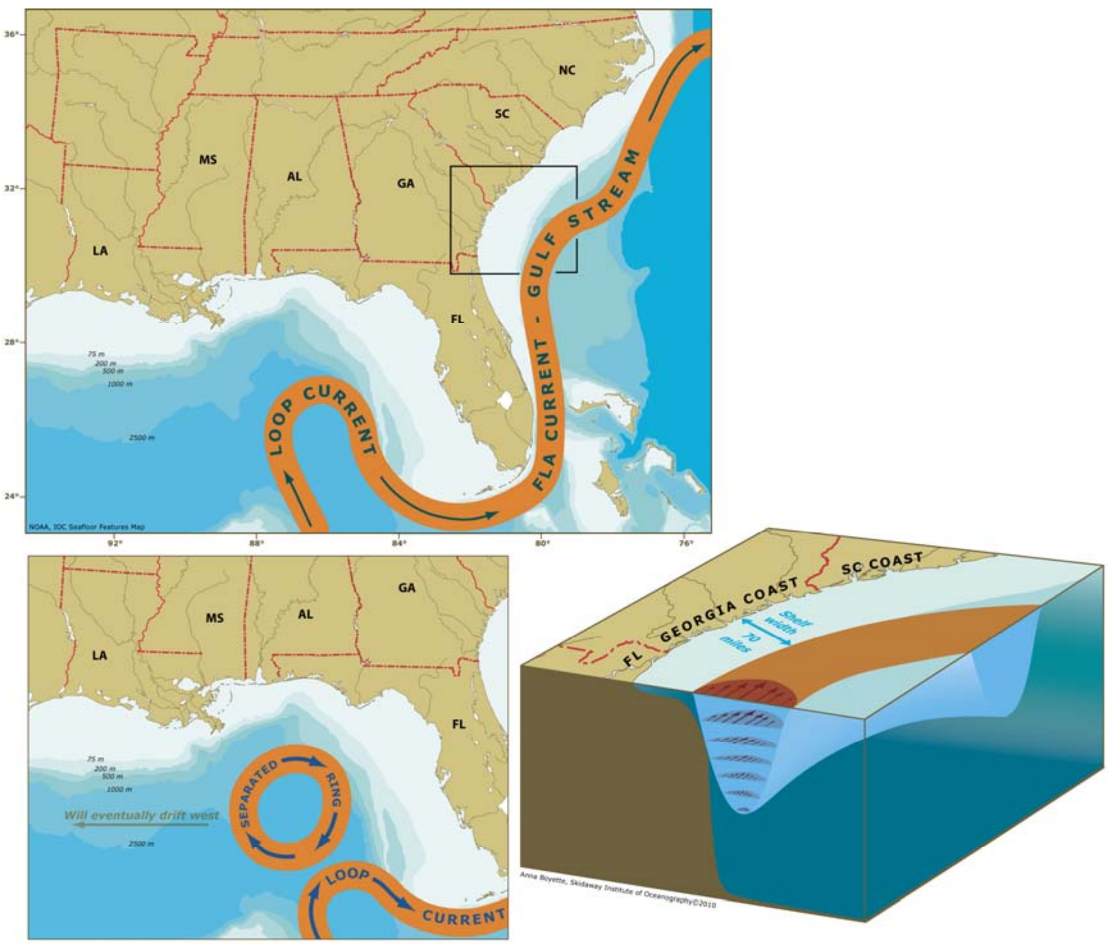
Oil Spill Physical Oceanography Summit

June 9, 2010 - Skidaway Institute of Oceanography, Savannah, Georgia
Organized by: South Atlantic Sea Grant College Programs
Summary by: Georgia Coastal Research Council



Figures from D.K. Savidge, Skidaway Institute of Oceanography

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Background

The Deepwater Horizon drilling platform explosion in the Gulf of Mexico on April 20, 2010 is one of the worst oil spills in U.S. history. It is not yet known how much oil has already been released into the Gulf, nor whether it can be contained. Although there are immediate and acute effects of this disaster in the Gulf of Mexico itself, there is also concern that the oil from this incident will be transported out of the Gulf of Mexico via the Loop Current. The Loop Current is a surface current that moves water in the top 500-800 m (the spill site is at a depth of 1,800 m.) It is a large meander of the Florida Current that extends northward to varying degrees into the Gulf of Mexico and then exits again around the southern tip of Florida. Water from the current then joins the Gulf Stream proper and travels northward along the western boundary of the Atlantic Ocean, potentially affecting the coastal areas of the southeastern U.S. (Fig. 1).

