Tracking Subsurface Oil in the Aftermath of the *Deepwater Horizon* Well Blowout

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The flow of oil and other hydrocarbons from the ruptured *Deepwater Horizon* wellhead posed a tracking problem not only for the oil that reached the surface, but also for the hydrocarbon compounds that remained at depth. By applying an existing nowcast/forecast model for the ocean circulation of the eastern Gulf of Mexico, we were able to respond immediately to this tracking need. Our approach was based on advection. We did not attempt to include thermodynamic considerations because there were too many unknowns. Instead, we assumed that some compounds would reach certain levels and be carried three dimensionally by the currents there. Without a priori knowledge, we deployed virtual drifters at depths of 1400, 1200, 1000, 800, 600, 400, 200, 100 m and at the surface, and to mimic the continual flow of oil, we added new virtual particles every 3 h from 20 April 2010, when the rig exploded, to 15 July 2010, when the ruptured wellhead was capped. We then continued tracking these virtual particles until 22 March 2011 when most of them were found to have exited the model domain. Our results are in qualitative agreement with the limited observations and inferences of subsurface hydrocarbon locations obtained by ship surveys made throughout the spill. Our work was also used to successfully inform some of these cruises on where to look for subsurface hydrocarbons. Our findings are discussed and comments are provided toward becoming better environmental stewards of the coastal ocean going forward.

1. INTRODUCTION

Limited to anecdotal accounts, there was ample reason to believe that some portion of the hydrocarbons issuing from the *Deepwater Horizon* Macondo lease block 252 wellhead would remain subsurface to be carried by the prevailing circulation. For instance, a portion of the hydrocarbons from the Ixtoc well remained in the water column [*Hooper*, 1981], oil ensconced in the sediments offshore of St. Pete Beach, Florida, blackened the beaches for a second time in summer 2000, some 7 years after being spilled by a Tampa Bay barge collision in 1993, and the potential for subsurface oil is discussed in the National Research Council report [*NRC*, 2003]. Thus, in the aftermath of the *Deepwater Horizon* drill rig explosion on 20 April 2010 and subsequent sinking on 22 April 2010 along with the tracking of the oil at the surface, there was an immediate need to estimate the transport and location of subsurface hydrocarbons. Our approach was to adapt an existing ocean circulation model, which was available as part of a coordinated coastal ocean observing and modeling system for the West Florida Continental Shelf (WFS), as described by *Weisberg et al.* [2009].

Our chapter is organized as follows. We first discuss the physical underpinnings on why the hydrocarbons were transported as observed in section 2. Section 3 then describes the modeling methods that were used, and section 4 shows the results. Section 5 comments on residence times within the model domain, and section 6 concludes with a discussion and recommendations.

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2. BACKGROUND

The movement of water and hence the trajectories of hydrocarbons transported by the ocean circulation is constrained through a combination of mass and angular momentum conservation. In essence, fluid tends to travel along lines of constant depth unless there are mitigating conditions to relax this constraint. Being that the Macondo 252 well site was located on the continental slope, where the bathymetric gradient is large, this constraint was a formidable one. Mass conservation alone would suggest that fluid in deep water would tend to stay in deep water because a column of deep fluid would have to spread horizontally over a large area (displacing the water already there) in order to flow up onto a shallow region. Similarly, fluid in shallow water would tend to stay in shallow water. Were across-isobath motions by mass conservation not difficult enough, the constraint by angular momentum conservation is even larger. Thus, near the bottom, the a priori expectation was for hydrocarbons to flow along the isobaths. Higher up in the water column, as baroclinicity through the density gradient field increasingly decouples the bottom pressure gradient field from that at the surface, this constraint lessens, and close to the surface, where the direct effects of wind stress torque are manifest, the bathymetric constraint (at least in deep water) is further diminished. Further amplification on these mass and angular momentum conservation concepts leading to bottom pressure, baroclinic and stress torques may be found in texts on Geophysical Fluid Dynamics such as that by *Pedlosky* [1987] or in many applications to the deep ocean such as that by *Ezer and Mellor* [1994], or to the coastal ocean such as that by *Weisberg et al.* [2001].

Given this background, and before showing the results, certain generalizations may be made. Beginning at the surface [*Liu et al.*, 2011, this volume], and again as a consequence of mass and angular momentum conservation, we may appreciate why oil evolved as it did. Because fluid in deep water tends to stay in deep water and fluid in shallow water tends to stay in shallow water, it is easy to appreciate why the region of the Mississippi River Delta, the Birdsfoot as it is called, was the first landed region to be oiled. It is where the deep ocean comes closest to the shoreline, and hence, it is the region where breaking the along-isobath constraint was the easiest; hence, the Birdsfoot was the first land area to be oiled. Wind stress along with nonlinear eddy formation was able to do this. The next shoreline region to be oiled was in the vicinity of Pensacola, Florida, and for similar reasons. That is where the DeSoto Canyon brings deep isobaths closest to the northern Gulf of Mexico shoreline to the east of the Birdsfoot. Once oil was in shallow water (by virtue of the Birdsfoot and Pensacola encounters), the surface oil was then able to move more freely with the wind, thereby causing contacts with beach communities to the west along the Mississippi Sound and to the east, almost as far as Cape San Blas. In this way and subjected to the least topographic constraint, the broadest spatial distribution of hydrocarbons from the *Deepwater Horizon* event was at the surface.

