Ecological Connectivity in Northeastern Gulf of Mexico – The Deep-C Initiative

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ABSTRACT #300240

The Deepwater Horizon blowout injected massive quantities of carbon in the form of crude oil and gas into the otherwise oligotrophic northeastern Gulf of Mexico. This sudden and unprecedented event dramatically affected ecosystem function, reverberating throughout the physical, chemical, and biological realms. Characterizing the acute and chronic effects of the spill set the stage for the Deep-C Consortium's focus on the geomorphologic, hydrologic, and biogeochemical settings that influence the distribution and fate of oil and its impact on the ecology in the region. Detecting the chemical constituents of oil and the decay rates and by-products of biodegradation has enhanced our qualitative and quantitative accounting of "missing" oil and allowed the assessment of the sensitivity of marine organisms to specific compounds. The delayed response of oil-eating microbes created lags in carbon biodegradation that allowed ecological damage to occur. Microbes themselves appear to serve as conduits delivering petroleum-based carbon to marine food webs. While this carbon appears at the other end of the trophic spectrum — in deep-sea animals either actually or virtually unknown to science — the levels measured in their tissues are relatively low, which begs the question, *"Does oil exposure affect their life history and general health?"* To address this question and predict the long-term ecological effects of the Deepwater Horizon oil spill, we are incorporating historical and newly-derived data into linked food web-earth system models that can forecast how spills impact ecological and economic communities, including human health. This approach also provides a powerful tool for identifying data gaps that require our attention, and assessing the influences of hydrocarbon releases on biological productivity in the Gulf of Mexico ecosystem.

INTRODUCTION

The oligotrophic system of the northeastern Gulf of Mexico (NEGOM) is adapted to relatively low carbon and nutrient concentrations. Thus, a sudden injection of massive amounts of crude oil or nutrients can initiate dramatic and long-term changes in ecosystem function that reverberate throughout the physical, chemical, and biological realms. The Deepwater Horizon (DwH) oil spill represents just such an event, releasing 600,000 tons of oil (McNutt *et al.*, 2012), 300,000 of tons of gas (Joye *et al.*, 2011), and at least 7,500 tons of dispersants into these waters (Kujawinski *et al.*, 2011). While scientists worked intensively to document the acute effects of the spill, the chronic effects remained largely unknown, with significant uncertainty about the fate of the oil and gas released. Large subsurface plumes of crude oil-detergent mixtures and gas permeated the water column, and unknown amounts of oil hydrocarbons invaded deep Gulf muds, coastal sands, and entered the food web. But to what effect?

The overarching goal of the "Deep Sea to Coast Connectivity in the Eastern Gulf of Mexico" (Deep-C) Consortium, funded by the Gulf of Mexico Research Initiative (GoMRI), is to investigate that question against the geomorphologic, hydrologic, and geochemical backdrops in which the spill occurred (*Figure 1*). This interdisciplinary approach (*Figure 2*) uses resulting empirical and quantitative data to develop, populate, and parameterize region-specific and realistic food web and earth system models. These data, alone or in concert, improve our ability to forecast the pathways, fate, and ecological consequences of extreme natural and anthropogenic events in the NEGOM. This paper highlights some of the key results derived from Deep-C research to date.

