2014

Research overview of the consortium for advanced research on transport of hydrocarbon in the environment (CARTHE)

Ozgokmen, Tamay M.; Beron-Vera, Francisco J.; Bogucki, Darek; Chen, Shuyi S.; Dawson, Clint; Dewar, William; Griffa, Annalisa; Haus, Brian K.; Haza, Angelique C.; Huntley, Helga...

IOSC

Özgökmen, Tamay M., et al. "Research overview of the consortium for advanced research on transport of hydrocarbon in the environment (CARTHE)." International Oil Spill Conference Proceedings. Vol. 2014. No. 1. American Petroleum Institute, 2014.
http://hdl.handle.net/10945/65772

300194

Research Overview of the Consortium for Advanced Research on Transport of Hydrocarbon in the Environment (CARTHE)

Tamay M. Özgökmen(1), Francisco J. Beron-Vera(1), Darek Bogucki(2 , Shuyi S. Chen(1), Clint Dawson(3), William Dewar(4), Annalisa Griffa(5), Brian K. Haus(1), Angelique C. Haza(1), Helga Huntley(6), Mohamed Iskandarani(1), Gregg Jacobs(7), Bert Jagers(8), A.D. Kirwan, Jr.(6), Nathan Laxague(1), Bruce Lipphardt, Jr.(6), Jamie MacMahan(9), Arthur J. Mariano(1), Josefina Olascoaga(1), Guillaume Novelli(1), Andrew C. Poje(10), A.J.H.M. Reniers(1), Juan M. Restrepo(11), Brad Rosenheim(12), Edward H. Ryan(1) , Conor Smith(1), Alexander Soloviev(13), Shankar Venkataramani(11), Ge-Cheng Zha(1), Ping Zhu(14)

(1) University of Miami, Miami, USA
(2) Texas A & M University, Corpus Christi, USA
(3) University of Texas, Austin, USA
(4) Florida State University, Tallahassee, USA
(5) CNR, La Spezia, Italy
(6) University of Delaware, Newark, USA
(7) Naval Research Laboratory, Stennis Space Center, Mississippi, USA
(8) Deltares, Netherlands
(9) Naval Postgraduate School, Monterey, USA
(10) City University of New York, New York, USA
(11) University of Arizona, Tempe, USA
(12) University of South Florida, Tampa, USA
(13) Nova Southeastern University, Fort Lauderdale, USA
(14) Florida International University, Miami, USA

ABSTRACT 300194:

CARTHE (http://carthe.org/) is a Gulf of Mexico Research Initiative (GoMRI) consortium established through a competitive peer-reviewed selection process. CARTHE comprises 26 principal investigators from 14 universities and research institutions distributed across four Gulf of Mexico states and other four states. It fuses into one group investigators with unique scientific and technical knowledge and extensive publications related to oil fate/transport processes, oceanic and atmospheric turbulence, air-sea interactions, tropical cyclones and winter storms, and coastal and nearshore modeling and observations.

Our primary goal is to accurately predict the fate of hydrocarbons released into the environment. Achieving this goal is particularly challenging since petroleum releases into the environment interact with natural processes across six orders of magnitude of time and space scales. We are developing a multi-scale modeling tool by incorporating state-of-the-art hydrophysical models, each applicable for a restricted range of scales, into a single, interconnected modeling system to predict the physical dispersal of hydrocarbons across scales ranging from the microscale at the wellhead to oceanic and atmospheric mesoscales. CARTHE is also conducting novel in-situ observations and laboratory experiments specifically designed for quantifying submesoscale dispersion as well as for both model validation and parameterization. Finally, we are providing a robust set of uncertainty metrics and analysis tools to assess model performance and quantify predictive uncertainty.

HYDROCARBON TRANSPORT IN THE ENVIRONMENT:

When the Deepwater Horizon (DWH) oil drilling platform at BP's Macondo well exploded and sank on April 20, 2010, an unprecedented oil spill resulted. Unlike previous spills, the source was located at a depth of more than 1500 m. This fact complicates not only the science of observing and modeling the released hydrocarbons, it also added layers of complexity and difficulty to the response and mitigation effort. Over the course of 87 days, crude oil was released into the Gulf of Mexico (GoM), before the well was finally successfully sealed. The extent of the environmental impact remains largely unknown. The DWH incident was the largest accidental oil spill into marine waters with an estimated 4.4 million barrels released into the DeSoto Canton (Crone and Tolstoy, 2010). The surface plume alone resulted in wide-spread ecological and economic disruption for four states. A significant portion of the spill, however, likely never reached the surface, as it was entrained into the water column, where it is hard to track and assess.

Forecasting efforts using ocean models, needed for planning an efficient and effective response, retained large (often unknown) uncertainties because of the challenging nature of the transport problem. As shown schematically in Fig. 1, the overall physical dispersion of buoyant contaminants released at the sea floor (as in the Deepwater Horizon event) incorporates a large number of interacting processes which take place over a vast range of spatial and temporal scales. Readily identifiable stages of transport include:

a) The rise of the oil, gas, and dispersant mixture in the water column, and subsurface dispersion due to turbulent interactions with deep ocean stratification.
b) Surface dispersion under the action of Langmuir circulation, mixed layer dynamics, river outflows, mesoscale currents, wind and waves, including tropical storm conditions. In this paper, the term dispersion is used to describe the spreading of tracer patches by the

underlying velocity field, as opposed to the break up of oil into small droplets, as commonly understood in oil literature (Boufadel et al., 2006).

c) Transport across the inner shelf, complex coastal geometry, and the surf zone.
d) Release of gas into the atmospheric boundary layer by air-sea interaction processes, as well as burning of surface oil.
e) Transport of gas in the atmosphere.

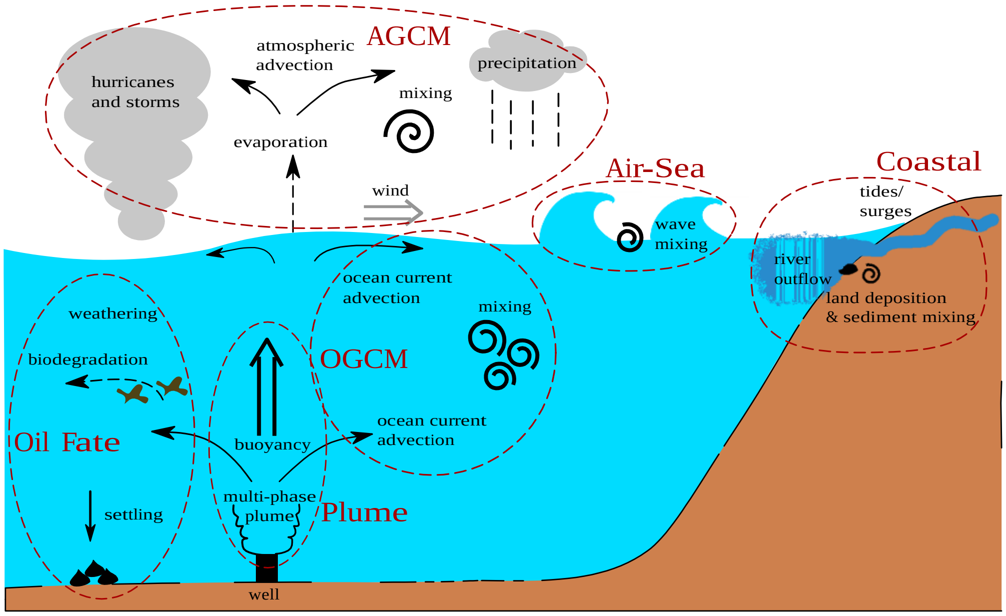

Figure 1: Schematic depiction of processes and modeling components needed to address the transport problem in deep water oil blow-outs near coastal regions. (OGCM = Ocean General Circulation Model; AGCM = Atmospheric General Circulation Model)

