Trajectory Forecast as a Rapid Response to the *Deepwater Horizon* Oil Spill

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In response to the Gulf of Mexico *Deepwater Horizon* oil spill, a Lagrangian trajectory modeling system was implemented immediately upon spill onset by marshaling numerical model and satellite remote sensing resources available from existing coastal ocean-observing activities. Surface oil locations inferred from satellite imagery were used to re-initialize the positions of virtual particles in this ensemble of trajectory models, and the particles were tracked using forecast surface currents, with new particles added to simulate the continual release of oil from the well. A challenge to this modeling effort was that much information remained unknown throughout the spill event, with additional uncertainty due to intensive mitigation activities. By frequently re-initializing the trajectory models with satellite-inferred locations, the effects of in situ mitigation and forecast error growth were implicitly accounted for and minimized. The simulated surface oil trajectories were compared to the satellite observations in subsequent forecast cycles for veracity testing. Although similar results were obtained, in general, differences were seen in the simulated trajectories by different models. However, no one model performed consistently better or worse than the others throughout the event with one exception. The lessons learned from the event may be useful in preparing rapid trajectory forecast systems in the future.

1. INTRODUCTION

The *Deepwater Horizon* drill rig, located southeast of the Mississippi River delta within the Mississippi Canyon Block 252, exploded on 20 April 2010. The subsequent sinking on 22 April 2010 resulted in the largest offshore oil spill in U.S. history. This spill, which continued for 3 months, presented an unprecedented threat to the Gulf of Mexico (GOM), its coastal zone and living marine resources [e.g., *Mearns et al.*, 2010; *Jernelöv*, 2010; *Hu et al.*, 2011], and possibly to that of the southeastern United States of America [e.g., *Maltrud et al.*, 2010]. Needed for mitigation efforts and for guiding scientific investigations was a system for tracking the oil, both at the surface and at depth.

Monitoring and Modeling the *Deepwater Horizon* Oil Spill:
A Record-Breaking Enterprise
Geophysical Monograph Series 195

10.1029/2011GM001121

The fate of oil spilled into the ocean depends on many factors, including transport and dispersion by the ocean circulation, physical weathering (evaporation, emulsification), other chemical transformations, and biological consumption [e.g., *Spaulding*, 1988; *Yapa*, 1996; *Reed et al.*, 1999; *Li*, 2000; *Ji et al.*, 2004]. Here we focus on the conservative aspects (the ocean circulation) because these are fundamental to all else, and they are the most readily implemented within existing coastal ocean-observing and modeling systems [e.g., *Weisberg et al.*, 2009]. The ocean circulation is also what determines either landfall or movement toward biologically sensitive areas in both deep and shallow water regions [e.g., *Weisberg*, 2011; *Ji et al.*, this volume].

Along with chemical and biological processes, the mitigation activities that were ongoing throughout the *Deepwater Horizon* oil spill, for instance, the use of dispersants [e.g., *Kujawinski et al.*, 2011], containment, and fire at sea [e.g., *Crout*, 2011], and off-loading to, or skimming by, boats added further uncertainty to oil spill trajectory modeling efforts. Information on the locations and effects of these actions were generally unknown throughout the spill duration.

The *Deepwater Horizon* oil spill also differed from previous spills in many ways. Crude oil was introduced at the ocean bottom in 1500 m of water, a depth that was much deeper than those of previous oil spills. For instance, the IXTOC-1 oil spill was in 50 m deep water [e.g., *Jernelöv and Lindén*, 1981]. Three months of flow, ending with the capping of the wellhead on 15 July 2010, further distinguished this event from major tanker incidents, e.g., the *Prestige* [e.g., *Abasca et al.*, 2009; *Jordi et al.*, 2006] and the *Exxon Valdez* [e.g., *Koburger*, 1989]. Moreover, the amount of hydrocarbons being released remained unknown throughout the event. All of these factors complicated traditional oil trajectory model forecasts [e.g., *Aamo et al.*, 1997; *Daniel et al.*, 2004]. These challenges called for an effective, rapidly implemented oil spill tracking/predicting system to augment the work of the agencies and industries comprising the Incident Command.

Such a response system [*Liu et al.*, 2011a] was implemented at the University of South Florida (USF) immediately upon spill onset, by marshaling numerical model and satellite remote sensing resources available from existing coastal ocean-observing activities [e.g., *Weisberg et al.*, 2009]. The concept of this system was briefly reported in the work of *Liu et al.* [2011a], and its methodology was later explained in the work of *Liu et al.* [2011b]. Here in this paper, we provide a fuller description of the oil spill trajectory model development, along with model/data comparisons. The purpose is not to hindcast the oil spill trajectory for the entire event; rather, it is to summarize our use of the available coastal modeling and observing resources and to provide some performance measures. The goal is to offer lessons learned that may be useful in responses to future events, recognizing the increasing demand for oil production from deep water regions.

The next section 2 describes the evolution of our surface oil trajectory modeling system. Section 3 then discusses trajectory model veracity testing by comparing the simulated surface oil trajectories with satellite imagery-inferred oil locations. The purpose is to see which models, if any, may have performed better or worse than others. Challenges to such modeling efforts and lessons learned throughout the event are discussed in section 4.

