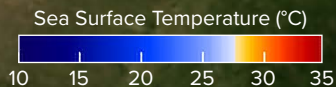


The Gulf of Mexico AN OVERVIEW

By Larry D. McKinney, John G. Shepherd, Charles A. Wilson, William T. Hogarth,
Jeff Chanton, Steven A. Murawski, Paul A. Sandifer, Tracey Sutton, David Yoskowitz, Katya Wowk,
Tamay M. Özgökmen, Samantha B. Joye, and Rex Caffey

Sea surface temperature in the Gulf of Mexico on March 1, 2008. The Loop Current can be recognized as the lighter region in the Gulf between the Yucatán Peninsula and Florida. *Image credit: NASA/Goddard Space Flight Center Scientific Visualization Studio*



“While the Deepwater Horizon oil spill was one of the great environmental disasters in US history, the research that it engendered, including that funded by GoMRI, significantly contributed to expanding our knowledge and, perhaps most importantly, to guiding the work to restore the damage from that oil spill.”

ABSTRACT. The Gulf of Mexico is a place where the environment and the economy both coexist and contend. It is a resilient large marine ecosystem that has changed in response to many drivers and pressures that we are only now beginning to fully understand. Coastlines of the states that border the Gulf comprise about half of the US southern seaboard, and those states are capped by the vast Midwest. The Gulf drains most of North America and is both an economic keystone and an unintended waste receptacle. It is a renowned resource for seafood markets, recreational fishing, and beach destinations and an international maritime highway fueled by vast, but limited, hydrocarbon reserves. Today, more is known about the Gulf than was imagined possible only a few years ago. That gain in knowledge was driven by one of the greatest environmental disasters of this country's history, the Deepwater Horizon oil spill. The multitude of response actions and subsequent funded research significantly contributed to expanding our knowledge and, perhaps most importantly, to guiding the work needed to restore the damage from that oil spill. Funding for further work should not wait for the next major disaster, which will be too late; progress must be maintained to ensure that the Gulf continues to be resilient.

INTRODUCTION

The environment and the economy of the Gulf of Mexico both coexist and contend with one another. The Gulf hosts a productive and resilient marine ecosystem, ever-changing in response to multiple drivers and pressures. This large system is extremely complex, and certain aspects are only now beginning to be fully appreciated. We must better understand the Gulf ecosystem to ensure its continued resilience as it faces unprecedented natural and human-driven pressures (NASEM, 2018). The articles in this special issue illuminate the complex interactions and processes at work in the Gulf and summarize what we have learned about their effects since the Deepwater Horizon disaster, viewed

through the lens of research and outreach activities of the Gulf of Mexico Research Initiative (GoMRI).

The Gulf is neither pristine nor an industrial wasteland. It has, however, been altered by human activities, and it faces many challenges, some common to all oceans and some unique. The Gulf ecosystem is dynamic, and its response to the drivers and pressures that influence its present and future state is complex. It is pressured by temperate influences from the north and tropical influences from the south. With Gulf states boasting about half of the US southern seaboard and capped by the vast Midwest, the Gulf is an ecological and economic keystone for the Americas. It drains much of North America, absorbing

both good and bad of what flows down the Mississippi, America's greatest river. Despite these pressures and because of its resilient nature, the Gulf is a renowned for its seafood markets, recreational fishing, and holiday beach destinations. It produces and refines much of the petroleum consumed and exported by the United States. As an international maritime highway, the Gulf provides an essential link for world trade and commerce. As a complex physical system, its influence, via the Gulf Stream, reaches far across the Atlantic Ocean. Growing our knowledge of the interactions that generate and affect these attributes is essential for all who live around the Gulf and depend upon it, if we are to take appropriate and effective actions to assure its future.

Today we know more about the Gulf of Mexico than we might have imagined possible only a few years ago (Figure 1). While the Deepwater Horizon (DWH) oil spill was one of the great environmental disasters in US history, the research that it engendered, including that funded by GoMRI, significantly contributed to expanding our knowledge and, perhaps most importantly, to guiding the work to restore the damage from that oil spill. Furthering this work should not wait for the next major disaster. That would be too late. We must find the political support and funding to build upon the foundations of the last 10 years and do it now.

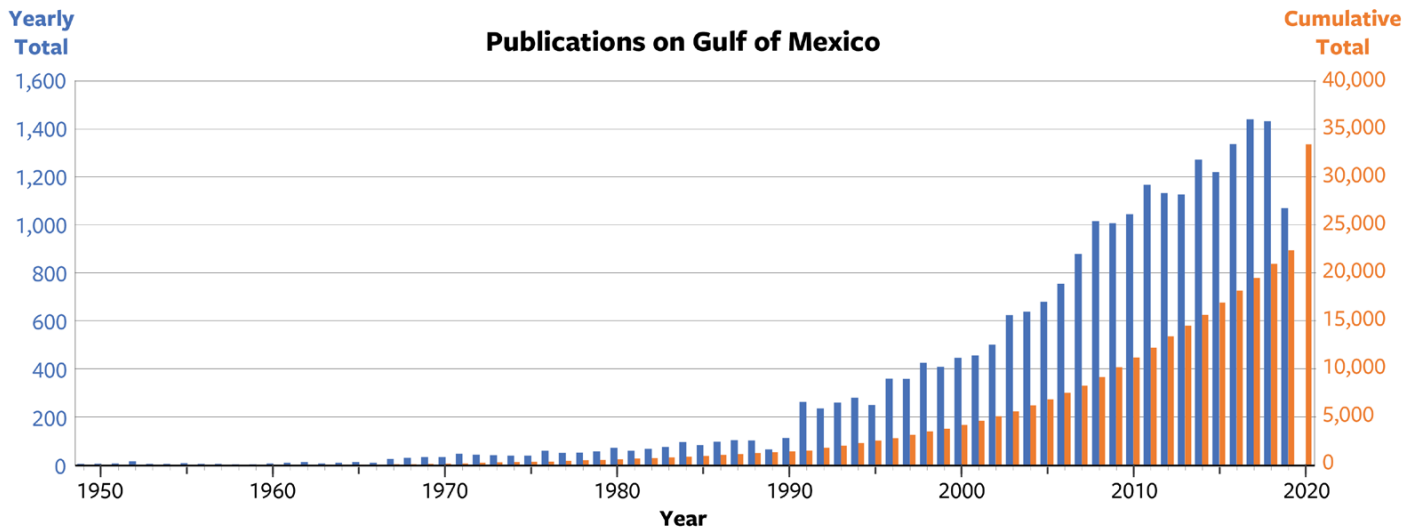


FIGURE 1. The graph shows the results of a web-based search of all documents using the term Gulf of Mexico. It includes articles, proceedings, reviews, meeting abstracts, and book chapters. Source: Web of Science, <https://clarivate.com/webofsciencegroup/solutions/web-of-science/>

What we know today will likely not suffice to support either management efforts or responses to future disasters. Our goal must be to assure the continued resilience of the Gulf of Mexico.

