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Tracking Oil Slicks and Predicting their Trajectories Using Remote Sensors and Models: Case Studies of the Sea Princess and Deepwater Horizon Oil Spills

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ABSTRACT

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Oil spills can harm marine life in the oceans, estuaries, and wetlands. To limit the damage by a spill and facilitate cleanup efforts, emergency managers need information on spill location, size and extent, direction and speed of oil movement, and wind, current, and wave information for predicting oil drift and dispersion. The main operational data requirements are fast turn-around time and frequent imaging to monitor the dynamics of the spill. Remote sensors on satellites and aircraft meet most of these requirements by tracking the spilled oil at various resolutions, over wide areas, and at frequent intervals. They also provide key inputs to drift prediction models and facilitate targeting of skimming and booming efforts. Satellite data are frequently supplemented by information provided by aircraft, ships, and remotely-controlled underwater robots. The Sea Princess tanker grounding off the coast of Wales and the explosion on the Deepwater Horizon rig in the Gulf of Mexico provide good examples for studying the effectiveness of remote sensors during oil-spill emergencies.

ADDITIONAL INDEX WORDS: *Oil spills, oil remote sensing, tracking oil spills, oil spill response, remote sensing.*

INTRODUCTION

Oil spills can destroy marine life as well as wetland and estuarine animal habitat. To limit the damage by a spill and facilitate containment and cleanup efforts, the shipping operators, oil companies, and other responsible agencies must rapidly obtain information on spill location, size and extent of the spill, direction and speed of oil movement, and wind, current, and wave information for predicting future oil drift and dispersion.

Most of the large oil spills in the oceans stem from tanker groundings, break-ups, and collisions, resulting in a large fraction of the oil spreading along the surface of the ocean and frequently endangering marine and coastal ecosystems (Table 1). They are also caused by tankers emptying their billage tanks. The first five tanker accidents described in Table 1 are good examples of such major spills. In each of these cases, a wide range of remote sensors have provided the required data for tracking and predicting the future movement of the spilled oil in a timely and reliable manner, helping guide rescue and defensive efforts, including the deployment of skimming vessels and protective booms. Users of remotely-sensed data for oil spill applications include the Coast Guard, environmental protection agencies, oil companies, shipping/insurance/ fishing industries, and defense departments.

Deepwater oil spills during offshore drilling operations are not as numerous as tanker breakups, but they can cause more long-term damage to the environment, as the Deepwater Horizon oil spill proved. Also the sizes of oil spills stemming from tanker accidents can be calculated knowing the holding capacity of the wrecked tanker. One of the frustrating aspects of the Deepwater Horizon oil spill after the BP-operated oil platform exploded on April 20, 2010 in the Gulf of Mexico, was the inability to accurately estimate the amount of oil gushing from the broken and bent riser pipe at one-mile depth. The estimates obtained by BP, Coast Guard, and other specialists ranged from about 200,000 to several million gallons per day. These rough estimates were based on visual images obtained by submarine robots carrying color cameras. Remote sensors on

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Table 1. *Summary of some major ocean oil spills.*

Ship Name	Date	Location	Spill (in gallons)	Impact (coastline)	Cause
AMOCO Cadiz	March 16, 1978	Brittany (France)	70 million Light Crude	Fishing, marshes (360 km)	Steering broke, hit breakers, towing delayed
Exxon Valdez	March 24, 1989	Prince William Sound (Alaska)	30 million Crude Oil	Birds, eagles, otters, seals, salmon, orcas (1900 km)	Icebergs, steering error, hit reef
Sea Empress	February 15, 1996	Milford Haven (SW Wales)	23 million N. Sea Crude	Marsh, fish, shellfish, wildlife refuge (200 km)	Ran aground, holed on rocks, offloading delay
Prestige	November 13, 2002	Galice (Spain)	15 million Fuel Oil	Marine life, seabed, coastline (240 km)	Storm damage, ship split, tank burst, port refused entry
IXTOX Well	June 3, 1979 – October 9, 1979	Bay of Campeche (Gulf of Mexico)	140 million Crude Oil	Coastline, wetlands, estuaries	Well blew out, capped (4 months)
Deepwater Horizon (BP)	April 4, 2010	Gulf of Mexico	126+ million Crude Oil	Wetlands, estuaries, seabed (400 km)	Well blew out, pipe leaked oil, cap failed

satellites and aircraft cannot penetrate to such depth, however they were indispensable for tracking the resulting oil slicks just beneath and on top of the water surface. The daily satellite overpasses tracked the oil slicks and allowed some predictions to be made on their future drift towards coastal wetlands and beaches (Figure 1). A wide range of environmental data, such as local currents and surface winds, were needed as inputs for the predictive models. Much of this additional information was also obtained with remote sensors.

