2014 INTERNATIONAL OIL SPILL CONFERENCE

Overview of Research into the Coastal Effects of the Macondo Blowout from the Coastal Waters Consortium: A GoMRI Consortium

Linda M Hooper-Bui, Nancy N Rabalais, Annette S Engel, R Eugene Turner, G McClenachan, B Roberts, Edward B Overton, Dubravko Justic, Kersey Strudivant, Ken Brown, Jennifer Conover
Lhoope1@lsu.edu: To whom correspondence should be addressed; Louisiana State University, Baton Rouge, LA 70803 (nrabalais@lumcon.edu, aengel1@utk.edu, euturne@lsu.edu, gmccle2@tigers.lsu.edu, broberts@lumcon.edu, Eboverton@lsu.edu, djusti1@lsu.edu, kersey.sturdivant@duke.edu, kmbrown@lsu.edu, mconover@lumcon.edu)

ABSTRACT 300243:

The Coastal Waters Consortium (CWC) led by Louisiana Universities Marine Consortium is one of eight Gulf of Mexico Research Initiative research consortia. The CWC focuses on: oil transport and fate, chemical evolution and biological degradation, and environmental effects.The following is an overview of a portion of the research conducted within the consortium. The consortium works in a system that was impacted by the Deepwater Horizon oil disaster and additionally impacted by freshwater diversions resulting in changes in salinity, tropical storms, and hurricanes. First, we conducted model simulations assessing oil transport into the Barataria Bay estuary, which indicate that easterly winds and feeding of the anticyclonic gyre in the Louisiana Bight pushed the oil into Barataria Bay. In subtidal sediments adjacent to oiled marshes, marsh detritus from eroding marsh edges eventually became entrained in the sediment column.

Biotic impacts vary. The above-ground plant biomass appears healthy at the individual sampling sites; overall the most seaward (i.e., likely oil-impacted) areas of Terrebonne and Barataria Bay have shown, via satellite data, a distinct decline in marsh vegetation coverage since 2010. Oysters appear to be affected by predation and salinity variation.

Microbial diversity from marsh-edge sediments is distinct from before and after the spill, and between unoiled and oiled marshes, with lower diversity in oiled marshes; but the greatest community composition shifts are in marshes affected by the freshwater diversions. Changes in microbial diversity in the water column at the stream-side edge of oiled marshes are extensive and are related to marsh edge erosion. In contrast, oiling of marshes had no impact on ammonia oxidizer or denitrifier abundances and on soil biogeochemical process rates 2+ years post-spill. Analysis of long-term offshore phytoplankton community and hypoxia data indicate some signal of the Macondo oil, but these components of the ecosystem remain mostly influenced by the fresh water and nutrients delivered by the Mississippi River. The consortium continues to work to tease apart oil impacts, effects of salinity, natural variation, and disturbance from tropical storms and hurricanes to determine the trajectory for health of shelf waters and Louisiana's marshes.

INTRODUCTION:

During the Deepwater Horizon oil spill (DWH), millions of gallons of oil were leaked and an unprecedented amount of dispersant was added to the waters in the Gulf of Mexico. Little is known of the physiological affects of oil and dispersant on marine organisms and the resulting ecological and environmental impacts. Nearly 30% of coastal marshes in the United States occur along the Louisiana coast (Barras 2006, Barras et al 2003), where they are important for commercial fisheries and coastal ecosystem management, as well as global biogeochemical cycling of carbon, nitrogen, and other essential nutrients, metals, and gases and more significantly storm protection services. Coastal marshes are dynamic land-ocean transitional interfaces that accumulate and store large quantities of carbon in predominately anoxic soils, but being the interface between land and sea has put marsh ecosystems at risk due to both marine and terrestrial environmental stressors from tropical storms and hurricanes, sea-level rise, subsidence, and diminishing sediment supply (Blum and Roberts 2009, Kriwan and Temmerman 2009, and Kim et al 2011), as well as from anthropogenic activities like leeves, road, and pipeline corridor building (Kennish 2002, Turner and Rabalais 2003) or accidents like oil or chemical spills (Reddy et al 2002, Peacock et al 2007). Ecological stress is defined as a condition or parameter in excess of its normal range and variability that may adversely affect the way populations or communities function (Barrett et al 1976).

The Gulf of Mexico coastal ecosystem is not a pristine “natural” ecosystem, due to historical land use, coastal development, and resource management practices in the region. Add those interacting variables to dynamic issues such as tropical storms and sea level rise, the challenge of defining environmental baselines at a given point in time becomes problematic. The ecosystem, as a result of natural and human-caused disturbance, is transformed into an area of high losses of wetlands and sediments contaminated with petroleum hydrocarbons, including polycyclic aromatic hydrocarbons (PAHs), trace metals, and pesticides (www.btnep.org/BTNEP/news/oilspill/oilspillmaps.aspx).

