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Functioning of Coastal River-Dominated Ecosystems and Implications for Oil Spill Response: From Observations to Mechanisms and Models

Adam T. Greer
University of Southern Mississippi, adam.greer@usm.edu

Alan M. Shiller
University of Southern Mississippi

Eileen E. Hoffman
Old Dominion University

Jerry D. Wiggert
University of Southern Mississippi

Sally J. Warner
Oregon State University

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Authors

Adam T. Greer, Alan M. Shiller, Eileen E. Hoffman, Jerry D. Wiggert, Sally J. Warner, Sabrina M. Parra, Chudong Pan, Jeffrey W. Book, DongJoo Joung, Steven K. Dykstra, Jeffrey W. Krause, Brian Dzwonkowski, Inia M. Soto, M. Kemal Cambazoglu, Alison L. Deary, Christian Briseño-Avena, Adam D. Boyette, Jessica A. Kastler, Virginie Sanial, Laura Hode, Uchenna Nwankwo, Luciano M. Chiaverano, Stephan J. O'Brien, Patrick J. Fitzpatrick, Yee H. Lau, Michael S. Dinniman, Kevin M. Martin, Peng Ho, Allison K. Mojzis, Stephan D. Howden, Frank J. Hernandez, Ian Church, Travis N. Miles, Su Sponaugle, James N. Moum, Robert A. Arnone, Robert K. Cowen, Gregg A. Jacobs, Oscar Schofield, and William M. Graham

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Functioning of Coastal River-Dominated Ecosystems and Implications for Oil Spill Response

FROM OBSERVATIONS TO MECHANISMS AND MODELS

By Adam T. Greer, Alan M. Shiller, Eileen E. Hofmann, Jerry D. Wiggert, Sally J. Warner, Sabrina M. Parra, Chudong Pan, Jeffrey W. Book, DongJoo Joung, Steven Dykstra, Jeffrey W. Krause, Brian Dzwonkowski, Inia M. Soto, M. Kemal Cambazoglu, Alison L. Deary, Christian Briseño-Avena, Adam D. Boyette, Jessica A. Kastler, Virginie Sanial, Laura Hode, Uchenna Nwankwo, Luciano M. Chiaverano, Stephan J. O'Brien, Patrick J. Fitzpatrick, Yee H. Lau, Michael S. Dinniman, Kevin M. Martin, Peng Ho, Allison K. Mojzis, Stephan D. Howden, Frank J. Hernandez, Ian Church, Travis N. Miles, Su Sponaugle, James N. Moum, Robert A. Arnone, Robert K. Cowen, Gregg A. Jacobs, Oscar Schofield, and William M. Graham

ABSTRACT. Coastal river-dominated oceans are physically complex, biologically productive, and intimately connected to human socioeconomic activity. The Deepwater Horizon blowout and subsequent advection of oil into coastal waters of the northern Gulf of Mexico (nGOM) highlighted the complex linkages among oceanographic processes within this river-dominated system and knowledge gaps about it that resulted in imprecise information on both oil transport and ecosystem consequences. The interdisciplinary research program implemented through the CONsortium for oil exposure pathways in COastal River-Dominated Ecosystems (CONCORDE) is designed to identify and quantitatively assess key physical, biological, and geochemical processes acting in the nGOM, in order to provide the foundation for implementation of a synthesis model (coupled circulation and biogeochemistry) of the nGOM shelf system that can ultimately aid in prediction of oil spill transport and impacts. CONCORDE field and modeling efforts in 2015–2016 focused on defining the influence of freshwater input from river plumes in the nGOM. In situ observations, combined with field-deployed and simulated drifters, show considerable variability in the spatial extent of freshwater influence that is related to wind direction and strength. Increased primary production and particle abundance (a proxy for secondary production) was observed during the spring when nGOM shelf waters were becoming stratified. Zooplankton and marine snow displayed intense vertical and horizontal patchiness during all seasons, often aggregating near the halocline. Simulations of a neutrally buoyant tracer released offshore of the Mississippi Bight showed surface advection of low tracer concentrations onto the inner shelf under high river discharge, high stratification, and variable wind conditions compared to almost no advection onto the inner shelf under low discharge, negligible stratification, and generally northeasterly winds. The interconnectedness of environmental variables and biological activity indicate that multiple factors can affect the transport of oil and the resulting ecological impacts. The process-oriented understanding provided by CONCORDE is necessary to predict ecosystem-level impacts of oil spills, and these results are applicable to other river-dominated coastal systems worldwide that often support oil extraction activities.

BACKGROUND

The April 2010 explosion of the Deepwater Horizon (DWH) drilling rig resulted in the loss of 11 lives, as well as the release into the Gulf of Mexico of ~5 million barrels of oil, 1.7×10^{11} g of methane, and other gaseous hydrocarbons from the Macondo well located at ~1,500 m depth (Reddy et al., 2012). The unprecedented magnitude of this 87-day spill eventually led to oil washing up along the northern Gulf of Mexico (nGOM) coast from Louisiana to Florida, producing substantial environmental damage (Michel et al., 2013; Murawski et al., 2016). Wind-driven circulation interacting with complex freshwater flows derived from numerous river inputs influenced the trajectory of oil on the shelf (Kourafalou and Androulidakis, 2013; Özgökmen et al., 2016) and made predictions of oil transport and impacts difficult (Joye et al., 2016; Özgökmen et al., 2016). The ability to forecast the movement of the oil was further complicated by river diversions that augmented river discharge in an attempt to keep oil from coming ashore in certain areas (O'Connor et al., 2016).

The challenges of predicting DWH spill effects were exacerbated by the three-dimensional (3-D) movement of the oil from depth. Approximately half of the released oil reached the surface (Federal Interagency Solutions Group, 2010; Passow and Hetland, 2016) as a weathered, reddish-brown substance, less cohesive compared to crude oil (Peterson et al., 2012). The other half formed a deepwater plume that settled at approximately 1,100 m (Diercks et al., 2010), where it was advected by midwater and deep-sea currents (Camilli et al., 2010). Marine snow particles provided a mechanism to export some of this midwater oil to depth (Hazen et al., 2010; Valentine et al., 2014; Daly et al., 2016; Passow and Ziervogel, 2016), where it likely had an impact on sensitive and poorly studied deep-sea ecosystems (Schrope, 2011; Fisher et al., 2014). Surface oil was observed in the Mississippi Bight (MacDonald et al., 2015) and reached the nearby coastlines (Nixon et al., 2016), yet there are no reliable estimates of the exact percentage of spilled oil that was transported to the coast, which necessitates approximations in oil fate budgets accounting for oil recovery/burning, evaporation, microbial degradation, sedimentation, and advection (Passow and Hetland, 2016). Because biological production and fisheries activity is concentrated on the nGOM shelf and in coastal habitats (Grimes, 2001), oil in this region can have a disproportionately strong ecological impact that is directly connected to human social and economic well-being.

The Mississippi Bight region of the nGOM (Figure 1) represents a critical intermediary between the DWH oil spill site and coastal ecosystems. Flanked by the Mobile Bay outflow to the east and barrier islands to the north and west, this region is characterized by dynamic river- and wind-influenced flows. In addition to the substantial freshwater discharge from Mobile Bay (annual average of ~2,200 $m^3\ s^{-1}$; Gelfenbaum and Stumpf, 1993), numerous smaller rivers empty directly into Mississippi Sound (shallow waters north of the barrier islands) or enter indirectly through Lake Pontchartrain, totaling ~928 $m^3\ s^{-1}$ (Sikora and Kjerfve, 1985). While an estimated 47% of the Mississippi River discharge travels east and offshore (Dinnel and Wiseman, 1986), the amount that moves toward the inner shelf of the Mississippi

FACING PAGE. Surface convergence at a density front near Main Pass at the mouth of Mobile Bay. Exchange between fresher estuarine and saltier shelf waters can generate these features, which are common in the northern Gulf of Mexico shelf ecosystem and influence the distributions of biogeochemical constituents. *Photo credit: Brian Dzwonkowski*

Bight has not been quantified. Under circumstances when the Mississippi River reaches flood stage near New Orleans, as it did in January 2016, the Bonnet Carré Spillway is used to divert river water into Lake Pontchartrain, which then flows into Mississippi Sound.

The wide and shallow nGOM shelf receives a seasonally variable supply of nutrients and particulates from the rivers that flow into Mississippi Sound and Mobile Bay, or directly onto the shelf. This riverine input is essential to maintaining the high primary production (Lohrenz et al., 1997) and fertile fishing grounds (Grimes, 2001) that characterize the nGOM. Circulation near the shelf edge and beyond is influenced by winds, river plumes, and mesoscale eddies spawned by and interacting with the Loop Current (Sturges and Leben, 2000; Ohlmann et al., 2001; Oey et al., 2005). The physical processes that affect nGOM shelf circulation act at a range of spatiotemporal scales, making accurate forecasting of oil transport patterns challenging. The biological and chemical processes that impact oil fate and toxicity contribute additional complexity to these challenges.

