300173
2014 INTERNATIONAL OIL SPILL CONFERENCE

FROM BLOWOUT TO BEACH: AN INTEGRATED MODELING APPROACH

Piers Chapman[1], Scott Socolofsky[2], Robert Hetland[1]

1. Department of Oceanography, Texas A&M University, College Station, TX 77843
2. Department of Civil Engineering, Texas A&M University, College Station, TX 77843

ABSTRACT 300173:

As part of the response to the BP Deepwater Horizon spill in 2010, we have been funded by the Gulf of Mexico Research Initiative to construct a nested model suite that can follow an oil particle from its first release to its arrival on a shoreline, taking into account natural rates of mixing and degradation of the oil components. The model suite incorporates (at increasing levels of resolution) a coupled ocean-atmosphere model of the full Gulf of Mexico and North Atlantic Ocean, a deep Gulf of Mexico model, a regional model of the Texas-Louisiana shelf, a 3D, non-hydrostatic bay model, a 3D Navier-Stokes model of the spill plume, and a particle tracking and transformation model for dispersed and dissolved oil and gas fate and transport integrated within the full flow domain. The models are supported by a series of laboratory and field experiments, including studies of single droplets, with and without dispersant, plumes, a deep-sea tracer release experiment and bubble releases to simulate an underwater blowout. The laboratory experiments will improve modeling of small-scale, near-field processes such as bubble and droplet formation, dissolution, droplet-turbulence interaction, and evaporation and dispersion at the air-sea interface. We show how the models are linked and how we are making progress towards the complete nested model suite, which will be available for use in future spills.

INTRODUCTION:

The blowout at the BP-operated Deepwater Horizon Rig in April 2010 resulted in 11 deaths, 16 injuries, and the loss of about 700,000 tons of crude oil and 250,000 tons of gas into the Gulf of Mexico (GoM) before it was capped in July (National Commission, 2011). This major incident, the first deep, underwater ocean spill in the history of oil exploration, resulted in the fouling of many miles of coastline between Atchafalaya Bay, LA and Apalachicola, FL, the closure of about 37% of the U.S. Gulf fishery area for several months (NOAA, 2013), and the loss of at least one summer's takings from vacationers in LA, MS, AL and FL. Both federal agencies (mainly the National Science Foundation) and BP quickly made funding available for research, with BP providing $500 million over a 10-year period. These funds are supplied through the U.S. Consortium for Ocean Leadership, which has set up the Gulf of Mexico Research Initiative (GoMRI) to handle research applications and disseminate results (see http://gulfresearchinitiative.org/). BP is not involved in the review of research proposals.

GoMRI made an initial disbursement of $50 million to researchers in the four states most affected by the spill (LA, MS, AL and FL) in summer 2010. In April 2011, GoMRI released a Request for Proposals (RFP) for three-year projects, specifying that researchers should put together consortia to study five possible topics. A final decision to fund eight such consortia was made in August 2011, with one such consortium being the Gulf Integrated Spill Research consortium (GISR), based at Texas A&M University.

GISR includes 21 principle investigators from 11 universities (Table 1). The vision of the consortium is to understand and predict the fundamental behavior of petroleum fluids in the ocean environment, and the aim of the project is to construct a multi-scale nested model suite, varying from molecular to ocean basin scale and validated by field and laboratory experiments, to follow an oil drop from its first release to its arrival on a shoreline, taking into account natural rates of mixing and degradation.

METHODS:

The modeling program is shown in Figure 1, which separates the system into a set of hydrodynamic models and a second set of smaller-scale models that cover oil evolution and degradation within the water column. The base model covering the full domain is a high-resolution coupled ocean-atmosphere model that covers much of the Atlantic Ocean, including the Gulf of Mexico, featuring a high-resolution (down to 3 km) Weather Research and Forecasting (WRF) model for the atmosphere and a 9 km ROMS model of the ocean (Patricola et al. 2011). Nested within the ROMS-WRF model is a 5 km resolution ROMS model of the South Atlantic Bight and GoM (SABGOM), with 36 vertical layers, that assimilates continuous monitoring data from satellites of sea surface height and temperature (Hyun and He 2010). These models provide a comprehensive understanding of meso-scale eddies, tropical cyclones, and the associated air-sea interactions critical to surface and subsurface oil fate and transport in the deep GoM. The next finest scale is covered by a ROMS model of the Texas-Louisiana shelf (Zhang et al., 2012) that capture the interaction of meso-scale Gulf eddies with the continental slope and the complex, energetic currents on the shallower shelf. These processes are critical to transporting suspended hydrocarbons and surface oil slicks from the deep Gulf to the coast. Because there are many shallow bays along the northern GoM coastline, susceptible to several different forcing functions, we include a 3D, non-hydrostatic, unstructured grid, bay model (Fringer et al., 2006) in the suite, that covers hydrodynamic scales down to 50m.