The objective of this paper is to describe the remote-sensing techniques and models used to track oil spills and predict their drift and dispersion. The effectiveness of these techniques is then illustrated by means of two “real world” case studies, one involving a tanker breakup and the other a deepwater well blowout.

REMOTE SENSING OF OIL SLICKS

For oil-spill emergencies the main operational data requirements are fast turn-around time and frequent imaging of the site to monitor the dynamics of the spill. Remote sensors on satellites and aircraft meet these requirements by tracking the spilled oil at various resolutions and over wide areas at frequent intervals through multi-temporal imaging. They also provide key inputs to drift prediction models and facilitate targeting of clean-up and control efforts. Most of these sensors use electromagnetic waves, even though acoustic sensors on boats and cameras on submerged robot-like vehicles may have to be used to view the subsurface behavior of the oil.

Table 2 summarizes the various methods of detecting oil slicks on water using electromagnetic waves. In the ultraviolet region, oil has a significantly higher reflectivity than water, even for very thin slicks. However, ultraviolet light is strongly scattered by the atmosphere and, in order to avoid such scattering, can be used only on aircraft at low altitudes. Ultraviolet sensors can also be confused by sun glint, wind slicks, and biogenic materials. To minimize this confusion, they are sometimes used in combination with other sensors, such as thermal infrared or radar.

Visible wavelengths are used more commonly due to the availability of relatively-inexpensive digital cameras on aircraft and multispectral imagers on satellites. There is also a reasonable atmospheric transmission window for visible wavelengths. In the visible region, oil has a slightly higher reflectivity than water and can be even more readily detected if horizontally-aligned filters are used. Oil sheen shows up as silvery and reflects light over a wide spectral region. Heavy oil appears brown, peaking in the 600 to 700 nm region, while mousse looks red-brown and peaks closer to 700 nm. Image analysts have to contend with many false signals at visible wavelengths, including sun glint, wind slicks, and biogenic material which can be mistaken for oil sheens. In some cases, sun glint can have a positive effect by enhancing the appearance of oil slicks and sheen. Furthermore, visible sensors cannot operate at night. But since they are widely available, less costly, and easy to use, visible sensors are frequently used to create the basic data set in coastal areas and for documentation purposes. The reflected (near) infrared is somewhat better than the visible region for detecting the slicks, but faces some of the same identification problems as the visible region.

Improvements in sensor technology have led to the development of hyperspectral sensors, such as the Airborne Visible/Infrared Spectrometer (AVIRIS) and the Airborne Imaging Spectrometer (AISA). A hyperspectral image consists of tens to hundreds of spectral bands and can provide a detailed spectral identification of a feature, such as differentiating between light and crude oil, and detecting small concentrations of oil. Their drawback is that conventional techniques for analyzing multispectral data cannot be used to analyze hyperspectral images (Brekke and Solberg, 2005;Jensen, 2007; Jha, Levy, and Gao, 2008). High-resolution hyperspectral imagers on aircraft and satellites can also be used to map the extent and condition of wetlands and coral reefs (Klemas, 2009; Purkis, 2005; Purkis and Pasterkamp, 2004).

At thermal infrared wavelengths, “optically thick” oil layers absorb solar radiation and re-emit it as thermal energy in the 8 to 14 micrometer region. Thin oil slicks or sheen cannot be detected by thermal infrared sensors. However, layers thicker than about 150 μm appear hot or bright, while layers less than about 50 μm appear cool and dark. There have been several theories proposed to explain the switch of the oil from “hot” to “cold” as the thickness of the slick decreases, but this change is not yet fully understood (*e.g.*, the evaporative cooling of the slick exceeds its radiative heating below a certain thickness and therefore appears cool compared to water (Jah *et al.*, 2008). This variability in apparent temperature may help distinguish

Figure 1. Deepwater Horizon oil spill captured on April 29, 2010, by MODIS imager on NASA's Aqua satellite. With the Mississippi Delta on the left, the silvery oil slick is clearly visible. Credits: NASA Goddard Space Flight Center.

Table 2. *Applicability of different electro-magnetic wave bands for oil detection.*

EM Band	Wavelength	Detection Mechanism	Contrast *vs.* Water	Thickness	Night Operation	Weather Limitations	False Targets
Ultraviolet	0.3–0.4 μm	Reflectivity Fluorescence	Bright	No	No	Clear	Low
Visible bands	0.4–0.7 μm	Reflectivity	Bright	No	No	Clear	High
Reflected infrared	0.7–3 μm	Reflectivity	Bright	No	No	Clear	High
Thermal infrared	3–14 μm	Emissivity	Dark/Bright	Relative	Yes	Light fog	Medium
Radar	1–30 cm	Damped Ripples	Dark	No	Yes	Heavy fog and rain	High
Passive microwave	0.2–0.8 cm	Emissivity Reflectivity	Bright	Relative	Yes	Heavy fog and rain	Low

thick layers of oil from thin layers, yet it also can cause interpreters to have difficulty distinguishing oil from water. Thermal infrared scanners are quite common on satellites and aircraft, however they have the disadvantage of requiring their detectors to be cooled to low temperatures and thus are more expensive and complex.