The clear need to understand transport and oil exposure pathways in the pulsed, river-dominated Mississippi Bight led to the implementation of the CONsortium for oil spill exposure pathways in COastal River-Dominated Ecosystems (CONCORDE). The CONCORDE research agenda centers on three scientific objectives: (1) to characterize the complex, 3-D physical oceanographic setting in order to understand potential oil pathways; (2) to describe spatiotemporal distributions of planktonic organisms, as well as geochemical and bio-optical parameters at scales relevant to processes transporting oil; and (3) to generate a synthesis model (Box 1) to predict oil transport on continental shelves and potential ecological impacts during future spill events for pulsed, river-dominated coastal ecosystems that incorporates new information on physical,

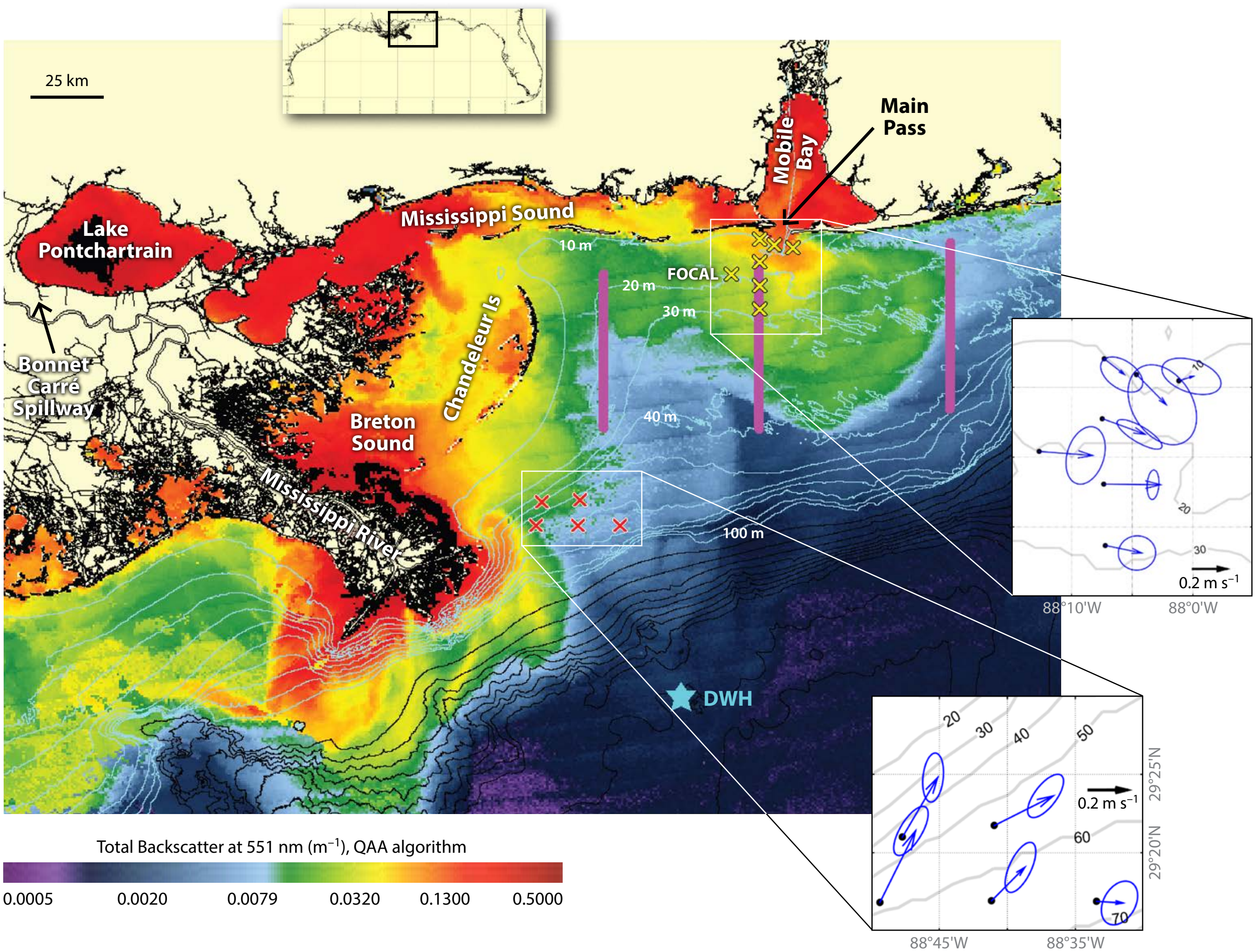

FIGURE 1. Map of the CONCORDE (CONsortium for oil exposure pathways in COastal River-Dominated Ecosystems) study region showing field sampling corridors within the Mississippi Bight (magenta lines, samples between corridors not shown) and the locations of moored instruments (red and yellow Xs). The color shading shows surface optical backscatter (a proxy for relative chlorophyll-*a* distribution obtained from the Visible Infrared Imaging Radiometer Suite, VIIRS) on April 5, 2016, corresponding to a high river discharge event. Inset maps for the mooring arrays show the depth-averaged current vectors with ellipses encompassing, on average, 93% of the current variability for April 5, 2016. The blue star marks the location of the Deepwater Horizon (DWH) drilling platform.

Box 1. Synthesis Model

The CONCORDE synthesis model, which simulates various oceanographic conditions by incorporating several data sources, can be used for assessment and prediction of the effects of future oil spills entering the Mississippi Bight. The circulation model is based on a 400 m resolution implementation of the Regional Ocean Modeling System (ROMS; Shchepetkin and McWilliams, 2005; Haidvogel et al., 2008) within the Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modeling system (Warner et al., 2010). The model encompasses Mobile Bay and the Mississippi Sound and Bight, extending to 87.30°W and 29.25°N. Boundary conditions are from the 1 km resolution Navy Coastal Ocean Model (NCOM), with river discharge estimated from US Geological Survey data. The biogeochemical model is based on a nitrogen, phytoplankton, zooplankton, detritus model (Fennel et al., 2006; Hofmann et al., 2008; Druon et al., 2010) and simulates nitrogen in various states (dissolved organic nitrogen, nitrate, ammonium, inorganic suspended particulate matter) using two size classes of phytoplankton and detritus, three size classes of zooplankton, and larval fish, all of which can be used to estimate dissolved oxygen concentrations (following Wiggert et al., 2017). CONCORDE field measurements and routine in situ data sets provide calibrations and verification of the ecosystem parameter settings.

Atmospheric forcing is from an hourly 0.01° gridded meteorological reanalysis product composed of several parameters. The Real-Time Mesoscale Analysis (RTMA; De Pondeca et al., 2011) provides surface momentum and thermodynamic atmospheric data. Radiation parameters and total cloud cover percentage are from North American Mesoscale Forecast System (NAM) fields. Hourly precipitation is provided by the Next Generation Weather Radar Level-III (NEXRAD). Gridded sea surface temperature fields (SST) are computed daily using a 10-day running mean of the Advanced Very High-Resolution Radiometer (AVHRR) SST product. The Coupled Ocean-Atmosphere Response Experiment (COARE) flux algorithm calculates sensible heat flux and surface momentum stresses (Fairall et al., 2003).

The CONCORDE synthesis model examines responses to oceanographic conditions and river plume dynamics, providing insights into ecosystem impacts from oil reaching the shelf and nearshore waters. The simulations are designed to evaluate several processes, including (1) environmental controls (e.g., river discharge) on retention/flushing of plankton and dissolved constituents in the study region; (2) physical-biological controls on organism distributions; and (3) suspended particle dynamics and its role in particle aggregation and sinking, with emphasis on toxin transport, removal/retention, and resuspension. Additional simulations consider climate change or management responses (e.g., spillway openings, agricultural practices) that modify freshwater discharge, nutrient forms, and concentrations of terrigenous particulates into coastal waters of the nGOM.