It is important that our research is accessible to the general public. Many of our publications are in review in or in prep for open-access journals, and we employ an Education and Outreach Team. CWC Education & Outreach strives to offer high quality educational experiences for people of all ages and interests. Our series of public events are design to impact the diverse audiences that comprises of the citizenry of the gulf coast. Our K-12 and university field trips are hosted to support students in their desire to learn more and experience coastal science first-hand, and have reached more than 1250 people in the last year. They learn methods being used by our scientists and learn important skills that they can use in their careers. Their ability to understand coastal and marine environments means that one day they can help advance oil spill prevention and response in the Gulf of Mexico. CWC offers many types of teacher-education workshops and experiences. These activities are designed to give educator the information and experiences they need to translate the scientific methods and data generated by our scientists. By reaching out to the teachers CWC impacts many more individuals through the K-12 system. Our outreach through social media, regular media outlets, and participation at public festival extends CWC reach into the forefront of the public’s attention. As our followers and network broadens so does our impact.

The objectives of the Coastal Waters Consortium are to quantify of the impacts (or lack there of) of the PAHs from the DWH on a variety of organisms and onshore and offshore marsh processes.

MATERIALS AND METHODS:

General sampling and oil fate

For May 2010, September 2010, June 2011, and September 2011, sediment and water sampling was conducted at nine different marshes as part of a broad ecological survey of the potential impact of the DWH oil spill on the marsh ecosystems in Louisiana, USA (Figure 1). Continued sampling of a subset of marshes in Terrebone and Barataria bays (Fig. 1) has also been done twice a year as part of the CWC research from 2011 through 2013. At each sample location, water pH, temperature, and salinity data were acquired using standard electrode methods, and marsh inland water depth, canopy height (i.e. the height of the vegetation, such as marsh grass or mangroves), and other parameters pertaining to the marsh were measured (such as insects). Sediment samples for petroleum hydrocarbon concentrations are taken from the top few cm from the marsh edge and 10 m inland. Surface oil transport over the inner Louisiana shelf was investigated using a high-resolution three-dimensional Finite Volume Coastal Ocean Model (Justic and Wang, 2013).

Shoreline erosion

Data were derived from a spectral mixture (Rogers and Kearney 2004; Kearney and Riter 2011), and has been refined for use in marshes of the Mississippi Delta (Kearney et al. 2011). Both satellite imagery and on-the-ground measurements were used to target questions about shoreline erosion. We collected data on shoreline erosion, soil strength, percent cover of *Spartina alterniflora*, and marsh edge overhang at 30 closely-spaced low-oil and high-oil sites in Bay Batiste, Louisiana.

Biogeochemistry

We quantified the effects of the Deepwater Horizon oil spill on Louisiana salt marsh biogeochemical process rates 2-3 years post-spill through a combination of high temporal resolution sampling (monthly from May – September 2012 and bi-monthly beginning in March 2013) in Terrebonne Bay (TB), high spatial resolution sampling (at least 2 paired sets of unoiled and oiled marshes in Terrebonne Bay, western Barataria Bay (WB), and eastern Barataria Bay (EB) regions of the southeast Louisiana coast) 3 times/year, and/or in focused, intensive studies during summer. We quantified phosphorus sorption using the phosphorus sorption index (PSI) (for methods see Marton and Roberts 2014). Potential nitrification and potential denitrification and DNRA rates were determined using standard techniques that we have adapted for use in marshes (Bernhard et al. 2007; Koop-Jakobsen and Giblin 2010).

Microbes

For May 2010, September 2010, June 2011, and September 2011, sediment and water sampling was done as described above for the sediment sampling. Continued sampling of a subset of marshes in Terrebone and Barataria bays has also been done as described above. To understand microbial community diversity from the marsh sediment, samples have been taken approximately 1 m from the marsh edge offshore (i.e. the natural break in land slope where vegetation terminated into the open water) and about 5-10 m inland using replicate push-cores. Sediments were sectioned into sterile whirl bags in 1-cm increments from the surface to 10 cm depth, and then frozen to -20^{o} C within 12-24 hours of collection.

For microbial community diversity, total environmental nucleic acids was extracted within one week of collection from ~0.5 g sediment in triplicate using a modified sucrose lysis method (Mitchell and Takacs-Vesbach 2008) specific for the organic-rich soils (Liu 2011, Engel and Gupta In review). Methods for FLX amplicon pyrosequencing of the V1-V3 region of 16S rRNA genes, sequence validation and processing, for taxonomic assignments, as well as for statistical analyses were done using methods previously described, including Bray-Curtis similarity distance calculations, non-metric multidimensional scaling analyses, and similarity percentage (SIMPER) analyses to identify microbial groups that contributed the observed dissimilarity (or similarity) among clusters of data from different marshes over time (e.g., May 2010 versus May 2011), were done (Clarke 1993, Hammer et al 2001, Ramette 2007, Dowd et al 2008, Schloss et al 2009, Sun et al 2011, Gray and Engel 2013, Headd and Engel 2013).

Nearshore coastal waters

We asked a question early during the spill as to whether the hypoxia was affected by the oil spill. Data were also available to identify any long-term changes in the phytoplankton community. The 2010 shelf-wide cruise for determining the size and characteristics of the hypoxic zone occurred in late July 2010 after the capping of the well, but during a period when dispersed Macondo oil was measured in surface waters. The 2010 phytoplankton data were compared with data from years most similar in terms of river discharge and nitrogen loading.