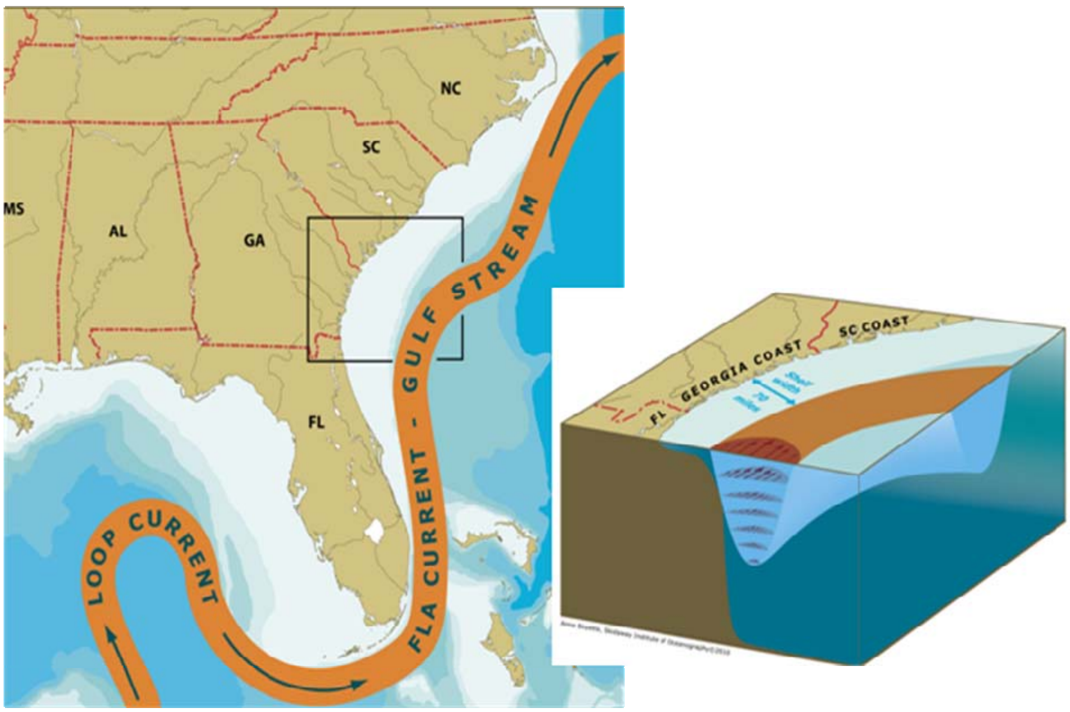

Figure 1: Location of the western boundary current, showing the connection between the Loop Current, the Florida Current (as it is sometimes known), and the Gulf Stream. Inset shows the vertical cross-section of the Gulf Stream along the East Coast. Figure from D.K. Savidge, Skidaway Institute of Oceanography.

The four Sea Grant programs in the South Atlantic region (NC, SC, GA and FL) organized a panel of physical oceanographers to discuss what is known about circulation patterns in the region and the various mechanisms by which contaminated water might be transported to the southeastern coast (see Appendix A for a list of participants). This report summarizes the information that was presented at the meeting. The discussion below is organized into three main sections, which address the following questions: 1) How might oil move from the spill site into the Loop Current? 2) Once oil enters the Loop Current, what factors affect its transport to the

Gulf Stream? and 3) Once oil is in the Gulf Stream, what are the mechanisms by which it might come onshore? At the end of the report is a description of the types of research and observations identified at the meeting that would aid in evaluating these questions.

Question 1: How might oil move from the spill site into the Loop Current?

The oil from the spill is being released into the water from a depth of approximately 1,800 m (Fig. 2). Much of this oil comes up to the surface, where it is subject to surface winds and currents that serve to push it onshore. Surface winds in the Gulf average towards the west, and surface currents run in a clockwise direction (Fig. 3). However, circulation is variable at both annual and seasonal scales, and events such as storms can transport water in pathways that are very different from long-term means. Under average conditions during spring, the surface currents should have pushed the oil west towards Texas. Instead, it is being pushed to Louisiana, Mississippi and northern Florida due to prevailing current and wind conditions.

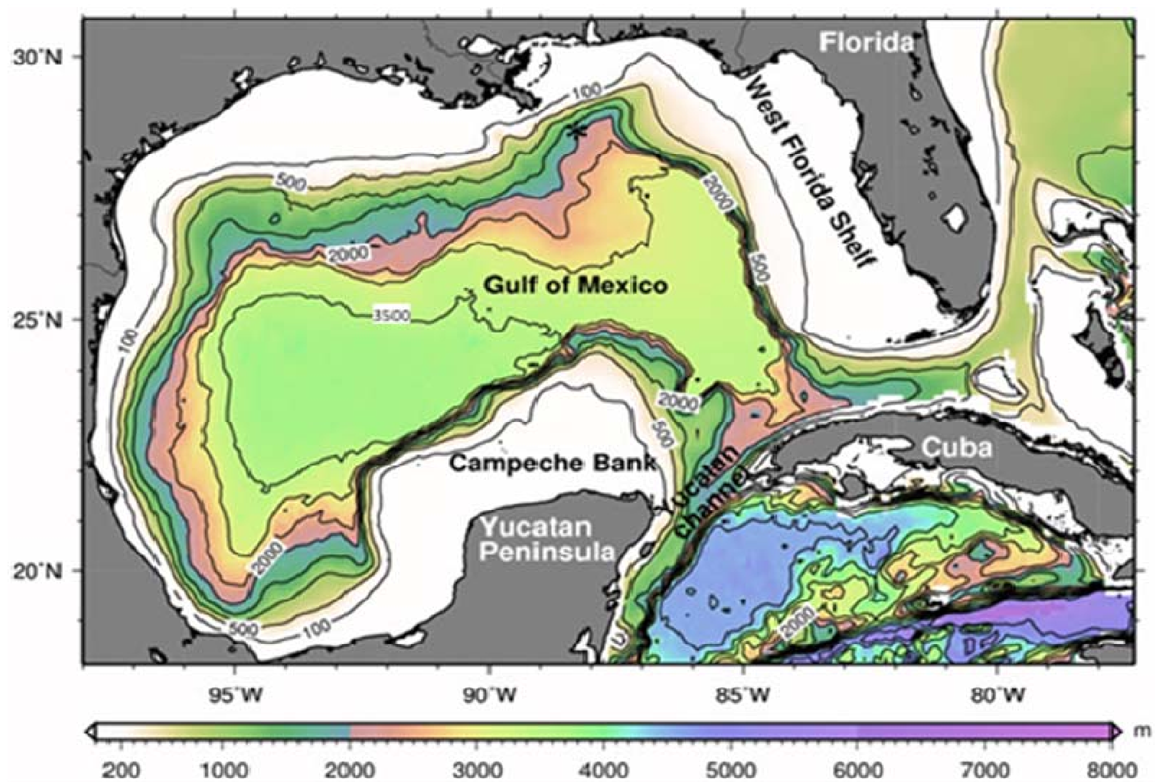

Figure 2: Bottom bathymetry of the Gulf of Mexico. Asterisk shows approximate location of the leaking oil well. Source: University of Miami, http://coastalmodeling.rsmas.miami.edu/Models/View/GULF_OF_MEXICO