Opposite to that described for the surface, the most constrained distribution of hydrocarbons was near the bottom, as we will show in section 4. The gradation from strongest constraint near bottom to weakest constraint at the surface varied systematically in between.

3. METHODS

Knowing neither the hydrocarbon mass flux, nor composition at the wellhead, the environmental and thermodynamic conditions there, or the vertical structure of the water column, it was not possible to estimate the initial distributions of hydrocarbon compounds between the surface and the bottom. Certain expediencies were therefore necessary to facilitate an immediate response to tracking the potential distributions of subsurface hydrocarbons. Our starting point was an existing Lagrangian particle trajectory tracking tool already in use for tracking harmful algal blooms in three dimensions across the water column and for search and rescue purposes at the surface. This was embedded in a numerical ocean circulation model for the eastern Gulf of Mexico and the WFS consisting of Regional Ocean Modeling System (ROMS) [*Shchepetkin and McWilliams*, 2005; *Haidvogel et al.*, 2008] nested in the Global Hybrid Coordinate Ocean Model (HYCOM) [*Chassignet et al.*, 2003, 2007]. The rationale for the use of ROMS nested in HYCOM was to downscale from the deep ocean across the continental shelf. HYCOM through its data assimilation maintains the structure of the Gulf of Mexico Loop Current and its eddies, which at times are important drivers of the shelf circulation, and ROMS provides increased resolution and local control of the experiments and applications to be performed. This University of South Florida (USF) WFS (ROMS nested in HYCOM) model [e.g., *Barth et al*, 2008a, 2008b, 2008c; *Weisberg et al.*, 2009] contained the Macondo lease block 252 well site, and it provided a means by which oil could be tracked both at the surface [e.g, *Liu et al.*, 2011, this volume; *MacFadyen et al.*, this volume] and at depth. The model domain is shown in Figure 1; the horizontal resolution varied from that of the Global HYCOM (~8 km along the open boundary to the range of 2–4 km near the coast, and the vertical was resolved with 33 terrain following s-coordinate layers. Lagrangian tracking was performed using neutrally buoyant, virtual particles advected three-dimensionally by