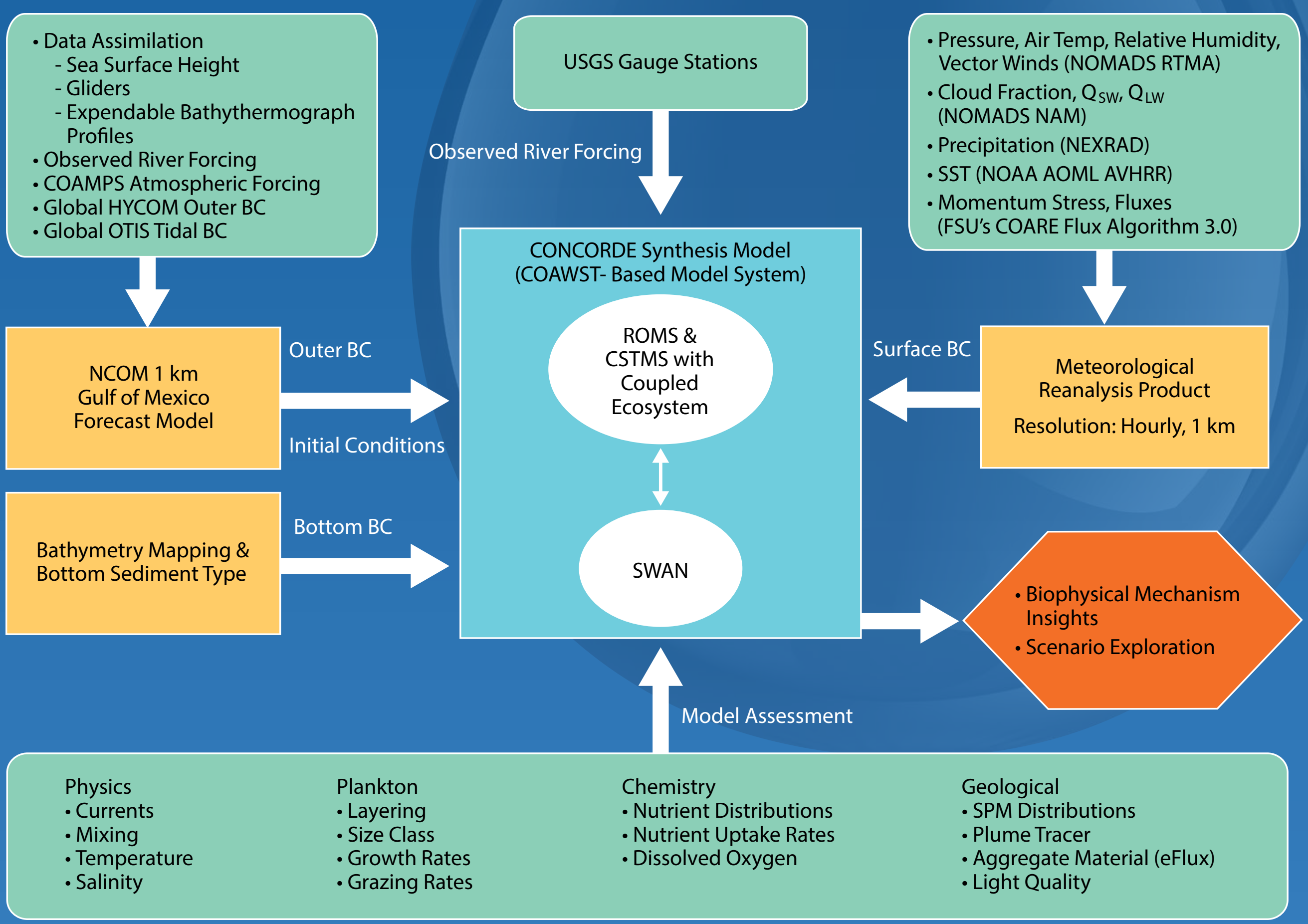

FIGURE B1-1. Conceptual diagram showing the data (green boxes) informing the initial and boundary conditions (BC; tan boxes) for the 4-D synthesis model. Field-collected data (green box at the bottom) are used for model assessment and validation. SWAN (Simulating WAves Nearshore) and the CSTMS (Community Sediment Transport Modeling System) simulate the impact of surface wave-current interactions and suspended sediment fields, respectively, within the coupled physical-biogeochemical model. The model runs under different oceanographic conditions to examine mechanisms of oil impact on the nGOM ecosystem (orange hexagon).

biological, and biogeochemical processes. This effort includes outreach activities designed to disseminate findings and build public trust in scientific information related to the DWH spill (see Box 2).

CONCORDE results are directly applicable to risk assessment, coastal system management, and examination of how ecosystem-level oil impacts may vary depending on the season when an oil spill occurs. Here, we highlight new information generated from sampling different zones of freshwater influence, and we explore how this information supports an emerging oil spill response paradigm (Graham et al., 2011; Peterson et al., 2012) that involves the use of four-dimensional (4-D) descriptions (3-D spatial plus temporal) to predict transport patterns and ecosystem impacts. The processes elucidated from this research are relevant to other ecologically and economically important river-dominated coastal ecosystems found throughout the world.

CONCORDE APPROACH

Research Cruises

The CONCORDE field research approach combined continuous observations from satellites, moored platforms, and autonomous gliders with seasonal ship-based field sampling campaigns in 2015 and 2016 under differing vertical stratification regimes and shifts in wind direction/intensity (Figure 2, Table 1). The ship-based sampling, which focused on zones in the Mississippi Bight with varying degrees of freshwater influence, consisted of fixed surveys and adaptive sampling to document fine-scale processes that influence oil transport and exposure of organisms (e.g., river plumes, fronts, layers with high plankton concentrations).

Physical Oceanography

Physical oceanographic measurements were obtained using a variety of instruments deployed from small boats, moorings, autonomous gliders, and research vessels, providing a 4-D description of the physical dynamics. The moored (fixed position) observations were supplemented by three deployments of autonomous underwater gliders prior to and during cruises. Small boat surveys were conducted to examine the freshwater pulses exiting Main Pass at the mouth of Mobile Bay, an example of a major tidal inlet associated with the barrier islands found in the nGOM. The near-field physical properties (e.g., plume depth, spreading rate, and frontal features) and their impact on the overall fate of freshwater discharge and particulate export along the coastal boundary of the CONCORDE sampling domain were determined from drifter releases and CTD and Laser In Situ Scattering and Transmissometer casts (for suspended particulates).

Moorings were deployed in two regions to capture the freshwater flows over different seasons (Figure 1). During the fall, a season typically characterized by low freshwater discharge, five line and bottom moorings were placed near the shelf break on the western side of the study area, where Mississippi River plumes were most likely to traverse (Figure 1, red Xs). Line moorings with sensors measuring temperature, salinity, and turbulence were deployed for the month of November 2015. Bottom moorings with upward-looking acoustic Doppler current profilers (ADCPs) and pressure sensors remained until mid-April 2016. In the spring, an array of six bottom moorings and three line moorings (Figure 1, yellow Xs) was placed just south of the Main Pass of Mobile Bay to observe plume dynamics and exchanges onto the shelf. This mooring array near the Mobile Bay outflow supplemented existing long-term observations by the Fisheries Oceanography in Coastal Alabama (FOCAL) mooring, allowing better resolution of the complex plume structure. Turbulence was estimated using bottom ADCPs and high-resolution thermistors and pitot-static tubes on χ-pods (Moum and Nash, 2009) tethered to line moorings.

Research vessels collected high-resolution measurements over broad

Box 2. Outreach Program

Because CONCORDE research is directly applicable to several environmental and economic issues affecting the nGOM coast (e.g., fisheries, hypoxia, tourism), outreach activities are organized to distill research findings in order to make them accessible to a broader audience. Outreach activities targeted to specific audiences include (1) a seminar series about scientific progress in the nGOM five years after the Deepwater Horizon spill, (2) teacher professional development, and (3) a citizen science initiative with multi-ethnic fishing community members from the nGOM coast.

Three teacher workshops coincided with the deployment of several autonomous underwater vehicles (known as the "AUV Jubilee") and aircraft in July 2015. In the first workshop, participating teachers worked with CONCORDE researchers and external scientists to conduct a synchronous data collection event in the nGOM to explore basic concepts in oceanography. At the end of this workshop, each teacher submitted a lesson plan based on concepts relating to the nGOM oil spill. Teachers in subsequent workshops offered input on the lessons, which are being distributed as a high school science curriculum.

Members of the fishing community are engaged with the CONCORDE project by learning to collect oceanographic data (e.g., YSI CastAway portable CTD) that can be used to validate model outputs. During training sessions, scientists and fishermen interact with the objective of improving trust in scientific findings within the fishing community, which is frequently at odds with regulatory agencies. Additionally, local knowledge provided by the fishing community may inspire new lines of scientific inquiry, and scientists provide advice on effective participation in local decision-making. These efforts are examples of fruitful collaboration among public, research, and regulatory groups.