Producing better and more useful predictions of hydrocarbon transport faces three main challenges: (1) The physics affecting the problem ranges over many spatial and temporal scales. No one model can adequately resolve all of these. (2) Existing observations are inadequate to describe the complex processes that oil undergoes in the ocean or how the presence of oil may change the physical properties of the surrounding fluid. (3) The uncertainties in available predictions are not well estimated and typically only available ex post facto.

The main goal of Consortium for Advanced Research on Transport of Hydrocarbon in the Environment (CARTHE) is to accurately predict the fate of hydrocarbons released into the environment, thereby guiding risk management and response efforts to minimize damage to human health, the economy, and the environment.

To accomplish this goal, CARTHE is following an approach which relies on three elements:

1) The incorporation of a number of state of the art geo-physical models into a single, interconnected modeling tool to predict the physical dispersal of contaminants across a vast range of spatial and temporal scales, and physical processes.
2) A dedicated set of in-situ and laboratory experiments specifically designed for both model validation and parameterization.
3) A robust set of uncertainty metrics and analysis tools to assess model performance and quantify predictive uncertainty.

DESCRIPTION OF INDIVIDUAL MODEL SYSTEM COMPONENTS:

CARTHE scientific modeling instrument consists of the following components: (a) Large Eddy Simulations for multi-phase plume dynamics, (b) multi-phase air-sea interface model, (c) regional ocean general circulation models (OGCMs), (d) coastal models, (e) inner shelf and surf zone models, and (f) a fully-coupled modeling system. Some of these modeling components are described in the following.

Large Eddy Simulations of Subsurface Plume Dynamics

We model subsurface and near-surface dynamics using Large Eddy Simulation (LES). This approach lies between the extremes of direct numerical simulation, in which all turbulence is resolved, and Reynolds-averaged Navier-Stokes implementations, in which all turbulence is parameterized. LES models integrate the full Navier-Stokes equations without resorting to significant simplifications or parameterizations. In particular, the hydrostatic approximation, which prevents fast vertical motions, is avoided. The underlying concept relies on the fact that in turbulent flow fields large eddies transport smaller-scale disturbances with them as they migrate through the flow. These large eddies are fully resolved in the computation.

After exploring the dynamics of single-phase buoyant plumes (e.g., Fig. 2), CARTHE's plume modeling group made three important advances. First, by modifying the Boussinesq equations, we were able to represent the dynamics of bubbly buoyant plumes and obtained multiple intrusion layer formations that are characteristic of two-phase plumes (Fig. 3). Second, simulations have been conducted with buoyant, gas and mixed plumes and their differences have been quantified in great detail. Third, simulations of buoyant plumes in the presence of rotation indicate that sustained deep blowouts can significantly modify the oceanic circulation surrounding the plume.

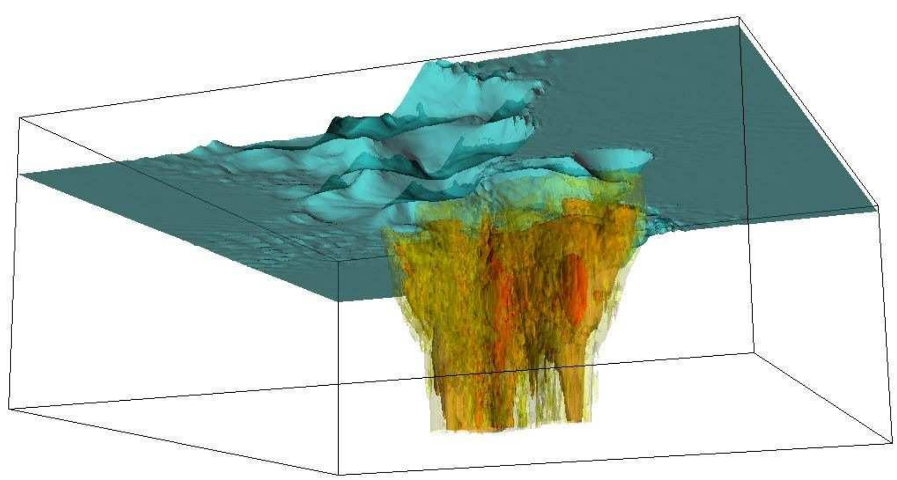

Figure 2: (Left panel) Large scale subsurface structure of a single-phase buoyant plume interacting with density gradients at the base of the near-surface mixed layer.

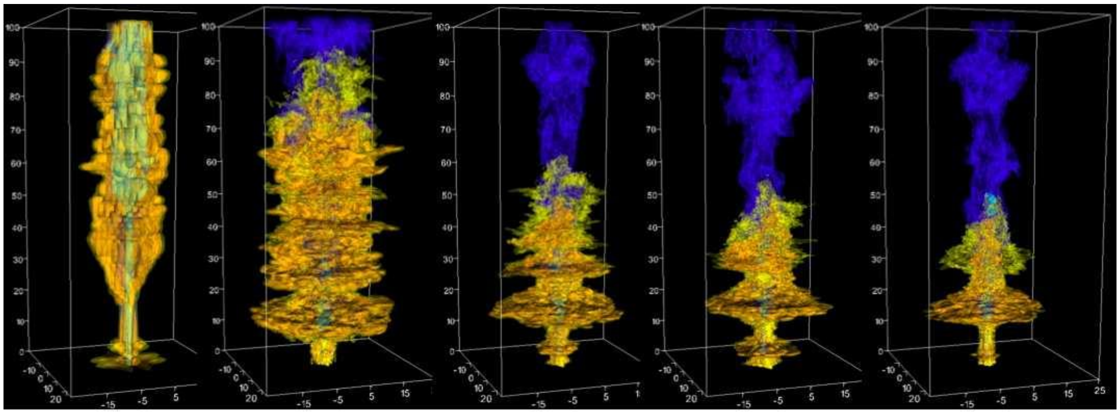

Figure 3: Convergence of two-phase plume simulations in a stratified environment as a function of the number of mesh points. From left to right: 2.5 × 106, 12 × 106, 32 × 106, 48 × 106, 125 × 106 mesh points. The blue color shows the gas concentration surface, while orange is a passive tracer released to track the oil phase. The domain dimensions are 50D × 50D × 100D where D is the pipe diameter.