With this article, we provide a brief overview of the Gulf and its complex nature, summarize some of what has been learned since the DWH disaster, and describe how that knowledge has illuminated important aspects of this complex marine ecosystem. Using a conceptual framework to illustrate the linkages between natural and anthropogenic forces that act upon the Gulf and the range of human responses to mitigate or manage the stresses created by those forces, we provide context for how that new knowledge has increased our understanding of system interactions, both natural and human. It will also become evident that much still remains to be learned, and we will provide some fresh ideas about research needs. The future Gulf faces many challenges from climate change and ongoing development pressures. The resilient nature of the Gulf is and will be tested. The more we understand about how the Gulf “works,” the more impactful will be our management and restoration efforts in assuring future resilience that is so necessary for its sustained health and productivity.

THE GULF OF MEXICO AS AN INTEGRATED SYSTEM

Using the Gulf of Mexico as a model, Harwell et al. (2019) introduced the EcoHealth Metrics framework as an integrated indicators-and-assessment tool. The framework (Figure 2) can be used to understand the environmental condition of the Gulf in relation to natural and anthropogenic factors (drivers, pressures, stressors, conditions, and responses) as overlaid by management actions, including those focused on restoration. This simple model can be valuable for understanding how chemical, physical, and biological processes affecting the Gulf interact to influence this large marine ecosystem as a whole and how the effects of our actions, both positive and negative, can be discerned through various indicators. Those indicators can then inform both management and research strategies to address problems.

Drivers, among the Figure 2 components, are fundamental natural and anthropogenic forces. The diverse pressures generated by drivers force changes in ecosystems (Oesterwind et al., 2016). In the case of the Gulf of Mexico, drivers push against its resilient nature. *Pressures* are human activities and natural processes arising from drivers that tend to be large scale but spatially and temporally vari-

able. Human activities affecting the Gulf include oil and gas extraction, commercial and recreational fishing, and altered freshwater inflows, among others. Natural processes include hurricanes, nearshore current patterns, and sediment dynamics. Anthropogenically derived pressures can generally be acted upon through various management actions, while natural pressures are beyond management intervention. *Stressors* act upon the ecosystem directly as a result of pressures; physical, chemical, and biological stresses directly cause environmental effects. Physical stressors include changes in salinity and ocean acidification. Chemical stressors include altered nutrient inputs, and oil and chemical spills. Biological stressors include nursery habitat destruction, harmful algal blooms, overfishing, invasive species, and pathogens and disease. Restoration activities are often directed at stressors. Stressors result in a series of impacts on the system and its capacity for resilience in the face of cumulative stressors. *Responses* are human systems reactions to stressors; they include restrictive fishery management, habitat restoration, and limits on the release of toxic chemicals into the environment.

The EcoHealth Metrics framework illustrates how post-DWH knowledge can be used to positively influence the future

condition of the Gulf. Our new knowledge has also posed as many questions as it has answered, and this work must continue. The EcoHealth Metrics framework will help prioritize research needs as part of the adaptive management strategies contemplated by Natural Resource Damage Trustees (set up under the Oil Pollution Act of 1990), the RESTORE Gulf Ecosystem Restoration Council, and others who will direct billions of dollars in Gulf restoration and recovery. A better understanding of how these drivers and pressures affect the complex interactions of Gulf physical, chemical, and biological systems helps to refine our responses in maintaining a desirable state or condition of the Gulf that meets societal needs and expectations while assuring its resilient nature.

Management responses may remediate pressures through legislation, regulation, policy, or altered human behavior through education. Restoration may directly address stressors to the same

end and contribute to maintaining or restoring a desired “state” or condition that sustains ecosystem services. Our scientific understanding, or lack of it, directly affects our ability to enable effective management responses to maintain that desired state. When adequate, this knowledge can inform adaptive management strategies that will synergistically and iteratively build on lessons learned to enhance their effectiveness. That ability hinges on our understanding of system interactions at the most fundamental level.

The resilience of the Gulf system is determined by the interactions of anthropogenic drivers and pressures with natural processes. People are an integral part of the environment in the Gulf of Mexico, and human interactions are part of the problem as well as (hopefully) its solution. The Gulf can be regarded as a large marine ecosystem, an approach that is widely applied across the world’s oceans and coastal regions (Sherman,

2015). However, within the Gulf, there are unique interactions and relationships that define what has come to be called America’s Sea (Darnell, 2015). Oil spills in the Gulf can be natural or man-made and constitute a source of organic matter input that may be either productive or toxic. There are interactions between inshore, nearshore, offshore, and deep environments, not all of which are yet well understood. In perhaps few other places are people, environment, and economy so intimately linked, and we are only now learning the cost of ignoring those interrelationships. Effective pursuit of actions that sustain these linkages requires understanding the relationships between drivers, pressures, and stressors, their impacts, and societal responses to them within a framework that helps guide effective action. The framework and adaptive management driven by it will be informed by our scientific understanding of the system interactions that are generated by those forces.