2. THE SURFACE OIL TRAJECTORY MODELING SYSTEM

2.1. Numerical Ocean Circulation Models

The *Deepwater Horizon* rig site, located less than 100 km from the Mississippi River delta is on the GOM continental slope, the region of rapid transition from the relatively shallow continental shelf to the deep ocean. Given the different dynamical regimes of the deep ocean, the continental shelf slope, the continental shelf, and the estuaries, modeling the flow fields themselves is a challenge. The deep ocean currents are characterized by the GOM Loop Current and its eddies [e.g., *Sturges and Lugo-Fernandez*, 2005] that are generally in geostrophic balance (wherein the pressure gradient force of the sloping sea surface and depth varying water density is balanced by the Coriolis force due to flow in the presence of the Earth's rotation). Figure 1 shows such an analysis of the surface geostrophic currents (with oil trajectories superimposed) based on the Archiving, Validation and Interpretation of Satellites Oceanographic data gridded sea surface height anomalies [e.g., *Pascual et al.*, 2006] to which a mean field is added [e.g., *Alvera-Azcarate et al.*, 2009]. Such results for the deep ocean are generally excellent, and further improvements may be obtained by adding the direct effects of local winds (hence the use of numerical circulation models). Moving water across the steep continental slope requires large changes in angular momentum that are difficult to effect, and this constraint tends to steer currents parallel to lines of constant depth (isobaths). Once on the shelf and transiting toward shallower water, bottom friction [e.g., *Brink*, 1986, 2010] begins to play an ever-increasing role in the vertical structure and the momentum balance of the currents [e.g., *Weisberg et al.*, 2000; *Liu and Weisberg*, 2005]. Finally, in the estuaries, the density differences between fresh river water and salty ocean water become a major factor. Thus, required for tracking the oil, either at the surface or at depth, are ocean circulation models of sufficient complexity to account for the physics that govern the region's flow fields.

During the *Deepwater Horizon* oil spill, six such numerical ocean circulation models were available with nowcast/forecast fields downloadable on the internet: (1) the USF West Florida Shelf (WFS) model [e.g., *Barth et al.*, 2008, http://ocgweb.marine.usf.edu] consisting of the Regional Ocean Modeling System [ROMS; e.g., *Shchepetkin and McWilliams*, 2005; *Haidvogel et al.*, 2008] nested in the Global Hybrid Coordinate Ocean Model (Global HYCOM); [e.g., *Chassignet et al.*, 2007], (2) the Global HYCOM (http://www.hycom.org), (3) the GOM HYCOM, (http://www.hycom.org), (4) the South Atlantic Bight-GOM model (SABGOM) [*Hyun and He*, 2010, http://omglnx6.meas.ncsu.edu/sabgom_nfcast], which also consists of ROMS nested in the Global HYCOM, (5) the Real Time Ocean Forecast System for the North Atlantic Ocean (RTOFS) [*Mehra and Rivin*, 2010; http://polar.ncep.noaa.gov/ofs], and (6) the Navy Coastal Ocean Model (NCOM) Intra America Seas Nowcast/Forecast System (IASNFS) [e.g., *Ko et al.*, 2008]. The USF WFS model is forced by NOAA National

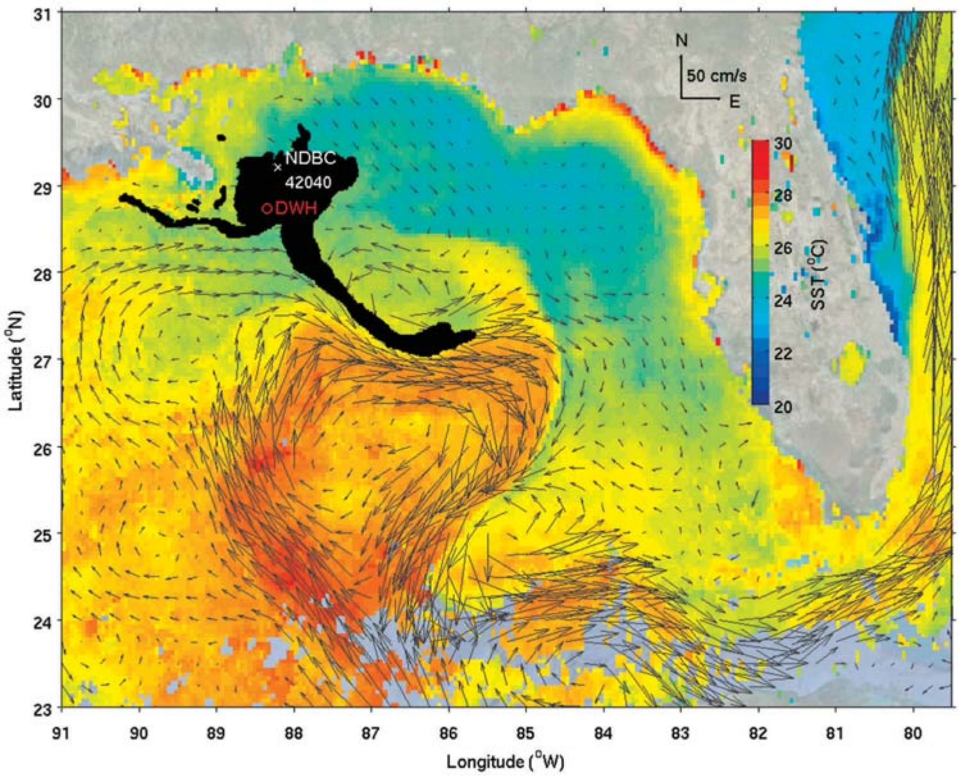

Figure 1. A snapshot of the surface oil location (black) inferred from Moderate Resolution Imaging Spectroradiometer (MODIS) imagery, superimposed on the satellite altimetry-derived surface geostrophic currents (vectors) and Geostationary Operational Environmental Satellites (GOES)-derived sea surface temperature (SST) on 18 May 2011. Note the entrainment of the oil into the Gulf of Mexico Loop Current at this time and therefore the potential for oil to be advected through the Florida Straits. The shedding of an eddy within 2 days of this snapshot, broke the connection between the well site and the Florida Straits thereby sparing most of Florida from the direct impacts of the *Deepwater Horizon* oil. Also shown are the well site (o) and National Data Buoy Center (NDBC) Buoy 42040 (x). Geostrophic velocities are computed with sea level gradients derived from satellite sea surface height analyses plus a model mean field, following a procedure in the works of *Alvera-Azcárate et al.* [2009] and *Liu et al.* [this volume].

