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Research Gaps in the Understanding of the Impacts of the Mississippi River and its Delta on the Gulf of Mexico

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Executive Summary

This paper describes research that is needed to better understand the impacts of the Mississippi River and its delta on the oceanography, ecology and economy of the Gulf of Mexico. It has long been recognized that the river and its delta play a large role in influencing the Gulf, as the river is the largest source of freshwater, nutrients and the sediments to the Gulf of Mexico and the Mississippi River Delta plays provides food and habitat for numerous estuarine dependent species, Despite decades of research on river/ocean interactions many questions remain about the specific impacts of both the Mississippi River and its delta on oceanographic and ecological processes in the Gulf, and their cascading economic impacts. To address these issues, a working group was formed consisting of researchers, scholars and practitioners who have all worked in the Gulf for large sections of their careers. This group was tasked with synthesizing the literature on known impacts of the river and delta on the Gulf (presented in a companion paper), and determining major research gaps. The group examined research gaps in five major topic areas: conceptual gaps, modeling gaps, measurement gaps, gaps that could be filled by synthesis and gaps in research organizations.

Conceptual gaps that need further research include biogeochemical cycles an environmental fluxes, the impacts of the Mississippi River on coastal circulation, the importance of ecosystem services and valued ecosystem components, and how human community interact with the interface between the Mississippi River, its delta and the Gulf of Mexico.

Modeling Gaps include a need for improved parameterization and calibration, improved boundary condition definition, model integration, and a fundamental understanding of river-ocean processes, improved decision support tools, and a need for improved spatial and temporal coverage/resolution.

Measurement gaps include processes where improved measurement can lead to enhanced understanding (e.g. salinity dynamics, biogeochemical processes, river diversions), geographic regions that could be improved by further measurement (the eastern section of the Mississippi River and its delta, as well as the mouth of present-day and future distributaries), a need for improved baseline data, and a need to invest in emerging sensors.

There is a pressing need for transdisciplinary synthesis that can bring together diverse knowledge from across scientific disciplines develop a new or improved understanding of the ways that the Mississippi River and its delta influence the Gulf of Mexico. Synthesis can address a range of issues ranging from air/sea/land interactions to the impacts of invasive species on the environment to the integration of the physical and social science in the river and delta influenced areas of the coastal zone. Synthesis is best done with highly collaborative, diverse, groups that span a range of academic backgrounds, professional levels, and experiences.

This team also examined the role of research organizations that were best suited for Gulf-based work. While it was recognized that successful research can be done by a range of organizations, often government agencies are best at long-term monitoring and data collection, universities are best at hypothesis driven or experimental research, and that there is a developing

role for private (both non-profit and for-profit) organizations in research. Finally, this team recognized the importance of involving managers into research at all stages in order to enhance restoration and protection efforts that are needed in the Gulf in the decades ahead.

I. INTRODUCTION

This paper describes research that is needed to better understand the impacts of the Mississippi River and its delta on the oceanography, ecology, and economy of the Gulf of Mexico. It has long been recognized that the river and its delta play a large role in influencing the Gulf. The river is the largest source of freshwater, nutrients and the sediments to the Gulf of Mexico, and as such, impact the basin's circulation, geochemistry and ecology (Dunn 1996; McKee et al. 2004; Kolker et al. 2018- In Press). The Mississippi River Delta plays a large role in the ecology of the Gulf of Mexico as it provides food and habitat for numerous estuarine dependent species, traps sediments and nutrients in developing deltas, and liberating them in degrading wetlands. Despite decades on river/ocean interactions (Rabalais et al. 1996; Rabalais, Turner, and Wiseman 2002; McKee et al. 2004; Wright 1997) many questions remain about the specific impacts of both the Mississippi River and its delta on oceanographic, ecological processes in the Gulf of Mexico, and their cascading economic impacts.

To address these issues, a working group was formed consisting of researchers, scholars and practitioners who have all worked in the Gulf for large sections of their careers. This group was tasked with synthesizing the literature on known impacts of the river and delta on the Gulf (presented in a companion paper), and determining major research gaps. The group examined research gaps in five major topic areas: conceptual gaps, modeling gaps, measurement gaps, gaps that could be filled by synthesis and gaps in research organizations. The team defined the Mississippi River system as including the Mississippi River watershed and its' major distributaries, the river's mainstem, the Atchafalaya River, and flood control and other human-made distributaries (Fig.1). This report only examines research and knowledge gaps as they relate to the impacts of the river and the delta on the Gulf; it does not examine research gaps that focused only on river, delta or Gulf-based processes, but for which there is limited interaction.

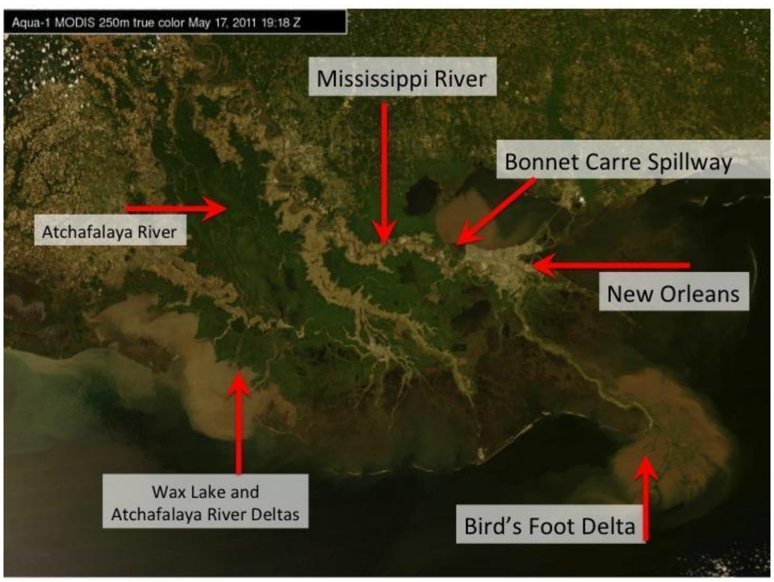

Fig.1. NASA/Modis imagery of the Mississippi River Delta and its coastal zone, with key areas highlighted. Image date: May 17, 2011. Image credit: Louisiana State University Earthscan Laboratory. www.esl.lsu.edu

II. CONCEPTUAL GAPS

One set of knowledge gaps relate directly to the scientific community's lack of understanding of fundamental scientific processes that govern the Mississippi River, its Delta, and the Gulf of Mexico. These gaps include physical, ecological and geochemical processes, or they can also include economic and social processes. The material presented below lists these processes, and describes the dearth of knowledge that exists.

II.A. Biogeochemical Cycles and Fluxes

The last three to four decades have experienced substantial progress in the scientific community's understanding of the Mississippi River's influence on biogeochemical cycling (Rabalais et al. 1996; Rosenheim et al. 2013; Sampere, Bianchi, and Allison 2011; McKee et al. 2004; Cai et al. 2011; Xue et al. 2013). However, much additional work needs to be done to understand the fluxes of nutrients and organic material from the river and its delta to the ocean, and the cycling of this material after it enters the ocean. Critical areas of research include:

1) The carbon cycle. Currently, researchers need to better quantify the flux of carbon from both the river and the delta to the ocean, and better determine the chemical composition of this material, and how various chemical constituents of the carbon cycle vary with both space and time (Sampere, Bianchi, and Allison 2011; Bianchi et al. 2007), and how this material is processed from the river, through the continental shelf, and into the deep sea. Research on the chemical composition of organic matter fluxes includes, but is not limited to, the terrestrial site of origin, and fluxes of organic contaminants (Mitra and Bianchi 2003). Furthermore research is needed into how the delta can acts as a sink for carbon -for example by burying it in developing deltas such as the Wax Lake Delta, and how the delta can act as a source for carbon to the Gulf- for example through the liberation of organic matter from eroding marshes (Wilson and Allison 2008; Bianchi et al. 2011; Shields et al. 2017). Furthermore, the river-influenced continental shelf in the northern Gulf of Mexico acts as an overall sink for atmospheric carbon as demonstrated by both ship-based observations (Huang et al., 2015), biogeochemical modeling (Xue et al., 2016) and satellite-based characterizations (Lohrenz et al., 2018). Interannual variations in carbon uptake have also been linked to variability in dissolved inorganic nitrogen inputs from the Mississippi-Atchafalaya river system, an indication that human- and climate-related changes in river exports will likely impact coastal carbon budgets in the future (Lohrenz et al., 2018).