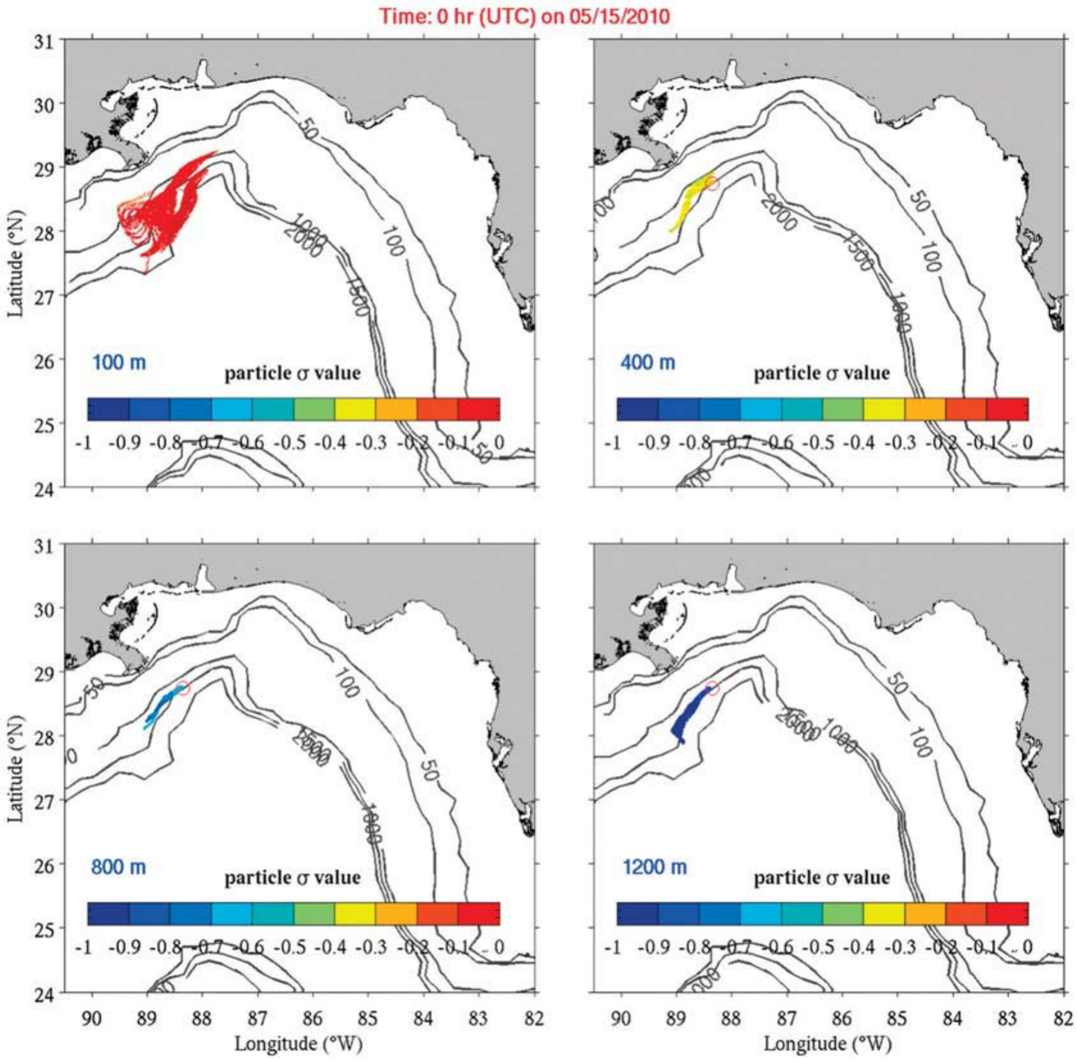

Figure 1. Subsurface trajectories for virtual particles deployed about the Macondo lease block 252 well site beginning on 20 April and continuing every 3 h through 15 May 2010. The color coding refers to the vertical sigma coordinate layer. Counterclockwise from the upper left are trajectories for virtual particles beginning at depths of 100, 400, 800, and 1200 m.

the model's simulated velocity field. Integration was by a fourth-order Runga-Kutta routine, and previous applications are given by *Alvera-Azcárate et al.* [2009] and *Weisberg et al.* [2009].

Initialization of the virtual particle field began on 20 April (we implemented this tracking system on 23 April). Without a priori knowledge of initial distributions, we chose to insert virtual particles at nine different depths (1400, 1200, 1000, 800, 600, 400, 200, 100, 50 m and at the surface) at the well site and at one grid box to the north-northwest and to the south-southeast along the bottom depth gradient. Following the initial insertion of these particles, new particles were then added every 3 h to represent the continual flow of hydrocarbons from the ruptured well. Such insertion of particles continued until 15 July 2010 when the wellhead was capped, and oil ceased flowing. Model hindcasts and forecasts were updated daily from the initialization on 20 April through 22 March 2011, and the results were made publically available on the internet at http://ocgweb.marine.usf.edu. In an attempt to minimize the errors owing to mismatch between the

Global HYCOM and the USF-WFS model (ROMS nested into HYCOM), we re-initialized the USF-WFS model fields with those of the Global HYCOM on a weekly basis. Thus, our forecasts made daily throughout the spill were indeed USF-WFS based forecasts, whereas our extended hindcast simulations made use of the data assimilation for the deep ocean as provided by the Global HYCOM. This is important because throughout the *Deepwater Horizon* event, increasingly more data were being assimilated into the Global HYCOM with time, thereby increasing the Global HYCOM's accuracy within its deep water regimes (F. Bub, personal communication, 2010).

4. RESULTS

Unlike the surface, where analyses from satellite imagery [e.g., *Liu et al.*, this volume; *MacFadyen et al.*, this volume] allowed for regular re-initializations of oil location, there were few instances of subsurface observations for comparison with the model simulations. Nevertheless, when available (in the form of limited shipboard samples and proxy inferences), qualitative agreements between such observations/inferences and the model simulations were very good. Additionally, in some such instances, the model simulations were used to guide the shipboard surveys. Below are a few snapshots of simulated particle trajectories to illustrate the relative constraint by bottom topography across the water column and to compare with the limited observations/inferences.

The potential distribution for subsurface hydrocarbons on 15 May 2010 is illustrated by Figure 1. We reiterate that these distributions, shown for virtual particles first deployed about the Macondo lease block 252 well site on 20 April 2010 and every 3 h thereafter, were arrived at without any justification for where oil may actually have resided at depth. As such, they merely represent virtual particles, not hydrocarbons. For particles initialized at the 1200, 800, and 400 m depths, we see a strong topographic constraint with all such particles tending along the isobaths toward the southwest. Higher in the water column at 100 m, we see a relaxation of this constraint, with particles spread across isobaths and with some tending toward the northeast.

The first indication of subsurface oil that may be compared with the virtual particle distributions of Figure 1 are from a cruise of the R/V *Pelican* from 10 to 16 May 2010 and reported upon in a news article by *Schrope* [2010]. Proxy inferences on hydrocarbons located at depths between 1000 to 1400 m were obtained through fluorescence and transmissometer observations, which were later confirmed by water samples. These observations were found to extend some 45 km to the southwest of the wellhead along the same line as shown in Figure 1.

Some 2 weeks later, we see in Figure 2 that the virtual particle distribution grew in space. Movement toward the southwest continued at all depths, along with a reversal of flow increasingly so from the near bottom to the near surface. The topographic constraint is still readily apparent and again increasingly so with depth. Closest to the bottom, where the isobaths diverge south of the Mississippi River delta, we see a similar divergence in the virtual particle trajectories. Higher in the water column, where the flow toward the northeast is larger, we see the trajectories wrapping around the DeSoto Canyon isobaths, again indicating the strong constraint by topography. Highest in the water column, however, we see a lessening of the topographic constraint. We also see a shortcoming of this model simulation, namely, that the open boundary was reached by several of the virtual particles. For the purposes of this simulation, we specified that once a particle hit the open boundary, it was removed from the analysis. Hence, the open boundary provides no negative impact on the trajectory modeling other than limiting the analyses to what remains inside the model domain. As we will see later, this also provides a metric for virtual particle residence time within the model domain.

