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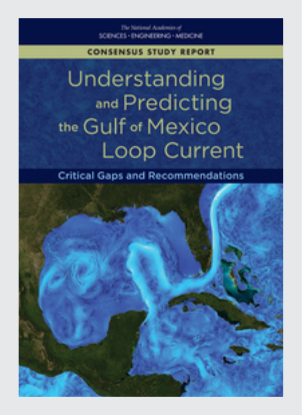

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Understanding and Predicting the Gulf of Mexico Loop Current: Critical Gaps and Recommendations

Committee on Advancing Understanding of Gulf of Mexico
Loop Current Dynamics

Gulf Research Program

A Consensus Study Report of
The National Academies of
SCIENCES · ENGINEERING · MEDICINE

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This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

PAT HOGAN, Naval Research Laboratory
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JAMES J. RILEY, University of Washington
NAN D. WALKER, Louisiana State University
CARL WUNSCH, Harvard University

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by **DAVID M. KARL,** University of Hawaii. He was responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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APPENDIXES

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SUMMARY

The Loop Current (LC) is the dominant physical process in Gulf of Mexico waters. As the LC meanders from the Yucatan Channel through the Gulf of Mexico to its exit through the Florida Straits, it brings with it a large, deep mass of warmer water and strong currents (see Figure S.1). The LC's position varies greatly from its retracted state in the Yucatan Channel, directly east of the Florida Straits, to its extended state into the far north and western Gulf. Why and when the LC suddenly intrudes north has not been able to be predicted with sufficient skill. Occasionally, an eddy (Loop Current eddy [LCE]) sheds from the LC and slowly migrates westward, bringing with it the LC's warm water and strong currents. What triggers that separation and when are also not skillfully predicted. Research in this area is not new; field and numerical studies of the Gulf of Mexico's circulation have been conducted for decades, yet vexing questions remain:

- What controls the penetration of the LC into the Gulf of Mexico?
- What controls the shedding of an eddy from the parent LC?

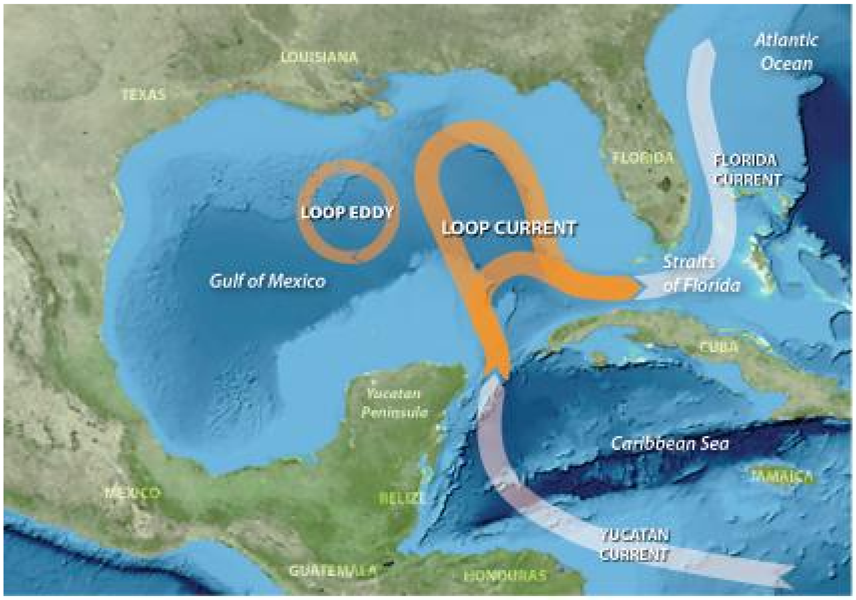

FIGURE S.1 Loop Current System (LCS) showing the Loop Current (LC) in its (1) retracted state and (2) extended state, with (3) a typical Loop Current Eddy (LCE).
SOURCES: UCAR and NASA. https://www2.ucar.edu/atmosnews/perspective/3968/what-happened-oil.

Answers to these two fundamental questions are necessary for advancing the ability to predict Loop Current System (LCS) behavior and thereby providing invaluable information for Gulf of Mexico oil and gas operations, disaster response, ecologically based management of living marine resources, tropical cyclone intensification predictions and track forecasting, and estimating the moisture flux into the U.S. heartland and the latent heat flux that drives extratropical storms and tornados. This study aims to describe critical components of a field campaign that would fill those gaps, thereby leading to significant improvements in both short-term and long-range predictions of the LCS.

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Statement of Task for This Report

The committee will develop recommendations to design a suite of activities—including research, observations, and analyses—needed to characterize Loop Current dynamics and improve the effectiveness of predictive modeling efforts. The study committee will:

- Summarize the existing scientific understanding of the physical forces that shape and energize the Gulf of Mexico Loop Current and associated eddies, as well as the current state of ocean current modeling specific to the Gulf of Mexico.
- Determine what critical information is needed to better understand the variability in strength, location, depth, and size of the Loop Current (i.e., observational, modeling, and research priorities). Specify the measurements needed to improve analytical models and forecasts of the Loop Current System that are useful for facilitating safe oil and gas operations and effective mitigation and response activities, as well as managing environmental resources and protecting Gulf communities.
- Assess the capacity of current technologies to meet the overarching goal of characterizing Loop Current dynamics and suggest opportunities for new approaches, improved technologies, or transfer of technologies from other fields.
- Describe critical components of a field campaign necessary to fill in gaps identified by the Committee in observations and observational technology, data assimilation, and physics and analyses that are needed to improve understanding of Loop Current variability and improve modeling and forecasting skill.
- Where possible, include estimated costs of field campaign components and identify collaboration needs and opportunities among public, private, academic, and international sectors.

In carrying out this task, the committee seeks to advise the National Academies of Sciences, Engineering, and Medicine's (the National Academies') Gulf Research Program (GRP) in investing funds that will ultimately allow modelers to:

- Improve predictive skill in forecasting the LC and/or LCE current speed, vertical structure, and duration out to a forecast period of a few days to 1 week
- Improve predictive skill in forecasting the extension of the LC's location and duration and LCE propagation out to a forecast period of approximately 1 month
- Improve predictive skill in forecasting an eddy shedding event from an extended LC out to a forecast period of approximately 3 months

The committee's overarching recommendation is to create a comprehensive, long-term, vertically integrated, coordinated set of observations over the climatologically relevant LCS active area. This should lead to new analyses that result in new theory and understanding, which in turn can update model physics and provide opportunities to assimilate more near-real-time data. The campaign recommendation is divided into observational components, technological advancements, data assimilation and modeling, and analyses and theory:

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1. Observational components:
    - A comprehensive, long-term (approximately a decade), LCS active area-wide ocean dynamics observation program that gathers data from the air–sea interface to the seafloor.
    - New inflow/outflow investigations with targeted analyses of archival data, especially from international colleagues, and improved access to surface and water column observations in LCS inflow/outflow areas.
    - A new investigation of bathymetric effects with targeted analyses of archival data and new access to water column observations across the shelves that bound the LCS area.
2. Technology enhancements: Generally, current sensor and vehicle technologies adequately address the observational gaps, but there are opportunities for technological advancements to more affordably and reliably observe the LCS in a more relevant and timely manner for sustained periods.
3. Numerical modeling and data assimilation: The gaps in numerical modeling and data assimilation relate first to relevant and timely assimilation of critical data and inclusion of the physical expressions that reflect new understanding gained by an improved observational program in the full water column, at the inflow/outflow points, and as bathymetry affects LCS variability. Since observations will always be limited, the utilization of uncertainty predictions, multivariate data assimilation schemes, efficient adaptive sampling, and accurate Bayesian inference are equally important.
4. Analyses and theory: The new observational wealth resulting from the proposed campaign will allow for new analyses and for the testing and emergence of new theories. Together with observations, technology enhancements, data assimilation, and modeling improvments, scientific analyses and theory are the key to increasing our understanding of LCS dynamics.

The recommendations included in the report are components for a comprehensive campaign directed to the GRP, so that it can devote available resources to these efforts through fair, competitive processes. The components are organized into recommended near-term activities and larger campaign-scale activities that will build on the near-term activities. The campaign is envisioned as an international, multi-institutional, collaborative effort designed to support an approximately decade-long campaign of targeted observations. Rough cost estimates based on committee experience are, over the span of a decade, in the $100–$125M range.

Summary of Recommendations	
1	Additional instrumented surface drifters should be deployed when the LCS becomes active and throughout the LCS area to collect data on surface currents, sea surface temperature, wind speed, air temperature, and air pressure at the air–sea interface.
2	Space-based altimeters providing critical sea surface height (SSH) observations and space-based radiometers providing sea surface temperature (SST) and ocean color should have their data assimilated into models and continue to be championed by the campaign team.
3	In the near term, at least three multi-static high frequency (HF)radar systems should be procured and operated from fixed platforms in the oil and gas operations area to provide new, real-time data for model assimilation and validation and to better understand the evolution of the LCS.
4	The continually deployed vertical profiler fleet (e.g., Argo Floats, 0–2,000 meters) in the Gulf should be doubled to approximately 40 floats; the new floats should be deployed in the LCS active area.
5	Approximately 20 gliders should be procured for operation in the LCS active area. This LCS glider fleet should be outfitted primarily to observe and report near-real-time currents, temperature,

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	salinity, and 4D time/position for scientific analyses and assimilation into models.
6	Over the course of a decade, a field array of bottom-mounted sensors that measure bottom pressure and integrated currents from near bottom to the surface should be procured and deployed at laterally correlated approximately 60 kilometers spacing in the LCS area (25°–28° North Latitude, 85°–91° West Longitude). In the near term, deployments of 20–25 bottom mounted instruments should be procured and deployed in a coherent sub-array for process-understanding and/or feature-mapping in a critical region.
7	For the duration of the campaign, at least one mooring should be installed and operated in the central LCS area (in 2,000 meter depths, between 24°–28° North Latitude and 83°–89° West Longitude) to provide lower and upper layer observations of currents, temperatures, salinity and air–sea surface interface data in real-time for data assimilation, and to serve as a calibration reference for other deep instrument installations and vehicles/profilers working in the upper layer.
8	Available Florida Straits data should be retrieved and used in outflow analysis. In the near term, the GRP should work with Mexican institutions on gaining access to the data from the Yucatan Channel mooring arrays. These recommendations can be undertaken by supporting a collaborating team of Mexican oceanographers or a joint U.S.–Mexico collaboration team.
9	The GRP should work closely with the appropriate Mexican institutions, in the near term, to keep the Yucatan Channel and Florida Straits mooring arrays operating beyond 2018 (for the next decade) with appropriate data sharing. The Yucatan Channel array should take priority over the Florida Straits array.
10	HF radars should be procured and operated to provide new real-time data, in the near term, for model assimilation and validation and to better understand complex and variable surface inflow/outflow regions.
11	The GRP should advocate that Mexico install and operate at least two HF radar systems in the inflow area, one looking north (from the Cozumel Island area) and at least one looking across the inflow from the upper Yucatan Peninsula. If operational support is not available within Mexico, support for these radars and real-time sharing of their data output should be negotiated.
12	The data from the Bureau of Ocean Energy Management (BOEM)-Mexico project timeframe should be analyzed to better understand the effect of bathymetry on LCS behavior. In the near term, attempts should be made to access the data from these moorings from 2011 to the present day, and to negotiate terms to keep these mooring arrays in operation beyond 2018 (for the next decade).
13	A linear array of 4–6 moorings should be deployed in the water column to observe temperature and currents in depths from 75–1,000m, on the southwestern extent of the West Florida Shelf, north of the Dry Tortugas. This moored array should be sustained for several years to cover the evolution of several LCS extension-relaxation cycles.
14	Secondary to Recommendation 13, deploy a similar cross-shelf array (a) seaward of the Florida "Big Bend" along 28.5° North Latitude, and (b) west of the south Louisiana "Bird's Foot."
15	A single real-time mooring should be deployed, in the near term, at the "pressure point" (Liu et al., 2016), or the shelf break region, just to the northwest of the Dry Tortugas to get the long-term time-series effort started earlier and to confirm times when the LC is driving the West Florida Shelf circulation, a phenomena hypothesized to also be controlling the LC itself.
16	In the near term, a team of scientists and engineers familiar with acoustic data communication networks should be supported to determine the feasibility of installing (and, if feasible, designing) an acoustic data communications network that might be adopted by bottom-moored arrays and provide near-real-time data to the surface in an affordable manner, considering the

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	specific acoustic environment in the LCS campaign area.
17	Autonomous surface vehicles (ASVs) should be considered as deployment and data retrieval platforms.
18	The GRP-supported campaign should demonstrate the sustained operation of HF radar mounted on moored buoys or other platforms in the Gulf from which there can be reliable communications to shore.
19	The GRP-supported campaign should be open to adopting new technologies (e.g., larger gliders, hybrid gliders, new power sources, new guidance algorithms, shore launch and retrieval, and emerging long endurance underwater autonomous vehicles (UAVs) in its sensing fleet as the campaign matures.
20	The GRP should advocate with funding agencies, inside and outside of government, for the creation of a national glider training syllabus and certification program.
21	Data assimilation and modeling experts should be brought into the program at the onset of the campaign.
22	A new skill assessment among existing gulf prediction systems should be completed in the near term to test current model performance in resolving both surface and subsurface circulation, long-range prediction capabilities, and to better inform the campaign's final design.
23	Modeling tasks funded under the GRP should be given the latitude, and encouraged, to adopt new methods as they mature.
24	The GRP should actively solicit cost sharing or other computer center collaborations to ensure that the results of the campaign can be supported continually and operationally.
25	The GRP campaign should encourage the development and testing of the statistical and stochastic modeling approach, especially for the mid- to long-term (a few months and beyond) prediction of the LCS.
26	Numerical modelers should be consulted when developing the specific observational programs' design, and "adaptive sampling," based on model results, should be continually practiced throughout the campaign, especially for those observational subprograms that have a choice in timing, areas of deployment, and vertical/horizontal spacing.
27	In the near term, the GRP should support a desktop-style study to digitally compile (and make publicly accessible) physical oceanographic data from Gulf of Mexico field studies carried out between 2002 to 2018.
28	Science teams should be engaged early in the campaign process and campaign leaders should encourage focused process studies and the testing of new theories.
29	By the end of this project, success should be measured by the ability to predict currents (including uncertainty) in the LCS active area (see Figure 3.1) and in areas where the LCEs propogate. The committee recommends a hierarchy of forecast periods, matched to the relevant processes and regions of interest: • Improve predictive skill in forecasting the LC and/or LCE current speed, vertical structure, and duration in the oil/gas operating area out to a forecast period of days to 1 week • Improve predictive skill in forecasting the extension of the LC (location and duration) and LCE propagation out to a forecast period of approximately 1 month • Improve predictive skill in forecasting an eddy shedding event from an extended LC out to a forecast period of approximately 3 months
30	As the crafting of the funding opportunity continues, the GRP should engage stakeholders, including federally operated and sponsored organizations, Mexican and Cuban agencies, and private industry to discuss the campaign goals, explain the opportunities it supports, bring the ocean modeling community into the planning early, and explain the legal restrictions associated

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with the GRP funds.

The report concludes with the committee's advice to the GRP on a set of campaign-related solicitations. The advice may be viewed in four principal parts: recommendations on several near term funding opportunities for initial observations and studies that will better inform the campaign at large; advice on the major campaign solicitation, including selection process alternatives and organizational relationships between the GRP and its campaign performers; advice on the wide range of collaboration opportunities with various potential partners over the next decade; and estimated costs of carrying out the campaign, including procurements, operations and maintenance costs, data management, overall management and administration, scientific analyses, and data assimilation/modeling tasks.

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1

Introduction

One of the most significant, energetic, yet not well understood, oceanographic features in the Americas is the Gulf of Mexico Loop Current System (LCS), consisting of the Loop Current (LC) and the Loop Current Eddies (LCEs) it sheds. The LC originates as the Yucatan Current moves northward into the Gulf of Mexico. It then bends to the east and exits through the Florida Straits. The current is typically described in two states (see Figure 1.1): (1) the "retracted state," wherein the current turns rather abruptly to the east and travels just off the north coast of Cuba before directly exiting the Florida Straits, and (2) the "extended state," wherein the LC continues north (as far as approximately 28° North Latitude) before turning anticyclonically (clockwise) to the east and then south along Florida's west coast before turning east again (left) to exit the Florida Straits.

FIGURE 1.1 LCS showing the LC in its (1) retracted state and (2) extended state, with (3) a typical LCE. SOURCES: UCAR and NASA. https://www2.ucar.edu/atmosnews/perspective/3968/what-happened-oil.

Current intensities of 2–4 knots have been observed within the LC, and LC structures can be sensed down to depths of about 1,000 meters. In the extended state, the LC will spin off warm core, anticyclonic eddies, roughly 300 kilometers across and 500 to 1,000m deep, that can maintain current speeds of up to 4 knots within the circulations even after disconnecting from the LC. These energetic LCEs generally propagate to the west (see Figure 1.1, position 3) and often threaten oil and gas operations in the northern, central, and western Gulf. Smaller, yet more measurable and significantly cyclonic, cold core eddies have been observed to spin from the edges of the LCE and the extended LC

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itself (Rudnick et al., 2015). Just like hurricanes, tropical cyclones, and strong winter storms, LCEs are named (e.g., the first three LCEs of 2016 were named Michael, Nautilus, and Olympus). The LCS sees an extended state with significant eddy shedding occurring at intervals ranging from a few weeks to as long as 19 months, with an average shedding period of 8 to 9 months (Hall and Leben, 2016). A more detailed description of LCS processes is included in Appendix A (Sturges and Lugo-Fernandez, 2005).

Understanding the dynamics of the LCS is fundamental to understanding the Gulf of Mexico's full oceanographic system, and vice versa. Hurricane intensity, offshore safety, harmful algal blooms, oil spill response, the entire Gulf food chain, shallow water nutrient supply, the fishing industry, tourism, and the Gulf Coast economy are all affected by the position, strength, and structure of the LC and associated eddies. Although the LC is the dominant physical oceanographic feature in the Gulf, the episodic northward intrusion into the Gulf of Mexico and the associated eddy shedding are not clearly understood (Sturges and Lugo-Fernandez, 2005).

The scientific community has spent more than 50 years trying to understand LC dynamics and the variability of associated eddy shedding. Most of the scientific observations of the LCS have been limited to surface features in the Gulf such as sea surface height (SSH) and sea surface temperature (SST), largely from satellite observations. Routine observational data assimilated into numerical models of the LCS, therefore, have been largely limited to these surface data.

There have been a number of full water column "field studies" in discrete parts of the LCS. However, they are limited in geographic scope and are not long term in nature. While they have advanced the general description of the LCS and provided valuable insight on forcing mechanisms, there are still significant gaps in understanding the formation, variability, and structure of the LCS and its interaction with other dynamic processes in the Gulf or the Gulf's varying bathymetry. As a result, numerical predictions of the LCS spanning more than a few days have not improved enough to be used for operational or strategic planning and emergency response. Recent advances in observational technologies for measuring the Gulf's subsurface waters over significantly larger spatial scales and/or over longer time periods will relieve some of that constraint.

