.

The latter solution is more difficult to set up because the number of service providers is reduced in comparison with the previous solutions, especially the first one.

In any case a precise positioning system is necessary to enable reliable and fast sonar image mosaicing, thus an integrated INS possibly complemented with an acoustic positioning system is necessary to achieve this imaging.

The definitive confirmation, or “groundtruth”, as well as slick thickness estimation, will only be obtained from samples of the detected “supposed slicks” or “area of accumulation” by means of divers or possibly from close video shots realised by divers or an underwater vehicle. This stage can be performed immediately after the initial survey provided that the mosaicing is produced over a short time period.

The global survey strategy including the selection of the type of sonar and support vehicle will be decided by the response team, according to the local waves and current conditions and seafloor topography.
ABBREVIATIONS

AC  Acoustic Camera (a kind of fast imaging FLS)
AUV  Autonomous Underwater Vehicle
DVL  Doppler Velocity Log
ES  Echo-Sounder (single beam)
FOG  Fibre Optic Gyro
FLS  Front-Looking Sonar
H  Heading of the fish
INS  Inertial Navigation System
LBL  Long Base Line (acoustic positioning system)
MBES  Multi-Beam Echo-Sounder
MRU  Movement Reference Unit (Roll, Pitch and Heading)
SAS  Synthetic Aperture Sonar
SSS  Side Scan Sonar
P  Pitch (of the fish)
R  Roll (of the fish)
USBL  Ultra Short Base Line (acoustic positioning system)

SOME REFERENCES

“Assessment and Recovery of Submerged Oil: current state analysis” (Research and Development Center- US Coast Guards- Prepared by J. Michel – June 2006)

APPENDIX D

Oil Spill Model development (WP2.3)
Oil Spill Model development

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Weathering processes

Physical properties of oil

The term oil describes a broad range of hydrocarbon-based substances. Hydrocarbons are chemical compounds composed of the elements hydrogen and carbon. This includes substances that are commonly thought of as oils, such as crude oil and refined petroleum products, but it also includes animal fats, vegetable oils, and other non-petroleum oils. Each type of oil has distinct physical and chemical properties. These properties affect the way oil will spread and break down, the hazard it may pose to aquatic and human life, and the likelihood that it will pose a threat to natural and man-made resources.

Spreading

Immediately after a spill, the oil spreads out onto the surface of the ocean as a thin slick. This is important because it exposes a maximal amount of surface area to each of the subsequent weathering processes. Just 1 g of spilled oil can form a slick of up to 10 m², and a 1 ton spill can form a slick of up to 12 km².

The rate at which an oil spill spreads will determine its effect on the environment. Most oils tend to spread horizontally into a smooth and slippery surface, called a slick, on top of the water. Factors which affect the ability of an oil spill to spread include surface tension, specific gravity, and viscosity.

- Surface tension is the measure of attraction between the surface molecules of a liquid. The higher the oil’s surface tension, the more likely a spill will remain in place. If the surface tension of the oil is low, the oil will spread even without help from wind and water currents. Because increased temperatures can reduce a liquid’s surface tension, oil is more likely to spread in warmer waters than in very cold waters.

- Specific gravity is the density of a substance compared to the density of water. Since most oils are lighter than water, they float on top of it. However, the specific gravity of an oil spill can increase if the lighter substances within the oil evaporate. Heavier oils, vegetable oils, and animal fats may sink and form tar balls or may interact with rocks or sediments on the bottom of the water body.

- Viscosity is the measure of a liquid’s resistance to flow. The higher the viscosity of the oil, the greater the tendency for it to stay in one place.