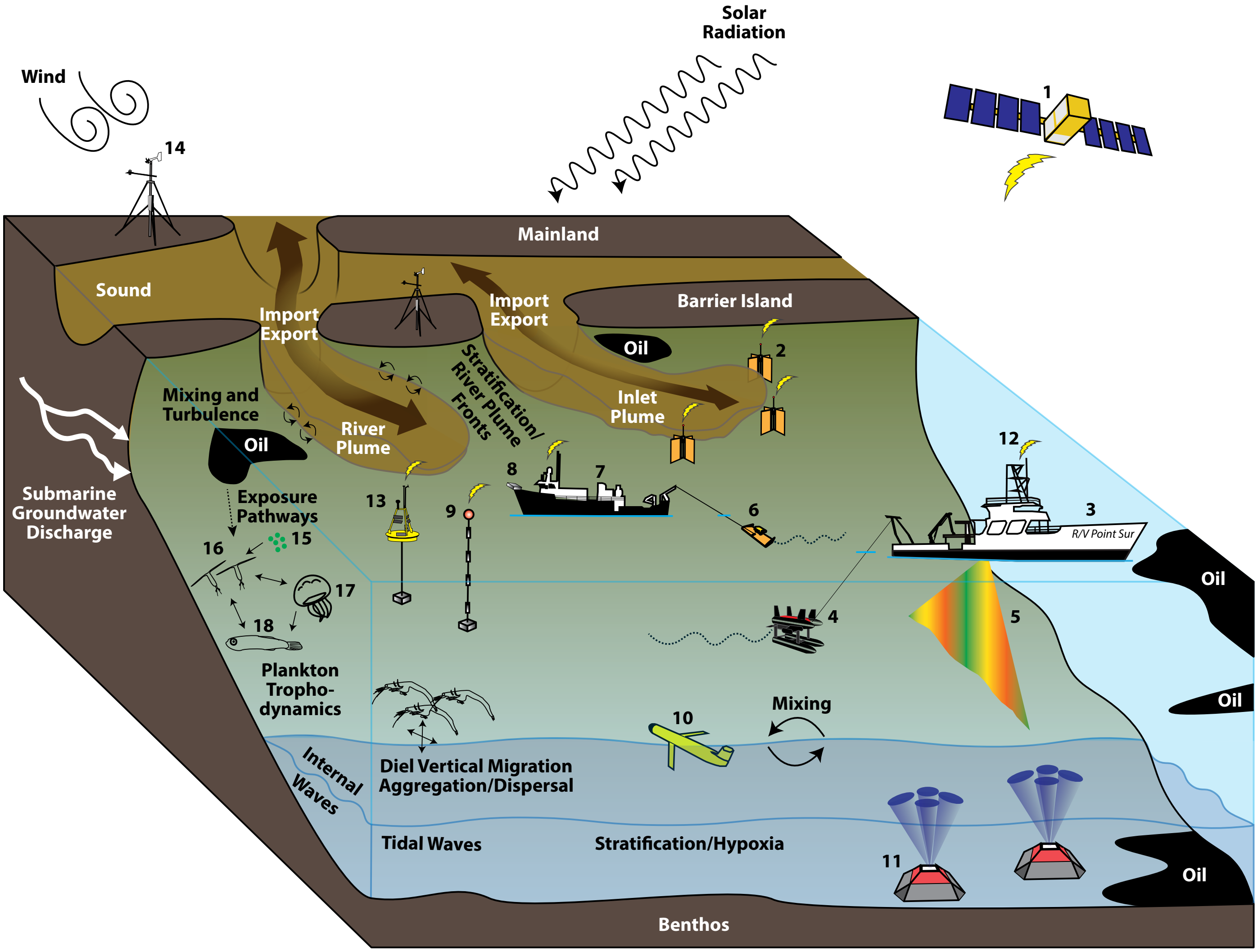

FIGURE 2. Schematic representation of the dynamic processes in the nGOM that influence the distribution, transport, and exposure pathways of oil in the planktonic community. Measurements related to these processes were collected with (1) the Suomi National Polar-Orbiting Partnership satellite equipped with a Visible Infrared Imaging Radiometer Suite; (2) surface drifters; (3) R/V *Point Sur* equipped with a CTD rosette, a sediment multicorer, a BIONESS multi-net system sampling at different depths, and an incubator as well as (4) an In Situ Ichthyoplankton Imaging System (ISIIS) and (5) Reson multibeam acoustics; (6) a Scanfish system shown being towed by (7) R/V *Pelican*, which is equipped with a CTD, a Chameleon microstructure profiler, and (8) ship-based Lidar; (9) a line mooring with sensors measuring current velocity, temperature, salinity, dissolved oxygen, turbulence, and optical properties; (10) an autonomous underwater glider; (11) bottom moorings with ADCPs and bottom pressure sensors; (12) satellite communication; (13) a Central Gulf of Mexico Ocean Observing System (CenGOOS) buoy and Fisheries Oceanography in Coastal Alabama (FOCAL) moorings; and (14) weather stations that include anemometers and various samplers for measuring biological properties of the plankton community, which includes (15) phytoplankton, (16) micro- and mesozooplankton, (17) gelatinous zooplankton, and (18) ichthyoplankton.

spatial and short temporal scales compared to moored and glider observations, which were limited in their spatial coverage. R/V *Point Sur* towed the undulating In Situ Ichthyoplankton Imaging System (ISIIS; Cowen and Guigand, 2008), which provided measurements of temperature, salinity, depth, dissolved oxygen, and downwelling irradiance while collecting in situ images of planktonic organisms. In conjunction with the ISIIS tows, a Reson SeaBat 7125 multibeam sonar was used to map the bathymetry of the study region and to collect water column backscatter data to detect physical and biological features. R/V *Pelican* towed a Scanfish to measure temperature, salinity, depth, and bio-optical properties in the water column. In the spring, R/V *Pelican* also deployed the Chameleon microstructure profiler (Moum et al., 1995), which measured microscale turbulence, temperature, conductivity, optical backscatter (800 nm), and fluorescence throughout

TABLE 1. Dates for the CONCORDE field sampling campaigns.

Expedition	Dates	Research Vessels
Fall Cruise	October 28–November 7, 2015	*Point Sur* & *Pelican*
Bonnet Carré Spillway Cruise	February 11–February 13, 2016	*Point Sur*
Spring Cruise	March 29–April 11, 2016	*Point Sur* & *Pelican*
Summer Cruise	July 24–July 30, 2016	*Point Sur*

the water column from the surface to within 2 cm of the seafloor. The resultant 4,201 Chameleon profiles were combined with acoustic imaging, radar tracking of fronts, shipboard ADCP, and a near-surface towed temperature-conductivity chain to yield a detailed view of river plume dynamics and corresponding oceanographic changes.

Shelf Biological Productivity, Plankton Distributions, and Nutrients

The ISIIS acquired images with two cameras in ~0.06 second intervals, capturing planktonic organisms between ~400 µm and ~13 cm in size using a shadowgraph lighting technique, with no discernible bias in detectability among zooplankton groups (Cowen et al., 2013). The ISIIS images were processed following methods similar to those described in Greer et al. (2015). Images from the smaller camera (4.3 cm field of view, 8.9 cm depth of field, ~40 µm pixel resolution) were automatically segmented, a process that extracted particles greater than 500 pixels in cross-sectional area (~1.0 mm equivalent spherical diameter). These high-resolution images were supplemented with depth-discrete and surface plankton net tows, both of which provided biological samples needed for verification of the image classifications and further laboratory analyses.

Discrete water samples were used to characterize lower trophic level biological processes and nutrient concentrations. Rates of primary production, nitrate-based uptake, and biogenic silica production were measured from shipboard incubations. Chlorophyll (>0.6 µm and >5.0 µm size fractions) concentrations, bulk particulate organic carbon, and particulate organic nitrogen concentrations (among other parameters) were obtained from the water samples. Microplankton (20–200 µm) assemblage composition, size distribution, and abundances were described by imaging water samples with a FlowCAM® Benchtop B3 Series.

Chemical Tracers of Water Masses

Seawater samples for chemical tracer analysis were collected at the surface to characterize the freshwater river input, at midwater depth, and at the bottom to investigate the development of hypoxia based on evidence of previous hypoxic events that occurred in the Mississippi Bight (Brunner et al., 2006). The sampling and analysis strategies follow the methodology previously applied on the Louisiana Shelf (Joung and Shiller, 2014). Conservative parameters such as water isotopes ($\delta^{18}O$ and δD) and molybdenum (Mo) and cesium (Cs) concentrations were measured to identify the sources of freshwater to the Mississippi Bight. Barium (Ba) concentrations and radium isotopes (Ra) provided an estimate of the role submarine groundwater discharge plays in the development of bottom water hypoxia (Moore, 2010; Peterson et al., 2016).

Remote Sensing and Circulation Model

Satellite-derived products were combined with circulation model forecasts to characterize daily nGOM biophysical properties. The ocean circulation forecast fields, obtained from a 1 km horizontal resolution implementation of the Navy Coastal Ocean Model (NCOM), were used in planning portions of the CONCORDE field sampling campaigns. The three-hourly circulation fields were integrated with daily satellite-derived temperature and ocean color to provide visualization of environmental conditions that were used to optimize cruise and glider sampling in near-real time. This approach allowed for targeting features of interest, such as fronts and river plumes.

The effects of different environmental scenarios on transport pathways were evaluated with the CONCORDE synthesis model (Box 1) using simulations in which a neutral tracer (neutrally buoyant, passively following the current field) was released continuously throughout the water column along the southernmost boundary of the CONCORDE model domain. Simulations illustrated the fate of the tracer released over 21 days in the fall (October 1–October 21, 2015) and the spring (March 18–April 7, 2016). The integrated tracer concentration in the shallowest 1 m was used to determine surface transport patterns. This depth range was chosen because the mixed layer is shallow in the Mississippi Bight, and using a fixed depth allows for a comparison that is independent of seasonal and spatial changes in mixed layer depth. The tracer was designed to simulate surface water transport that could contain surface crude oil or droplets mixed just below the air-sea interface. Wind roses at 88.5°W, 29.4°N (near the southern boundary of the model domain) were calculated from the wind analysis field.

RESULTS AND DISCUSSION

River Plume Transport

Results from one survey day (April 10, 2016) illustrate some physical processes and transport mechanisms involving the Mobile Bay plume. River plumes flowing into the nGOM contribute to vertical stratification that varies in strength throughout the year. The highest freshwater input occurs in spring, resulting in a stratified system with high-salinity shelf water at depth, an intermediate layer of old plume water that has been mixed over time with deeper waters (Figure 3a), and the occasional presence of a thin surface plume from the Mobile Bay outflow (Dzwonkowski et al., 2015). The strong stratification between layers limits vertical exchange of passive constituents such as sediments (as observed in optical backscatter, Figure 3b) and chlorophyll-*a* (inferred from fluorescence, Figure 3c). To counteract the effects of stratification, opposing current velocities (surface vs. bottom, Figure 3e) create vertical shear, inducing turbulence via shear instability (Figure 3d; Smyth and Moum, 2012) that drives a Fickian-like diffusion of salt and other constituents between layers (Shroyer et al., 2016). The depth-integrated change in salinity over time (dS/dt) within the intermediate layer (thickness H) correlates with the turbulent salt flux across the pycnocline (depicted in Figure 3f as the product of turbulence diffusivity, K_ρ, and the vertical salinity gradient). This correlation suggests that turbulent mixing can account for the exchange of passive constituents between layers despite the stratification that opposes this exchange. Strong winds, which enhance mixing, would erode stratification and homogenize the water column in the absence of periodic injections of freshwater by river plumes.