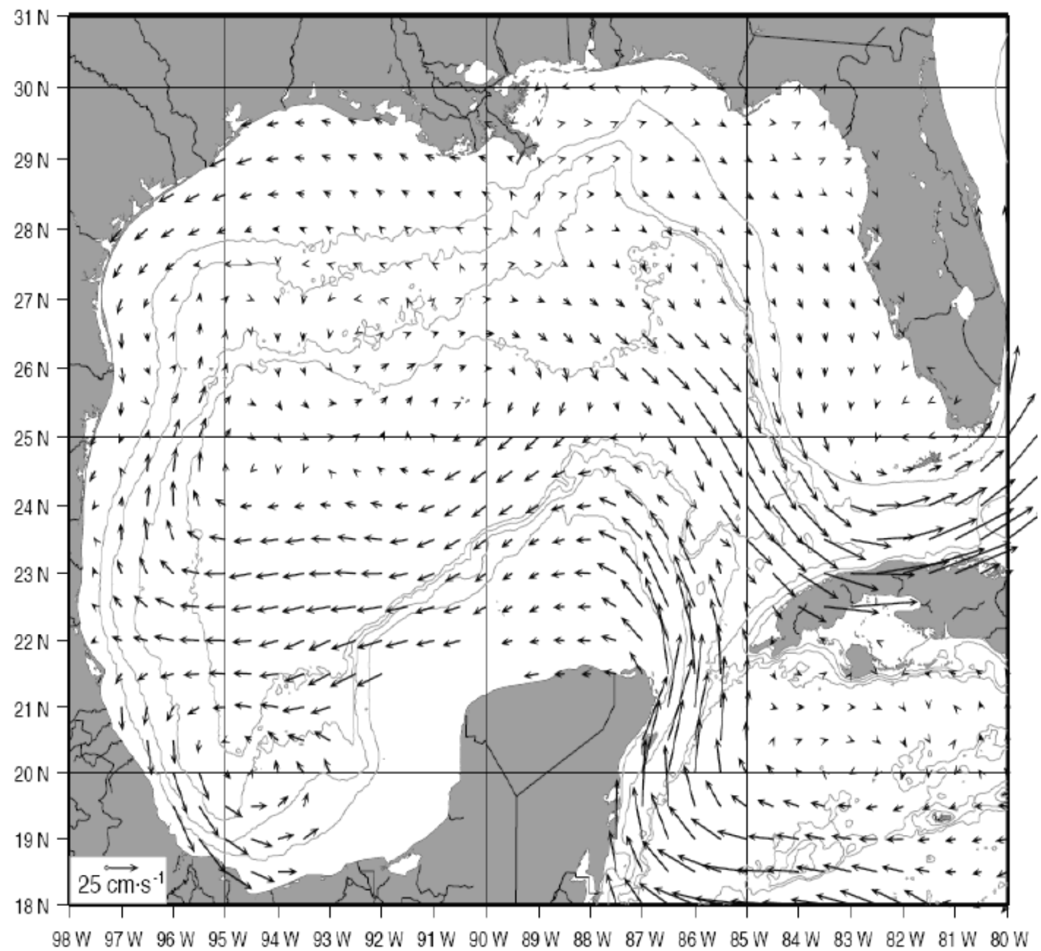

Figure 3: Average surface currents in the Gulf of Mexico. Near surface velocity estimates for each 1.5 x 1.5° bin based on averaging all drifter velocity estimates in that bin for the period 1989-1999. Shown are 200, 1000, 2000, and 3000-m isobaths. Source: DiMarco et al. (2005).

It is not clear how much of the oil that is released from the spill is actually making it to the surface. Some of it could remain in deep water, where it would be subject to deeper circulation patterns. Oil has also been observed in deep water plumes at depths of 1,100 to 1,300 m (S. Joye, pers. comm.). Deep water is effectively isolated from surface waters by steep vertical gradients in temperature and salinity. Exchange across these density gradients is limited. As can be seen by both drifter observations and model simulations (Fig. 4), the mean deep-water circulation runs counterclockwise. Note that the deep water is confined to the central area of the Gulf by the ocean bathymetry south of Florida, so it does not have a direct connection with the Atlantic coast. Although the current patterns mean that deeper water is generally isolated, it can be brought to the surface through upwelling. Upwelling in the Gulf occurs along the edge of the shelf, particularly along the Florida panhandle. Another process by which water can be mixed upward is due to large storms and hurricanes. However, hurricanes do not generally entrain water from more than 100-200 m and so this is not a likely pathway for the deep-water plumes to be brought to the surface. Although there are several other mechanisms by which deep water might be transported to the surface (reviewed below under Question 3), it is likely that most of the contaminated water that is found in deeper layers will remain there until it is transformed by microbial processes.