2) Ocean acidification. The increase in global atmospheric CO_2 concentrations is linked to a decrease in the pH of earth's oceans (Doney et al. 2009). The need to understand ocean acidification is a pressing issue in many oceanographic sub disciplines, and it is particularly important to study in Mississippi River Delta and plume region, given that the Mississippi

River is a large source of fluvially-derived carbon to the GOM, and the nutrients from the Mississippi River fuel large plankton blooms (Raymond et al. 2008; Cai et al. 2011). In the Gulf, more research is needed to quantify the magnitude of ocean acidification, the role of fluvial processes in driving ocean acidification, and its impacts on marine organisms, the marine food webs, and people whose livelihoods depends on these organisms.

3) Nutrient Co-limitation. While nutrients have been studied in depth in the Gulf of Mexico for decades, there are still important areas that deserve further attention. One of the most important of these is understanding the role of co-limitation.

4) Contaminant fluxes. The Mississippi River watershed drains an area of 3.2×10^6 km^2, which includes much of the central United States, including large areas that are used for agriculture and industry (Rabalais et al. 1996; Alexander, Wilson, and Green 2012; Mitsch et al. 2001). As such, the watershed serves as a source of contaminants to the river, and through that, the Gulf of Mexico. Over the past 3 decades, there has been extensive progress made on understanding how agriculturally-derived nutrients are involved the development of a seasonal hypoxic layer that adversely affects key ecosystem components (Rabalais, Turner, and Wiseman 2002; Rabalais et al. 1996). However, the role of other contaminant fluxes is less well known. The research that has been conducted on both organic contaminants (Santschi et al. 2001; Z. Wang et al. 2014), and inorganic contaminants (Shiller 1997; Shim, Swarzenski, and Shiller 2012) suggests that the river is a major source of these contaminants to the Gulf of Mexico, prompting the need for further research.

5) Sediment flux: While it has long been known that the Mississippi River is the largest source of sediments to the Gulf of Mexico, many key questions remain unanswered. One area that needs further research is understanding the hysteresis of sediment/water fluxes and the timing differential between water fluxes and sediment fluxes (M. A. Allison and Meselhe 2010; M. A. Allison et al. 2017). These gaps are particularly important for understanding how a diversion in the flow of the Mississippi River, as planned by the State of Louisiana, will impact the Gulf of Mexico (Peyronnin et al. 2017). Another area where research is needed is to understand the role of episodic events, such as large floods, on the flux of sediment to the ocean, and whether the shift in the river from a transport-limited system to a supply-limited system would impact the flux of sediment to the ocean (Leonardi, Kolker, and Fagherazzi 2015/6; Kolker et al. 2014).

6) Groundwater discharge. The last two decades has seen a recognition that there are important fluxes of groundwater to the global ocean (Burnett et al. 2003; Cable et al. 1996), which is often termed submarine groundwater discharge (SGD). Recent research has indicated that SGD fluxes in the Mississippi River Delta average about 1,000 m^3 s^{-1}, and may exceed 2800 m^3 s^{-1}, at high river flow (Kolker et al. 2013). Despite this early research, more study is

needed to understand the magnitude, spatial variation, and timing of this flow, as well as its impacts on ecosystems and coastal biogeochemistry (Telfeyan et al. 2017; Coleman, Kolker, and Johannesson 2017).

II.B. River Impacts on Ocean and Coastal Circulation

Physical circulation patterns in the Gulf of Mexico can be highly complex, given the large freshwater inputs, the importance of wind-driven circulation, and complex geomorphology of the system lead to complex transport pathways (Walker et al. 1996, 2005; Y. S. Androulidakis, Kourafalou, and Schiller 2015; Yannis S. Androulidakis and Kourafalou 2013; Wright and Coleman 1971; Walker 1996). Given the importance of circulation to a wealth of coastal ecosystem processes, further research on coastal circulation is warranted. Critical areas of research include:

1) Coastal currents: Coastal currents in this river-dominated zone of the Gulf of Mexico are complex, and driven by a multitude of processes that include river discharge, tides, and winds that interact with a complex shoreline (Georgiou, FitzGerald, and Stone 2005; Walker et al. 1996; Y. S. Androulidakis, Kourafalou, and Schiller 2015; Walker 1996; Walker and Hammack 2000). Continued research is needed to understand the magnitude and direction of these currents, as well the mixing of river, estuarine, and shelf waters across the Gulf of Mexico (Fig. 2). Furthermore, continued research is needed into how changes in the magnitude, direction, and mixing characteristics of various water masses impacts a range of geological biogeochemical and ecological processes, including but not limited to patterns of sediment dispersal, transport of material to the open ocean and deep sea, coastal hypoxia, fisheries production, and the distribution and abundance of species of interest, and concern.

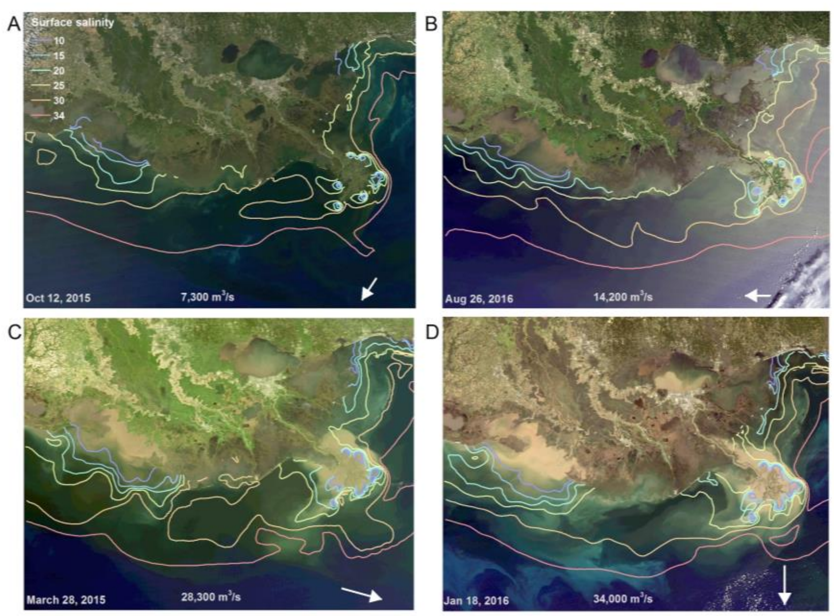

Fig. 2. Evolution of the Mississippi River plume, with salinity contours, following the development of a seasonal flood. Source: Kolker et al., (Accepted and Refs therein).

2) River diversions: The State of Louisiana proposes to construct multiple, "river diversions," each of which will divert a maximum of 1,000- 2000 $m^3\ s^{-1}$ of freshwater into subsiding and degrading basins, with the goal of restarting natural deltaic land building processes (LACPRA 2017). The creation of these features will force large quantities of freshwater into the shallow regions of the MRD, and the nearshore regions of the continental shelf. This has the potential to influence the distribution of freshwater in the Gulf of Mexico, coastal currents, the distribution of sediments along the continental shelf, and a cascading series of ecological impacts driven by such changes in circulation (Kolker, Miner, and Weathers 2012; M. A. Allison et al. 2017; Meselhe et al. 2012; Peyronnin et al. 2017; De Mutsert et al. 2017). Despite some recent advances driven largely by numerical modeling (LACPRA 2017), the ultimate impacts of such diversion remains in need of further attention- both during the design and planning phase, and once structures are constructed.

3) Loop Current: The impacts of the Mississippi River on the Gulf of Mexico are partially mediated by offshore currents, and the Loop Current and associated mesoscale eddies are the most important open-ocean circulation features in the Gulf of Mexico. Satellite imagery has revealed that eddies shed from, or along the margin of, the Loop Current can entrain Mississippi River water 100s of km seaward (Walker et al., 2005; Schiller et al., 2011). Since an extensive agenda for the Loop Current was recently released based on a comprehensive study, readers are referred to that report (National Academies of Sciences, Engineering and Medicine 2018).