Multi-Phase Air-Sea Interface Modeling

The sea surface altering properties of oil (with and without applied dispersants) affect horizontal spreading of oil spills as well as their vertical mixing in the upper ocean and evaporation into the atmosphere. The presence of oil on the sea surface is known to dampen surface waves even in very strong winds. Under hurricane conditions, a two-phase mixture consisting of air bubbles and spray particles develops at the air-sea interface, which significantly changes the regime of air-sea interaction (Soloviev and Lukas, 2014). However, little is known about the physical mechanisms involved in the disruption of the air-sea interface under hurricane force winds.

CARTHE investigators have developed a two-phase model of the air-sea interface using the Volume of Fluid multi-phase capabilities of ANSYS Fluent (Soloviev and Lukas, 2010). This numerical model reveals the effect of direct disruption of the air-sea interface under very strong winds, resembling the Kelvin-Helmholtz instability, and the formation of a two-phase environment (Fig. 4). We have also extended this analysis to include oil. Accompanying laboratory experiments are being conducted at the University of Miami's Air-Sea Interaction Saltwater Tank using hurricane force winds as well as oil.

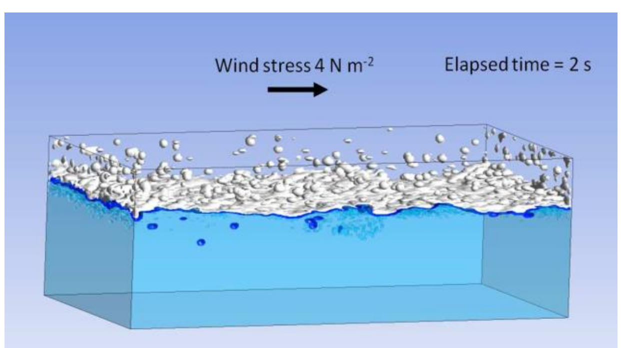

Figure 4: A numerical experiment with an initially flat air-sea interface illustrates the formation of the two-phase environment under hurricane force winds. (After Soloviev and Lukas (2010).)

Coupled Atmosphere-Wave-Ocean System

The atmospheric and oceanic circulations, particularly in extreme weather events such as hurricanes and winter storms, are key factors affecting hydrocarbon transport. A high-resolution fully coupled atmosphere-wave-ocean regional model is required to produce accurate circulation forecasts and to assess the range of variability in wind speed, surface waves, and ocean currents from climatologically normal to storm-induced extreme conditions. The research group at SMAS/UM has developed a cloud-resolving (1 km grid spacing) coupled atmosphere-wave-ocean model that has been evaluated using observations from three major tropical cyclone field programs: the Coupled Boundary Layer Air-Sea Transfer (CBLAST) in the Atlantic, the Hurricane Rainbands and Intensity Change Experiment (RAINEX), and the Impact of Typhoons on the Ocean in the Pacific (ITOP).

CARTHE investigators are developing a physically based and computationally efficient coupling at the air-sea interface that is flexible for use in a multi-model system and portable for transition to the next generation research and operational coupled atmosphere-wave- ocean-land models. To explore new air-sea coupling physics, we developed the new University of Miami Wave Model (UMWM, Donelan et al. (2012)). UMWM is a predictive model for wave energy and wind stress on the interface between a liquid and a gas, providing the full wave energy spectrum, stress vectors, and dissipation rate at each time step at chosen grid points. It was developed specifically to enable stress coupling in coupled hurricane models.

The coupled modeling system, denoted University of Miami Coupled Model (UMCM, Chen et al. (2013)), consists of atmospheric, wave, and ocean model components. These are currently the high-resolution, non-hydrostatic, multi-nested grid Weather Research and Forecast (WRF) model, UMWM and WW3, and the Hybrid Coordinate Ocean Model (HYCOM). We use a subdomain of the eddy-resolving (1/24◦, 4 km mid-latitude resolution) Atlantic HYCOM, which includes the GoM and Caribbean Sea, with data assimilation. Examples of the coupled model simulation of tropical cyclones are shown in Fig. 5.

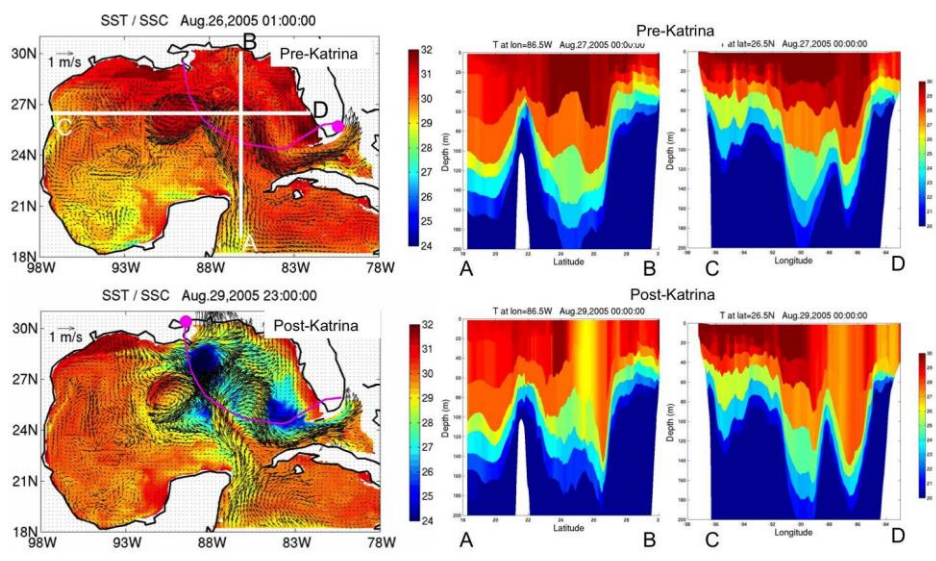

Figure 5: Coupled WRF-HYCOM forecast of pre- and post-Hurricane Katrina (2005) SST and surface current (left panels). The pre-and post-Katrina vertical cross-sections of ocean temperature (South-North A-B, and West-East C-D) over the Loop Current and warm eddy in the GoM are shown in the right panels. The WRF EnKF data assimilation was used in this coupled model forecast. Sections indicate a significant deepening/cooling of the mixed layer over the northern GoM and near Florida coastal regions after the passage of Katrina.

Coastal Modeling

Coastal models must faithfully reproduce tidal circulation, the entire wave environment from generation to dissipation, and the wind forcing that pushes oil along the surface of the water column. These models must also provide a high-resolution depiction of the entire domain of interest, from deeper waters to the relatively shallow continental shelf to the marshes, rivers and man-made channels of the complex nearshore environment.