Centers for Environmental Prediction (NCEP), North American Mesoscale Model reanalysis (http://www.emc.ncep.noaa.gov) and forecast winds and heat fluxes modified by blending with observed winds and SST for improving the accuracy of the coastal ocean circulation simulations [*He et al.*, 2004]. The SABGOM model, operated at the North Carolina State University, is forced by NOAA National Operational Model Archive and Distribution System winds and heat fluxes [*Rutledge et al.*, 2006]. Both the Global HYCOM and GOM HYCOM, maintained by the Naval Research Laboratory and the HYCOM Consortium, are forced by Navy Operational Global Atmospheric Prediction System surface fluxes [*Rosmond et al.*, 2002] and use the Navy Coupled Ocean Data Assimilation system [*Cummings*, 2005]. The RTOFS, operated by NOAA/NCEP, is a data assimilative Atlantic basin-scale ocean forecast system based on HYCOM. The NCOM IASNFS is operated at the Naval Research Laboratory with output served through the Northern Gulf Institute (http://www.northerngulfinstitute.org). All of these models (in their state of readiness at the time) are capable of considering the transitions from the deep ocean to the continental shelf. None, however, are constructed to treat the estuaries.

Our starting point for these analyses was the USF WFS model because we had immediate access to it, and our nowcast/forecast system was readily adaptable to the new situation. Within a day of the rig sinking, we added additional particle tracking sites to the suite of existing sites in use for search and rescue readiness. We then contacted NOAA Hazmat (G. Watabayashi, personal communication, 2010), and within a week or so, we were providing our results for their inclusion in the Incident Command forecasts in which our USF contributions were subsequently acknowledged on a daily basis. With time, we then refined our analysis scheme and added additional models as their information became available to us. The order of inclusion was: (1) USF WFS, (2) Global HYCOM, (3) RTOFS, (4) SABGOM, (5) GOM HYCOM, and (6) NCOM IASNFS.

2.2. Satellite Data

Data from the Moderate Resolution Imaging Spectroradiometer (MODIS, http://modis.gsfc.nasa.gov) and the Medium Resolution Imaging Spectrometer Instrument (MERIS, http://envisat.esa.int/instruments/meris) were used to interpret the location and size of the surface oil slick. These data were collected either by a local antenna or downloaded from NASA in near real time. The principles of using MODIS imagery for oil spill detection are summarized in recent literature [e.g., *Hu et al.*, 2003, 2009]. Depending on the viewing angle (relative to the sun), ocean state (waves), and bio-optical water properties, oil can appear brighter or darker than the surrounding waters. For an oligotrophic ocean, thin films can only be observed under sun glint (same principles as used for Synthetic Aperture Radar (SAR) [*Wackerman et al.*, 2001]). 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 SAR satellite instruments were used to help delineate oil slicks [*Liu et al.*, 2000]. The satellite data interpretation was performed on a daily basis, depending on the availability of the data. For instance, 25 April 2010 provided the first clear satellite image showing a discernible surface oil patch after the spill onset (Figure 2a). The next three available satellite images were on 2 day intervals, i.e., 27 April 2010, 29 April 2010, and 1 May 2010, respectively. Beginning with the oil rig explosion, all subsequent satellite oil location interpretations and the associated ocean color imagery [*Hu*, 2011] were archived and made available to the public at the USF Optical Oceanography Laboratory website (http://optics.marine.usf.edu/events/GOM_rigfire/). Note that it is currently difficult to differentiate surface oil sheen from weathered oil or thicker oil slicks. Therefore, we simply used oil presence/absence as the surface oil information to initialize the numerical models and check upon their performance.

2.3. Surface Oil Trajectory Models

The tracking of surface oil using numerical circulation models traditionally employs Lagrangian particle trajectories [e.g., *Spaulding*, 1988; *Reed et al.*, 1999; *Beegle-Krause*, 2001; *Price et al.*, 2006; *Sotillo et al.*, 2008]. Our approach was to seed the oil locations inferred from the MODIS and MERIS satellite images with virtual particles and then advect these particles with the surface velocity fields as forecast by the six aforementioned numerical ocean circulation models. Similar methods exist for linking satellite bio-optical water properties with physical circulation models to predict the space-time evolution of these properties [e.g., *Arnone et al.*, 2010] and in existing NOAA oil spill forecast models [*MacFadyen et al.*, this volume].

To simulate the continual flow of oil from the wellhead, new particles were released on the surface at the well site every 3 h. These new particles (added to the satellite-inferred initialized particles) contributed to the spatial expansion of the surface oil. The number of the new particles is estimated from the difference of the pixels of the satellite images during the first several days. Figure 2 shows an example of this re-initialization process using the WFS model-based

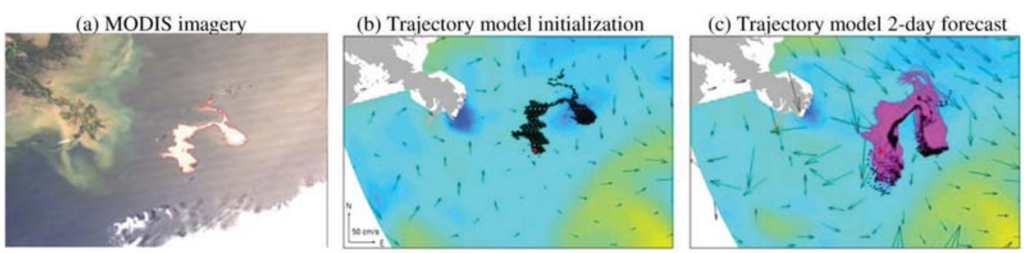

Figure 2. Illustration of the re-initialization of the surface trajectory analyses based on the West Florida Shelf (WFS) circulation model: (a) surface oil slick inferred from MODIS satellite imagery on 18:55 UTC, 25 April 2011 (outlined in red); (b) virtual particles seeded at the locations covered by the satellite-derived surface oil slick; (c) trajectory forecast 2 days after the initialization. Black denotes virtual drifters; purple denotes areas swept out by virtual drifters. Background fields are instantaneous sea surface temperature (SST) and surface currents. This figure is adapted from the work of *Liu et al.* [2011b].