Secondary lateral currents also impact the transport of these constituents (Figure 3e). Southeasterly winds can drive a current in the intermediate layer to the northeast, forcing the intermediate layer toward shore. Consequently, constituents near the surface are advected toward shore, while deeper waters are advected offshore due to the pressure head of the outflow and downwelling wind. Mixing between layers defines a more complex pathway in which initially deep constituents are mixed upward and then transported shoreward. Lateral transport is further complicated by the presence of tidally reversing currents and rotating inertial oscillations, the clockwise turning near the local inertial frequency (~24-hour period at nGOM latitudes) caused by Earth's rotation.

In mid-April, the river plume was advected along the coast, but its position varied in response to other environmental conditions. Under weaker wind conditions, plume-tracking drifters moved offshore and to the west, consistent with a buoyancy-driven plume (Figure 4a). However, the stronger upwelling conditions (westerly winds) forced the plume offshore where it continued to be pushed eastward by shelf currents (Figure 4b). The trajectories of simulated drifters are similar to those of observed drifters under different wind forcing conditions, indicating the model skill in resolving the Mobile Bay plume response to winds. The observed and simulated drifter pathways show that the eastern-most CONCORDE sampling transect (87.53°W, Figure 1) can receive freshwater input derived from Mobile Bay during periods of upwelling wind.

Additional drifter releases simulated by the circulation model (Box 1) show transport pathways for different prevailing wind, tidal, and freshwater discharge conditions. Transport depicted from drifter simulations for the winter cruise (during the period of the Bonnet Carré Spillway opening) agreed with water mass distributions determined from underway bio-optical measurements.

Oxygen isotope analysis showed that the Mississippi River plays a surprisingly small role in freshwater input to the Mississippi Bight (relative to freshwater from Mobile Bay and other sources). The Bonnet Carré Spillway opening was an exceptional freshwater discharge event where Mississippi River water entered through Lake Pontchartrain, north of the main Mississippi River Delta, with a seemingly more direct connection to the Bight. Even under these circumstances, only waters in the westernmost part of the Bight showed Mississippi River influence. Chemical tracers also indicated

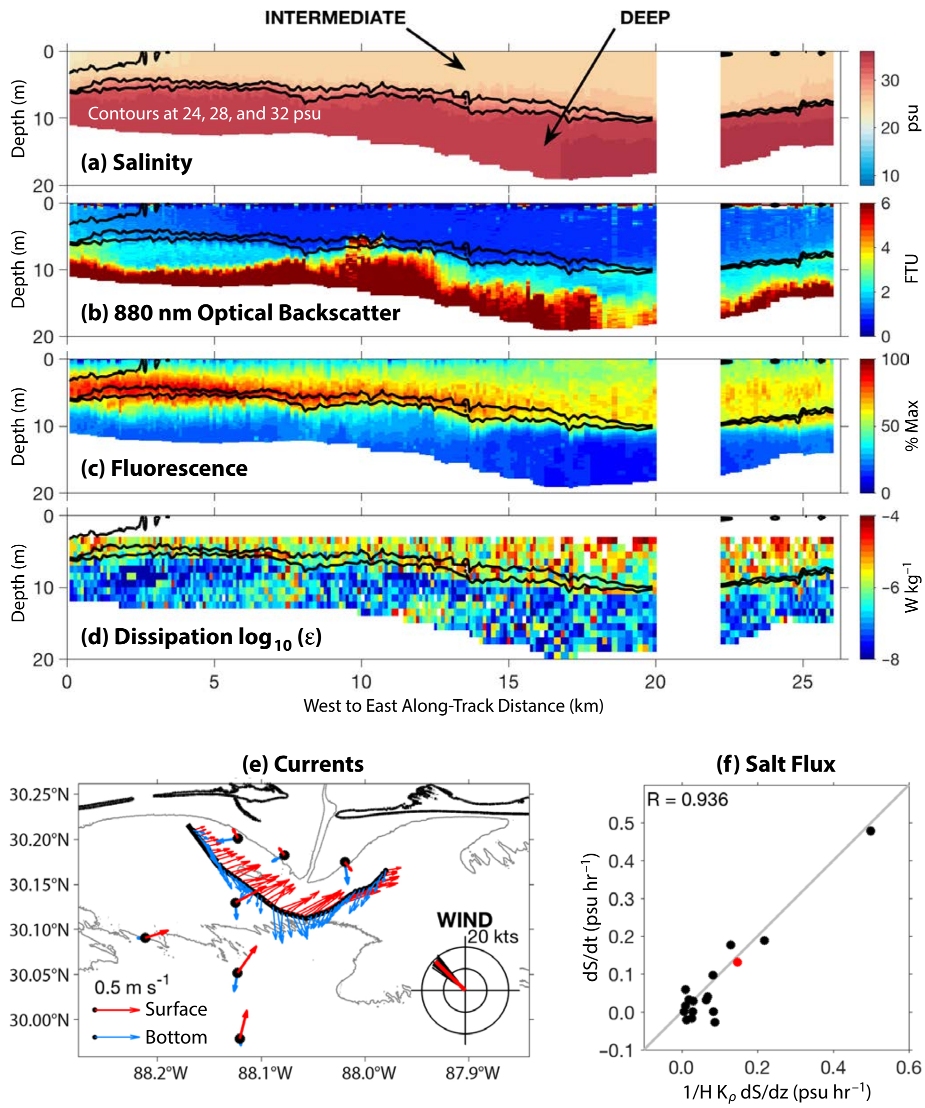

FIGURE 3. Observed distribution of (a) salinity, (b) 880 nm optical backscatter, (c) chlorophyll fluorescence, and (d) turbulent kinetic energy dissipation rate measured with the Chameleon microstructure profiler during the evening of April 10, 2016, along the semicircular transect shown in (e), located ~5 km south of Mobile Bay. (e) Near-surface (red) and near-bottom (blue) currents measured by a 1,200 kHz shipboard ADCP along the transect path, and current vectors at the mooring locations averaged over the 4.5 hours it took to complete the shipboard transect. Inset shows average wind direction (southeasterly) and speed (20 knots). (f) Turbulent salt flux divergence across the intermediate layer (x-axis) compared with the measured change in salt in the intermediate layer (y-axis). The transect shown in a–d is plotted in red.

transport of local river waters, including Mobile Bay outflow, to the western part of Mississippi Sound during this event. Most of the Mississippi River water (from both the Delta and the Bonnet Carré Spillway) appears to hug the Louisiana coast and move toward the south and west, leaving the Bight to be primarily influenced by Mobile Bay outflow and smaller rivers. This oxygen isotope data set, indicating strong south and eventually westward trajectory of the Mississippi River outflow, provides an approach for assessing the skill of the simulated circulation patterns.

Shelf Circulation and Transport Pathways

Throughout the sampling period between fall 2015 and spring 2016, mooring arrays (Xs in Figure 1) provided a broader context for the higher-resolution physical and biogeochemical measurements. Currents near the Mississippi River Delta were generally oriented along the isobaths, with typical variation ranging between 30 cm s^{-1} and 50 cm s^{-1} in both along-isobath directions (e.g., Figure 1, lower inset), while mean speeds were an order of magnitude smaller at 2–5 cm s^{-1}. The large difference between the variations and mean suggests that there is no dominant orientation for the currents east of the Mississippi River Delta from fall to spring. Currents often oscillated with a near-inertial frequency (clockwise rotation), primarily forced by the passage of cold fronts through this region that occur every 2–15 days. Despite its proximity, the Mississippi River outflow did not play a significant role in driving weekly variations of currents during the study period. Rather, local southeasterly winds drove southwestward currents with slight offshore fluxes, and northwesterly winds drove northeastward currents with slight onshore fluxes.

The potential pathways that result in oil exposure on the nGOM continental shelf and their variability were assessed with the circulation model using simulations that tracked the concentration of a continuously released neutral tracer throughout the model domain. Tracers were released during the fall and spring for a 21-day period. The fall tracer release (October 1–October 21, 2015) shows consistent surface transport from west to northeast, with little northward advection into the inner shelf region of the Mississippi Bight (Figure 5a). In contrast, the spring release (March 18–April 7, 2016) shows the tracer transported northward to the nGOM inner shelf region, as well as surface spreading of the tracer over most of the CONCORDE model domain (Figure 5b). Major differences between these two cases include the winds (Figure 5c,d—stronger speed peaks and greater directional variability in the spring period relative to the fall), the stratification (stronger in spring), and the river discharge (higher in spring). The fall and spring simulated tracer patterns indicate that the timing of an oil spill can greatly influence its distribution on the shallow nGOM shelf, and high river discharge does not necessarily obstruct the onshore transport of surface water constituents to the shelf and coastal habitats. These simulations provide a basis for further studies that address the effects of environmental complexity and uncertainty on oil transport in the nGOM and on ecosystem processes.

