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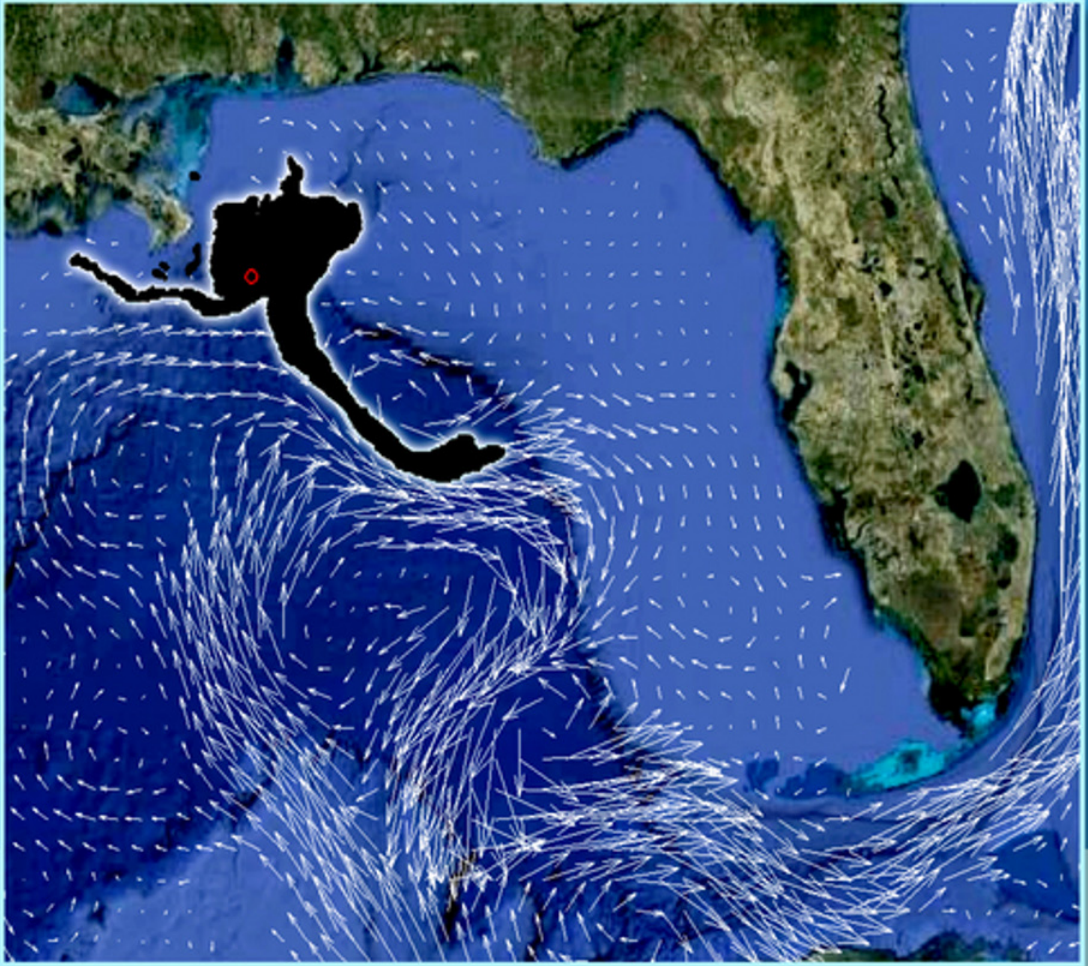
Monitoring and Modeling the *Deepwater Horizon* Oil Spill

A Record-Breaking Enterprise



Yonggang Liu, Amy MacFadyen, Zhen-Gang Ji,
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Monitoring and Modeling the *Deepwater Horizon* Oil Spill: A Record-Breaking Enterprise

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Cover Image: *Deepwater Horizon* surface oil slick inferred from NASA MODIS imagery on 17 May 2010 16:37 UT (courtesy of Chuanmin Hu, Optical Oceanography Laboratory, College of Marine Science, University of South Florida) superimposed on the surface geostrophic currents estimated from AVISO sea level data (http://www.aviso.oceanobs.com/).

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CONTENTS

PREFACE

As the largest offshore oil spill in U.S. history, the *Deepwater Horizon* incident in spring–summer 2010 presented a significant threat to the coastline and the marine ecosystems of the Gulf of Mexico. Aiming to help and guide mitigation efforts, scientists from operational agencies, the academic community, and the private sector responded rapidly by making use of ocean-observing and ocean-modeling resources as well as oil spill detection technologies. The monitoring and modeling conducted over the following months was unprecedented in the amount of oceanographic and oil spill observations collected, the number of numerical models employed, and the number of scientists and agencies involved in the effort. It was the most intensive oceanographic and oil spill research enterprise ever performed.

The contents of this book were primarily derived from three special sessions (OS33C, OS41D, and OS42A) organized by the editors at the American Geophysical Union 2010 Fall Meeting, "Lessons Learned From the *Deepwater Horizon* Oil Spill: Physical Oceanography." The sessions brought together many of the scientific leaders in the field. A total of 23 presentations on the "experiences and lessons learned" were contributed by the oil spill first responders from academic institutions, the private sector, and governmental agencies. The presentations covered observing and modeling of the oil spill and provided state-of-the-art overviews on the science and technology of this field. This broad-based approach exposed for the participants the need for a synthesis. Along with the meeting participants we also invited several scientists with expertise in Gulf of Mexico oceanography to contribute to this book.

Effective oil spill monitoring and modeling systems were critical to the rapid responses achieved for the *Deepwater Horizon* event. Now in the aftermath, accurate hindcast modeling systems remain essential for damage assessment and improved understanding and prediction of long-term impacts. With the increasing demand for energy resources, gas and oil production has shifted to deeper-water regions in recent years, highlighting the need for continued knowledge to support rapid and effective responses to any subsequent deepwater oil spill. The scientific response to the *Deepwater Horizon* oil spill was timely, and the lessons learned may be beneficial going forward. It is our hope that this book will provide a basis for motivating additional marine research in the Gulf of Mexico and on the potential long-term consequences of the *Deepwater Horizon* oil spill.

The production of this book is partially supported by the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE), now Bureau of Ocean Energy Management (BOEM), of the U.S. Department of the Interior. The federal agency, BOEM, itself is also a benefactor of the research work presented in this book. Special thanks are extended to Rodney E. Cluck, Chief of the Division of Environmental Sciences of BOEM, for approving the financial support. We gratefully thank all our contributors for their time and efforts with the chapters and the reviewers for their constructive comments and helpful suggestions. We would like to extend our thanks to Maxine Aldred, Assistant Director, Books and Publishing Services, and Colleen Matan, our AGU Acquisitions Editor, for their encouragement and tremendous help to bring this project to fruition; to Kenneth H. Brink (Woods Hole Oceanographic Institution), our Oversight Editor, for important and helpful guidance; to Telicia Collick for her timely assistance throughout the peer-review process; to Maria Lindgren for her careful technical editing; and to the AGU production staff.

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Introduction to Monitoring and Modeling the *Deepwater Horizon* Oil Spill

Yonggang Liu,[1] Amy MacFadyen,[2] Zhen-Gang Ji,[3] and Robert H. Weisberg[1]

In response to the massive *Deepwater Horizon* oil spill in the Gulf of Mexico, scientists from the operational response agencies, the academic community, and the private sector employed the oil spill detection technologies and ocean-observing and modeling resources to map the discharged hydrocarbons and simulated their transport with the aim of aiding mitigation efforts. Numerous types of instruments and sensors were used, many numerical models were applied, and a broad array of scientists were involved. These studies represent a new generation of applied oceanography with a focus on a historical oil spill. Preliminary research results reported in 21 chapters of this book are categorized and summarized.

1. BACKGROUND

The Gulf of Mexico (GOM) is a semienclosed marginal sea on the western side of the North Atlantic Ocean. Within the GOM, the Caribbean Current, entering via the Yucatan Strait, transitions to the Loop Current and the Florida Current exiting through the Florida Straits. Thus the GOM provides the connectivity between the tropical Atlantic and the North Atlantic and serves as the inception point for the North Atlantic's western boundary current, the Gulf Stream. With abundant oil and gas storage underneath the ocean bottom, rich commercial and recreational fisheries in the water column, and beautiful beaches and wetlands along the coast, the GOM has been referred to as "a jewel among the natural resources of the western hemisphere" [*Sturges et al.*, 2005].