Lagrangian trajectory model. New trajectory forecasts were made daily and re-initialized whenever new satellite image interpretations permitted. The frequent re-initialization of oil location controlled trajectory error growth, especially given the unknown effects from mitigation activities. The combined effects of weathering, consumption, and mitigation are therefore implicit in the re-initializations.

Upon the spill onset, both the WFS- and the HYCOM-simulated surface currents were available, and they were immediately and successively used to set up surface trajectory analyses without the re-initialization. On 25 April 2010, the satellite imagery, showing a discernible size of surface oil, was used to re-initialize these surface trajectories. The re-initialization process was repeated when the next satellite images became available on 27 April 2010, 29 April 2010, and 1 May 2010, and so forth. On 1 May 2010, the RTOFS-based surface trajectory analyses were added to the system, and on 4 May 2010, the SABGOM-based trajectory analyses were also included. The GOM HYCOM-based trajectory analyses began on 11 May 2010 after the Global HYCOM stopped updating its forecast for about a week. The sixth and final trajectory analyses based on the NCOM IASNFS was added on 23 June. In essence, we added analyses as soon as we could access their surface velocity fields.

3. COMPARISON OF MODELED SURFACE TRAJECTORIES WITH SATELLITE IMAGERY

3.1. Forecast for Different Days

Comparisons between actual oil locations inferred by satellite imagery and the model forecast positions from the latest forecast cycle provide a qualitative measure of model forecast veracity. Such assessments within an ensemble of model forecasts are useful for determining relative model forecast behaviors and the existence of systematic bias that may distinguish the models from one another. An initial comparison between the WFS and the Global HYCOM-based trajectory forecasts re-initialized with the satellite imagery of 27 April 2010 are shown in Figure 3 viewed against the subsequent satellite imagery-inferred surface oil locations for 2, 3, and 4 days later. The trajectory forecasts showed some success in simulating the surface oil locations for 2 days. The forecast skills then degrade for the 3 and 4 day forecasts for a variety of reasons. First, all models have errors, which are exacerbated by errors in the model forcing functions. Second, information on mitigation activities was unavailable; for instance, the first controlled burn of surface oil was on 28 April 2010 [e.g., *Crout*, 2011].

It would mislead from Figure 3 for this time interval that the 3 and 4 day trajectory forecasts based on HYCOM performed better than those based on the WFS model, whereas the WFS model better represented the shelf circulation at that time. During 29 April to 2 May 2010, the local wind was southwesterly, with (36 h low-pass filtered) wind speed of 7~10 m s^{-1} (Figure 4). In response to this strong wind event, the surface currents near the well site might be expected to flow northward. Such northward wind-induced currents are seen in the WFS model, but not in the HYCOM (Figure 3). Why, then, might the HYCOM-based trajectory forecasts appear closer to the satellite observations for the 3 and 4 day forecasts? One explanation might be the intensive mitigation activities such as the controlled burning that started in late April [*Crout*, 2011]. Booming, burning, and the use of dispersants may have dissipated the northward-extended limbs. This discussion highlights the need for frequent re-initialization from satellite observations.

Limited information on the uncertainty of the surface trajectory models are available from model performance evaluated against data from surface drifters deployed during the *Deepwater Horizon* event [*Liu et al.*, this volume]. For the Global HYCOM-based analyses, the mean separation distance between modeled and observed surface trajectory endpoints after 2 day duration simulations was about 57 and 18 km for the deep ocean and shelf regions, respectively [*Liu and Weisberg*, 2011]. These mean separation distances increased to 91 and 29 km, respectively, after 3 days. A 3 day separation distance of 78 km for the GOM, including both the deep ocean and shelf regions, was also found by *Price et al.* [2006]. Given such error growth, subsequent comparisons will focus on 2 day simulations. If satellite imagery was unavailable for the next 2 days, 3 day simulations will be examined.

3.2. Multiple Models

Forecasts from the WFS, Global HYCOM, GOM HYCOM, SABGOM, and RTOFS model-based surface trajectory analyses are shown against subsequent satellite images for the period of 6–17 May 2010 in Figure 5. All of the models used performed reasonably well for these short-term forecasts, and in composite, the ensemble provides some degree of confidence that any single model alone might not. Reasons why different model results may deviate are that they use different numerics (ROMS, HYCOM, NCOM), grids (all), parameterizations, data assimilation schemes/data, and domains. Commonalities also enter into these findings. For instance, the WFS model is nested into the Global HYCOM, so its deep ocean conditions are determined by the Global HYCOM. Similarly, the SABGOM, while nested into the Global HYCOM outside of the GOM, derives its initial conditions from the Global HYCOM. With a regular update cycle, it cannot deviate much from Global HYCOM anywhere within