Radar imagers such as Side-Looking Airborne Radar (SLAR) on aircraft and Synthetic Aperture Radar (SAR) on satellites have the major advantage of not being bothered by cloud cover and other atmospheric effects, which frequently eliminate visible and infrared wavelengths from contention (Table 2). Features found frequently in SAR data are regions of low backscatter caused by the presence of oil or other slicks on the sea surface. SAR imagers view the ocean surface at incidence angles between approximately 20° and 30° from the local vertical. Capillary waves and short gravity waves cause the radar pulse to be scattered, including some backscattering to the radar transmitter. As short surface gravity waves or capillary ripples propagate through a region where an oil film is present, their energy is absorbed as the surface film strains, causing damping of these short waves. The film-covered area backscatters less energy to the radar receiver, since most of the radar pulse is reflected from the flatter surface, somewhat like from a mirror in optics, sending the radar energy in the opposite direction, away from the radar antenna. Thus ocean surface areas covered by oil or other slicks show up as dark in radar images. For this to work, low to moderate winds must exist to create the short surface waves. Since the short waves being dampened are similar in wavelength to waves used by C- and X-band SARs, Bragg reflection can cause a strong radar signature (Brecke and Solberg, 2005; Martin, 2004; Robinson, 2004).

When analyzing SAR images to distinguish oil slicks from other surface films, such as organic films generated by natural biological processes or wind-generated slicks, one must consider additional information. This can include the general shape of the slick, its proximity to oil-tanker lanes or oil-drilling platforms, the local wind speed, and other dynamic causes, such as internal waves and ocean fronts. SAR can also detect other phenomena that modulate the short waves on the sea surface, including ocean fronts and internal waves. For instance, large ocean internal waves and oceanic fronts on continental shelves strongly influence acoustic wave propagation, submarine navigation, mixing of nutrients to the euphotic zone, sediment re-suspension, cross-shore pollutant transport, coastal engineering, and oil exploration.

Oil on top of the ocean is a stronger emitter of microwave radiation than water and therefore appears as a bright feature on a darker sea. The emissivity of oil is about 80% while that of water is only about 40%. Therefore a passive microwave radiometer can detect the difference in emissivity and map the oil slicks. However, this technique has not been used much, because the signal-to-noise ratio is poor, the signal strength varies with oil layer thickness in a cyclical fashion, and other surface materials can cause false alarms.

The case studies below will clearly illustrate the effectiveness of radar and multispectral (visible/near IR) scanners on satellites in detecting and tracking oil slicks over large ocean or coastal areas. Agencies like the Coast Guard perform their more detailed aerial surveillance using integrated multi-sensor systems, including X-band side-looking radars, infrared/ultraviolet line scanners, active gated television, and aerial reconnaissance cameras. At medium altitudes these side-looking radars provide ship and oil spill detection and mapping out to 80 miles on both sides of the aircraft. The real-time television cameras provide day/night high-resolution real-time detection and identification. The reconnaissance cameras provide high resolution daytime documentation.

OIL SPILL TRAJECTORY MODELS

There are various models being used to predict the drift and dispersion of oil spilled in the ocean. One such model is the general NOAA Operational Modeling Environment (GNOME) oil spill trajectory model used by the National Oceanic and Atmospheric Administration's (NOAA) Emergency Response Division (ERD). GNOME is used by ERD in a diagnostic mode to set up custom scenarios quickly. It is also available in a Standard Mode to outside users to predict how wind, currents, and other processes might move and spread the spilled oil, learn how predicted oil trajectories are affected by uncertainties in current and wind observations and forecasts, and see how spilled oil is predicted to "weather." After entering information on an oil spill scenario, GNOME displays the trajectory of the oil. Location files with prepackaged tide and current data make it easier to work with GNOME (NOAA/ERD, 2010).