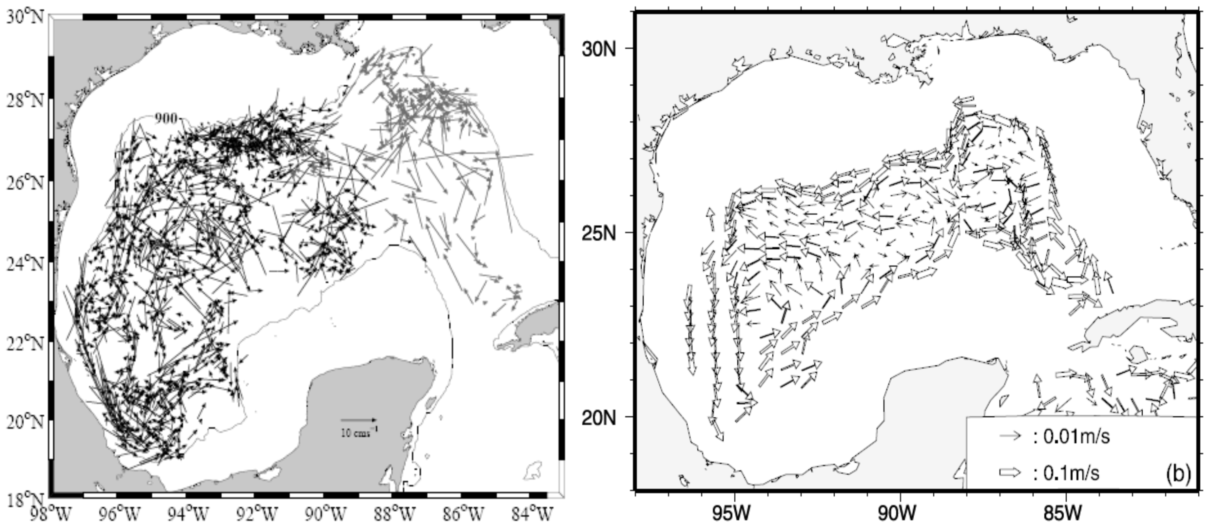

Figure 4. Deep ocean circulation in the Gulf of Mexico. Left: drifter data at 900 db (1,315 m) from Weatherly et al. (2005). Right: Model simulation at 1,500 m from Lee and Mellor (2005).

Some proportion of the contaminated water that reaches the upper portion of the water column (the top few hundred meters), either directly or from the deep water, can enter the Loop Current. However, both the amount of oil that will end up in the Loop Current and the amount of time that it might take for this to occur are difficult to predict. Part of this is due to the fact that the location of the Loop Current is highly variable. At times it reaches north, well into the Gulf, and at other times it is confined to the south, near the Yucatan Strait. Part of the reason for the changes in the location of the Loop Current is due to a process known as Loop Current "eddy shedding" wherein meanders occasionally break off from the main current. Large warm-core eddies are self-contained and circulate in a clockwise direction. When such warm-core eddies form and break off, the Loop Current retreats to the southeastern edge of the Gulf.

From late May through early July 2010, a large eddy has pinched off from the main Loop Current (Fig. 5). This newly formed eddy is serving to partially block mixing of oil into the Loop Current itself, as contaminated water that gets entrained in the eddy is somewhat isolated and therefore has a reduced chance of entering the Loop Current. It is not clear how long the eddy will remain in place, as eddy shedding occurs at various intervals. However, the longer the oil remains in the eddy, the more degraded it becomes and hence the less toxic it would be if the eddy reattached to the Loop Current. Eddies can break off and drift westward, but they can also be reconnected with the Current. In a study that looked at the process of eddy formation over a period of 11 years (1993 to 2004), intervals between eddy formation varied from as little as two weeks to 20 months. Separation intervals cluster near 4.5-7, 11.5 and 17-18.5 months, with an average of approximately 6 months (Leben 2005). The eddy that is now in the Gulf formed in late May 2010 after a separation interval of about 14 months. Although eddies can be readily observed based on sea surface height, quantifying and predicting the processes that cause their formation is a topic of active research.

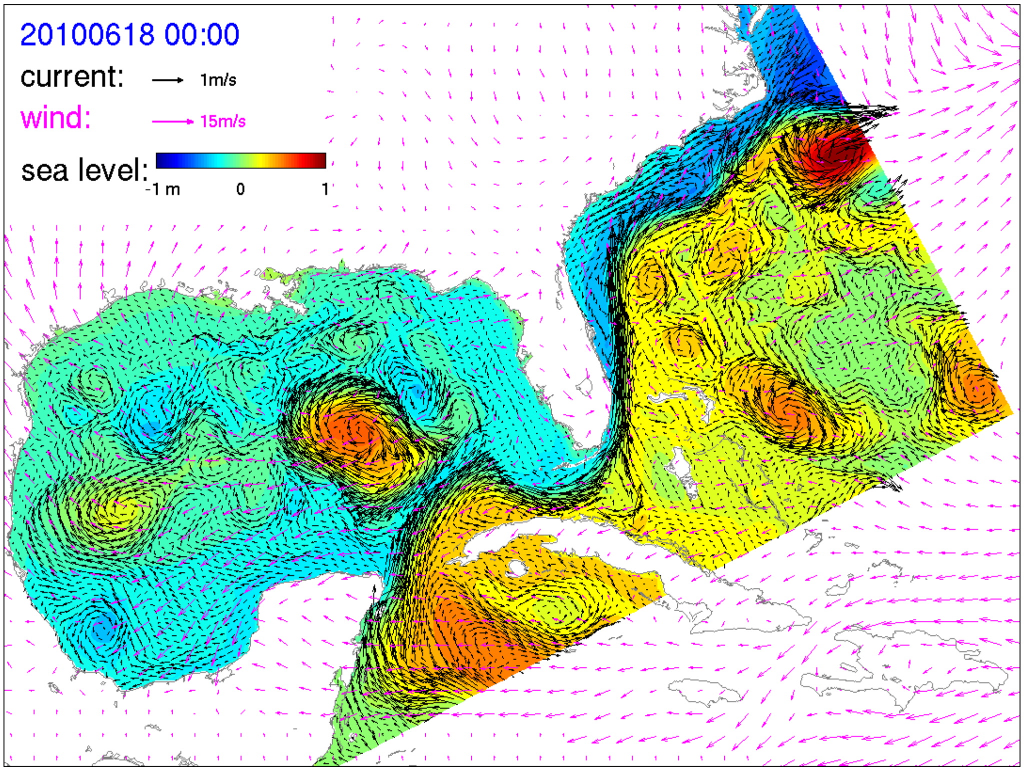

Figure 5. Modeled sea surface height (color shading) in the Gulf of Mexico, June 18, 2010. A loop current eddy can be clearly seen as an elevated feature in the center of the Gulf, separated from the main Loop Current to the south. Source: Ruoying He, North Carolina State University; http://omglnx6.meas.ncsu.edu/sabgom_nfcast/