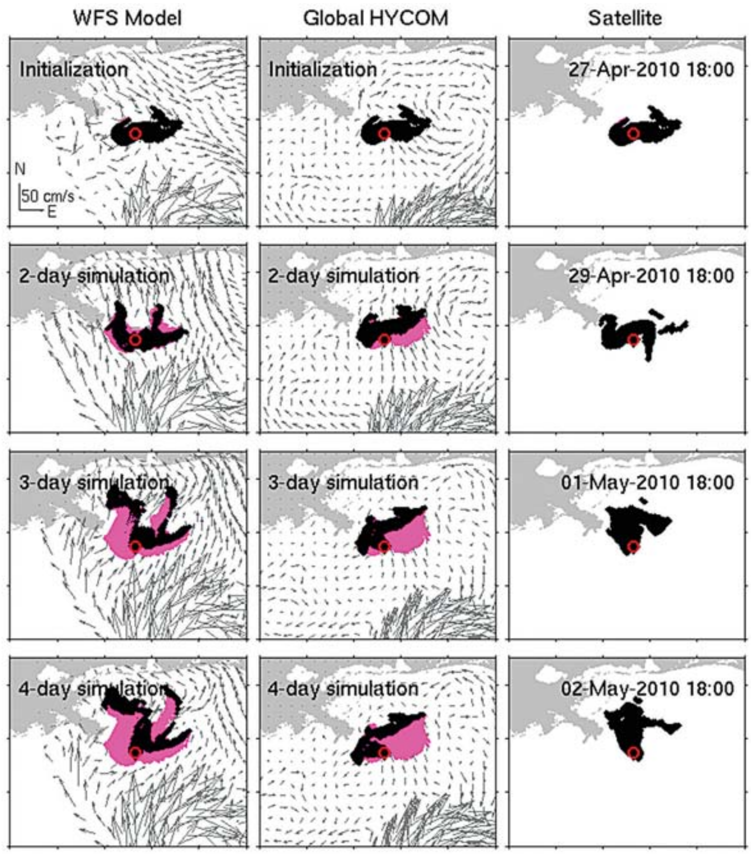

Figure 3. Comparison of the WFS- and Global Hybrid Coordinate Ocean Model (HYCOM)-based trajectory forecast analyses compared against the surface oil locations inferred from satellite imagery. The trajectories were re-initialized with surface oil locations inferred from MODIS satellite imagery around 18:00 UTC, 27 April 2011, and then forecast for 4 days. Black denotes virtual drifters; purple denotes areas swept out by virtual drifters. Background vector fields are instantaneous surface currents.

its domain. Nevertheless, there were times when some models fared worse than others. In particular, with different assimilation schemes used by the RTOFS and HYCOM, there were times when the RTOFS did not account well for the Loop Current position and hence the roles of the Loop Current and its shed eddy in influencing the overall circulation. Again, the ensemble helps to assess an outlier from the rest of the ensemble.

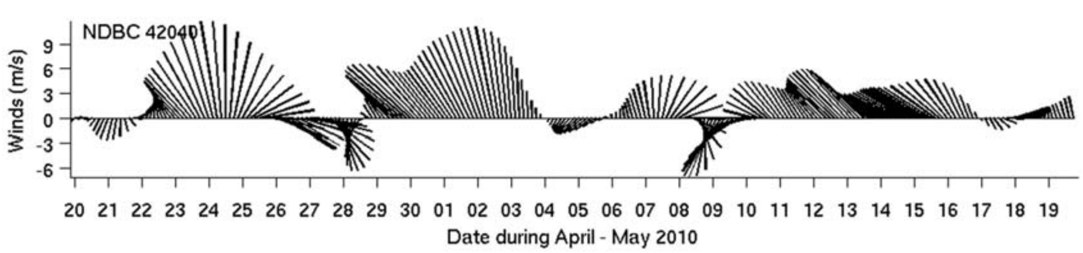

Figure 4. Stick plot of the 36 h low-pass filtered winds at NDBC Buoy 42036 during April–May 2010. The wind sticks are shown every 3 h. Southwesterly winds prevailed during 29 April to 2 May 2010.