Our subsurface trajectories were used to inform the R/V *Weatherbird II*, 26 May to 2 June, cruise on the potential locations for subsurface hydrocarbons. Like the previous R/V *Pelican* cruise, scientists aboard the R/V *Weatherbird II* (D. Hollander, E. Peebles and D. Naar, personal communication, 2010) used proxy information from the ship's fathometer and flourometer to infer the existence of subsurface hydrocarbons along with water samples taken to provide confirmation after the fact. Samples taken some 35 km to the northeast of the well site yielded hydrocarbon observations (of low concentration) later confirmed to be of Macondo lease block 252 well origin (D. Hollander, personal communication, 2010) at a depth range of around 1000 to 1400 m, consistent with Figure 2. Also observed were subsurface hydrocarbons centered on 400 m depth at the head of DeSoto Canyon as seen in Figure 2, and also consistent with the 100 m distribution in this figure was oil picked up on the Rosette sampler from a CTD cast made farther to the southeast near 28°N, 86°W. Thus, our subsurface trajectory estimates, using virtual particles, provided valuable guidance for the Weatherbird II sampling, and the Weatherbird II sampling, in turn, provided qualitative veracity testing for the modeled subsurface trajectories. At about the same time in NOAA scientific response cruise GU-10-02 (27 May to 4 June 2010), autonomous underwater vehicle operations were performed to locate deep hydrocarbon plumes in the Gulf. The ship hydrocast survey localized maximum optical signatures of a deep plume, centered at ~1150 m depth, approximately 13 km southwest of the blowout [*Ryan*

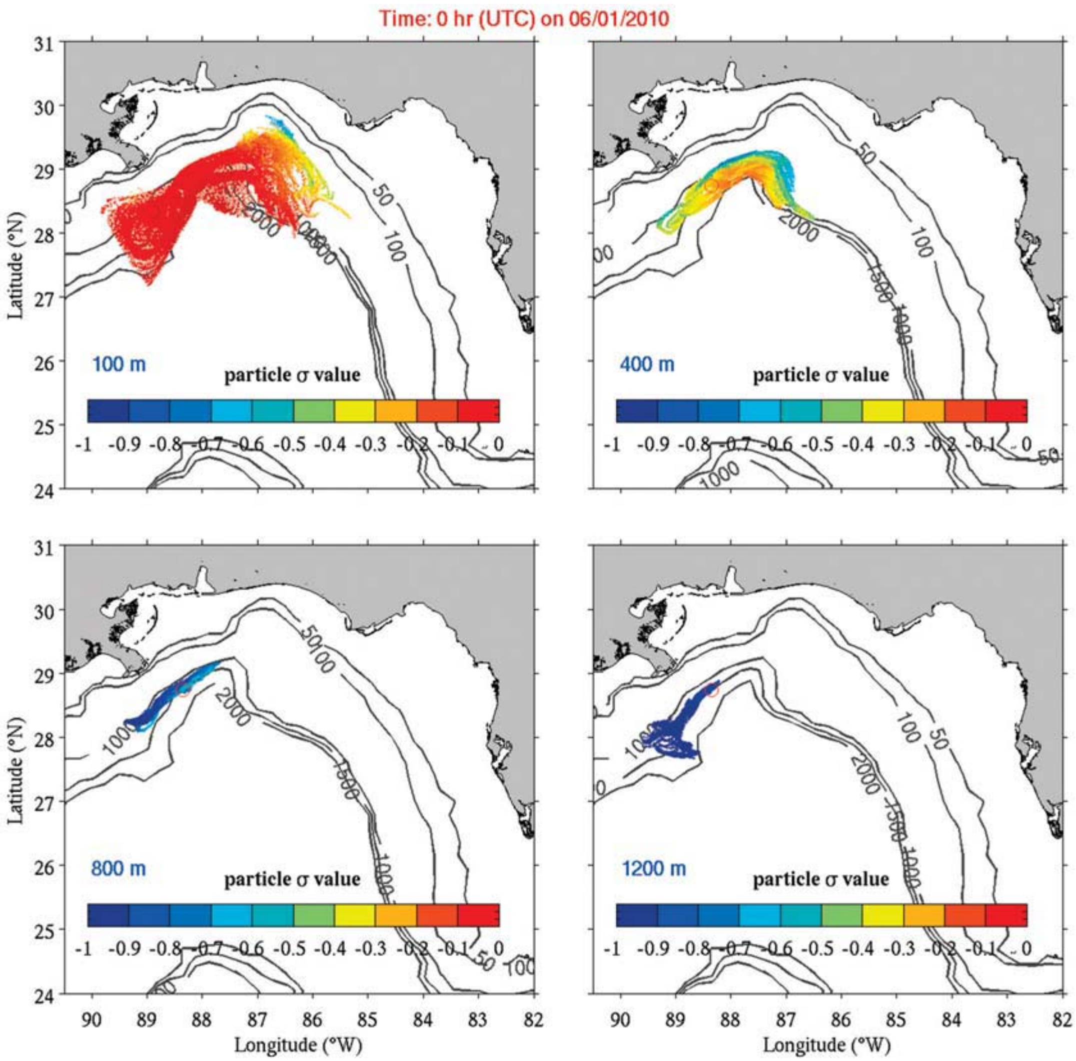

Figure 2. Same as Figure 1 except for a snapshot on 1 June 2010.