The *Deepwater Horizon* oil platform (situated about 80 km southeast of the Mississippi River delta in the Mississippi Canyon Macondo Block 252) exploded on 20 April 2010, claiming 11 lives. The explosion and subsequent sinking of the rig on 22 April began what would become the largest offshore oil spill in U.S. history. Large amounts of crude oil and gas gushed from a well blowout at the ocean bottom (~1500 m depth) into the GOM for nearly 3 months. The discharged hydrocarbons, along with chemical dispersants applied as part of the response, presented a significant threat to the coastline and the living marine resources of the GOM. The "jewel" was subjected to a historical level of marine pollution. Thus, on 29 April the spill was designated a "spill of national significance"; that is, it was recognized that the size of the spill would necessitate a response effort requiring extraordinary coordination of federal, state, local, and responsible party resources.

The oceanographic community response to the *Deepwater Horizon* incident was also immediate. Along with federal, state, and local agencies, academic and private sector scientists applied available resources to map the discharged hydrocarbons and forecast their transport with the aim of aiding mitigation efforts. Many of these efforts are documented in this book. Individual chapters present applications of state-of-the-art research employed in monitoring and modeling of the oil spill behavior and/or of the oceanographic conditions that were associated with the oil transport and fate throughout the incident.

The chapters dealing with observations are arranged in the first half of the book, and those focusing on modeling are

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arranged in the second half. The sequence of the chapters also generally follows the rule of "from surface to subsurface." Thus, interested readers can quickly find the relevant chapters of specific interest in this book.

2. MAPPING THE SURFACE OIL

Satellite remote sensing has been increasingly applied in detection of surface oil slicks. It was especially valuable during the *Deepwater Horizon* oil spill because of the large extent of the surface oil and the spill duration. Moderate Resolution Imaging Spectroradiometer (MODIS) (see http://modis.gsfc.nasa.gov) and other optical data from satellites have been shown to be useful for detecting the existence of oil on the ocean surface [e.g., *Hu et al.*, 2003, 2009, 2011], as have data from synthetic aperture radar (SAR) imagery [e.g., *Liu et al.*, 2000; *Cheng et al.*, 2011; *Zhang et al.*, 2011]. Reviews on the strengths and weaknesses of different sensors ranging from ultraviolet and visible sensors to passive microwave and SAR may be found in the literature [e.g., *Fingas and Brown*, 2000; *Jha et al.*, 2008].

Throughout the *Deepwater Horizon* incident, satellite imagery analyses of surface oil were performed by many groups. The lead chapter in this book, *Streett* [this volume], describes the work of the National Oceanic and Atmospheric Administration (NOAA) Satellite Analysis Branch. Both SAR and high-resolution visible/near-infrared-range multispectral satellite imagery as well as a variety of ancillary data sets are used to map the surface oil location. Valuable lessons learned about the oil spill response are also provided in this chapter. The response to the *Deepwater Horizon* oil spill included work by international scientists. The chapter by *Grimaldi et al.* [this volume] proposes a new algorithm for automatic near-real-time oil spill detection and continuous monitoring by optical satellite data. This work demonstrates utility even for nighttime data acquisitions.

Aircraft-borne sensors also played an important role in detecting the *Deepwater Horizon* surface oil slicks. This was particularly important for the relatively smaller oil patches that were not resolvable by satellite-borne sensors. *Jones et al.* [this volume] describe an application of an uninhabited aerial vehicle synthetic aperture radar (UAVSAR) platform for scientific studies of the oil spill and its impact. Focusing on oil-affected wetlands in Barataria Bay, Louisiana, they find that a fine-resolution L band radar can detect surface oil with sufficient sensitivity to identify regions with different types of oil emulsions and areal extent.

New airborne sensors for oil spill detection were also tested during the *Deepwater Horizon* incident. A thermal imaging radiometer, an ultraviolet to visible hyperspectral imaging radiometer, and a visible high dynamic range context imager were deployed at the same time on an aircraft flown over the oil slicks in the GOM with overlapping fields of view as discussed by *Good et al.* [this volume].

3. MAPPING OF SUBSURFACE HYDROCARBONS

Not all of the hydrocarbons released at the seafloor during the *Deepwater Horizon* oil spill made it to the surface. Subsurface plumes of either hydrocarbons issuing from the wellhead or proxies for such hydrocarbons were found at depth, first southwest from the well site and later to the northeast [e.g., *Camilli et al.*, 2010; *Diercks et al.*, 2010; *Joint Analysis Group*, 2010; *Hazen et al.*, 2010; *Schrope*, 2010; *Kessler et al.*, 2011; *Joye et al.*, 2011; *Hollander et al.*, 2010]. Three chapters in this book are devoted to subsurface observation efforts.

Detection of subsurface hydrocarbons via optical sensors deployed on an autonomous underwater vehicle (AUV) is reported by *Ryan et al.* [this volume]. By shipboard survey, maximum optical signatures of a deep plume, centered at ~1150 m depth, approximately 13 km southwest from the blowout were chosen for a high-resolution AUV survey, which showed the effects of small-scale topographic feature influences on plume transport. Maximum plume intensity was observed along the western slope of the Biloxi Dome.

Along with optical proxies, actual surface and subsurface water samples collected in the vicinity of the *Deepwater Horizon* wellhead from 24 May 2010 to 6 June 2010 and analyzed for polycyclic aromatic hydrocarbons confirmed the presence of subsurface hydrocarbon plumes near the wellhead. *Wade et al.* [this volume(a)] discuss these samples and analyses.

Complementing the previous samples that were localized about the *Deepwater Horizon* well site, *Wade et al.* [this volume(b)] consider 282 discreet water samples collected at various depths over a larger area inclusive of the Loop Current and associated eddies. When compared to historical data dating back to the 1970s, the trace concentrations of hydrocarbons detected at these sampling stations were found to be low. Although it remains unclear whether these low concentrations were of *Deepwater Horizon* origin, total scanning fluorescence is demonstrated to be a valuable screening tool in detecting the presence of oil.

4. OBSERVATIONS OF OCEAN CIRCULATION

The ocean circulation through advection and turbulent mixing is what connects a point of hydrocarbon origin with distant regions [e.g., *Spaulding*, 1988; *Yapa*, 1996]. In the *Deepwater Horizon* oil spill, the hydrocarbons issued from the continental slope in the northern GOM, a transition zone between the shallow continental shelf on its northern side and the deep ocean on its southern side. It is also a place where complex bathymetry further affects ocean circulation [e.g., *Biggs et al.*, 2005; *Hamilton and Lee*, 2005; *Brink*, 2010]. On the continental shelf (northern) side, the currents tend to be generally weaker and mostly wind driven [e.g., *Weisberg et al.*, 2005; *Morey et al.*, 2005] when compared with the southern side, where the deep ocean currents, embodied by the GOM Loop Current system, tend to be much stronger [e.g., *Kirwan et al.*, 1988; *Sturges et al.*, 1993; *Leben and Born*, 1993]. Thus, the Loop Current system posed a threat for the expansion of the *Deepwater Horizon* disaster because of the potential for rapid southward advection of oil. Such concern existed throughout the *Deepwater Horizon* spill [e.g., *Weisberg*, 2011]. In this book, four chapters are devoted to observations of the Loop Current circulation during the spill.

The ocean circulation patterns of the GOM Loop Current system and their effects on the advection of the surface oil discharged during the *Deepwater Horizon* incident are described by *Liu et al.* [this volume(a)] based on in situ surface drifter trajectories and satellite observations that include altimetry-derived surface geostrophic velocities, sea surface temperature, ocean color, and surface oil locations. They show an anticyclonic eddy in its formative stage that detached from the northern part of the Loop Current in the latter part of May 2010, thereby tending to break the direct connection between the northern Gulf with points farther south.

Walker et al. [this volume] contribute a chapter that also employs satellite data, in tandem with in situ current and wind measurements, to track the surface oil and to explain the causes for observed large-scale motions during the event. They show the merger of three cyclonic eddies along the Loop Current's northern margin, which played a role in the accumulation of the oil within the larger cyclonic eddy.