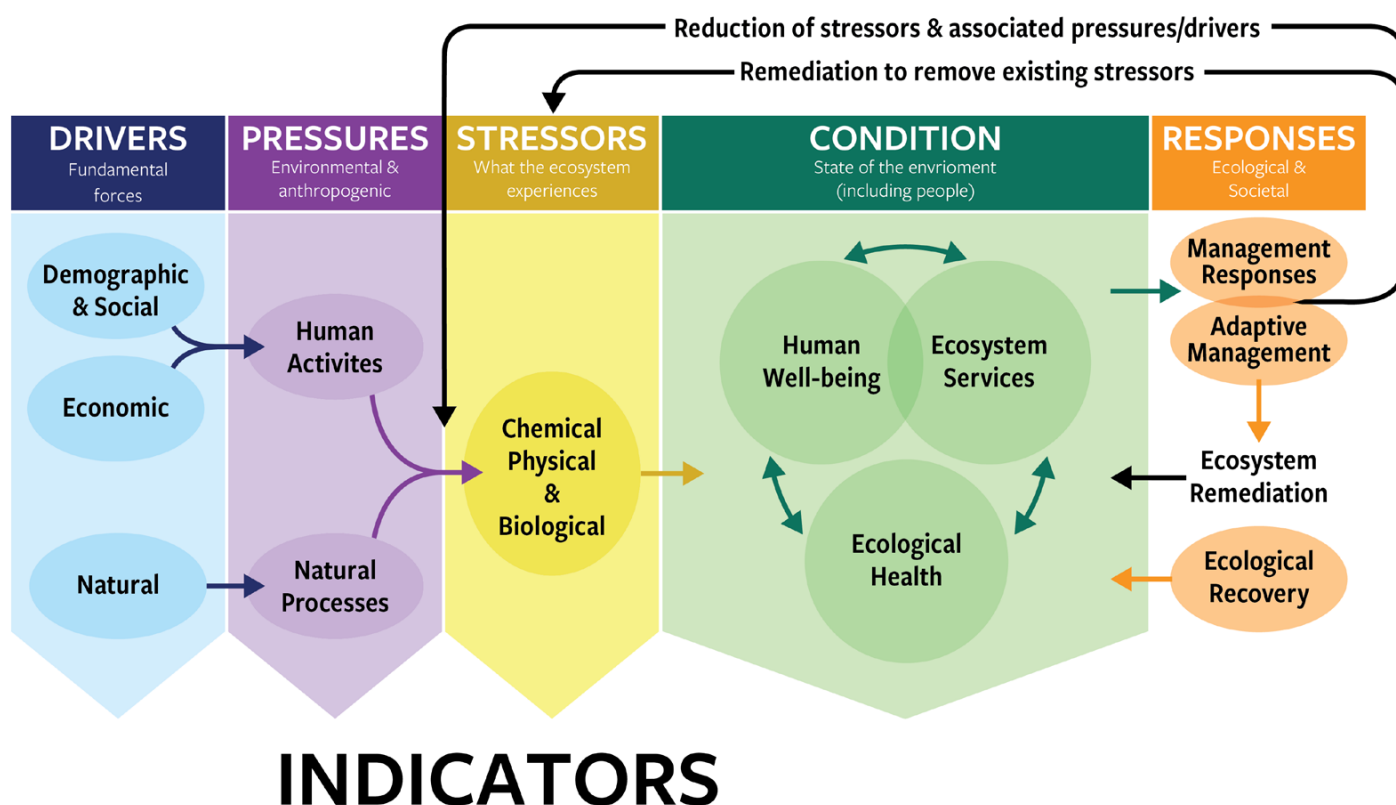


FIGURE 2. EcoHealth Metrics framework. Modified from Harwell et al. (2019)

UNDERSTANDING GULF SYSTEMS INTERACTIONS

The Gulf of Mexico is a complex system comprising physical, biogeochemical, ecological, socioeconomic, and human components and processes and their interactions. **Figure 3** illustrates this complexity by emphasizing four major subsystems: the ocean environment, the ecosystems that are foundational to that environment, socioeconomic interactions, and human health, all of which affect the environment and are affected by it. This simplified “four-box” view of the Gulf will reappear in elsewhere in this issue in a discussion of attempts to build fully integrated assessment models of the Gulf of Mexico system (Westerholm et al., 2021, in this issue).

Among the four primary domains noted above, there is an overall cyclic progression. The ocean environment is created by the spatial distribution of materials, which is largely determined by physical processes that include the circulation and mixing of water, and modification of those materials (whether living or

nonliving) by biogeochemical and micro-biological processes. Living resources are supported and influenced by the ocean environment, and they interact with one another to create spatially diverse ecosystems comprising a number of ecotypes that sustain the living resources exploited by humans. Human activities depend upon and modify these natural systems—exploiting them for food, energy, transport, and recreation, among other things. Diverse human communities interact with each other through social and economic processes that ultimately influence their physical and mental health. These in turn determine the nature and extent of their activities, and thus feed back to the state of the systems upon which they depend. The interactions among these subsystems are of primary importance. They need to be understood and modeled as realistically as possible, considering the very long timescale (decades and beyond) for the full effects of human interventions to materialize.

All parts of this system are subject to external driving forces exerted by the

natural pressures that establish boundary conditions (climate and seasonal variation), including extreme weather events such as hurricanes and anthropogenic drivers such as the states of global and national economies manifested through pressures such as fishery activities, tourism, and petroleum production. GoMRI has made major contributions to understanding all the components of this system and the interactions between them, and to modeling them (Westerholm et al., 2021, in this issue). Our understanding of the dynamics of human health and well-being (Sandifer et al., 2021, in this issue), however, needs further advances so that a truly holistic approach can become feasible (Helena Solo-Gabriele, University of Miami, *pers. comm.*, 2021).

ADVANCES IN INTEGRATED UNDERSTANDING AND MODELING DURING GOMRI

The GoMRI years saw rapid development of integrated modeling systems that linked together ocean physics, chemistry, biology, and socioeconomic systems.