Oysters

We also placed out mesh bags filled with cultch to examine effects on commensal diversity in three seasons in 2012 and 2013. Finally, we placed concrete surfaces on PVC poles ("reefcicles") to determine long-term differences on benthic succession. For shorter-term effects, we soaked settlement tiles and cultch in Louisiana light crude oil, placed them in the field, and retrieved them after one month.

Wormcam

We employed Wormcam (Sturdivant et al. 2012), a real-time benthic observing system consisting of a sediment profile camera and water quality datasonde, adjacent to two marshes in Terrebonne Bay, Louisiana, USA. To comparatively assess benthic function and sediment dynamics between the subtidal areas adjacent to oiled and clean marshes, two wormcam systems were deployed in September 2012, adjacent to marsh TB1 (clean marsh) and TB3 (oiled marsh) in Terrebonne Bay (Figure 1). The systems collected a time-lapse series of images and water quality data every half-hour, and have been collecting data from September to the present.

RESULTS & DISCUSSION:

Oil Fate

Figure 2a shows the average concentrations of individual PAH compounds and their respective alkyl homologs, in µg/Kg, in surficial sediment samples collected from marsh areas visually impacted by the Macondo spill from post spill 2010 to 2012. The insert shows analyses conducted by Overton where average individual PAH levels in sediments before the oil reached the shorelines in 2010 for reference. Oil is distributed heterogeneously in the environment. The oily residues in 2010 post-spill sediments reflected the composition of emulsions that came ashore during the active portion of the spill. The PAH composition of 2010 samples is composed predominately of two- and three-ringed PAHs and the alkyl homologs with the phenanthrenes dominating. As expected with environmental weathering, the two- and three-ringed compounds are degraded over time and the PAH composition in subsequent years has shifted to the four-ringed PAHs with chrysene and its alkyl homologs predominating (Bejarano and Michel 2010, Wang and Fingas 2003).

The Justic model accurately described formation of a quasi-permanent anticyclonic gyre in the Louisiana Bight region (Fig. 3). The strength and location of the gyre depend on the strength and duration of local wind forcing and the interaction of wind forcing and the Mississippi River plume. The gyre was present only during easterly winds with the maximum radius of 34 km and the longest freshwater residence time in the Louisiana Bight of about 15 days. Easterly winds initiate westward flow of Mississippi River waters around the delta. The westward current usually turns towards the coast between 89.5 and 89.8 W and subsequently splits into two branches before approaching the coastline between Terrebonne and Barataria Bays, one feeding the anticyclonic gyre in the Louisiana Bight and the other flowing westward along the Louisiana-Texas coast. During easterly winds associated with the peak river discharges, the westward current was about 20 km wide, exhibit velocities of 0.4-0.9 m s^{-1} and transports in excess of 10^5 m^3 s^{-1} of river and shelf water. Simulation experiments revealed that 44%, 39%, and 17% of the overall transport is due to wind forcing, buoyancy forcing, and offshore forcing, respectively. Model results indicate that the entrainment of oil into this anticyclonic gyre was the likely mechanism by which oil was transported into the Barataria Bay near the estuary in the aftermath of the Deepwater Horizon spill.

Effects on shoreline erosion

Using satellite imagery, trend for changes in percent vegetation based on Landsat Thematic Mapper imagery from 1984 to 2012 in Breton Sound, Barataria Basin, and Terrerbonne Basin are shown in Fig. 4. Variation in percentage of pixels covered by 40% or more vegetation between 1984 and 2011 based on spectral unmixing of composite NDVI, NDWI, and NDSI data sets calculated from Landsat TM and ETM+ surface reflectance in Terrebonne, Barataria, and Breton Sound basins. The data in the figure (organized in 20 km zones) indicate that marshes (mostly low mesohaline to tidal freshwater systems) in the most landward areas of Barataria Basin and Terrebonne Basin have been relatively stable, with even minimal effects from Hurricanes Katrina and Gustav, which tracked over the general region in 2005 and 2008, respectively. Upper brackish marshes in Breton Sound were not examined because previous work (Kearney et al. 2011) demonstrated that these marshes have undergone substantial, anthropogenic losses as a result of high nutrient loads from the Caernarvon freshwater diversion.

By comparison, marshes closest to the Gulf of Mexico (salt marshes to high salinity mesohaline marshes) show a progressive decline in vegetation percentage over the study period. This reflects a decline in marsh area, not vegetation vigor. The greatest change in these marshes was associated with Hurricanes Katrina (2005) and Gustav (2008), but the trends show that rapid recovery to previous conditions within two years or so. Declines in salt marshes (Zone 1) of Barataria Basin and Terrebonne Basin after 2010 could be the result of oil intrusion from the Macondo Oil Spill, but more data from succeeding years will be needed before this interpretation can be more certain.

Roughly 1,000 km of Louisiana's shoreline was oiled, equaling about 60% of the total oiled shoreline in the Gulf of Mexico (Owens et al 2011). The rate of land loss in Louisiana was significant before 2010 (42.92 km^2 y^{-1} from 1985 to 2010; (Couvillon 2011), and so the threat of increased erosion rates from the oiling in 2010 are an additional concern. The results are reported in McClenachan et al. (2013).