4) Coastal set up, storm surge and associated coastal hazards: The shoreline of the Gulf of Mexico is one of the most vulnerable coasts to storm surges and other coastal in the nation- a function of the tropical climate, low gradient shoreline, and numerous human impacts over the past century. Storm surges in the Gulf of Mexico caused by tropical cyclones often have impacts measured in the billions of dollars, and smaller surges caused by more regular cold fronts, can also be damaging - though at a lower dollar amount per storm than many tropical cyclones. While storm surges are largely caused by atmospheric and oceanographic factors that are largely beyond the scope of this document, some areas of research emerge. Particularly, with respect to this review, relatively little is known about how Mississippi River discharge to the Gulf of Mexico elevates sea level locally, and how such local sea level rise impacts water levels in the Gulf of Mexico during a storm. Further research is also needed into how the changing geomorphology of the Mississippi River Delta impacts set-up and set-down in the Gulf of Mexico. While such issue are discussed in Louisiana's Coastal Master Plan, and associated research, often such work was conducted at a scale large enough to determine project effectiveness, but not as a scale fine enough to understand the range of geomorphological responses or provide a detailed understanding of resulting coastal hazards

(LACPRA 2017).

II.C. Ecosystem Services and Valued Ecosystem Components

Ecosystem services are the benefits to society that natural systems provide. They can be categorized into direct benefits, such as food and clean water, and indirect benefits such as nutrient recycling and contaminant removal, and can include not only ecological functions, but also cultural and aesthetic benefits. (http://www.habitat.noaa.gov/abouthabitat/ecosystemservices101.html). The Mississippi River and its Delta have long been recognized as providing a wealth of important benefits that include fisheries production, nutrient removal, storm surge protection and carbon sequestration (Costanza, Mitsch, and Day 2006; Day et al. 2007; Shields et al. 2017; Chesney and Baltz 2000). In terms of the impacts of the Mississippi River and its Delta on the Gulf of Mexico, several key areas stand out as need for future research:

1) Commercial fisheries Production in Offshore Environments: The Mississippi River provides the basis for a large complex food web in the GOM- by supplying large amounts of organic carbon and by fueling plankton blooms. While it has long been recognized that this contributes to the major fisheries of the Gulf of Mexico - e.g., shrimp, tuna, mackerels, jacks, Gulf menhaden and multiple reef fishes (https://www.st.nmfs.noaa.gov/commercial-fisheries/commercial-landings/annual-landings/index), the interannually productivity is variable and thus much remains unknown.

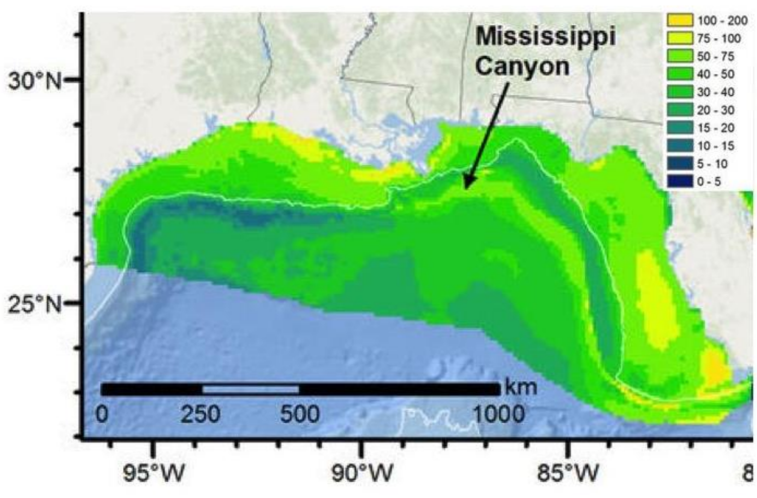

Fig. 3. Distribution of delphinoids in the Gulf of Mexico determined from multi-decadal surveys. Source: Roberts et al., (2016). The arrow pointing to the Mississippi Canyon is offest by ~ 100 km

2) River Diversions/Land Building and Storm Surge Mitigation: The State of Louisiana's plans to partially divert the flow of the Mississippi River to rebuild wetlands is likely to transform the river dominated coastal zone. As such, it is critical to understand the ecosystem functions that are gained or lost as these river diversions are implemented. Critical ecosystem services could include changes in fisheries production, bird habitat, nutrient cycling and storm surge abatement. While some of these issues are being studied as part of Louisiana's Master Plan, and as part of the Mississippi River Hydrodynamic and

Delta Management Study (LACPRA 2017; De Mutsert et al. 2016; Little and Biedenharn 2014; De Mutsert et al. 2017), and as independent work (Peyronnin et al. 2017; M. A. Allison and Meselhe 2010), further work is warranted, particularly after the diversions are operational. Additionally, diversions in the lower Mississippi River could occur without direct human intervention, as evidenced by the growing developing crevasse at Ft St. Philip (Suir et al. 2014).

3) Marine Mammals: The impact of the Mississippi River and its delta on the ecology, and status of marine mammals is poorly studied, particularly given the importance of these species conferred upon them by the Marine Mammal Protection Act (Mullin et al. 2017; Hayes et al. 2017). Research to date has indicated that the distribution of species like the coastal stocks of Bottlenose Dolphin are complex, and often related to a combination of processes that are influenced by the Mississippi River, including water temperature, the variance in water temperature, and the abundance of food (Baumgartner et al. 2001). Despite the complexities, some the greatest abundance of small delphinoids, including the Bottlenose Dolphins in the Gulf of Mexico (Fig. 3), occur near the outfalls of the Mississippi and Atchafalaya Rivers (J. J. Roberts et al. 2016). Given the fluctuations in time and space of the Mississippi River plume that typically occur (Walker et al. 2005; Walker 1996; Fitzpatrick, Kolker, and Chu 2017), and which could continue to occur with both climate change and Louisiana's plans to partially divert the flow of the river (LACPRA 2017), more research is clearly needed on how such current and future variability in the area of the Mississippi River plume could influence the diversity and abundance of marine mammals.

4) Impacts of spatial and temporal variability in the river plume on ecosystem services and valued ecosystem component: The regions of the Gulf of Mexico that are influenced by the Mississippi River plume are highly dynamic environments (Fig. 2; Fig. 4). While there are statistical norms (e.g. high river flow in April/May, high plume area in June; low river in Aug-Oct, low plume area Sept-Nov), the location and depth of the river plume can vary substantially from one year to the next (Kolker et al. 2014; Walker et al. 2005; Yannis S. Androulidakis and Kourafalou 2013; Fitzpatrick, Kolker, and Chu 2017; Schiller et al. 2011). Looking into the future, much less is known about how climate change will impact the spatial and temporal distribution of the Mississippi River plume, as the size, shape and intensity of the plume is dependent is dependent on a myriad of factors that are dependent on both climate and weather (Wuebbles et al. 2017). This current and projected variability calls for further research on how this variability influences the provisioning and flow of ecosystem benefits to humans both now, and in the future.