The Advanced CIRCulation (ADCIRC) model has been applied to coupled wind, windwave, tide, and riverine flow simulations on unstructured meshes in the GoM, specifically focusing on recent hurricanes which have made landfall in southern Louisiana. For this purpose, a high resolution description of the GoM, continental shelf, Mississippi River delta, and southern Louisiana coast has been developed over the past decade; see left panel of Fig. 6. This shows a plot of the domain and finite element mesh focusing on southern Louisiana and Mississippi. Here the elements range in size from hundreds of meters in the deeper waters of the GoM to around 30-50 meters in the nearshore, channels, rivers, wetlands, and levee systems. The ADCIRC model has been applied extensively to hurricane forecasts and hindcasts (Dietrich et al., 2010) and is now used routinely for the development of floodplain risk assessments and the design of levee protection systems. ADCIRC has been coupled recently to the Simulating WAves Nearshore (SWAN) model, so that both models run on the same unstructured meshes and on the same computational cores. The resulting SWAN+ADCIRC model is well-positioned to simulate accurately and efficiently the propagation of wind-waves, tides, and storm surge onto the continental shelf, as well as their dissipation in the nearshore.

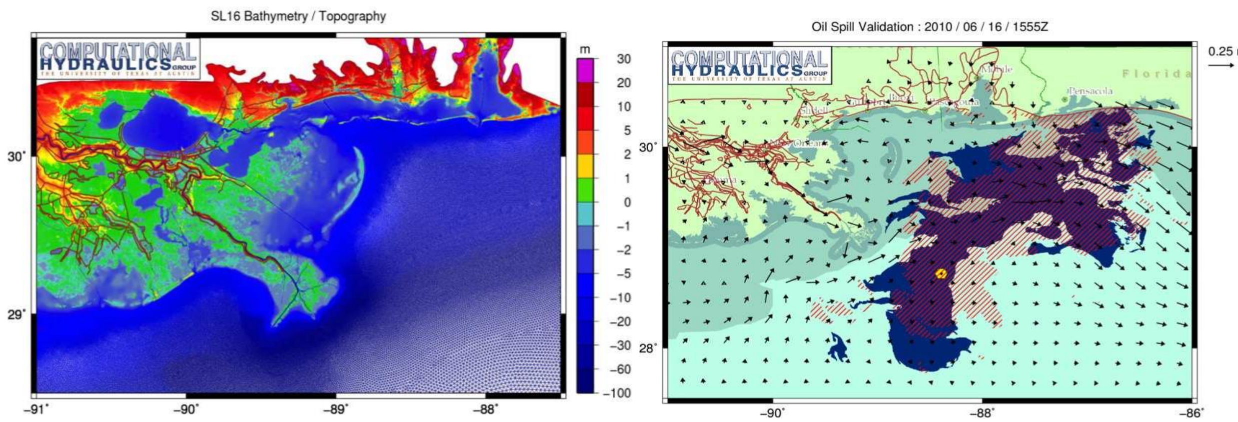

Figure 6: (Left panel) Plot of the ADCIRC computational domain in the southern Louisiana region. The colors represent bathymetry and the finite element mesh is overlaid. (Right panel) Comparison between observed (solid blue) and modeled (hatched red) spill coverage after 72hr of simulation in the northern GoM.

SWAN+ADCIRC was used in an operational mode during the DWH spill event (Fig. 6). Wind advisories provided forcing to both models, which produced fields of wave and circulation across the northern GoM coastline. These fields were then taken as input for a Lagrangian particle-tracking model, which was used to simulate the movement of the oil spill. The currents contain the effects of wave dissipation in the nearshore and were combined with 2% of the wind speeds to better simulate the movement of the oil layer over the water column. This particle-tracking model has been evaluated against the observed coverage from satellite images (Dietrich et al., 2012).

Under CARTHE, the SWAN+ADCIRC multi-physics code is undergoing rigorous development and testing for the modeling of 3D flow and transport in coastal environments. This development is leading to improved barotropic/baroclinic circulation and wave models with unstructured finite element discretizations, which are capable of resolving near-shore physics and coastal features, and model exchanges between the coastal ocean, bays, estuaries and rivers. In addition, improved oil transport capabilities are being investigated which will allow for a more complete picture of surface/subsurface oil movement, biogeochemical processes, dissipation, and other physics which are currently lacking in 3D oil spill models.

DIRECTED FIELD EXPERIMENTS:

Recent realization of the transport impact of energetic submesoscale features, i.e. fronts, filaments, ageostrophic instabilities, and coherent vortices on spatial scales ranging from 100 m to 10 km and temporal variability scales of less than 1 day, give a strong motivation to obtain a highly resolved depiction of the velocity field at these scales for oil spills. Data on which to base subgridscale closures and perform robust model-data comparisons are virtually non-existent. Hence the accuracy of ocean models at the submesoscale is not verified, and the ability of current numerical models to accurately predict the Lagrangian dispersion properties, essential for oil spill transport forecasts, has yet to be thoroughly tested. Given the unique regional conditions in the GoM (Loop Current, Mississippi River Plume, hurricanes, etc.), experiments specific to this region are needed. Field experiments conducted by CARTHE are briefly reviewed next.

Grand Lagrangian Deployment (GLAD)

CARTHE's first major experiment, denoted Grand LAgrangian Deployment (GLAD), was designed to explore transport pathways near the DWH site. GLAD is the largest synoptic surface drifter deployment in oceanography to date, comprising some 317 Lagrangian instruments that have been deployed in fractal triplet arrays over 10 days in the Summer of 2012. GLAD relied on the near-simultaneous deployment of a large number of drifters to quantify upper ocean dispersion.

The advective transport and stirring of contaminants by ocean currents produces an inherently multi-scale phenomenon (Jones et al., 2011); the trajectories of tracer-marked fluid parcels reflect the time-integrated effects of a velocity field over a wide range of scales (Olascoaga and Haller, 2012). The nature of flows over the spatial range from 100 m to hundreds of km, or submesoscales (Thomas et al., 2008), poses the main frontier in our theoretical understanding of oceanic multi-scale turbulent interactions and energy pathways (McWilliams, 2008). Submesoscales also influence the transport of biogeochemical tracers (Levy et al., 2012), as well as global overturning circulation important for climatic studies (Fox-Kemper et al., 2011). Development of accurate estimates for pollutant dispersion is of wide public socio-economic concern and requires a quantification of the effect of all scales of motion on ocean transport.

The unprecedented data densities revealed a detailed snapshot of the near surface velocity field in the summertime DeSoto Canyon that clearly indicated the importance of ageostrophic, submesocale motions in setting local dispersion rates (Poje et al., 2014). GLAD observations allowed the amount of scale-dependent dispersion missing in current operational circulation models and satellite altimeter-derived velocity fields to be quantified, and these observations have been used to assess and improve predictive models and remote-sensing data sets (Olascoaga et al., 2013; Arnott et al., 2014; Carrier et al., 2014; Coelho et al., 2014; Jacobs et al., 2014; Berta et al., 2014).