Boots-on-the-ground measurements saw no significant difference in aboveground cover or wave energy for our low and high oiled sites, yet we documented differing erosion rates and soil parameters. Heavy oiling weakened the soil below 50 cm, creating a deeper undercut at the marsh edge and causing the appearance of micro headlands at low oil sites. These micro headlands then received more wave energy than those that had eroded, causing an accelerated rate of erosion that cascaded along the shoreline (Figure 5; table 1). The compromised integrity of the marsh should, therefore, eventually lead to greater erosion at the high oil sites, which is what we observed in 2012. We conclude that the increased erosion documented at the high oil sites is most likely due to oiling and not background conditions. Although we are unsure of the exact processes involved in a cause-and-effect manner, our data provides evidence that quantifying belowground health up to 1 meter deep may be needed to accurately evaluate the impact that heavy oiling may have on coastal marshes.

Biogeochemistry

Nitrification potentials vary significantly in space and time in Louisiana marshes with rates being higher than other published marsh values from other regions. Nitrification showed either no differences or lower rates in oiled marshes with the strongest patterns in occurring in TB soils in 2013 and in *Avicennia germinans* compared to *Spartina alterniflora* soils in laboratory incubations. Total nitrate reduction rates across the Louisiana coast are very high compared to other regions with dissimilatory nitrate reduction to ammonium (DNRA) rates being comparable or higher than denitrification rates, but there not significant differences in rates with oil status. Oiled marshes had lower net soil CO2 and N2O fluxes and higher net CH4 fluxes than unoiled marshes. This pattern was observed in both seasonal field studies in Terrebonne Bay marshes and in laboratory incubations with Terrebonne and western Barataria Bay soils.

Additionally, results suggest mineral composition of marsh soils, influenced by elevation-inundation gradients, are critical in dictating P loading to estuaries and open waters, and overall marsh functioning. Further, within two years of the Deepwater Horizon oil spill, oiled marshes are able to sorb phosphorus at comparable levels as unoiled marshes.

Microbes

There were highly weathered inland oil (May 2010) originally from historical, unknown contamination, which suggested that oil contamination is likely a chronic stressor in the marshes (Odum 1985). As summarized by Engel et al. (In review) the pre-spill marsh bacterial communities were dominated by Firmicutes, *Gammaproteobacteria*, and Bacteroidetes, representing a combined 47-83% of the relative abundances of all major taxonomic groups depending on the marsh. By September 2010, some of the marshes were visibly contaminated by oil, all sampled inland and marsh edge sediments had detectable concentrations of total alkane and PAH compounds, and oil in several marshes could be traced specifically to MC252 oil (Turner et al. 2013). Of the marshes sampled for microbial community diversity, western Terrebonne Bay marshes had the greatest petroleum hydrocarbon contamination, and these bacterial communities had the greatest changes in community diversity according to statistical analyses.

Collectively, these results provide evidence that the function of microbial communities from the marshes impacted by the DWH oil spill may have shifted. Moreover, because community compositions became more dissimilar to each other over time for most of the marshes sampled, these results may indicate that microbial communities may have not recovered to pre-spill compositions. These communities may indicate a regime shift in community composition, whereby multiple taxonomic groups are capable of similar metabolic function, but it is possible that sustained shifts in community composition over time will change microbial functional within the marsh ecosystems, including changes to nutrient cycling. Continued investigations need to determine the combined effects of oiling at the marsh edge to inland sediments, functional (i.e. metabolic) changes at the microbial level, and the confounding effects of physical changes to the marshes over time, such as from flooding and marsh erosion.

Nearshore Coastal Waters

There are limited but complete sets of baseline data for some coastal waters, for example, the long-term monitoring of low-oxygen waters (hypoxia) on the inner Louisiana shelf since 1985. In addition, the phytoplankton community of these coastal waters has been enumerated since 1989. A question was raised early during the spill, because of the overlap in the geography of the low-oxygen zone and the distribution of dispersed oil in surface waters, as to whether the hypoxia was affected by the oil spill. Data were also available to identify any long-term changes in the phytoplankton community. Dispersed Macondo well oil was visible in the area of hypoxia from April through August of 2010. Crude-oil analyses of the water-column samples collected, however, found very little to no evidence of Macondo oil and were inconsistent with the oil fluorescence data. Multidimensional-scaling analysis from years most similar in terms of river discharge and nitrogen loading demonstrated that June and August 2010 samples had phytoplankton assemblages that were distinctive from other samples in 1999, 2008, and from April, May, July, and October of 2010, but that river-related parameters (e.g., nutrients and salinity) were most instrumental in influencing the composition of the phytoplankton community. The Mississippi River discharge in 2010 was well above average with three peaks in spring, and above-average flow from July to October. The high flow had the effect of extending conditions sustaining hypoxia formation and maintenance through the summer (high nutrient-enhanced production in surface waters, carbon flux of carbon to the seabed, and strong stratification). The size of the 2010 hypoxia area was within 10 percent of the predicted size (http://www.gulfhypoxia.net). Thus, we conclude that the oil spill did not affect the size of the hypoxic zone in 2010.