Hamilton et al. [this volume] report on their moored observations of currents and bottom pressure in the eastern GOM deepwater area. They find that the circulation was dominated by the interaction between the Loop Current and the anticyclonic eddy during the *Deepwater Horizon* event. On the basis of altimetry data, the detachment/reattachment of the Loop Current eddy is also discussed from a historical perspective.

Finally, airborne ocean surveys of the Loop Current complex in support of the *Deepwater Horizon* oil spill response are also reported by *Shay et al.* [this volume]. Ocean current, conductivity, temperature, and depth profiles acquired in the Loop Current system region were used to reveal the complex eddy-shedding processes. These profiles provided additional observations that were assimilated into the Navy Hybrid Coordinate Ocean Model analyses that were used along with other ocean circulation models to forecast oil trajectories.

5. MODELING OF THE OIL SPILL TRAJECTORY

An important aspect of the *Deepwater Horizon* oil spill response was numerical modeling of the oil trajectory in support of mitigation efforts (e.g., skimming and booming). These modeling efforts were conducted both in an operational mode based on nowcast/forecast numerical ocean circulation models [*Liu et al.*, 2011, this volume(b); *MacFadyen et al.*, this volume; *Weisberg et al.*, this volume] and in a statistical manner based on multiple-year hindcast simulations [*Ji et al.*, this volume; *Barker*, this volume; *Tulloch et al.*, this volume]. Also included in this book are several follow-up studies on Lagrangian trajectory modeling [*Huntley et al.*, this volume; *Pugliese Carratelli et al.*, this volume], trajectory hindcasting that considers oil droplet sizes [*North et al.*, this volume], and a laboratory model that investigates subsurface plume dynamics in the presence of stratification [*Adalsteinsson et al.*, this volume].

5.1. Surface Trajectory Models

Surface trajectory modeling as an immediate response from the University of South Florida is reported in a chapter by *Liu et al.* [this volume(b)], which is an expansion of their feature article [*Liu et al.*, 2011]. Surface oil locations inferred from satellite imagery were used to reinitialize the positions of virtual particles in an ensemble of trajectory models, and the particles were tracked using surface currents forecast from multiple ocean circulation models, with new particles added to simulate the continual release of oil from the well. By frequently reinitializing the trajectory models with satellite-inferred locations, the effects of in situ mitigations and forecast error growth were implicitly accounted for and minimized.

Surface oil forecasts for the *Deepwater Horizon* oil spill were provided throughout the response by NOAA's Office of Response and Restoration. This effort is described in a chapter by *MacFadyen et al.* [this volume]. The surface oil distribution was initialized daily from analysis of satellite imagery and incorporation of visual overflight observations. The computation of surface oil trajectories utilized currents from multiple ocean circulation models allowing an ensemble forecasting approach. Results from the suite of trajectories were then combined to produce a final forecast product for distribution to the Incident Command Posts.

Results from surface Lagrangian trajectory modeling are presented in a chapter by *Huntley et al.* [this volume]. They diagnosed the Lagrangian trajectory model with different initializations of two satellite products and proposed two new model assessment metrics. They also explored the role of wind and found it to be negligible away from the coastal areas.

In another follow-up paper by *Pugliese Carratelli et al.* [this volume], the surface wave effects on the drift and dispersion of the surface oil are investigated. The effects of mean Stokes' drift were confirmed to be an important element in most situations. The diffusion due to random wave movement was also shown to be relevant for smaller spills; however, for large incidents like the *Deepwater Horizon* spill, its effects appear to be less important.

5.2. *Subsurface Trajectory Models*

A subsurface trajectory simulation based on a nowcast/forecast ocean circulation model of the eastern GOM is reported by *Weisberg et al.* [this volume]. Assuming that some compounds would reach certain levels and be carried three-dimensionally by the currents, virtual drifters were deployed at different depths and advected by the forecast currents. New particles were also added every 3 hours to simulate the continual release of hydrocarbons from the wellhead during the event.

Another three-dimensional Lagrangian transport model is reported in a chapter by *North et al.* [this volume]. This model considered oil droplets of different sizes dispersed at depth from the *Deepwater Horizon* spill. The plume model predicted a stratification-dominated near field, in which small oil droplets detrained from the central plume containing faster rising large oil droplets and gas bubbles and became trapped by density stratification. Model results suggested that the subsurface plume looped around to the east, with potential subsurface oil transport to the northeast and southeast.

5.3. *Statistical Models*

Ji et al. [this volume] contribute a chapter on the oil spill risk analysis (OSRA) model used by the Bureau of Ocean Energy Management, Regulation and Enforcement (now Bureau of Ocean Energy Management) to estimate potential oil spill shoreline contacts and potential contact with offshore resources. Trajectories of a long duration originating from the location of the well site were analyzed statistically using historical wind and current data from 1993 to 1998. The statistical patterns and results from the OSRA model were compared with the patterns of surface oil transport for the *Deepwater Horizon* oil spill.

Barker [this volume] reports on a Monte Carlo simulation generated by running an oil spill trajectory model hundreds of times, each with a different set of possible conditions based on historical data. This statistical outlook of where the spilled oil might go and when it might arrive there was requested of NOAA's Office of Response and Restoration early in the response when it became apparent that there was potential for a very large spill of long duration. The results of this analysis were required to aid in response preparation and to determine whether foreign governments should be notified.

Tulloch et al. [this volume] discuss possible spreading of buoyant plumes and local coastline sensitivities using observationally constrained models spanning 1992–2007. The results were obtained from an ensemble of simulations where a buoyant dye was injected at the site of the *Deepwater Horizon* blowout from April 20 to July 15. When combined with accurate estimates of historical currents and winds, an adjoint approach is proposed as a useful regional planning and preparedness tool.

5.4. *Laboratory Model*

In addition to in situ observations and numerical models, laboratory experiments have been utilized to study the subsurface hydrocarbon plumes in the GOM. For example, in the chapter by *Adalsteinsson et al.* [this volume], they demonstrate that buoyant immiscible plumes like those that occurred during the *Deepwater Horizon* spill could be trapped as they rise through an ambient, stratified fluid. The addition of surfactants is an important mechanism by which trapping can occur. They also introduce a theory on trapping/escape of multiphase oil plumes in a stratified water column.

6. CONCLUDING REMARKS

In response to the massive *Deepwater Horizon* oil spill in the GOM, scientists from the operational response agencies, the academic community, and the private sector have worked unselfishly, marshaling the existing and emerging oil spill detection technologies and ocean observing and modeling resources to help provide accurate information to assist mitigation efforts and to aid in public awareness. Numerous types of instruments and sensors provided oil and ocean observations, many numerical models were utilized, and a broad array of scientists devoted their time to this endeavor. The overall effort involved in this rapid response was truly a record-breaking enterprise. Many of the individual studies are reported in this book, which represents a new generation of applied oceanography with a focus on a historical oil spill.

These studies are focused on the GOM, but their influences are far-reaching both temporally and geographically. Most of the chapters report only preliminary results obtained from the rapid response efforts; however, they provide valuable information for ongoing aftermath studies of the ecological impacts of the *Deepwater Horizon* oil spill to participants from broader communities around the world for years or decades to come. Also, with increasing energy demands, explorations of deepwater resources have been in a trend of expansion [e.g., *Karl et al.*, 2007]. There is a need for effective rapid response systems in support of management and mitigation efforts for the world's oceans. The chapters collected in this book illustrate how existing observing systems and models can be leveraged to benefit society in a time of crisis.

The authors in this book benefited from previous studies of the physical oceanography in the GOM [e.g., *Capurro and Reid*, 1972; *Boicourt et al.*, 1998; *Sturges and Lugo-Fernandez*, 2005]. New insights are gained, and new data from 2010 are presented in this book. Nevertheless, there is a realization that much more remains to be learned about the complex Loop Current system, its eddies, and how these impact the overall flow structures of the GOM from the deep waters to the estuaries and wetlands. Further advances will require the coordination of increased observations and a hierarchy of models to better describe, understand, and predict the complex, multidisciplinary workings of the GOM.