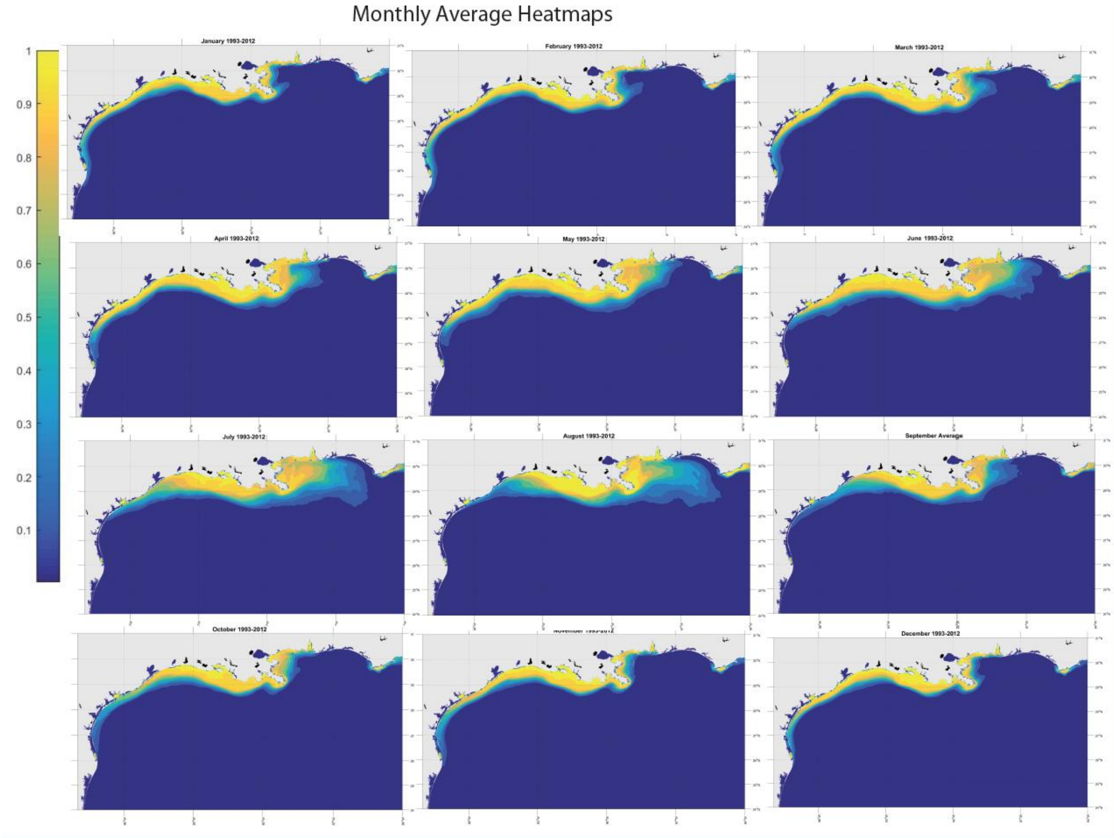

Fig. 4. Monthly averages of frequency of the 33PSU contour, used to determine the distribution of the Mississippi River plume. Source: Fitzpatrick et al., (2017).

II.D. Human Communities

Understanding human communities and their interactions with the Mississippi River and the Gulf of Mexico is an emerging area for research. The need for such research can be seen in Louisiana's Coastal Master Plan, which plans to reconnect the Mississippi River to its delta as part of coastal restoration and protection plans (LACPRA 2017). This sets up a need for research on how the river, delta and ocean interact, and how these interactions influence the people who live, work, and rely on the region. There are multiple ways in this problem could be investigated. Such ways could include:

1) Impacts of the changes in the river's discharge point on fishers in the Gulf of Mexico. While it is commonly viewed that the mouth of the Mississippi River has remained stable for the last century, this view is currently being changed. Recent studies have indicated that exit points are shifting northward, potentially a result of high rates of subsidence and relative sea level rise (Kemp, Day, and Freeman 2014). Furthermore, the State of Louisiana (Fig. 5) and its partners have developed two small (< 300 $m^3 s^{-1}$) and one large (>1,000 $m^3 s^{-1}$) system that divert water into subsiding and degrading wetlands, while also planning for multiple

large(1,000- 2,000 m^3 s^{-1}), "diversions" as part of its Coastal Master Plan (LACPRA 2017). While there have been some studies of the impact of existing and planned diversions on the impacts of economically important fish and the people who harvest them (De Mutsert and Cowan 2012; De Mutsert et al. 2016, 2017; De Mutsert, Cowan, and Walters 2012), much remains unknown about how construction and management of these structures will impact critical species, their harvesters, and the cascading economic conditions that are likely to occur (Peyronnin et al. 2017; LACPRA 2017).

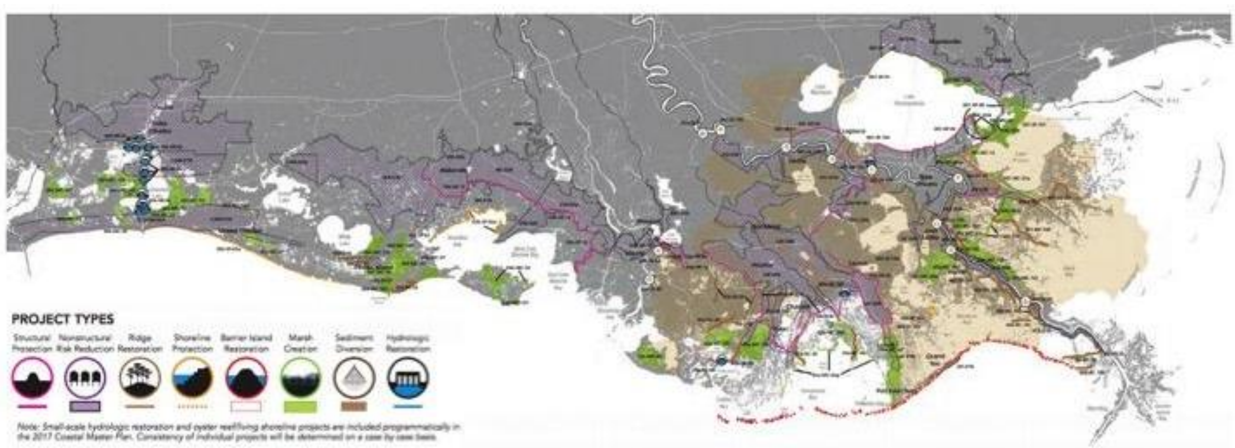

Fig. 5. Project distribution for Louisiana's Coastal Master Plan. (LACPRA 2017).

2) Impacts of changes in the river's discharge point on navigation, pilots, boat crews and mariners. Much of the current anthropogenic architecture of the Mississippi River was established to maintain navigation in one of the nation's most important shipping pathways. However, the forces maintaining channel and navigational stability could change in the years ahead as subsidence, global sea level rise, and the development of planned and unplanned river diversions change the flow distribution of the Mississippi River (Kolker et al. 2018- In Press). While there has been considerable research on maintaining channel and navigational stability as part of the Mississippi River Hydrodynamic and Delta Management Study (Little and Biedenharn 2014), more work in needed on how changes in channel hydro and morphodynamics will impact how ships navigate through the lower Mississippi River and the Gulf of Mexico, and the cascading impacts on global shipping pathways.

3) Impacts of changes in the Mississippi River watershed on the ways that people interact with the lower river, its delta and plume. Over the past century, humans have had substantial impacts to the Mississippi River watershed, which include an increase in nutrient loads, a decrease in river pH, and a decrease in sediment loads (Alexander, Wilson, and Green 2012; Meade and Moody 2010; Kaushal et al. 2018). Human impacts to the watershed are likely continue to change this century. While it is beyond the scope of this review to speculate on

specific human impacts to the watershed, it is within the boundaries of this review to suggest that watershed impacts to plume will continue to need research and monitoring.

III. MODELS

There exist a wealth of numerical (i.e. computer-based) models that are used to understand and predict conditions in the Gulf of Mexico. These models are used over time scales that runs from hours to centuries, and have applications that include vessel operations, coastal restoration, storm-surge and hazard management, and climate change. Short-time scale applications of numerical models (hours to days) include the need to understand storm surges, and local hydrodynamics, and for which models like NOAA's FVCOM model and ADCIRC are particularly useful (Wamsley et al. 2009; Cobell et al. 2013). Models such as the hybrid coordinate model (HYCOM) are used to resolve ocean currents on time scales that run from about 8 hours to 10 days, and can be run at a spatial scale that covers the entire Gulf (Zhang et al. 2012; Y. S. Androulidakis, Kourafalou, and Schiller 2015). Other models, like DELFT3D, Flow-3D, and the network of regional ocean models (ROMS) are used to understand coastal morphodynamics over daily to decadal time scales, and are well suited for understanding the impacts of coastal restoration, protection or harbor modification projects (H. Wang et al. 2017; W and Fagherazzi 2012; Yuill et al. 2016; M. A. Allison et al. 2017; Shchepetkin and McWilliams 2005; Xu et al. 2011). Over longer time scales, 1-dimensional models are well suited for understanding the multi-decadal impacts of changes in river hydrodynamics.

Despite rapid progress in recent decades, many areas stand out as areas where improvement in models are needed.