Oysters

Tile experiments suggested similar oyster recruitment among oiled and control sites, and that salinity and predation were more important drivers of recruitment success. The commensal bag and reefcicle experiments had similar results. Shorter-term studies indicated oiled tiles had fewer and smaller barnacles, but only at some sites. Oiled cultch did however lower short-term recruitment and biodiversity. Our working hypothesis is that hydrocarbon contamination was not high enough or consistent enough to lower oyster recruitment or reef biodiversity in Barataria Bay. “Spin off” experiments are looking in more detail at predation effects on oyster recruitment and substrate type on commensal diversity.

Wormcam

Early assessments found the sediment-water interface adjacent to both marshes to be highly dynamic, but different. Sediment change was significantly higher at the oiled site ($T=1783.5$, $p=0.002$), with sediment eroding or accreting as much as 7 cm hr^{-1}. The change in sediment at the oiled site was positively correlated with wind velocity ($F=14.5$, $p<0.001$), though neither wind nor tide was related to sediment change at the clean site. At the oiled site, during high wind events marsh detritus was documented to be advected into the subtidal and contained black hydrocarbon-like substances. The wind driven change in sediment at the oiled site was positively correlated with the presence of these hydrocarbon-like substances ($F=15.2$, $p<0.001$). These dynamics were not observed at the clean site. It is plausible that during the outwelling process sequestered hydrocarbons may be reintroduced into the subtidal (Dame et al. 1986).

Summary

Part of the experimental design was to conduct similar measurements, process studies, and experimental applications to pairs of “oiled” and “unoiled” in Terrebonne Bay, western Barataria Bay, and eastern Barataria Bay to historical research conducted by the 26 principal investigators. The paired study areas were not determined by the NOAA SCAT Data, but by repeated hydrocarbon analyses that indicated the presence of Macondo well oil and levels of exposure. The two did not necessarily coincide. It was also evident that there are many coastal sediments that are contaminated by a background level of hydrocarbons and PAHs. These features can be used to characterize the exposure of wetlands and subtidal sediments to background and Macondo well sources of hydrocarbons. Subsequent results from CWC research observations can be used in a BACI (before after control impact) or as paired levels of exposure “oiled” and “unoiled.” The original field design also took into account that shorelines were exposed to heavier oiling than the interior of marshes. These same shorelines are affected by multiple stressors of slow erosion rates, oil-induced loss of plants and then shorelines, typical wave and surge energy depending on direction and force, and hurricane surges. In other words, the “baseline” within the “baseline” is also evolving. Taken with a knowledge of high variability within marsh and subtidal habitats, it may seem difficult to identify impacts related to oil exposure. Still, these observations have been and are being verified. Where there were no differences, the variability was high or alternatively there was no difference. In either case, a solid set of background data are now in place for aspects of the Louisiana coastal ecosystem against which further change can be detected.

REFERENCES:

Barras JA 2006. US Geological Survey Open File Report 06-1274.

Barras JA, Beville S, Britsch D, Hartley S, Hawes S, et al. (2003). USGS Open File Report 03-334.

Barrett GW, Van Dyne GM, Odum EP. BioScience 26: 192-194**.**

Bejarano, AC and Michel, J. 2010. Environmental Pollution 158: 1561–1569.

Blum MD, Roberts HH (2009) Nature Geoscience 2: 488-491.

Bernhard AE, Tucker J, Giblin AE, Stahl DA. 2007. Environmental Microbiology 9, 1439-1447.

Clarke KR 1993. Aust Ecol 18: 117-143.

Couvillion BR, Barras JA, Steyer GD, Sleavin W, Fischer M, Beck H, Trahan N, Griffin B, and Heckman D 2011 Land area change in coastal Louisiana from 1932 to 2010: U.S. Geological Survey Scientific Investigations Map 3164, scale 1:265,000, 12 p. pamphlet.

Dame R, Chrzanowski T, Bildstein K, Kjerfve B, McKellar H, Nelson D, Spurrier J, Stancyk S, Stevenson H, Vernberg J, Zingmark R (1986). Marine Ecology Progress Series 33:217-229.

Dowd SE, Sun Y, Wolcott RD, Domingo A, Carroll JA. 2008. Foodborne Pathogens and Disease 5: 459-472.

Engel AS, Gupta A (In review) PLoS ONE.

Gray CJ, Engel AS. 2013. ISME Journal 7: 325-337.

Hammer O, Harper DAT, Ryan PD. 2001. Palaeontologia Electronica 4: 1-9.

Headd B, Engel AS. 2013. Applied and Environmental Microbiology 79: 1171-1182.

Justic D and Wang L. 2013. Continental Shelf Research, DOI:10.1016/j.csr.2013.08.006.

Kearney MS and Riter A. 2011. Wetland Ecology and Management. DOI 10.1007/s11273-011-9222-6.

Kearney MS, A Riter and Turner RE. 2011. Geophysical Research Letters 38: DOI:10:1029/2011GL047847, 2011.

Kennish MJ 2002. Environmental Conservation 29 78-107

Kim D, Bartholdy J, Jung S, Cairns DM 2011. Geography Compass 5: 219-236.

Kirwan M, Temmerman S 2009. Quaternary Science Reviews 28: 1801-1808.