To cover near-field effects (scale of cm-m) close to the blowout site, two additional models are used. One is a three-dimensional hydrodynamic model of the deep oil and gas plume that uses an existing large-eddy simulation solver (HYDRO3D; e.g., Palau-Salvador et al. 2010; Stoesser et al. 2009), nested in a larger hydrodynamic model using the Reynolds Averaged Navier-Stokes (RANS) approach. The LES-RANS model serves as a computational laboratory for full-scale simulation of the spill plume in a density-stratified, turbulent crossflow, which is extremely difficult to simulate at reduced scale in the laboratory. A second model, based on the Stratified Integral Multiphase Plume (SIMP) model developed for direct ocean carbon sequestration (e.g., Socolofsky et al. 2008), can predict intrusion formation by density stratification and is being extended to include oil chemistry (Socolofsky et al., 2011). Finally, once the oil and dissolved gas leave the strongly non-hydrostatic, upward-rising plume, whether in a deep intrusion layer or the upper water column, the far-field fate and transport is accomplished using the Lagrangian particle tracking (LTRANS) model (e.g., North et al., 2011). LTRANS predicts the behavior of both discrete particles and dissolved constituents, and includes degradation rates. Oil reaching the surface is treated in LTRANS using the algorithms in the General NOAA Operational Modeling Environment (GNOME) model.

Experimental work has concentrated largely on areas of uncertainty in the models, including bubble and droplet formation with and without dispersant application, dissolution, droplet-turbulence interaction, and evaporation and aerosol formation (see later). Field work included a tracer release experiment to measure vertical and horizontal dispersion (see Ledwell et al., 1998 for details of a previous experiment), as well as moorings, hydrography, and chemical measurements for oil, dissolved gases, and oil degradation products.

RESULTS/DISCUSSION:

Modeling:

The goal of the GISR modeling effort is to link different models at different resolutions and domain sizes such that oil may be tracked from the wellhead to the beach or bay within an integrated modeling system. During the Deepwater Horizon incident, a number of models were used to track the surface slick, including GOM-HYCOM (NRL), SABGOM (NC State), TABS (TAMU), and WFS (USF). However, these models did not interact, or pass information between them, and they also all covered similar spatial scales, with a similar numerical resolution. Oil entering Barataria Bay, for example, was not well resolved by any model, which led to questions about whether to open the Davis Pond freshwater diversion to prevent oiling within the bay. Subsequent analysis (Bianchi et al, 2011) showed that the diversion did indeed prevent oil from entering the half of the bay that it influenced . Thus, there was a demonstrated need to have a series of models that can resolve processes that occur at Gulf-wide, shelf, and bay scales, and the goal of the GISR modeling effort is to develop and test such a system so that in the event of future spills, the methodology for running a series of coupled models is clear.

There was an opportunity to study a potential spill at the Hercules 265 blowout on July 23, 2013. This blowout did not release a significant amount of hydrocarbons into the environment, but nevertheless early efforts to track any potential spills highlighted the weaknesses of modern modeling and observational efforts for this purpose. SABGOM (He, NC State) predicted a southward track, CRCM (Chang, TAMU) predicted a westward track, and TXLA (Hetland, TAMU) predicted an eastward track. Surface drifters, released four days after the spill event generally followed a southward path, and two current meters at the Flower Garden national reserve located at the southern edge of the Louisiana shelf (about 200 km west of the blowout, separated from each other by about 50 km) show a rotating diurnal current structure, and little correlation in the flow between the two observation sites. The Hercules 265 incident highlights the importance of using an array of models, and using data assimilation where possible. However, it is not clear how much data assimilation could have improved the skill of the models, as very few data were available at the site, and temporal and spatial decorrelation scales are very small along the edge of the shelf, where the blowout occurred.

Experiments in coupling models show that, as expected, higher resolution models give different answers in critical regions. For example, Figure 2 shows an example where numerical surface drifters are passed to a child one-way nested Galveston Bay model. These tracks are then compared to those predicted by the parent model. Retention of particles is much higher in the nested child model, as compared to the lower-resolution parent model. Also, there are many more particles in the child model that make it into West Bay, the region of Galveston Bay behind Galveston Island. Thus, in terms of predicting oil spills these two models give very different answers. It is clear that, in the absence of other information or observations, the higher-resolution model is preferable to the coarse shelf model in this region.

A second example is of particles released at the Deepwater Horizon site, shown in figure 3. In this case, the particles are released into the shelf model at the very edge of the domain. Particles are allowed to cross between the shelf domain (TXLA, Hetland, TAMU) and whole-gulf domain (SABGOM, He, NC State). The interesting thing about this study is that while both models assimilate information about the Loop Current, they are not directly coupled. This demonstrates that particles can be tracked across different models, even when these models were not designed to be used together, offering more flexibility to any system used to respond to a future spill, and suggesting that all available models from many different sources may be used in the spill response.