The purpose of this consensus study is to recommend a strategy for addressing the key gaps in general understanding of LCS processes, summarized in Box 1.1, thereby leading to a significant improvement in predicting LC/LCE position, evolving structure, extent, and speed, which will increase overall understanding of Gulf of Mexico circulation and to promote safe oil and gas operations and disaster response in the Gulf of Mexico. This strategy includes advice on how to design a long-term observational campaign and complementary data assimilation and numerical modeling efforts.

Box 1.1 Key Gaps for Improving Predictive Skill of the LCS

- The LCS area is not well observed over long periods of time, nor is it comprehensively observed from air–sea surface interaction to the bottom. Therefore, the full LCS dynamics are not well understood. This raises two questions:
    - What controls the penetration of the LC into the Gulf of Mexico?
    - What determines the shedding of an anticyclonic eddy and the retraction of the LC back to its more southern inflow–outflow position?
- Predictions of the current velocities and structure in the extended LC and its eddies are needed for weeks and longer timeframes beyond the present limitation of a few days.

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As reflected throughout the report, a combination of efforts need to occur in conjuction to improve understanding and prediction of the LCS:

1. Incorporation of existing federally, internationally, and privately funded observational and modeling efforts,
2. Collaboration with U.S., Mexican, and Cuban government agencies and/or institutions as well as with private industry, and
3. Investments in new observations, new technologies, and improved data assimilation and ocean-atmosphere modeling for the Gulf of Mexico.

THREE CASES FOR ADVANCING THE UNDERSTANDING OF THE LOOP CURRENT SYSTEM

Deepwater Horizon

Improved predictive skill of the LCS could benefit those who respond to oil spills. For example, the immediate response decisions following the *Deepwater Horizon* oil spill event were hampered by a lack of real-time *in situ* observations in the deep ocean (below 1,000m) in the northern Gulf of Mexico at the time of the oil spill (Liu et al., 2011). Such observations are necessary to provide first responders with information on the transport and dispersion of the subsurface oil plume and how and what fraction of the spilled hydrocarbon mixture reached the surface. The lack of deep water observations failed to inform data assimilation schemes and, hence, numerical circulation models. Deep water observations, if properly accounted for in models, could have improved model prediction skill and response decision makers could have had a better understanding about the interaction of LCS with the oceanographic processes of the continental shelf in the northern and eastern Gulf of Mexico.

The impact of the *Deepwater Horizon* disaster could have been far more environmentally and economically damaging if the LCS had been in its extended position and hence present in the immediate vicinity of the spill. As shown in Figure 1.2, the surface oil trajectory did reach the upper extent of the LC on May 17, 2010, but immediately thereafter, the LC shed an eddy, effectively breaking a direct connection between the region of the spill and the West Florida Shelf and Florida Straits.

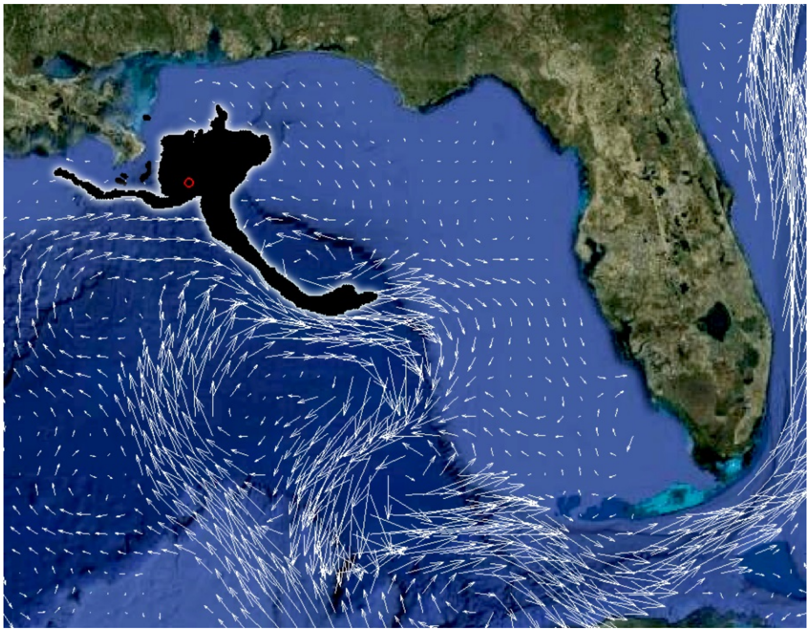

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FIGURE 1.2 *Deepwater Horizon* surface oil slick superimposed on surface geostrophic currents for May 17, 2010.
SOURCE: Liu, Y., A. MacFadyen, Z.-G. Ji, and R.H. Weisberg (Editors) (2011), Monitoring and Modeling the Deepwater Horizon Oil Spill: A Record-Breaking Enterprise, Geophys. Monogr. Ser., 195, 271 PP., ISBN 978-0-87590-485-6, AGU/geopress, Washington, D.C.

Hurricane Katrina

The northward instrusion of the LC (or lack thereof), as well as the position of LCEs, play an important role in hurricane intensification in the days prior to landfall. Hurricane Katrina's maximum sustained winds increased to 173 mph on August 28, 2005, as the tropical storm moved over and along the LC and LCE vortex (see Figure 1.3), which were the areas with the highest upper ocean heat content in the Gulf of Mexico at that time (Scharroo et al., 2005). Near-real-time information from satellite altimeters was used to monitor the LC and LCEs. Their presence can be delineated by SSH greater than 17 cm (about 7 inches) in elevation, as shown by the black contour line in Figure 1.3. As Katrina moved into the Gulf, it intensified from a Category 3 storm to a Category 5 storm while it traversed the LC for just 1 day. Rapid intensification of tropical cyclones by the oceanic heat content in the LC and LCEs (Shay et al., 2000; Zambon et al., 2014) poses a significant threat to offshore drilling and production in the Gulf (Kaiser and Yu, 2010), not to mention the impact on coastal communities, their inhabitants, their natural resources, their economy, and their survival.

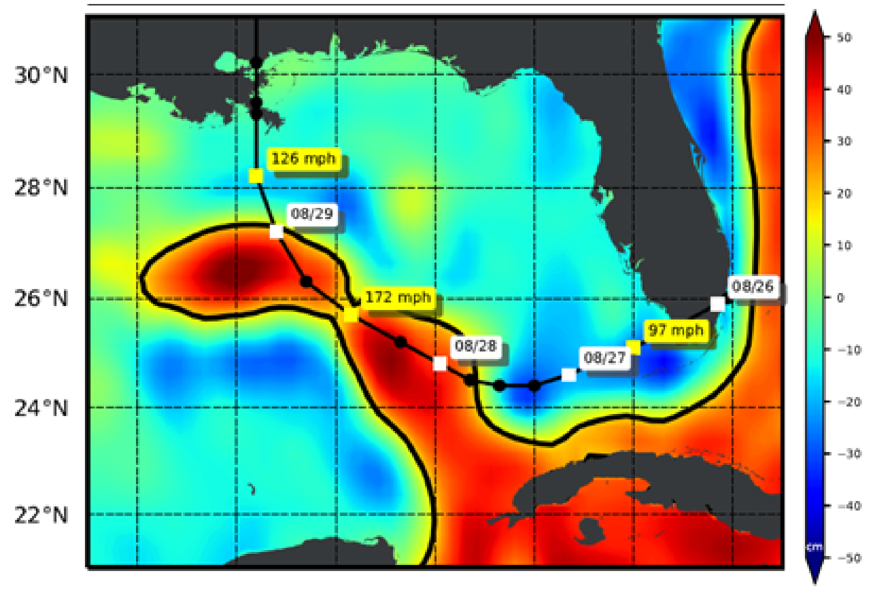

FIGURE 1.3 Deep LC intrusion on August 28, 2005 overlaid with the track of Hurricane Katrina. AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic data) satellite altimeter data are shown overlaid with the best track data for Katrina (Knapp et al., 2010). The 17-cm SSH contour overlaid to highlight the LCS within the Gulf.

Katrina is not an isolated example of tropical cyclone-LC interaction. Hurricane Ike is another good example. The impact of the LC on Hurricane Ike has been shown and predicted by a fully coupled atmosphere-wave-ocean model (see Figure 1.4). Ike was initially weakened by its first landfall over Cuba and re-intensified by going over the LC and an LCE in the western Gulf before making the second landfall near the Galveston Bay on September 13, 2008. The fully coupled model showed the extreme wind, high

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waves, ocean currents, and the storm impacts near landfall, which highlights the importance of the state of the ocean conditions and the atmosphere-ocean coupling process in predictions of hurricanes and their full impacts (Chen and Curcic, 2016).

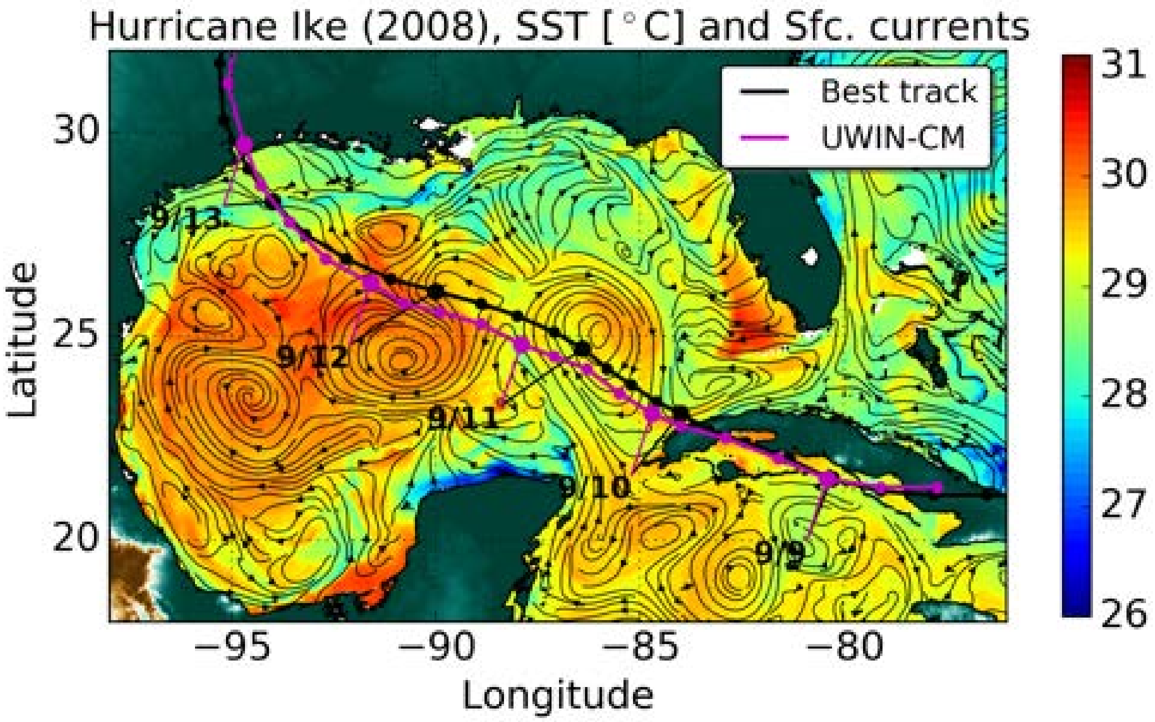

FIGURE 1.4 Observed (black) and coupled atmosphere-wave-ocean model (magenta, UWIN-CM described in Chen and Curcic 2016) forecast of Hurricane Ike tracks from 8-13 September 2008, and the SST (color) and currents (streamline vectors).
SOURCE: Chen and Curcic, 2016.

Impact on Industry: Recent Highly Active Years

Prolonged periods with the LC in its extended state can be devastating for oil and gas operations, as not only do the strong currents cause additional fatigue on infrastructure, they present significant operational safety concerns for the operator, causing activities to be restrained or even shut down at significant cost. The 18-month period from June 2014 to December 2015 is of particular interest because of the uncharacteristically active LCS behavior and its correspondingly significant detrimental effects on offshore oil and gas operations. This hyperactivity event affected sites across the entire northern, central, and even some portions of the western Gulf of Mexico for prolonged periods with strong and highly variable current velocities. The precise cause(s) for this level of activity remains unclear. The LC extended well north of 27°00’N and occasionally crossed 28°00’N into the vicinity of the Mississippi River Delta as it evolved. Anticyclonic eddies that shed from the LC during this event—Eddies Lazarus, Michael, Nautilus, and Olympus—maintained relatively large structures following their initial detachments, and exhibited reconnections, in some cases repeated, with the LC within days to weeks of separation. Both Nautilus and Olympus also exhibited split circulations, resulting in the formations of Eddies Nautilus II and Olympus II, respectively. At the same time, *in situ* surface drifter measurements taken by oil and gas service providers indicated frequently recurring ocean current intensities upward of 3.0 knots which were sustained for several weeks at a time, with peak observed amplitudes over 4.0

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knots throughout the 18-month time period (Sharma et al., 2016). During this period, the Gulf of Mexico Research Initiative (GoMRI) was supporting a number of field studies that further added to the unusual wealth of observations (e.g., CARTHE [Consortium for Advanced Research on Transport of Hydrocarbon in the Environment], Deep-C [Deep Sea to Coast Connectivity in the Eastern Gulf of Mexico], C-Image [The Center for the Integrated Modeling and Analysis of the Gulf Ecosystem]).

Most operators in the Mississippi Canyon, Atwater Valley, Green Canyon, and Walker Ridge lease areas (see Figure 1.5) observed significant delays and downtime due to the adverse impact of elevated currents on critical current-sensitive operations, including, but not limited to, platform installation, hull wet tows, spar upending, drift-ins, riser installation, suction pile installation, unlatching the rig, subsea tree installation, pipe-laying, ROV deployments, and dynamic positioning (Sharma et al., 2016). Chevron's Big Foot Tension Leg Platform site was one of the many affected by ocean currents. Nine out of the rig's 16 tendons that anchor it to the ocean floor parted. As a result, the project, valued at $4 billion, was delayed (at the time) indefinitely.[1]

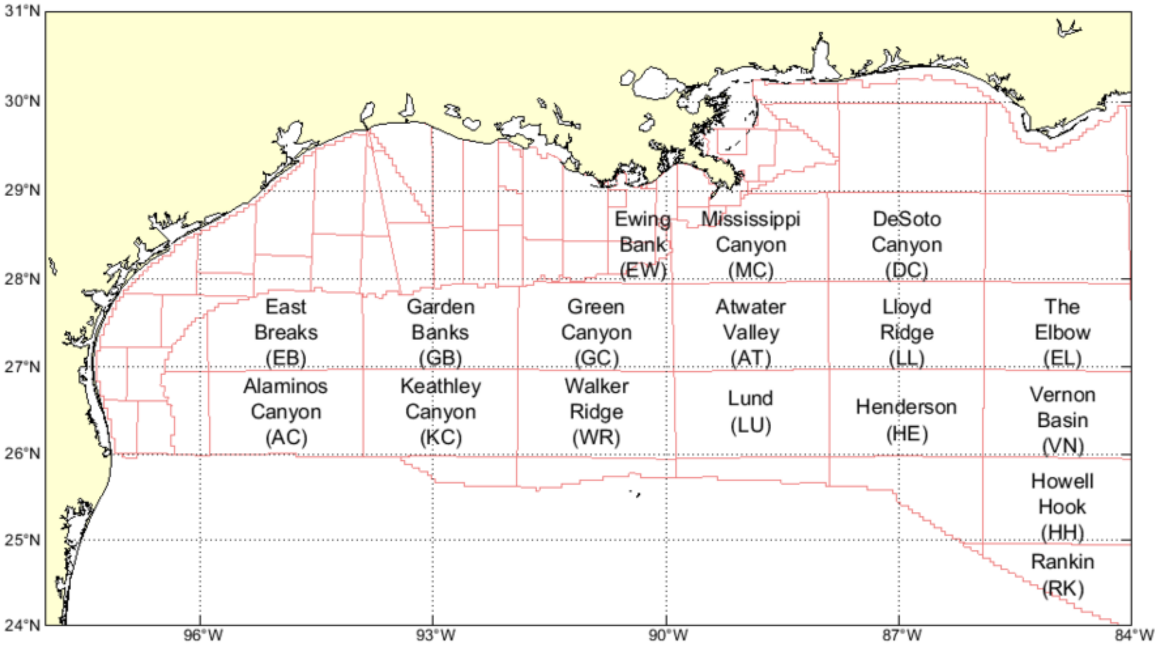

FIGURE 1.5 Bureau of Ocean Energy Management's (BOEM's) Gulf of Mexico Outer Continental Shelf leasing areas.
SOURCE: BOEM.

This 18-month period of heightened LC activity (and thus additional monitoring), along with relatively rich data sets collected by GoMRI and industry partners during the same period, present a unique opportunity for analyses of models, and will be further discussed in Chapter 3.

CHARGE TO THE COMMITTEE

This report was prepared by the Committee on Advancing Understanding of the Gulf of Mexico Loop Current Dynamics in response to a request by the Gulf Research Program (GRP) of the National Academies of Sciences, Engineering, and Medicine (the National Academies) to design a suite of

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[1] Information Source: http://www.offshoreenergytoday.com/chevron-no-big-foot-oil-till-2018.

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activities needed to better understand, model, and forecast the LCS (see Box 1.2). The committee's goal was to provide the GRP with a set of actionable recommendations on a long-term observational set of campaigns, with complementary efforts in data-assimilative numerical circulation modeling necessary to improve the general understanding of LCS processes, thereby leading to significant improvements in both short-term and long-range predictability of LC/LCE position, evolving structure, extent, and speed. We seek to aid the GRP in investing research funds that will ultimately allow modelers to

- Improve predictive skill in forecasting the LC and/or LCE current speed, vertical structure, and duration out to a forecast period of a few days to 1 week
- Improve predictive skill in forecasting the extension of the LC (location and duration) and LCE propagation out to a forecast period of approximately 1 month
- Improve predictive skill in forecasting an eddy shedding event from an extended LC out to a forecast period of approximately 3 months

Box 1.2 Committee on Advancing Understanding of the Gulf of Mexico Loop Current Dynamics Statement of Task

The committee will develop recommendations to design a suite of activities—including research, observations, and analyses—needed to characterize Loop Current dynamics and improve the effectiveness of predictive modeling efforts. The study committee will

- Summarize the existing scientific understanding of the physical forces that shape and energize the Gulf of Mexico Loop Current and associated eddies, as well as the current state of ocean current modeling specific to the Gulf of Mexico.
- Determine what critical information is needed to better understand the variability in strength, location, depth, and size of the Loop Current (i.e., observational, modeling, and research priorities).
- Specify the measurements needed to improve analytical models and forecasts of the Loop Current System that are useful for facilitating safe oil and gas operations and effective mitigation and response activities, as well as managing environmental resources and protecting Gulf communities.
- Assess the capacity of current technologies to meet the overarching goal of characterizing Loop Current dynamics and suggest opportunities for new approaches, improved technologies, or transfer of technologies from other realms.
- Describe critical components of a field campaign necessary to fill gaps identified by the Committee in observations and observational technology, data assimilation, physics, and analyses that are needed to improve understanding of Loop Current variability and improve modeling and forecasting skill.