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NOAA's Satellite Monitoring of Marine Oil

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During the *Deepwater Horizon* (DWH) spill, NOAA imagery analysts in the Satellite Analysis Branch (SAB) issued more than 300 near-real-time satellite-based oil spill analyses. These analyses were used by the oil spill response community for planning, issuing surface oil trajectories, and tasking assets (e.g., oil containment booms, skimmers, overflights). SAB analysts used both synthetic aperture radar and high-resolution visible/near IR multispectral satellite imagery as well as a variety of ancillary data sets to map the surface oil location. Satellite imagery included Envisat advanced synthetic aperture radar (European Space Agency (ESA)), TerraSAR-X (Deutsches Zentrum für Luft- und Raumfahrt), Cosmo-Skymed (Agenzia Spaziale Italiana), Advanced Land Observing Satellite (Japan Aerospace Exploration Agency (JAXA)), RADARSAT (MacDonald Dettwiler and Associates, Canadian Space Agency), Envisat MERIS (Medium-Resolution Imaging Spectrometer, ESA), SPOT (SPOT Image Corp., Centre National d'Etudes Spatiales), Landsat (NASA, United States Geological Survey (USGS)), Aster (JAXA, NASA), MODIS (Moderate Resolution Imaging Spectroradiometer, NASA), and advanced very high resolution radiometer (NOAA). Ancillary data sets included ocean currents, winds, natural oil seeps, and in situ oil observations. SAB personnel also served as the DWH International Disaster Charter Project Manager (at the official request of the USGS). The Project Manager's primary responsibility was to oversee the acquisition and processing of satellite data generously donated by numerous private companies and nations in support of the oil spill response. All SAB DWH analyses, starting with one issued 5 h after the rig sank through the final one in August, are still publicly available at the archive on the NOAA/NESDIS website http://www.ssd.noaa.gov/PS/MPS/deepwater.html. SAB has now acquired a 24 × 7 oil spill response capability and is addressing goals that will enhance its routine oil spill response as well as help assure readiness for the next spill of national significance.

Monitoring and Modeling the *Deepwater Horizon* Oil Spill:
A Record-Breaking Enterprise
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1. INTRODUCTION

The NOAA Satellite Analysis Branch (SAB) conducts near-real-time monitoring of satellite imagery and ancillary data for a variety of hazards including volcanic ash, tropical storms, fires, smoke, and heavy precipitation. In 2009, NOAA's Emergency Response Division (ERD) formally requested SAB's mission be expanded to include detection and analysis of marine oil spills. SAB's expertise using human satellite analysts (augmented but not replaced by various automated tools), their 24 × 7 operational capability, and their ability to seamlessly integrate a variety of satellite and nonsatellite data sources was determined to be the best fit for developing this ability within NOAA.

Initially, there was concern that SAB would not have the personnel, resources, or access to imagery to effectively respond in the event of a catastrophic or prolonged oil spill. However, these fears were assuaged by the International Disaster Charter (see below), as well as the Oil Pollution Act of 1990 and the National Oil and Hazardous Substances Pollution Contingency Plan (40 C.F.R. Part 300), which not only mandate a role for NOAA in support of oil spill response, but also provide a mechanism to help fund the response. With these concerns adequately addressed, the ERD request, deemed important to NOAA's mission, was approved, and capability development began.

By early 2010, development efforts had yielded preoperational products that were demonstrating significant potential. As part of the development efforts, SAB had successfully identified user needs, established access to imagery and ancillary data, created product generation capabilities, conducted operational training, and made required changes to staffing and systems. Then, in April, the *Deepwater Horizon* (DWH) spill occurred, resulting in a unified effort throughout the federal government to bring all possible capabilities to bear for this environmental and economic disaster.

Since development of the satellite oil spill analysis capability had reached the stage of routinely issuing preoperational products, SAB was able to respond immediately to the DWH disaster. Within hours of the rig sinking, SAB had issued its first product depicting the location of the surface oil, had accepted the role of International Disaster Charter project manager for the spill and had ramped up staffing in

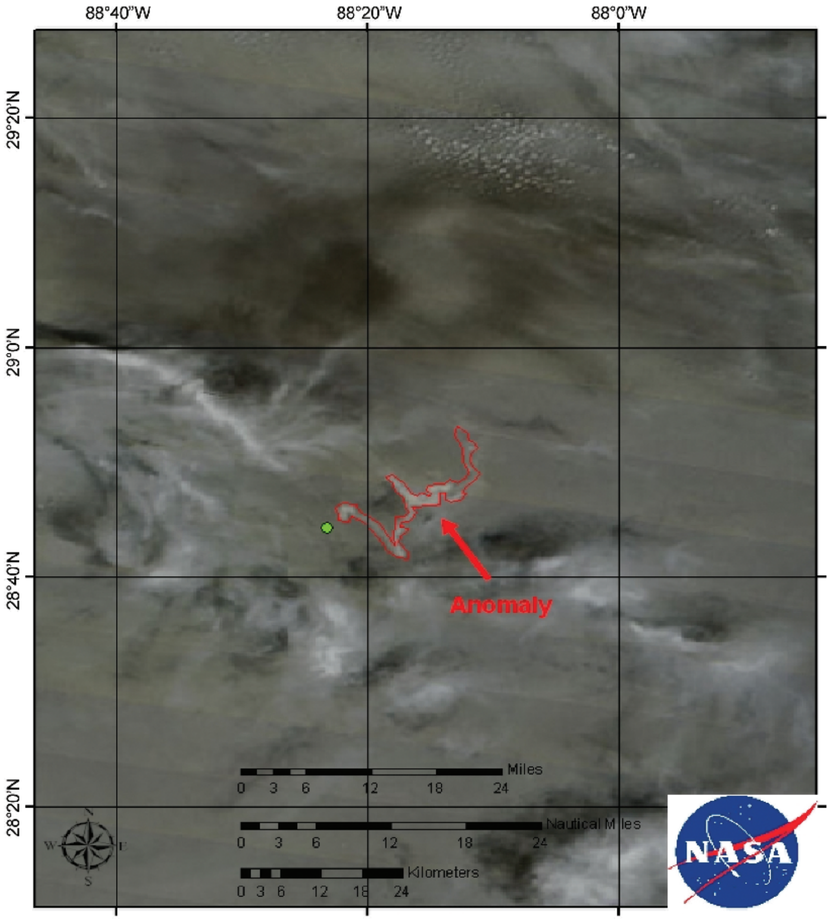


Figure 1. A satellite image from NASA's Terra satellite (showing a 250 m resolution visible channel from the MODIS instrument) was acquired at 1630 CDT on 22 April 2010, a few hours after the rig sank. Here the rig location is depicted with a green dot and the red outlined area is believed to show the oil starting to move toward the east and northeast.

anticipation of a possible prolonged and catastrophic event. SAB's first DWH-related product was based on the satellite image shown in Figure 1. By the time the well was capped and the surface oil had dissipated, SAB had issued over 300 products in response to the spill that were used in a variety of ways ranging from positioning on-scene response assets to daily Presidential briefings. The product also served as input to oil spill trajectory models and its ability to provide a comprehensive daily view of the large spill area was useful to those planning long-range mitigation strategies. Adverse weather or the large area covered by the spill sometimes prevented successful overflights, further adding to the importance of the satellite-based oil analyses.

Among government environmental satellite organizations in other nations, oil monitoring programs have been developed largely in response to Annex 1 to the International Convention for the Prevention of Pollution From Ships (MARPOL I), an international agreement that addresses illegal oil dumping from ships. For example, the European Space Agency (ESA) and the European Maritime Safety Agency (EMSA) collaboratively generate the satellite-based CleanSeaNet, which monitors spills and dumping in support of European nations' oil response. Both ESA and EMSA provided advice to the nascent SAB oil program. Environment Canada operates Integrated Satellite Tracking of Pollution (ISTOP), and ISTOP provided SAB with guidance, system design information, and demonstrations. Further collaborative activities with ISTOP are planned in the interest of developing a more unified North American oil spill and oil dumping response (see section entitled "Future" below).

A concern is that many nations do not have ongoing satellite-based oil spill or oil-dumping mitigation agencies, putting them at risk of being unprepared in case of a catastrophic spill in their waters. NOAA's Emergency Response Division (ERD) has occasionally provided assistance in the past for other nations experiencing significant spills, and whenever possible, SAB will support ERD's efforts internationally as well as within U.S. waters.