Koop-Jakobsen K and Giblin AE. 2010. Limnology and Oceanography 55: 789-802.

Liu C 2011. Geomicrobiology of Louisiana coastal marshes before and after the *Deepwater Horizon* oil spill. Baton Rouge: Louisiana State University. 68 p.

McClenachan G, Turner RE, and Tweel AW. 2013. Environmental Research Letters 8: 044030

Marton JM and Roberts BJ. 2014. Biogeosciences. 10.1002/2013JG002486.

Odum EP. 1985. BioScience 35: 419-422.

Owens EH, Santner R, Cocklan-Vendl M, Michel J, Reimer PD, and Stong B. 2011. International Oil Spill Conference Proceedings 2011(1): 271.

Peacock EE, Hampson GR, Nelson RK, Xu L, Frysinger GS, Gaines RB, Farrington JW, Tripp BW, Reddy CM. 2007. Marine Pollution Bulletin 54:214–225.

Ramette A. 2007. FEMS Microbiology Ecology 42: 142-160.

Reddy CM, Eglinton TI, Hounshell E, White HK, Xu L, Gaines RB, and Frysinger GS. 2002. Environ. Sci. Technol., 36: 4754–4760

Rogers AS and Kearney MS. 2004. International Journal of Remote Sensing 12: 2317-2335.

Schloss PD, Westcott SL, Ryabin T, Hall JR, Hartmann M, et al. 2009. Appl Environ Microb 75: 7537-7541.

Sun Y, Wolcott RD, Dowd SE. 2011. Methods in Molecular Biology. pp. 129-141.

Sturdivant SK, Diaz RJ, Cutter GR 2012. Public Library of Science ONE, 7(4); DOI 10.1371/e34539.

Sun Y, Wolcott RD, Dowd SE. 2011. Methods in Molecular Biology. pp. 129-141.

Turner RE and Rabalais NN. 2003. BioScience 53: 563-572.

Turner RE, Overton EB, Ashton BM, Miles MS, McClenachan G, Hooper-Bui L, Summer Engel A, Swenson EM, Lee JM, Milan CS, and Gao H. 2014. Marine Pollution Bulletin in review.

Wang Z and Fingas MF. 2003. Marine Pollution Bulletin 47:423–452

Figure 1. Marsh area in south Louisiana where the Coastal Waters Consortium work is conducted. Map from USGS.