Another typical model is the Community Climate System Model (CCSM), a powerful software tool designed by the National Center for Atmospheric Research (NCAR) and the Department of Energy. This model simulates how a liquid released at the spill site would disperse and circulate. For the Deepwater Horizon spill in the Gulf of Mexico the scientists tracked the rate of dispersal in the top 65 m of the water and at four additional depths, with the lowest being just above the seabed. The modeling study was analogous to releasing a dye into the water and then watching its pathway. The computer simulations showed that once the oil in the uppermost ocean layers becomes entrained in the Gulf's fast-moving Loop Current, it may reach Florida's Atlantic Coast within weeks. It can then move north up to Cape Hatteras, North Carolina, with the Gulf Stream before turning east at that point (Figure 2). It would take unusual and sustained northerly winds to blow oil from the Gulf Stream onto beaches in Virginia and North Carolina. Cape Hatteras on North Carolina's Outer Banks may be especially vulnerable, since it juts into the ocean and is only about 15 miles from the Gulf Stream. Six different scenarios showed the same overall movement of the oil through the Gulf to the Atlantic and up the East Coast. It also showed that by the time the oil reached the East Coast its concentration might be diluted by several orders of magnitude (UCAR, 2010).

Most of the models include key processes such as advection and spreading, three-dimensional hydrodynamics, evaporation, dispersion, sinking, emulsification, and beaching. Their outputs include three-dimensional flow field of the region, trajectory, distribution of oil from surface to bottom, fate of oil

Figure 2. Oil trajectory after 130 days, predicted by the CCSM model for the Deepwater Horizon oil spill. Credits: National Center for Atmospheric Research and Department of Energy.

(evaporated, etc.), and information for defensive booming and skimming of the oil.

A major concern is what would happen if a hurricane were to hit the oil slick. NOAA's Climate Prediction Center was predicting an active Atlantic hurricane season from June to December 2010, with 14 to 23 named storms in the Gulf of Mexico, including 8 to 14 hurricanes. A hurricane could drive oil inland, not only damaging beaches and wetlands, but also pushing polluted water up river estuaries (Klemas, 2009). Researchers at the University of Texas at Austin's Texas Advanced Computing Center (TACC) are using the Ranger supercomputer to produce 3-D simulations of the impact of BP's massive oil spill on coastal areas. The team hopes to provide information to disaster responders who may need to make critical management decisions based on a hurricane's predicted behavior. The modelers receive satellite imagery of the spill and download meteorological data every six hours. The model is detailed enough to help determine how the oil may spread in environmentally sensitive areas.

ENVIRONMENTAL DATA REQUIREMENTS

In order to predict the trajectories and fate of spilled oil, the models require a wide range of environmental data inputs, such as wind conditions, currents and tides, oil properties, bathymetry and shoreline characteristics, defensive skimming and booming lines, and some typical ship data. Some of this data can also be obtained by remote sensors on satellites and aircraft, the rest using ships, shore-based radars, and other ancillary sources. For instance, surface winds and currents can be measured with satellite radar scatterometers and altimeters, respectively.

Three active microwave devices, radar altimeters, scatterometers, and SAR imagers, are of particular value during oil spill emergencies, because they provide real-time accurate information on ocean elevation, currents, winds, and waves. The application of these radars depends on the character of the pulse emitted and on what properties of the reflected pulse are measured. For a nadir-pointing radar, the timing of the returned pulse after reflection from the ocean surface, knowing the speed of light (EM waves), allows one to measure the distance between the radar and the sea-surface. This is the basic principle of radar altimeters. Oblique-viewing radar instruments that measure the backscatter from the sea-surface can be divided into two types. Those that measure average backscatter from a wide field of view are called scatterometers, and are used primarily to measure wind characteristics, which create the surface roughness. Imaging radars (radars that have a much finer spatial resolution, such as SAR), provide maps of the sea surface capable of defining a variety of small and mesoscale ocean characteristics, such as wave fields, and also track the actual oil slicks (Elachi and van Ziel, 2006; Ikeda and

Dobson, 1995; Robinson, 2004). The general surface configuration of major current systems, such as the Gulf Stream, can also be obtained with thermal infrared scanners on satellites.

Closer to the coast, shore-based high frequency (HF) and microwave Doppler radar systems can be used to map currents and determine swell-wave parameters over large areas with considerable accuracy (Bathgate, Heron, and Prytz, 2006; Graber *et al.*, 1997; Paduan and Graber, 1997; Teague, Vesecky, and Fernandez, 1997). HF radars can determine coastal currents and wave conditions over a range of up to 200 km (Cracknell and Hayes, 2007). While HF radars provide accurate maps of surface currents and wave information for large coastal areas, their spatial resolution, which is about one km, is more suitable for measuring mesoscale features than small-scale currents. Estimates of currents over large areas, such as the continental shelves, can also be obtained by tracking the movement of Lagrangian drifters or natural surface features which differ detectably in color or temperature from the background waters. Examples of such tracked natural features include chlorophyll plumes, patches of different water temperature, and surface slicks. Ocean drifters are specifically designed to track the movement of water (currents) at various depths.