Lesson learned: Ongoing oil monitoring by operational agencies (regardless of whether their mission is to handle accidental oil spills or inform their Coast Guards about illegal oil discharges from ships or both) provides readiness capabilities that become essential in case of a disastrous oil spill. Nations without such operations are likely to have difficulty ramping up an effective, prolonged satellite analysis response to a significant spill in their waters. In the event of a disaster, preexisting, ongoing monitoring operations assure the availability of suitable product generation systems, appropriate imagery and additional data sets, and experienced analysts with a trained eye for identifying surface oil in satellite imagery.

2. NOAA OIL ANALYSIS PRODUCTS

2.1. System and Product Generation

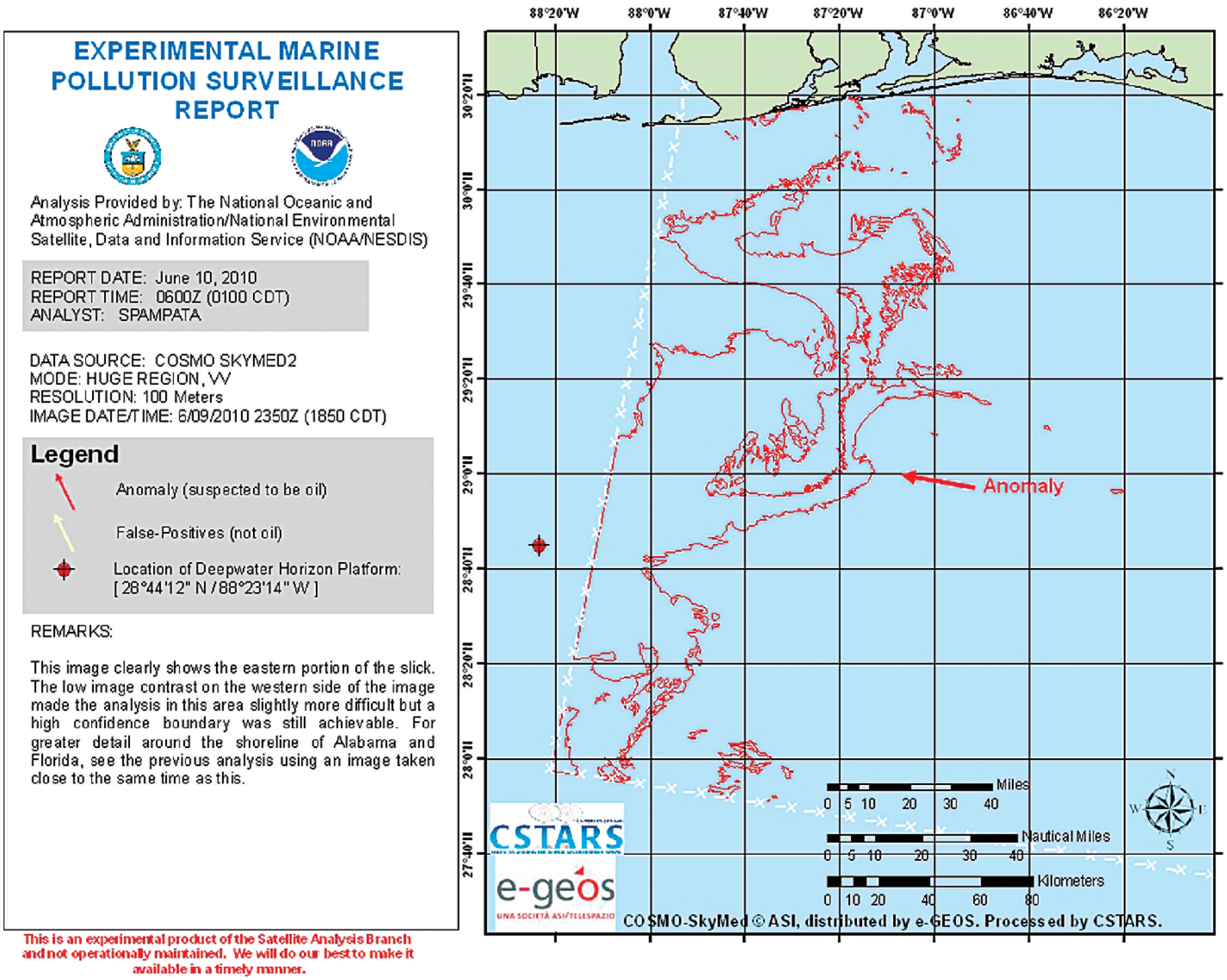
Image analysis and product generation were performed on an ArcGIS system loosely modeled after the ISTOP system. Unfortunately, when the DWH spill occurred, some of the streamlining capabilities of the ISTOP system had not yet been fully incorporated into the SAB system. Within the geographic information system (GIS), satellite analysts could quickly import, display, and analyze data. Some data, considered standard for the oil program (locations of natural oil seeps, oil platform location, surface winds, etc.), were automatically loaded as part of the customized template. Analysts would convert a satellite image (and sometimes additional ancillary data described below) to a GeoTIFF or shapefile format and import it into the GIS template. SAB satellite analysts could then perform a visual inspection of a variety of relevant layers (e.g., currents, natural oil seeps) overlaid on the satellite image. The analyst then drew an outline of areas they believed to be oil, taking into account previous oil location, direction of likely transport based on currents and winds, possible false positives, and ancillary data.

The final oil analysis product was created by superimposing the outline of analyzed oil on a geographic map and adding text describing the satellite, resolution, pass time, and remarks. Remarks would often highlight any sources of uncertainty. The product was exported in pdf, jpg, and shapefile formats. (Google Maps made the oil analyses available as KML files as well.) The oil products were disseminated by email and via the SAB webpage. This data was also imported directly into the Emergency Response Mapping Application used by the Federal On Scene Coordinator for tactical and strategic response decision support.

Public access to the imagery was also provided by numerous media outlets and websites such as GeoPlatform, Google, and the NOAA Visualization Lab. A fascinating chronology of the spill response against a backdrop of looping satellite analyses was created by the New Orleans Times Picayune and can be found at http://www.nola.com/news/gulf-oil-spill/deepwater-disaster/index.ssf.

2.2. Basic Products and Products Customized for the DWH Spill

2.2.1. Marine Pollution Surveillance Reports (MPSR). Initially, the only product SAB issued was the MPSR such as the one shown in Figure 2. The areas on the map outlined in red represent a satellite analyst's assessment of the location of oil on the surface of the water. The full extent of the oil might not be shown since analysts cannot see very thin oil,



EXPERIMENTAL MARINE POLLUTION SURVEILLANCE REPORT

Analysis Provided by: The National Oceanic and Atmospheric Administration/National Environmental Satellite, Data and Information Service (NOAA/NESDIS)

REPORT DATE: June 10, 2010
REPORT TIME: 0600Z (0100 CDT)
ANALYST: SPAMPATA

DATA SOURCE: COSMO SKYMED2
MODE: HUGE REGION, VV
RESOLUTION: 100 Meters
IMAGE DATE/TIME: 6/09/2010 2350Z (1850 CDT)

Legend

Anomaly (suspected to be oil)

False-Positives (not oil)

Location of Deepwater Horizon Platform:
[28°44'12" N / 88°23'14" W]

REMARKS:

This image clearly shows the eastern portion of the slick. The low image contrast on the western side of the image made the analysis in this area slightly more difficult but a high confidence boundary was still achievable. For greater detail around the shoreline of Alabama and Florida, see the previous analysis using an image taken close to the same time as this.

This is an experimental product of the Satellite Analysis Branch and not operationally maintained. We will do our best to make it available in a timely manner.