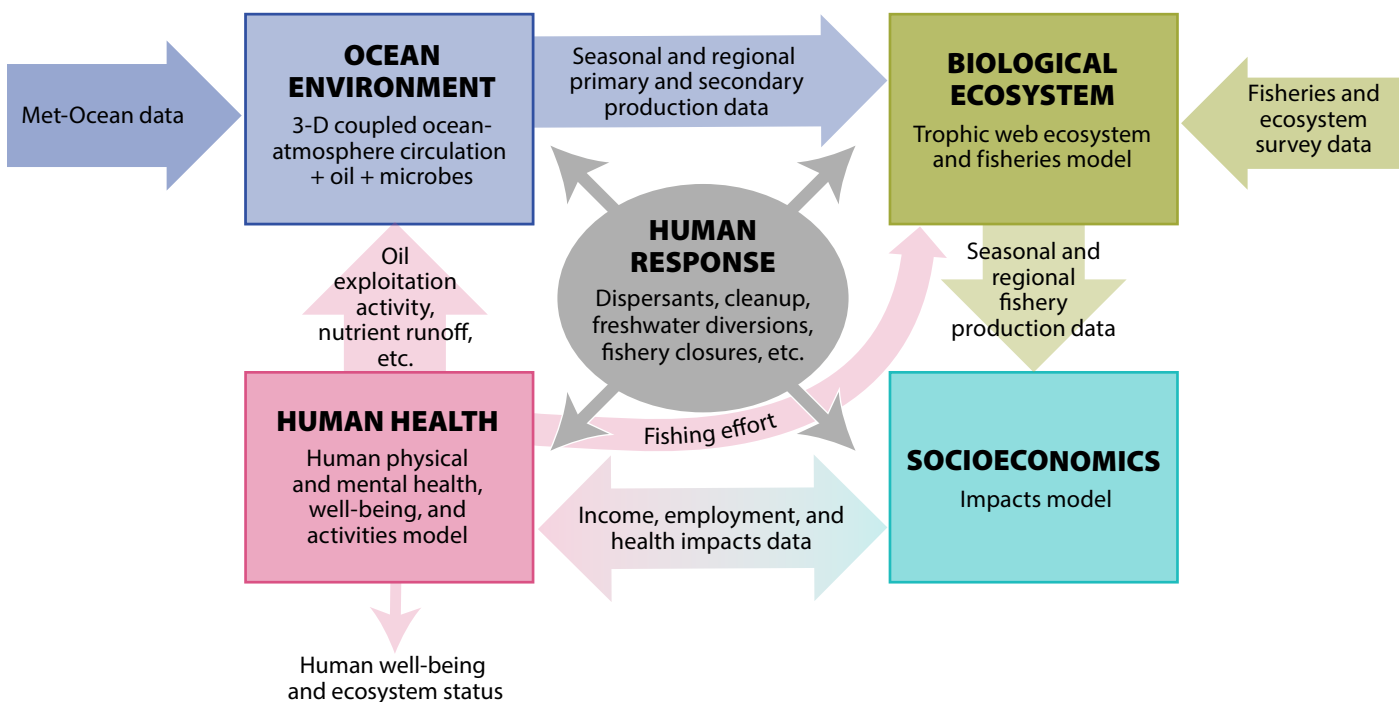


FIGURE 3. Schematic of the four major functional subsystems that interact and ultimately need to be understood and modeled together: the ocean environment (physical, chemical, and biological), the ecosystems that depend upon it, human socioeconomic activities that rely on the ocean ecosystems, and human health and well-being.

Examples include the use of velocity fields from hydrodynamic models coupled to Lagrangian deep-sea oil and gas spill models, the use of oil concentration distributions from these models to drive impacts in ecosystem models, and further chaining of ocean and ecosystem processes to derive inputs for health and socioeconomic models. The collaborative process of integrated modeling requires a broad knowledge base, and it must be amenable to very different model development times and to the timelines of supporting empirical studies. Therefore, a sustained effort is needed, and GoMRI provided a rare consistency and focus across disciplines. An important element is communication, and GoMRI successfully promoted interaction between researchers through events like its annual symposium. Integrated modeling was supported by a robust and responsive program of field and laboratory work. Specific examples include the use of drifters to help validate hydrodynamic models (Beron-Vera and LaCasce, 2016), physiological experiments to determine the rate of clearance of polycyclic aromatic hydrocarbons in fishes (Snyder et al., 2015), high-pressure experiments to determine biodegradation rates (Lindo-Atichati et al., 2016), and oil droplet size distribution experiments conducted under the influence of pressure and gas to support plume modeling (Li et al., 2017; Malone et al., 2018; Pesch et al., 2018).

PHYSICAL, CHEMICAL, AND BIOLOGICAL INTERACTIONS IN THE GULF

The driver-generated pressures that influence the Gulf of Mexico's natural processes and create the physical, chemical, and biological interactions or stressors that constantly test the Gulf's resilience are in some respects unique to the Gulf and in other respects are common across the world ocean (Singleton et al., 2016; Ainsworth et al., 2018; Eklund et al., 2019). The following sections explore some of the interactions most closely associated with the unique

character of the Gulf and consider what GoMRI research has revealed regarding those interactions.

Physical and Biochemical Interactions

The Gulf of Mexico is a semi-enclosed sea (Turner and Rabalais, 2019)—a sort of ocean in a bowl—with an area of 1,507,639 km², an average depth of 1,615 m, and a volume of 2,434,000 km³. It is distinctive because it has all the major features of an ocean within the confined space of its semi-enclosed bowl-shaped basin. The Gulf is also distinctive because it is partitioned by numerous rivers, most with watersheds that drain extensive land areas, including about half of the continental United States (Gulf Coast Ecosystem Restoration Taskforce, 2011). The Mississippi River ranks among the world's top 15 rivers in discharge and is responsible for most of the freshwater inflow into the Gulf. Much of what happens to affect water quality in the middle of the United States extends to the water that flows into the Gulf (Robertson, 2010). More toxic waste is released into the Gulf than into any other significant US coastal water body (<https://www.epa.gov/trinationalanalysis/watersheds>) by almost every measure. In addition to diverse chemical constituents, that inflow brings vast nutrient (Rabalais et al., 1996) and sediment loads (Turner, 2017) from the continental watershed to the Gulf. Unparalleled anywhere in the United States, this outflow enhances both physical and biogeochemical interactions, such as carbon and nutrient cycling from the surface to the deepest Gulf (Fisher et al., 2016). Understanding the Gulf's complex physical and biochemical interactions and their temporal and spatial scales is key to modeling and even managing the health of the Gulf as a large marine ecosystem with more than a local focus.