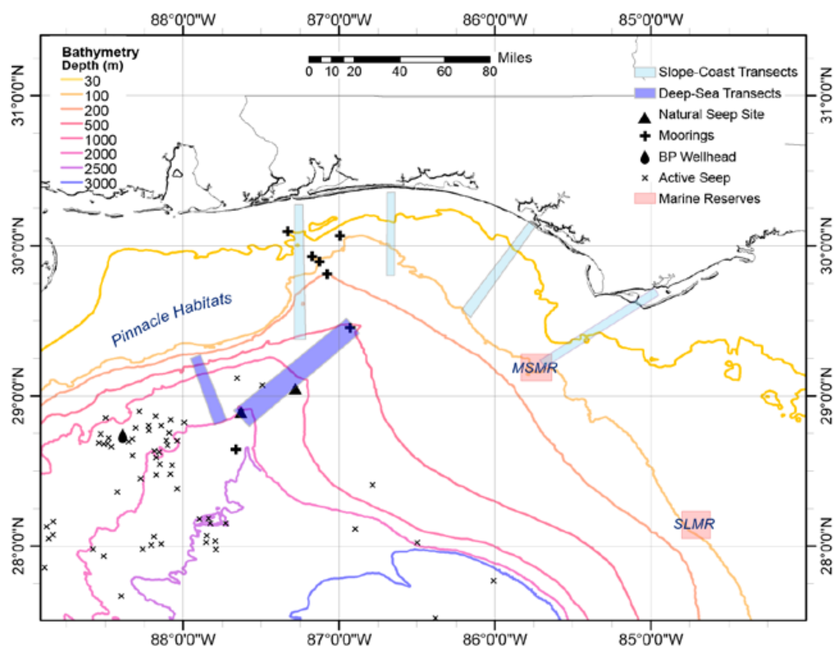

Figure 1. The Deep-C study area. Site selection was informed by side-scan and multibeam imagery produced by the NOAA Ocean Exploration Okeanos cruise.

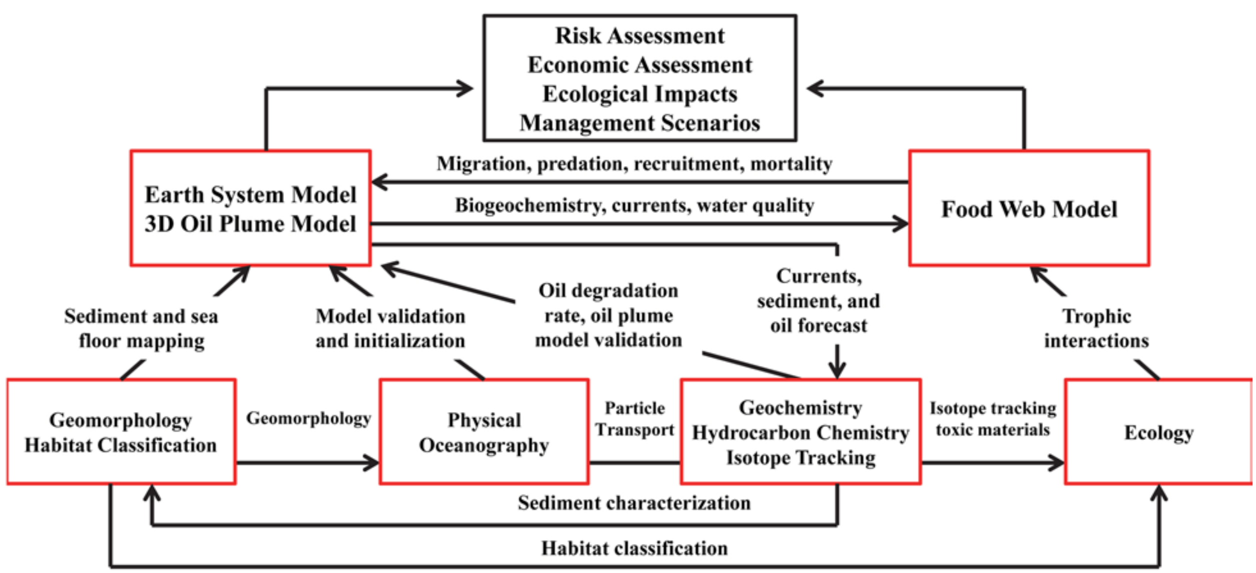

Figure 2. Interactions among the components of the Deep-C Consortium.

METHODS, RESULTS, AND DISCUSSION

Geomorphology, Circulation, and Atmospheric Forcing

Connectivity of the deep Gulf of Mexico to the NEGOM coast involves complex interactions between bottom topography, circulation (e.g., deep circulation, upper ocean eddies and currents like the Loop Current, riverine plumes, and upwelling) (*Figure 3*), and atmospheric forcing. By contrasting circulation pathways between strong topographic indentations (i.e., the De Soto Canyon) and less dramatic features (i.e., the outer shelf edge and river deltas), we can gain a far more complete understanding of the transport and fate of oil released during the spill.