  Where possible, include estimated costs of field campaign components, and identify collaboration needs and opportunities among public, private, academic, and international sectors.

STUDY APPROACH AND METHODOLOGY

The Committee on Advancing Understanding of the Gulf of Mexico Loop Current Dynamics was formed in late 2016 and completed its work over the course of 9 months. It held three meetings, two of

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which were used to gather input from numerous agencies and institutions on the history and current state of LCS research, observations, modeling efforts, emerging technology, and international efforts. Report recommendations were developed and agreed on at the third meeting. Subcommittees of the committee responsible for specific topics within the study consulted regularly during the study period by phone and by email to exchange information.

Report Organization

This report begins with a brief primer on the LCS. In Chapter 2, it summarizes the current understanding of LCS dynamics, the state of observational data and technology availability, and numerical modeling and data assimilation limitations. In Chapter 3, the report then identifies gaps and makes recommendations to fill those gaps in the areas of observations, observational technology, data assimilation and modeling, and scientific analyses. Finally, in Chapter 4, the committee recommends features and boundaries to the GRP regarding a solicitation to undertake an LCS observation and model improvement campaign during the ensuing decade.

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2

Setting the Stage

The current state of understanding on LCS dynamics is briefly summarized in this chapter through three sections describing the fundamental processes influencing the LCS, understanding the current state of observations and observational technology, and understanding the current level of predictive skill in terms of LC/LCE position, evolving structure, extent, and speed. The evolution of LCS research and associated fundamental theory are described in more depth in Appendices A and B, respectively.

FUNDAMENTAL PROCESSES

The committee seeks to make recommendations to improve dynamic forecasts of the LCS (i.e., LC evolution and LCE formation, reattachment, separation, and propagation). To accomplish this, new observations, both sustained for regular, near-real-time assimilation by the forecast models, and short-term for process studies that increase understanding of targeted processes, are key.

There have been many informative studies of individual processes in the Gulf, but few are of the LCS as a complete system or over a broad enough geographic area or study period that could be characterized as long term in nature. Long term, comprehensive studies have been found to be among the most difficult to sustain, but once in place, they provide strong leverage for embedding additional short-term studies. For example, to date, satellite observations are the Gulf's best long-term sources of oceanographic data, albeit for the surface only. Along-track altimeter data (SSH) is assimilated in near-real-time into models. Nevertheless, today, there is virtually no complementary near-real-time or long-term water column measurement set. This is critical in forecasting the LCS in that scientists do not fully understand the interaction between the boundaries (surface, inflow/outflow, and bathymetry) and the primary LC structure in the upper 1,000 meters range, or between the upper ocean (dominated by baroclinic processes) and the deeper ocean.

Within the LCS, when the LC is in its extended state (see Figure 2.1a), it will eventually spin off an anticyclonic eddy (see Figure 2.1b) that then propagates with significant current structure toward the west, after which the LC retreats (see Figure 2.1c). The interval at which an LCE separates varies considerably (about 0.5–19 months), but it averages about every 8 to 9 months (Leben, 2005). There is some evidence of a higher probability of separation during the spring and fall (Hall and Leben, 2016), but there is notable variability in the timing of separations. In terms of mechanisms, Sturges et al. (2010) suggested that these separation events may be influenced by 20- to 30-day signals propagating upstream into the Gulf from the Carribbean Sea. This is based on observations of increased eastward transport through the Florida Straits, as well as increases in sea level on the offshore side of the LC flow in the weeks prior to a separation and builds on earlier work by Maul (1977). There is also evidence that cyclonic eddies along the LC front influence both LC extension and eddy separation (Gopapakrishnan et al., 2013b; Schmitz, 2005; Walker, 2011). Bottom flows out of the Yucatan are also linked to eddy separation (Oey, 1996). Additionally, bottom topography is likely to have a role in LCS dynamics (e.g., Cherubin et al., 2005). Furthermore, the LCS sits in the Gulf, where atmospheric forcing may be important all of the time, not just during tropical cyclone passage (Judt et al., 2016). It would be useful to understand these processes and their influence on LCS behaviors at the air–sea interface.

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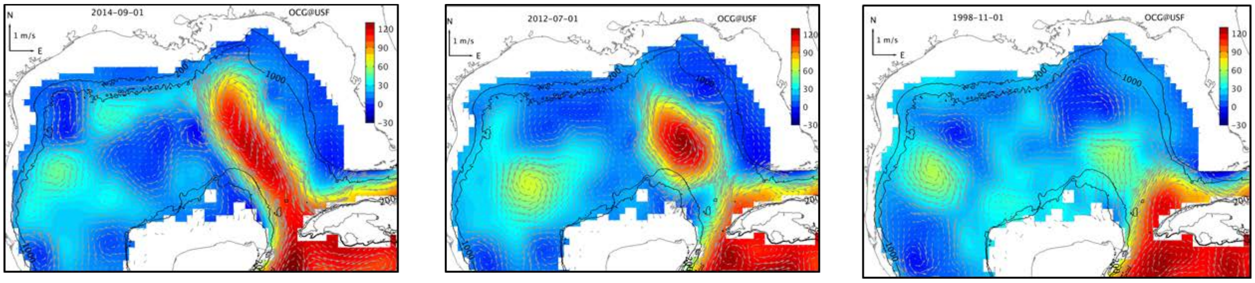

(A) (B) (C)

FIGURE 2.1 Stages of the LC, (a) Extended LC State, (b) Eddy Detachment, (c) Retracted LC State. SOURCE: The figure is courtesy of Yonggang Liu and Robert Weisberg, College of Marine Science - University of South Florida. The observations derive from AVISO+ satellite sea level anomaly data produced by the Ssalto/Duacs with support from the Cnes, and distributed by the CMEMS, plus the mean dynamic topography MDT_CNES-CLS13. Further analyses include subtracting the domain average and estimating surface geostrophic currents from the sea level gradient similar to that in Liu, Y., R.H., Weisberg, S. Vignudelli, and G.T. Mitchum (2016), Patterns of the Loop Current system and regions of sea surface height variability in the eastern Gulf of Mexico revealed by the self-organizing maps, J. Geophys. Res. Oceans, 121, 2347–2366, http://dx.doi.org/10.1002/2015JC011493.

General LCS discussions describe the LC forming as the Yucatan Current enters northward into the Gulf. In either its extended or retracted state, the LC exits by heading east through the Florida Straits, where it feeds into the Gulf Stream. The relationships between inflow and outflow, and their impact on LC extension/retraction, are not fully understood, nor are counterflows and underflows in these areas, especially in the Yucatan Channel. These are important boundary conditions, and the linkages between their temporal variability and LCS state change are not fully understood or included in the physical expressions in the numerical models.

As the LCS evolves over time, there will be interactions with the unique bathymetry of the Gulf. The LC brushes by Mexico’s Campeche Bank as it enters the Gulf. As the LC extends north of 26^{o}N, it encounters the deep Mississippi Fan, which shoals from 3,000 meters to 2,000 meters by 27^{o}N and has an important influence on the LC interaction with deep eddies and topographic Rossby waves (TRWs). Once in the extended state, as the LC heads back south and then east toward the Florida Straits, it encounters the West Florida Shelf/Escarpment.

The direct impacts of shoaling depths on the LCS and the impacts of the deep mesoscale structures on the outer continental shelf are not well known. One interaction of the mesoscale circulation with bathymetry is the generation of TRWs. The generation processes are poorly understood, as are the consequences of the TRW energetics. The TRWs travel around the Gulf with the upslope bathymetry to their right, so their origin could be as far east as the southwest corner of the West Florida Shelf. Theories hypothesized over the years (Liu et al., 2016; Weisberg and Liu, 2017) postulate that there is an interaction between the LC’s position and bathymetry. One notion theorizes that the LC interacts substantively with a shallow area in the southwest West Florida Shelf, north of the Dry Tortugas, known as the “Pinch Point,” which can dampen or trigger an LCS extension and eddy formation (Liu et al., 2016; Weisberg and Liu, 2017). While there are gaps in understanding of both shelves that bind the LC, it is also important to know where the mesoscale eddies impact the oil exploration and production platforms in the western Gulf when the LC penetrates deep into the Gulf, or when the LCEs break off and propagate westward. Approximately 2 years of current data on Mexico’s Campeche Shelf are publicly available through BOEM’s 2009–2011 Loop Current Dynamics Experiment;

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the initial analysis on the variability of the LC along the Campeche shelf break is described by Sheinbaum et al. (2016). In contrast with these other regions of topographic influence, there are/have been no similar moored time series observations along the West Florida Shelf on which the LC regularly makes contact.

In summary, the fundamental physics questions to be answered with this campaign are specified in Box 2.1.

Box 2.1 Fundamental Physics in Question

1. How do the LCS's layered ocean dynamics, from the bounding atmosphere to its bounding basin topography, interact with each other and how do they vary spatially and temporally?
2. How do the inflows and outflows of the Gulf relate to changes of the LCS within the Gulf?
3. What is the role of the shelf slopes in the Gulf on LCS dynamics?

CURRENT STATE OF OBSERVATIONS AND OBSERVATIONAL TECHNOLOGY

Loop current observations have included a variety of methods (e.g., mechanical, thermal, chemical, acoustic, gravitational, electromagnetic, optical) and deployment strategies including fixed structures (i.e., moorings, platforms, land based installations) and moving platforms/instruments (i.e., ships, satellites, profilers, gliders, autonomous vehicles, mammals, drifters). The current status of surface and water column observational technologies considered for use in the Gulf are described here.

Surface Observations

Satellites

Satellites are required to provide broad spatial coverage of the sea surface for assimilation and adaptive sampling guidance. Altimeters provide along-track measurements of SSH. Imagers provide SST and ocean color.

Altimetric space-time coverage is dependent on the status of the international satellite altimeter constellation, including the number of satellites in orbit, and each individual satellite's selected trade-off between cross-track spacing and repeat interval. Along-track altimeter data (SSH) is assimilated in near-real-time into models. Models then can assimilate deeper temperature/salinity (T/S) profiles that are synthetically constructed by considering SSH, SST, and deeper climatology. For example, the Navy Global Ocean Forecast System model uses the Modular Ocean Data Assimilation System (MODAS, an operational sub-model that combines surface information with deep climatology) to synthetically extend the altimetric topography down into the water column. The Navy is currently testing an improvement to MODAS-created synthetic profiles, called ISOPs (Improved Synthetic Ocean Profiles). However, how an ISOP, once operational, can accept new near-real-time data from the upper 1,000 meters if it becomes available is still unknown. Nevertheless, today, there is virtually no complementary near-real-time or long-term water column measurement set. In some models, along-track SSH data are first objectively mapped from multiple overpasses into mapped fields before assimilation.

A new NASA wide-swath altimeter, the Surface Water and Ocean Topography (SWOT) altimeter, has been proposed that will, when/if flown, provide a higher spatial resolution of the ocean surface topography than what was previously available. SWOT will provide high and unique resolution observations along its swaths (with an effective wavelength resolution of 15 kilometers as stated in the mission science requirement document), but will not be able to observe high frequency signals (for

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periods greater than 20 days). When combined with the array of traditional altimeters and subsurface measurements, a new capability in ocean forecasting will be available for assessment in data-rich areas.

Most radiometric imaging satellites provide multiple views of the Gulf for SST each day that the ocean surface is not obscured by clouds. The fast movement of cloud features in the atmosphere compared to ocean features has led to the development of image compositing techniques. Still, SST definition of the LC during the summer months is often difficult due to the intense solar heating of the surface. Tropical cyclones and storms can provide temporary views of the LC structure as the strong winds mix water across the relatively shallow thermocline on the outer edge of the LC, allowing the LC front to be defined until it is again masked by solar heating. Ocean color often helps discriminate between more productive coastal waters and less productive LC waters (again due to thermocline and hence nutricline depth), but the algorithms have more difficulty in humid regions like the Gulf, making the data most useful after the movement of frontal passages that move dry air over the Gulf.

Satellites for sustained wide-area observations combined with aircraft for enhanced event response is an effective combination for tracking LC position and surface current speeds, which has been demonstrated for decades in the Gulf.

High Frequency Radar

High frequency (HF) radar has been used in the United States for the past 40 years to measure surface current speed and direction from a few kilometers up to 200 kilometers offshore. The HF radar network is organized as a quasi-National Network within the National Oceanographic and Atmospheric Administration's (NOAA's) Integrated Ocean Observing System (IOOS) program, and is implemented regionally by non-profit IOOS Regional Associations. There are nearly 180 HF radars registered in the National Network, with about 150 of them reporting hourly data to the IOOS HF radar data assembly center (DAC). As shown in Figure 2.2, coverage is most concentrated on the U.S. West Coast and Mid-Atlantic. HF radar operations are principally supported in the NOAA IOOS budget. Initial procurement of HF radar sets and their installation has been enabled by a mix of federal and state funds. HF radar coverage in the Gulf of Mexico, however, lags behind the rest of the United States. Although Gulf HF radar coverage is sparse, its value was demonstrated in a small area: the shelf area of the Northern Gulf generally south of Mississippi, Alabama, and the Florida Panhandle during the *Deepwater Horizon* oil spill (Harlan et al., 2010). The few existing Gulf HF radar installations are now located to continually observe the LC, its inflow/outflow, or LCEs.

Each HF radar site produces a map of what are known as the "radial" currents, which are the components of the surface current flowing toward or away from the radar. The radial current components from multiple adjacent radars are then combined to produce a map of the "total" vector surface currents where overlapping coverage is available. Radial current data from individual HF radar sites are sent to the National HF Radar DAC every hour, where the integration of the various data into total vectors takes place. The total vector fields are then made publicly available, although the radial data from individual radars are not.

Ocean modelers have demonstrated an ability to assimilate both total vector maps from a network and the radial component maps from individual radars. Assimilating the radial component maps has the advantage of expanding the area with surface current data beyond the regions of overlap. This will be especially important for HF radars placed on isolated offshore platforms or small islands where nearly 360-degree radial current coverage is possible, but overlap areas with adjacent HF radars are small or non-existent. At present, however, the National HF radar DAC does not serve the radial data maps that go into the total vector maps. If the National HF radar DAC were to serve both radial and total vector current data, it would benefit HF radar assimilation nationwide. Until that time, the radial data from each new Gulf site (recommended in Chapter 3) can be set up to transmit directly

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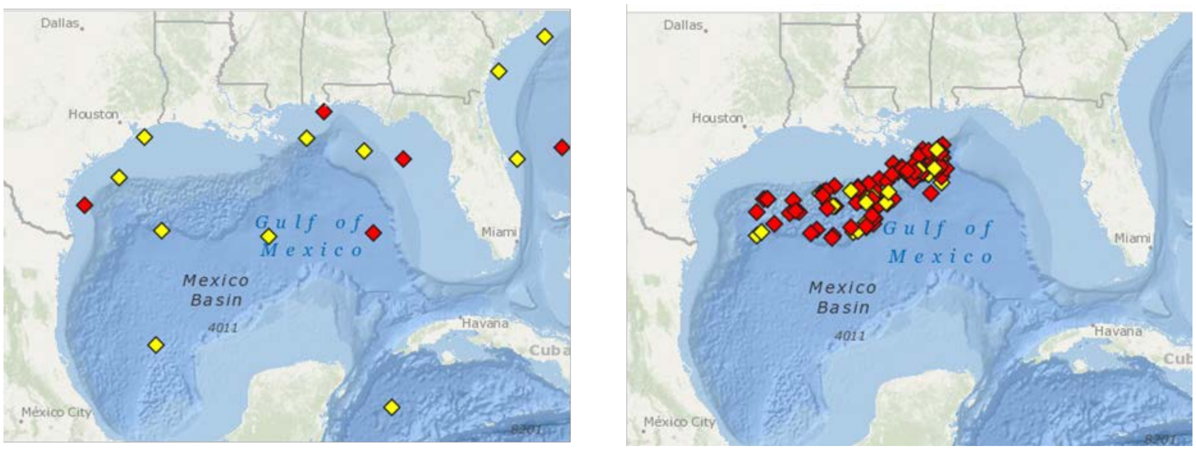
to a dedicated data management location and to Gulf modelers for the greatest return on new HR radar investment.

FIGURE 2.2 IOOS national HF radar installations. Courtesy of NOAA National Data Buoy Center.
SOURCE: NOAA National Data Buoy Center.

Moored Buoys and Ocean Sensors on Fixed Platforms

Moored buoys are located in coastal and offshore waters, as shown in Figure 2.3a, and are used to measure air–sea interaction variables such as barometric pressure, wind speed and direction, air temperature, sea surface temperature, wave energy spectra, and wave direction. These are principally meteorological buoys. Historic and near-real-time buoy data are available from the National Data Buoy Center (NDBC). Examination of the NDBC website shows several continually reporting NDBC-operated buoys and several buoys from other programs affiliated with IOOS and various universities. The NDBC website also depicts observational instruments mounted on fixed oil/gas field platforms (see Figure 2.3b). They can collect valuable air/sea surface data, but cannot be considered as continuous or regular reporting sites.



(a) (b)

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FIGURE 2.3 NOAA NDBC (a) weather and ocean observing buoys, and (b) installations on oil/gas platforms. The yellow diamonds indicate data has been returned within the last 8 hours at the time the figure was created. Red diamonds indicate no data has been returned within the last 8 hours at the time the figure was created.
SOURCE: NOAA NDBC.

Ocean Surface Drifters

Surface drifters are backbone components of the industry-sponsored programs for LC monitoring and are also used for small-scale process studies. Early versions provided position and ocean temperatures through the Argo communication satellite network. Today, although drifters can be outfitted with a selection of near-sea surface oceanographic and atmospheric sensors, most operationally deployed drifters are inexpensive devices that communicate GPS positions to analysts on shore using the Globalstar and Iridium communications networks. The CARTHE Consortium (Schroeder et al., 2012) has demonstrated the efficacy of deploying large numbers of low-cost, biodegradable surface drifters for monitoring small-scale processes and oil slicks.

Large-scale drifting buoy deployment programs for monitoring surface currents in the Gulf of Mexico include those conducted by Horizon Marine, Inc. (HMI), a private sector service provider to the oil and gas industry, and the CARTHE Consortium, a research organization funded by GoMRI for studying oil spill impacts on the Gulf's ecosystems. HMI has deployed over 4,300 Far Horizon Drifters in the Gulf and drogued at approximately 45 meters below the sea surface over the past 33 years as a part of their EddyWatch™ program for daily monitoring, analysis, and forecasting of ocean currents. The CARTHE Consortium was established in response to the 2010 *Deepwater Horizon* spill with the goal of guiding risk management and response efforts in the event of an oil spill. As part of the Grand LAgrangian Deployment (GLAD), the consortium has deployed over 2,200 biodegradable surface drifters in the northern Gulf of Mexico over the course of several expeditions, ranging from several weeks to months at a time (see Figure 2.4).