Biological Production and Aggregation on the Shelf

Biological constituents responded to variable salinities and nutrient inputs from nearby rivers. During the fall, minimal freshwater input led to a well-mixed

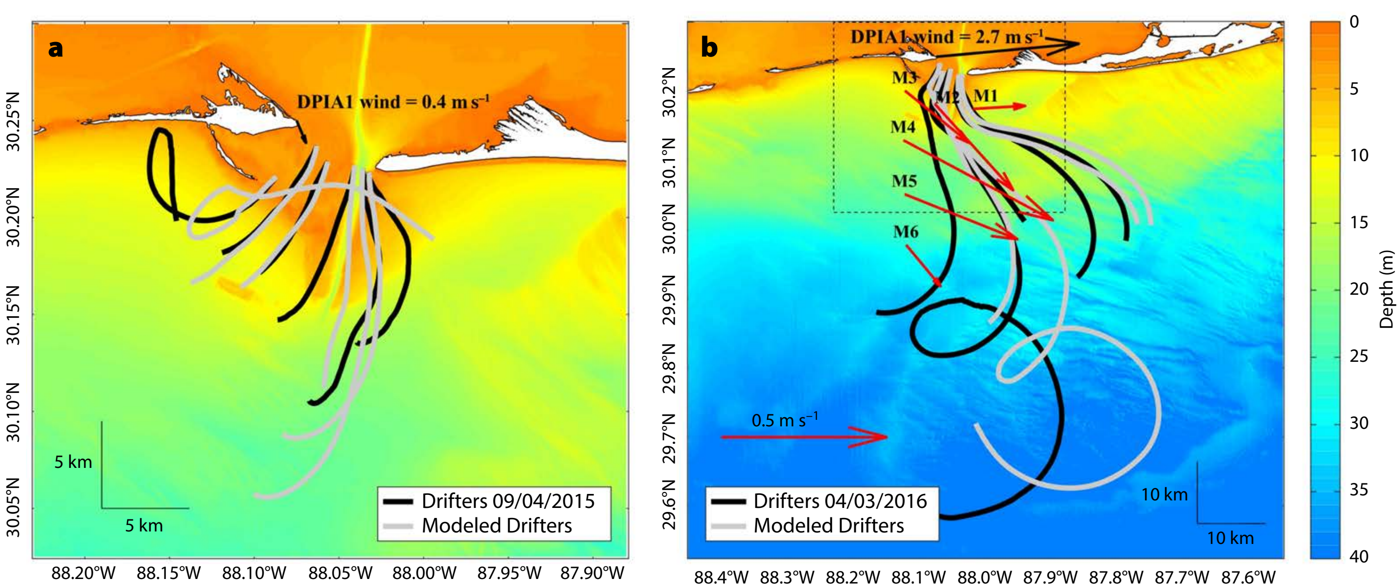

FIGURE 4. Example trajectories for observed (black) and simulated (gray) drifter releases on (a) September 4, 2015, during a weak sea breeze cycle, and (b) April 3, 2016, after a frontal passage. The drifters were released at Main Pass approximately a quarter of the way into the ebb tide; however, the drifter recovery varied from 5 hours to 60 hours, resulting in extended trajectories for some drifters. Wind vectors (black) at Main Pass show average wind speed and direction during drifter releases (NOAA/NDBC station DPIA1). Red vectors (panel b only) indicate the near-surface currents at the moorings averaged over the duration of the drifter release.

water column with relatively high salinity (Cambazoglu et al., 2017) and low biological productivity (Figure 6a,b), as measured by both primary production and zooplankton abundances (Dzwonkowski et al., 2017). The water column underwent a dramatic change as spring rains led to increased river discharge from Mobile Bay, directly affecting large portions of the shelf and producing a large vertical salinity range (salinity of ~24 at surface and ~36 at depth). These nutrient-rich river discharges produced higher biological productivity, with the zooplankton and marine snow particle distributions closely following the halocline (Figure 6c,d). The mooring near the northern end of the transect (southernmost yellow X in Figure 1) showed two-layer cross-shelf transport caused by an inertial oscillation likely created by a wind event. During the inertial cycle, currents were oriented offshore in the surface layer and onshore in the lower layer. They slowly turned clockwise in each layer to reverse course over the next 12 hours, reaching the opposite pattern of onshore flow in the surface layer and offshore flow at depth. These currents then slowly turned clockwise over the next 12 hours to return to the original flow pattern (the period of inertial oscillations is diurnal at these latitudes). This is an example of differential advection set up by stratified conditions, which has implications for understanding oil transport in this region.

During summer, the vertical salinity range was lower, but the halocline was strongest with apparent vertical oscillations (i.e., internal waves; Figure 6e,f). The zooplankton and marine snow distributions were confined to a narrow range of intermediate salinity levels, but the peak concentrations were not as high as those measured during spring. The spring to summer halocline strengthening appeared to correspond to vertically confined distributions of zooplankton, as well as to a reduced capacity for ventilation of the deeper shelf waters that generates favorable conditions for the development of hypoxia. In summer, bottom waters showed radium enrichment, a key indicator of submarine groundwater

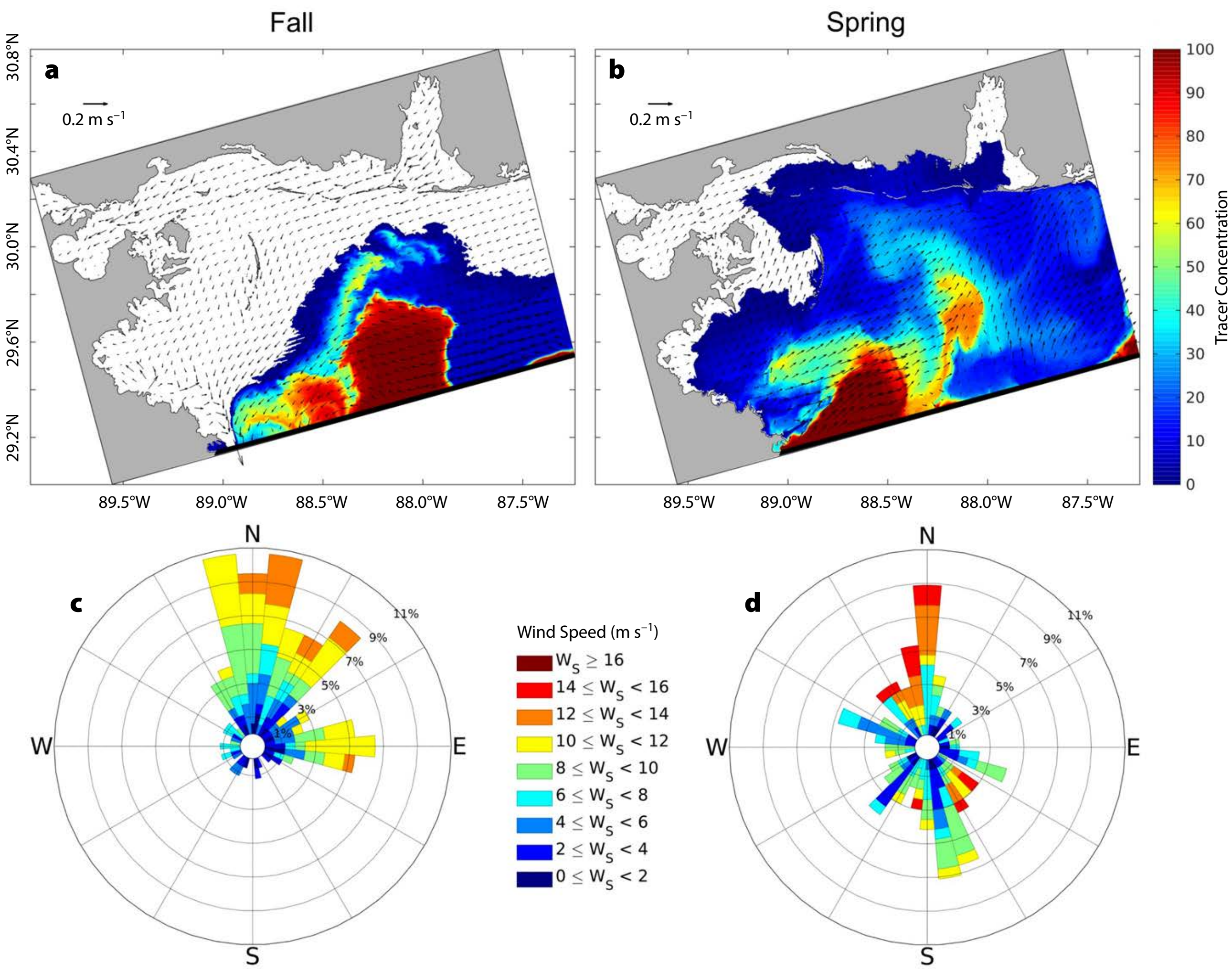

FIGURE 5. Simulated neutrally buoyant tracer release (color shading) at the southern edge of the CONCORDE model domain in the Mississippi Bight. Tracer distribution (integrated 1 m surface concentration in arbitrary units ranging from 0 to 100—concentration is 100 at the site of the release) is shown after 21 days of continuous release and passive advection during (a) fall (October 1–21) and (b) spring (March 18–April 7) seasons, respectively (see online supplemental material for tracer advection animation). Regions with tracer concentrations <0.1 (white areas) and current vectors (simulation day 21) are also shown. Wind roses (showing direction wind is coming from) were produced from the wind analysis field (meteorological reanalysis product – see Box 1) from the (c) fall and (d) spring during the same 21-day period near the southern boundary of the model domain (29.4°N, 88.5°W).

discharge, and this was correlated with high dissolved silica, inorganic nitrogen, and phosphate, and low dissolved oxygen. Thus, in addition to river discharge, submarine groundwater appears to play a role in nutrient delivery in the Mississippi Bight, with possible concomitant effects on productivity and bottom water hypoxia.