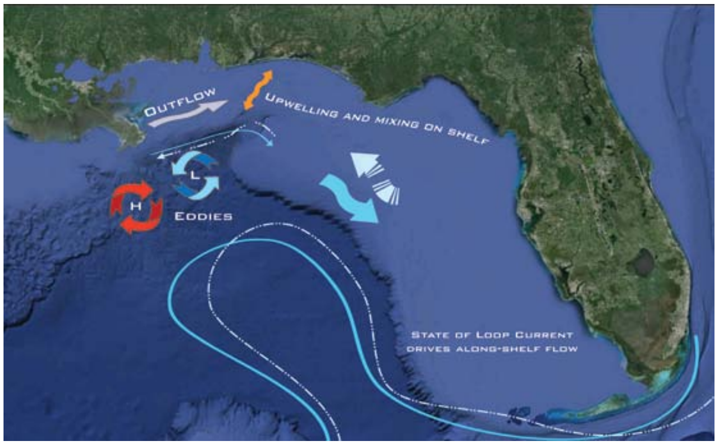

Figure 3: Overview of physical processes affecting the northern Gulf of Mexico and De Soto Canyon.

While the shelf is mostly considered to be sediment starved (Locker *et al.*, 2000), the inner shelf exhibits hot spots of mud accumulation that are enigmatic. Indeed, we found distinct strata truncated by narrow, steep canyon walls (*Figure 4*) that represent a highly dynamic sedimentary regime with mud-rich units consistent with slump deposition under conditions of abrupt gravity debris flows. These data on channel morphology are highly pertinent for interpreting circulation patterns within the canyon.

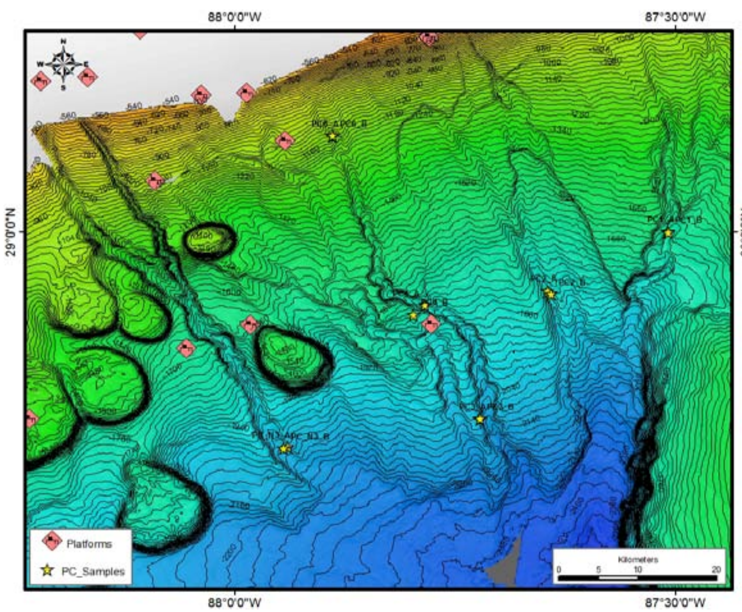

Figure 4: Multibeam bathymetry from the northwest slope of Desoto Canyon showing channels systems.

Much of our knowledge of the De Soto Canyon circulation comes from velocity and hydrographic measurements, with satellite observations and numerical models (Wang *et al.*, 2003; Hamilton and Lee, 2005). At times, the Loop Current and eddies can profoundly impact the circulation within the canyon and locations farther southeast (Walsh *et al.*, 2003; Weisberg and He, 2003; Vukovich, 2007). Morey *et al* (2003a,b) and Kourafalou and Androulidakis (2011) show that the combined effects of wind forcing and entrainment by eddy circulation result in offshore transport of riverine-influenced shelf waters over the deep De Soto Canyon.

Deep-C drifter studies (subsurface drifters ballasted near 400-m depths for one year) measuring connectivity between the slope and deep Gulf of Mexico revealed along-slope movement that occasionally reversed direction under the influence of strong (e.g., tropical storm, hurricane) events. Additional moored measurements suggest that near-inertial oscillations in the steep canyons are intensified both up- and down-slope and aligned with the bottom topography. Strong events clearly affect circulation around the De Soto Canyon by forcing upwelling and deep sea responses. For instance, during Hurricane Georges, current velocities exceeded 40 cm/s at 1290 m (Quanan *et al.,* 2006) whereas during Hurricane Ivan, velocities were found to exceed 50 cm/s on the slope (Teague *et al.,* 2007). Figure 5 shows the deep penetration of the wind-driven flow and how the mixed layer extends well below the initial depth during Hurricane Isaac in 2012. The question then arises as to whether these strong events can lead to the re-suspension of weathered oil in the water column and onto the shelf. Deep-C researchers demonstrated that this is possible, based on a modeling study combined with data derived from a field study in which they dropped profilers from a NOAA P-3 aircraft along the shelf and shelf break of the De Soto Canyon before and after Isaac's passage.