Ships and buoys can also provide valuable data, including samples for chemical analysis of the oil, the oil concentration versus depth, and local meteorological information. For observing the oil distribution at greater depths, such as the Deepwater Horizon accident in the Gulf, there is a wide range of remotely-controlled robot vehicles available. These Remotely Operated Vehicles (ROV), Autonomous Underwater Vehicles (AUV), and ocean gliders can carry various instruments, including visible cameras and acoustic sensors (such as side-scan sonar) for observing subsurface features, including oil plumes.

CASE STUDIES

Sea Empress Tanker Grounding Near Wales, U.K.

On February 15, 1996, the 147,000 ton single-hulled supertanker Sea Empress was carrying 38 million gallons of North Sea crude oil from Scotland to the Texaco refinery in Milford Haven, Wales, when it ran aground and ruptured its oil tanks in heavy seas on the rocks at the mouth of Milford Haven. The tanker was finally freed from the rocks on which it had been grounded midships a week later and towed to Milford Haven docks after losing 12 million gallons of medium to light crude oil.

The spill contaminated about 200 km of the Pembrokeshire coast, including several marine and nature reserves and conservation and fishery sites. Three weeks after the initial oil spill, persistent beach contamination from new oil coming ashore was being reported over beaches on the western Carmarthen Bay. The oil spill also impacted 35 sites of scientific interest and 20 National Trust properties. A large tide at the time of the accident worsened the impact of the oil onshore by pushing the oil-polluted water higher up onto the shore. Large oil slicks remained at sea and the shores were polluted with oil for several months until a massive clean-up effort of the beaches was completed.

During the entire duration of the incident, surveillance aircraft were flown regularly over the tanker and the oil spill, sending back reports to the Milford Haven Coastguard of the extent of the pollution and guiding the deployment of booms to protect sensitive areas, such as estuaries, wetlands, and beaches. The aircraft were equipped with Side-Looking Airborne Radar (SLAR) and visible, infrared, and ultraviolet sensors. Most of the day-time observations were made with visible sensors, while the SLAR was used primarily to ascertain the outer limits of the light sheen during wide-area searches. Most of the oil remained close to the Welsh coast. When the oil started coming ashore, helicopters proved to be the best means of bringing back detailed reports of oil location and environmental impact (Harris,1997).

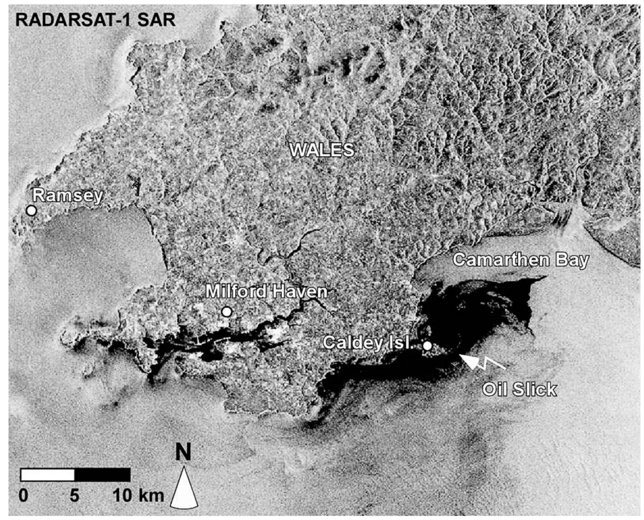

Figure 3. RADARSAT-1 SAR image of oil slicks off Milford Haven, Wales, after the oil tanker Sea Empress ran aground on February 15, 1996. Credits: RADARSAT International and Canada Centre for Remote Sensing.

A NOAA Advanced Very High Resolution Radiometer (AVHRR) satellite image taken of the oil slick on February 21 showed a long streak of oil spreading eastwards along the coast. Southwesterly winds initially spread much of the oil offshore, but shifting winds throughout this period pushed large amounts of the crude towards the coastlines. By February 26 oil sheen was reported in the middle of the Bristol Channel, about 65 km SSE of Saint Ann's Head. The final spill estimate for this disaster was 23 million gallons of oil (Clemente-Colon, Pichel, and Yan, 2010).

SAR satellite imagery was provided by RADARSAT-1 and Earth Resources Satellites ERS-1 and ERS-2 . The SAR image in Figure 3, obtained by the SAR radar on RADARSAT-1, clearly shows the dark oil slicks off the coast of Wales near Saint Ann's Head. The areas covered by oil show up as dark compared to the clear ocean surfaces because the short ocean waves, which normally backscatter radar energy to the receiver, are dampened by the oil as their energy is absorbed when the surface film strains. Thus the oil-covered areas backscatter less energy to the radar receiver, since most of the radar pulse is reflected from the flatter surface in the opposite direction, like from a mirror in optics. In Figure 3, the spill is spreading to the east along the coast of Wales. The discharge from the Tyvi River is keeping the immediate shore clear. Between the river discharge and the currents in Carmarthen Bay the slick extends south into the Bay. The potential impact of the oil decreases as the oil emulsifies and breaks down. As less-concentrated oil remains on the surface, the capillary waves are not as effectively damped and the area appears lighter in the SAR image. The image resolution was about 25 m and in RADARSAT's Standard Beam Mode each image covers an area of about 110 km × 100 km. RADARSAT SAR images were available within six hours of data acquisition (Canadian Space Agency, 1996). Since this region is frequently covered by clouds, SAR data was useful, because radar can penetrate most types of clouds and operate regardless of weather conditions, including rain, haze, and smoke.