At present, it is not clear how much of the oil being released from the spill is making it to the surface (either directly or indirectly), nor how much of it is entrained in either the eddy or the Loop Current itself. However, the location of the eddy and timing of its formation should serve to decrease the amount of oil that reaches the Loop Current. It is therefore likely that the majority of the oil is not currently entering the Loop Current. For information on the exact location of the eddy and Loop Current, please see http://polar.ncep.noaa.gov/ofs/viewer.shtml?-gulfmex-cur-0-large-rundate=latest. Near-term forecasts can be found at http://omglnx6.meas.ncsu.edu/sabgom_nfcast/.

Question 2: Once oil enters the Loop Current, what factors affect its transport to the Gulf Stream?

The Loop Current is a surface current that moves water in the top 500 to 800 m (The central Gulf is approximately 4,000 m deep.) The Loop Current itself is fed by the Caribbean Current, and is then connected to the Gulf Stream in a continuous boundary current. Surface water entrained in this current therefore moves from the Caribbean, into the Loop Current, and then via the Florida Straits into the Gulf Stream (Fig. 6). (Note that off the coast of Florida the Gulf Stream is sometimes known as the Florida current.) Once it enters the Gulf Stream the current extends to approximately 1,000 m in depth.

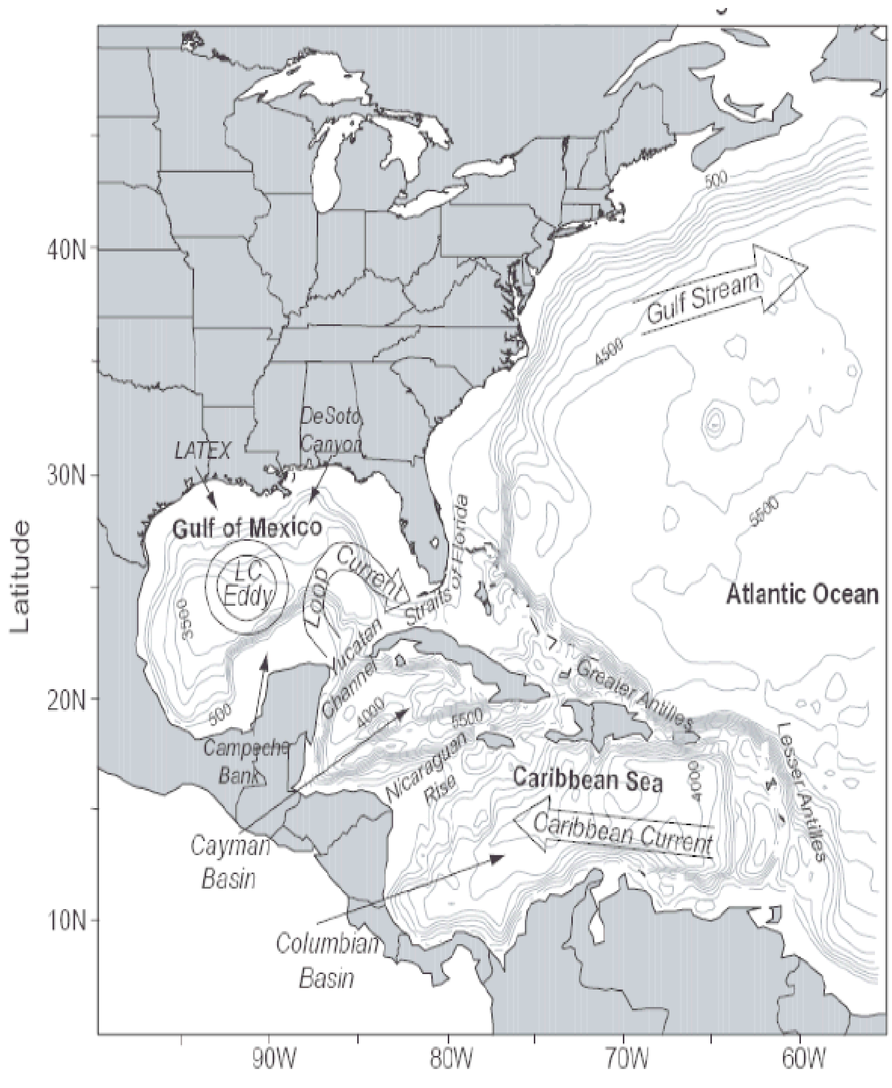

Figure 6. Generalized circulation features showing the Caribbean Current, the Loop Current, and the Gulf Stream. Adapted from Oey et al (2005).

The speed of water within the Loop Current and Gulf Stream varies with its vertical and horizontal position in the current. Water near the surface and toward the middle of the current can travel quite fast – reaching speeds of 200 cm/sec. Water that is deeper or near the edges travels more slowly. A good estimate for the speed of oil if it was entrained in shoreward edges or subsurface parts of the boundary current is approximately 50 cm/sec., which is one mile per hour or approximately half a degree of latitude per day. At this rate, it would take about one week to move from Louisiana to Miami, and another two weeks to get to Cape Hatteras. However, any oil that is transported in this manner will be diluted by first the Loop Current itself and then the deeper Gulf Stream. (Although dilution is likely to be less important once it enters the Gulf Stream.) In addition, the oil may be degraded either through exposure to sunlight or uptake by bacteria, both of which would serve to reduce the concentration during transport, or by other chemical transformations.