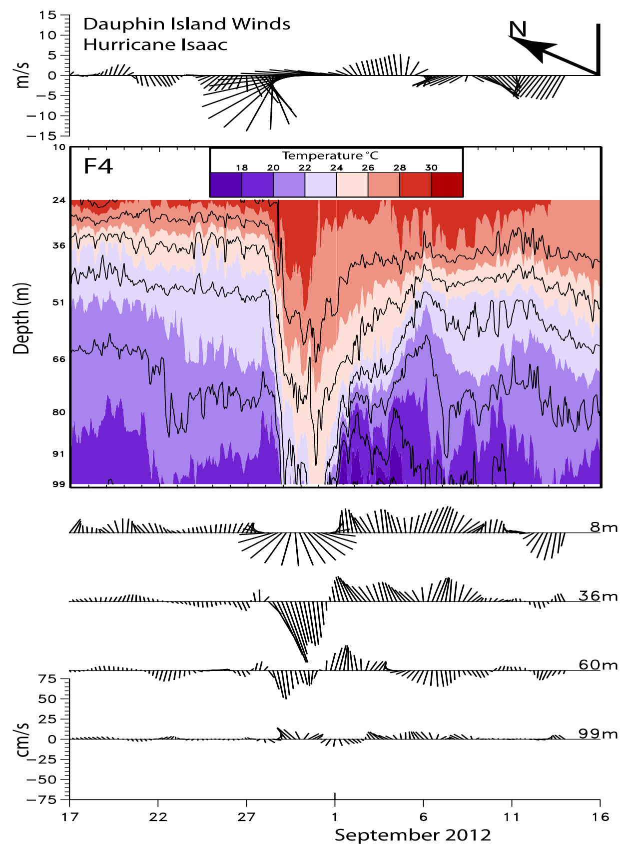

Figure 5: Hourly temperature measurements and 40-hr low-pass filtered current observations from a mooring near the head of the De Soto Canyon during Hurricane Isaac in late Aug/Sept 2012.

Geochemistry – Oil, Gas, and Dispersants

Most of the oil from the DwH succumbed to microbial- or photo-oxidation either on shore, in the water column, or on the sea floor. On shore, crude oil appeared on beaches and in the marshes across the NEGOM. Hydrocarbons released to the water column, interacted with detritus, and sank to the sea floor (Passow *et al.,* 2012; Brooks *et al.,* 2014). The portion consumed by microbes, particularly methane (CH_4), undoubtedly ended up in the food web (Hazen *et al.,* 2010; Chanton *et al.,* 2012; Cherrier *et al.,* 2014).

At the time of the spill, it was impossible to predict how long buried DwH oil would persist on Gulf of Mexico beaches and in adjacent sublittoral sediments, and how deep cleaning procedures implemented after the spill would affect them. This led Deep-C collaborators to examine changes in the hydrocarbon composition of buried oil over time so that they could project its persistence in beach sediments and determine any associated influences on and risks to the abundance, diversity, and composition of indigenous microbial communities.

Oxygen-consumption and dissolved inorganic carbon (DIC) production rates in the beach sediment reflect aerobic microbial decomposition. High degradation rates occurred in the partly waterlogged sands in the presence of warm Florida temperatures, intense light at the sediment surface, and the availability of oxygen. Similarly, rapid decay of polycyclic aromatic hydrocarbon (PAH) compounds — of concern because of their known toxicity to both humans and marine organisms — occurred in the surface layers of the beach. Because some of these PAHs have limited solubility in water, pore waters support transport to deeper sediment layers.

Zuijdgeest and Huettel (2012), using an experimental approach, demonstrated that the application of dispersants in coastal waters increases PAH mobility, allowing it to permeate faster and deeper into permeable saturated sands where anaerobic conditions slow its degradation. This could contribute to PAH persistence in coastal environments and the possibility of groundwater contamination with PAH residues.