RADARSAT, ERS-1, and ERS-2 SAR images were also used to study the evolution of the oil slicks from February 22 to 26. Using the Maximum Similarity Shape Matching Method (MSSM) for feature tracking enabled scientists to calculate drift speeds for the oil. The MSSM technique was used to derive velocity vectors from observed oil slick patterns on the SAR images. This method used the concept of maximum similarity between features for which a centroid is calculated through a radius-weighted mean. The MSSM calculated drift speeds were about 10cm/s. Observations of the slick pattern evolution with the SAR imagery during the five-day period were in agreement with available reports of ground conditions (Clemente-Colon, Pichel, and Yan, 2010). One limitation of satellite radar was that it seemed to be more sensitive to the surface sheens than to the thicker oil, which is usually the prime target for oil skimmers and other responders to a spill.

The Marine Pollution Control Unit made use of the computer model Oil Spill Information System (OSIS) in the early days of the spill when significant amounts of oil remained at sea. A number of scenarios using up-to-date weather forecasts were used to determine likely oil movement and probable shoreline impact areas. The model was particularly useful in estimating the probability of oil reaching other critical areas, such as the North Devon coast (Harris, 1997).

This oil spill was one of the worst environmental disasters on record, measuring nearly twice as large as the Exxon Valdez spill in 1989. The damaging effects of this spill were felt by the wildlife residing in Milford Haven Estuary and along the southwest coast of Wales, which serve large breeding concentrations of local and migratory seabirds, grey seals, and other animals. Because of the area's ecological importance, the effects of the oil on the wetland and estuarine ecosystems, including animals and their habitat, were studied in great detail. The area's bird populations were most impacted by the spill with thousands of casualties. Populations of invertebrates, shellfish, and rock pool fish were also severely damaged. While the area seemed to recover quickly, the potential for future damage remained because residues of oil remain along the shores of muddy beaches (DeAngelo, 2008).

The BP Deepwater Horizon Oil Spill

On April 20, 2010, an explosion rocked the Deepwater Horizon oil drilling rig operated by BP 50 miles southeast of the Mississippi delta, igniting a massive fire. When the rig sank, the riser (the pipe that runs from the wellhead to the surface) fell also, kinking as it did and causing three breaks from which several million gallons of crude oil per day gushed into Gulf waters from a depth of 1.5 km below sea level. Within several weeks the surface oil slick covered an area of nearly 10,000 square kilometers (Wikipedia, 2010).

The Deep water Horizon was an ultra-deepwater, dynamically positioned, column-stabilized floating drilling rig and could operate in waters up to 2400 m (8000 ft) deep, to a maximum drill depth of 9000 m (30,000 ft). It was located about 66 km (41 miles) off the Louisiana coast where the water depth was 1500 meters (5000 ft). The fire aboard the rig started in the evening of April 20, 2010, producing billowing flames and intense heat. After burning for more than a day, the Deepwater Horizon rig sank on April 22, 2010. At the time of the explosion the rig was drilling but was not in production.

Estimating the flow was very difficult, since there was no metering of the flow underwater. Estimates of the flow provided by BP, the Coast Guard, and other sources ranged from about 200,000 to several million gallons per day. These estimates were primarily obtained from cameras mounted on deep-sea robots viewing the oil leaking from the wellhead. The spread of the oil was increased by strong southerly winds caused by an impending cold front. Within a week the oil spill covered 1500 square kilometers (580 square miles) and was only 50 km (31 miles) from the ecologically sensitive Chandeleur Islands, and by April 30 the oil had spread over 10,000 sq. km (3850 sq. miles).