Question 3: Once oil is in the Gulf Stream, what are the mechanisms by which it might come onshore?

The Gulf Stream travels up the edge of the continental shelf along the southeastern U.S. coast, before turning to the northeast off Cape Hatteras (Fig. 7). In order for contaminated water to reach the shore, water from the Gulf Stream must cross the continental shelf. There are several points that should be kept in mind when considering the ways in which contaminated water might reach the shore. First, the continental shelf is only 60 m deep whereas the Gulf Stream is transporting water to depths up to 1,000 m. The Gulf Stream itself travels along the outer edge of the continental shelf and does not bodily enter the shallow shelf, although near surface tendrils of the current can move onshore in what are sometimes called “filaments.” Another consideration is that not all areas of the East Coast are equally vulnerable to contamination, as this will vary depending on proximity to the Gulf of Mexico and also the distance the Gulf Stream is from the shore. Because Florida south of Cape Canaveral is both the closest to the Gulf of Mexico and has an extremely narrow continental shelf, it is the area on the East Coast that is most likely to be affected by contaminated water. A second potentially vulnerable area is just south of Cape Hatteras, where the land juts eastward along the Outer Banks of North Carolina, and the continental shelf narrows to about 35 km, down from its maximum width of 125 km off Georgia. However, since North Carolina is further from the Gulf of Mexico the water should have lower oil concentrations by the time it reaches this point due to dilution and degradation. Finally, areas with river discharge have a band of low-salinity water that presents a barrier to mixing from the middle shelf into the regions very nearshore. This provides additional protection to the central portion of the region (off Georgia and South Carolina).

There are several processes by which water from the Gulf Stream can be carried toward shore. These include Gulf Stream effects, wind forcing (including upwelling), tidal effects, bathymetric effects, and fronts formed by the meeting of waters of different origin, each of which is described more fully below. In most cases, a combination of these factors may be at work. It should be noted that these processes are not continuous, which means that they would serve to bring pulses of Gulf Stream water onshore that would be seen as discrete events.

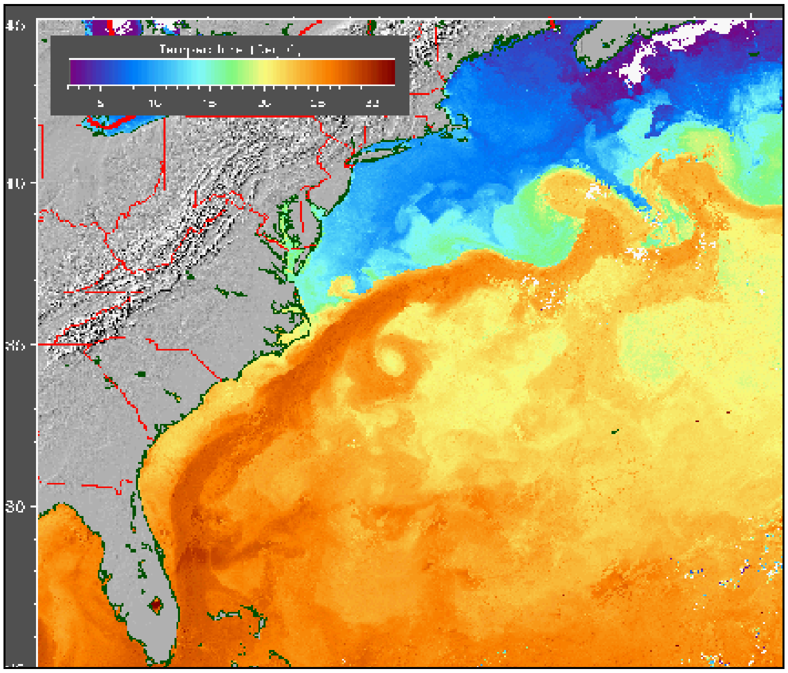

Figure 7. Temperature signal for the Atlantic Ocean, showing the warm Gulf Stream water, which travels northward along the southeastern U.S. and then branches eastward toward Europe. Orange and red represent temperatures between 22-32 °C. Source: Coastal Carolina University, http://kingfish.coastal.edu/gulfstream/p3.htm

The Gulf Stream meanders as it moves northward, moving it closer or further offshore. Gulf Stream meanders can cast near surface waters across the shelf as filaments, and can also upwell deeper water (from several hundred meters) onto the outer shelf. The cold waters upwelled from the Gulf Stream stimulate phytoplankton production, as the deeper water contains high concentrations of nutrients. In summer these subsurface intrusions can extend well across the continental shelf toward the shore, usually due to wind. These meanders are fairly common; a new meander may pass by a given location every several days.

Gulf Stream water can be moved toward the shore by winds. Large storms and hurricanes are probably the most important consideration, as they are known to transport water downwind and inundate low-lying areas through storm surge and increases in nearshore water levels above the predicted tide height. High wind and wave conditions can also set up Langmuir circulation cells, which can potentially transport water across the entire shelf. Steadier, non-storm conditions can also transport water onto the shelf. For example, seasonal changes in typical wind direction can result in net seaward or shoreward motion of water across the shelf, particularly in response to abrupt changes that affect sea level at the coast. It is not clear how the presence of surface slicks of oil would affect these processes.