The spreading of the slick was investigated by Fay. There are 3 theoretical phases of the spreading process of an oil spill. Different physical forces governs the spreading process in each phase.
1. Gravity-inertia
2. Gravity-viscous
3. Surface tension - viscous

Field observations almost always show a rapid spread to a size which increases with volume of the spill, followed by a long period of no further growth. This behaviour can be described by a sudden reduction of the net surface tension when evaporation and dissolving the lighter components of the oil has occurred. Therefore the third theoretical phase of the spill is not implemented in this model. Fay described the size of the slick \( l \) in the 2 initial phases with the following expressions:

**Gravity-inertia**

The width of the oil lens \( l \) is

\[
l = (\Delta g V t^2)^\frac{1}{2}
\]

From this expression it can be found that the front of the slick spreads with the following speed

\[
\frac{dl}{dt} = \Delta g^\frac{1}{2} \cdot V^\frac{1}{2} \cdot \frac{1}{4} t^\frac{1}{2}
\]

**Gravity-viscous**

\[
l = \left( \frac{\Delta g V^2 t^2}{\nu^2} \right)^\frac{1}{2}
\]

This leads to a front speed

\[
\frac{dl}{dt} = \frac{\Delta g^\frac{1}{2} \cdot V^\frac{1}{2}}{\nu^\frac{1}{2}} \cdot \frac{3}{4} t^\frac{1}{2}
\]

**Horizontal direction of the spreading oil particles**

Horizontal direction of each oil particle is calculated as the direction with the highest gravitational gradient. The gravitational gradient is calculated as the gradient in the lens height \( H \) evaluated in a eulerian mesh. When the oil temperature reaches the pour point the horizontal spreading stops.

\[
H = \sum_{i=1}^{\text{particles}_{\text{cell}_m}} m_i \frac{1}{A_m \cdot \rho_{\text{oil}}}
\]
**Evaporation**

In the first hours and days of the spill, evaporation at the surface of the slick is the dominant weathering process. If the spill consists of a lightweight, highly refined product like gasoline, evaporation can very effectively remove nearly all of the spill contamination in as little as 24 hours. For spills of most medium-weight crudes the removal is less complete but substantial nevertheless. Typically, 10-30% of the material from these spills can be removed through evaporation in the first 24 hours.

Other factors effecting the evaporation of a spill include the amount of the spill exposed at the surface of the slick, wind and sea surface conditions, air temperature, and insolation intensity. Another factor is emulsification of the slick, which significantly retards the rate of evaporation.

The evaporation process for one particle that is in contact with the water surface is calculated as:

\[ evaporation = -k_{evap} \cdot M \]

Where

- \( k_{evap} \): Evaporation rate [1/s]
- \( M \): Mass of particle

\( k_{evap} \) is user specified and function of

- Oil temperature
- Vapour pressure of oil
- Molecular weight
- Density
- Slick surface area
- Wind speed
- Emulsification

Rough estimate of the \( k_{evap} \) value are given in the following table:

<table>
<thead>
<tr>
<th>Material</th>
<th>Evaporation rate ( k_{evap} ) [1/d]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light fuel oil (for instance gasoline)</td>
<td>1 - 5</td>
</tr>
<tr>
<td>Medium weight oil</td>
<td>0.1 - 0.4</td>
</tr>
<tr>
<td>Heavy fuel oil</td>
<td>0.01 - 0.05</td>
</tr>
</tbody>
</table>
**Vertical dispersion**

An important factor moving the oil into the water column is vertical dispersion. Strong winds, currents, and turbulent seas facilitate the process of dispersion. Dispersion is assumed to occur by means of two mechanisms:

1. dispersion due to wave action. When the turbulent pressure fluctuation force becomes greater than the sum of the buoyancy force and the surface tension force, oil droplets will be released. Probability of a particle to disperse vertically due to wave action \( p_{\text{wave}} \) is a simple function of significant wave height \( H_{\text{wave}} \). For wave heights above a reference wave height \( H_{\text{ref}} \) the probability is 100%:

\[
p_{\text{wave}} = \text{MIN}
\left(1, \frac{H_{\text{wave}}}{H_{\text{ref}}} \right)
\]

The distance that the oil droplets are dispersed into the water column \( \text{disp}_{\text{wave}} \) depends on the wave height and on the density of the oil \( \rho_{\text{oil}} \) and the water density \( \rho_{\text{water}} \):

\[
\text{disp}_{\text{wave}} = k_1 \cdot H_{\text{wave}} \cdot N(1,0) \cdot \left(1 - \frac{\rho_{\text{water}} - \rho_{\text{oil}}}{\rho_{\text{water}}} \right)
\]