Field work:

The main component of the field work was a tracer release experiment, carried out in the Gulf of Mexico between July 2012 and August 2013 (Ledwell, Woods Hole Oceanographic Institute). 17 kg of the tracer, trifluoromethyl sulfur pentafluoride (CF_3SF_5), were released in a series of streaks on 28 July 2012 at about 1100m depth near 28° 20’N, 88° 50’W, along the density surface 32.254 $kg.m^{-3}$. The depth of this density surface varied between 1090 and 1180 m over the injection track, and the experiment was designed to mimic the deep plume of dissolved oil and small oil droplets predicted and measured following the rig blowout (Camilli et al., 2010; Socolofsky et al., 2011). Sampling around the streaks within two weeks of the tracer release showed that it was mainly within about 30m of the selected density surface. Two additional cruises to determine the horizontal and vertical distribution of the tracer were carried out in November-December 2012 and July-August 2013 (Fig. 4). Immediately prior to the release, a series of six current meter moorings were deployed around the release site to provide data on the local flow field (DiMarco and Guinasso, TAMU), while numerous samples were taken to provide information on the background field of dissolved oil in the waters of the deep Gulf of Mexico (Wade (TAMU). The experiment has provided new information on mixing rates within the deep Gulf of Mexico that will be used to constrain the models.

Initial movement of the tracer was to the southwest along the continental slope, as reported for the subsurface oil plume (Ledwell et al, in prep.). After four months, the tracer had reached 92°W, and several slugs appeared to have moved south, under the influence of the anticyclonic rings in the western Gulf (we believe that some of the tracer entered the Mexican sector of the Gulf, but did not have clearance to sample in that region). The 2013 cruise confirmed the continuing westward and southward movement, including flow into Mexican waters (Fig. 4) south of 26°N. However, some of the tracer had also moved eastwards along the slope into De Soto Canyon and southeast into the region of the Loop Current by this time, showing the additional mixing that had taken place during the intervening eight months. During both cruises it was apparent that the tracer, although initially a coherent mass, had been transformed into a series of patches and filaments with greatly differing concentrations. This is similar to previous experiments (e.g., Ledwell et al., 1993), where horizontal advection in the

North Atlantic was primarily in one direction. In the Gulf of Mexico the flow pattern is strongly affected by the intense local eddy field, as shown by the superimposition of the sea surface height anomaly on the tracer distribution in Fig. 4. Spatial covariance after four months in the Gulf was very similar to that found in the North Atlantic after 12 months, showing that horizontal mixing is more intense in the Gulf.

The vertical distribution of the tracer also changed over the course of the experiment. Initially a roughly 30m thick layer, by December 2012 the thickness had increased to about 350m, and several stations showed multiple tracer layers. The maximum vertical distribution (<450m) was seen in tracer samples taken along the shelf, where vertical mixing is known to be stronger than in the ocean interior. Interior samples generally showed spreading of only about 150m (Fig. 5). Similar multiple layers are known from previous experiments of this sort.

Additional fieldwork associated with the tracer and mooring cruises included sampling for background oil concentrations and “standard” hydrographic components. Sampling for inorganic and organic carbon was of particular interest because of the need to try to determine where oil released during the spill ended up. Methane and oxygen measurements taken after the spill suggest that essentially all the methane remained dissolved in the water column, rather than escaping to the atmosphere, and that the local bacterial population could have respired about 60% of the total amount of oil and gas released during the spill (Du and Kessler, 2012). Whether this was respired completely to carbon dioxide, converted into intermediate products, or incorporated into biomass for later release is unknown.

Laboratory studies:

The program includes a number of lab studies of droplet-scale processes. These include evaporation and surface aerosol production and droplet-turbulence interaction (Goldstein and Variano, U.C. Berkeley; e.g., Variano and Cowen, 2013), dissolution with and without dispersants (Masutani, U. Hawaii), turbulence properties of buoyant plumes and the effects of crossflow and stratification (Socolofsky, TAMU), and the intrusion of liquid oil into subsurface layers (Adams, MIT). The aim of these experiments is to define a model of the fate of bubbles and oil droplets that includes the full non-ideal equations of state and comprehensive particle dynamics and mass transfer. These experiments link to the overall program by providing parameterizations of processes at scales below those of the nested models, and a number of papers describing the results are currently in various stages of preparation.

The life and motion of small oil droplets (100 nm - 1 mm) suspended in an aqueous medium depends on their initial concentration and the rate at which this changes through dissolution, degradation, or coalescence. Variano is monitoring the motion of individual droplets in 3-D, including their interactions with “marine snow” to determine how they are affected by natural organic material in the water column and to investigate their behavior near the air-water interface. Once oil hits the surface, evaporation becomes important. Most surface slicks of crude oils lose a significant percentage (20-50%) of their mass through evaporation within 48-72 hours (NRC, 2005) and the Macondo release was no exception; the official figure was that about 25% of the total amount of oil released during the spill evaporated or dissolved, with another 24% being dispersed into the water column (National Commission, 2011). Evaporation and subsequent aerosol formation is being studied by Goldstein with novel GC-MS procedures

(Isaacman et al., 2012) that use soft UV synchrotron radiation to split the organic compounds into their integral components. The methodology allows researchers to split oil components by carbon number, degree of branching, degree of unsaturation, and the number of rings.