III. A. Improved Parameterization and Calibration

Many numerical models could benefit from improved parameterization and calibration efforts. For example, coastal hydrodynamic/oceanographic models such as the Hybrid Coordinate Model (HYCOM) do not accurately represent the distribution of water discharge in the lower Mississippi River. Instead, they rely on discharge measurements made at either Belle Chasse (75 km above Head of Passes) or Tarbert Landing (250 km above Head of Passes), and extrapolate how water is discharged through the numerous passes in the lower Mississippi River (Allard et al. 2014; Fitzpatrick, Kolker, and Chu 2017). This stems, in part, from the fact that there are no daily discharge measurements on passes in the Birdsfoot Delta, and the most state of the art measurements to date (e.g. Allison et al., 2012) rely on a small number of field surveys, coupled with a limited number of stage measurements. Given the large fluxes from these distributaries (500 - 2,000 $m^3 s^{-1}$), and the highly dynamic nature of lower river's geomorphology (Suir et al. 2014; Kolker et al. 2018- In Press), large errors associated with discharge could be occurring. Other parameterization gaps include parameters that are challenging to measure and/or quantify from satellites and/or difficult measurements to extrapolate broadly from in situ sensors (Habib et al. 2007). This can include salinity (both surface and deep), sediment fluxes (in the river and in the open ocean), and phytoplankton distributions.

III.B. Boundary Condition Definition

In many models boundary conditions play an important role in setting the overall calculations of the modeling tool (Fig. 6). In some cases, the difficulties in assessing boundary stems from the highly heterogeneous, and dynamic nature of the Louisiana coast, or the complexities associated with understanding the morphodynamic evolution of the bed of the Mississippi River (Pereira et al. 2009). In other cases, boundary conditions are set administratively. For example, some of the E-W boundaries employed by the models grid used for Louisiana's Coastal Master Plan are near state boundaries (Fig.6), i.e. the LA/TX border and the LA/MS border (Brown et al. 2017).

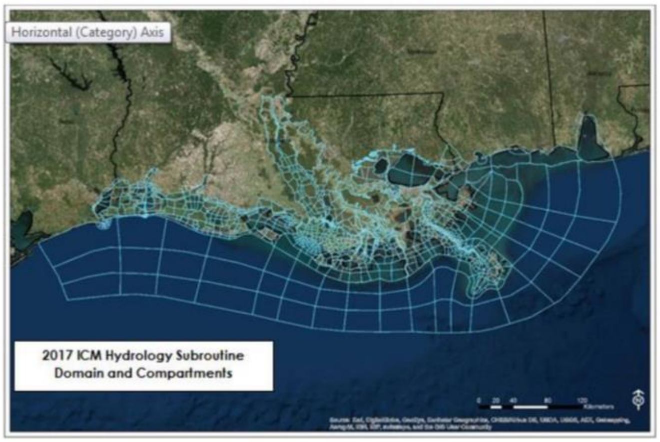

Fig. 6. Domain for the intercompartmental model used by Louisiana's Comprehensive Master Plan (Brown et al., 2017, LACPRA 2017)

III.C. Model Integration

The integration of the multiplicity of models use in the northern Gulf of Mexico is another priority area for research. Indeed, models are used for many purposes, and many models have different levels of spatial and temporal resolution and range. However, these models are often used for intersecting goals, and it is thus critical that such models are have the ability to integrate and interface. Examples for the need for model integration include:

1) Integration of river models with ocean models to better predict river-ocean interactions: At present, many of the numerical models used are specific to a particular waterbody, or set of waterbodies (i.e. ocean, estuary, river). This is a reasonable approach, given the different physical processes that occur in each region, and the computational complexity associated with each model domain - e.g., spatial resolutions (ocean cells tend to be larger due to the size of the spatial scales at which operational models work). However, in the years ahead as computational power becomes ever less expensive, integration across model domains will become easier - e.g., resolve at multiple spatial resolutions and thus integrating seamless products at relevant coastal scales. Such an integration would allow researchers,

practitioners, and decision makers to better understand the regional implications of changes to the Mississippi River, its delta and the Gulf of Mexico.

2) Integration of physical hydrodynamic models with ecological and biogeochemical models: At present many models used are specific to a particular process (physical, ecological). As above, this is a reasonable approach given the computational complexity of each process. However, better integration between physical and ecological models would allow researchers to better predict response ecosystem response to change, species distributions (niches), fisheries production, and harmful algal blooms. To date, some improvements have been made in this field- DELFT-3D, originally a morphodynamic model has a water quality module (H. Wang et al. 2017), and Louisiana’s Coastal Master Plan featured an intercompartmental model, which is a step in the direction of incorporating a diversity of models (which in this case range from physical to ecological to economic) into one component (LACPRA 2017; Brown et al. 2017). Examples of approaches that have come far in end-to-end modeling (from physics to fish) are a coupled physical-biological ROMS model (Fennel et al. 2011), which has subsequently been coupled to an Ecospace model (de Mutsert et al. 2016); a Delft-3D model coupled to a water quality and vegetation model (Meselhe, Baustain, and Allison 2015), which was subsequently coupled to an Ecospace model (de Mutsert et al. 2017); and a hydrodynamics-water quality model developed in FVCOM and WASP (Justić and Wang 2014), subsequently coupled to an individual-based population model for Atlantic Croaker (Rose et al. 2018).

3) Integration of morphological models and storm surge models to predict how coastal systems will change in response to extreme events, and therefore how the human community and critical infrastructure risk will be affected dynamically. At present, many models used to predict storm surge consider geomorphic features on the coast to be constant, and unchanged by storms. However, extreme events such as tropical cyclones can play a major role in changing the morphology of the coast during events (incl. wind, waves and flooding). A better understanding of how morphodynamics change during an event, or set of repetitive events, will enhance disaster response and emergency management, in addition to our understanding of coastal geomorphology in general.

III.D. Improved Understanding of Fundamental River-Ocean Processes

As discussed in sections II.A and II.B, understanding fundamental scientific processes is critical to advancing the performance of river-ocean models. Indeed, numerical models are only as good as our understanding of the scientific processes underlying them. Specific areas of improvement include:

1) Mixing dynamics of the Mississippi River plume: Understanding mixing dynamics of freshwater from the Mississippi River plume are critical understanding not only the physical oceanography of the region (Fig. 2; Fig. 4), but also understanding the distribution of fish, endangered and protected species (i.e., sea turtles and marine mammals), and the drivers, impacts and distribution of hypoxia. An improved understanding of the mixing dynamics of the Mississippi River, and an integration of that into numerical models that can be used to predict physical and ecological processes in the Gulf of Mexico is critical.

2) Particle flocculation in fresh and saltwater mixing zones: Understanding particle flocculation has long been recognized as critical research need in oceanography and the modeling of oceanographic processes as it impacts the flux of particulate, dissolved and sorbed material to the ocean. However, despite some advances in our understanding of this process (Galler and Allison 2008), it remains challenging to both measure and model. Further research is clearly needed on this topic.

3) Biogeochemical Cycles and the processing of nutrients in coastal and wetland environments: While the basics of nutrient cycling remain well known (Day et al. 2012), many of the complexities of nutrient dynamics, and biogeochemical cycles in the river and delta dominated regions of the coastal zone remain poorly understood, and this reduces our ability to understand how the Mississippi River and its delta impact the Gulf of Mexico. Critical sub questions include: understanding hypoxia on the continental shelf (Turner, Rabalais, and Justić 2012; Bianchi et al. 2010), understanding the impacts of Mississippi River diversions (planned as part of Louisiana's Coastal Master Plan) on water quality (Peyronnin et al. 2017; H. Wang et al. 2017; LACPRA 2017), and understanding how wetland loss impacts the flux, fate and transport of carbon and nutrients to the continental shelf (Fry et al. 2015; Wilson and Allison 2008).

4) Controls on primary and secondary productivity: While it has long been known that the Mississippi River plays a dominant role in fueling primary and secondary productivity on the continental shelf, much remains unknown about the full controls on productivity, and the scaling factors between riverine flux of freshwater, nutrients and organic matter on the productivity of particular species. Despite decades of research in other areas (Kavanaugh et al. 2016), the scientific community's ability to fully predict productivity in the Gulf of Mexico, remains somewhat limited.