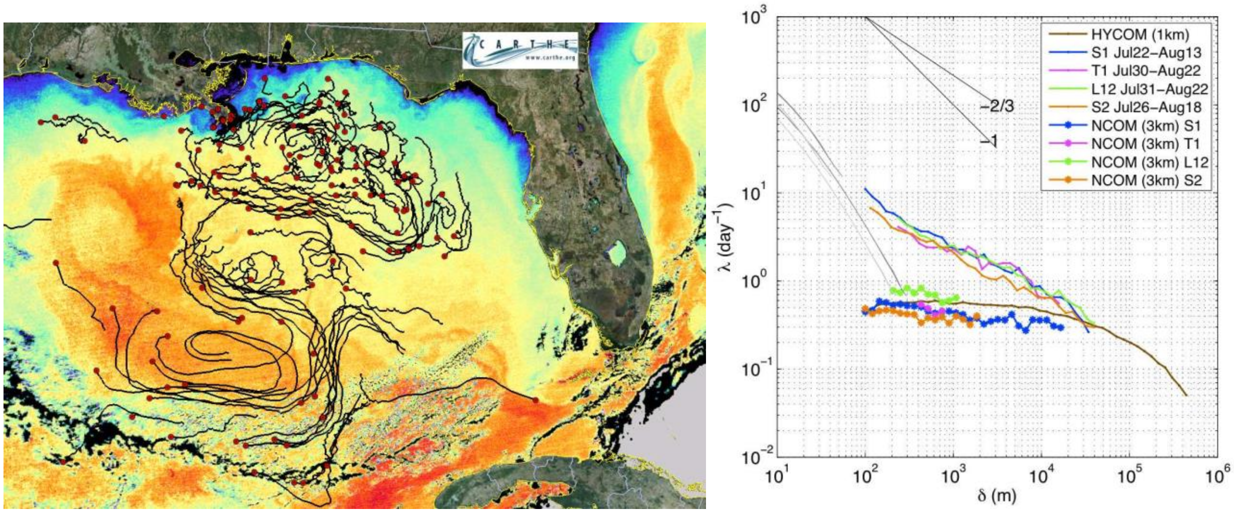

Figure 7: (Left panel) Trajectories of GLAD drifters (with two-week tails) superimposed on a image of MODIS SST from October 20, 2012. (Right panel) The scale-dependent finite scale Lyapunov exponent λ(δ) (Poje et al., 2010; Haza et al., 2014) from Navy Coastal Ocean Model (NCOM), Hybrid Coordinate Ocean Model (HYCOM) and GLAD clusters (S1, L12 and T1). The Richardson's regime ($\lambda \sim \delta^{-2/3}$) and ballistic regime ($\lambda \sim \delta^{-1}$) are shown in the background. The grey lines indicate the noise associated with the GPS position errors; note that the error is less that the measured curves for particle separation scales of $\delta > 200$ m.

Rapid Response to the Hercules Incident

CARTHE participated in a rapid response effort to the Hercules incident in the summer of 2013. Our role was to deploy drifters around the rig to track surface water masses, and to make the data available to other consortia in real-time to support decision making for ocean sampling and evaluation of circulation models (Fig. 8). The short, yet intense collaborative effort during this incident helped illustrate the utility of deploying drifters to track surface water masses from oil spills (Joye et al., 2014).

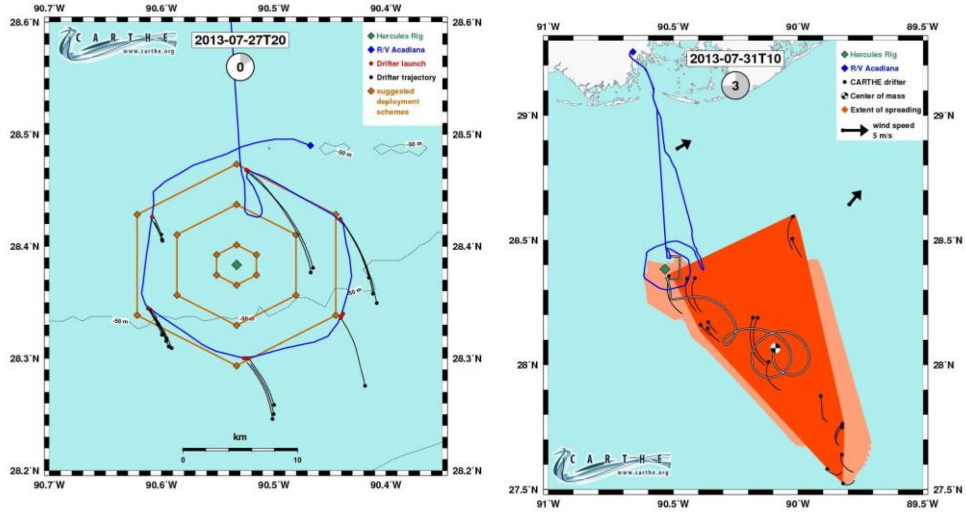

Figure 8: (Left panel) R/V Acadiana cruise track, suggested launch templates and actual drifter deployments. (Right panel) The state of the drifter cluster after 92 hours of release. The trajectories have six-hour tails. The center of mass of the cluster shows clear oscillations as well as southward stretching due to an anticyclonic eddy in the Gulf of Mexico. Dark red marks the instantaneous coverage of the cluster while the light red depicts all the regions occupied by the drifters. The arrows show wind data from the NOAA NDBC website (stations SPLL1 & KMDJ). An animation is available at: http://carthe.org/hercules_info/carthe_hercules_v2.mov

Surfzone and Coastal Oil Pathways Experiment (SCOPE)

The Surf-zone Coastal Oil Pathways Experiment (SCOPE) took place in December 2013 on the coastline across the northern tip of the DeSoto Canyon. This program involved hundreds of targeted launches of surface drifters over the inner shelf, dye releases observed from aerial platforms (Fig. 9), high-resolution air-sea interface observations, upper ocean turbulence measurements, in-situ meteorological data collection, as well as three classes of models (UMCM, 3D ADCIRC and NCOM) that were run in real-time for forecasting and evaluation purposes. One of the significant preliminary results of SCOPE is the importance of density fronts from estuaries and over the shelf in trapping and transporting surface material even under highly-variable winter storm wind conditions.