The Macondo spill was the first spill to occur at a depth of more than 1,000m in the ocean. It was also the first spill where direct injection of dispersants into the plume was used. While dispersants have been used for many years to disperse surface oil slicks, their behavior at depth was unknown and even it is still not clear whether they were effective during the Macondo spill given the large shear effect of the gas dissolved in the oil plume, although droplet size analysis suggests they did reduce mean drop size (Curtis Cooper, Chevron, pers. comm.). Masutani's experiments on dissolution and breakup of individual oil droplets aim to predict the effects of dispersant on water column transformations. The work involves using a downward-flowing stream of water to counteract the oil drop's buoyancy (Fig. 6), so that the oil drop is held stationary in the flow and its evolution can be followed on video. These experiments at constant pressure (atmospheric) but potentially varying temperature, allow single or multiple droplets to be studied, and dispersants can be mixed into the system. Dissolved hydrocarbon concentrations can also be followed after solid-phase extraction and GC/MS analysis.

Individual droplets appeared to outgas and form droplet-bubble couples, but mm size droplets remained coherent over long periods (>20 hours) with no obvious change in size or composition when no dispersant was used. When dispersant (Corexit 9527) was added at ratios between 1:50 and 1:1000, however, Oseberg oil (similar to Macondo oil) droplets disintegrated rapidly by shedding and tearing so that ~3mm size droplets were no longer observable after about 30 minutes. GC/MS data indicated enhanced dissolution of oil components in such cases. Increasing water temperature from 25°C to 50°C suggested that dispersant effectiveness may decrease considerably at the higher temperature.

Although the model of Socolofsky et al. (2011) agrees well with the observations made following the Macondo spill as regards predicting the height above the bottom of a number of intrusion layers (Spier et al., 2013), the model does not account for everything observed. It is not clear how cross-flow or stratification affect the entrainment of oil and gas into plumes, and we are therefore working to provide validation data and a new modeling paradigm that will predict better how such plumes evolve.

For an underwater blowout, the behavior of the plume depends on the Froude number

$$Fr_d = \frac{u_\infty}{\sqrt{g'H}}$$

where u is the velocity of the water into which the plume extends. If Fr_d is < 0.8, the plume exhibits subcritical behavior and multiple, distinct subsurface intrusions are formed. Such plumes are stratification dominated. For values of $Fr_d > 0.8$, however, the behavior is supercritical and only one plume forms (cross-flow dominated). During the Deepwater Horizon blowout u was about 0.3 $m.s^{-1}$, and the plume remained in the subcritical, stratification dominated zone, with layers observed at about 1100-1200m, 850m, and about 210-250m (Spier et al., 2013).

In a mixed plume, containing both fluid and gas, the rise rates of the two components depend on the difference in buoyancy between them. Figure 7 shows a tank experiment with cross-flow; there is simultaneous injection of a bubble plume and a dye, the dye representing a plume of oil droplets, and the origin of the plumes is being towed across the plane of the figure from left to right. The flow lines are the predicted paths of the flow of the dye, and the agreement with theory is excellent. The break in flow corresponding to the bubble plume is also in good agreement with theory. Ongoing experiments are aimed at elucidating and modeling the structure of the plume in stratified and cross-flow conditions.

Another way to examine how oil enters (and leaves) subsurface plumes is to look at the problem from upside down, using glass beads of diameter < 1mm falling into a tank (Adams, MIT). Beads with these small diameters (0.0064-0.072 cm) behave in an analogous manner to oil droplets rising, producing different plumes depending on the velocity of the cross-flow U_N.

CONCLUSIONS:

While much is known about the behavior of oil in the sea after over 40 years of research following the Torrey Canyon spill off the English coast in 1967, the Deepwater Horizon blowout in 2010 made us realize how much remains unknown. Our experimental and modeling work on crucial aspects of oil behavior, with and without dispersants, is helping to fill some of these gaps. As the GoMRI program continues, we can expect more results and a better understanding of how oil behaves when it is released at sea. We anticipate that the modeling suite described here will be of use to managers and responders in future spills, whether in the Gulf of Mexico or elsewhere.

ACKNOWLEDGEMENTS:

This research was made possible by a grant from BP/The Gulf of Mexico Research Initiative.