III.E. Improved Spatial and Temporal Coverage

To be more effective numerical models need both improved spatial coverage, and better spatial and temporal resolution. For example, ecological models are particularly hampered by a lack of spatial and temporal resolution for the distribution of organisms and the rates of biogeochemical processes (Fennel et al. 2016). This is derived, in part, from the difficulties in understanding the behavior and movements of many animals, and a lack of ecological and biogeochemical measurements to calibrate such models severely limits their capabilities (Fennel et al. 2016). Other constraints come from the difficulty resolving the flow dynamics that result from the complex geomorphology of the coastal zone in the northern Gulf of Mexico (L. Wang and Justić 2009; Georgiou, FitzGerald, and Stone 2005; Meselhe et al. 2012). Further constraints are the amount of computational power required to run models with an increased number of time steps or grid-blocks.

III.F. Decision Support Tools

As the ultimate goal of many modeling efforts is improved management, decision support tools stand out as an area for operational model improvement. One example of an area where decision support tools have proven useful is Louisiana's Coastal Master Plan (LACPRA 2017). This plan used a decision support to predict the suite of projects that created and/or maintained land and reduced annual damages, while also providing some analyses regarding other scenarios (Groves and Sharon 2013). In the years ahead, decision support tools will be needed to optimize decision making in the coastal zone, including a need to understand how the coastal zone will respond to sea level rise, how to select the best projects for coastal restoration and protection, how to manage mineral and energy resources in the coastal zone, and how to sustainably manage fisheries. Incorporating satellite image measurements as a decision support tool could provide significant benefits. The Mississippi and Atchafalaya River water can be detected during all seasons using satellite imagery of reflectance (for sediments) and sea surface temperatures. The ability to track river water in the diversion areas could provide an important tool for decision support. .

IV. MEASURMENT GAPS

The analysis examined areas where improved measurements would enhance our understanding of the impact of the Mississippi River and its Delta on the Gulf of Mexico large marine ecosystem. This analysis focused measurement gaps on three specific areas where more data could lead to measurable improvements in the scientific community's understanding of the impact of the Mississippi River and its delta on the Gulf. These areas were: 1) oceanographic processes that needed further measurements, 2) specific locations that would benefit from more detailed measurements, 3) emerging sensors and 4) the need for baseline data.

IV.A. Process Understanding to Be Improved by Measurement

1) Salinity Dynamics: Salinity is one of the primary mechanisms driving ocean circulation, and such salt/freshwater dynamics are important in the northern Gulf of Mexico (Fig. 2) because

it is the receiving basin for North America's largest river, the Mississippi. However, salinity is one of the most difficult oceanographic parameters to determine from satellite remote sensing and thus to integrate it in operational models, though there are emerging methods to do so (Chen and Hu 2017). Challenges in understanding salinity dynamics also emerge from the complex nature of the discharge of the Mississippi River, which debauches through distributaries that have poorly constrained discharges.

2) Biogeochemical Processes: The research, scientific, fisheries, and restoration communities would all benefit from enhanced measurements of biogeochemical processes. Measurements of biogeochemical rates often depend on logistically complex procedures that involve field sample collection and water and/or sediment incubations (B. J. Roberts and Doty 2015). As such, these measurements are generally low in number relative to the size of the area potentially influenced by the Mississippi River, and the variability associated with the northern Gulf of Mexico (Fennel et al. 2016). Associated with this is a need to understand the dynamics of nutrients and carbon in the Gulf of Mexico, and how nutrients are processed in the river-influenced regions of the Gulf of Mexico(L. Wang and Justić 2009; Fry et al. 2015). Indeed, as will be discussed below there is even a need to more fully understand which parts of the Gulf of Mexico are most influenced by river-derived nutrients- despite decades of research in some targeted areas.

3) River Diversions: As the State of Louisiana moves forward with plans to partially divert the flow of the Mississippi River (Fig. 5), the need to understand the dynamics of these systems will become increasingly important. Indeed, Mississippi River Diversions are likely to become among the largest and most complicated river-influenced system in the nation, as they will carry between 1,000 and 2,000 $m^3 s^{-1}$ at high flow (LACPRA 2017). There are some systems in place that could serve as starting point for such measurements, such as Louisiana's Coastwide Reference Monitoring Service, and surface water measurements made by the US Geological Survey, the Army Corps of Engineers, and the National Oceanographic and Atmospheric Administration. However, intensive measurement at these system will be necessary to understand how they change the way the Mississippi River and its delta impact the Gulf. Such studies should have measurements that include, but are not necessarily limited to salinity, temperature, currents, nutrients, ecosystem metabolism rates, sediment dynamics and transport, and the distribution and abundance of both plankton and nekton.

4) Multiple Stressors: Many of the dynamics that occur in the river- and delta-influenced regions of the Gulf of Mexico are the function of a multitude of physical, ecological and human processes working in a complex combination of synergy and antagonism. The case of hypoxia, which is a function of freshwater dynamics, biogeochemical reactions, and human decisions governing fertilizer usage stands out as one of many examples of a multi-stressor process (Rabalais et al. 1996; Rabalais, Turner, and Wiseman 2002). Looking to the the

future, research should prioritize studies that examine the multiple drivers that govern the processes that impact of the river and its delta on the Gulf.

IV.B. The Following Geographic Regions are Considered Areas that Deserve Specific Attention

1) The Eastern Mississippi River plume: A statistical analysis of the distribution of the Mississippi River plume shows that the eastern river dominated coastal zone receives river water a substantial fraction of the year (Fitzpatrick, Kolker, and Chu 2017), and yet this area is less well studied than the western areas receiving river water - i.e. the Louisiana-Texas Bight (Shim, Swarzenski, and Shiller 2012). This eastern area, termed here as the LAMI-ALFA bight, extends from about 28-30°N, 89-85°W and comprises about 93,000 km^2. The LAMI-ALFA is also significant for its proximity to the Deepwater Horizon well explosion, which caused a contaminant spill totally nearly 4.5 million barrels of oil (Diercks et al. 2010; O'Connor et al. 2016). Data collection here is needed to thus both understand the impacts of the Mississippi River and its Delta on the Gulf of Mexico, as well as to better understand the long-term impacts of the DWH oil spill (Turner et al. 2014; Silliman et al. 2012; Michel et al. 2013; Colwell 2014).

2) The Eastern Delta of the Mississippi River: This area, defined here as the region north of Venice, and south of Pointe-a-la-Hache, receives about 25% of the total flow of the Mississippi River (Mead A. Allison et al. 2012), and yet it also remains poorly studied. Some studies suggest that the amount of flow here is actually increasing- perhaps as a result of increased crevassing (Suir et al. 2014). Several parts of this area are also targets for restoration that may result from Louisiana's comprehensive Master Plan for a Sustainable Coast, including the mid-Breton Diversion (LACPRA 2017).

3) Mississippi River Distributary Outfalls: At present, there is relatively little data collected on the discharge of the Mississippi River outfalls. While there are stage monitors at some of the key outfalls of the Mississippi River (e.g. tide gauges at south and southwest pass), there are no discharge gauges south of Belle Chasse. Thought discharge has been measured through individual boat-base surveys (Mead A. Allison et al. 2012), these values can fluctuate with discharge, and over time as the channel shoals, as crevasses form, and as relative sea-level rises (Little and Biedenharn 2014). This uncertainty in distributary discharge makes it difficult in general to determine the flow of water that is headed in any particular direction, which can potentially confound both the interpretation of in-situ measurements and the development and implementation of oceanographic models (Fitzpatrick, Kolker, and Chu 2017).

4) Regions that could be influenced by river diversions: River diversions are expected to carry 1,000-2,000 m^3s^{-1} of water- enough that if taken on their own, these systems would be among the largest sources of freshwater to the Gulf of Mexico (LACPRA 2017). Given the magnitude of these systems, and their importance to Louisiana's coastal restoration plans, and their potential ecological impact, these systems would benefit from additional monitoring (Peyronnin et al. 2017).

IV.C. Baseline Data

The need for good baseline biophysical data remains a critical research need. This need was highlighted during the BP/Deepwater Horizon Oil Spill, when the full impacts of the spill were hard to gauge, at least at the beginning, given the lack of baseline data. This need for baseline data will continue to grow in the years ahead as climate changes, as global sea levels rise, and as humans also seek to restore and protect coastal ecosystems and infrastructure. Collecting quality baseline data requires the acquisition, maintenance, expansion of sensors/direct measurements, and development of comprehensive monitoring programs.