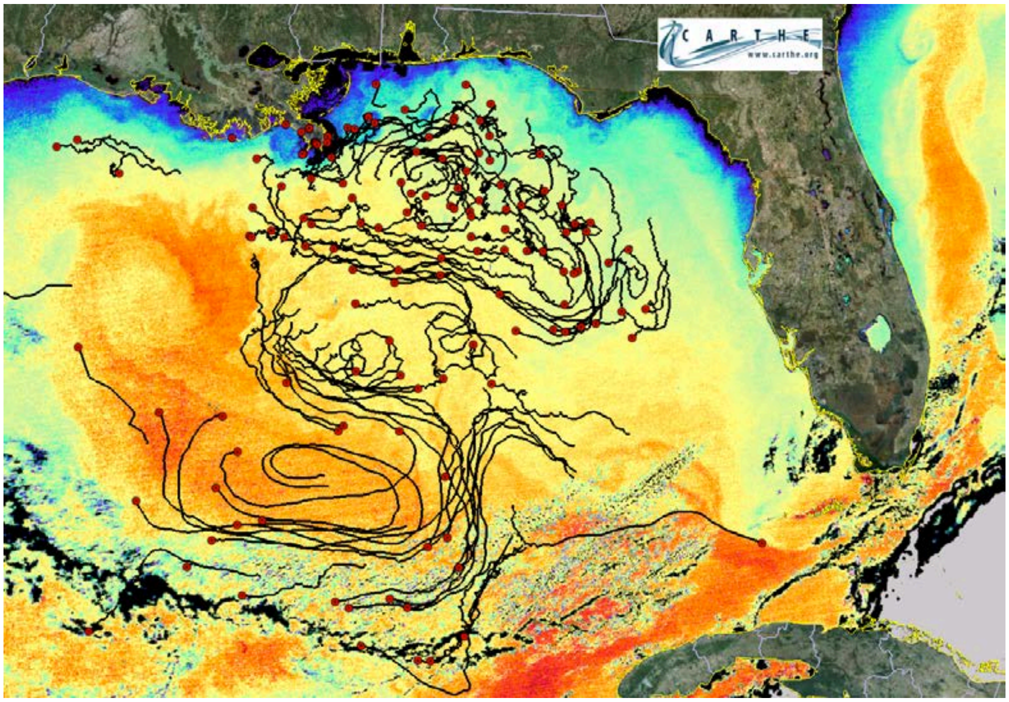

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FIGURE 2.4 CARTHE GLAD summer drifter experiment layered on satellite SST; more than 300 drifters were deployed in the northern Gulf of Mexico in August 2012 and sampled the Gulf for 4–6 months (http://carthe.org/glad).
SOURCE: Tamay Özgökmen.

Water Column Observations

Acoustic Doppler Current Profiler (ADCP)

The ocean is relatively transparent to sound, and acoustic methods have been widely used to study Gulf currents. ADCPs, which measure the travel time of high frequency sound pulses, are often used, especially close to shore (e.g., Liu and Weisberg, 2003). They have a limited range (i.e., a few to hundreds of meters depending on frequency of operation) and require "an adequate supply of suspended particles" to scatter the acoustic energy (Wunsch, 2015), but can be attached to moorings or fixed structures (looking either up or down) in a way that can capture a time series of partial or full water column current speed and direction measurements at predetermined depths of the instrument's range. In accordance with regulatory requirements (U.S. Department of Interior [DOI] Bureau of Safety and Environmental Enforcement [BSEE] Notice to Lessees and Operators [NTL] No. 2005-G02 and subsequent renewals), currents within the upper 1,000 meters of water depth are required to be measured by ADCPs on operational Gulf of Mexico platforms; data are available through NOAA's NDBC. ADCPs are a rather common feature on ship-based surveys, moorings, and buoys deployed by the scientific community in the Gulf, and the technology is moving forward rapidly to integrate ADCPs on autonomous platforms, such as surface vehicles and gliders.

Pressure-Recording Inverted Echo Sounders (PIES)

A sequence of BOEM (and its predecessor agency, the Minerals Management Service [MMS]) field studies from 2003–2011 (see the note below) also used acoustic techniques to make observations using a pressure-recording inverted echo sounder (PIES). PIES instruments are deployed in a bottom-mounted array (typically tens of kilometers apart) together with near-bottom current meters to measure mesoscale features of the LCS (Cox et al., 2010; Donohue et al., 2006, 2008, 2016a,b; Hamilton et al., 2003, 2014). PIES instruments measure the round-trip travel times of regularly spaced acoustic pulses from the seafloor to the surface while simultaneously measuring pressure from a fixed platform on the seabed. The tidal signal is removed from the pressure, and the small residual pressure signal measures the variations due to deep eddies (Donohue et al., 2010). When data from an array of PIES is analyzed, it can determine temporal variability in the vertically integrated heat content (Talley et al., 2011). These data can be used to estimate thermocline depth and dynamic height. A PIES array can also determine geostrophic current changes and study the evolving eddy field (Talley et al., 2011).

PIES arrays, along with with moored current meters, have been used in the Gulf (and in other field studies in other locations) and combined into a single instrument known as current PIES (CPIES). CPIES map the time-varying upper current and temperature structure to track TRWs and to study the dynamic coupling between the near-surface current structures and abyssal eddies (Donohue et al., 2010, 2016b). The deep currents were shown to be nearly depth independent (Hamilton, 2009).

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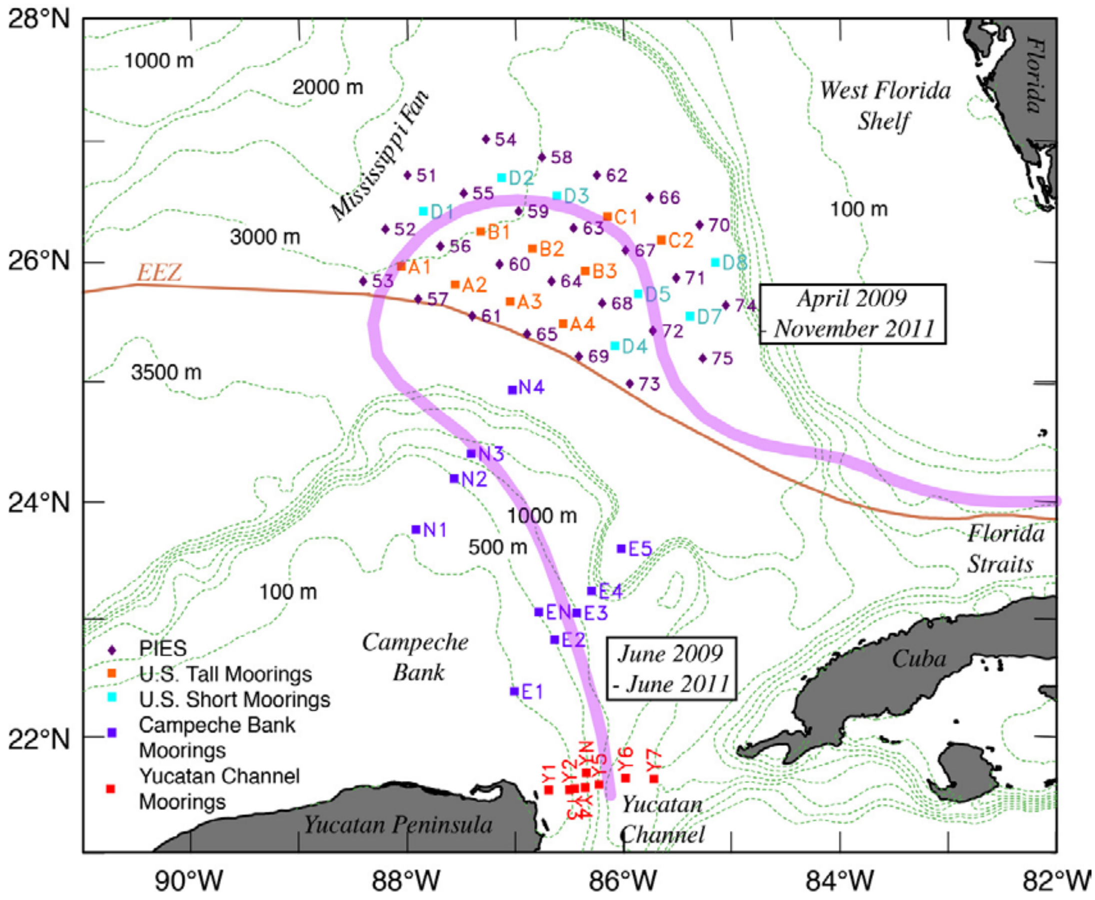

FIGURE 2.5 Locations of moorings and PIES deployed in the U.S. and Mexican sectors in the eastern Gulf of Mexico during the study of LC dynamics. The purple line shows the mean boundary (17 cm SSH contour) of the LC for the June 2009 to June 2011 interval.
SOURCE: Hamilton, et al., 2014.

An array that combined PIES instruments and current meter moorings was deployed in the Central Gulf (Donohue et al., 2006; Hamilton et al., 2003), followed by small arrays in the Northwestern and Northeastern Gulf (Cox et al., 2010; Donohue et al., 2008), leading to a field study of LC dynamics in 2009–2011 show in Figure 2.5 (Donohue et al., 2016a,b; Hamilton et al., 2014). The 2009–2011 array of PIES, plus separate current meters was focused on the region where the LC was likely to form a narrow neck from which an LCE would likely separate. In all of these locations, the current records generated from the PIES data demonstrated excellent agreement of depths throughout the water column when compared with independent records on moorings (Donohue et al., 2016a).

Gliders

Underwater gliders profile vertically by changing buoyancy and traveling horizontally through the water on wings (Eriksen et al., 2001; Rudnick, 2016; Rudnick et al., 2004; Schofield et al., 2007; Sherman et al., 2001). Typically, underwater gliders may profile from the surface to 1,000 meters deep, completing a cycle from the surface to the given depth and back in 6 hours, while covering 6 kilometers horizontally. The resulting horizontal speed through water is therefore about 1 kilometers/h, or 0.25 meters/s. Mission durations of 3–6 months are common, producing several hundred profiles of the 1,000 meters depths over thousands of kilometers of track. Gliders come in several shapes and designs,

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but they are generally small (about 2 meters length) and light (about 50 kg), and may be easily deployed from vessels as small as an inflatable boat or as large as a global class research vessel. Much of the efficiency of gliders for sustained operations is realized through the use of small boats making repeated deployments and recoveries near the coast. Such sustained efforts have been going on for over a decade in a few locations in the Gulf.

Underwater gliders have carried a wide range of sensors; the main limitations are sensor power consumption and volume. As sensor power source volumes decrease and glider volumes increase, gliders will be able to carry more sensors, be more agile, and operate for longer durations.

Figure 2.6 illustrates the path of two gliders that were deployed on December 9, 2011, and were recovered on April 19, 2012, to complete their 132-day missions (Rudnick et al., 2015). The glider tracks are shown superimposed on SSH (Leben et al., 2002), averaged over the first 90 days of 2012. One of the gliders (black line) was piloted to enter and exit the LC and an LCE. The other glider (white line) was piloted to find cyclonic eddies on the edges of the main currents. Two such cyclonic eddies were found, as seen by the spirals in the white track. These missions were part of a project that had gliders in the Gulf nearly continuously from 2010 through 2014. The two glider tracks shown in Figure 2.6 demonstrated a new level of skill and accuracy in glider operations, successfully navigating through the LC front and sucussfully measuring vertical structure within the LC itself.

Underwater gliders are a proven adaptive sampling platform for sustained collection of near-real-time subsurface profile data for the upper 1,000 meters in both deep water and coastal areas of the Gulf. Underwater glider capabilities are rapidly expanding, including operations in very shallow (10 meters or less), highly stratified coastal zones, and the extension in capabilities of deep gliders that are able to analyze full water column profiles in the Gulf. Hybrid gliders equipped with thrusters further expand the operational envelope of these platforms. New sensors are constantly being integrated into glider platforms, including the Laser In Situ Scattering and Transmissometry sensor mandated to be deployed in response to the *Deepwater Horizon* oil spill. Likewise, dramatic increases in on-board energy may be available soon, in which case hybrid gliders could become much more useful in areas with high currents like the Gulf. These many options enable gliders to be customized for the most cost-effective use in the Gulf.

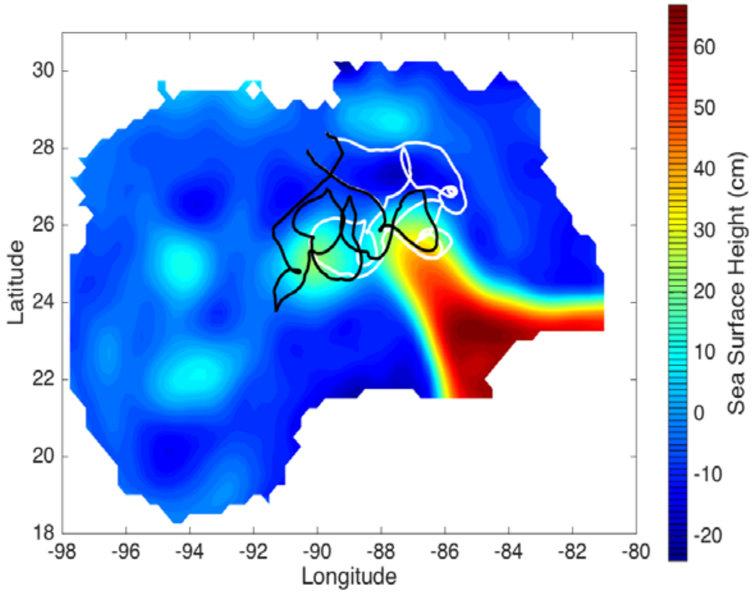

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FIGURE 2.6 Tracks from two Spray underwater gliders (black and white lines) during December 9, 2011, through April 19, 2012, superimposed on sea surface height averaged over the first 90 days of 2012.

Profiling Floats

Profiling floats used in the Argo program deliver one conductivity-temperature-depth profile from the surface to 2,000 meters deep every 10 days. These floats are deployed globally for climate and general oceanographic data, with 3,800 operating at this time. About 20 Argo floats are currently deployed in the Gulf of Mexico.[2] There are other profiling float designs that are useful for specific scientific studies, such as biogeochemistry. For example, as with gliders, sensor capabilities that can be incorporated into profiling floats are expanding. Similar to gliders, profiling floats have demonstrated increased depth capabilities, all the way down to 6,000 meters. A profiler that uses acoustic methods for geolocation, used in a Gulf field study (Hamilton, 2009), is the RAFOS float. Rapid profiling capabilities also are being established by the U.S. hurricane forecasting community (Shay et al., 2008).

Surface Vessels

Surface vessels operated by a wide range of government, academic, industry, commercial and recreational fishing, diving, and private individuals are active in the Gulf. Some are dedicated to ocean exploration and observing; they can deploy and retrieve tethered or expendable instruments and autonomous vehicles. They are normally outfitted with hull-mounted and topside-installed sensors such as multi-beam bathymetric sonar, ADCPs, SST sensors, and air temperature and pressure instruments. Non-scientific vessels can serve as “vessels of opportunity” to deploy instruments or autonomous vehicles. Dedicated oceanographic ships can be deployed to a specific area of interest and can either loiter in a spot or move to follow a feature. However, ships are expensive, costing tens to hundreds of thousands of dollars per day.

Airborne EXpendable BathyThermograph (AXBT)

Released by aircraft, these AXBTs measure temperature from the surface to approximately 350 meters below the surface. AXBTs are useful for determining the thermal structure in the upper ocean and for validation of modeling efforts. Like surface vessels, while they are agile, able to observe specifically designated areas, and report in real time, they also rely on aircraft. If the AXBT payload is large, they must rely on manned aircraft with high flight hour costs. The operational tempo for AXBT deployment must be characterized as episodic; it is useful when weather permits and can be additive in adaptive sampling schemes, but expense remains an issue.

Autonomous Underwater Vehicles (AUVs)

AUVs have a wide range of scientific missions worldwide and rapidly expanding capabilities. Short duration shipboard deployments (on the order of 24 hours) are most common, but recent missions up to 1 month in duration have been demonstrated. Improvements in on-board energy generation and storage are expanding the range and power and corresponding sensor capacity for AUVs. In the Gulf, AUVs are capable of sensing at all depths, and can be a useful augmentation to gliders and profilers.

Autonomous Surface Vehicles (ASVs)

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[2] See argo.ucsd.edu.

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ASVs provide an adaptive sampling surface platform for sustained data coverage across the air–sea interface or as a communication gateway between satellites and subsurface instrumentation. ASVs are available as a turnkey service from ASV companies or can be acquired and operated by a buyer/leasee. The ASV paradigm is evolving rapidly. Some ASVs resemble small conventional surface vessels (typically powered by diesel engines) but are controlled with on-board intelligence supplemented by remote human supervision. Such platforms have been used to gather data, and, in a few cases, deploy (but not recover) gliders and floats. Other ASVs extract energy from the environment (waves, wind, and solar), and these are usually smaller platforms that are well suited to making observations over broad areas for extended periods of time. In addition to gathering data themselves, ASVs can act as mobile acoustic communications hubs that can interrogate certain specifically equipped water column and seafloor instruments and return those data immediately to shore via satellite.

Observational Moorings

Observational moorings can be instrumented in a variety of ways to measure oceanographic parameters through the full water column, and, as they are fixed platforms, they offer a viable way to obtain long-term data, though this option is often cost-prohibitive. Moorings have been installed in the Gulf of Mexico to measure currents throughout the water column during targeted campaigns such as the 2009–2011 BOEM Loop Current Dynamics Experiment (see Figure 2.5), but very few moorings have been installed and maintained overall and even fewer have been operated for more than a few years. The exceptions are several arrays of moorings operated in Mexican and Cuban waters on the Bank of Campeche and across the Yucatan Channel and the Florida Straits (further explained in Chapter 3 and mapped in Figure 3.2).

Shell is leading the march toward new opportunities to use oil and gas infrastructure as platforms of opportunity to expand oceanographic measurements in deeper Gulf waters. Shell's Stones mooring development, located about 3,000 meters deep and approximately 200 miles southwest of New Orleans, includes a standard oceanographic mooring, independent from the Turitella Floating Production Storage and Offloading facility. This mooring was deployed to measure currents in the upper 1,000 meter range in accordance with the BSEE NTL No. 2009-G02 for the lifetime of the Stones development (upward of 20 years). Shell has been building a public–private partnership with several universities, NOAA, and others to transform this existing structure into a deep sea ocean observatory. The mooring line is serviced every 6 months, and data are made publicly available through NOAA's NDBC and Gulf of Mexico Coastal Ocean Observing System. The idea of transforming regulatory moorings and potentially other oil and gas assets into scientific platforms could offer new opportunities to build observing capacity on the shelf and deep Gulf and obtain water column data (among other observations) that otherwise would be cost prohibitive and difficult to sustain over long periods of time.