Where

- \( N(0,1) \): Standard normal distribution (\( \mu = 0, \sigma^2 = 1 \))
- \( k_1 \): Coefficient for wave action

2. dispersion due to wave breaking. Breaking waves cause the oil droplets to be moved far into the water column. This is by far the most important dispersion mechanism. The probability of a particle to disperse vertically due to wave breaking:

\[
p_{\text{wbreak}} = \text{MIN}
\left(1, \frac{\Delta E_{\text{wave}}}{\Delta E_{\text{ref}}} \right)
\]

The distance that the oil droplets are dispersed into the water column \( \text{disp}_{\text{wbreak}} \) depends on the wave energy gradient and on the density of the oil \( \rho_{\text{oil}} \) and the water density \( \rho_{\text{water}} \):

\[
\text{disp}_{\text{wbreak}} = k_2 \cdot \Delta E_{\text{wave}} \cdot N(1,0) \cdot \left(1 - \frac{\rho_{\text{water}} - \rho_{\text{oil}}}{\rho_{\text{water}}} \right)
\]

Where:

- \( \Delta E_{\text{wave}} \): Wave energy gradient
The oil physico-chemical properties varies with the temperature, and the fluid dynamics are therefore strongly temperature dependent. As the temperature of the spilled oil has temperature above the pour point immediately after the spill, the density is rather low, making the oil buoyant and therefore the oilslick is forced towards the watersurface in the beginning. However as the oil slick cools down, the density increases and minimizes the density difference to the enclosing water, and therefore the slick can react to turbulent waters by dispersing under the surface.

Oil density temperature dependency:

\[ \rho(\text{temp}) = 1016.3 - 1.42 \cdot \text{temp} \quad \text{[kg/m}^3\text{]} \]

Redispersion of oil

Usually the oil density is smaller than the water density. The dispersed oil droplets therefore tend to resurface. However, they can remain dispersed for a long time, due to water turbulence.
Dissolution

Still more of the oil slick is removed as the water-soluble portion of the petroleum hydrocarbons are dissolved into the surrounding seawater. Although this reduces the size of the slick it presents an environmental problem since the water-soluble spill components and breakdown products are those that are most toxic to marine life. Small aromatic hydrocarbons like benzene, and toluene, and somewhat larger polycyclic aromatic hydrocarbons (PAHs) like naphthalene, are among the water-soluble petroleum components known to have toxic effects.

Other factors effecting the dissolution of a spill include the amount of the spill exposed at the surface of the slick, wind and sea surface conditions, air temperature, and insolation intensity. Another factor is emulsification of the slick, which significantly retards the rate of evaporation.

The dissolution process is calculated as:

\[
dissolution = -k_{diss} \cdot M
\]

Where

\( k_{diss} \): Dissolution rate \([1/s]\)
\( M \): Mass of oil particle

\( k_{diss} \) is user specified and function of

- solubility of oil
**Emulsification**

Emulsification is the formation of a mixture of two distinct liquids, seawater and oil in the case of a marine spill. Fine oil droplets are suspended within (but not dissolved into) the water and the emulsification formed occupies a volume that can be up to four times that of the oil it formed from. Moreover, the viscous emulsion is considerably more long-lived within the environment than the source oil, and its formation slows subsequent weathering processes.

Emulsification tends to occur under conditions of strong winds and/or waves and generally not until an oil spill has persisted on the water for at least several hours. A persistent, partially emulsified mixture of water in oil is sometimes referred to as a "mousse." Mousse is resistant to biodegradation, the important final weathering stage, and in shallow marsh environments it can persist within sediments for years to decades.