1) Improved monitoring programs: The area of the Gulf of Mexico that is influenced by the Mississippi River and its delta is a highly dynamic coastal zone, controlled by a competing mix of fluvial, oceanographic, geological, climatic and human processes. Understanding baseline conditions requires intensive, long-term monitoring programs that are inherently structured to collect data before, during and after, extreme events occur. There are monitoring programs that exist across the region that include in-situ sensor measure physical and water quality parameters run by organizations such as NOAA, the USGS, the Army Corps of Engineers, and Louisiana's Coastwide Reference Monitoring Service. Remotely sensed data is available from NASA, NOAA, and Louisiana State University's Earth Scan Laboratory which compiles and processes remotely sensed data for the Mississippi River delta and plume region. These networks can and should be maintained, and enhanced in order to provide additional baseline data on the impacts of the Mississippi River and its Delta on the Gulf of Mexico.

2) Data archaeology: One area that also deserves further consideration is data synthesis and data archeology programs that analyze historic and previously collected data to better understand the historical baseline conditions. Indeed, the Gulf of Mexico has been studied for decades by a range of governmental, academic and private organizations, with both in-situ and remote sensors. These data can be synthesized and analyzed to more fully understand historic conditions in the Gulf of Mexico.

IV.D. Emerging Sensors

Environmental sensors are rapidly advancing in their sophistication and availability, and as such, have the potential to help answer critical research questions. Several areas stand out for further research:

1) Deployment of large numbers of sensors to aid in science and to inform management: Environmental sensors are potentially available in such numbers that it is possible to develop high spatial-density sensor networks. One example of this is Louisiana's Coastwide Reference Monitoring Service, which consists of over 300 stations located across Louisiana coastal wetlands (www.lacoast.gov/crms). To understand the impacts of the Mississippi River and its Delta on the Gulf of Mexico, this network, and those of federal agencies that deploy monitoring networks, could be expanded to include higher density in lowermost Mississippi River and adjacent offshore regions (or even into the TX-LA shelf where the hypoxic area expands during the summer).

2) Use of real-time data collection to aid in incident management: The need for improved real-time sensors to aid in incident management in the river dominated regions of the Gulf of Mexico was illustrated during the Deepwater Horizon Oil Spill (Michel et al. 2013). This was the largest marine oil spill in US history, and the transport of this oil was partially driven by the Mississippi River plume. Improved sensors in the river-dominated sections of the coastal zone, including both in-situ sensor, and remotely operated sensors could aid in the management of critical incidents such as major oil spills.

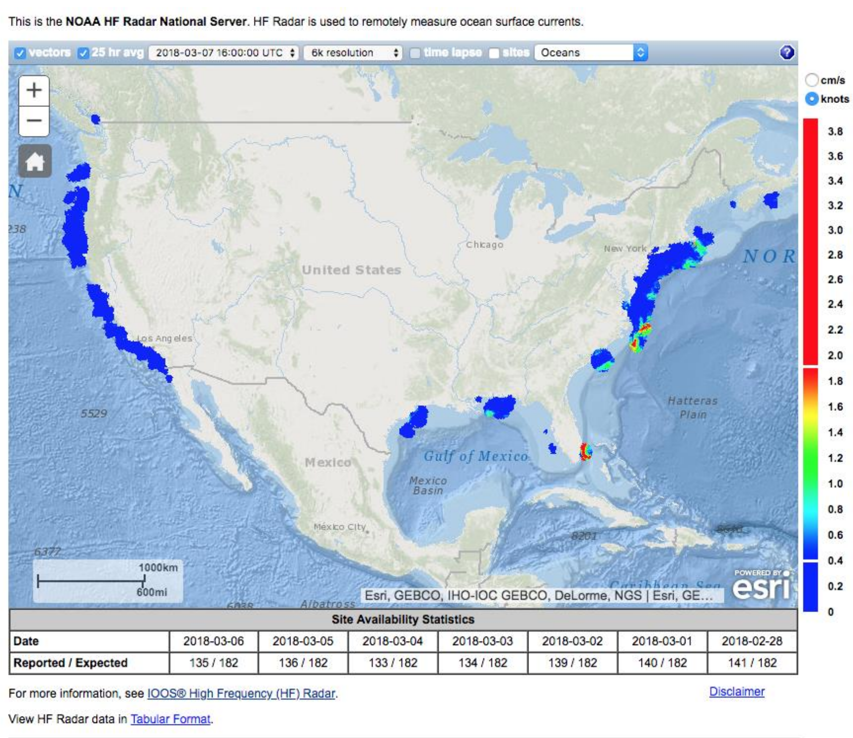

Fig. 7. HF Radar in the continental US for March 6, 2018. Note that areas likely to be influenced by the Mississippi River are poorly/not covered by these measurements. http://hfradar.ndbc.noaa.gov/.

3) Deployment of advanced sensors: New sensors are rapidly becoming available to sense environmental parameters in the river dominated sections of the coastal zone. One emerging sensor is high frequency, land-based radar, which can be used to measure wave dynamics (Fig. 7; https://ioos.noaa.gov/project/hf-radar/). However, despite widespread deployment of this technology across the Atlantic and Pacific Coast, its availability in the river and delta influenced sections of the Gulf Coast is lacking. Another example is satellite-based synthetic aperture radar, which has been used to map the Deepwater Horizon Oil Spill (Minchew, Jones, and Holt 2012; Rangoonwala, Jones, and Ramsey 2016), and determine subsidence patterns in the Louisiana Coastal Zone (Jones et al. 2016).

V. A NEED FOR TRANSDISCIPLINARY SYNTHESIS

V.A. Overview and Description

Scientific synthesis brings together diverse knowledge from across scientific disciplines in an effort to increase the generality and applicability of the results of complex scientific questions (Carpenter et al. 2009; Hampton and Parker 2011). Synthesis blends disparate information and knowledge in new ways in an effort to yield novel insights or innovations and is especially important to the environmental sciences where the scale and complexity of environmental issues require synthesis. Synthesis work typically takes the form of repeated and sustained interactions between individuals that have access to a range of knowledge, data and tools that make it possible to mine or combine existing knowledge and data sets and gain new perspectives, develop visualizations and modeling tools that lead to new insights and bring a cross-disciplinary approach to existing problems (Carpenter et al. 2009).

While scientific synthesis has a long history, in the U.S., the field was furthered through National Science Foundation (NSF) funding of synthesis centers. Initiated in 1995, the program has funded four synthesis centers: 1) National Center for Ecological Analysis and Synthesis (NCEAS), 2) the National Evolutionary Synthesis Center (now called the Triangle Center for Evolutionary Medicine) 3) the National Institute for Mathematical and Biological Synthesis (NIMBioS) and 4) Socio-Environmental Synthesis Center (SESYNC). These synthesis centers were created to use existing data and using that data through collaboration across multi research disciplines to address “big picture” questions (Rodrigo et al. 2013). More recently, in the Gulf, funding opportunities for synthesis science projects has been made available through the NOAA RESTORE Act program and the National Academy of Sciences Gulf Research Program. In the NOAA RESTORE Act Science Plan and NAS Gulf Research strategic vision, the importance of synthesis and integration of existing data to help identify data gaps, pressing research questions and extract novel insights from existing data sets was noted (NOAA 2015; National Research Council 2014).

Synthesis centers, such as NCEAS, have a model that they follow to build a working group to collaborate on an issue which includes 12 to 18 expert from different disciplines, sectors (e.g., academia, government, non-governmental organizations, and businesses), career levels and geographic locations. The working groups meet face-to-face for a week at a time, typically 10-12 hours days over a 2-3 years period, bringing with them, their data, expertise, and methods. An analysis of 200 NCEAS working groups found that the number of meetings and the number of different institutions had a positive effect on the productivity and scientific impact of the working group (Hampton and Parker, 2011).

V.B. Research Projects Suitable for Synthesis

Synthesis is a wide-scope field of research that has the potential to address a wide range of questions for a variety of disciplines. In the river- and delta- influenced regions of the Gulf, there are vast scope of questions that could be addressed by synthesis, a partial list of which is presented here. Synthesis could examine discipline-specific projects, such as exploring the physical and/or chemical linkages between the land, air and sea using a combination of remote and in situ sensors coupled with numerical analyses, or the impacts of invasive species on river, delta and Gulf ecosystem. Alternatively, synthesis could examine different branches of marine science, such as the linkages between physical, ecological and biogeochemical processes. Topics that cover a long time span are particularly well suited towards synthesis studies, such as ecological connectivity, the impacts of climate change on the Mississippi River Delta and its connection to Gulf ecosystem. Synthesis studies can also play a role in advancing management, for example by connecting autonomous physical/ecological/biogeochemical measurements with management questions and decision support tools to improve restoration planning, or by comparing and contrasting individual-species based management and ecosystem-based management.