CURRENT STATE OF MODELING AND PREDICTIVE CAPABILITY

Progress has been made since Hurlburt and Thompson's (1980) pioneering work in modeling the LC and eddies in the Gulf of Mexico. Today, most models use finite difference or finite-volume methods, but some models also use the finite-element method. They can be conveniently distinguished by their vertical grid system: layers (NLOM), z-level (MOM, MITgcm), terrain-following sigma-level (POM, ROMS, FVCOM), and hybrid (NCOM, HYCOM, MSEAS, SUNTAN). However, they also differ in detailed implementation of model physics, horizontal grids, differencing schemes, etc. Despite the model differences, similarities in their gross behaviors are found, mainly because they numerically approximate the same governing equations of motion. Features such as the LC eddy-shedding periods, eddy propagation, flow profiles in the Yucatan Channel, and production of deep cyclones under the LC are

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similar in the different models. However, there are several important details to be examined and contrasted. These include the simulations of TRWs, deep currents, inflow/outflow variability, LCS shelf/slope interaction, cyclonic eddies, and LC eddy-shedding dynamics. In recent years, several Gulf circulation modeling efforts have been funded by the GoMRI. Such efforts, however, mostly focus on the northern Gulf circulation, surface/subsurface transport processes, and shelf-estuarine interaction.

Progress has been made in predictive capability and data assimilation. So far, most modeling efforts to predict LC variation and its eddy shedding process apply primitive equation numerical models. Some of these efforts have the capability of assimilating remote sensing observations and limited *in situ* observations. For example, Oey et al. (2005a) performed a study to predict the LC and its eddy frontal position. Yin and Oey (2007) applied the bred-ensemble forecast technique to estimate the locations and strengths of the LC and LC eddies from July to September 2005. Counillon and Bertino (2009) presented a small-ensemble forecast using the Hybrid Coordinate Ocean Model (HYCOM) to predict LC eddy shedding. Mooers et al. (2012) evaluated several different community ocean models' performances at LC eddy shedding prediction using various prediction skill assessment methods in the report of the Gulf 3-D Operational Ocean Forecast System Pilot Prediction Project (GOMEX-PPP). The Navy Coastal Ocean Model (NCOM) was also utilized for multiple applications in the Guf of Mexico (e.g., Barron et al., 2006; Jacobs et al., 2014) and compared to other models within an ensemble forecasting framework (Wei et al., 2016). More recently, Xu et al. (2013) applied the local ensemble transform Kalman filter to the Princeton Ocean Model (POM) to estimate the states of the LC and LCE from April to July 2010. With the four-dimensional variation (4DVar) method, Gopalakrishnan et al. (2013) tested the prediction of the LCE shedding process using the MITgcm model. All of these studies are focusing on a single LCE or a small number of LCE shedding events. The lack of generality makes the assessment of these models' predictability difficult (e.g., Mooers et al., 2012).

The operational real-time global HYCOM and high-resolution Gulf of Mexico HYCOM models use the Navy Coupled Ocean Data Assimilation (NCODA) (Cummings, 2005) system to assimilate available satellite altimeter SSH and SST observations. These systems also assimilate vertical temperature and salinity profiles that are either measured *in situ* (when available) or synthetically constructed using climatological relationships between the SSH anomaly and a T/S profile, at depth, derived from the historical profile archives. The latter approach is known to misrepresent true subsurface density and energetic flow fields from time to time (Carnes et al., 1994; Cummings, 2005; Guinehut et al., 2004). Recent advancements in ocean variation and ensemble data assimilation methods, uncertainty prediction, and adaptive sampling with autonomous observation systems are expected to significantly improve model performance (see Section 3.4) in forecasting LC events and dynamics.

In addition to primitive equation dynamic models, recent developments in statistical modeling based on long-term satellite observations are showing good potential in offering long-range LC forecasts (see Figure 2.7). Zeng et al. (2015), for example, reported a novel method based on artificial neural network (ANN) and empirical orthogonal function (EOF) analyses to predict LC variation and its eddy shedding process. Validations against independent satellite observations indicate that the neural network-based model, in these trials, predicted LC variations and the associated eddy shedding process over a 4-week period. In some cases, a reliable forecast for 5 to 6 weeks may be possible. In the future, such statistical modeling and machine learning efforts can be merged with governing-equation-based ocean modeling (see Chapter 3). These are relatively new techniques that require more exploration and validation over longer periods of time.

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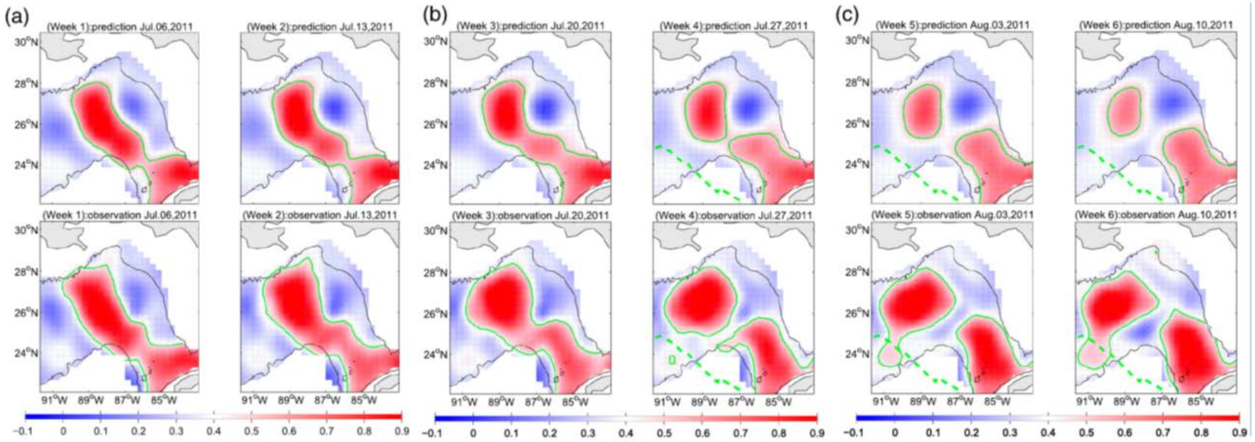

FIGURE 2.7 Comparison between forecasted (upper panel) and observed (lower panel) SSH in (a) weeks 1 and 2, (b) weeks 3 and 4, (c) weeks 5 and 6, representing a complete cycle of one LCE shedding event. Black lines are 1,000-meter isobaths. Red areas are the LC and LCEs. Green solid lines are 0.45-meter contours for observation, and 0.51-meter contours for prediction.

SOURCE: Reprinted from X. Zeng, Y. Li, and R. He. “Predictability of the Loop Current variation and eddy shedding 25 process in the Gulf of Mexico using an artificial neural network approach.” *Journal of Atmospheric and Oceanic Technology. 2015.* Vol. 32(5), pg. 1108.

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3

Critical Gaps and Recommendations

The purpose of this report, which is largely contained in this chapter, is to identify the critical gaps preventing us from understanding the LCS, and thus accurately modeling and predicting the LCS, so that the committee can make the appropriate recommendations for filling those gaps. The committee has identified fundamental gaps in observational schemes, which, if filled, would allow for better physical understanding, new data assimilation opportunities, and improved numerical modeling techniques, all leading to improved forecasts. The three fundamental observational gaps (reflective of the three fundamental physics questions presented in Chapter 2 and later illustrated in Figure 3.1) that, if filled, would improve understanding are:

1. There is/has been no comprehensive, LCS active area-wide, long-term, vertically inclusive campaign to measure physical oceanographic features (e.g., currents, temperature, etc.) throughout the full water column or include atmospheric information at the air–sea interface.
2. The variation in inflow, outflow, counterflow, and underflow are not comprehensively measured and therefore are not well understood. The relationship between the inflows/outflows and development of the LC's extended state is not known.
3. The interaction of the LCS with shoaling waters to its west as it enters the Gulf and to its east as it starts to exit the Gulf is not well understood.

Because such observational gaps exist, understanding is limited, comprehensive data (other than SSH, SST, and episodic surface drifter data) are not assimilated, and numerical models may not include the necessary physical expressions of inflow/outflow, bathymetric effects, deep and upper ocean coupled dynamics, or air–sea boundary information.

Generally, sensor and vehicle technologies exist to adequately address the observational gaps, but there are opportunities for technological advancements to more affordably and reliably observe the Gulf in a more relevant and timely manner for sustained periods of time.

There are also some gaps in numerical modeling and data assimilation. They relate first to the relevant and timely assimilation of critical data and inclusion of the physical expressions that reflect new understanding gained by an improved observational program in the full water column at the inflow/outflow points and as bathymetry affects LCS variability. Since observations will always be limited, the utilization of uncertainty predictions, multivariate data assimilation schemes, efficient adaptive sampling, and accurate Bayesian inference is equally important.

In this chapter, the committee identifies critical gaps and provides recommendations for observations, technology, data assimilation and numerical modeling techniques, and analyses and theory needed to fill those gaps. It is important to keep in mind that the committee sees the recommendations that follow as being most successful when implemented as an integrative whole (between observations, analyses, technology and modeling, as will be discussed further in Chapter 4). It will be possible only through extensive collaboration and leveraging with those already playing an important role in advancing our understanding of Gulf of Mexico circulation. This integrative execution of the study recommendations will then lead to a better understanding of the dynamics of the LCS and thus increase predictive skill of LCS behavior. (Many of the recommendations include the phase "in the

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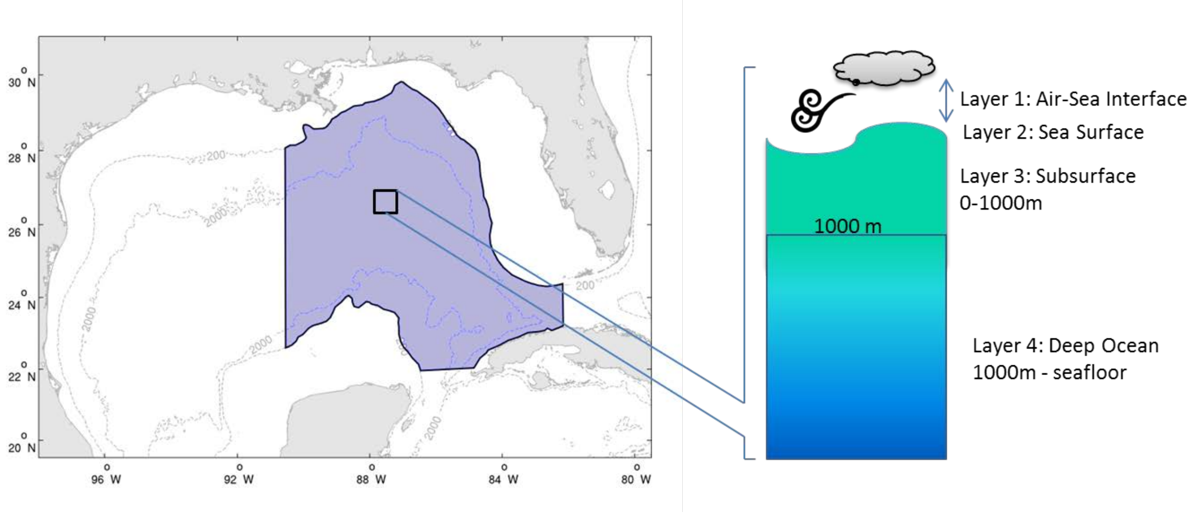
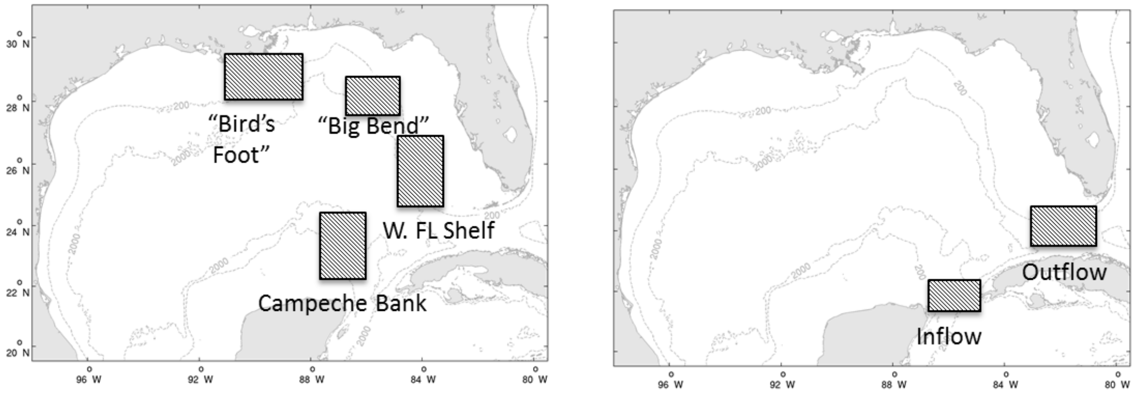
near term,” which are activities that the committee believes should start as soon as possible and not wait until the full campaign is organized.)



(a) LCS Active Area **(b) Vertical Layers of Interest**



(c) Cross-shelf Study Areas **(d) Inflow-Outflow Study Areas**

FIGURE 3.1 Study area for the GRP’s LC Dynamics campaign: (a) LCS Active Area, (b) Vertical Structure of Study Area, (c) Cross-shelf study areas, and (d) Inflow-outflow study areas.

OBSERVATIONS

A key step in improving knowledge of the physics of the LCS, and then feeding improved numerical models of the LCS, is a comprehensive ocean and air–sea interface observation program. Many of the committee’s recommendations will include near-real-time observations. Such observations are most critical and valuable if they are intended to be assimilated. This is important because arranging for near-real-time data acquisition can drive costs. The committee is careful to recommend near-real-time data collection only if the observables will be useful to the modeler and, even then, if the cost is reasonable.

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The committee's approach for identifying observational gaps and recommendations to fill them begins with supplying data to better understand the different physical features, processes, or forcing functions desired in the LCS forecast models. These gaps are organized into three areas (see Box 3.1).

Box 3.1 Fundamental Observational Gaps

- Vertically comprehensive, long-term observations to better understand the LCS's layered ocean dynamics system, from atmosphere to seafloor, including:
    - Air–sea Interaction: atmospheric forcing
    - LCS Surface Mapping: LCS's surface expression
    - Subsurface Dynamics: internal interactions including LC with LCEs or between mesoscale anticyclonic and cyclonic eddies within the top 1,000 meters
    - Deep Ocean Dynamics: internal interactions between the upper ocean (top 1,000 meters) mesoscale and the deep ocean (greater than 1,000 meters)
- Inflow/Outflow forcing: role of flow through the Yucatan Channel and the Florida Straits
- Interactions with Bathymetry: internal interactions between the mesoscale circulation with bathymetry, including the continental shelves

The LCS's Layered System

Within the LCS active area—an area roughly defined by the 200 meter isobaths on the Campeche Bank, West Florida Shelf and North Gulf Coast, 91° West and Gulf areas west of the Texas/Mexico coast when an LCE is propagating westward, and by the areas of inflow and outflow (see Figure 3.1a)—the GRP should support a decade-long, vertically inclusive observational program (the campaign) that is adapted over time based on the positive impact on model skill, model suggestions, and emerging technologies, as well as new theory. Specific gaps and recommendations within this region, from atmosphere to seafloor, follow.

Atmospheric Forcing

The impact of atmospheric forcing and extreme events is not well understood with today's limited observations (e.g., Judt et al., 2016). While air–sea interaction at the surface may be an LCS behavior driver, the important missing piece is the integrated air–sea effect over the whole LCS area and beyond. Dynamic ocean forecast models will require forcing from atmospheric models, or in a more advanced case, the ocean and atmosphere evolve simultaneously via a coupled ocean-atmosphere model. In either case, spatially distributed validation data are required to ensure that the atmospheric model is on track, especially over water, where observations are less frequent. For instance, Mayer et al. (2017) demonstrated that model wind estimates are in high fidelity with observations at locations where the observations are assimilated, whereas the atmospheric model tends to underestimate the wind where the observations are not assimilated. This demonstrates that ocean weather forecasts are greatly improved when adequate observations are available for atmospheric model assimilation. Virtually all moored weather buoys in the NOAA NDBC database and C-Man weather observing coastal towers are north of U.S./Mexico exclusive economic zone (EEZ) delineation, as shown in Figure 2.3. There is one NDBC buoy in the central north Gulf of Campeche and one in the Caribbean Sea south of the Yucatan Channel. Observations are lacking over a vast portion of the LCS region. The committee sees value in considering integrated air–sea effects in the LCS area. While surface drifters can carry SST, air temperature, wind, and air pressure sensors, they typically give the position only and are not deployed widely or at regular time intervals.

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Recommendation 1: Additional instrumented surface drifters should be deployed when the LCS becomes active and throughout the LCS area to collect surface currents, SST, wind speed, air temperature, and air pressure at the air–sea interface. *Regular, wide area deployment is desirable, as costs allow.*

LCS Surface Mapping

The LC has been monitored by satellites for nearly 40 years. Altimeters provide along-track SSH and radiometric "imagers" provide maps of SST and ocean color. Current satellite altimetry and radiometric measurements, while not perfect in coverage, are the best long-term, near-real-time observations of the LCS area, even if they measure surface phenomena only. Deeper along-track T/S profiles are derived from surface satellite data and climatology, and do not provide true near-real-time hydrographic conditions in the upper 1,000 meters. The proposed SWOT Altimeter can be expected to add value to scientific studies of the LCS (see Chapter 2 for details on SWOT).

Recommendation 2: Space-based altimeters providing critical SSH observations and space-based radiometers providing SST and ocean color should have their data assimilated into models and continue to be championed by the campaign team. *Additional space-based instruments, such as the envisioned SWOT Altimeter, are supported by the Committee as evolutionary improvements to the science and near-real-time along track surface observation set. This program is an important example of why continuing support for the U.S. array of Earth Observing Satellites is important for the U.S. government.*

Satellite remote sensing data have been augmented with surface drifters to better define the LCS for more than 30 years. The drifters report their locations via satellite multiple times per day. They are sometimes equipped with simple sensors (e.g., ocean temperature). Drifters, like the ocean currents themselves, flow along fronts, so the objective is often to seed a feature of interest with drifters so that it can be tracked. Surface drifters have an extensive and proven industry-supported commercial history in the Gulf that requires confidentiality of the data to continue. Human analysis of satellite altimetry, satellite imagery, and surface drifters has documented an extensive data-derived history of LC path evolution and eddy shedding events.