This phenomenon is not restricted to beach sediments with strong hydraulic gradients. Indeed Zuijdgeest and Huettel also documented enhanced release of fluorescent aromatic oil components from crude oil embedded in the surface layer of sandy subtidal Gulf sediments. The high permeability of these sands, which dominate the sediments of the inner shelf most severely impacted by the DwH oil spill, allows strong pore-water flows that can transport solutes and small particles from deeper sediment layers, to the surface of the seabed (Huettel *et al.*, 2014), and ultimately to the overlying water.

Reports as recent as early 2014 of buried tar mats in the inner shelf of the NEGOM suggest that buried oil still serves as a source of oil compounds to Gulf waters. However, comparison of oil degradation activities in the shallow sandy shelf sediments and from muddy shallow and deeper seabeds revealed that the permeable Gulf of Mexico shelf sands, despite the much smaller specific surface area of the sediments, have a higher degradation activity then their fine-grained counterparts. An active oil-degrading microbial community in the sands and the characteristics of these sediments allowing oxygen-rich pore waters to reach buried oil promotes rapid hydrocarbon degradation in permeable beach and shelf sands (Kostka *et al.*, 2011).

Marine Snow: Two remarkable events occurred coincident with the DwH oil spill and captured the attention of scientists across the Gulf of Mexico[1]: (1) the appearance of high concentrations of marine snow on the surface of the Gulf of Mexico; and (2) the subsequent appearance of significant flocculent material on the sea floor. What we know is that flocculation is initiated by petro-carbon and marine snow interactions at the sea surface (Passow *et al.*, 2012) that lead to dramatic increases in sediment accumulation rates on the deep-sea floor (Brooks *et al.*, 2014). Three distinct transport mechanisms account for this: rapid settling of oil-contaminated marine snow, sinking of burned-oil particles, and advective transport of oil within the deep sub-surface intrusion impinging on the slope sediments at depths ~900-1300 m (Romero *et al.*, 2014). Changes in microbial community composition and activity over time clearly showed a massive input of surface-derived planktonic organisms (Brooks *et al.*, 2014), and a concommittant decline in benthic foraminifera accumulation rate (Schwing *et al.*, 2014).

[1] Broad interest in this event led to a GoMRI-funded workshop on Marine Oil Snow Sedimentation and Flocculent Accumulation (MOSSFA) in 2013 that included scientists from six GoMRI consortia (including Deep-C), individual scientists funded through other GoMRI initiatives, and experts outside of these two groups,. The report from the workshop appears at: http://deep-c.org/images/documents/MOSSFA_WorkshopReport2014.01.17.pdf.

Biodegradation of molecular fossils or biomarkers: Petroleum biomarkers are typically used to investigate the source and fate of petroleum hydrocarbons in the environment because they are considered recalcitrant. The DwH oil biomarkers were tested for changes induced by natural weathering following the spill from oil samples collected from 2010 through mid-2012. Patterns of depletion suggest that biodegradation and photooxidation acted as the main degradation pathways. While the utility of these biomarkers for oil spill forensics is still under development, they remain ideal indicators for assessing advanced stages of oil weathering, when most *n*-alkanes and PAHs have already degraded.

Ecological Pathways

The ecological component of Deep-C research focuses on defining changes in community structure and function associated with the DwH blowout and its aftermath, while developing post-spill baselines of heretofore-unstudied environments. Collaborators focus on biodiversity, species distribution, and the effects of exposure to oil.

Microbial responses: Microbes serve as a vehicle for transferring hydrocarbons into the food web (Chanton *et al.*, 2012; Cherrier *et al.*, 2014). Within weeks of oil reaching and penetrating beach sands, the proportion of hydrocarbon-degrading species increased by orders of magnitude, reducing both the relative abundance of other microbial groups and their biological diversity (Ruddy *et al.,* 2014; Kostka *et al.*, 2011). In response, rates of oil degradation increased. Evidence for this in near-shore environments is derived using next-generation sequencing methodologies (Kostka *et al.* 2011). The changes in diversity of oil-eating microbes followed temporal and functional lines (Kostka *et al.*, 2011; Overholt *et al.*, 2013). In deep sea sediments, the presence of protest grazers mediated rate of degradation, causing declines as protists preyed upon oil-degrading microbes (Beaudoin *et al.,* 2014). Regardless of the environment, as oil degraded, the diversity and species composition apparently is beginning to re-approach baseline conditions. This indicates that oil-degrading microbes were ubiquitous in the sediments, that they bloomed in response to the presence of hydrocarbons, and that the overall community is resilient.