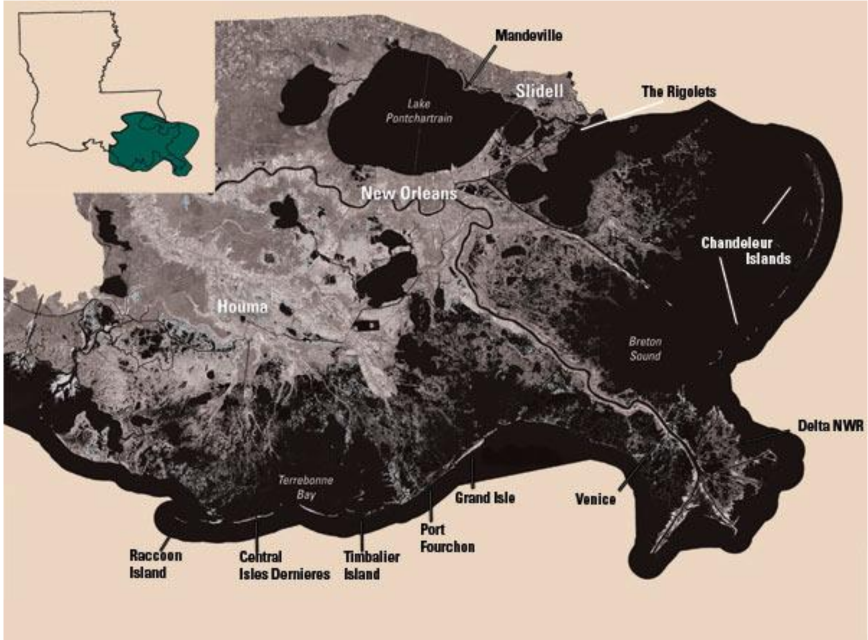
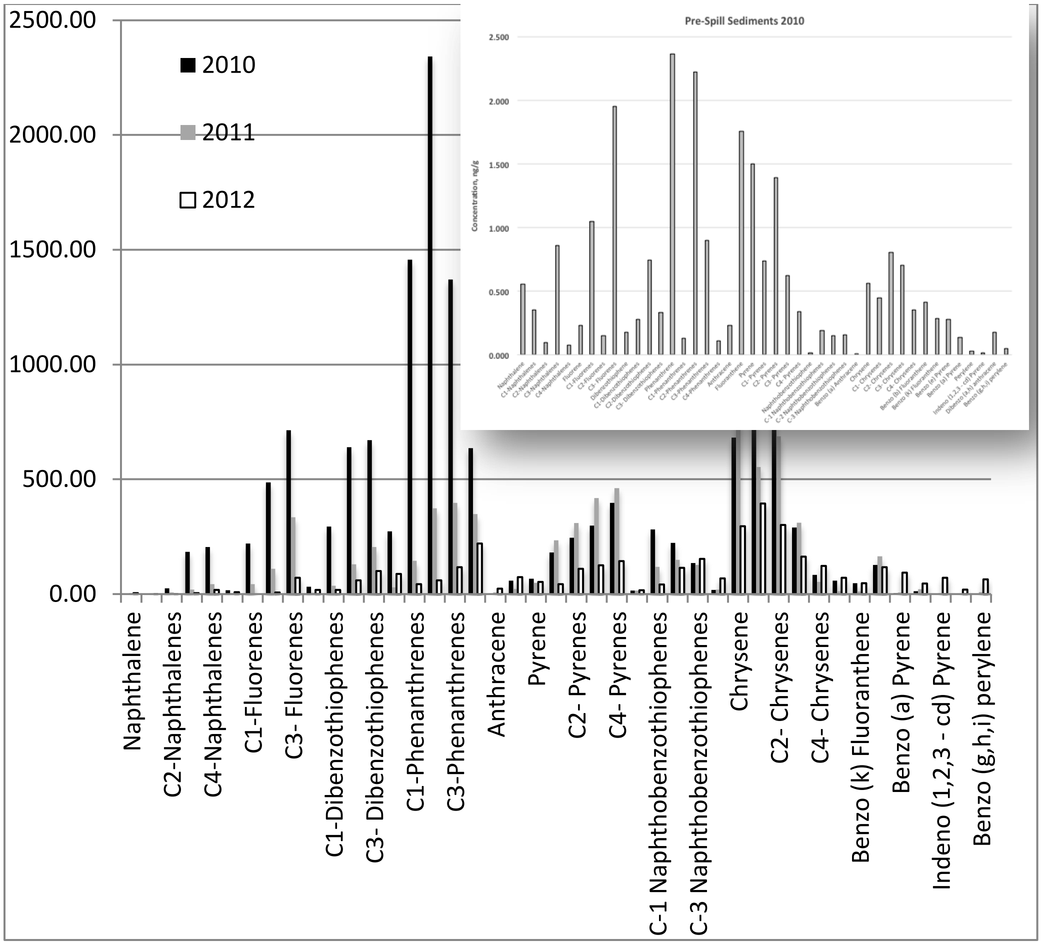
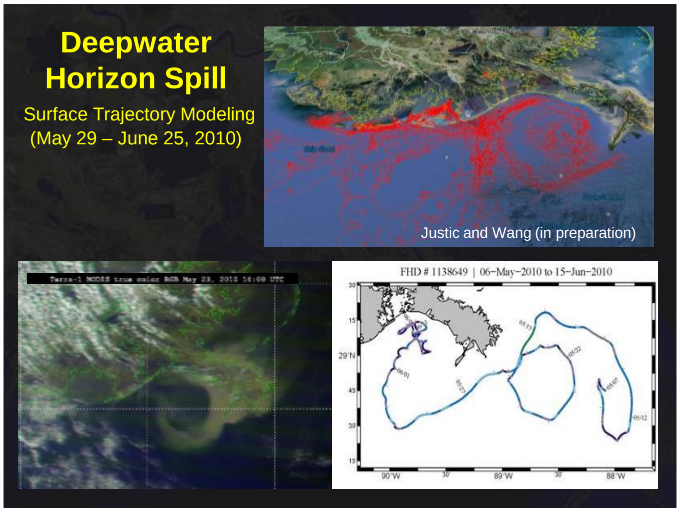


Figure 2. Depicted is the average concentrations of the individual PAH compounds and their respective alkyl homologs, in µg/Kg, in surficial sediment samples collected from marsh areas visually impacted by the Macondo spill over the time frame from post spill 2010 to 2012.





Deepwater Horizon Spill

Surface Trajectory Modeling (May 29 – June 25, 2010)

Justic and Wang (in preparation)

Figure 3. Comparison of modeled (upper rt panel) and observed (lower rt panel) drifter trajectories for period May 29 – June 25, 2010. MODIS image in the lower left panel shows an anticyclonic gyre in the Louisiana Bight on May 23, 2010.