Simple surface drifter buoys that transmit position are actively used when the LC is extended and when LCEs are forming and propagating to the west (though data are mostly proprietary), but more continual deployments over a wider area (before the LCS begins to threathen oil and gas operations) are missing for scientific analysis and assimilation into models. Furthermore, drifters outfitted with other sensors (e.g., SST, sea surface salinity, air temperature, air pressure) are not available in synoptic timeframes. Deployment of additional surface drifters to fill this gap is included in Recommendation 1.

Internal, horizontal, and vertical interactions between the LC and an LCE, including formation, reattachment, eventual separation, and then propagation across the Gulf, are some of the most significant LC processes to correctly understand and model. A particularly important interaction is between the anticyclonic LCEs and the smaller, yet significant, cyclonic eddies that form along the edges of the anticyclone and exhibit a significant and observable surface expression. The eddies are often identified via government-supplied satellite remote sensing data, and are tracked with industry-sponsored surface drifters, as has been done for decades. HF radar (5 MHz) can sense ocean surface currents out to 150–200 kilometers from a transmitter/receiver site. They have been operational for several years as a part of IOOS. Yet coverage is spotty, especially in the Gulf of Mexico (see Figure 2.2). There are no HF Radars near influential shoaling areas, in oil/gas operating areas, in LCS inflow/outflow regions, or where LCS currents and fronts might be observed and predictions validated.

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Recommendation 3: In the near term, at least three multi-static HF radar systems should be procured and operated from fixed platforms in the oil/gas operations area to provide new, real-time data for model assimilation and validation, and to better understand the evolution of the LCS. *The committee notes that NOAA will be procuring and operating HF radars in the south Louisiana "Bird Foot" area and Texas has procured and committed to installing new HF radars along its coast. A recommendation, in the Inflow/Outflow Recommendations section below, will be made to, in the near term, procure and/or install and operate HF radars to observe surface flows in the inflow/outflow areas (Yucatan Channel and Florida Straits). Should the HF radar recommendation above be acted on, in whole or in part, it will be important to collaborate with the non-profit IOOS Regional Associations and with the NOAA IOOS HF Radar DAC.*

Subsurface LCS Dynamics

Subsurface data—from just below the surface to approximately 1,000 meters—within the general LCS active area are sporadic at best. Critical subsurface data on the vertical density and velocity structure are usually missing. Thus, the vertical structure downward from the surface—the most energetic baroclinic mode—is rarely available in real time. This is a critical gap, because forecasting the evolution of the baroclinic structure of the LC and related instability leading to eddy shedding relative to observations will be an important metric for success. Continual subsurface vertical profile data are missing, but especially required, in "pinch points" where the extended LC narrows before creating and shedding an eddy or re-attaching an eddy; in the cooler water transported from the West Florida Shelf when eddies do separate; in areas where the anticyclonic LCEs interact with the cyclonic eddies; and as the LC front moves north into the Gulf, potentially interacting with bathymetry. As mentioned above in the LCS Surface Mapping section, there are both horizontal and vertical interactions between the LC and an associated LCE's behavior, but the subsurface observations necessary to fully describe and understand this complex process are missing.

Recommendation 4: The continually deployed vertical profiler fleet (e.g., Argo Floats, 0–2,000 meters) in the Gulf should be doubled to approximately 40 floats; the new floats should be deployed in the LCS active area. *This will enhance coverage to at least equal the global average envisioned for the Argo float array. As has been noted in Argo coverage statistics, this will not provide coverage in regions of strong boundary currents.*

Recommendation 5: Approximately 20 gliders should be procured for operation in the LCS active area. This LCS glider fleet should be outfitted primarily to observe and report near-real-time currents, temperature, salinity, and 4D time and position for scientific analyses and assimilation into models. *A benefit of the glider is that when it is at apogee near the surface, it transmits data observed in near-real-time and can receive course directions, for example, steering to cross the LC or penetrate an LCE. Both features are useful in observing this critical layer of the LCS. Additional sensors may be deployed on some gliders for shorter durations, depending on the scientific need. It is assumed that by obtaining a fleet of 20 gliders, approximately two-thirds of the gliders will be in the water at all times. The Committee developed several scenarios adequatetly covering areas of interest with 12–16 Gliders in operation. Collaboration with the IOOS Glider DAC will be important.*

See Recommendations 6 and 7 for additional recommended subsurface measurements.

Deep Ocean Dynamics

A relative blind spot in observations is mapping the currents, temperature, and pressure in the LCS active area from below approximately 1,000 meters to the bottom (as deep as about 4,000 meters).

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Deep ocean observations, however, are rare and sparse. A key field study (see Figure 2.8) was carried out under BOEM sponsorship for 30 months during June 2009–November 2011 (Lugo-Fernandez, 2016), and several other deep observation field studies have been mounted in the last several decades. However, none of them lasted long enough to get sufficient seasonal, interannual, or LCS state change observations. It was not possible during those studies for a widely deployed and highly populated field of deep water instruments to report observations in near-real-time in an affordable manner. The recovered data were used by scientists to better understand the role of the deep ocean in LCS behaviors, and, as stressed above, the interaction between the deep barotropic layer with the baroclinic region above it; however, longer time series are clearly required to sample the variety of processes that affect different events. One can also consider a subset of deep instruments to be queried in a timelier manner. Neither a long-term array of deep instruments nor a near-real-time query program are/have been available. The BOEM field study mentioned above was highly regarded by the Committee as a field campaign targeting LC dynamics; the Committee found the bottom array of CPIES to be valuable, but sees greater value in extending a similar array of this general type to the north and west to cover a much longer period. Furthermore, deep abyssal eddies and TRWs are prevalent everywhere in the LCS. This leading mode of nearly depth-independent abyssal current variance has, with few exceptions, not been observed in the Gulf. It is thought that interactions between the upper baroclinic mode and the barotropic mode strongly influence their joint development, the evolution of the LC state, and the separation of LCEs. The energetic TRW and abyssal eddy currents and mapped pressure centers have typical horizontal wavelengths of approximately 50–200 kilometers and periods of about 10–100 days, so the mapping methods are geostrophic (Donohue et al., 2010; Firing et al., 2014).

Recommendation 6: A field array of bottom-mounted sensors that measure bottom pressure and integrated currents from near bottom to the surface should be procured and deployed for a decade, at laterally correlated approximately 60 kilometer spacing in the LCS active area (25°–28° North Latitude, 85°–91° West Longitude). In the near term, deployments of 20–25 bottom mounted instruments should be procured and deployed in a coherent sub-array for process-understanding and/or feature-mapping in a critical region. *This gets the long-term observational effort started earlier and will inform the optimal spacing and locations for the eventual full array. In the technology recommendations section, the committee will address near-real-time query of the bottom mounted instruments. Note that this effort would need to be coordinated with Mexican colleagues since several instruments could be deployed in the Mexican EEZ.*

Moorings can be deployed to measure oceanographic features from the air–sea interface all the way to the bottom. The oil and gas industry is deploying some such moorings in the near term in 3,000 meters of water in the oil/gas operating areas (refer to Chapter 2); these will likely be able to sense nearby westward propagating LCEs. No mooring has been envisioned for the LC active area.

Recommendation 7: For the duration of the campaign, at least one mooring should be installed and operated in the central LCS active area (in at least 2,000 meters of depth, between 25°–28° North Latitude and 85°–89° West Longitude) to provide lower and upper layer observations of currents, temperatures, salinity, and air–sea surface interface data in real time for data assimilation, and to serve as a calibration reference for other deep instrument installations and vehicles/profilers working in the upper layer.

Inflow/Outflow

Gulf of Mexico regional-scale ocean forecast models are required to have boundary conditions for inflow and outflow supplied from a larger scale global- or basin-scale model. Multiple models are

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available, so important choices must be made and justified. LC inflow and outflow conditions are expected to have an impact on the evolution of the LCS inside the Gulf. The inflow/outflow connections to LCS state evolution (retracted-to-extended states) are neither comprehensively observed at surface or at depth and hence are not well understood or sufficiently considered in model physical expressions. Modern uncertainty quantification methods were employed to quantify how uncertainties in the inflow from the Caribbean Sea affect the Gulf of Mexico fields (Thacker et al., 2012). The unanswered questions are not about the difference between the total volume in or out, but rather more about the variable horizontal and vertical structure of the inflow and outflow, and ensuring that at these control points, the LC in the forecast models have a reasonable structure with respect to the maximum velocities and the horizontal and vertical current shears. On the inflow side between the Yucatan and Cuba (western boundary), the upper water column flows mostly into the Gulf, but the bottom water can flow in either direction. Oceanographers have not been able to explain the onset and end of the underflow (Sheinbaum et al., 2002, 2016). On the outflow side between the Florida Keys and Cuba/Bahamas, the flow is understood to be mostly eastward to the Atlantic, where the LC becomes the Gulf Stream. The outflow is intensified on the U.S. side of the Florida Straits.

Measurements to understand the complexity of inflow and outflow in the Yucatan Channel and varying speed of the outflow in the Florida Straits have generally not been available for inclusion in LCS model physics. No vertical or horizontal current data are available for model assimilation in near-real-time. Some archived mooring data across the Florida Straits from Mexican academic observers have recently been made public by El Centro de Investigación Científica y de Educación Superior de Ensenada (CISESE).[3] Data are included from July 2012 to the time this report was written, but it has not been fully analyzed. During the 2009–2011 BOEM supported field study, a mooring array was positioned across the Mexican EEZ portion of the Yucatan Straits (moorings Y1–Y7 in Figure 2.5). The data acquired during the 2009–2011 BOEM experiment are available; however, data collected in the 2011–present timeframe have not been made publicly available. Outside the scope of the BOEM study, the array shown in Figure 2.5 extends all the way to Cuba, with 3 additional moorings in Cuban waters (see Figure 3.2). These moorings are operated by CISESE and some aspects of the data have been published (Sheinbaum et al., 2016); however, the data have not been released to the public. The committee was briefed by CICESE that its mooring arrays (two arrays across the Campeche Bank, across the Yucatan Channel, and across the Florida Straits) will likely stop functioning in 2018 without securing new funding. One additional source of public data across the Yucatan is the 1999–2001 Yucatan Channel Experiment funded by the Deep Star Consortium. Mooring data aside, there are no continual measurements of surface LC speed for either control point.

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[3] At the time of report release, the data are publicly available at the following site: https://www.dropbox.com/sh/6wwwjfp3r5iae5x/AAA2PWnTmATpAeg3LhtRWlsoa?dl=0.

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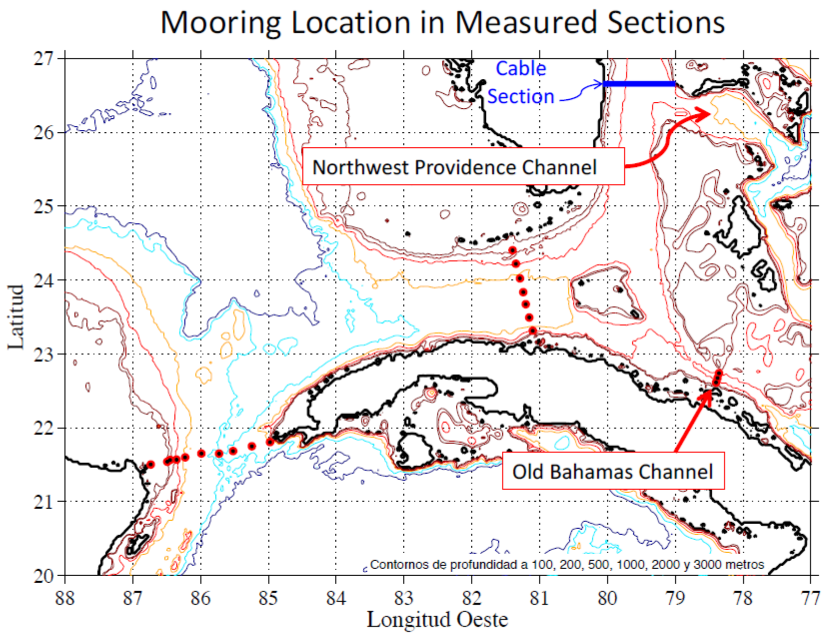

FIGURE 3.2 CISESE Moorings across Yucatan Channel and Florida Straits.
SOURCE: Julio Sheinbaum and Julio Candela.

Recommendation 8: Available Florida Straits data should be retrieved and used in outflow analysis. In the near term, the GRP should work with Mexican institutions on gaining access to data from the Yucatan Channel mooring array, as well as support for additional analysis. Furthermore, these recommendations can be undertaken by supporting a collaborating team of Mexican oceanographers or a joint U.S.-Mexico collaboration team.

Recommendation 9: The GRP should work closely with the appropriate Mexican institutions, in the near term, to keep the Yucatan Channel and Florida Straits mooring arrays operating beyond 2018 (for the next decade) with appropriate data sharing; the Yucatan Channel array should take priority over the Florida Straits array.

Recommendation 10: HF radars should be procured and operated to provide new real-time data, in the near term, for model assimilation and validation and to better understand complex and variable surface outflow regions. Specific regions include:

- **Elbow Cay, Bahamas-looking west at the oncoming outflow,**
- **In the lower Keys looking across the outflow, and**
- **In the Dry Tortugas, looking across the western beginning of the outflow and north into the general location where the LC interacts with the West Florida Shelf.**

Collaboration with the IOOS Regional Associations and the NOAA IOOS HF Radar DAC will be important in all such installations and their operations.

Recommendation 11: The GRP should advocate that Mexico install and operate at least two HF radar systems in the inflow area, one looking north (from the Cozumel Island area) and at least one looking across the inflow from the upper Yucatan Peninsula. If operational support is not available within

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Mexico, support for these radars and real-time sharing of their data output should be negotiated. *Mexican colleagues, in their presentation to this committee, indicated that Mexico had procured several HF radars that are not installed or funded for operation. Should the HF radar recommendations above be acted on, in whole or in part, it will be important to collaborate with the nonprofit IOOS Regional Associations and with the NOAA IOOS DAC.*

Interactions with Bathymetry

The LC interacts with the Campeche Bank soon after formation, and in its extended state, it interacts with the West Florida Shelf while heading south and east. An extended LC that reaches far to the north can interact with shoaling waters along the Gulf Coast, as can LCEs as they propagate west. Today, there are no mooring arrays along the LCS boundaries in U.S. waters that extend from shallow to deep depths, crossing the shelves from approximately 75–1,000 meters. There is increasing interest in the role that bathymetry plays in triggering LC extension and its role in generating TRWs that then interact with the LCS's vertical structure. During the 2009–2011 BOEM supported field study, in cooperation with Mexican colleagues, two mooring arrays were positioned across the Campeche Bank (moorings "N" and "E" in Figure 2.5). The Mexico-BOEM data were collected for 30 months and are publicly available. The moorings continue and will continue to be operated into 2018, but data collected in the 2011–present timeframe have not been made available.

Recommendation 12: The data from the BOEM-Mexico project timeframe should be analyzed specifically to better understand the effect of bathymetry on LCS behavior. Furthermore, in the near term, attempts should be made to access the data from these moorings from the 2011–present time period, and to negotiate terms to keep these mooring arrays in operation beyond 2018 (for the next decade). *These recommendations can be undertaken by supporting a collaborating team of Mexican oceanographers or a joint U.S.-Mexico collaboration team.*

LC observational programs have focused on the central portion of the Gulf of Mexico, where the LC and LC related eddies (anticyclonic and cyclonic) tend to be located, along with regions of ongoing oil and gas operations. This has left the bounding escarpment regions largely undersampled. By their support of TRW propagation, the escarpments provide an important avenue by which mechanical energy may radiate away from a region forced by either LC or LC-related eddy interactions.

The West Florida Shelf region was generally not targeted by prior BOEM studies because of the absence of oil and gas operations there. This fact, plus the physics of TRW propagation, makes this a suspected origination site and establishes the priority for moored observations across the West Florida Shelf and a real-time mooring at one point of transect (see Figures 3.1c and Figure 3.3). If resources permit, a long term array west of Florida's "Big Bend" and an array west of "Bird's Foot" would increase understanding of the role that the Gulf's northern boundary topography plays in LCS dynamics (see Figure 3.1c).

Recommendation 13: A linear array of 4–6 moorings should be deployed in the water column to observe temperature and currents in depths from 75–1,000m, on the southwestern extent of the West Florida Shelf, north of the Dry Tortugas. This moored array should be sustained for several years to cover the evolution of several LCS extension-relaxation cycles. *See Figure 3.3 for the approximate location of the proposed mooring array.*

Recommendation 14: Secondary to Recommendation 13, deploy a similar cross-shelf array (a) seaward of the Florida "Big Bend" along 28.5° North Latitude, and (b) west of the south Louisiana "Bird's Foot."

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From an energetics perspective, a new, observationally based theory has been advanced, positing that the broad west Florida continental shelf may provide dissipation and buoyancy (when acted on by the LC in the southwest corner near the Dry Tortugas) that is sufficient for negating the ability of the LC to do work against the ambient Gulf of Mexico fluid, which is required for the LC to penetrate into the Gulf of Mexico (Weisberg and Liu, 2017, in press). The testing of this new concept requires observations at a critical controlling region referred to as the pressure point (see Figure 3.3) by Liu and Weisberg (2016).

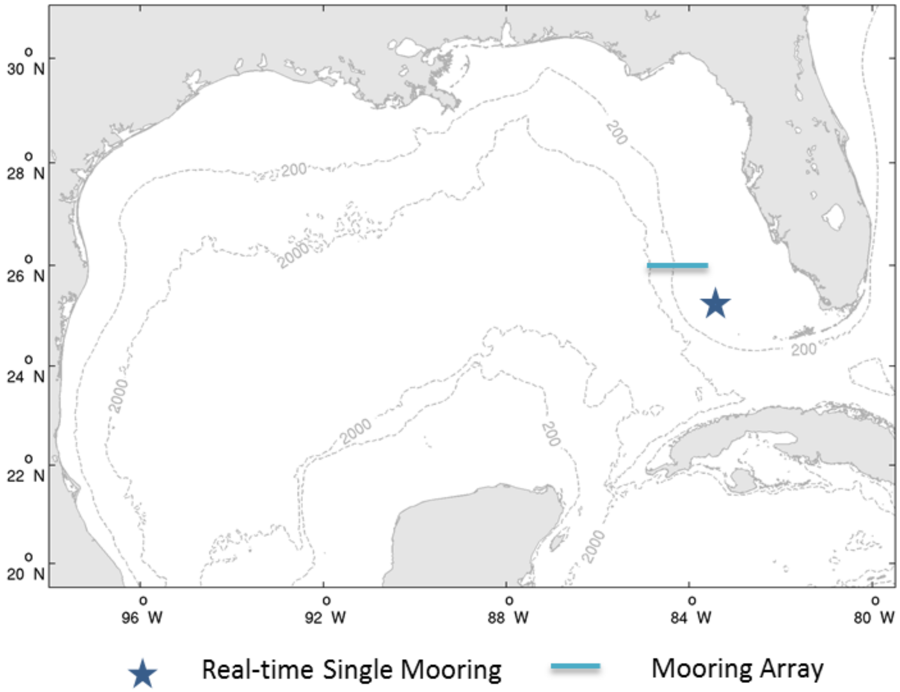

FIGURE 3.3 The “star” indicates the “pressure point” mooring, and the line indicates the approximate location of the across escarpment array with moorings at the 75 meters, 150 meters, 300 meters, 500 meters, 1,000 meters, and 2,000 meters isobaths.