Oil Date and Persistence in the Water Column and Sediments

The release of oil to the environment left a signature in both the water column and in the sediments. CARTHE participated in two ocean sampling expeditions in June-July 2012 and June 2013, during which participants and affiliates took water samples, sediment samples, and macro-fauna samples. Researchers have linked elevated presence of polycyclic aromatic hydrocarbons (PAHs) to decreases in stable carbon isotope composition of the sedimentary organic material (Rosenheim et al., 2014). This offers a robust and inexpensive way to map the effects of an oil spill on the sediment and benthic ecology that can be applied at a scale for comparison to dynamic modeling of a spill plume. Water column samples taken by CARTHE scientists and affiliates show the diverse effects of seep hydrocarbon and river plume effects on the dissolved inorganic carbon of the water column. Being a semi-enclosed sea with a two major sources of carbon in addition to the atmosphere (the Mississippi River and natural hydrocarbon seeps), profiles of stable carbon isotopes and radiocarbon are variable in space and time. The lack of these types of data before the oil spill precluded useful measurements to determine the relative rates of microbial metabolism versus evaporation of the oil in the water column following the spill, and resulted in significant debate. CARTHE data will provide a better understanding of the baseline conditions in the Gulf of Mexico that can be applied in future spills of this magnitude.

UNCERTAINTY QUANTIFICATION:

Numerical simulations of environmental flows and of pollution transport and fate are subject to numerous sources of uncertainty that include incomplete knowledge of initial and boundary conditions, uncertain model parameters, imperfect models, and inconsistent, sparse, and noisy estimates of hydrocarbon location. It is therefore critical to model these uncertainties in the hydrocarbon transport prediction problem and to provide model users with a quantitative assessment of the impact of these uncertainties on model results.

The CARTHE team has been developing and applying Polynomial Chaos (PC) methods to oceanic uncertainty problem. In PC methods, the uncertain input data are considered as functions of random variables with known probability density functions. The solution's dependence on those random variables is then expressed as a truncated series expansion made up of a judiciously chosen orthonormal basis for the stochastic space and initially unknown coefficients. The unknown coefficients can be determined through a weighted residual formalism (Le Maître and Knio, 2010); in particular, the non-intrusive approach allows the determination of these coefficients without code modification and via ensemble simulations with carefully selected choices of the random variables. Most of the computational burden in PC concerns the estimation of the series coefficients, and these are obtained by sampling the model output adaptively (Winokur et al., 2013) and non-intrusively (no code modification is necessary making the approach model-neutral). The adaptive sampling ensures the fidelity of the series representation while minimizing the number of expensive forward model runs. Once the series fidelity is established it can be used in lieu of the model for MonteCarlo sampling, for sensitivity analysis, for estimating statistical moments of specific model outputs, and for estimating the gradients of the model dependent variables with respect to the uncertain parameters without the use of an adjoint code. The methodology has been applied to study the impact of nesting (Thacker et al., 2012) and initial boundary conditions on HYCOM simulations of the Gulf of Mexico circulation, and to quantify parametric uncertainties in HYCOM's mixed layer parameterization (Alexanderian et al., 2012) and drag parameterization during hurricane conditions. Sraj et al. (2013a,b) illustrate how PC and observational data can be used in parameter estimation using either Bayesian inference or variational methods. In addition the PC approach is currently being applied to analyze uncertainties in Lagrangian oil-fate models and in oil plume models.

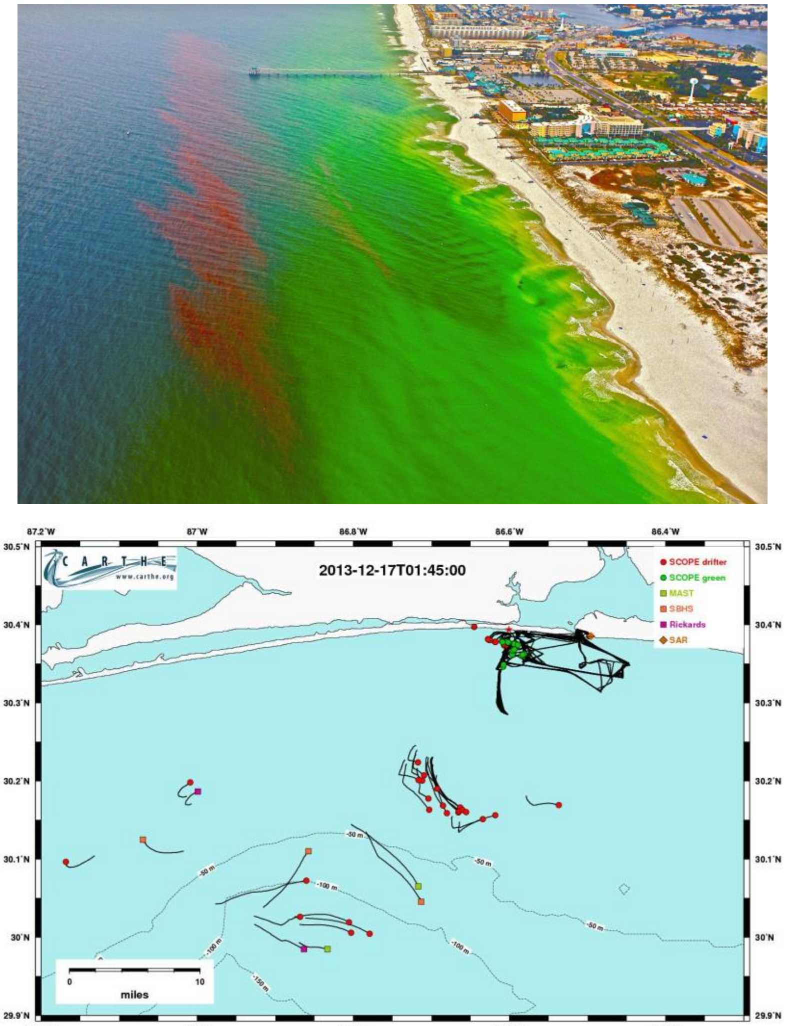

Figure 9: (Upper panel) Aerial view of a dye release just outside of the surf zone near Ft. Walton Beach, FL, on December 13, 2013. (Lower panel) The state of the SCOPE drifter array sampling the Florida panhandle shelf on December 17, 2013. The tails are 12h long.

MAIN SCIENTIFIC FINDINGS OF CARTHE:

Over the past two years of research activity, CARTHE conducted two major observational programs; GLAD is the largest upper ocean dispersion carried out in oceanography to date and SCOPE involved an unprecedented simultaneous use of drifters, dye, satellite remote sensing and targeted upper-ocean measurements. In addition, we have participated in a rapid response effort to the Hercules rig blow out. All of these observational programs included multiple modeling streams, both in real time and reanalysis modes. Independently from these studies, we are conducting process modeling, laboratory experiments and measurements at the bottom of the ocean. Some of the primary findings of CARTHE are summarized below:

i. Analysis of drifter dispersion was carried out by computing Lagrangian coherent structures using the geodesic method (Haller and Beron-Vera, 2012) from satellite altimeter fields during GLAD (summer 2012, Olascoaga et al. (2013)) and the Hercules incident (summer 2013). Both studies indicate that mesoscale features have a significant effect in constraining drifter motion outside of the DeSoto Canyon for GLAD and south of the continental shelf during Hercules. This result emphasizes the importance of getting the mesoscale circulation features in the right place, and the fidelity of data assimilation in general circulation models (Jacobs et al., 2014).