The Loop Current and the Gulf of Mexico Circulation

The Loop Current dominates the general circulation in the Gulf of Mexico. It

is influenced by freshwater inflow from rivers and altered through water density differences and bathymetry. The Loop Current is part of the global ocean circulation, which is a response to temperature and salinity gradients between polar regions and the equator. This global circulation is three dimensional, transporting heat to northern latitudes where colder, denser water sinks near the poles and then upwells to spread above much of the deep ocean at extremely low velocities. It is further modulated by persistent zonal atmospheric winds (which are also driven by the polar-to-equatorial heat difference), as well as by land masses. The circulation is intensified toward the western side of the ocean due to the change in Earth's rotation with latitude. The Loop Current forms near the Yucatán Peninsula, where disorganized flow patterns in the Caribbean Sea are compressed against the continent and merge as they flow into the Gulf of Mexico as a single current.

The Loop Current sheds some of the largest mesoscale eddies in the world ocean and exits the Gulf through the Florida Straits (at which point the western boundary current is called the Florida Current) to become the Gulf Stream. The Gulf Stream flows along the continental slope to Cape Hatteras and then leaves the coastline to flow toward the open ocean, heading across the North Atlantic toward Europe. The extent of the northern intrusion of the Loop Current in the Gulf of Mexico changes greatly on an annual basis, sometimes extending all the way to the northern Gulf and at other times staying close to southern Florida and the northern coast of Cuba. It is modulated by eddy-shedding events, in which Loop Current eddies detach and migrate slowly to the western Gulf, where they slowly dissipate against the continental slope. The meridional position of the Loop Current also affects transport across the Florida continental shelf. It also impacts the strength of hurricanes because it affects the upper ocean heat content, and hence the heat energy driving the hurri-

canes on their trajectories within the Gulf of Mexico. Finally, there are smaller-scale instabilities along the rim of the Loop Current that interact with freshwater inflow and bathymetry and influence transport near the Louisiana, Mississippi, and Alabama coastlines.

Biogeochemistry of the Waters and Sediments of the Gulf of Mexico

The Gulf of Mexico is a subtropical marginal sea that extends from 21°N to 30°N latitude. Its waters derive primarily from the major inflow through the Straights of Yucatán and a suite of rivers, including the Mississippi-Atchafalaya system, the Usumacinta River that flows into the Bay of Campeche, and the Mobile River along the northern coastline, among many others (Osburn et al., 2019). The Gulf receives drainage from 40% of the continental United States, one-third of Mexico, and parts of Canada, Cuba, and Central America. In addition to river inputs, fluids discharge directly into the Gulf through permeable sediments and sedimentary rock associated with two main types of geologic features. First are the two large karst limestone platforms that define the boundaries of the Gulf. The Florida and the Yucatán platforms deliver significant submarine groundwater to the Gulf via seepage and spring flow (Kohout, 1966; Cable et al., 1996; Burnett et al., 2003). At the base of these platform escarpments, deep seepage brings energy-rich brines to the seafloor, supporting chemosynthetic communities (Chanton et al., 1991; Paull et al., 1991). A second type of permeable seafloor also exists in both the northern and southern Gulf. Salt domes deform the sediments, resulting in faults that serve as conduits for seepage of natural gas, oil, and even asphalt, onto the seafloor (Roberts and Carney, 1997; Sassen et al., 1993; MacDonald et al., 2004).

Rates of ecosystem production are linked to the nutrient content of the specific types of water inputs to the Gulf. The Caribbean waters that enter via the Yucatán Straits are low in the vital nitrogen and phosphorous nutrients that

fuel primary production, so the central Gulf is oligotrophic. Riverine and groundwater inputs are more nutrient-rich. The Mississippi-Atchafalaya inputs are particularly enriched, as they drain the heavily fertilized farmlands of the US Midwest. Chlorophyll distributions are surrogates for primary production and can be measured from satellites. Gulf chlorophyll typically shows elevated concentrations in areas associated with surface and groundwater outflow such as the mouths of rivers, particularly the Mississippi, and near the coast of the karst platforms (Bosman et al., 2020). These inputs fuel biological production, resulting in rich fisheries and the deposition of organic matter to the seafloor. Seepages associated with hydrocarbons and brines on the seafloor support chemosynthetic communities (Paull et al., 1984; MacDonald et al., 1990; Fisher et al., 2007), and later the hard grounds that result from this seepage (Roberts and Aharon, 1994) become attachment sites for deepwater corals (Cordes et al., 2008).

In the northern Gulf, the nutrient-laden, low-salinity waters from the Mississippi system flow from the mouth of the river, and a portion of them wrap around the coast to the west. On the continental shelf, they spread out over the saltier and denser seawater. The nutrients in this fresh surface layer drive high primary productivity, and when the phytoplankton die, they sink and deplete the oxygen in the denser, saltier layers of water below. This has resulted in a New Jersey-sized hypoxic zone on the west Louisiana shelf that prohibits macrofauna and fish from fully utilizing the region (Turner and Rabalais, 1991; Rabalais et al., 2002; Bianchi et al., 2010). Sediments transported to the mouth of the Mississippi are rapidly deposited primarily off the shelf edge because of the channelized and levied engineering of the current river flow, thereby starving wetlands of their historic sources of sand, clay, and silt necessary to sustain land mass.

One of the important aspects of sedimentary processes in the Gulf is their role

in mitigating the impact of Deepwater Horizon, as shown by a GoMRI-funded project that compared aspects of the Deepwater Horizon spill and the Ixtoc 1 spill that occurred some 31 year earlier, in 1970–1980, in the Bay of Campeche in the southern part of the Gulf. Montagna (2019) noted that the sedimentary environment of the Gulf is highly dynamic, especially within the influence of the Mississippi River outfall in the northern Gulf. Montagna and his team have been studying the impact of Deepwater Horizon on the deep Gulf (Reuscher et al., 2017) and were also able to sample the Ixtoc 1 site to assess how long it would take for normal deposition to cover contaminated sediments to the extent that biological availability was minimized. They found that it would take 100 years to cover the remains of the Ixtoc 1 spill and only 50 years to cover the DWH remains to the extent necessary to isolate contaminated sediments. The driver of this difference is the prodigious sediment output of the Mississippi River, which reaches even into the deepest Gulf. Understanding the biogeochemistry of the water and sediments of the Gulf and its circulation helps explain this phenomenon.