The intense aggregation of plankton and marine snow, particularly during spring and summer, has important implications for the propagation of oil and contaminants throughout the food web (Figure 6b,d,f). Sinking marine snow provides a mechanism for transport of oil to depth and potentially serves as a trophic exposure pathway for oil into the planktonic food web (reviewed by Daly et al., 2016). The association between seasonal changes in salinity structure and zooplankton/marine snow distributions provides requisite data for quantifying spatial overlap (e.g., Greer and Woodson, 2016) and contact rates between marine snow particles and various zooplankton groups, along with information about behavioral interactions (e.g., orientation and predation events; see Figure 6g–m for example images). These measurements can be used to generate taxon-specific understanding of vulnerability to oil exposure and of detailed trophic pathways for oil incorporation into the planktonic food web (Graham et al., 2010; Buskey et al., 2016).

SUMMARY AND FUTURE APPLICATIONS OF CONCORDE

Analysis of high-resolution, near-synoptic measurements that cross traditional oceanographic disciplines has improved

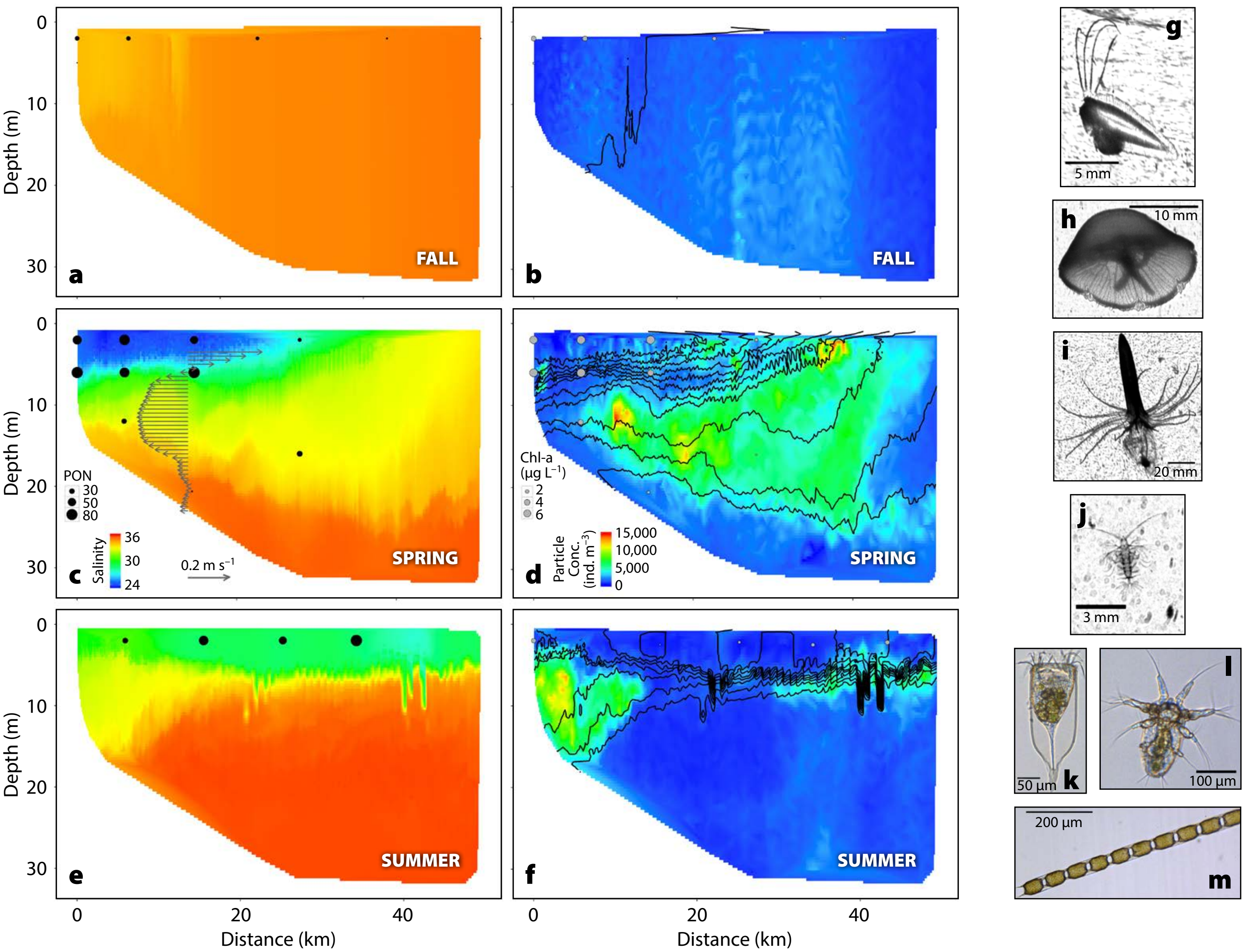

FIGURE 6. Measured salinity versus distance from start of the ISIIS transect (left is north) in (a) fall (October 30, 2015), (c) spring (April 4, 2016), and (e) summer (July 25, 2016) along the middle sampling corridor (Figure 1) and measured particulate organic nitrogen concentrations (black dots). Panel c shows the current vectors from a mooring averaged between 10:00 and 12:00 CDT on April 4, 2016 (southernmost yellow X in Figure 1). Particle concentrations (zooplankton and marine snow) during (b) fall, (d) spring, and (f) summer, with measured chlorophyll-*a* (Chl-a) concentrations (gray dots) along the same sampling corridors. Salinity between 25 and 35 is indicated by black lines in 1 unit increments. The legend for (c) also applies to (a) and (e), and (d) contains the legend for (b) and (f). Example images of fauna captured with the ISIIS and within the size range of particles show (g) a larval flatfish, (h) a juvenile moon jelly (*Aurelia* spp.), (i) a larval tube anemone consuming a salp, and (j) a eucalanoid copepod. Images k–m, captured with the FlowCAM®, show (k) a tintinnid ciliate, (l) a copepod nauplius, and (m) a diatom chain (*Odontella sinensis*) that were all below the ~1 mm size threshold of plankton plotted in (b), (d), and (f).

our understanding of the Mississippi Bight, a critical region separating offshore oil drilling sites and coastal habitats. Complex physical processes in this river-influenced region of the nGOM contribute to the structuring of ecological communities, but measurements on scales appropriate for resolving many processes relevant to oil transport (hourly temporal scales and centimeter to meter spatial scales), and the interactions of oil with biological and other chemical components, have been lacking. Several new findings have emerged from this research, including the discovery of both direct and indirect transport pathways driven by the wind and consistent plankton aggregations that track salinity variations.

Wind has a major influence on transport of river plume waters, which in turn impacts other ecosystem properties. Mooring observations suggest that wind is the dominant control on the currents to the east of the Mississippi Delta, and wind variations can move Mississippi River water along the shelf break and into or out of the Bight. However, chemical distributions indicate that Mississippi River water actually makes up a relatively small proportion of the freshwater entering the Bight, suggesting that much of the Mississippi River water that flows eastward is advected either along the shelf break or offshore. Wind can also drive the Mobile Bay plume westward or eastward and plays an indirect role in setting up the shear observed in the Mobile Bay plume, producing the observed mixed layer salinity changes and generating inertial oscillations that diurnally advect plumes after a wind event. Biological sampling demonstrates that strong salinity gradients influence the distributions of zooplankton, marine snow, and nutrients. The distributions of plankton and geochemical constituents are therefore connected to wind speed and direction, as the wind forcing modulates the halocline through mixing and impacts plume fronts through advection. These connections, which can only be revealed with an interdisciplinary approach, show that different, seasonally dependent environmental factors structure the distribution of constituents and can also influence oil advection and the magnitude of oil spill impacts on the ecosystem.

Improved forecasting of oil spill transport and impacts requires understanding oceanographic processes that change with depth. Although most oil spill transport research has focused on atmospheric forcing and circulation near the sea surface, the Deepwater Horizon blowout demonstrates that understanding oil transport and interactions should be considered a 4-D problem, with depth adding a complex new dimension that is difficult to observe (Peterson et al., 2012). This understanding is becoming critical given that oil extraction is taking place in deeper, offshore sites (Graham et al., 2011). Accurate prediction of ecosystem-level impacts from oil spills is the foundation for effective response planning, so observations and modeling must be extended to include interactions throughout the water column between oil (and dispersants) and the biological and geochemical constituents that serve as a mechanistic link to bulk ecological and economic impacts. The dynamics of pulsed river plumes adds an additional degree of complexity for predicting physical advection and chemical-biological interactions. Even though river-dominated shelf ecosystems are relatively shallow, their physical, chemical, and biological properties can change dramatically with depth. CONCORDE provides detailed new information on river-dominated systems, as spilled oil traversing these regions directly threatens coastal habitats and human populations.