V.C. Strategies to Build Successful Gulf-based Synthesis Groups

There is a need for working groups that fall outside of the traditional model of scientific synthesis for restoration efforts in the Gulf. The complexity of restoration needs, different funding streams and their restrictions, and the numerous stakeholders, would benefit from frequent, collaborative meetings, whether that’s federal and state agencies meeting to discuss specific projects, share data, and identify information that is needed to help find ways to streamline project timeline from concept to construction or working groups of community members to plan climate adaptation strategies.

Synthesis working groups typically tackle challenging questions that require collaborative knowledge to address. Gulf-based synthesis projects can be initiated in a number of manners. One potentially successful manner is for an organization to put out a call for a synthesis group and a specific topic. The organization could be a Gulf-oriented funding organization such as the Gulf Research Program or the NOAA Restore Act Science Program, or it could be a Gulf-based academic institution with expertise in synthesis, such as the Louisiana Universities Marine

Consortium’s Marine Synthesis Center (https://lumcon.edu/marine-synthesis-center/). Other synthesis efforts can result from the culmination of efforts by a given research team- such as the Mississippi River Hydrodynamic and Delta Management Study (http://coastal.la.gov/project/hydrodynamic-and-delta-management-study/). The Sediment Diversion Operations Expert Working Group was established to discuss and make recommendations about how and when to operate a sediment diversion to maximize land-building while also considering other potential effects (Peyronnin et al. 2017). In each meeting, a single parameter was discussed (e.g., River Hydrodynamics, Fish and Wildlife) by transdisciplinary core group of experts. This approach facilitated a better understanding of the issues across disciplines and helped facilitate a more holistic discussion of the river-estuarine-community system (Peyronnin et al. 2017). Workshops would also be a useful tool as a method to draw together experts to identify specific smaller-scale problems to address, and help to focus areas of expertise on different aspects of a single issue.

It is worth exploring other models in developing a synthesis-type approach to research gaps related to the Gulf of Mexico. Concepts associated with sustainable development, from an ecological economics approach, have led to transdisciplinarity research. This approach seeks to break down cognitive styles and standard barriers between broad disciplines, such as natural sciences versus social sciences (Hadorn et al. 2006). Transdisciplinarity also recognizes different sectors of society (extending to scientists and agency specialists) as cultures, which are bridged through familiarity and respect within the transdisciplinary framework to address issues that impact multiple stakeholders (Pohl 2008). Using a transdisciplinary approach, Australia’s ACEAS acted at a level *above* synthesis centers to address complex environmental issues based on synthesis-generated data for use by managers and policy makers, as well as scientists (Lynch et al. 2015). There is also a model to bridge transdisciplinarity to sustainable science, as a way of 1) exploring new options for problem-solving, and 2) encouraging transferable knowledge between science and society (Lang et al. 2012). These approaches all seek to embed policy makers and other stakeholders into the process, as a method to encourage participation and acceptance of research being conducted on issues in a given area of concern.

Synthesis centers focused on how the Mississippi River and its Delta impact the Gulf of Mexico should follow guidelines and best practices established by other synthesis centers such as NIMBIos, and NCEAS. These practices include involving the right members with a variety of expertise that are interested in the topic, a diversity of ages and experiences, and breakdowning disciplinary jargon and translating methodologies that may be unfamiliar to other working group members. These practices help ensure that work is completed- for example- groups of senior researchers only often do not produce papers because senior researchers do not have the time to dedicate to details and figure generation. Furthermore, breaking down jargon can be particularly important when synthesizing highly different fields- such as physical and social sciences.

VI. RESEARCH ORGANIZATIONS

Conducting research in the Gulf of Mexico often requires research teams of researchers with different specialties. This section examines how the location, organization structure of research teams could impact how researchers study the impacts of the Mississippi River and its Delta on the oceanography of the Gulf of Mexico. Indeed, while many associate research as a university oriented affair, and indeed universities do excel at research, research can be conducted by a range of organizations in the academic, public, private, non-profit and for profit sectors. Understanding which research is best conducted by which sector may help funding organizations plan strategically, and optimize fund allocation. A further examination of these issue may also help plan for applied research that incorporates management needs, - a particularly important goal as the Gulf recovers from the BP/Deepwater Horizon Oil Spill, and Gulf States like Louisiana plan to restore and protect their shorelines and natural resources.

VI.A Roles of University and Government-Based Research Institutions

While both university-based research and government-based research provide tremendous value to the river/ocean studies, key differences do exist, and it is worthwhile to be mindful of some of these differences. For example, governments are often better at establishing and maintaining long-running gauging stations, and large monitoring programs. These programs often require long-term funding- which is difficult to count on at universities, and they can provide value without leading to a publication- which is often a requisite for university-based researchers. Long-term gauging data may also be collected for non-research related purposes, like disaster management- often a government responsibility. Governmental organization that provide excellent gauge-based data useful to study the impacts of the Mississippi River and its Delta on the Gulf of Mexico include the National Oceanographic and Atmospheric Administration, the US Geological Survey, the National Aeronautics and Space Administration, the US Army Corps of Engineers. At the state level, programs such as Louisiana's Coastwide Reference Monitoring System provide useful data. On the other hand, university-based research is often well suited for hypothesis-based research, for research that may be controversial, and for research that trains future researchers.

VI.B. Strategies to Incorporate Managers into Research Measurements

Given the importance of management and environmental restoration to programs like those associated with the RESTORE ACT, Natural Resources Damages Assessment process, and state-based restoration programs like Louisiana's Coastal Master Plan, there is a need for research in sections of the Gulf of Mexico influenced by the Mississippi River to incorporate management and managers. Input from this working group about their management needs, as well as insights provided by others suggest several strategies for incorporating applied research.

For example, including managers in proposal formation at an early stage and keeping them involved throughout the research is often more successful that involving managers only after the research is conducted (e.g., as they manage the site/area where the research will take place and produce most benefits). The National Science Foundation, which almost always requires that Broader Impacts be including in a proposal, often suggests that proposals to directly incorporate broader impact statements into the structure of the research, rather than have broader impact sections that only peripherally-related to data collection and analysis. Both scientists and managers often agree that it is useful to create opportunities for managers and researchers to closely interact, so that researcher can learn about managers' needs, and so that managers can learn the tool available to researchers, and the potential and limitations of these tools. Conferences such as Louisiana's State of the Coast Conference, and the GOMOSES conference sponsored by the Gulf Research Initiative are examples of such opportunities.

VI.C. Role of the Private Sector

The private sector has an important role to play understanding how the Mississippi River impacts the Gulf of Mexico. Engineering firms often play an important role in designing water control structures along the Mississippi River, habitat restoration, and understanding their impacts. Non-profit organizations, some of which have and advocacy focus, can provide valuable science and data. A study led by the Environmental Defense Fund on the operations of river diversions is one such example (Peyronnin et al. 2017), and the biweekly reports on hydrographic conditions in the delta provided by the Lake Pontchartrain Basin Foundation is another (https://saveourlake.org/lpbf-programs/coastal/hydrocoast-maps/). A new model is emerging of private non-profit research firms, such as the Water Institute of the Gulf. This organization provides field, analytical and modeling work that is often focused on the Mississippi River Delta for the State of Louisiana. This organizational structure may provide this organization with the capacity to do technically valuable for the State of Louisiana, independent of the profit motive of an engineering firm, and the scholarly publication requirements of university. Finally, private sector firms may also be more institutionally nimble than universities, and which could have benefits in terms of human resources, and publication structure. However, these added flexibilities must be balanced against other attributes of universities that make them appealing places for research. Universities typically expressly confirm academic freedom on researchers, which is critical to reducing biases in research. Universities often have extensive instrumentation that is not available to the private sector. Finally, universities have a capacity to attract researchers from national and international locations which can bring new talent to study the how nation's largest river and its delta impact the Gulf of Mexico.

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