Micro and Macro Biological Interactions

Gulf of Mexico biodiversity is equaled only by its productivity. Its 15,419 species (Felder and Camp, 2009) are a subtropical composite of species whose habitats range from emergent wetlands to coral reefs (Ward and Tunnell, 2017). The fish and macrofauna of the Gulf, especially those commercially sought (Chen, 2017), are much studied. Even some of its special habitats, such as those sustaining chemosynthetic vent communities (Cordes et al., 2007), are well known. We know less about the microbial fauna and the impact on it of DWH, especially in the deep Gulf (Reuscher et al., 2020). The same is true for those macrofauna that have little commercial value but are integral to the Gulf ecosystem from the shoreline to the deep waters.

Gulf Microbial Communities and Their Responses to Deepwater Horizon

We often think of oil spills in the Gulf as being accidental, but according to Kennicutt (2017), in normal times 60% of oil annually discharged into the northern Gulf originates from natural seeps, exceeding 160,000 tonnes released per year. There has been considerable speculation and study as to how naturally generated deep-sea oil seeps may help to “prime” the Gulf to recover from man-made spills. The contributions of these seeps to the support of phytoplankton/bacterial communities are now better understood (D’Souza et al., 2016), as are the roles microbes play in bioremediation (Xu et al., 2018). Many questions still remain regarding the Gulf’s natural responses to anthropogenically driven insults in these areas. The microbial community of the Gulf is considered a foundational element, and understanding microbes’ roles in assimilating both naturally derived and anthropogenic oil inputs depends upon understanding that broader context, as discussed in Farrington et al. (2021) and Weiman et al. (2021), both in this issue.

Natural seepage of oil and gas supports some of the Gulf’s microbial community, enriching its sediments and waters with hydrocarbon-degrading bacteria. These hydrocarbonoclastic microorganisms occupy a “rare biosphere” in the Gulf (Kleindienst et al., 2015). The Deepwater Horizon hydrocarbon infusion initiated a bloom of well-adapted *Gammaproteobacterial* oil and methane degraders throughout the Gulf’s waters (Hazen et al., 2010; Crespo-Medina et al., 2014), sediments (Mason et al., 2014; Handley et al., 2017), beach sands (Kostka et al., 2011), and marsh soils (Atlas et al., 2015). Methane oxidation was also stimulated early in the discharge (Crespo-Medina et al., 2014) and may have transmitted organic matter into the food web (Chanton et al., 2012; Wilson et al., 2016; Rogers et al., 2019). Oxidation of oil components occurs through the activities of a series of microbial populations, each pre-

ferring a specialized substrate (oil constituent) (Dubinsky et al., 2013). Some oil-degrading bacteria produce natural biosurfactants (Head et al., 2006; Das et al., 2014) to enhance their access to oil and expedite biodegradation. Production of biosurfactants likely stimulated oil biodegradation following DWH, but it also initiated the formation of massive quantities of marine oil snow (MOS), which served to transport oil to the seabed (Suja et al., 2019; Quigg et al., 2021, in this issue). The role of microorganisms in generating MOS and the likelihood that MOS sedimentation short-circuited oil degradation in the water column was unexpected, but in retrospect was also found at the Ixtoc site. Omics-enabled tracking of microbial dynamics in the wake of the Deepwater Horizon (Kostka et al., 2020) also revealed unexpected community dynamics following this massive environmental perturbation. These issues are considered further in Farrington et al. (2021) and Weiman et al. (2021), both in this issue. The application of omics approaches to other environmental disturbances, small and large, will provide an important tool in the future to reveal sentinels of change and indicators of recovery in real time.

Multicellular Biota and Ecosystems

The DWH oil spill occurred in a region of the Gulf inhabited by abundant, diverse, and valuable communities of species that support critical ecosystem services (NRC, 2013). Because of the spill’s origination offshore in 1,500 m of water and the prevailing ocean and atmospheric transport processes (currents, surface winds), the spill impacted a surface area of over 147,000 km². This area encompassed not only the deep sea, but also the continental slope and shelf as well as coastal habitats of beaches and marshes (Boufadel et al., 2021, in this issue). Given the thousands of species involved, it is efficient to summarize the ecosystem in four broad “ecotypes”: (1) deep benthic, (2) open-ocean water column, (3) continental shelf, and (4) coastal/nearshore. These

ecotypes are discussed in more detail in Murawski et al. (2021a) and Halanych et al. (2021), both in this issue. Deep-sea benthic habitats consisting of foraminifera (forams), cold-water corals, crustaceans (e.g., crabs, amphipods), bivalves, worms, and bottom-dwelling fishes exhibit a wide range of life-history traits that influence the fates of populations and their recovery potential. Corals are generally very slow growing and long-lived, making impacts on coral communities in the vicinity of the spill severe (Fisher et al., 2016; Schwing et al., 2020). In contrast, many foram species recovered to pre-spill levels within a few years.

The Gulf of Mexico open-ocean community of nekton (pelagic shrimps, squids, fishes, and marine mammals) constitutes one of the most biodiverse mesopelagic (200–1,000 m deep) and bathypelagic (>1,000 m) ocean ecosystems in the world (Sutton et al., 2017, 2020). Typically, many of the constituents of the mesopelagic nekton undergo diel (daily) vertical migrations from very deep waters during the day to surface waters at night, and the reverse, constituting the largest animal migration on Earth (Boswell et al., 2020). Due to the presence of extensive subsurface oil “plumes” and the steady stream of oil rising from the DWH wellhead to the sea surface, the open-ocean nekton communities occurring in those areas were continuously exposed to oil (Romero et al., 2018). These communities, and the open-ocean nekton communities located elsewhere, have been notoriously undersampled. Before the DWH spill, there was no sustained sampling effort to estimate the abundance and biodiversity of these communities. However, beginning in 2010 and through 2018, a number of depth-stratified sampling expeditions were undertaken (Cook et al., 2020; Sutton et al., 2020). Results of these sampling cruises document a precipitous decline in small nekton of the open ocean, on the order of two-thirds to three-quarters for invertebrates and fishes (recent work of author Sutton). As of the 2018 expedition, this

community had failed to return to 2010 abundance levels. Offshore populations of marine mammals (whales and dolphins) were also observed swimming in oil-contaminated waters, and some had shifted their distributions to the south and away from the region where DWH oil was apparent (Aichinger-Dias et al., 2017; Frasier et al., 2020). Sea turtle populations were likely affected by oil exposure, as well as oil spill cleanup efforts including skimming and burning activities (Wallace et al., 2017).