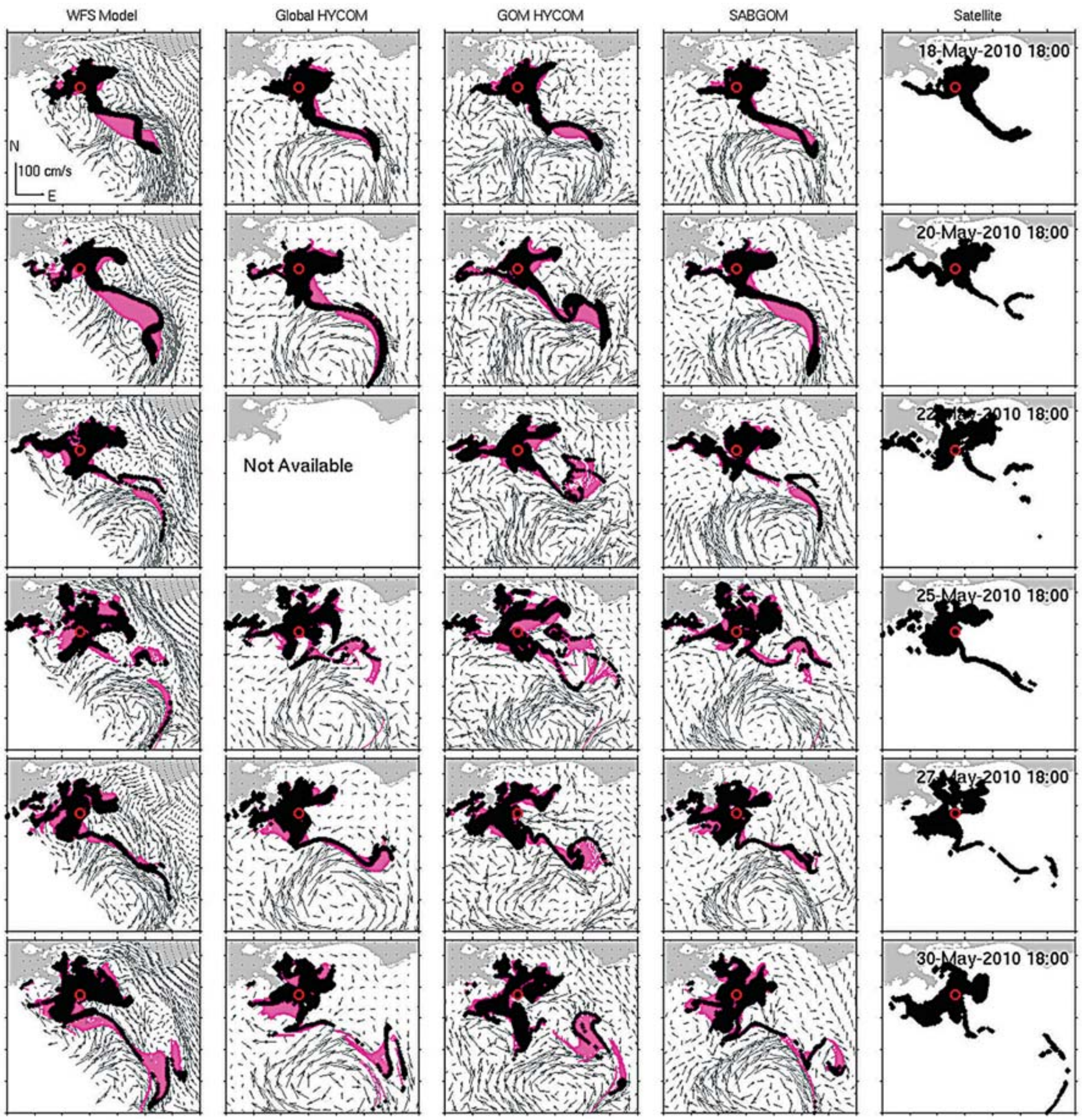

Figure 5. Comparison between different trajectory model forecasts and the subsequent surface oil locations inferred from satellite imagery. The trajectory forecasts were re-initialized with surface oil locations inferred from MODIS satellite imagery 2 days before the comparisons, except for the 11 May 2011 case, which was 3 days due to the non-availability of the satellite imagery. Note that the Global HYCOM results were not available after 8 May 2011 and were substituted with the Gulf of Mexico (GOM) HYCOM results in the same column after that time. Black denotes virtual drifters; purple denotes areas swept out by virtual drifters. Background vector fields are instantaneous surface currents.

A particular concern throughout the oil spill was the possibility of oil entrainment into the Loop Current and subsequent transport through the Florida Straits. Entrainment did occur in May (Figure 1), but the shedding of a Loop Current eddy toward the latter part of May broke the connection between the *Deepwater Horizon* site and the Florida Straits sparring much of Florida from direct oil encounter. Model/data comparisons for the period of 18–30 May 2010 are shown in Figure 6, where we see that the trajectory forecasts accounted for this entrainment.

Given our ensemble analysis approach, we chose to serve a subset of the results on a daily basis, choosing four among the six analyses, which we deemed to be the most representative (the other two were also made available daily, but not within the same four-panel presentation). An example is provided in Figure 7. We also supplemented such information available on our http://ocgweb.marine.usf.edu website, with disseminated briefings that used other available