Methane, another important source of hydrocarbons on which microbial communities could act, represented a significant portion of the hydrocarbon plume that entered the Gulf of Mexico following the oil spill. Indeed, Deep-C collaborators identified methane as a significant source of fossil carbon in the suspended detritus (particulate organic carbon or POC) characteristic of microbial trophic loops, suggesting that methane-derived carbon from the oil spill entered the food web via methanotrophy (Chanton *et al.*, 2012; Cherrier *et al.,* 2014). In fact, methane may prove to have been more effective at finding its way into the food web than oil, based on these findings. Whatever the case, hydrocarbon degrading microbes serve as an important vehicle for petro-carbons to move from microbial loops into the planktonic food web.

Macrofaunal Assemblages: Benthic macrofauna provide critical links between the microbial and planktonic communities on which they depend and the transfer of hydrocarbons throughout the trophic web by their role as prey in deep-sea environments. Preliminary results from comparisons of recent (2012-2013) collections from sediments in the De Soto Canyon with existing pre-spill (2000-2002) data (Wei *et al.,* 2012) suggest that while the overall biodiversity changed little, macrofaunal density increased and community structure changed significantly (Baco *et al.*, 2014) perhaps as a result of organic enrichment. If this turns out to be the case, then an important source of food for demersal species could have increased at least in the short term, as well as the transfer of hydrocarbons. This benthic response may be related to the increased sedimentation event (Brooks *et al*, 2014).

Fish Ecology: Characterizing demersal fishes of the NEGOM that represent important prey, predators, and scavengers in the Deep-C study, requires intensive and long-term fishery independent surveys across geographic regions and depth strata. Regions represent relative distances from the wellhead and thus likelihood of exposure to oil extending from the Mississippi Canyon to the west Florida shelf and slope. Depth strata include the continental shelf-edge (68 to 150 m), upper slope (200-400 m), mid-slope (400-900 m), and deep slope (>900 m to 2,645 m). Nearly 4,000 fishes captured (92 species) resulted in over 10,000 biological samples — from whole fish to whole organs and varied tissue samples — that support research at 18 institutions globally on fish taxonomy, physiology, ecology, and ecotoxicology. These contributions reveal new species, new associations, and much needed ecological information on these poorly known taxa (White *et al.*, 2013; Moura *et al.*, in press).

While their biological diversity declines with depth, as does basic life history information, there are distinct depth-mediated faunal assemblages. Catch rates (a proxy for abundance) of teleosts (the bony fishes) was much higher off the De Soto Canyon and Louisiana shelf than off the West Florida shelf, while differing little for elasmobranchs (sharks and relatives), *except* when considered by depth strata. Species assemblages, however, differed among regions. We interpret regional similarities in catch rates as a positive indication that the DwH may not have had population-level effects on these species. However, given the slow growth rates, long maturity schedules, and low reproductive rates of many of these taxa (Coleman *et al.*, 2000), it is also possible that DwH-mediated effects have yet to manifest. Further, where differences occur, they relate to habitat differences resulting from mesoscale geological processes, edaphic features, and terrestrial and riverine influences — all excellent targets for investigating PAH exposure and trophically-induced effects.

PAH exposure and toxicology: In testing the hypothesis that PAH exposure and effects changed over time following the DwH spill, Deep-C collaborators examine multiple biomarkers of PAH exposure in hundreds of sharks and bony fishes[2], including pollutant biotransformation enzymes induced by exposure to several PAHs used to evaluate previous oil spills (Springman *et al.*, 2008; Martinez-Gomez *et al.*, 2009). Also measured are relative levels of PAH metabolites with special focus on those characteristic of non-weathered and/or weathered Macondo oil that increased in fish following past oil spills (Jewett *et al.*, 2002; Jung *et al.*, 2011).

Some of these data suggest that deepwater sharks exhibit physiological signs of increased exposure to and effects of organic contaminants possibly originating from the DwH blowout, despite the time that has elapsed since wellhead containment. Ongoing studies examine whether these results are toxicologically relevant, and, where evidence suggests declines in PAH biomarkers, whether these indicate paced recovery. These results point to the value of determining the extent to which these events compromise physiological and life history traits.