Wind driven upwelling is another mechanism by which subsurface water from the outer shelf gets to shore. This occurs particularly during summertime when mean winds are upwelling favorable (from the south) and waters are stratified due to solar radiation (warm surface water and cooler bottom water). These conditions can result in two-layer flow across the shelf, with the bottom layer moving onshore and the surface layer moving offshore. However, the degree and intensity of this onshore transport depends on the persistence and intensity of the winds. High winds mix the water column and destroy the two-layer flow. Medium intensity oscillating winds, which occur commonly in the Southeast in response to the passage of meteorological fronts, promote the development of this "cross-shore" flow pattern (e.g., Gutierrez et al. 2006). Recent observations of dissolved oxygen depletion in the nearshore of the Grand Strand area of South Carolina have been linked to onshore transport of shelf water under conditions of high stratification and oscillating wind patterns. In this case, the winds start to induce upwelling and then relax before they have mixed the water column, which would destroy the stratification. Repetition of this pattern helps bring subsurface material to the beach.

Tides are strong along the southeastern U.S. continental shelf, but since the flood and ebb tidal currents average out over time they generally result in little net movement of water across the shelf. Two tidal processes that may result in net shoreward transport are internal tides and tide-correlated eddies along the inshore edge of the Gulf Stream. Internal tides are waves that move deeper water at the same frequency as the tides. They can be detected by evaluating density patterns with subsurface instruments such as gliders. Although internal tides can occur under highly stratified conditions at the shelf edge, they are not thought to propagate very far shoreward in the southeastern U.S. However, this process may be relatively more important off North Carolina where the shelf is narrow. Eddies that form along the inner edge of the Gulf Stream in response to tidal variability on the shelf have been documented with radar off the coast of Georgia. These also transport some material shoreward on the outer shelf, but their importance is the subject of ongoing research. It is also currently unknown whether these shelf edge eddies exist in other areas as radar observations are limited.

Variations in the bathymetry of the shelf also affect water movement. The direction of the surface currents can be affected by bumps and troughs on the bottom, potentially diverting flow towards the shore. The Gulf Stream path is also influenced by variations in shelf and slope bathymetry, so its interactions with the shelf change as it moves alongshore, which thus may contribute to convergence or divergence zones on the shelf. For example, there is a likely convergent region between mean northward flow off Georgia and net southward or near zero mean alongshelf velocity off South Carolina during winter.

An additional mechanism for onshore transport has been established off the coast of Cape Hatteras: in this region cold shelf water from the northeastern U.S. continental shelf meets the warm waters of the southeastern U.S. continental shelf, separated by a strong cross-shelf oriented front known as the Hatteras Front (Churchill and Berger 1998). This front supports strong shoreward velocities from September through April or May that could effectively transport water from the shelf edge to the very nearshore regions over the course of a few days (Savidge 2002). However, the front is relatively ineffective at moving shelf edge waters shoreward in summer.

There is currently not enough information to determine the relative importance of each of the above processes, nor accurately predict when and where they will be active, due primarily to a lack of appropriate observations. Below we provide a list of the types of data that would be required to increase our understanding of these phenomena and therefore be in a better position to predict the potential transport of contaminated water along the East Coast of the United States. (Note also that each of these mechanisms could affect water movement within the Gulf of Mexico as well, so similar considerations might apply.)

Research and Modeling

There are numerous factors that will affect the location and transport of contaminated water that are simply not known at this time. These include information regarding the amount of oil being released from spill; the amount, location, depth and density of the oil that is below the surface; the effects of surface oil on heat flux and wind forcing; and the effects of dispersant on oil characteristics such as density and buoyancy. The rates and pathways by which oil might be degraded are also unclear, which has implications for transport (slicks will move differently than tarballs). The stochastic nature of the events that affect circulation patterns in the Gulf, such as changes in wind patterns and the formation and evolution of loop eddies, also make forecasting difficult. There are, however, several items that were identified at the workshop that would be useful for evaluating the transport of contaminated oil to the East Coast.

Radar – Radar can be used to track the movement of surface water. Because Gulf Stream water is warmer than the surrounding water, satellites can readily see Gulf Stream meanders and other features that move surface water towards shore (e.g., during storms). Radar can be used to actually measure near surface currents in the coastal ocean. When coupled with satellite information on the presences of surface slicks, radar provides a useful tool for understanding the movement of water across the shelf. NOAA is working with the Scripps Institution of Oceanography and the National Data Buoy Center to combine high frequency radar data measured by partners of the Integrated Ocean Observing System, and funded by the Southeast Coastal Ocean Observing Regional Association. At present, this includes three installations off the coast of Georgia and southernmost South Carolina, and an installation at Cape Hatteras (Fig. 8). The University of Miami also operates a high frequency radar system along the northern

Florida Keys and South Florida (not shown). Additional radar coverage in the southeast would be extremely useful both for tracking water movement during the current crisis as well as for future events.