The present model describes the emulsification as an equilibrium process between the two stages oil + water and water in oil. The changes in the water content is the water uptake (R₁) minus the water release (R₂).

\[
\frac{dy_w}{dt} = R_1 - R_2
\]

\[
R_1 = \frac{K_1 \cdot (1 + U)^2 \cdot \left(y_{w}^{sat} - y_w\right)}{\varepsilon_{oil}}
\]

\[
R_2 = \frac{K_2 \cdot y_w}{(A_s \cdot Wax \cdot \varepsilon_{oil})}
\]

Where:

- \(K_1\) and \(K_2\): are coefficients to be estimated
- \(y_w\) and \(y_{w}^{sat}\): are the actual water content and the maximum or saturation content respectively
- \(\varepsilon_{oil}\): oil slick viscosity
**Sedimentation**

Very few crudes are dense enough to sink on their own in seawater, and few of them weather fully enough to yield a residue dense enough to do so either (unless the oil is ignited, in which case sufficiently dense residues may be formed). Yet oil spill components and residues do find their way into marine sediments. This is because adhesion of suspended silt or particulate organic matter to the oil over time increases the effective density of the aggregate that is formed allowing it to sink.

Coastal habitats are particularly vulnerable to input of sinking oil contaminants because the suspended solids load in these areas is conducive to the formation of sinking oil/silt aggregates. Moreover, oil washing up on beaches and marshes and given ample opportunity to mix with sand and mud is likely to be of sinking density if it gets washed back offshore. Sedimentation is not included in this model.

**Photooxidation**

Chemical oxidation of the spilled oil also occurs, and this process is facilitated by exposure of the oil to sunlight. Oxidation contributes to the total water-soluble fraction of oil components. Less complete oxidation also contributes to the formation of persistent petroleum compounds called tars. The overall contribution of photooxidation to oil spill removal is small. Even exposed to strong sunlight, photooxidation only breaks down about a tenth of a percent (0.1%) of an exposed slick in a day.

The dissolution process is calculated as:

\[
\text{photooxidation} = -k_{\text{photo}} \cdot M
\]

Where

- \(k_{\text{photo}}\): Photooxidation rate [1/s]
- \(M\): Mass of oil particle

**Biodegradation**

Microbial oil degradation is a critical late-stage step in the natural weathering of petroleum spills, as it is the stage that gradually removes the last of the petroleum pollutants from the marine environment.

Microbial breakdown of petroleum compounds occurs most rapidly via the oxidative metabolic pathways of the degrading organisms. As such, biodegradation is predicted to occur fastest in environments with ample oxygen as well as a diverse and healthy oil-degrading flora. Conversely, oxygen-starved marine sediments that are often sites of petroleum contamination are among the habitats where aerobic metabolism is severely limited and microbial oil breakdown must therefore proceed via slower anaerobic
pathways. Even though breakdown within these sites is slow, it may still have a substantial cumulative impact over time.

$$\text{biodegradation} = -k_{\text{bio}} \cdot M$$

Where

- $k_{\text{bio}}$: Biodegradation rate [1/s]
- $M$: Mass of oil particle
Drift
The combined effects of current, wind drag and bed drag cause the drift of the oil particles. The drift vector is normally varying in space. It represents the combined effects of current and wind drag that cause the advection of the particles.

\[ a(x, y, z, t) = f(current, wind \ drag, bed \ drag) \]

The drift profile is a description of the vertical variation of the drift regime that influences the particles. It will normally be the currents and the wind that governs the shape of the drift profile. Currents and wind are already calculated in the hydrodynamic setup, but for 2D hydrodynamics it is the depth average values that are the output of the hydrodynamic setup. By assuming some shapes of the vertical drift profile it is possible to get a more realistic current profile than just a depth integrated value, and therefore a more realistic drift of particles.
**Bed Shear Profile (Logarithmic Profile)**

The shape of the velocity profile within a turbulent boundary layer is well established by both theory and experiment. The profile has specific characteristics very close to the bed where viscosity controls the vertical transport of momentum, and different characteristics farther from the bed where turbulence controls the vertical transport of momentum. The region closest to the bed boundary is called the laminar sub-layer or viscous sub-layer, because within the region turbulence is suppressed by viscosity. The viscous, laminar sub-layer only plays a significant role for smooth flows, where a typical thickness of the viscous layer is about 2 cm, whereas for rough flows the viscous sub layer is typically less than 1 mm, and instead the flow is set to zero for z smaller than z0.