et al., this volume]. This also supports our trajectory model result (1200 m) in Figure 2.

Fifteen days later, the virtual particle distributions continued to evolve over larger areas (Figure 3). For those released at 1200 m depth, we see particles extending southwest to the model domain boundary and some extending a few tens of kilometers to the northeast. The distributions to the northeast (and then wrapping around the DeSoto Canyon isobaths) increase higher up in the water column. For those initialized at 400 m depth, the extension into DeSoto Canyon is evident as is the entrainment by an anticyclonic eddy at the Canyon entrance. Movement both to the northeast and southwest further increased for those initialized at 100 m depth.

The Macondo lease block 252 wellhead was capped on 15 July 2010, effectively stemming the flow of oil. Figure 4 shows the estimated trajectories for virtual particles on that date. As expected, the trajectories continued to evolve, and the constraint by the topography once broken by particles entering the abyssal Gulf of Mexico remained broken. A few points warranting mention are as follows. For particles released at 1200 m depth, the trajectory pattern on this date looks similar to that a month earlier. This is because many of the particles had already exited through the open boundary thereby leaving the model domain. Similar may be said of the particles initialized at 800 m depth, although some of these remained in the abyssal Gulf of Mexico. Particles initialized

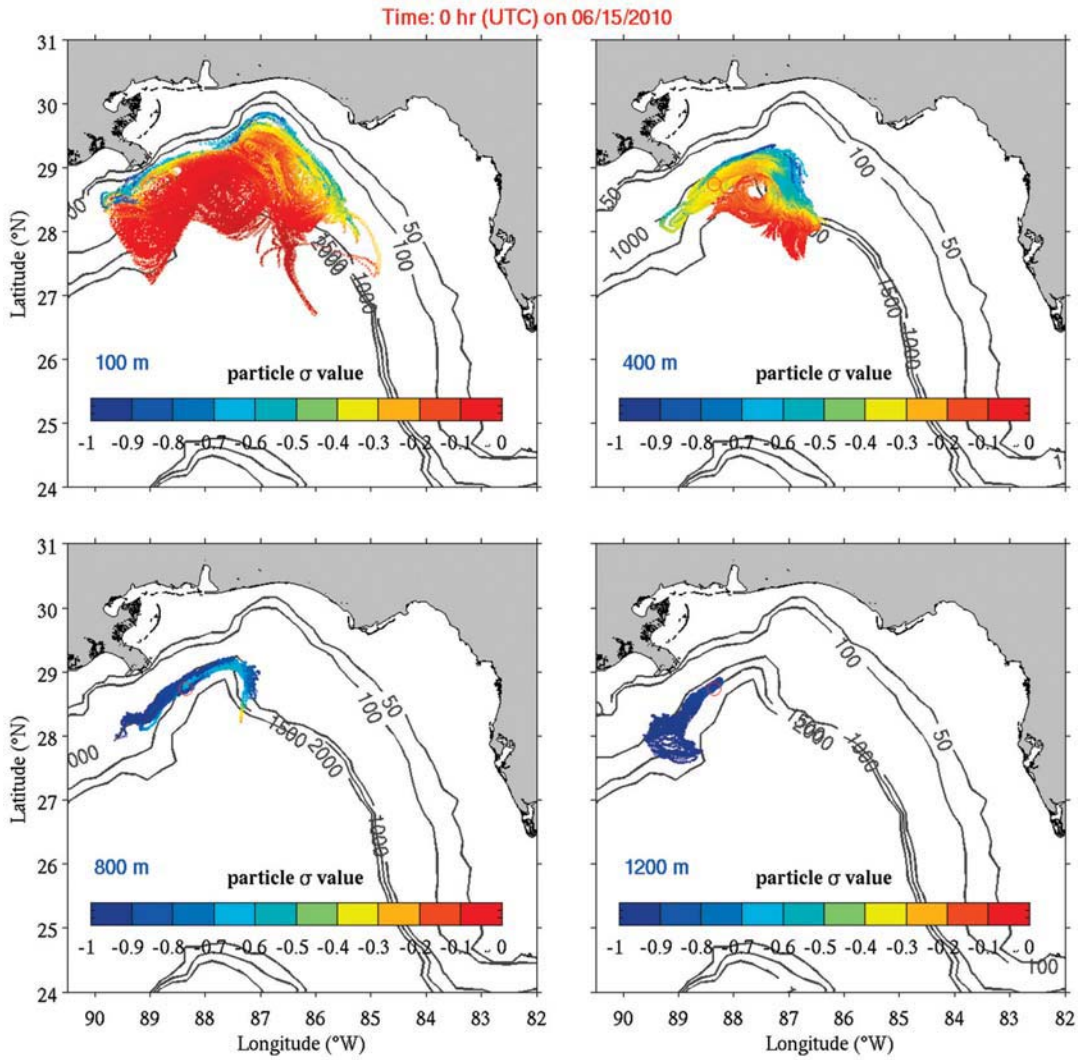

Figure 3. Same as Figure 1 except for a snapshot on 15 June 2010.