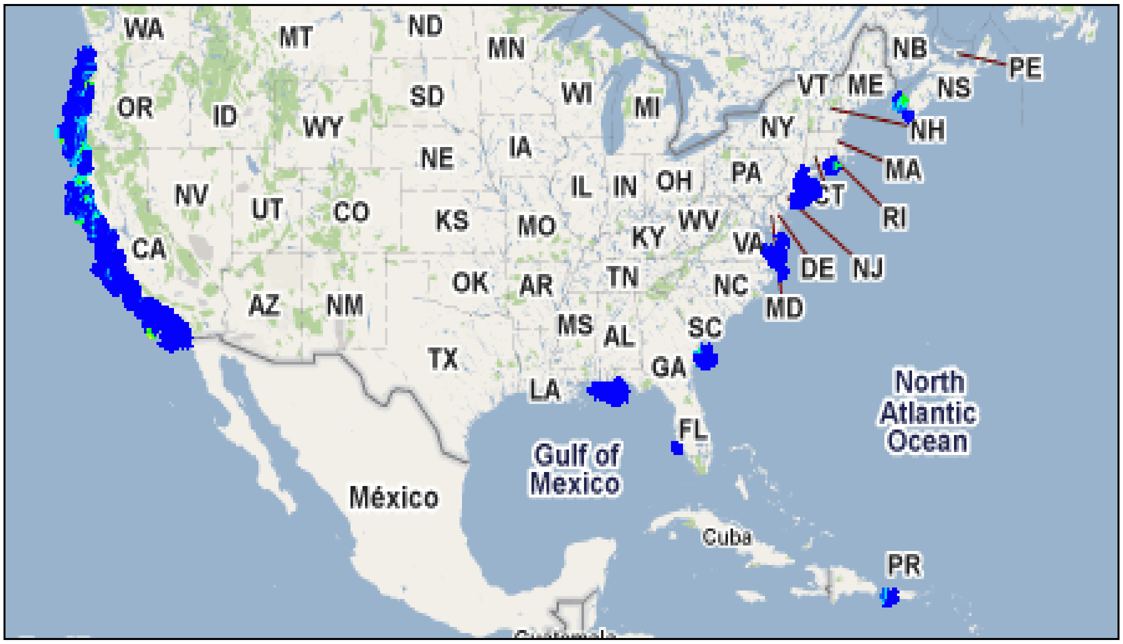

Figure 8. High frequency radar measurements included in the Integrated Ocean Observing System. Source: National Data Buoy Center, NOAA, http://hfradar.ndbc.noaa.gov/

Gliders – Subsurface gliders can collect information at depth. The information collected by gliders would provide the type of density data necessary to initialize circulation models, and could also be used to evaluate internal tides at the shelf edge. Gliders are currently being used in the Gulf of Mexico (see http://rucool.marine.rutgers.edu/deepwater/) and would be useful along the East Coast as well. Gliders additionally armed with colored dissolved organic matter (CDOM) and oxygen sensors could provide information on the presence of contaminated water and whether it is affecting biological activity. A combination of shipboard monitoring and gliders in the Florida Straits could document whether, and at what depth, oil might be present in the Gulf Stream as it rounds the tip of Florida. This is important particularly if a substantial portion of the contaminated water is not visible at the surface.

Flotsam – The wind often carries organisms, such as Sargassum and Man-of-Wars, from the continental shelf onto the shore. A regular observation program might be useful as a proxy for identifying where surface-blown oil might come ashore.

Ships of Opportunity – Standardized protocols and data collection methods could be established for ships of opportunity, particularly where oil is likely to arrive (e.g., Miami and Cape Hatteras).

Modeling – Three-dimensional ocean circulation models can fill the temporal and spatial gaps of observations, and make short-term (up to 72 hr) predictions of ocean sea level, current, temperature and salinity. North Carolina State University's SABGOM ocean circulation nowcast /forecast system (http://omglnx6.meas.ncsu.edu/sabgom_nfcast/) is an example. Such physical models need to be coupled with information on the location, buoyancy and decay properties of oil to understand how contaminated water might be transported; efforts of this type are currently underway at North Carolina State University. There is also a need to integrate in-situ, satellite remote sensing observations with model predictions to be able to develop effective monitoring and prediction tools for tracking oil along the southeastern coast.

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Appendix A: List of Participants

Participating Experts

Catherine Edwards, Assistant Professor, Skidaway Institute of Oceanography, catherine.edwards@skio.usg.edu
Physical oceanography of continental margins, especially at the nearshore boundary and shelfbreak. Currently examining the interaction of winds and currents and the correlation of tides and shelf edge eddies in the South Atlantic Bight. (http://www.skio.usg.edu/people/edwards)

Ruoying He, Associate Professor, North Carolina State University, ruoying_he@ncsu.edu
Coastal and estuarine circulation dynamics; numerical modeling and data assimilation; coastal ocean observing system; bio-physical interactions; air-sea interaction; satellite oceanography. (http://www.meas.ncsu.edu/faculty/he/he.html)

Rick Luettich, Director, Institute of Marine Sciences, University of North Carolina-Chapel Hill, rick_luettich@unc.edu
Research has dealt broadly with modeling and measurement of circulation and transport in coastal waters. Co-developed the ADCIRC circulation and storm surge model that is widely used by the academic, government and private sectors and has been applied extensively for modeling storm surge in the Southern Louisiana and New Orleans areas. Participated in the development of pieces of the SEACOOS component of the national Coastal Ocean Observing System effort. (http://marine.unc.edu/people/Faculty/luettich)

Dana Savidge, Associate Professor, Skidaway Institute of Oceanography, dana.savidge@skio.usg.edu
Observational physical oceanography; dynamics of episodic, seasonal and mean processes accounting for the transport of water and the material it contains through different ocean regimes, from open ocean to shelf settings. Boundary current variability, coastal circulation effects, wind and buoyancy effects at subtidal, tidal and super-tidal temporal scales. (http://www.skio.usg.edu/people/dsavidge/)

George Voulgaris, Professor, University of South Carolina, gvoulgaris@geol.sc.edu
Shoreline evolution; nearshore and beach processes; surf-zone and continental shelf sediment transport; wave - current interaction; sediment re-suspension; hydrodynamic and turbulence measurements in the field and laboratory; time-series analysis; tidal propagation in estuaries and lagoons; numerical model applications to coastal zone. (http://www.geol.sc.edu/gvoulgar/gvoulgaris_cv.html)

Note: Experts invited from Florida were unable to attend because of prior commitment, including commitments made in response to the Deepwater Horizon incident.

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