The continental shelf regions, where the most lucrative Gulf of Mexico commercial fisheries occur, exhibited a variety of species and community-level changes associated with the spill. Monitoring of natural and artificial reefs saw sharp abundance declines post-DWH in small demersal fish species (e.g., damselfishes) but a concomitant rise in the abundance of invasive lionfishes (Lewis et al., 2020). Coastal and nearshore species and communities exhibited a continuum of effects both from direct oil exposure and due to some of the spill countermeasures deployed (Murawski et al., 2021b). Bottlenose dolphin populations, particularly in Barataria Bay, showed severe health effects and reduced reproductive

that resulted from opening of river diversions in an attempt to forestall oil entering marshes (Powers et al., 2017a,b,c).

PEOPLE ARE PART OF THE GULF ENVIRONMENT—BOTH PROBLEM AND SOLUTION

Over 15.8 million people, 4.9% of the US population, live along the US Gulf of Mexico coast (Cohen, 2018). It may be the smallest of the US coastal regions, but it has been the fastest growing by far. Between 2000 and 2017, the Gulf added three million people, a growth rate of 26.1%, while the average of all other coastal regions was 15.3%. Jobs, climate, cost of living, and the coastal setting have driven that growth, but there is a price to pay for living on the Gulf coast, because between 2000 and 2017 seven hurricanes caused \$456.5 billion dollars in property damage.

More than any other coastal region, Gulf citizens have natural-resource-related occupations, ranging from oil and gas work to fisheries and construction. The connection between Gulf residents and the place they live has broad resonance, and people continue to flock to the region because of that connection. However, the growth and economic

1,040 km², between 2004 and 2009), making up 71% of all US losses. Land subsidence due to oil as well as gas removal and water extraction accounted for much of this loss. Other wetland losses were caused by coastal development, saltwater intrusion from storms and freshwater diversions, attenuation of normal sediment deposition from rivers, and climate-forced sea level rise.

As a large resilient marine ecosystem, the Gulf is surprisingly indifferent to many of our most destructive actions. It reacts to resist change, recover from pressures and stressors, or adapt to new conditions. We must either live with the result or take action to return the Gulf to what we consider to be a desirable state. Natural and man-made pressures combine to impinge on Gulf resilience, and the linkage between the Gulf's environment and its people is most evident not only in the socioeconomic condition but also in the health of its citizens.

Gulf Economics and Socioeconomics

The Gulf of Mexico, like other ocean and coastal areas of the world, provides a tremendous amount of traditional and nontraditional goods and services

“Some of the impacts of the disaster will be with us for 50 or 60 years, until sediments accumulate to bury the oil and its products in the deepest parts of the Gulf and similarly in salt marshes, where Deepwater Horizon oil is readily identifiable and remains toxic to biota.”

output, and they continue to exhibit these symptoms (Schwacke et al., 2014, 2017). There were billions of excess mortalities in Eastern oyster populations in Breton Sound and Barataria Bay, presumably associated with persistent low salinity

development has come at a cost to the Gulf environment. The Gulf's wetlands make up 37% of US coastal wetlands, the most of any region (Dahl, 2011). Wetland loss is also greater in the Gulf than in any other US coastal region (257,150 acres, or

that impact human well-being. In the five US Gulf States, 882,000 people are employed in the ocean economy—living marine resources, marine construction, ship and boat building, marine transportation, offshore mineral extraction, and

tourism and recreation—and its gross domestic product (GDP) is \$117 billion (<https://coast.noaa.gov/enowexplorer/>). The ocean economy of these five states would, in fact, rank 58th in the world GDP.

The Gulf is therefore a major economic engine for the United States, and two of the biggest natural resources supporting this are fisheries and oil and gas. One-sixth of the commercial fish landings and almost one-third of recreational angling trips come from just the five states, adding \$2.3 billion and \$9.5 billion, respectively, to the US economy in 2017 (NMFS, 2018, 2020). On a production basis, the Gulf led the lower 48 and was second only to Alaska in commercial landings. Additionally, the aftermath of the DWH oil spill revealed the high value that recreational anglers place on the resource (Alvarez et al., 2014; Court et al., 2017). With respect to the impacts of Deepwater Horizon on fish consumption from the Gulf, the short-term impacts on seafood demand may largely have been attributed to perception rather than reality (Carmichael et al., 2012; Fitzgerald and Gohlke, 2014).

Natural resource use extends to oil production where offshore (federal waters) Gulf of Mexico oil accounts for 15% of US output; when the five Gulf-state waters are included, this figure increases to 59% (EIA, 2020). The spill put a more urgent focus on improving risk management (Reader and O'Connor, 2014; Skogdalen et al., 2011) and response (Leifer et al., 2012; Michaels and Howard, 2012) by bringing new approaches to improve safety, reduce accident probabilities, and hopefully lessen the impacts of future spills through more rapid and effective responses.

The value of our natural environment not captured in typical market transactions can be significant and should be explicitly accounted for in evaluations of oil spills and other disasters in order to make a full assessment of the impacts on human well-being (NRC, 2012, 2013). As part of the process to assess damages of Deepwater Horizon—both biophysical

and social—a national valuation survey was conducted and found that there was support to invest at least \$17.2 billion to prevent the same type of injuries in the future (Bishop et al., 2017).

Gulf Health and Human Health Are Linked

Disasters occurring in the Gulf impact not only the biota and ecosystems of this large marine ecosystem but also the people that inhabit its shores. This is especially true because the Gulf is situated in a naturally precarious region that is subject to a variety of natural and human-made threats, and the area population exhibits health disparities and suffers continued exposure to environmental contaminants (Lichtveld et al., 2016; Slack et al., 2020). The DWH disaster had extensive adverse physical and mental human health impacts for some responders, cleanup crews, and residents in coastal communities. Two pervasive issues were the lack of baseline health information against which to compare after-spill effects and the overarching role of spill-associated stress on adverse health outcomes (Sandifer et al., 2021, in this issue).