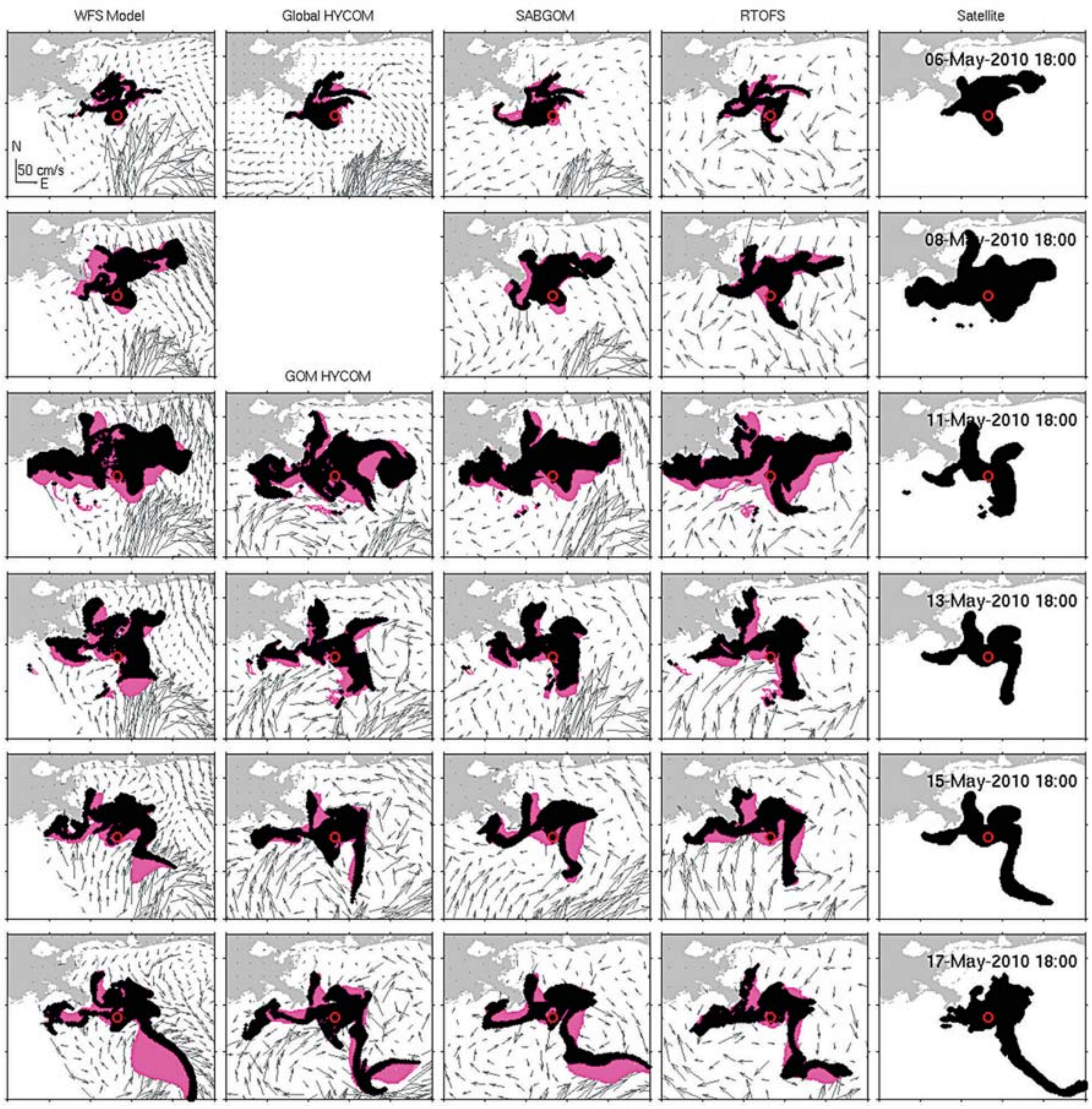

Figure 6. Comparison between different trajectory model forecasts and the subsequent surface oil locations inferred from satellite imagery. The trajectory forecasts were re-initialized with surface oil locations inferred from MODIS satellite imagery 2 days before the comparisons, except for the 25 and 30 May 2011 cases, which were 3 days due to the non-availability of the satellite imagery. Note that the Global HYCOM results were not available for 22 May 2011. Black denotes virtual drifters; purple denotes areas swept out by virtual drifters. Background vector fields are instantaneous surface currents.

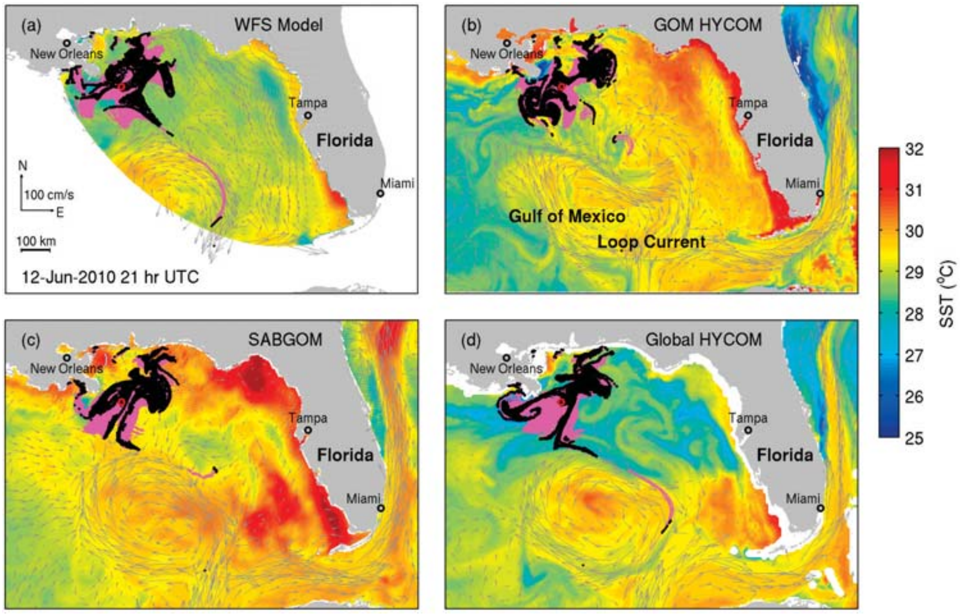

Figure 7. A 3.5 day surface oil trajectory forecast using (a) WFS model, (b) GOM HYCOM, (c) South Atlantic Bight-GOM model, and (d) Global HYCOM. Black denotes virtual particles, purple their swept-out areas. Background fields are sea surface temperatures and currents. This figure is adapted from Figure 1 of the work of *Liu et al.* [2011a].

information (geostrophic current and trajectory analyses from satellite altimetry, surface currents by HF-radar, water column velocity observations from fixed moorings, and water property transects from gliders) to help explain why surface oil may have been trending in certain directions. For instance, whereas it took nearly a month and a half for oil to reach the vicinity of Pensacola Florida, once there, oil then moved eastward nearly approaching Cape San Blas in only a week. The reasons for this were clear from our coastal ocean-observing system data, plus knowledge gained from regional studies. The rapid eastward movement was derived from a combination of anomalous winds, anomalous Loop Current, and Loop Current eddy interactions with the shelf slope. Whereas the Incident Command strived to remove the oil, we strived to remove some of the mystery of why the oil moved where it did.

4. SUMMARY AND DISCUSSIONS

Building upon existing observing and modeling resources supporting our coastal ocean-observing system activities in the eastern GOM, we responded rapidly to the *Deepwater Horizon* oil spill by implementing a set of surface and subsurface Lagrangian trajectory analyses based on existing primitive equation, ocean circulation models, and satellite imagery. An ensemble of six surface trajectory forecast analyses were initiated using the nowcast/forecast velocity fields from our WFS model, the Global HYCOM, the SABGOM, the GOM HYCOM, the RTOFS, and the NCOM IASNFS. Surface oil locations inferred from satellite imagery were used to re-initialize the positions of the virtual particles in this ensemble of trajectory forecasts, and the particles were tracked using forecast surface currents, with new particles added to simulate the continual release of oil from the well.