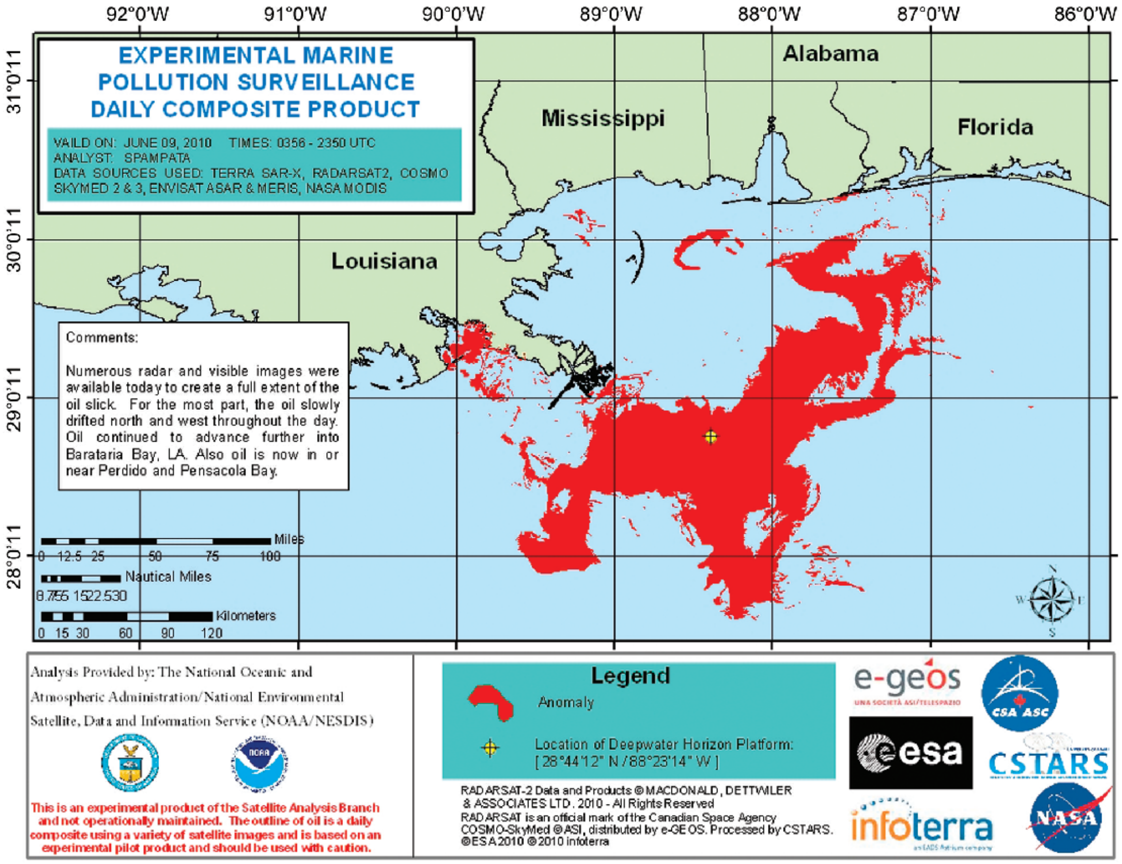
COSMO-SkyMed © ASI, distributed by e-GEOS. Processed by CSTARS.

Figure 2. Marine Pollution Surveillance Report: Based on individual satellite pass. (The white dashed x-x- line indicates the boundary of the pass.)

subsurface oil, oil located beneath heavy rain, or oil outside the boundaries of the satellite pass. Information about the satellite, pass times (denoted by Coordinated Universal Time) and uncertainties in the analysis are described in the text to the left of the analysis. All MPSR issued for the spill are now archived at ftp://satepsanone.nesdis.noaa.gov/OMS/disasters/DeepwaterHorizon/mpsr/.

An MPSR was issued as each new pass was received and was therefore the timeliest means to get information to the Incident Management Command. One limitation for a spill the size of DWH is that a single satellite pass (and therefore a single MPSR) does not typically show the entire spill area. The exception was Moderate Resolution Imaging Spectroradiometer (MODIS) or Medium-Resolution Imaging Spectrometer (MERIS) satellite imagery whose lower spatial resolution enabled them to sometimes cover the entire spill in a single pass.

2.2.2. Daily composite product. Based on user feedback and the need to incorporate multiple satellite passes to cover the areal extent of the spill, a Daily Composite Product (Figure 3) was created that represented an analyst's synthesis of all satellite passes during that day. Since this product was only issued once daily, it was not as timely as the MPSR; however, many users found the Daily Composite very useful, particularly as a briefing tool or for an overview. In the Daily Composite, as with the MPSR, the full extent of the oil might not be shown since analysts cannot see very thin oil, subsurface oil, or oil outside the boundaries of the day's available passes. Different areas of the spill were observed in satellite images at different times, but all oil depicted in the Daily Composite was within the time range shown in the green box on the upper left corner of the product. Further information about the composite, including any uncertainty, was contained in the comments section (white text box) on the product. The apparent areal extent of the outline of the oil might vary from day-to-day based on the amount of available imagery, the locations imaged, the presence of clouds obscuring visible imagery, and thunderstorms disrupting the sea surface. Occasionally, areas of synthetic aperture radar (SAR) imagery had to be discarded because of low wind fields (see below). The Daily Composite Products are



Numerous radar and visible images were available today to create a full extent of the oil slick. For the most part, the oil slowly drifted north and west throughout the day. Oil continued to advance further into Barataria Bay, LA. Also oil is now in or near Perdido and Pensacola Bay.

This is an experimental product of the Satellite Analysis Branch and not operationally maintained. The outline of oil is a daily composite using a variety of satellite images and is based on an experimental pilot product and should be used with caution.

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Figure 3. Daily Composite Product: based on multiple satellite passes.

archived at ftp://satepsanone.nesdis.noaa.gov/OMS/disasters/DeepwaterHorizon/composites/.

Lesson learned: For very large spills, the creation of a Daily Composite Product provides a daily summary ideal for briefings and other important uses. Products based on a single satellite pass should also be maintained to maximize timeliness for operational users.

2.2.3. Loop current analyses. An additional type of product focusing on the eastern Gulf of Mexico was issued to help response personnel address concerns about oil possibly becoming entrained in the loop current and being transported to the east coast of the United States. When good quality satellite passes occurred over the eastern Gulf, SAB would review these passes, and if no oil was detected, SAB would issue a text message indicating where the analyst had looked for oil but not seen any. These "no oil" products were used by planners in deciding whether redeployment of resources toward central Florida or the southeast coast of the United States was imminent.

3. NEW USERS AND NEW TIME FRAMES

Under normal circumstances, operational procedures for NOAA's satellite analysis products are created only after a detailed assessment of the needs of users who have formally requested the creation of a product . . . in this case, NOAA's National Ocean Service. However, the DWH spill resulted in an explosion of new users with whom SAB had no previous interactions. Certainly, SAB had no documentation of their needs, their deadlines, or how best to generate products to optimize their operations. In order to meet these new requirements and in response to the NOAA Administrator's call for "All hands on deck," SAB adopted a highly adaptive and flexible posture. In particular, new users of the Daily Composite Product were continually being identified, and as the needs of these users became clear, SAB adjusted its shifts and deadlines to accommodate them.

Lesson learned: Large spills create an entirely new set of users, each with their own needs and deadlines. Early in the spill, it is necessary to identify the most critical of these users and determine the best means for meeting their deadlines and requirements. Furthermore, throughout extended response periods, it is necessary that these users' needs be continually tracked and prioritized.

Satellite data, barring unexpected delays, was typically received in SAB within 2 h of pass time (the time the image is acquired by the satellite) and often within 1 h. Analysis began on each image almost immediately upon its receipt in SAB. However, as the area of the Gulf covered by oil increased and as small areas of oil separated from the main body, the time devoted to doing a detailed satellite-based analysis of the oil also increased. As oil analysts began to spend several hours analyzing individual images of oil, the timeliness of the product began to suffer. For some users, as long as deadlines were reached, a several hour delay was not critical; for others, the product lost substantial value as the delay lengthened. To save time, one possible approach (used on only a few occasions in SAB) is to have two people analyze different parts of an image and then merge their shapefiles into one overall analysis, but the product generation process and equipment need to be set up to facilitate this approach. Another possible approach, geared toward users who need timeliness more than detail, is to issue a preliminary quick analysis and then later issue a final more detailed analysis. The most straightforward approach is simply to compromise on detail since capturing details that will disappear in a few hours (as currents move the oil) is probably not worth delaying product issuance. In choosing an approach, an understanding of the needs of the broad user community is essential.

Lesson learned: Timeliness is exceptionally important to many of the responders, and a variety of approaches are possible to optimize timeliness while still providing adequate detail.

4. DATA SOURCES

4.1. Satellite Imagery

All satellite imagery used for SAB's spill response was from one of three types of sources:

1. Imagery that is part of the large and growing amount of imagery that is freely and openly available from space agencies around the world.
2. Imagery that normally has an associated cost but was donated by space agencies and companies under the auspices of the International Disaster Charter.
3. Imagery that was available to federal government agencies as part of data buys by the Department of Defense or the United States Geological Survey (USGS).

