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

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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
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 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 [Li 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; Pagliese 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.
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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.

Acknowledgments. The production of this book was partially supported by the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE) of the U.S. Department of Interior, award M11PX00063. This is CPR contribution 22.

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