Various attempts by BP to stop the oil leak kept failing. First BP attempted to use ROVs to close the failed blowout preventer valves on the well head at 1500 meters below sea level. When that failed, BP attempted to place domes over the well leaks and pipe the oil to a storage vessel on the surface. Attempts were also made to pump heavy drilling mud into the crippled blowout preventer on top of the well, then permanently entomb the leak with concrete. Eventually BP succeeded in cutting and removing the bent and broken riser pipe and placing a cap with a suction tube on top of the well and siphon off about 600,000 gallons of oil per day, a fraction of the estimated two million gallon per day leak from the well. BP also obtained permission to burn the collected oil and gas piped up from its broken seafloor well. With all attempts to fully close the oil leak being unsuccessful, the final plan was to drill two relief wells into the original well to relieve it. The first relief well would be aimed at the 7-inch wide steel-casing pipe located just above the spot where the original well enters the oil reservoir at 6000 meter (18,000 feet) depth. The relief wells were supposed to intersect the leak hole far beneath any leaking fractures of the pipe and faulty blowout preventer, then pour mud and cement to seal it permanently. However, the relief wells would take several more months to complete, while the oil continued to gush out of the well at a rate of several million gallons per day (Walsh, 2010).

With crude oil already being reported along the barrier islands of Alabama and Mississippi and having polluted about 125 miles of Louisiana coastline, it seemed inevitable that the oil would eventually impact most beaches and wetlands in the Gulf states. By June 19 it was estimated that a total of about 126 million gallons of oil had escaped and oil was indeed impacting Florida marshes and tar balls were showing up on its northern beaches. While BP was leading the cleanup, it employed ROVs, nearly a thousand workers, various aircraft, and several dozen ships. As the spill spread, various government agencies (such as the Coast Guard) and private companies and citizens groups joined in. By the middle of June there were thousands of vessles and tens of thousands of personnel involved in the cleanup effort, including thousands of volunteers. Chemicals were sprayed from aircraft and remotely-controlled submarine robots to break up the oil, but with limited success and potentially negative impact on marine animals and plants. While most of the oil drilled off Louisiana is a lighter crude, this oil leaked from deeper under the ocean surface and consisted of a heavier blend, containing asphalt-like substances. The oil emulsified rapidly and was difficult to handle since it produced a very sticky substance (Wikipedia, 2010).

Satellite remote sensors and observers on aircraft were deployed as soon as the spill occurred. As shown in Figure 1, the MODIS sensor on NASA's Terra and Aqua satellites and the Advanced Land Imager on board of NASA's Earth Observing-1 satellite were able to clearly image the oil slick on the surface of the Gulf and track its drift and spreading behavior over time. As described earlier, the oil can be detected by multispectral/hyperspectral scanners, such as MODIS, because its reflectivity in some of the shorter visible bands differs from that of water. For instance, MODIS was able to produce clear images of the oil slick on April 21, 25, 29, and May 4, showing the spreading and drift of the oil towards the Louisiana coast due to easterly and south-easterly winds, as predicted by NOAA's 72-hour forecast. As the winds changed, MODIS images taken on June 7 and 9 showed a major portion of the slick expanding northeast and by June 12 invading the beaches along the Florida panhandle. Based on the June 12 MODIS images, it was estimated that the slick and sheen was covering an area of 23,500 km^2 (9100 square miles). Thermal infrared sensors on various satellites were also used for mapping sea-surface temperature, which is important because it allows scientists to track ocean currents that determine where the oil will be travelling (NASA, 2010).

SAR images of the slicks were also obtained with the European Space Agency's Envisat satellite on various dates, including April 22, 29, and May 2, showing the oil slick drifting towards the Louisiana barrier islands and wetlands. As shown in Figure 3, SAR can detect oil slicks because the oil damps the short and capillary wavelets on the sea surface and thus backscatters a smaller amount of the radar pulse than the water. In the case of the Sea Empress oil spill off the coast of Wales, SAR imagery was particularly useful, because radar is not affected by cloud cover.

Detailed continuous observations of the surface slick's dynamics and environmental impact were also conducted by aircraft and helicopters. The information obtained on a near-real–time basis was used to plan defensive measures, such as the deployment of oil containment booms, skimming operations, and even creation of artificial sand barriers. But the aircraft could not present the large overview of the spill as provided by satellite sensors. Aircraft were also used in various other applications, such as to spread chemical dispersants over the slicks, but with questionable success, since there was too much oil to disperse and questions about the potentially negative impact of the chemicals on marine life and coastal ecosystems.

To view the oil gushing from the broken well, cameras on robotic submarines (ROVs and AUVs) were used even at the 1500-m depth of the well. These robotic submarines and ocean gliders may be the best way to map out any submerged oil plumes at various depths in the Gulf created by the oil spill. ROVs are remotely controlled and AUVs and ocean gliders can be preprogrammed to perform tasks automatically at various depths, such as inspecting oil and gas pipelines on the ocean floor. Ocean gliders are remotely operated robots that swim in a saw-tooth pattern and can scan the interior for traces of oil. This was particularly important for the Deepwater Horizon case, since there were reports of submarine oil plumes originating from the spill. All of these robots can carry a large complement of instruments, including cameras, side-scan sonar, laser profilers, and a wide assortment of oceanographic sensors. They can transmit their data directly to a research ship or to a distant control center via satellite links (Marine Technology Reporter, 2010).

