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Tracking the Deepwater Horizon Oil Spill: a Modeling Perspective

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The Deepwater Horizon oil spill was caused by a drilling rig explosion on 20 April 2010 that killed 11 people. It was the largest oil spill in U.S. history and presented an unprecedented threat to Gulf of Mexico marine resources. Although oil gushing to the surface diminished after the well was capped, on 15 July 2010, much remains to be known about the oil and the dispersants beneath the surface, including their trajectories and effects on marine life.

A system for tracking the oil, both at the surface and at depth, was needed for mitigation efforts and ship survey guidance. Such a system was implemented immediately after the spill by marshaling numerical model and satellite remote sensing resources available from existing coastal ocean observing activities [e.g., *Weisberg et al.*, 2009]. Analyzing this system's various strengths and weaknesses can help further improve similar systems designed for other emergency responses.

Challenges and Practical Considerations

There were several challenges that hindered accurate oil tracking. First, all forecast models have errors that grow with time. Second, the fate of oil spilled into the ocean depends on many factors [e.g., *Spaulding*, 1988; *Yapa*, 1996; *Reed et al.*, 1999; *Ji et al.*, 2004], including transport and dispersion by ocean circulation along with chemical transformations and biological consumption of the oil itself. Third, the amount of oil released into the Gulf remained unknown throughout the event. Finally, mitigation activities to collect or destroy the oil, for example, by use of dispersants, burning at sea, and skimming by boats, added uncertainties to the fate of the oil. In short, important information on the effects of these techniques and the locations and amounts of spill-related hydrocarbons at both surface and depth was unknown, and all of these factors complicated traditional oil trajectory model forecasts.

By Y. Liu, R. H. Weisberg, C. Hu, and L. Zheng

Nonetheless, ocean circulation is fundamental to planning mitigation strategies and to determining both landfall of oil and movement of oil toward biologically sensitive areas in deep and shallow waters. Thus, to gain a better understanding of uncertainties in forecasts of oil trajectories, an ensemble of various circulation models was used to examine circulation in the Gulf. Satellite observations of oil at the ocean surface helped to frequently reinitialize the models and to partially account for other uncertainties.

Ensemble Models and Their Initialization

For tracking oil, a system of ocean circulation models, each with sufficient veracity in accounting for the complex flow fields of the region, is needed. The models' flow fields must include both the deep-ocean currents embodied by the Gulf of Mexico Loop Current system (Figure 1) and the shallow-water currents of the continental shelf, all in a fully three-dimensional, density-dependent manner.

Six such numerical ocean circulation models were available from different institutions: (1) the West Florida Shelf (WFS) model [*Barth et al.*, 2008], (2) the Global Hybrid Coordinate Ocean Model (Global HYCOM [*Chassignet et al.*, 2007]), (3) the Gulf of Mexico HYCOM (http://www.hycom.org), (4) the South Atlantic Bight–Gulf of Mexico model (SABGOM [*Hyun and He*, 2010]), (5) the Real Time Ocean Forecast System for the North Atlantic Ocean (RTOFS [*Mehra and Rivin*, 2010]), and (6) the Intra-Americas Sea Nowcast/Forecast System (IASNFS [*Ko et al.*, 2008]). All but the RTOFS, which is an operational model of the U.S. National Oceanic and Atmospheric Administration (NOAA), include academic research partnerships (see the online supplement to this *Eos* issue (http://www.agu.org/eos_elec/)).

Satellite-observed surface oil locations, whenever available, were used to initialize the models. Specifically, data from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Medium Resolution Imaging Spectrometer (MERIS) were used to interpret the location and size of the surface oil slick [*Hu et al.*, 2003, 2009]. Depending on viewing