A range of negative health effects were reported for some response workers, including respiratory, heart, skin, gastrointestinal, and other issues, as well as depression and post-traumatic stress disorder (Kwok et al., 2017; Rusiecki et al., 2018). Among residents, mental health impacts from the spill were varied. However, adverse psychological effects were common among those exposed to the spill physically or through associated socioeconomic impacts (e.g., job/income loss; Finucane et al., 2020). Natural resource-dependent communities (e.g., fishers) were particularly vulnerable to mental health effects (Cope et al., 2013; Parks et al., 2020; Slack et al., 2020), as were those who suffered socioeconomic disparities. While children are of special concern for negative health effects from spill exposure and exhibited some impacts (Abramson et al., 2010; Slack et al. 2020),

studies of children's seafood consumption (Sathiakumar et al., 2017) and beach play (Ferguson et al., 2020) showed little if any additional health risks associated with potentially contaminated seafood or exposure to contaminated beach sediments (Sandifer et al., 2021, in this issue).


It is also important to consider potential impacts from other types of disasters in the Gulf. In addition to major oil spills like the DWH event, hurricanes and other disasters can adversely impact people's health and well-being, and we know that previous traumatic experiences can exacerbate effects of the next event (Sandifer et al., 2020a,b). Additional research is needed in this area, particularly to document impacts on more vulnerable populations.

SUSTAINABLE SCIENCE FOR A SUSTAINABLE GULF OF MEXICO

As we struggled to respond to the Deepwater Horizon oil disaster, we paid a price for our ignorance about how the Gulf of Mexico works, rooted in the minimal research investments historically made there. Our lack of knowledge about linkages between the deep Gulf, the open ocean, and the coastal margins hindered response and early mitigation planning. The fate of oil spilled in the deep ocean and its interactions with novel use of chemical dispersants in the deep sea were not at all well understood. Some of the impacts of the disaster will be with us for 50 or 60 years, until sediments accumulate to bury the oil and its products in the deepest parts of the Gulf and similarly in salt marshes, where Deepwater Horizon oil is readily identifiable and remains toxic to biota. Long-lived animals such as sperm whales, porpoise, and turtles may not fully recover for a very long time. Beaches and wetlands still occasionally release traces of oil when disturbed by storms. Some fish, especially deep dwellers, continue to carry the effects of the spill in their tissues. As a result of research carried out since the spill—funded by penalty fines, the eventual settlement, and most espe-

cially GoMRI—we know so much more now than we did then. This research has vastly increased our knowledge of the Gulf but also raised many questions. As restoration actions go forward, even more questions regarding the sustainability of Gulf resources in the face of multiple simultaneous threats will emerge. But we must also be cognizant of and prepared for the *next* large spill in the Gulf of Mexico. The year 2019 (before the pandemic) saw record oil production from the US Gulf of nearly 700 million barrels, the majority of which was extracted from depths >1,500 m. As the industry changes and adapts to the frontiers of oil exploration and production, so too must our research vision focus on the Gulf as it will be and not as it was.

To answer these questions, we shall need to both understand and ultimately be able to model the interactions that we have described above. The GoMRI years brought rapid development of integrated modeling systems that link ocean physics, chemistry, biology, and socioeconomic systems of the Gulf. Examples include the coupling of velocity fields from hydrodynamic models with Lagrangian deep-sea oil and gas spill models, the use of oil concentration distributions from these models to drive impacts in ecosystem models, and further chaining of ocean and ecosystem processes to derive inputs for socioeconomic and human health models. A paper being prepared by Helena Solo-Gabriele, University of Miami, and colleagues will provide an up-to-date review of such integrated modeling in GoMRI. The collaborative process of integrated modeling requires a broad knowledge base that must be amenable to very different model structures and development times, and to the timelines of supporting empirical studies. Therefore, a sustained research effort is needed, and GoMRI has provided a rare opportunity to apply consistency and focus across all the disciplines involved. An essential prerequisite is communication, exemplified by GoMRI's successful promotion of interaction between

researchers in diverse disciplines through events like the Gulf of Mexico Oil and Ecosystem Science Conferences. Such efforts need to be maintained and enhanced in the future, most notably for better understanding of the interactions between socio-economic conditions and human health and well-being, where our knowledge remains relatively rudimentary. These are major challenges for the years to come. 

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AUTHORS

Larry D. McKinney (larry.mckinney@tamucc.edu) is Chair for Gulf Strategies, Harte Research Institute for Gulf of Mexico Studies, Texas A&M University-Corpus Christi, Corpus Christi, TX, USA. **John G. Shepherd** is GoMRI Research Board member and Professorial Research Fellow, School of Ocean & Earth Science, National Oceanography Centre, University of Southampton, Southampton, UK. **Charles A. Wilson** is Chief Scientific Officer, Gulf of Mexico Research Initiative, Fairhope, AL, USA. **William T. Hogarth** is Dean Emeritus, College of Marine Science, Florida Institute of Oceanography, St. Petersburg, FL, USA. **Jeff Chanton** is Professor, Department of Earth, Ocean and Atmospheric Science, Florida State University, Tallahassee, FL, USA. **Steven A. Murawski** is Professor, College of Marine Science, University of South Florida, St. Petersburg, FL, USA. **Paul A. Sandifer** is Director, Center for Coastal Environmental and Human Health, College of Charleston, Charleston, SC, USA. **Tracey Sutton** is Associate Professor, Oceanic Ecology Laboratory, Halmos College of Arts & Sciences, Nova Southeastern University, Fort Lauderdale, FL, USA. **David Yoskowitz** is Senior Executive Director, and **Katya Wowk** is Senior Associate for Strategic Planning & Policy, both at the Harte Research Institute for Gulf of Mexico Studies at Texas A&M University-Corpus Christi, Corpus Christi, TX, USA. **Tamay M. Özgökmen** is Professor, Department of Ocean Sciences, University of

Miami, Coral Gables, FL, USA. **Samantha B. Joye** is Professor, Department of Marine Sciences, University of Georgia, Athens, GA, USA. **Rex Caffey** is Professor, College of Agriculture, Louisiana State University, Baton Rouge, LA, USA.

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McKinney, L.D., J.G. Shepherd, C.A. Wilson, W.T. Hogarth, J. Chanton, S.A. Murawski, P.A. Sandifer, T. Sutton, D. Yoskowitz, K. Wowk, T.M. Özgökmen, S.B. Joye, and R. Caffey. 2021. The Gulf of Mexico: An overview. *Oceanography* 34(1):30–43, <https://doi.org/10.5670/oceanog.2021.115>.

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