Table 1. GISR principal investigators and institutions

Name	Institution	Research interest
Piers Chapman	Texas A&M University	Program Director, chemistry
Ping Chang		Large-scale ocean modeling
Steven DiMarco		Hydrography and moorings
Norman Guinasso		Hydrography and moorings
Robert Hetland		ROMS modeling
Matthew Howard		Data management
Scott Socolofsky		Near-field plume modeling
Istvan Szunyogh		Large-scale ocean modeling
Terry Wade		Hydrocarbon measurements
Shari Yvon-Lewis		Carbon cycling
Thorsten Stoesser	Cardiff University, U.K.	LES modeling
Eric Adams	Massachusetts Inst. of Technology	Oil intrusions
Ruoying He	North Carolina State University	ROMS modeling
Oliver Fringer	Stanford University	Coupled bay-shelf models
Allan Goldstein	University of California, Berkeley	Aerosol formation
Evan Variano		Droplet-turbulence effects
Thomas Bianchi	University of Florida	Carbon cycling
Stephen Masutani	University of Hawaii	Droplet dissolution
Elizabeth North	University of Maryland	Oil transformation models
John Kessler	University of Rochester	Methane degradation
Ben Hodges	University of Texas	Coupled bay-shelf models
Jim Ledwell	Woods Hole Oceanographic Inst.	Tracer release experiment

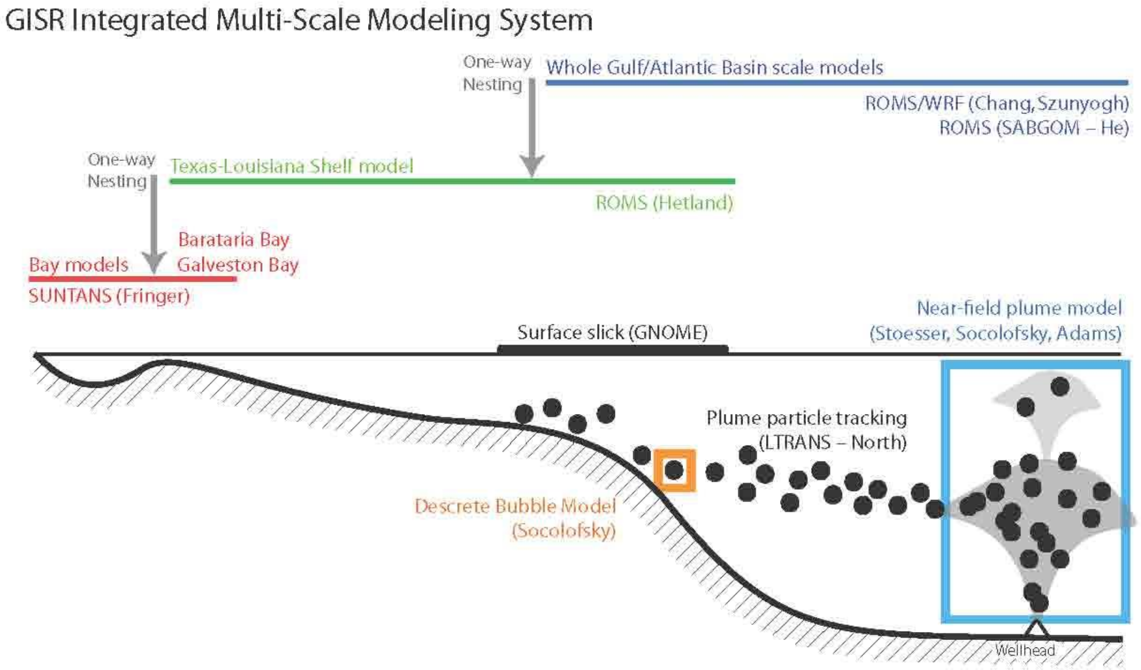

Fig. 1. Model suite used in the program. Researchers associated with each model are shown

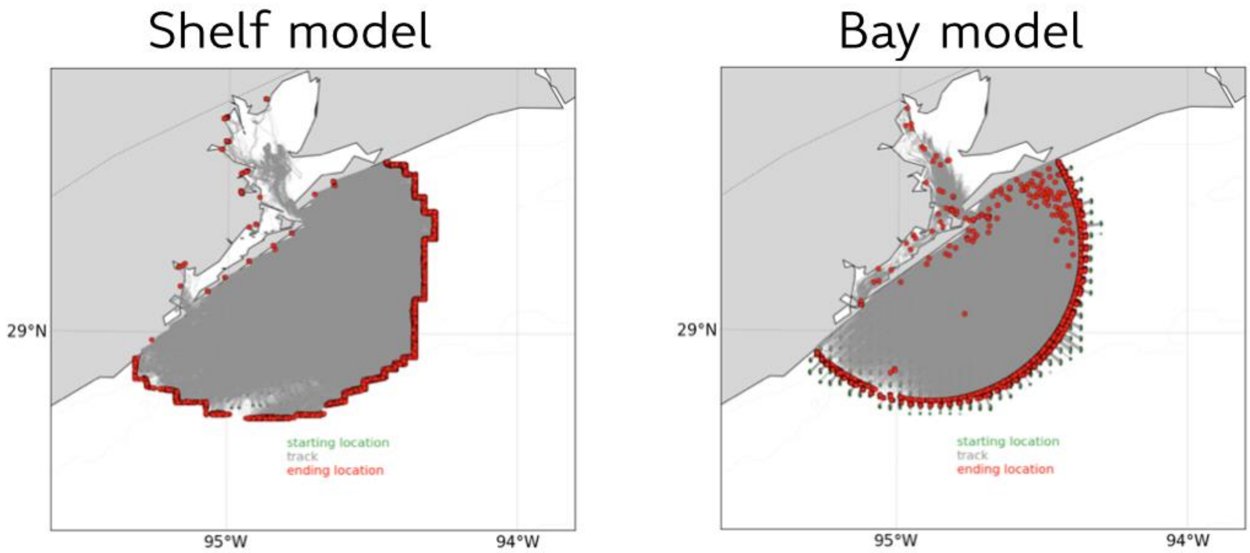

Fig. 2. Comparison of shelf and bay models. Particles were released along the boundary in both runs. Note how many more particles enter the bay in the bay model.