at 400 m depth and above spread farther afield, but for the most part toward deeper versus shallower water depths. This makes sense because the bottom depth gradient is larger toward the land, and for all of the three reasons stated in section 2, the decoupling from the bathymetry increases seaward rather than landward.

Additional supporting evidence may be found in the work of *Camilli et al.* [2010] for cruises made between 19 and 28 June 2010. Using flourometry and mass spectrometry, these investigators identified a continuous plume of hydrocarbons to the southwest of the wellhead, more than 35 kilometers in length, at approximately 1100 m depth that persisted for months without substantial biodegradation. It is worthy to mention that the topography-aligned subsurface features in our trajectory model are similar to those simulated with a Lagrangian trajectory model that considered oil droplet sizes [*North et al.*, this volume].

Cruises aboard the R/V *Weatherbird II* continued for several more months. Sediment samples taken at depths ranging from roughly 1500 to 1000 m along a line extending into, and wrapping around, DeSoto Canyon showed a layer of detritus with hydrocarbon signature growing with time over successive cruises (B. Flower and D. Hollander, personal communication, 2010), and these investigators also found flourometric evidence for hydrocarbons in the sediments farther up on the continental shelf as might be anticipated from Figure 4 (and later trajectories not shown).

5. RESIDENCE TIMES

Given the broad distributions of virtual particles and the model's open boundary arching from just west of the Mississippi River Delta to the Florida Keys, it was inevitable that some of these particles would leave the model domain. Whereas section 3 provides tracking information through 15 July, when the well was capped, we continued such tracking (albeit without adding any new particles beyond those deployed through 15 July) through 22 March 2011. Tracking then ceased when it became apparent that most of the particles had already left the model domain.

Particle age in days (beginning with the day of deployment) provides a measure of residence time. Two such examples are given in Figure 5 for particles deployed at the 400 m (left-hand panel) and 1200 m (right-hand panel) depths. The 400 m depth-deployed particle ages are shown on 5 November 2010, 200 days after spill onset. We see that very few trajectories are of an age of 200 days, which means that most of the initially deployed particles had already