Recommendation 15: **A single real-time mooring should be deployed, in the near term, at the “pressure point” (Liu et al., 2016), or at the shelf break region just to the northwest of the Dry Tortugas, to get the long-term observational effort started earlier and to confirm times regarding when the LC is driving the West Florida Shelf circulation, a phenomena hypothesized to also be controlling the LC itself.**

TECHNOLOGY

Chapter 2 describes the state of sensors, moorings, and other underwater emplacements and vehicles that carry sensors commonly used in measuring currents in the Gulf. Generally, existing technologies can now measure the variables that scientists need to better understand LCS behavior.

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There are, however, several opportunities to advance technology that will make observing the LCS more efficient in terms of time and cost.

Scientists whose research is based on observations and aim to sort out the physics in the LCS's behavior can rely on data collected and retrieved in non–real time. These scientists would then count on archival data for their analyses. Scientists whose research is based on modeling have different constraints. This program seeks not only to understand the LCS, but to provide improved predictions. To meet those goals, near-real-time data are required so they can be assimilated into models which serve as the basis for the needed predictions. Sensors that observe the surface (e.g., satellite altimetry and radiometry, HF radar, surface drifters, ship and aircraft observations, moorings with surface expressions, USVs, gliders, and vertical profiling floats) can provide near-real-time data to scientists and modelers. Gliders and floats (Argo) have gathered some deeper 1,000–2,000 meter data. Some critical observing systems, especially those moored to the bottom, do not have a continual or intermittent surface expression, but there are archived data from their deployments in earlier field studies. Later, in Recommendation 22, the committee will discuss the value of a near-term desktop modeling study, during which deeper data from bottom mounted PIES instruments, along with glider and float observations—data not currently assimilated in numerical models—can inform modellers about the impact of fully assimilated deep data and can therefore inform decisions about investments in near-real-time capture of deeper observations. The committee notes that NOAA's tsunami warning array illustrates that bottom-mounted instruments can transfer data acoustically to a nearby mooring, which then telemeters the data ashore. However, for this effort, individual surface moorings for each subsea node might be too costly for the spatial coverage envisioned. Given that continuous data return is not required (as it is for the tsunami moorings), ASVs could be used to periodically transfer data from subsea nodes. Such a solution provides many advantages over fixed moorings: clear and flexible tradeoffs between cost and update intervals, the ability to schedule more frequent updates when warranted by other observations, and the ability to avoid storm damage. While there have been initial demonstrations with purpose-built ASVs combined with acoustic modems that have shown the technical viability of subsea-to-surface acoustic data transmission capability, these are not widely used. The committee believes that adding the capability to communicate the data (or have their data retrieved) in near-real-time in a reasonably affordable manner would benefit modeling and predictive skill. This capability would also allow scientists to identify sensors that are malfunctioning in a timely manner.

Recommendation 16: In the near term, a team of scientists and engineers familiar with acoustic data communication networks should be supported to determine the feasibility of designing (and, if feasible, building) an acoustic data communications network that might be adopted by bottom-moored arrays and provide near-real-time data to the surface in an affordable manner, considering the specific acoustic environment in the LCS campaign area.

Recommendation 17: As funding may allow, a demonstration of near-real-time data collection from deep instruments using ASVs, or similar technologies, should be discussed, and, if funded, the data should be assimilated to inform their value to model skill.

Long-range HF radar (5 MHz) has proven effective in observing surface currents within approximately 150–200 kilometers of a transmitter/receiver site. In the case of the LCS, if installed, HF radar can cover the inflow and outflow areas from land-based HF Radar sites (Recommendation 10) and LCE propogation from fixed platforms in the oil and gas operating area (Recommendation 3). There is typically no HF radar coverage beyond 200 kilometers from shore during non-storm conditions, but if that were possible, scientists and modelers would be better able to observe the LCS extended state, LCE

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formation, and LCE propagation. HF Radar coverage "at sea" would help in the validation of LCS model skill as well.

Recommendation 18: The GRP-supported campaign should demonstrate sustained operation of HF radars mounted on moored buoys or other platforms in the Gulf from which there can be reliable communications to shore.

A key gap in LCS understanding and observations, as mentioned earlier, is observations in the baroclinic layer of the LCS area (ranging from the surface to about 1,000 meters). While autonomous vehicles (gliders, profilers, and UAVs) can meet many of the recommendations listed in this report and can gather useful data at their specified mobility rates, the committee envisions evolving needs for more capable and bigger vehicles that might carry larger payloads and provide the requisite power for longer operational duration, higher speed, or an ability to maneuver more quickly to capture data during a rapidly changing LCS event. Another potential benefit to future glider operations is on-board path-planning algorithms to better execute desired trajectories in the face of challenging, dynamic conditions. Over the ensuing decade, hybrid gliders (combining the attributes of a glider and an AUV) can contribute to an enhanced glider fleet, especially if improved energy sources become available.

Recommendation 19: The GRP-supported campaign should be open to adopting new technologies (e.g., larger gliders, hybrid gliders, new power sources, new guidance algorithms, shore launch and retrieval, and emerging long endurance UAVs) in its sensing fleet as the campaign matures.

The committee received briefings and had discussions with successful glider operators and sees their value principally in upper layer observation. The committee also discussed the uneven reliability of gliders, due to design flaws, uneven maintenance, or inadequate system operator skill/training. Glider reliability is an important consideration when procuring a glider fleet and deciding who will maintain and operate the gliders. The committee recognizes that gliders can be very effective when adequate funding is available for supporting well trained staff and ensuring adequate equipment maintenance.

Recommendation 20: The GRP should advocate with funding agencies, inside and outside of governments, for the creation of a national glider training syllabus and certification program. *Finally, the committee recommends that all glider operations in LCS campaign use the NOAA IOOS-developed "glider DAC" protocols.*

DATA ASSIMILATION AND NUMERICAL MODELING

Due either to the lack of data, or lack of long-term data, the physics involved in LCS behavior is not fully understood, hence it may not be completely included in models' physical expressions. As identified in Box 3.2, inflow–outflow complexities may not be in all models; nor the interactions between the surface and subsurface (baroclinic and barotropic) layers, and between cyclonic and anticyclonic eddies; nor LC interactions with bathymetry; nor do current model physics consider the full range of near surface air–sea interactions in the LCS area, among others. In addition, there is a range of models available and each may treat these relatively unconstrained processes differently. As the data observation situation is enriched in the next decade, new model physics and data assimilation modules will need to be included in the model package, and the approaches of different models will need to be assessed. Some appropriate "process" experiments can be designed to further refine theory and quantify relative contributions of the various forcing/mechanisms leading to the variability of LCS. The relaxation of the hydrostatic constraint in some processes that involve small-scale jets and mixing may be necessary.

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Box 3.2 Gaps in Current Modeling Systems

Current modeling systems do not include sufficient physics that describe:

- air–sea interaction at the near surface in the LCS active area
- interactions among the surface, subsurface layers, eddies, and waves
- inflow/outflow complexities
- interactions with bathymetry

As the LCS active area campaign develops and as other recommendations on bathymetric interaction and inflow/outflow complexities are addressed, there will be a general need to incorporate new physics into the models, assimilate newly acquired near-real-time data, adopt the most recent data assimilation methodology and long-range statistical modeling approach, and conduct process studies wherein ocean scientists and numerical modelers focus on the importance of certain processes discovered and described as a result of more robust observations. These will come in time as observations flow and new understanding is gained and transformed into model physics equations.

Recommendation 21: Data assimilation and modeling experts should be brought into the program at the onset of the campaign. *Transfer of knowledge between observersational scientists, scientific analysts, theoreticians, and the modeling community will be important to the success of this campaign.*

In addition to gaining a better understanding of and then checking the processes outlined above, models should also be intercompared for their skill in reproducing an observed time series. This requires hindcast studies and thorough skill assessments, a necessary step for achieving more accurate forecasts. In 2010, a 2-year program called GOMEX-PPP was funded to compare SSH prediction accuracy among the many advanced numerical models. Models have advanced further, and the metric for success that the committee sees as important has changed as well (viz., current velocity in the oil/gas operation region is the first/near term priority). We also note that using models in real time to guide the ocean observing campaigns would be most useful. Conversely, the new observations can be utilized to calibrate models and to improve the model parameterizations in real time.

During the period of June 2014–December 2015, surface observations of the LCS showed a high level of activity: an extended LC with various LCE sheddings, reattachments, and propagations. At the same time, a greater number of Gulf short-term field study observations were made under the GoMRI program and by industry supported drifter deployments. The set of observations during this period of high LCS activity has not been fully analyzed with LCS behavior in mind.

Recommendation 22: A new skill assessment among existing Gulf prediction systems should be completed in the near-term to test current model performance in resolving both surface and subsurface circulation, long-range prediction capabilities, and to better inform the campaign's final design. *This is a critical first step in that it will influence final campaign decisions on instrument selection, instrument deployment schemes, and investments in near-real-time data recovery and assimilation. As discussed in Recommendations 16 and 17, this desktop study should pay special attention to the assimilation of deep observations, noting their impact on model skill and value if provided in near-real-time. Furthermore, such analyses can inform decisions on the value of near-real-time deep, but not bottom mounted, instruments (e.g., deep gliders and Argo Floats) versus bottom mounted pressure/current instruments, and the complementarity if both types of instruments can transmit their data in near-real-time. The effort should have the participation of existing Gulf-scale data assimilative*

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prediction systems that are based on three leading community ocean models (HYCOM, MITgcm, ROMS) and consist of three phases:

- *Phase I of the project will include a retroscpective nowcast (i.e., hindcast) of the Gulf of Mexico circulation for two focus periods: (1) 2009–2011, when the BOEM-sponsored deep observations are available, and (2) 2014–2015, when the LCS was hyperactive, in which various LCE sheddings, reattachments, and propagations occurred.*

  Each modeling system will be tasked to use their latest models and data assimilation schemes to assimilate observations (e.g., BOEM deep observations in 2009–2012, along with other publically available surface observations such as satellite SSH, SST) to produce their best data assimilative hindcast of the gulf circulation in 2009–2011 and 2014–2015, respectively.

  Solutions from each model will be compared against independent observations (i.e., data that are not assimilated into the models [e.g, ship obs, industry ADCP and/or drifter data]) for skill assessment and intermodel comparisons.

  The evaluation of these best data assimilative hindcasts will also lead to an important consensus scenario of circulation conditions that occurred in GOM during 2009–2011 and 2014–2015. Next, process analyses will be pursed using these hindcasts to depict the time-space evolutions of LCS and the underlining mechanisms that triggered LCE shedding, reattachment, and propagation.

- *Phase II of the project includes a restrospective forecast for 2009–2010 and understanding the added values of deep observations. Each modeling system will be tasked to perform a retrospective 3-month forecast at 1-month intervals for 2009–2010. They are allowed to assimilate "past and current" surface and BOEM deep observations before making each sequential forecast.*

  Skill assessment and intermodel comparisons will be performed against not-yet-assimilated data in the corresponding forecast window. The goal here is to assess and document skills of the current state of models in forecasting GOM circulation over time scales ranging from days to months with observations from both the surface and subsurface.

  Back in 2011, the GOMEX-PPP project did a similar retrospective forecast experiment, but with the assimilation of surface data only. This new effort will provide an update on models' forecasting capabilities 8 years later, and provide an understanding of the added value of assimilating deep observations.

  Results for the study also serve as the baseline to evaluate future model development and skill improvement.

- *In Phase III of the project, each modeling system will be tasked to perform Observing System System Simulation Experiments (OSSEs) to quantitatively assess the values of different ocean observing system components to forecast. The goal of the OSSE is to measure the impact of several designated observing system components (e.g., radar, moorings, gliders) over model prediction. Ensembles from multi-model OSSE experiments are the expected outcome, and they will be used to provide references on observational design criteria, instrumentation locations, and sampling intervals before the start of the campaign.*

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For accurate long-term simulations, due to the multiple scales and region-dependent dynamics in the Gulf, model resolutions need to be refined in regions with larger dynamic gradients, steep topography, or complex bathymetry/coastlines. Tiling and nesting schemes use finer resolutions in targeted regions (Debreu and Blayo, 2008; Debreu et al., 2012; Haley and Lermusiaux, 2010; Haley et al., 2015; Ringler et al., 2013), while unstructured grids increase the mesh resolution progressively where needed within the same modeling framework (Deleersnijder and Lermusiaux, 2008; Deleersnijder et al., 2010; Ringler et al., 2013). New techniques that use different equations depending on the dynamic needs (e.g., non-hydrostatic only where needed) are also promising. Nesting schemes have been utilized in the Gulf (e.g., Barth et al., 2008; Oey et al., 2005; Prasad and Hogan, 2007; Zamudio and Hogan, 2008). Other numerical modeling research includes efficient schemes for air-sea-wave coupling to accurately represent the one-way forcing and two-way interactions of the atmosphere with the ocean. Similarly, improved mixing and diffusion parameterizations are needed for lateral and bottom boundary layer dynamics, and for the energy and vorticity cascading across different scales.

The assimilation of altimeter data in some LCS models relies on climatology-based synthetic T/S profiles that may deviate significantly from the real state, especially when energetic deep eddies perturb sea-surface height and the LCS is active. Sensitivities to the different climatological profiles used to assimilate the altimeter data are only beginning to be investigated. More work is required to establish the impact of new methodologies on the forecasts.

Closely connected with hindcasts and forecasts are data assimilation models that assimilate observations from satellite and some *in situ* observations. Most of the existing data assimilative models for the Gulf have not been thoroughly documented or adequately tested against independent observations. Existing data assimilation methods (e.g., Edwards et al., 2015; Lermusiaux et al., 2006) include using a simple optimal interpolation method (Daley, 1991) to directly assimilate satellite SSH anomalies (Mellor and Ezer, 1991) or assimilate synthetic temperature and salinity fields derived from a surface-subsurface correlation based on SSH anomalies (e.g., Oey et al., 2005). More sophisticated assimilation techniques, such as 3DVAR, and especially 4DVAR with the "adjoint" model, exist, but not in every model. The "adjoint" techniques (e.g., Chen and He, 2015; Chen et al., 2014; Li et al., 2015; Moore et al., 2015; Thacker and Long, 1988; Zeng and He, 2016) are particularly powerful methods used not only for hindcasts and forecasts, but also for linearized sensitivity analyses that can help with observing system designs. These analyses, in conjunction with OSSE (Halliwell et al., 2015), can provide valuable insights into physical processes and dynamics. Complementary to adjoint-based schemes are ensemble data assimilation methods (e.g., Evensen, 2003; Lermusiaux, 2007) that have also had successes in the Gulf region (e.g., Counillon and Bertino, 2009; Hoteit et al., 2013; Jacobs et al., 2014; Wei et al., 2016; Xu et al., 2013). Such Monte Carlo schemes run an ensemble of simulations with perturbed initial conditions, boundary conditions, and/or stochastic forcing (Lermusiaux, 2006; Lermusiaux et al., 2006, 2007). The resulting nonlinear quantification of uncertainty provides probabilistic forecasts that are useful for theoretical variability studies and for practical applications and risk analyses. Related to ensemble approaches are polynomial chaos schemes that also allow for nonlinear sensitivity studies (Thacker et al., 2012). Recently, differential equations have been derived for efficient reduced-order predictions of uncertainties in nonlinear fluid and ocean systems (Feppon and Lermusiaux, 2017; Sapsis and Lermusiaux, 1999; Ueckermann et al., 2013). Such methods reduce the cost of direct Monte Carlo ensemble schemes by orders of magnitude. They also allow for nonlinear estimations of predictability limits and are useful for quantifying the predictive capabilities of modeling systems.

Given the number of observations in the Gulf, it is critical to best utilize the observations that are collected. First, accurate multivariate and global data assimilation schemes should be used to correct one field or one location from the measurements of another field or location, without the need for *ad hoc* or artificial extensions. Both adjoint-based and ensemble-based schemes can complete such corrections. This capability is, for example, most useful to update deep properties from surface

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measurements. Second, targeted or adaptive observations (Leonard et al., 2007; Lermusiaux et al., 2017; Robinson and Glenn, 1999) (i.e., the prediction of the most informative observations to be collected) should be investigated. Such adaptive data collection (adaptive sampling) will be most useful for increasing the predictive capabilities of current modeling systems from short to longer term LC forecasts. With adaptive sampling, one can, for example, forecast the observations that are most informative to estimate the future fields of interest, such as the LC state. It can also identify the observations that best discriminate among competing model parameterizations or best estimate parameters. Finally, the use of principled Bayesian inference to perform all of the above accurately, possibly in full non-Gaussian ways, needs to be investigated for the Gulf of Mexico regions.

Recommendation 23: Modeling tasks funded under the GRP should be given the latitude, and encouraged, to adopt new methods as they mature. *New efforts in numerical ocean modeling will likely improve modeling skill over the period of interest. For the oil and gas applications, research should also emphasize long-range (within a time scale of up to 3 months) forecasts of the likelihood of specific events.*

As new sources of data become available in near-real-time and as models attempt to assimilate that new data, there will be a new burden on computational capacity. This is likely to be unaffordable to a nongovernmental program like the GRP or any private modeler. Collaborations between national research laboratories (e.g., Naval Research Lab [NRL], National Center for Atmospheric Research [NCAR], Geophyscial Fluid Dynamics Laboratory [GFDL], the Naval Oceanographic Office [NAVOCEANO], National Center for Environmental Prediction [NCEP]) and universities are likely to be most beneficial. It should be noted that the GRP's funding authorities do not allow for the funding of federal activities.

Recommendation 24: The GRP should actively solicit cost sharing or other computer center collaborations to ensure that the results of the campaign can be supported continually and operationally.

So far, most of the modeling efforts for the LCS use primitive equation ocean models. Recent developments in statistical modeling based on machine learning have shown promising potential in offering credible long-range LC and LCE separation forecasts. Applications of machine learning methods have demonstrated successes in predicting many other nonlinear natural processes such as *El Niño*. Their full potential for use in Gulf LCS prediction still needs to be determined. Combinations of previous governing-equation based modeling with machine learning schemes also have potential (e.g., Lermusiaux et al., 2016, 2017; Zeng et al., 2015a,b). Predicting the LCS deterministically can sometimes be as if doctors were providing a single forecast of the result of a single possible treatment, without using the concepts of risks or of the different initial conditions, i.e., each patient. It would also be as if doctors were deciding to not utilize machine learning and big data or other new emerging approaches to help them in their work and possibly increase the number of lives they can save. Of course, a big difference in ocean prediction is that governing equations are relatively well known; however, many parameterizations, initial and boundary conditions, and forcing mechanisms are uncertain, and, additionally, there are numerical and human errors. Hence, it appears essential to account for varied possible outcomes, for uncertainties, and for risks to the oil and gas activities and platforms. This is especially true for the mid- to long-range (a few months and beyond) forecasts where uncertainties cannot be ignored—stochastic approaches are then most useful. There is also some justification for a fully statistical approach (e.g., without a use of deterministic governing equations) and for machine learning because these approaches have been useful in varied settings (Hsieh, 2009; von Storch and Zwiers, 2002) and can be used for the LCS problem (Zeng et al., 2015a,b).