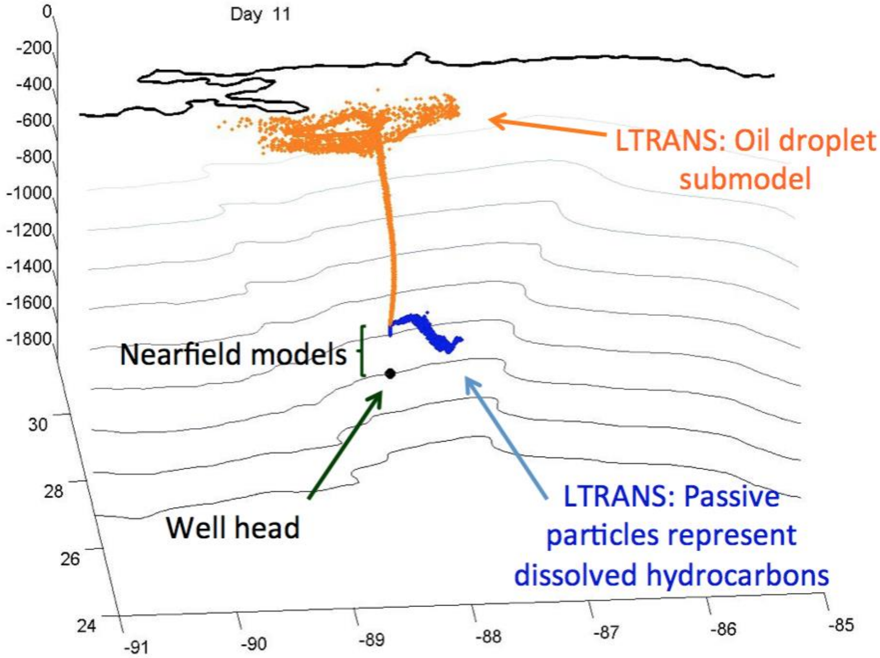

Fig. 3. Particle tracking within LTRANS. This model is coupled with the shelf and whole Gulf models so that advection is followed. (Figure courtesy of E. North.). The vertical axis shows water depth, the horizontal axes show latitude and longitude.

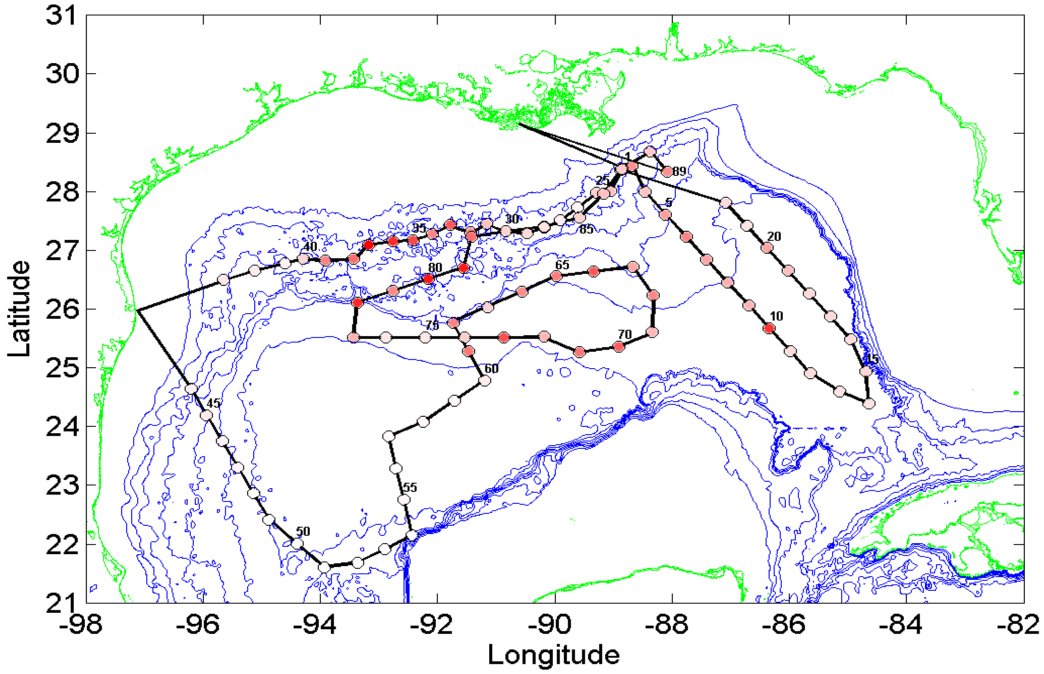

Fig 4. Distribution of the tracer CF_3SF_5 one year after release in the Gulf of Mexico, superimposed on sea surface height. The intensity of the color denotes the concentration of tracer found. (Figure courtesy of J. Ledwell.)