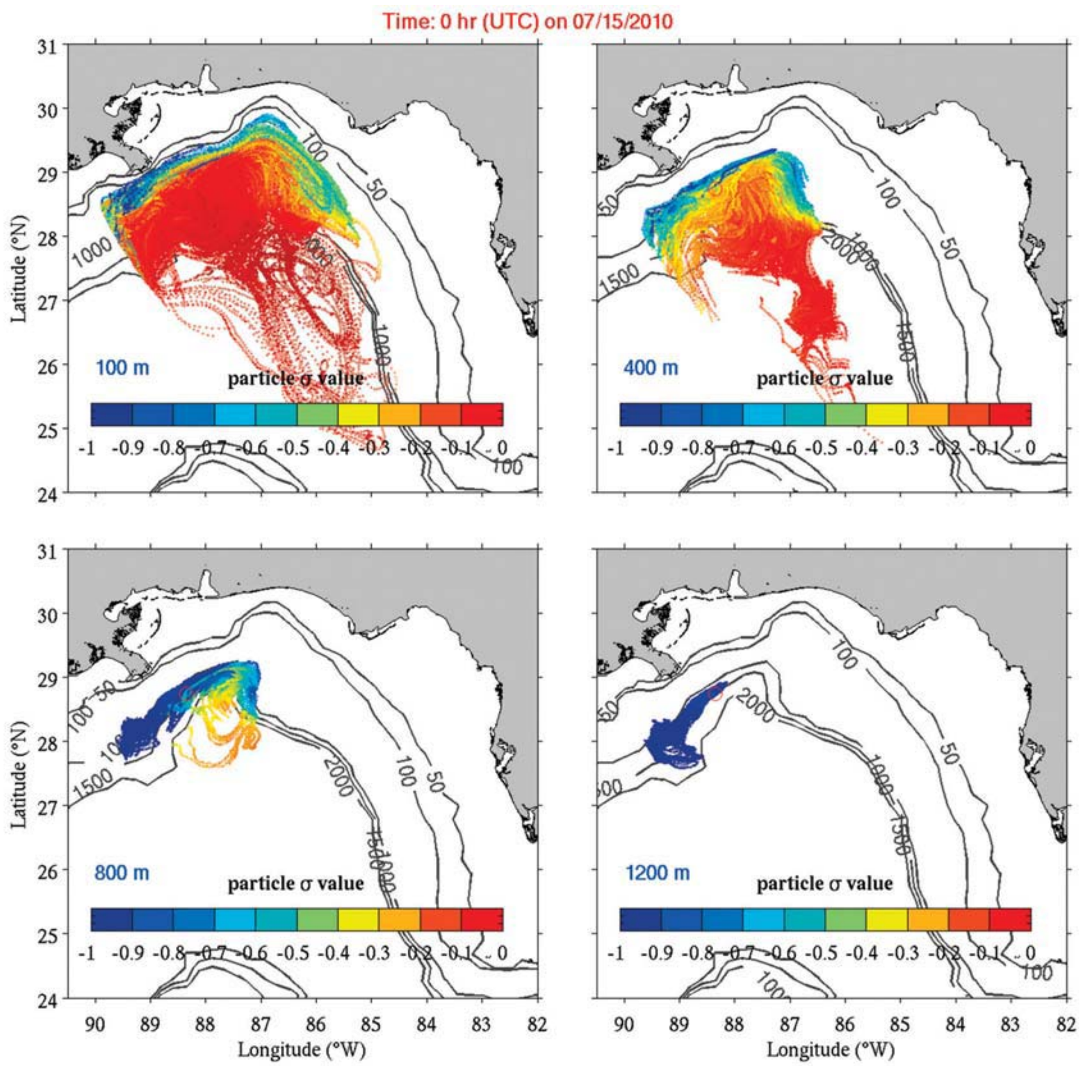

Figure 4. Same as Figure 1 except for a snapshot on 15 July 2010.

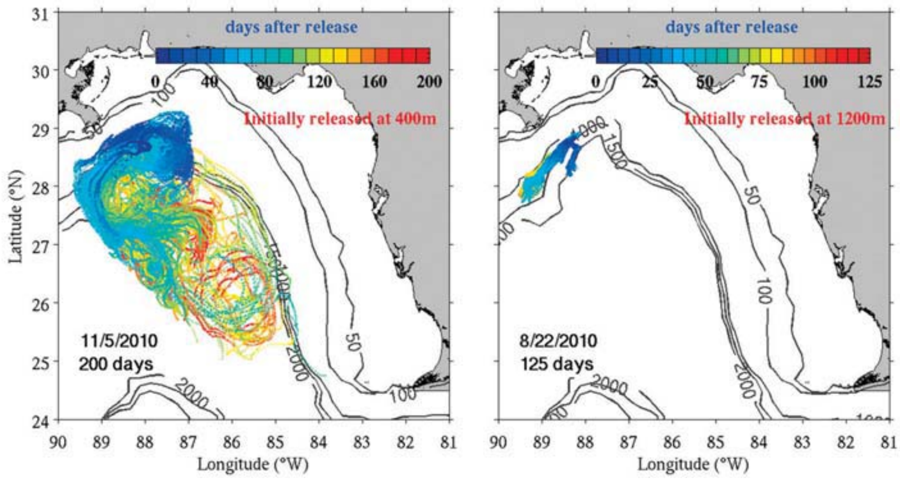

Figure 5. Virtual particle age (color coded in days after release) for two different initialization depths: (left) 400 m and (right) 1200 m. The left-hand panel is for 5 November 2010 (200 days after 20 April), whereas the right-hand panel is for 22 August 2010 (125 days after 20 April).

exited the domain. Similarly, the 1200 m depth-deployed particle ages are shown on 22 August 2010, 125 days after spill onset. We see that very few trajectories are of an age of 125 days, which means that most of these initially deployed particles had also exited the domain.

These results are extended for all deployed depths in Table 1. For each depth of initial virtual particle deployment (the left-hand column), we show the percentage of particles that had left the model domain as a function of time (top row) beginning on 20 April 2010. The bottommost particles exited the model domain most rapidly. For instance, by day 150, all of the particles that were deployed at 1400 m depth were gone, along with 99% of those deployed at 1200 m depth. The reason is that the flow was fairly unidirectional toward the southwest at these deepest depths, and hence, these particles encountered the model boundary relatively quickly. Farther up in the water column, the residence times first increased before decreasing again near the surface. For instance, the longest residence times were for particles initially deployed at the 800 and 600 m depths, which is consistent with the previous findings that many of their trajectories wrapped around DeSoto Canyon and were entrained and retained by an anticyclonic eddy there. In terms of an e-folding time scale, the residence time for these depths was in the approximate range of 200–250 days. Higher up in the water column, and with current speeds increasing and the topographic constraint lessening, more particles again reached the open boundary and escaped the model domain.

Table 1. The Percentage of Virtual Particles That Were Advected Out of the Model Domain as a Function of Time Beginning 20 April 2010[a]

Depth (m)	100 days (%)	150 days (%)	200 days (%)	250 days (%)	300 days (%)
0	51	77	95	97	99
50	30	70	84	87	97
100	41	74	84	88	97
200	43	75	83	86	96
400	16	69	75	81	91
600	13	58	64	69	90
800	19	59	66	71	88
1000	21	80%	86	90	96
1200	33	99%	100	100	100
1400	34	100	100	100	100

[a]As an example, for those particles deployed at 1200 m depth, 100% had left the domain by 200 days after the initiation of the spill.