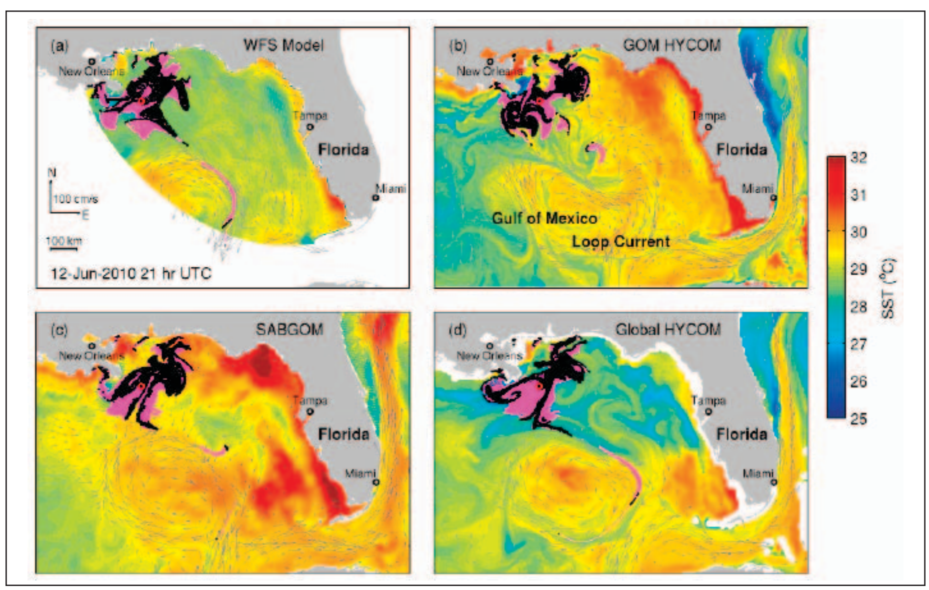

Fig. 1. Three-day oil trajectory forecast for 12 June 2010 based on (a) West Florida Shelf (WFS) model, (b) Gulf of Mexico Hybrid Coordinate Ocean Model (GOM HYCOM), (c) South Atlantic Bight–Gulf of Mexico model (SABGOM), and (d) Global HYCOM. Black denotes virtual drifters inferred from satellite imagery; purple denotes areas swept out by virtual drifters. Background fields are sea surface temperatures (SST) and currents.

angle, ocean state, and bio-optical water properties, oil can appear brighter or darker than its surrounding waters in the color imagery. In many cases, thin films of oil can be observed only under sun glint. Spectral shape and spatial texture were also visually examined to help differentiate oil films from other features such as clouds or phytoplankton blooms. When clouds prevailed, data from synthetic aperture radar (SAR) satellite instruments were used to help delineate oil slicks [*Liu et al.,* 2000].

Coupling Models With Observations

Oil tracking by numerical models generally uses virtual particles [e.g., *Reed et al.,* 1999]. Models here were seeded with oil locations inferred from satellite images with virtual particles. These particles were then advected with the surface velocity fields as forecast by the six aforementioned numerical ocean circulation models. To simulate the continual gushing of oil, new particles were released at the well site every 3 hours. These new particles (added to the satellite inferred particles) contributed to the spatial expansion of the surface oil (Figure 1). New 3.5-day forecasts, driven by forecasted winds (and thus currents), were made daily and reinitialized whenever satellite images permitted. All model trajectory forecasts and satellite-based observations were made available to the public in near real time at http://ocgweb.marine.usf.edu/ and http://optics.marine.usf.edu/events/GOM_rigfire/, respectively. WFS model fields made by researchers at the University of South Florida (USF) were also made available to the U.S. government–commissioned Incident Command of the Deepwater Horizon Response through NOAA for use in their daily forecasts.

Comparisons between actual oil locations inferred from satellite imagery and the model forecast positions from the latest forecast cycle provided a measure of model forecast veracity. While most of the models were generally similar (Figure 1), differences were observed, and it was unknown a priori which model would provide the best results for a given forecast cycle; hence, an ensemble forecast was used in analogy to ensemble forecasts for hurricane landfall.

In anticipation of subsurface oil but not knowing the depths of occurrence, the WFS model was used to track neutrally buoyant, virtual particles emanating from the well site at nine different depths (between 1400 meters and 50 meters). Subsequent advection by the three-dimensional flow fields was also tracked. Trajectories at depth tended to follow the bottom depth contour (isobath) at which the oil was released; however, because vertical density variations tended to decouple the flow field from the bathymetry, this constraint weakened toward the surface. Wind stress also tended to break the bathymetric constraint near the surface. Unlike the surface trajectories, a paucity of subsurface observations severely limited veracity testing or reinitializations. Consequently, subsurface trajectory forecasts are prone to much larger errors than surface trajectory forecasts.

Benefits of an Integrated Approach

Three novelties distinguished the forecast system from other oil-tracking efforts. First, by frequently reinitializing the trajectory models with satellite observations, the effects of in situ mitigation and forecast error growth were implicitly accounted for and minimized. Second, new particles were continuously added at the oil well location in both the surface and subsurface trajectory models. Finally, multiple surface oil trajectory models were used in an ensemble forecast, which helped to define the uncertainties from any individual model. Indeed, these models provided unique early-warning information that was not otherwise available, especially when either cloud cover or lack of in situ coverage limited knowledge of oil locations.

Applications of the forecast system showed its utility. For example, the surface forecasts suggested oil in the vicinity of the pervasive Gulf of Mexico Loop Current in mid-May, which was confirmed by aerial photographs and a survey by the R/V *Bellows* conducted between 19 and 23 May 2010. Likewise, subsurface forecasts suggested subsurface oil along isobaths first to the southwest of the well, as reported by *Schrope* [2010] and *Camilli et al.* [2010], and then to the northeast, which guided sampling and was confirmed by a deepwater survey by the R/V *Weatherbird II* conducted between 26 May and 2 June 2010 [*Hollander et al.,* 2010].