![Figure 1](image)

**Figure 1** Example of bed shear profile applied from 2D flow fields

**Logarithmic layer** ($z \geq \delta_v$, smooth flow) ($z \geq z_0$, rough flow)

$$u(z) = \frac{u^*}{\kappa} \log_{10} \left( \frac{z}{z_0} \right)$$

**Smooth flow: Laminar bed shear layer** ($z < \delta_v$)

$$u = (u^*)^2 \cdot \frac{z}{\nu}$$

Where:

- $\kappa$: Von Karman empirical constant 0.4
- $z_0$: Characteristic roughness
- $z$: Coordinate from bed towards water surface [m]
- $u^*$: Friction velocity
- $\delta_v$: Thickness of viscous bed shear layer
- $\nu$: Kinematic viscosity of water
**Wind Induced Profile**

The wind drag can also cause increased flow velocities in the upper part of the water column, and corresponding velocities in the opposite direction in the lower part. In 3D hydrodynamics this effect is included in the hydrodynamic output, but that is not the case with the depth averaged 2D hydrodynamics. So if this flow regime should be described with 2D hydrodynamics, a wind induced profile must be applied, which will distribute the depth averaged flow in the water column.

This has been done by calculating a wind drift vector that is multiplied with the current velocity vector.

The magnitude of the surface wind drift vector \( c_w^* \) is commonly assumed to be proportional to the magnitude of the wind speed 10 m above the sea surface. This factor \( c_w^* \) has a common value that varies from 3 to 4 per cent of the wind speed 10 m above the sea surface (from Al-Rabeh (1994)).

The vertical distribution of the wind drift vector consists of an offshore part and an onshore part. The onshore distribution is based on a parabolic vertical profile and is able to produce backflow at depths, where the offshore logarithmic profile does not.

The parabolic profile acts in shallow waters with a water depth less than a specified water depth, \( h_{sep} \), which is a positive value (in metres) and measured from the free water surface.

The vertical distribution of the parabolic onshore profile is given by:

\[
 c_w(z) = c_w^* \left( 1 - \frac{3z}{h} \right) \left( 1 - \frac{z}{h} \right) 
\]

Where:
- \( h \) Local water depth in meter
- \( z \) Vertical particle co-ordinate, measured from sea surface
- \( c_w^* \) Wind drift factor (input)

The parabolic profile causes the wind-generated flow in the upper third of the water column to be in the same direction as the current and the flow in the lower part to be in the opposite direction of the wind. There is no net depth averaged mass transport due to the wind.

The vertical distribution of the offshore wind drift vector is given by:

\[
 c_w(z) = c_w^* \exp \left( -k_0 z \right)
\]

Where:
- \( k_0 \) \( = 3/hw \) [m⁻¹]
- \( h_w \) Depth of wind influence [m]
- \( z \) Vertical co-ordinate measured from sea surface
- \( c_w^* \) Wind drift factor [-]
**Wind Acceleration of Surface Particles**

Particles that are exposed to wind in the water surface are affected according to the wind regime in 2 ways: indirectly via the currents that include the wind, but also directly as an extra force directly on the particle. How much of the wind speed that is transferred to the particle speed depends on the nature of the particle: how much is the particle exposed, etc. Therefore, it is a calibration factor that expresses how much of the wind speed that is added to the particle speed.

In the Particle Tracking Module the wind acceleration of surface particles affect the drift with the following modification:

When the particle is in the top 5 cm of water column:

\[
U_{\text{particle}} = U_{\text{current}} + \text{windweight} \cdot W \cdot \sin(Wind\ direction - \pi + \theta_w)
\]

\[
V_{\text{particle}} = V_{\text{current}} + \text{windweight} \cdot W \cdot \cos(Wind\ direction - \pi + \theta_w)
\]

Where:

- \(\theta_w\) Wind drift angle
- windweight Calibration factor for wind drag on particle

**Wind drift angle**

The Coriolis force is normally included in the hydrodynamic currents, but also for the wind acceleration of surface particles the Coriolis force must be considered.