Thus, for particles deployed above 400 m depth, the e-folding residence time scale was less than 150 days, and after 300 days, very few particles remained anywhere within the model domain. It was for this reason that we ceased tracking on 22 March 2011.

It is important to note that the residence times provided above are based on conservative, virtual particles without any consideration of decay by chemical weathering or biological consumption. With decay, the residence times would be less. As an example, *Adcroft et al.* [2010] tracked a tracer within a climatological circulation field under the influence of temperature-dependent decay. A limitation there was the use of a climatological velocity field versus what occurred in spring and summer 2010. In the future, given a re-analysis of the *Deepwater Horizon* event and substantiated estimates of the hydrocarbon compounds present at various depths and horizontal locations, analyses may ensue with these limitations lessened.

6. IMPLICATIONS AND SUMMARY

Much remains to be learned about the fate and effects of the hydrocarbons that emanated from the downed *Deepwater Horizon* rig and wellhead riser rupture. Whereas the oil at the surface was readily visible, washed up on beaches and marshes, and seemed to largely disappear within weeks of the flow being stemmed by capping the wellhead, the hydrocarbons that remained below the surface were not systematically sampled, and their fate and effects remain largely unknown. Granted, subsurface hydrocarbon concentrations had to be of very low magnitude because distributing any reasonable fraction of unaccounted for hydrocarbons over any reasonable volume of seawater would result in concentrations crudely on the order of parts per million to parts per billion or less over time. Nevertheless, prolonged exposures may still imply negative effects on the biota (e.g., J. Paul, personal communication, 2010).

Recognizing that ecology is not merely biology, but the sum total of all factors that unite nutrients with light to fuel primary productivity, distribute water properties of biological importance, and facilitate predator-prey interactions, estimating the distributions of the hydrocarbons from the *Deepwater Horizon* event was and remains an important aspect of determining fate and effects [e.g., *Ji et al.*, this volume]. A particular concern of ours was the potential for subsurface hydrocarbons to upwell across the shelf break and onto the WFS.

Upwelling itself is a regularly occurring event, and anomalously strong and prolonged upwelling basically resets the nutrient structure of the WFS. An example of the latter occurrence is the spring through fall 1998 event [*Weisberg and He*, 2003; *Walsh et al.*, 2003; *Weisberg et al.*, 2004]. We know from glider surveys that the summer of 2010 was also a period of anomalous upwelling [*Weisberg*, 2011; C. Lembke, personal communications, 2010]. Given the importance of the WFS shelf break region for reef fish habitat and spawning [e.g., *Fitzhugh et al.*, 2005], the potential for ecological damage on the WFS seemed palpable throughout the spill, which further justified subsurface tracking and systematic surveys of hydrocarbon fate and effects for the entire region southeast from the head of DeSoto Canyon to the Florida Keys and landward across the shelf. This is especially true of the bottom portion of the water column where landward transport is known to occur [e.g., *Weisberg et al.*, 2004, 2009]. Such surveys for fish effects are now planned (E. Peebles and S. Murawski, personal communication, 2010), and time will tell if any relationship between the WFS fisheries and the *Deepwater Horizon* event are to be found.

Whereas Figures 1–4 do not show virtual particle trajectories extending across the shelf break, we must still hold that out as a possibility for several reasons. First, and foremost, is that we did not have information available to re-initialize the subsurface trajectory forecasts (unlike the surface where data were available, sometimes on a daily basis). Thus, despite qualitative consistency checks using the limited available observations/inferences, we recognize that the trajectory errors are cumulative and potentially quite large [e.g., *Liu and Weisberg*, 2011]. Second, it is known from quantitative comparisons between model simulations and in situ observations that the model which we used tends to underestimate speed [e.g., *He and Weisberg*, 2003; *Weisberg et al.*, 2009]. Being that the trajectories integrate velocity, any systematic bias in velocity will result in a systematic bias in trajectory length. For an anomalous upwelling scenario, as occurred in spring and summer 2010, the upwelling onto, and then across, the shelf was likely underestimated.

As more observations are obtained and reanalyses of the period corresponding to the *Deepwater Horizon* oil spill are performed, we will reassess the trajectories as presented herein. For now, even though the virtual particles appear to have exited the model domain, we cannot rule out the impact that hydrocarbons may have had on the WFS. That additional samples were not collected systematically over a much larger region of the eastern Gulf of Mexico is an error that cannot be corrected. A lesson from the *Deepwater Horizon* event in preparation for any future environmental threat is that fate and effects cannot be fully assessed, nor can a system be restored to some prior state, if that prior state is not adequately described to begin with. For this, we must better observe and understand the workings of the deep Gulf of Mexico and its bounding coastal ocean (continental shelf and estuary) regions if we are to better manage our ocean resources and prepare for any future environmental crisis. We were not very well prepared for the *Deepwater Horizon* event, and until we place more attention toward developing and sustaining coordinated observing and modeling systems for the Gulf of Mexico, we will remain unprepared for future events.

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