These forecasts, together with other oceanographic observations by a variety of techniques and explanations of circulation behaviors made by various groups and agencies, were regularly disseminated (via the Internet and written briefings) and used by state and federal agencies responsible for mitigation and issuing public advisories. The activities in response to this oil spill provide an example of how an Integrated Ocean Observing System (IOOS; http://www.ioos.gov/), as a partnership between universities, government agencies, and the private sector, can be of great benefit to the nation.

Future Needs for an Improved Forecast System

Despite some success, the limitations of the modeling system call for several future improvements (see Figure S1 in the online supplement). First, like many previous oil spill forecast systems [e.g., *Beegle-Krause,* 2001; *Howlett et al.,* 2008], this system did not consider the physical-chemical weathering of crude oil or biological consumption. Similarly, subgrid-scale factors such as wave-induced Stokes drift or added windage were not included [e.g., *Sobey and Barker,* 1997]. Third, cloudiness and lack of SAR coverage highlight the need for a blended oil location product that combines all forms of observations (satellite, ship, aircraft, etc.). Fourth, the satellite-based observations provide information on oil location only, yet oil thickness (quantity) needs to be estimated to model the physical-chemical processes. Finally, more observations are needed to (1) improve the wind-forcing functions used to drive the ocean models, (2) improve the ocean circulation model forecast performance through data assimilation, and (3) provide for model veracity testing.

The findings here also demonstrate that an ensemble of models run by different groups is not only useful but also necessary to mitigation efforts. No single model is adequate, either for the deep ocean or for the coastal ocean and its estuaries. Better coordination of real-time data among all groups that monitor the Gulf of Mexico would help to improve all forecast systems. Most important, sustained funding is required for personnel and equipment to maintain and expand coastal ocean observing and modeling assets into the future.

For these reasons, improved coordination of observing and modeling across all parties—local, state, and federal agencies; the private sector; and educational institutions—may offer improved management of resources within the Gulf and other U.S. waters. The IOOS and its Coastal Ocean Observation System (COOS) concept were conceived to provide such partnerships. As demonstrated by the Deepwater Horizon spill, such partnerships will not only enhance the ability to collect, deliver, and use ocean information for scientific research and understanding but will also improve predictive capabilities for both natural and human-induced modifications to the sea.

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NEWS

U.S. Interior Department Issues Scientific Integrity Guidelines and Strategic Plan

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The U.S. Department of the Interior (DOI) issued detailed scientific integrity guidelines on 1 February, becoming the first federal agency to do so following a 9 July 2009 White House memorandum on the subject and 17 December 2010 White House guidelines for federal agencies.

DOI's guidelines indicate that the department "will not tolerate loss of integrity in the performance of scientific and scholarly activities or in the application of science and scholarship in decision making."

The guidelines, which formally are Interior's Departmental Manual Chapter on Integrity of Scientific and Scholarly Activities, include a code of scientific and scholarly conduct that applies to all department employees, including political appointees, as well as to all contractors, cooperators, partners, and others involved with developing or applying the results of scientific and scholarly activities. In addition, the guidelines specifically indicate that "in no circumstance may public affairs officers ask or direct Federal scientists to alter scientific findings."

There were some instances during prior administrations when political appointees allegedly pressured federal scientists to modify some findings.

The document also includes guidelines for the selection and retention of employees involved with scientific and scholarly activities, for employees to participate in nonfederal organizations and professional societies, and for an impartial review of alleged breaches of guideline principles.

"Because robust, high quality science and scholarship play such an important role in advancing the Department's mission, it is vital that we have a strong and clear scientific integrity policy," said Interior secretary Ken Salazar. He appointed Ralph Morgenweck, a senior science advisor with the department's U.S. Fish and Wildlife Service, to serve as DOI's first scientific integrity officer (SIO). DOI bureau heads will designate bureau SIOs.

In an interview with *Eos*, Marcia McNutt, director of the U.S. Geological Survey (USGS) and science advisor to the secretary of the interior, said that "the most important thing a scientific integrity policy can do is give the American public trust that the science that comes out of our federal agencies holds up to the highest standards of integrity and is exactly what we would expect, according to the principles of scientific quality and integrity, and that no other agendas have shaped the results."

McNutt said that Survey scientists often have looked to the USGS director as being their champion, and the new guidelines provide further assurance that science will be protected. "The important thing about this policy is that they will be able to say, 'it's now written in stone. We don't have to worry about being at the mercy of whatever might happen with the director. It is now in our department manual. It's codified forever after that there is a policy that applies to everyone, all the way up to the secretary.'"

She added that if a diverse agency such as DOI could write one policy that works for the entire department, "there should be no excuse, that any department in the federal government should be able to write a scientific integrity policy."

Jeff Ruch, executive director of Public Employees for Environmental Responsibility (PEER), indicated that the new guidelines confer new legal protections on both scientific information and the specialists who create it.

"This is very much a work in progress but appears to be a good faith effort to grapple with a basket of knotty issues which heretofore have been kept out of sight. Historically, the Department of Interior has been infamous for thorough-going political distortion of science," he noted, adding that if Interior can adopt scientific