Due to the influence from the Coriolis force, the direction of the wind drift vector is turned relatively to the wind direction. The angle \(\theta_w\) of deviation is termed with the wind drift angle. It turns to the right on the Northern Hemisphere and to the left on the Southern Hemisphere. From Al-Rabeh (1994), it is assumed that

\[
\theta_w = \beta \exp \left( \frac{\alpha |U_w|^3}{g \gamma_w} \right)
\]

Where:

- \(\alpha\) -0.3 \cdot 10^{-9}
- \(\beta\) 28o 38'
- \(\gamma_w\) Kinematic viscosity (kg m-1 s-1)
- \(g\) Acceleration due to gravity (m s-2)

The magnitude of the wind drift angle varies with the geographical location and wind speed and it is often estimated at 12-15 degrees in the North Sea.
Case study: Sea Venture II

Description of the oil spill

On Jan. 21st 2005 the Sea Venture II caused an oil spill in the Great Belt of Denmark. Approximately 10 tons of heavy fuel oil was spilled along the navigation route of the ship over a period of about 2 hours starting at 7.00 in the morning, see Figure 2. The temperature of the oil in the ship was about 40 deg. C, and the ambient water was about 2 deg. C.

The spill was caused when the ship stroke the Møllegrunden. After a couple of hours the oil was not visible from the air anymore. The oil did not disappear however, and in the weeks to follow the oil was observed on shores and dead seabirds far away from the area where the oil was spilled.

Figure 2 Navigation route for Sea Venture II on the 21-01-2007
A hydrodynamic 2D model was setup with a bathymetry that can be seen in Figure 3. The software used for the hydrodynamic simulation was MIKE 21 FM HD.

Hydrodynamic boundary conditions, and wind data were extracted data from the regional DHI online water forecast of the Danish waters.

The wind data used in the model can be seen in Figure 4. It can be concluded that the wind was relative strong at the time of the release with wind speeds of about 12 m/s coming from north/west.
In the weeks after the spill observations of oil in the Great Belt was reported. The observations are illustrated in Figure 5.
**Model results**

The model results are seen in Figure 6 to Figure 10. All the result figure show the cloud of oil particles at a given time. As background is the observation map from Figure 5 merged, so that the model results can be viewed together with observations. The shorelines of the observation map and the model area does not fit 100%, but keep in mind that the shoreline marked with a black line is the model shoreline. Figure 6 shows the oil spill shortly after the release. The route of the ship can still be seen as a track of particles that starts at the location Møllegrunden, where the ship started leaking the oil. In the beginning of the spill the oil spreads on the water surface or near the surface, and in this period the oil is driven mostly by the wind towards south/east despite of the north going current regime starting on the Jan. 22nd, see Figure 4 and Figure 7. The observations of oil from Sea Venture II south of the Great Belt Fixed Link on Jan. 21st and 22nd can only be explained by wind driven transport, so even though the oil became submerged a while after the spill, it must still have been near the surface, since the wind played such a major role. This wind effect stopped when both the wind had dispersed the oil vertically down the water column and therefore not influenced the oil so much anymore, but also the wind calmed down and the transport driven by currents started to dominate. It can be seen that the observations of oil on the Funen shores in the period Jan. 27th to 28th is well predicted by the model, see Figure 8. In the end of the simulation it can seen that the oil is moving back towards north. The simulation is not long enough to illustrate the oil observations found north of Røsnæs in medio February.
Figure 7 Model results 24-01-2005 and Oil Observations in the background

Figure 8 Model results 27-01-2005 and Oil Observations in the background
Conclusion

The modelling study of the Sea Venture II submerged oilspill shows that modelling is an efficient alternative surveillance method for oil spills, when air photos and other surveillance methods does not work because the oil is submerged.
In the Sea Venture II oil spill the oil disappeared from the water surface because of vertical dispersion generated by the strong winds at the time of the release and relative high oil densities due to the winter temperatures. The cooling of the oil increased the density of the oil and combined with the high flowresistance of tiny droplets, the oil could stay submerged for a long time. Weathering of the oil increased the density of the oil further as time went by.

The wind was able to affect the oil mostly in the beginning of the oilspill, when the oil was near the water surface. This explains why the oil was able to move south en a situation with northern currents. The further down in the water column the more the hydrodynamics influenced the horizontal transport of the oil.