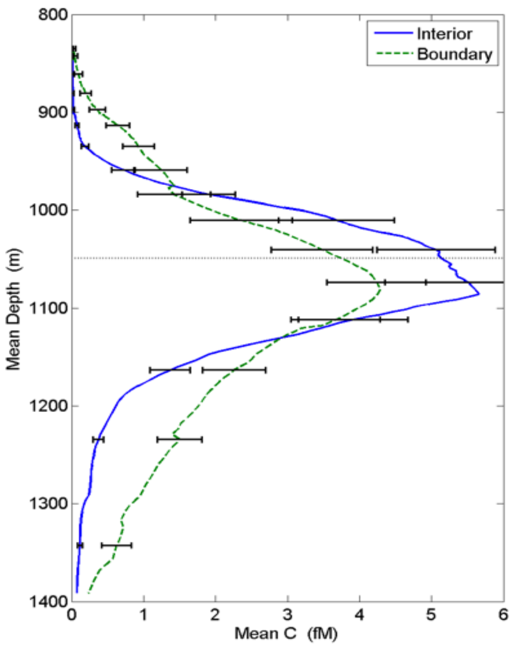

Fig 5. Vertical spreading of the tracer CF_3SF_5 four months after release. (Figure courtesy of J. Ledwell).

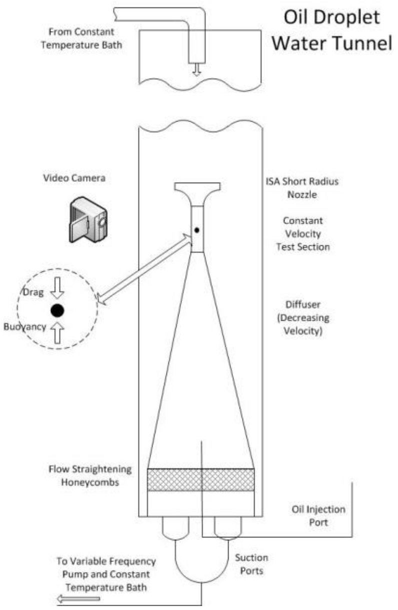

Fig 6. Countercurrent apparatus for studying single oil drops with and without dispersant (courtesy of S. Masutani)

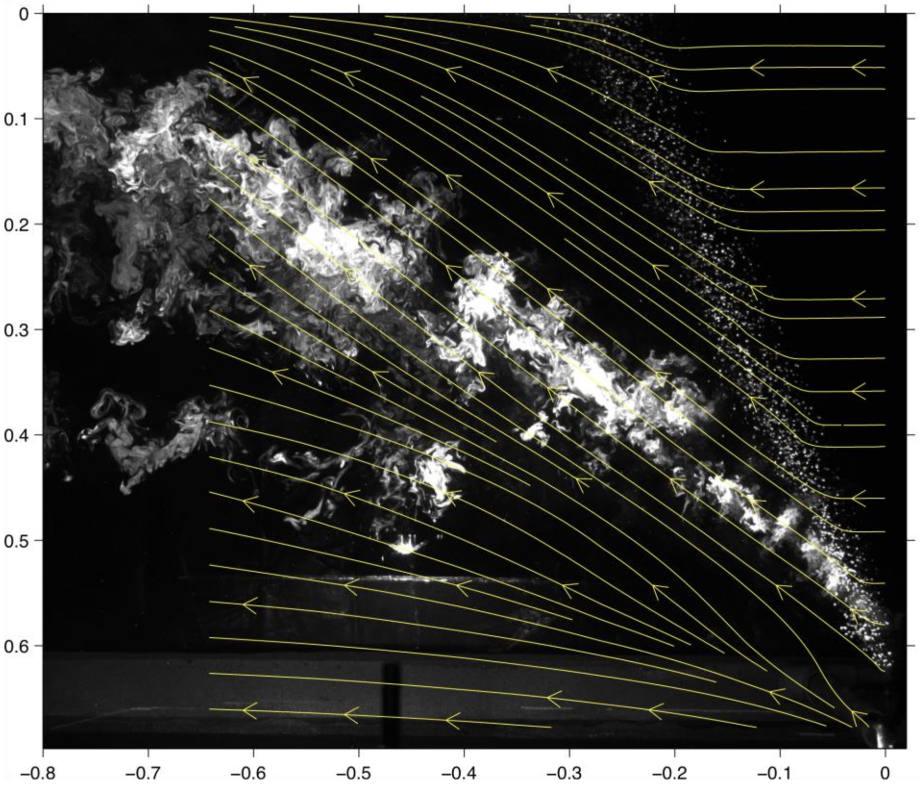

Fig 7. Bubble and dye plume under cross-flow conditions. Streamlines indicate predicted path of the dye. Note the break in the streamlines associated with the rising bubble plume. Dimensions are in meters.