ii. Two-point velocity differences from the GLAD experiment confirm the validity of classic turbulence scaling laws at 200m - 50km scales (Poje et al., 2014). The implication of this finding is rather significant in that it demands observations spanning a vast range of scales in order to capture the dispersive effect of motions in the ocean. Our findings allow quantification of submesoscale dispersion missing in current operational circulation models and satellite altimeter-derived velocity fields.

iii. CARTHE's efforts during both GLAD and the Hercules incident demonstrated the feasibility and utility of deploying large clusters of drifting instruments to provide synoptic observations of spatial variability of the ocean surface velocity field.

iv. From GLAD, we obtained direct diffusivity estimates 100 times greater than those typically reported by canonical ocean dye measurements (Okubo, 1970). This result (Poje et al., 2014) implies very high upper ocean shear, and warrants investigation of flows within the upper 1m of the ocean, which remain largely unknown to date.

v. We have shown, through a comparison of satellite altimetry (AVISO) derived surface velocity fields and those on the basis of GLAD drifter coverage using a blending method that satellite data fails completely in the DeSoto Canton and the nearby shelf region in providing accurate velocities (Berta et al., 2014).

vi. The influence of a deep/winter surface mixed layer on the underlying mesoscale transport barriers was investigated using a high-resolution (1km) ocean model of the GoM. We have found that near-surface submesoscale instabilities not only result in the formation of bands of surface material but there is also some leakage across transport barriers associated with mesoscale features.

vii. Using a combination of GLAD drifter data and UMCM, we have concluded that Stokes drift plays a significant role in transport. This effect is missing in most ocean models and needs to be included for higher accuracy predictions.

viii. We have discovered that coastal convergence zones, created by estuarine outflows and density fronts, can trap and transport the surface drifters released during SCOPE. This result indicates that research needs to be focused on how these convergence zones near the oceans surface are created, and be best captured in our numerical models.

ix. Multi-scale downscaling to model atmospheric plumes from the Deepwater Horizon and Hercules events showed that the transport is sensitive to the parameterization of turbulent mixing and air-sea interaction. Also diurnal variability of winds and sea surface temperature were found to be important for plume predictions.
x. Using several satellite images during the early part of the Deepwater Horizon event, analytical arguments and computations, we arrive at the conclusion that deepwater blowouts can significantly impact the circulation around them and should be considered as active participants of the fluid flow.
xi. The intrusion levels in gas plumes in stratified environments are found to be quite sensitive to numerical resolution, requiring large computations for accuracy. This problem is important in order to estimate how much of the deep oil plume gets to the surface, and how much remains subsurface.
xii. Long internal waves propagating along the shallow mixed-layer base due to strong summer stratification are shown to impact GLAD drifter motion (Arnott et al., 2014).
xiii. An international patent was awarded to the drifter assimilation scheme developed by the NRL group in order to incorporate GLAD data into their operational modeling system (also in Carrier et al. (2014)).
xiv. Core-top samples taken by CARTHE researchers, when compared to compilation of background of carbon isotope data from three decades of measurements of sedimentary organic material in the Gulf of Mexico, show a effects of the oil spill and relate to PAH content of the sediments (Rosenheim et al., 2014). These measurements and compilation indicate an inexpensive screening method for incorporation of hydrocarbon pollution into benthic communities that can be applied over large areas and used for comparison to surface plume mapping.

ACKNOWLEDGMENTS:

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

REFERENCES:

Alexanderian, A., J. Winokur, I. Sraj, A. Srinivasan, M. Iskandarani, W. C. Thacker, and O. M. Knio. Global sensitivity analysis in an ocean general circulation model: a sparse spectral projection approach. *Computational Geosciences*, 16(3):757–778, 2012.

Arnott, K., D. Bogucki, C. Mitchell, E. Coelho, T. M. Özgökmen, B. K. Haus, A. Reniers, M. Gough, and A. Valle-Levinson. Long Internal Waves in the Northern Gulf of Mexico: Unraveling Coastal Transport Mechanisms. *Journal of Marine Systems*, submitted, 2014.

Berta, M., A. Griffa, M. G. Magaldi, A. C. Poje, A. C. Haza, T. M. Özgökmen, M. J. Olascoaga, E. Coelho, G. Novelli, A. J. Mariano, M. Iskandarani, B. K. Haus, A. Reniers, E. H. Ryan, a. G. A. J. F. J. Beron-Vera, B. L. L. Jr., H. S. Huntley, and A. D. K. Jr. Blending surface drifters and altimetric currents in the Gulf of Mexico. *Deep-Sea Res. I*, submitted, 2014.

Boufadel, M., R. Bechtel, and J. Weaver. The movement of oil under non-breaking waves.

Marine Pollution Bulletin, 52:1056–1065, 2006.

Carrier, M., H. Ngodock, S. Smith, P. Muscarella, G. Jacobs, T. Özgökmen, B. Haus, and B. Lipphardt. Impact of ocean velocity observations inferred from Lagrangian drifter data using the NCOM-4DVAR. *Monthly Weather Review*, doi: 10.1175/MWR-D-13-00236.1:in press., 2014.

Chen, S. S., W. Zhao, M. A. Donelan, and H. L. Tolman. Directional wind-wave coupling in fully coupled atmosphere-wave-ocean models: Results from CBLAST-Hurricane. *J. Atmos. Sci.*, 70:3198–3215, 2013.

Coelho, E., P. Hogan, G. Jacobs, P. Thoppil, H. Huntley, B. Haus, J. B. Lipphardt, J. A. D. Kirwan, E. H. Ryan, J. Olascoaga, G. Novelli, F. Beron-Vera, A. C. Haza, A. C. Poje, A. Griffa, T. Özgökmen, D. Bogucki, S. Chen, M. Curcic, M. Iskandarani, F. Judt, N. Laxague, A. J. Mariano, A. Reniers, C. Smith, A. Valle-Levinson, and M. Wei. Ocean Current Estimation using a Multi-Model Ensemble Kalman Filter during the Grand Lagrangian Deployment (GLAD) experiment. *Ocean Modelling*, revised, 2014.

Crone, T. and M. Tolstoy. Magnitude of the 2012 Gulf of Mexico oil leak. *Science*, 330: 534, 2010.

Dietrich, J., C. Trahan, M. Howard, J. Fleming, R.Weaver, S. Tanaka, L. Yu, J. R.A. Luettich, C. Dawson, G. Wells, J. Westerink, A. Lu, K. Vega, A. Kubach, K. Dresback, R. Kolar, C. Kaiser, and R. Twilley. Surface trajectories of oil transport along the northern coastline of the Gulf of Mexico. *Cont. Shelf. Res.*, 41/1:17–47, 2012.