River-influenced coastal systems found throughout the world are productive habitats for a variety of culturally and economically important marine species. Oil drilling has resulted in repeated spills and significant environmental damage in areas such as the Niger River Delta (Ite et al., 2013) and will continue to threaten similar habitats globally (Figure 7). Principles derived, and patterns described, from CONCORDE's interdisciplinary approach to identifying and quantitatively assessing key physical, biological, and geochemical processes acting in the nGOM are applicable to other pulsed, river-dominated systems, even though there may be differing ecological communities, volumes of river discharge, and degrees of oil extraction activities relative to the nGOM. Moreover, many of these oil reserves near river mouths are currently relatively unexploited, such as those on the Alaskan shelf.

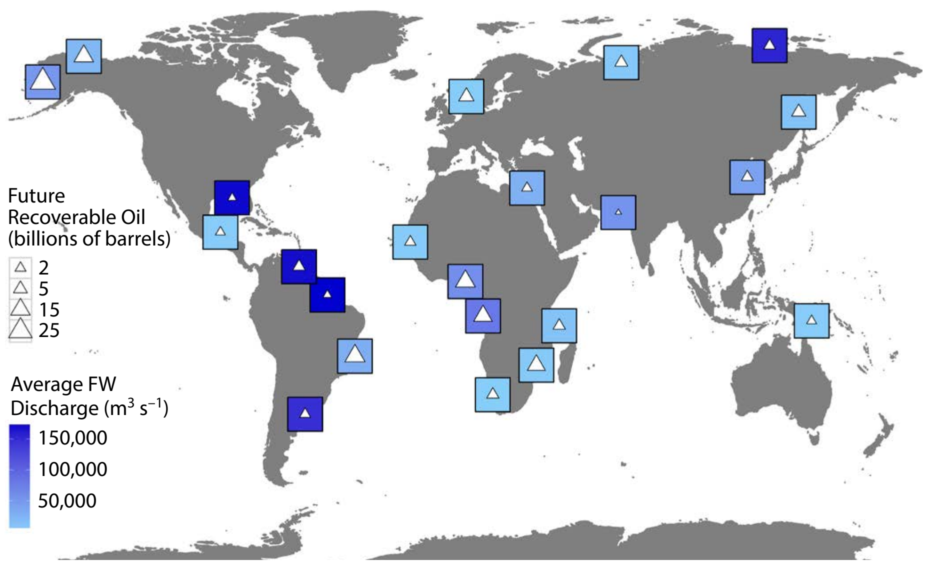

FIGURE 7. Locations of coastal river-dominated ecosystems around the world with nearby oil extraction activities that are similar to the CONCORDE domain. Color corresponds to the average freshwater (FW) river discharge, and the size of the triangle represents the current extent of oil reserves (see supplementary material data sets and references used to generate the figure).

Because accidents can have such dire consequences, as demonstrated during the Deepwater Horizon spill, understanding the physical pathways for oil and distributions of biological and chemical constituents under different oceanographic conditions must be a priority *before* extraction begins. This information provides the basis for oil spill transport modeling and estimation of exposure rates for planktonic organisms that can then be utilized in formulating response plans aimed at preserving the vital ecological functioning of the system.

SUPPLEMENTARY MATERIALS

An animation of simulated neutrally buoyant tracer release at the southern edge of the CONCORDE model domain, Gulf of Mexico is available at https://youtu.be/9FjC1bBnMSA. More information on global oil production in river-dominated ecosystems and the reference data sets used to generate Figure 7 and are available at https://doi.org/10.5670/oceanog.2018.302.

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AUTHORS

Adam T. Greer (adam.greer@usm.edu) is Postdoctoral Research Associate, and **Alan M. Shiller** is Professor, Division of Marine Science, University of Southern Mississippi (USM), Stennis Space Center, MS, USA. **Eileen E. Hofmann** is Professor, Center for Coastal Physical Oceanography, Old Dominion University, Norfolk, VA, USA. **Jerry D. Wiggert** is Associate Professor, Division of Marine Science, USM, Stennis Space Center, MS, USA. **Sally J. Warner** is Research Associate, College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR, USA. **Sabrina M. Parra** is American Society for Engineering Education Postdoctoral Fellow, US Naval Research Laboratory (NRL), Stennis Space Center, MS, USA. **Chudong Pan** is Postdoctoral Research Associate, Division of Marine Science, USM, Stennis Space Center, MS, USA. **Jeffrey W. Book** is Oceanographer, US NRL, Stennis Space Center, MS, USA. **DongJoo Joung** is Postdoctoral Research Associate, Division of Marine Science, USM, Stennis Space Center, MS, USA. **Steven Dykstra** is PhD Candidate, **Jeffrey W. Krause** is Assistant Professor, and **Brian Dzwonkowski** is Assistant Professor, University of South Alabama and Dauphin Island Sea Lab, Dauphin Island, AL, USA. **Inia M. Soto** is Postdoctoral Research Associate, and **M. Kemal Cambazoglu** is Research Associate, both in the Division of Marine Science, USM, Stennis Space Center, MS, USA. **Alison L. Deary** is Postdoctoral Research Associate, Division of Coastal Sciences, Gulf Coast Research Laboratory, USM, Ocean Springs, MS, USA. **Christian Briseño-Avena** is Postdoctoral Research Associate, Hatfield Marine Science Center, Oregon State University, Newport, OR, USA. **Adam D. Boyette** is PhD Candidate, Division of Marine Science, USM, Stennis Space Center, MS, USA. **Jessica A. Kastler** is Coordinator of Program Development, Gulf Coast Research Laboratory, USM, Ocean Springs, MS, USA. **Virginie Sanial** is Postdoctoral Research Associate, **Laura Hode** is a graduate student, and **Uchenna Nwankwo** is a graduate student, all in the Division of Marine Science, USM, Stennis Space Center, MS, USA. **Luciano M. Chiaverano** is Research Associate, Gulf Coast Research Laboratory, USM, Ocean Springs, MS, USA. **Stephan J. O'Brien** is PhD Candidate, Division of Marine Science, USM, Stennis Space Center, MS, USA. **Patrick J. Fitzpatrick** is Associate Research Professor, and **Yee H. Lau** is Research Associate, both at Mississippi State University Science and Technology Center, Stennis Space Center, MS, USA. **Michael S. Dinniman** is Research Scientist, Center for Coastal Physical Oceanography, Old Dominion University, Norfolk, VA, USA. **Kevin M. Martin** is Research Staff, **Peng Ho** is PhD Candidate, **Allison K. Mojzis** is Research Staff, **Stephan D. Howden** is Associate Professor, all in the Division of Marine Science, USM, Stennis Space Center, MS, USA. **Frank J. Hernandez** is Assistant Professor, Gulf Coast Research Laboratory, USM, Ocean Springs, MS, USA. **Ian Church** is Assistant Professor, Department of Geodesy and Geomatics Engineering, University of New Brunswick, Fredericton, NB, Canada. **Travis N. Miles** is Assistant Research Professor, Department of Marine and Coastal Sciences, Rutgers University, New Brunswick, NJ, USA. **Su Sponaugle** is Professor, Department of Integrative Biology, Hatfield Marine Science Center, Oregon State University, Newport, OR, USA. **James N. Moum** is Professor, College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR, USA. **Robert A. Arnone** is Research Professor, Division of Marine Science, USM, Stennis Space Center, MS, USA. **Robert K. Cowen** is Director, Hatfield Marine Science Center, Oregon State University, Newport, OR, USA. **Gregg A. Jacobs** is Oceanographer, US NRL, Stennis Space Center, MS, USA. **Oscar Schofield** is Distinguished Professor, Department of Marine and Coastal Sciences, Rutgers University, New Brunswick, NJ, USA. **William M. Graham** is Professor, Division of Marine Science, USM, Stennis Space Center, MS, USA.

ARTICLE CITATION

Greer, A.T., A.M. Shiller, E.E. Hofmann, J.D. Wiggert, S.J. Warner, S.M. Parra, C. Pan, J.W. Book, D. Joung, S. Dykstra, J.W. Krause, B. Dzwonkowski, I.M. Soto, M.K. Cambazoglu, A.L. Deary, C. Briseño-Avena, A.D. Boyette, J.A. Kastler, V. Sanial, L. Hode, U. Nwankwo, L.M. Chiaverano, S.J. O'Brien, P.J. Fitzpatrick, Y.H. Lau, M.S. Dinniman, K.M. Martin, P. Ho, A.K. Mojzis, S.D. Howden, F.J. Hernandez, I. Church, T.N. Miles, S. Sponaugle, J.N. Moum, R.A. Arnone, R.K. Cowen, G.A. Jacobs, O. Schofield, and W.M. Graham. 2018. Functioning of coastal river-dominated ecosystems and implications for oil spill response: From observations to mechanisms and models. *Oceanography* 31(3):90–103, https://doi.org/10.5670/oceanog.2018.302.