REFERENCES:

Camilli, R., Reddy, C.M., Yoerger, D.R., Van Mooy, B.A.S., Jakuba, M.V., Kinsey, J.C., McIntyre, C.P., Sylva, S.P. and J.V. Maloney, 2010. Tracking hydrocarbon plume transport and biodegradation at Deepwater Horizon. *Science*, 330, 201-204.

Du, M. and Kessler, J.D., 2012. Assessment of the spatial and temporal variability of bulk hydrocarbon respiration following the Deepewater Horizon oil spill. *Environmental Science and Technology,* dx.doi.org/10.1021/es301363k.

Fringer, O. B., Gerritsen, M., and Street, R. L. (2006). An unstructured-grid, finite-volume, nonhydrostatic, parallel coastal ocean simulator. *Ocean Modeling*, 14(3-4), 139-173.

Hyun, K. H., and He, R. (2010). Coastal upwelling in the South Atlantic Bight: A revisit of the 2003 cold event using long term observations and model hindcast solutions. *J Marine Syst*, 83, 1-13.

Isaacman, G., K.R. Wilson, A.W.H. Chan, D.R. Worton, J.R. Kimmel, T. Nah, T. Hohaus, M. Gonin, J.H. Kroll, D.R. Worsnop, and A.H. Goldstein, (2012). Improved Resolution of Hydrocarbon Structures and Constitutional Isomers in Complex Mixtures Using Gas Chromatography-Vacuum Ultraviolet-Mass Spectrometry, *Analytical Chem*istry, 84, 2335-2342.

Ledwell, J.R., Watson, A.J. and Law, C.S. (1993).Evidence for slow mixing across the pycnocline from an open-ocean tracer-release experiment. Nature, 364, 701-703.

Ledwell, J. R., Watson, A. J., and Law, C. S. (1998). Mixing of a tracer in the pycnocline. *Journal of Geophysical Research-Oceans*, 103(C10), 21499-21529.

National Commission. 2011. Deep Water: The Gulf oil disaster and the future of offshore drilling. Report to the President, National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, 391 pp. *www.gpo.gov/fdsys/pkg/GPO-**OIL**COMMISSION/content-detail.html*

NOAA. 2013. Deepwater Horizon/BP Oil Spill: Size and Percent Coverage of Fishing Area Closures Due to BP Oil Spill. **http://sero.nmfs.noaa.gov/deepwater_horizon/size_percent_closure/index.html** (accessed 11.07.2013).

North, E. W., Adams, E. E., Schlag, Z., Sherwood, C. R., He, R., and Socolofsky, S. A. (2011). Simulating oil droplet dispersal from the Deepwater Horizon spill with a Lagrangian approach. In: *Monitoring and Modeling the Deepwater Horizon Oil Spill: A Record-Breaking Enterprise*, Y. Liu, ed., American Geophysical Union.

NRC (2005). *Oil Spill Dispersants: Efficacy and Effects.* National Academies Press, Washington, D.C., 377 pp.

Palau-Salvador, G., Stoesser, T., Frohlich, J., Kappler, M., and Rodi, W. (2010). Large Eddy Simulations and Experiments of Flow Around Finite-Height Cylinders. *Flow Turbul. Combust.*, 84(2), 239-275.

Patricola, C. M., Chang, P., Saravanan, R., Li, M., and Hsieh, J.-S. (2011). An investigation of the Tropical Atlantic bias problem using a high-resolution coupled regional climate model. *U.S. CLIVAR Variations*, 9(2), 12 pp.

Socolofsky, S. A., Bhaumik, T., and Seol, D. G. (2008). Double-plume integral models for near-field mixing in multiphase plumes. *Journal of Hydraulic Engineering-ASCE*, 134(6), 772-783.

Socolofsky, S. A., Adams, E. E., and Sherwood, C. R. (2011). Formation dynamics of subsurface hydrocarbon intrusions following the Deepwater Horizon blowout. *Geophysical Research Letters* 38, L09602, doi:10.1029/2011GL047174.

Spier, C., Strinfellow, W.T., Hazen, T.C. and M. Conrad (2013). Distribution of hydrocarbons released during the 2010 MC252 oil spill in deep offshore waters.

Stoesser, T., Salvador, G. P., Rodi, W., and Diplas, P. (2009). Large Eddy Simulation of Turbulent Flow Through Submerged Vegetation. *Transp. Porous Media*, 73, 347-365.

Variano, E.A., and Cowen, E.A. (2013). Turbulent Transport of a High-Schmidt-Number Scalar

Near an Air-Water Interface. *Journal of Fluid Mechanics*, in press.

Zhang, X., Marta-Almeida, M, and Hetland R.D. (2012). A high-resolution pre-operational forecast model of circulation on the Texas-Louisiana continental shelf and slope. *Journal of Operational Oceanography*, 5, 19-34.