Biogeochemical signatures using stable isotopes and methyl mercury (MeHg): The sheer volume of oil reaching NEGOM coasts supports the use of biogeochemical signatures to trace exposure to oil. This follows two paths of evidence: (1) via fossil carbon isotope signatures in fish tissues, indicating consumption of oil-contaminated prey (Sarkodee-Adoo *et al.*, 2014); and (2) via

[2] A comparable number of teleost species from identical locations are currently being analyzed using the same biomarkers.

increased MeHg signatures. The latter is based on the premise that intense microbial activity following the DwH blowout increased low O_2 conditions (Hazen *et al.,* 2010; Ryerson *et al.*, 2012), favoring methylation of mercury and enhanced bioaccumulation in the food web.

MeHg levels in fishes from offshore reefs and the deep sea lend credence to the hypothesis that MeHg levels increased following the DwH blowout. Top-level pelagic predators had higher MeHg levels in post-spill (2012-2013) than in pre-spill (2007-2009) samples, while in benthic-associated predators, MeHg levels remained essentially unchanged. Results suggest that there are strong taxonomic differences that are not only more pronounced in fishes from the deep sea, but are higher in the Gulf of Mexico than they are in other parts of the world (Domi *et al.*, 2005; Asante *et al.,* 2008). These studies contribute significantly to our understanding of trophic ecology from coastal to deepwater environments.

Food Web and Earth System Models

The results discussed here refine our understanding of community structure in the NEGOM. They also provide data on the short-term (currently < 4 years) impacts of a major hydrocarbon release and environmental variability in the region that is essential to parameterize food web and earth system models. By synthesizing data across regions, these models can predict emergent and long-term effects of the spill and provide a means of forecasting the risks and consequences of events — from tropical storms to pollutant releases — that affect ecosystem function.

To predict long-term impacts of the spill on the connected ecological communities of the Gulf, Deep-C scientists couple new data they are producing with existing data to parameterize an Atlantis ecosystem model. Atlantis is a temporally- and spatially-explicit modeling framework that tracks the population dynamics, movement, and interactions of focus groups (species or groups of species considered together based on traits such as trophic level and habitat usage) across a specified study area. Following Deep-C's focus on connectivity and multidisciplinary expertise, this model tracks species (from planktonic organisms to top-level predators) across regions and depths. Focus groups (defined through collaborations of fishery ecologists, microbiologists, and benthic specialists) are tracked using data derived from their study to determine their distribution across the Gulf and potential impacts of exposure to oil. The modeling framework allows us to consider the "baseline" state of the Gulf and simulate how oil would move both passively and actively (via trophic interactions) through the environment while impacting population dynamics. Nutrient flux and passive transport across the Gulf are driven by long-term (50-year) HYCOM simulations, allowing us to capture potential impacts of the Loop Current on dispersing oil among communities. Overall, this model combines data being collected on multiple taxa and communities to offer estimates of how oil spills will ultimately affect ecological communities in the decades following a spill. We are also parameterizing a fishery portion of the model to extend our consideration to how human economies and communities may be impacted.

At the heart of the earth system model (ESM) is the coupled ocean-atmosphere-wave component. The ESM runs in hindcast/nowcast modes over a variety of high-resolution bathymetry-model grid configurations. Operational or quasi-operational nowcast/forecast products for atmosphere (Global Forecast System (GFS) 0.5° analysis), ocean (1/12° global HYCOM nowcast/forecast system), and wave (WAVEWATCH-III 1/15°) currently set initial and boundary conditions. The Oil Spill Prediction Environment (OSPRE) developed by Deep-C seamlessly ties the ESM high-resolution wind, wave and ocean components to state-of-the-art

3D oil spreading and weathering models to estimate the fate of discharged oil. A GIS-based user interface allows for the rapid evaluation of plausible scenarios which enhances the potential for informed decisions in cases of accidental spills. A biogeochemical component will be incorporated in the near future that bridges the ESM, OSPRE, and food web models, setting the stage for the integration of these models to capture the ways in which perturbations in one realm — ocean, atmosphere, land, and biosphere — reverberate throughout all others.

ACKNOWLEDGEMENTS

This research was made possible by a grant from BP/The Gulf of Mexico Research Initiative to the Deep-C Consortium.

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