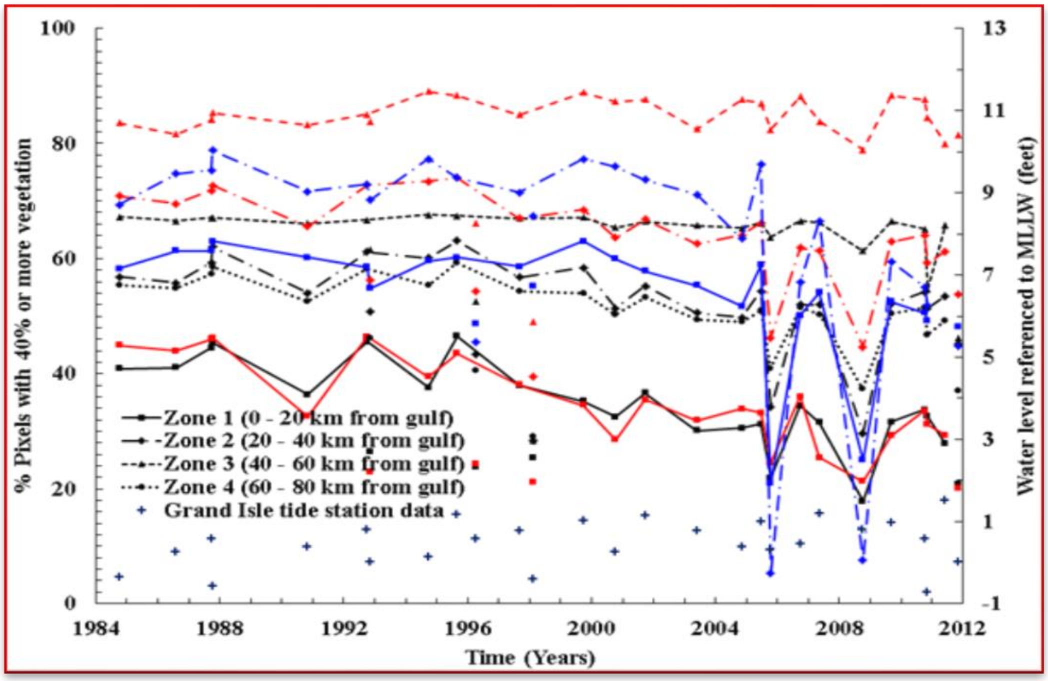


Figure 4. This graph shows the long-term changes in marsh vegetation for the Terrebonne Bay, Barataria Bay, and Breton Sound. Results are shown for 20 km wide zones as measured from the coastline of the Gulf of Mexico. Terrrebonne basin data is red, Barataria basin data is black, and Breton Sound basin is blue. Length of line decreases as distance from the coast increases (see legend on graph). Estimated error is ± 6.12%.

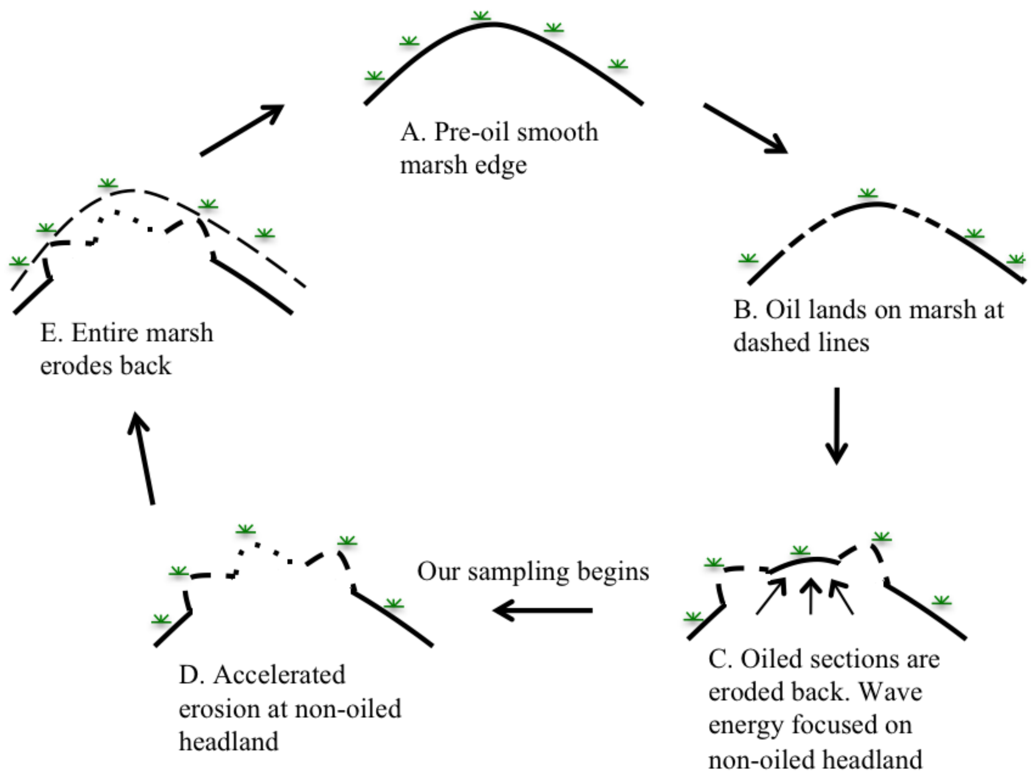


Figure 5. Schematic of oiling of portions of marsh edge. A. Marsh before oiling; B. Oil on certain portions of marsh and erodes those sections (dashed line). C. This erosion causes headlands to form, which in turn, are exposed to wave energy from more directions. D. Erosion rate accelerates at non-oiled section (dotted line). E. Equilibrium is reached and erosion rates slow to background rates until next event. From: McClenachan, et al 2013.

Table 1. Concentration of PAH ($\mu \pm 1$ SE) in sites contaminated with Macondo oil (MC252) and those without (No MC252), and low ($<1000\ \mu\text{g kg}^{-1}$) and high ($>1000\ \mu\text{g kg}^{-1}$) oiled categories.

	Sample size	PAH concentration ($\mu\text{g kg}^{-1}$)
MC252	19	$23\,648 \pm 7405$
No MC252	11	143 ± 15
High	17	$26\,390 \pm 8030$
Low	13	172 ± 30