SUMMARY AND CONCLUSIONS

Oil spills can destroy marine life as well as wetland and estuarine animals and their habitat. To limit the damage by a spill and facilitate containment and cleanup efforts, scientists, modelers, and emergency managers must obtain timely information on spill location, size and extent of the spill, direction and speed of oil movement, and wind, current, and wave information for predicting future oil drift and dispersion. The main operational requirements for oil-spill emergencies are fast turn-around time and frequent imaging of the site to monitor the dynamics of the spill. Remote sensors on satellites and aircraft satisfy most of these requirements by tracking the spilled oil at various resolutions, over wide areas, and at frequent intervals through multi-temporal imaging. They also provide key inputs to drift prediction models and facilitate targeting of clean-up and control efforts. Most of these sensors use electromagnetic waves, even though acoustic sensors on boats and cameras on submerged robot-like vehicles may have to be used to view the subsurface behavior of the oil.

Visible wavelengths are used more commonly due to the availability of relatively inexpensive digital cameras on aircraft and multispectral imagers on satellites. The oil can be detected by multispectral/hyperspectral scanners, such as MODIS, because its reflectivity in some of the shorter visible bands differs from that of water. A hyperspectral image consists of tens to hundreds of spectral bands and can provide a detailed spectral identification of a feature, such as differentiating between light and crude oil and detecting small concentrations of oil. High-resolution hyperspectral imagers on aircraft and satellites can also be used to map the extent and condition of wetlands and coral reefs.

Radar imagers such as SLAR and SAR on satellites have the major advantage of not being bothered by cloud cover and other atmospheric effects, which frequently eliminate visible and infrared wavelengths from contention. SAR can detect oil slicks because the oil damps the short and capillary wavelets on the sea surface and thus backscatters a smaller amount of the radar pulse power than the water.

There are various models being used to predict the drift and dispersion of oil spilled in the ocean, including NOAA's GNOME model and NCAR's CCSM model. Most of the models include key processes such as advection and spreading, three-dimensional hydrodynamics, evaporation, dispersion, sinking, emulsification, and beaching. Their outputs include three-dimensional flow field of the region, trajectory, distribution of oil from surface to bottom, fate of oil (evaporated, *etc.*), and information for defensive booming and skimming of the oil. Most of the modelers receive satellite imagery of the spill and download meteorological data every six hours. Some of the models are used to predict future general movement of the oil, while others are detailed enough to help determine how the oil may spread in environmentally-sensitive areas. In order to predict the trajectories and fate of spilled oil, the models require a wide range of environmental data inputs, such as wind conditions, currents and tides, oil properties, bathymetry and shoreline characteristics, defensive skimming and booming lines, and some typical ship data. Some of this data can also be obtained by remote sensors on satellites and aircraft, the rest using ships, shore-based radars, and other ancillary sources. For instance, surface winds and currents can be measured with satellite radar scatterometers and altimeters, respectively. Closer to the coast, shore-based high frequency (HF) and microwave Doppler radar systems can be used to map currents and determine swell-wave parameters over large areas with considerable accuracy. Ships and buoys can also provide valuable data, including samples for chemical analysis of the oil, the oil concentration versus depth, and local meteorological information. For observing the oil distribution at greater depths, such as the Deepwater Horizon accident in the Gulf, there is a wide range of remotely-controlled robot vehicles available.

The two case studies clearly illustrate the effectiveness of radar and multispectral (visible/near infrared) scanners on satellites in detecting and tracking oil slicks over large ocean or coastal areas. Satellite remote sensors and observers on aircraft were deployed as soon as the spills occurred. In the case of the Deepwater Horizon spill, MODIS sensors on NASA's Terra and Aqua satellites and the Advanced Land Imager on board of NASA's Earth Observing-1 satellite were able to clearly image the oil slick on the surface of the Gulf and track its drift and spreading behavior over time. Detailed continuous observations of the surface slick's dynamics and environmental impact were also conducted by aircraft and helicopters. The information obtained on a near-real-time basis was used to plan defensive measures, such as the deployment of oil-containment booms, skimming operations, and even creation of artificial sand barriers. To view the oil gushing from the broken well, cameras on robotic submarines (ROVs and AUVs) were used even at the 1500 meter depth of the well. These robotic submarines and ocean gliders may be the best way to map out any submerged oil plumes at various depths in the Gulf created by the oil spill. The robots can carry a large complement of instruments, including cameras, side-scan sonar, laser profilers and a wide assortment of oceanographic sensors (Schofield, Kohut, and Glenn, 2008).

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