The Disaster Charter (more formally known as the Charter on Cooperation to Achieve the Coordinated Use of Space Facilities in the Event of Natural or Technological Disasters) provides the means by which space agencies and companies contribute satellite (and occasionally some nonsatellite) data to mitigate natural or man-made disasters including, on a number of occasions, oil spills. Members include Europe's ESA, France's Centre National d'Etudes Spatiales (CNES) (with SPOT Image and Asia's National Space Organization), Canadian Space Agency (CSA), Indian Space Research Organisation, Argentina's Comisión Nacional de Actividades Espaciales, Japan's JAXA, DMC International, and China

National Space Agency, as well as NOAA and U.S. Geological Survey (USGS) from the United States. When responding to a large-scale disaster, national response agencies around the world can request, through one of the members, the activation of the charter on their behalf so that appropriate imagery can be acquired to support disaster response.

Nations requesting assistance do not have to be members of the International Disaster Charter. For example, the Charter was activated for a Chilean oil spill in 2007, oil off the Lebanese coast in 2006, a sunken oil tanker in the Philippines in 2006, etc. (Please see http://www.disasterscharter.org/web/charter/activations/tags/oilspills for a list of Charter activations for oil spills.)

Once the Charter is activated, a Project Manager is designated with responsibility for arranging and overseeing the acquisition of appropriate imagery from the Charter members (and if necessary its conversion to useful formats). The USGS is the authorized user in the United States for the Disaster Charter. USGS offers guidance for response organizations with potential needs for Charter assets, as well as training for members of response organizations (worldwide) who might want to serve as Charter Project Manager for a given event. In January 2010, the Satellite Analysis Branch sent two personnel to a USGS training course to learn how to fulfill the role of Disaster Charter Project Manager in case a significant oil spill occurred in U.S. waters.

When the Deepwater rig sank, the U.S. Coast Guard formally contacted the U.S Disaster Charter Executive Secretariat in the USGS. The Executive Secretariat successfully requested an activation of the charter and then assigned the role of Disaster Charter Project Manager to one of the SAB personnel who had taken USGS training for this role in January. The Project Manager in SAB worked with Charter members to arrange satellite data tasking, acquisition, and formatting. Having the Project Manager within the same operational response unit that was issuing satellite-based oil analyses was extremely advantageous, helping to assure appropriate acquisition choices, suitable format conversions, data timeliness, and optimal SAB staffing centered around imagery receipt, etc.

Lesson learned: Having trained Disaster Charter Project Managers in the remote sensing group that generates the oil analyses offers tremendous advantages. Oil spill satellite response units could benefit from sending one or more of their personnel to Charter Project Manager training in anticipation of having to someday respond to a large spill.

Charter activations typically are intended to cover events requiring imagery for days or perhaps a week or two. As the DWH event dragged on, contributing space agencies began to decrease their donations. When Charter imagery started to decrease, the Department of Defense, operating through their contract with the Center for Southeastern Tropical Advanced Remote Sensing, secured a large government-wide data buy for SAR satellite imagery over the Gulf, and this imagery became the primary source of "oil imagery" used for SAB products. Later during the event, satellite imagery purchased by USGS under a civilian government-wide license (primarily high-resolution visible and multispectral imagery) was also increasingly used in SAB. USGS-purchased imagery continues to be used by SAB to monitor oil throughout U.S. waters even today.

Owing to the huge size of the spill, it could be seen in a very large variety of imagery. However, a detailed image analysis required either SAR imagery or high-resolution visible/multispectral near IR imagery. SAR imagery is usable day or night and in cloud-free or cloud-covered conditions (assuming no heavy rain or deep convection). The most significant limiting factor in using SAR imagery for oil detection is strong sensitivity to surface wind conditions. SAR-based oil detection cannot be conducted over areas of low winds (generally less than 3–5 knots (5–9 km h^{-1})) [*Alpers and Espedal*, 2004] or areas of strong winds [*Demin et al.*, 1985] (usually greater than 25–30 knots (46–56 km h^{-1})). Most of the visible/multispectral imagery used ranged from 10 to 300 m resolution, with the higher-resolution imagery more useful for detailed analysis of an affected area and the lower-resolution imagery useful to get an overall picture of the entire spill. Visible/multispectral imagery was most useful in low-cloud conditions and in sunglint (defined in this context as the reflection of sunlight from the sea surface at a similar angle to the viewing angle of the satellite sensor). Imagery from the following satellites/instruments was used to generate the MPSRs and Daily Composites:

○ MODIS on Terra and Aqua (visible channels) from NASA

○ MERIS on Envisat (visible channels) from ESA

○ Advanced synthetic aperture radar on Envisat (SAR imagery) from ESA

○ TerraSAR-X (SAR imagery) from Deutsches Zentrum für Luft- und Raumfahrt

○ RADARSAT 1 and 2 (SAR imagery) from CSA and MDA

○ ALOS (SAR imagery) from JAXA

○ COSMO-SkyMed 1, 2, and 3 (SAR imagery) from Agenzia Spaziale Italiana

○ SPOT (visible and multispectral imagery) from CNES and SPOT Image

○ Aster (visible and multispectral imagery) from JAXA and NASA

○ Landsat (visible and multispectral imagery) from USGS and NASA

○ Advanced very high resolution radiometer (visible channels) from NOAA.

At the beginning of the DWH spill, SAB was not fully aware of the abundance of high-resolution visible and multispectral imagery available. In addition, its utility for oil detection [*Hu et al.*, 2003] was not fully appreciated. In some situations (in lakes, near shore, or in areas of very low winds), it is actually the imagery of choice. Moreover, in sunglint, visible/multispectral imagery also appears to readily contain at least relative information about the thickness of the layer of oil (O. Garcia-Pineda, unpublished data, 2010).

Lesson learned: It is important not to neglect non-SAR imagery sources. High-resolution (≤30 m) visible/multispectral imagery, particularly but not exclusively in sunglint conditions, has a role to play in oil spill response. It is especially valuable in conditions where SAR is not available or optimal [*Hu et al.*, 2003] (e.g., due to low winds, near shore, etc.). Numerous new sources of high-resolution optical imagery are becoming available from International Disaster Charter activations and other sources. Using all available imagery (both SAR and visible/multispectral) helps assure rapid updates as the oil moves. In addition, medium-resolution (~250 m) visible/multispectral imagery can show an entire large spill area, not a subset of the spill as is usually seen with high-resolution SAR/visible/multispectral imagery. In sunglint, optical imagery might also have the capability of conveying relative thickness information (see below).

4.2. Ancillary Data

Satellite analysts viewed a variety of ancillary data sets during the DWH spill to reduce the number of false positives (areas analyzed as containing oil but actually not having oil or areas of oil from known natural seeps not related to DWH). To a lesser extent, analysts also used ancillary data to help address false negatives (areas analyzed as oil-free but actually having oil). For both SAR and visible/multispectral near-IR imagery, SAB analysts often needed to use ancillary data to avoid false negatives and false positives.

In SAR imagery, low winds less than about 4 knots (7 km h^{-1}) can cause an area to appear to contain oil when it does not (false positive) [*Alpers and Espedal*, 2004] and high winds greater than 20–30 knots (37–56 km h^{-1}) can make an area that has oil appear to be oil-free (false negative) [*Demin et al.*, 1985]. Use of surface wind information was essential to avoid these errors whenever analyzing SAR images. In addition, bathymetric overlays were useful since various bathymetric features can also create false positives, but this seemed to be a less common occurrence than the low wind false positive.

Natural oil seeps, another source of false positives, were effectively negated by an overlay that contained the location of most of the natural seeps in the Gulf of Mexico. Oil originating from these natural seeps was not included in the analysis, since it was not related to the DWH event.

Sargassum was another source of false positives and the search for additional ancillary data to help address this is now underway but was not fully available to analysts during the spill. This became an issue toward the end of the spill monitoring when there were many small areas of possible oil no longer contiguous with the location of the rig. Sargassum can be difficult to differentiate in satellite imagery from these small oil areas.

Ocean current data was obtained in weekly briefings from satellite oceanographers who provided current forecasts and thus gave SAB analysts an idea where oil would likely be found in the upcoming week. Information about the availability and utility of some of these other ancillary data sets also came from these briefings.