Dietrich, J. C., S. Bunya, J. Westerink, B. Ebersole, J. Smith, J. Atkinson, R. Jensen, D. Resio, R. Luettich, C. Dawson, V. Cardone, A. Cox, M. Powell, H. Westerink, and H. Roberts. A high resolution coupled riverine flow, tide, wind, wind-wave and storm surge model for southern louisiana and mississippi: Part II - Synoptic description and analyses of hurricanes Katrina and Rita. *Monthly Weather Review*, 138:378–404, 2010.

Donelan, M. A., M. Curcic, S. Chen, and A. Magnusson. Modeling waves and wind stress. *J. Geophys. Res.*, 117:26, 2012.

Fox-Kemper, B., G. Danabasoglu, R. Ferrari, S. Griffies, R. Hallberg, M. Holland, M. Maltrud, S. Peacock, and B. Samuels. Parameterization of mixed-layer eddies: III. Implementation and impact in global ocean climate simulations. *Ocean Modelling*, 39:61–78, 2011.

Haller, G. and F. Beron-Vera. Geodesic theory of transport barriers in two-dimensional flows. *Physica D*, 241:1680–1702, 2012.

Haza, A., T. Özgökmen, A. Griffa, A. Poje, and P. Lelong. Quantification of drifter position uncertainty for ocean dispersion. *J. Ocean. Atmos. Techn.*, submitted, 2014.

Jacobs, G., B. Bartels, D. Bogucki, J. Beron, S. Chen, E. Coelho, M. Curcic, A. Griffa, M. Gough, B. Haus, A. Haza, B. Helber, P. Hogan, H. Huntley, M. Iskandarani, F. Judt, D. Kirwan, N. Laxague, A. Levinson, B. Lipphardt, A. Mariano, H. Ngodock, G. Novelli, J. Olascoaga, T. M. Özgökmen, T. Prasad, A. C. Poje, A. Reniers, E. Ryan, C. Smith, S. Smith, P. Spence, and M. Wei. Ocean Data Assimilation Predictability During the Grand Lagrangian Deployment (GLAD). *Ocean Modelling*, submitted, 2014.

Jones, C., B. Minchew, B. Holt, and S. Hensley. Studies of Deepwater Horizon oil spill with the UAVSAR radar. *In "Monitoring and modeling the Deepwater Horizon oil spill a record breaking enterprise" Eds: Y. Liu, A. MacFaden, Z-G. Ji, R.H. Weisberg,*, AGU monograph:33–50, 2011.

Joye, S. B., J. P. Montoya, S. A. Murawski, T. M. Özgökmen, T. L. Wade, R. Montuoro, B. J. Roberts, D. J. Hollander, W. H. Jeffrey, J. P. Chanton, and C. A. Wilson. Fast Action: A Collaborative, Multi-Disciplinary Rapid Response Study of the Hercules Gas Well Blowout. *AGU EOS*, submitted, 2014.

Le Maître, O. P. and O. M. Knio. *Spectral Methods for Uncertainty Quantification*. Scientific Computation. Springer Verlag, New York, 2010.

Levy, M., R. Ferrari, P. Franks, A. Martin, and P. Riviere. Bringing physics to life at the submescale. *Geophys. Res. Lett.*, L14602:doi:10.1029/2012GL052756, 2012.

McWilliams, J. Fluid dynamics at the margin of rotational control. *Environ. Fluid Mech.*, 8:441–449, 2008.

Okubo, A. Horizontal dispersion of floatable particles in vicinity of velocity singularities such as convergences. *Deep-Sea Res.*, 17(3):445–&, 1970.

Olascoaga, M. and G. Haller. Forecasting sudden changes in environmental pollution patterns. *Proc. Nat. Acad. Sci.*, 109:4738–4743, 2012.

Olascoaga, M. J., F. J. Beron-Vera, G. Haller, J. Trinanes, M. Iskandarani, E. F. Coelho, B. Haus, H. S. Huntley, G. Jacobs, J. A. D. Kirwan, J. B.L. Lipphardt, T. Özgökmen, A. Reniers, and A. Valle-Levinson. Drifter motion in the Gulf of Mexico constrained by altimetric Lagrangian coherent structures. *Geophys. Res. Letters.*, 40:6171–6175, 2013.

Poje, A., A. Haza, T. Özgökmen, M. Magaldi, and Z. Garraffo. Resolution dependent relative dispersion statistics in a hierarchy of ocean models. *Ocean Modelling*, 31:36–50, 2010.

Poje, A., T. M. Özgökmen., J. Bruce Lipphart, B. Haus, E. H. Ryan, A. C. Haza, G. Jacobs, A. Reniers, J. Olascoaga, G. Novelli, A. Griffa, F. J. Beron-Vera, S. Chen, P. Hogan,

E. Coelho, J. A.D. Kirwan, H. Huntley, and A. J. Mariano. The Nature of Surface Dispersion Near the Deepwater Horizon Oil Spill. *Proceedings of National Academy of Sciences*, submitted, 2014.
Rosenheim, B., M. Pendergraft, G. Flowers, R. Carney, J. Sericano, R. Amer, J. Chanton, Z. Dincer, and T. Wade. Employing extant stable carbon isotope data in Gulf of Mexico sedimentary organic matter for oil spill studies. *Deep-Sea Res. II,* in press., 2014.

Soloviev, A. and R. Lukas. Effects of bubbles and spray on air- sea exchange in hurricane conditions. *Boundary-Layer Meteorology*, 136:365–376, 2010.

Soloviev, A. and R. Lukas. *The Near-Surface Layer of the Ocean: Structure, Dynamics, and Applications. Second Addition*. Springer, 2014.

Sraj, I., M. Iskandarani, A. Srinivasan, W. C. Thacker, J. Winokur, A. Alexanderian, C.-Y. Lee, S. S. Chen, and O. M. Knio. Bayesian inference of drag parameters using axbt data from typhoon fanapi. *Monthly Weather Review*, 141(7):2347–2366, 2013a.

Sraj, I., M. Iskandarani, W. C. Thacker, A. Srinivasan, and O. M. Knio. Drag parameter estimation using gradients and hessian from a polynomial chaos model surrogate. *Monthly Weather Review 2013*, 2013b.

Thacker, W. C., A. Srinivasan, M. Iskandarani, O. M. Knio, and M. L. Henaff. Propagating boundary uncertainties using polynomial expansions. *Ocean Modelling*, 43–44:52–63, 2012.

Thomas, L., A. Tandon, and A. Mahadevan. Submesoscale processes and dynamics. *Ocean modeling in an Eddying Regime, edited by M. Hecht and H. Hasume,* Geophysical Monograph 177:17–38, 2008.

Winokur, J., P. Conrad, I. Sraj, O. M. Knio, A. Srinivasan, W. C. Thacker, Y. Marzouk, and M. Iskandarani. A priori testing of sparse adaptive polynomial chaos expansions using an ocean general circulation model database. *Computational Goesciences*, 17(6):899–911, 2013.