Major challenges to the surface trajectory forecasts were the paucity of oil location information for regular re-initializations of the forecast analyses and lack of information on mitigation activity results. For instance, the only re-initialization information available to us was that from our own satellite image analyses. One solution would be to better coordinate all of the various agency sampling activities to produce a unified daily product that could be used by all responders. Nevertheless, by frequently re-initializing the trajectory models with satellite observations, the effects of in situ mitigation and forecast error growth were implicitly accounted for and minimized.

Given the errors inherent to any model, its forcing fields, and its initialization and re-initialization data, an ensemble approach is sensible. In this application, it was found that no single model outperformed any other with any consistency, and when an outlier was found, that finding was within the context of the ensemble. Here for instance, two observations warrant mention. The first is that the Global HYCOM performance was found to improve as more observations (F. Bub, personal communication, 2010) were obtained for assimilation into the model. The second is that the RTOFS performance improved after adjustments were made to its satellite altimetry assimilation. Whereas these statements are qualitative, they do reinforce the concept of using an ensemble of models versus relying on any single model.

Our trajectory models did not consider the physical-chemical weathering of crude oil [e.g., *Zheng et al.*, 2002] or biological consumption [e.g., *Atlas*, 1981; *Venosa and Holder*, 2007; *Adcroft et al.*, 2010], as simplified in many previous oil spill forecast systems [e.g., *Jordi et al.*, 2006; *Howlett et al.*, 2008; *Sotillo et al.*, 2008; *Chang et al.*, 2011]. We also excluded any additional parameterized wind drift of oil relative to the sea surface [e.g., *Price et al.*, 2006; *Abascal et al.*, 2009] for two reasons. First, when comparing forecast cycle results with observations, the model performance was satisfactory. Second, by using relatively high resolution, 3-D, density-dependent data assimilative models or models nested into data assimilative models, it was unclear whether or not such parameterizations (designed for lower resolution, less physically complete models) would be applicable, and subsequently, *Huntley et al.* [this volume] showed that parameterized wind effects were generally negligible away from the coastal areas. Wave-induced Stokes drift was also not included, although under strong winds and waves of large slope, this has been argued to be important [*Sobey and Barker*, 1997; *Giarrusso et al.*, 2001]. *Carratelli et al.* [this volume] subsequently showed that Stokes drift had a non-negligible influence on the average movement of oil slicks. Oil droplet size [e.g., *Li and Garrett*, 1998; *North et al.*, this volume] has also been argued to be a factor. These effects all warrant possible inclusion in future trajectory models. Notwithstanding these other omissions, it must be stressed that deep ocean models require data assimilation to represent the strong currents such as the Loop current and its eddies that are controlling of the flow fields there and that also impact the continental shelf through interactions with the shelf slope.

Whereas most of the attention on the *Deepwater Horizon* oil focused on the surface distribution, there was ample reason to believe that a portion of the hydrocarbons emanating from the ruptured wellhead some 1500 m below the surface would remain in the water column [e.g., *Adcroft et al.*, 2010; *Socolofsky et al.*, 2011]. Our analyses therefore included subsurface trajectory forecasts based on the WFS model [see *Weisberg et al.*, this volume]. The combined surface and subsurface trajectory modeling results were consistent with certain findings by others [e.g., *Schrope*, 2010; *Camilli et al.*, 2010] and was helpful in guiding some of our colleagues in their sampling campaigns [e.g., *Hollander et al.*, 2010]. A limitation for subsurface trajectory modeling, however, was the scarcity of observations. In responses to any future environmental disaster, there should be provision made for systematic 3-D mapping of important environmental variables so that, in combination with models, we can better assess the distributions of materials throughout the water column.

In many respects, much of Florida and the Southeastern United States were spared the direct impact of *Deepwater Horizon* oil because the Loop Current, by shedding an eddy 1 month into the 3-month spill, broke its connection with the Florida Current and Gulf Stream. This kept the oil in the northern GOM and away from other equally sensitive regions. Finally, helpful for all coastal ocean matters of environment concern would be models that are capable of downscaling from the deep ocean, across the continental shelf and into the estuaries themselves. We were not aware of any such models that were available regionally at the time of the *Deepwater Horizon* event.

Acknowledgments. This work did not initiate based on any direct source of funding. We did benefit, however, from several existing grants, and midway through the effort, we received support from the Gulf Research Institute (GRI) set up by British Petroleum (BP). We were in a position to respond immediately to the *Deepwater Horizon* rig explosion and ensuing oil spill due to grants in support of a coordinated coastal ocean-observing and modeling activity by Ocean Circulation Group, College of Marine Science, University of South Florida. Contributing and active at the time were ONR grants: N00014-05-1-0483, N00014-10-0785, and N00014-10-1-0794; NOAA Ecohab grant NA06NOS4780246; NSF grant OCE-0741705; and support from South Carolina Seagrant as pass through from the NOAA IOOS Program Office, NOAA grant NA07NOS4730409. Subsequent support from British Petroleum came as a grant from the Florida Institute of Oceanography FIO-BP grant 4710-1101-05. Support for satellite work was provided by the US NASA Ocean Biology and Biogeochemistry Program and Gulf of Mexico Program. The HYCOM Consortium, NOAA, North Carolina State University (NCSU), and Naval Oceanographic Office provided model fields for ensemble forecasts. Satellite data were provided by NASA and NOAA. We particularly thank A. Barth and A. Alvera-Azcarate (University of Liège), E. Chassignet (Florida State University), R. He and K. H. Hyun (NCSU), O. M. Smedstad and P. Hogan (HYCOM Consortium), C. Lozano (NOAA), and F. Bub (Naval Oceanographic Office) for providing model results and F. Muller-Karger (USF) for assisting with satellite imagery. This is CPR Contribution 19.

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