Perhaps the single most important ancillary data set was the previous day's analysis and the known history of the spill. When oil would "appear" far from where it had been in recent analyses or when oil would "disappear" from areas where it had been seen, then the analyst would look at the Gulf currents and winds and see if the repositioning could have been due to movement of surface oil. Obviously, an upwind or upcurrent repositioning was a red flag to the satellite analyst, encouraging them to carefully examine other ancillary data sets to look for reasons for a false positive.

Lesson learned: Some false positives, primarily sargassum, need additional work for reliable differentiation from oil. Other false positives such as low winds or natural seep sites can be effectively addressed by existing ancillary data sets.

Ancillary data sets used during the DWH spill are listed below in bold and those that have been added since the spill or will be added in the future are printed in italics. An asterisk indicates that this data set is available to the public on the Internet.

WINDS

- **Maritime and surface observations for latest winds**
- **Advanced Scatterometer surface winds***
- *WindSAT surface winds**

OCEAN CURRENTS

- **Ocean currents from Navy Coastal Ocean Model* (NCOM), Navy Layered Ocean Model* (NLOM), and Hybrid Coordinate Ocean Model* (HYCOM)**
- **Altimetry data***
- *GOES sea surface temperatures (SSTs) ocean frontal product*

SST

- **SSTs from NCOM model***

ALGAE BLOOMS

- *MODIS satellite-derived ocean color products**
- *NOAA harmful algae bloom reports (available to public but not realtime)*

SOURCE POINTS

- **Oil/gas platforms, wells, and pipelines**
- **Natural seeps**
- *Automatic Identification System Ship Tracking System**

OTHER

- **Bathymetry data from multiple sources**

Data Specific to the DWH Spill

- **Overflight data (available on the web only in connection with DWH from NOAA's Office of Response and Restoration page or through Geoplatform.gov)**
- **Shoreline Cleanup Assessment Team surveys (available on the web only in connection with DWH from Office of Response and Restoration page or through Geoplatform.gov)**
- **Side-looking airborne radar**

5. FUTURE

SAB has begun to address several goals to improve routine oil spill response, as well as help ensure readiness for the next spill of national significance. In particular, SAB is attempting to (1) secure a steady, abundant, and timely stream of suitable satellite imagery even in the absence of large-scale emergencies such as the DWH spill, (2) acquire improved and expanded ancillary data sets to reduce the number of false positives (as discussed above), (3) acquire the ability to reliably differentiate, in a general qualitative way, thick oil ("recoverable oil") from oil sheens, and (4) collaborate with Environment Canada's ISTOP program to create a joint North American center for oil spill response.

Although high-resolution visible imagery, multispectral IR imagery, and SAR imagery all have utility (under various circumstances) for monitoring marine oil, the availability of suitable oil monitoring imagery has in the past been limited by the fact that much of this imagery is commercially available only at significant cost. There is, however, reason for increased optimism with the announcement by the ESA that data from their upcoming Sentinel-1 satellites will be freely and openly available. Sentinel-1 is a group of SAR satellites to be launched starting in 2013 and expected to be highly effective for oil monitoring. The CSA has indicated that the upcoming RADARSAT Constellation Mission (SAR satellites) will be a public mission and is deciding on a data access policy. The VIIRS (Visible Infrared Imager Radiometer Suite) instrument that will be on board future joint NOAA/NASA polar satellites will have imagery capabilities adequate for monitoring very large spills particularly in sunglint conditions. USGS and the Department of Defense both have plans to purchase commercial imagery on government-wide licenses, some of which is well suited for oil detection. Continued participation in the International Disaster Charter helps assure adequate imagery during disastrous spills.

During the DWH event, the oil spill response community frequently commented about the need for at least a general, qualitative, relative measure of oil layer thickness, something that SAB was not able to supply using satellite imagery. SAB was unable to differentiate a thin sheen from very thick oil, and the difference is crucial to skimmers and other responders. In addition, scientists trying to more accurately model the trajectory of the oil also needed oil thickness information as input for their models' physical-chemical processes [*Liu et al.*, 2011]. Under some optical and environmental conditions, research suggests that thickness information can be inferred from SAR data [*Franceschetti et al.*, 2002; *Jones*, 2001] or visible/IR imagery [*Ma et al.*, 2009; *Pinel et al.*, 2010; *Wettle et al.*, 2009; O. Garcia-Pineda, unpublished data, 2010]. There is a narrow range of winds in which optimal SAR-based thickness assessments can occur [*Jones*, 2001], so on many days during the DWH spill, this would have been difficult to achieve for large areas of the Gulf. However, feedback during the spill suggested that at least relative thickness information might indeed be feasible to derive in a timely manner using MODIS and MERIS visible imagery in sunglint (O. Garcia-Pineda, unpublished data, 2010). Further development and operational implementation of thickness assessments would vastly improve spill response.

Improvements in satellite technology are expected to be useful to satellite-based operational response groups such as SAB. Although a complete analysis of oil detection enhancing technical developments is outside the scope of this article, a few examples are worth noting. The increasing availability of quad-polarization SAR imagery [*Zhang et al.*, 2011], new SAR-based neural net approaches that incorporate wind fields [*Cheng et al.*, 2011], and sophisticated multispectral optical algorithms [*Chen and Chang*, 2010] are likely to enhance oil spill detection in the near future.

SAB is hoping to create an agreement with Environment Canada's ISTOP, whose substantial experience in oil monitoring was so useful in the development of the SAB program. The intent is for SAB and ISTOP to form a joint North

American organization for monitoring marine oil including illegal oil dumping from ships. Advantages would include mutual backup capabilities, a unified and consistent method of issuing products throughout Canadian and U.S. waters, smoother interaction at border regions, shared imagery, shared training etc., and a Memorandum of Agreement is being drafted.

In summary, logistical, technological, data access, and science issues remain, but there is every reason to believe that satellite-based oil detection capabilities will grow both in SAB and in its counterpart organizations around the world.

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A New RST-Based Approach for Continuous Oil Spill Detection in TIR Range: The Case of the *Deepwater Horizon* Platform in the Gulf of Mexico

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Oil pollution is a threat that increasingly concerns marine/coastal ecosystem. Timely detection and continuous update of information are fundamental to reduce oil spill environmental impact. EOSs, especially meteorological satellites, can be profitably used for a near real time sea monitoring thanks to their high temporal resolution and easy data delivery. In this paper, we present a new algorithm, based on the general Robust Satellite Technique (RST) approach, for automatic near-real-time oil spill detection and continuous monitoring (i.e., in both daytime and nighttime) by using optical data. The new RST scheme has been applied to the analysis of the recent oil spill disaster of the *Deepwater Horizon* Platform in the Gulf of Mexico. In particular, a dense temporal series of RST-based oil spill maps, obtained by using Moderate Resolution Imaging Spectroradiometer-thermal infrared records acquired in both daytime and nighttime during the 25–29 April 2010 period, are shown and commented. The results seem to confirm the good performance of the proposed approach in automatic detection of oil spill presence with a high level of reliability and sensitivity even in nighttime acquisitions. These achievements confirm the potential of optical data for oil spill detection and monitoring, thus suggesting their use in combination with radar acquisitions toward developing a multiplatform system that is able to furnish detailed and frequent information about oil spill presence and dynamics.

1. INTRODUCTION

Oil discharge is, nowadays, a serious threat to maritime and coastal environments. In recent years, the exploitation of marine resources has strongly increased, and as a consequence, platform or tanker accidents have become more and more frequent. The explosion of the *Deepwater Horizon* semisubmersible drilling platform in the Gulf of Mexico on 20 April 2010 was a clear demonstration of the environmental impact of such a technological hazard [*Mitsch*, 2010], which can also be directly caused by natural phenomena. As an example, more than 17,000 barrels of crude oil were released into the Gulf of Mexico as a consequence of the passage of the hurricanes Katrina and Rita over those areas during 2005 [*Hogarth*, 2005; *Pine*, 2006; *Cruz and Krausmann*, 2008, 2009].

Besides these huge events, the main causes of oil sea pollution are operational discharges from tankers (i.e., oil dumped during cleaning operations; ITOPF, International Tanker Owners Pollution Federation Limited, 2010, Handbook 2010/2011, available from http://www.itopf.com/information-services/publications/documents/itopfhandbook2010.pdf). All these phenomena can occur on a global scale with very different dynamics: from few hours for small illicit discharges up to

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