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Recommendation 25: The GRP campaign should encourage the development and testing of the statistical and stochastic modeling approach, especially for the mid- to long-range (a few months and beyond) prediction of the LCS.

Recommendation 26: Numerical modelers should be consulted in developing the specific observational programs' design, and that "adaptive sampling," based on model results, be continually practiced throughout the campaign, especially for those observational subprograms that have a choice in timing, areas of deployment, and vertical/horizontal spacing. Within 3 years of the commencement of the campaign, the impact of the new observations and new understanding of the LCS model should start to be presented and reviewed.

ANALYSES AND THEORY

It is important to note that many have studied the LCS over the past several decades. However, several critical gaps in understanding remain—a compilation of data from such studies would provide a useful tool for scientists to consult over the next decade. Each discrete "field study" had theory in mind when it was designed. Yet understanding, and, hence, predictive skill, have not advanced sufficiently to improve LCS forecasts beyond a few days (with the exception of times when the LCS is stable) even when existing data streams are available. The committee sees catalytic value in a set of comprehensive campaigns that will bring new and long-term observations ashore for scientific analysis and assimilation into improved models. During this period, as a result of the new observational wealth, new theories will emerge.

Recommendation 27: In the near term, the GRP should support a desktop-style study to digitally compile (and make publicly accessible) physical oceanographic data from Gulf of Mexico field studies carried out between 2002 to 2017. *The last database of observations was compiled during the MMS-sponsored "Deepwater Physical Oceanography Reanalysis and Synthesis of Historical Data Study" (Nowlin et al., 2001), which covered the time period from 1990 to 2001. Extending this compilation through 2017 will create a ready digital reference for the many field and theoretical scientists who will likely be supported in future LC observational and analytical studies.*

Recommendation 28: Science teams should be engaged early in the campaign process and campaign leaders should encourage focused process studies and the testing of new theories.

METRICS OF SUCCESS

There are two main parts to the campaign effort: the first is to use new observations to better understand the science, or dynamics, associated with the LCS; the second part and ultimate goal of the campaign is to use both the observations and the new scientific understanding to improve models of the LCS and thus increase predictive skill of LCS activity.

The first measure of success hinges on advances in our understanding of the dynamics driving the LCS. If efforts put forth by this campaign though new observations, technology, analyses, and modeling lead to a better understanding of what controls the penetration of the LC in the Gulf of Mexcico, and/or what determines the the shedding of an anticyclonic eddy, then the campaign will have succeeded in filling important gaps in the scientific understanding of the LCS.

With the ultimate goal of applying the new understanding to more accurately predict LCS activity, quantitative metrics of success are also required. These metrics must be both measurable from observations and predictable by models. A few past efforts at forecasting ocean conditions in the Gulf have focused on metrics of SSH, a variable that is measured effectively by satellite. State variables in the

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ocean include velocity, temperature, salinity, and density, all of which are functions of latitude, longitude, depth, and time. A practical metric for forecast evaluation will allow for the calculation of statistics over a defined volume and at a specific forecast lead-time. For example, forecasts of days to 1 week, 1 month (some refer to this period as “sub-seasonal”), and 3 months (some refer to this period as “seasonal”) are sensible targets. Spatial extents are as large as the entire Gulf for long-term forecasts of 1 to 3 months, and as small as the operational region of the northern Gulf at times of days to weeks. The processes that must be observed and modeled include the extension of the LC into the Gulf, the separation of an LCE, and the propagation of the eddy northward and westward across the Gulf. Skill at forecasting these processes can be appropriately quantified through metrics of velocity (e.g., feature-based tracking and overall velocity distribution statistics), whose measurement will be a focus, and frontal placement.

Recommendation 29: By the close of this project, success should be measured by the ability to predict currents (including uncertainty) in the LCS active area (see Figure 3.1) and in areas where the LCEs propogate. The Committee recommends a hierarchy of forecast periods, matched to the relevant processes and regions of interest:

- **Improved predictive skill in forecasting the LC and/or LCE current speed, vertical structure, and duration in the oil/gas operating area out to a forecast period of days to 1 week**
- **Improved predictive skill in forecasting the extension of the LC (location and duration) and LCE propagation out to a forecast period of approximately 1 month**
- **Improved predictive skill in forecasting an eddy shedding event from an extended LC out to a forecast period of approximately 3 months**

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4

Loop Current Campaign Solicitation Advice

The committee was asked to advise the GRP on components of a comprehensive “field campaign to improve understanding and forecast skill” for the LCS. The recommendations in Chapter 3 provided detail on observations, scientific analyses, technology, and the data assimilation and numerical modeling components needed to better understand and predict the LC. This chapter’s recommendations seek to help define how the funding opportunites should be organized.

In line with the three main physics questions (see Box 2.1) and the three main observational gaps (see Box 3.1), the committee recommends three geographic foci, with each looking at the LCS, or components thereof, in a new way.

1. A comprehensive, long-term (decadal), vertically inclusive “campaign” in the main climatological LCS active area (see Figures 3.1a and 3.1b)
2. An observational and scientific analysis component focused on the interaction between the LCS and shoaling bathymetry that virtually surrounds the LCS (see Figure 3.1c).
3. An observational and scientific analysis component focused on the complex inflow through the Yucatan Channel and outflow through the Florida Straits (see Figure 3.1d).

The recommendations are of two types: near-term (within the next year to 18 months) and those that require more time to solicit, select, and implement (i.e., the “campaign”). The near-term components are expected to greatly benefit and jumpstart the larger campaign.

As mentioned in previous chapters, and as dipected in Figure 4.1, the committee sees the recommendations put forth as an integrated whole. It is intended that new observations will feed new analyses, theory, and modeling and that new modeling, theory, and analyses, in addition to new technologies, will inform more targeted observational schemes which then feed back into improved analyses, theory, and modeling. As this loop continues, and with significant collaborative efforts (whether financial or in-kind), predictive skill in forecasting LCS activity will improve.

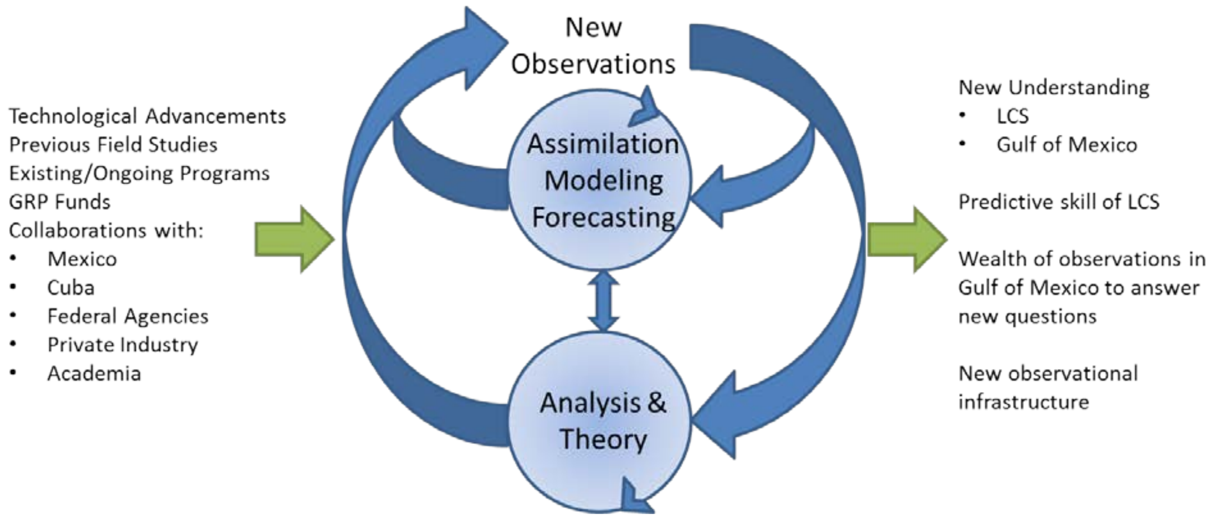

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FIGURE 4.1 LCS Integrated campaign.

A SUMMARY OF RECOMMENDATIONS FOR NEAR-TERM ACTION

Recommendations for near-term action are all actions that can be started or accomplished without extensive campaign planning—all activities included will either jumpstart the field campaign or inform the design of the campaign. The committee believes that a fast-track funding opportunity that includes the recommendations below will greatly benefit the overall campaign. Details supporting each recommendation can be found in Chapter 3.

- Observations:
    - Procure and/or install and operate HF radars on existing Gulf platforms and across the inflow/outflow areas (shown in red, Figure 4.2; see Recommendations 3 and 10)
    - Deploy a coherent feature-tracking, bottom-moored array for deep pressure and current observations in the LCS active area (shown as blue grid, Figure 4.2; see Recommendation 6)
    - Support the continued operation of the campaign's decadal duration of the Yucatan Channel, Florida Straits, and Campeche Banks mooring arrays (shown in teal, Figure 4.2; see Recommendations 9 and 12)
    - Deploy a West Florida Shelf real-time "pressure point" mooring (shown as a blue star, Figure 4.2; see Recommendation 15)
- Studies:
    - Conduct a data management exercise to compile existing Gulf of Mexico oceanographic data in support of future research efforts and process studies (see Recommendation 27)
    - Gain access to and/or analyze Campeche Bank, Florida Straits and Yucatan channel archived mooring data (see Recommendations 8 and 12)
    - Conduct a feasibility study for a deep acoustic data communication network (see Recommendation 16)
    - Conduct a model performance comparison study (see Recommendation 22)

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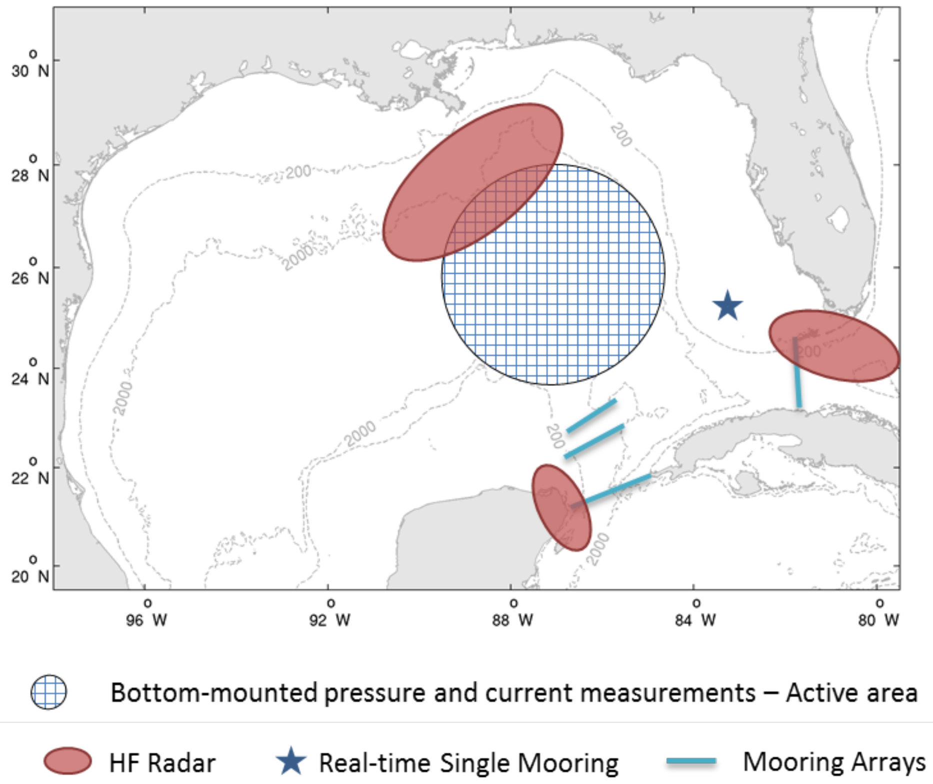

FIGURE 4.2 Near-term observational scheme.
NOTE: Red ovals indicate recommended HF radar installations, blue grid indicates the general area of bottom-moored array, teal lines indicate existing mooring locations from which data, historic and future, should be accessed, and the blue star indicates location of West Florida Shelf "pinch point" mooring.

THE "CAMPAIGN"

Overview

Although scientists have been collecting data in the LCS area for decades, there has been no *in situ* field study that has been long term in nature. Furthermore, most prior field studies have not comprehensively observed data from the near surface air–sea interface, surface, upper baroclinic, and lower barotropic areas at the same time. Therefore, this LCS campaign is unique in its temporal (decadal) and spatial (vertical and horizontal) extent. In addition, beyond observations, this campaign includes the scientific analyses of data collected and then the assimilation of new data and inclusion of new understanding (physical processes) and numerical techniques into the models. The following sections describe components that should be considered in crafting a funding opportunity.

Measures of Success and Validation

The funding opportunity should clearly articulate goals that will be measured and validated with observations at the campaign's midpoint and end. The processes that must be better observed,

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understood, and modeled include the extension of the LC into the Gulf, the separation of an LCE, and the subsequent propagation of the LCE northward and westward across the Gulf. If efforts put forth by this campaign though new observations, technology, analyses, and modeling lead to a better understanding of what controls the penetration of the LC in the Gulf of Mexcico, and/or what determines the the shedding of an anticyclonic eddy, then the campaign will have succeeded in filling important gaps in the scientific understanding of the LCS.

Skill at forecasting these processes can be appropriately quantified through metrics of velocity (e.g., feature-based tracking and overall velocity distribution statistics), whose measurement will be a focus, and frontal placement. By the close of this project, success should be measured by the ability to predict currents in regions used extensively by society.

The committee recommends these measures:

- Improved predictive skill in forecasting the LC and/or LCE current speed, vertical structure, and duration out to a forecast period of days to 1 week
- Improved predictive skill in forecasting the extension of the LC (location and duration) and LCE propagation out to a forecast period of approximately 1 month
- Improved predictive skill in forecasting an eddy shedding event from an extended LC out to a forecast period of approximately 3 months

Campaign Area

The campaign area includes the general LCS active area (see approximate aerial extent in Figure 3.1), from the air–sea interaction surface interface to the bottom, as defined by the 200 meter isobaths on the Campeche Bank, West Florida Shelf, and North Gulf Coast to 91° West Longitude and areas west to the Texas/Mexico coast when an LCE is propagating westward, and ultimately bound by the areas of inflow and outflow. The campaign also includes important target areas on the shoaling shelves and in the inflow/outflow areas.

Campaign Duration

The campaign is expected to last approximately a decade to ensure that several LCS retraction-extension cycles, seasonal changes, and interannual variations are all observed. The funding opportunity should be solicited for a 5-year period with the opportunity to document progress and propose a 5-year extension after approximately 3.5 years have elapsed.

Key Observation Variables

The funding opportunity should principally specify observing temperature, salinity, current vectors, and pressures from the surface through the entire water column and fundamental near-surface meteorological variables. Over the life of the campaign, there is likely to be emerging interest in other variables. The funding opportunity should be written to encourage and adopt new, useful observation data types. The base observational scheme recommended to capture key variables is shown in Figure 4.3.

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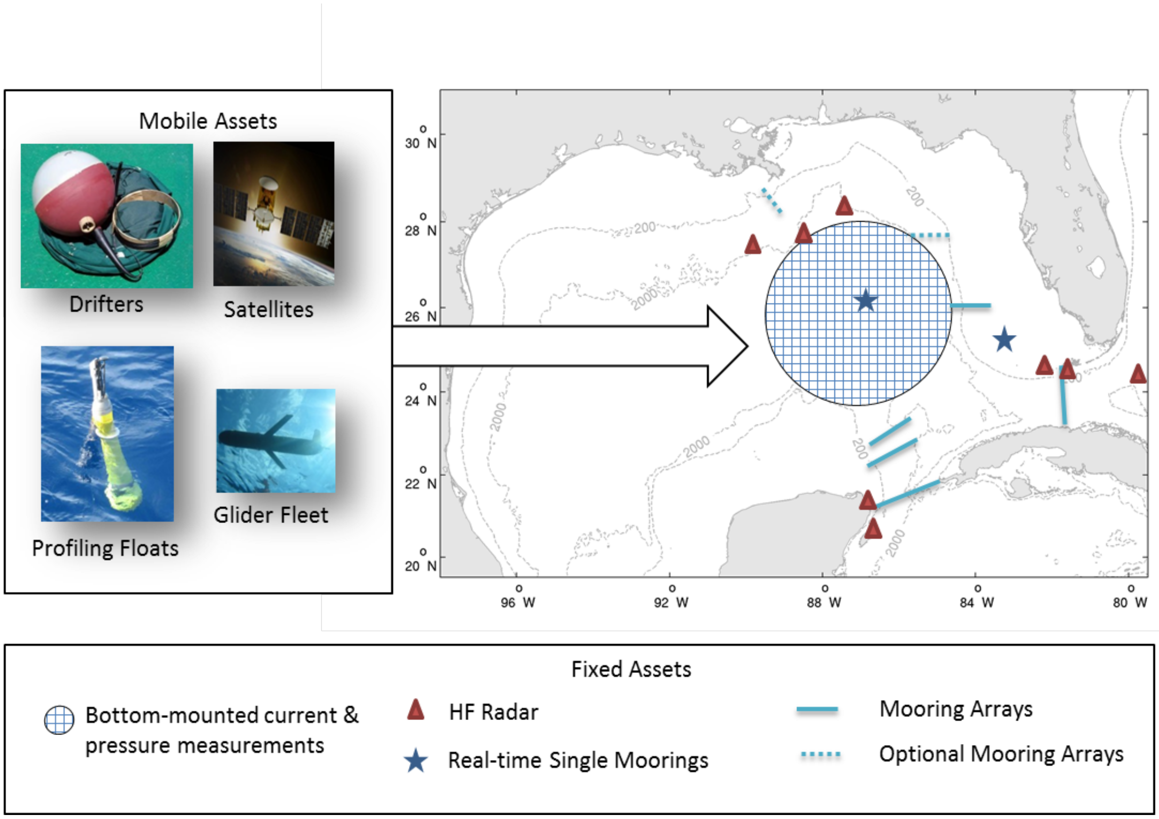

FIGURE 4.3 General proposed campaign observational scheme.
NOTE: Shown locations of fixed assets are approximations and should not be used for determining coordinates of observational campaign components.

Near-Real-Time Observations

The following information should be collected for use in analyses and immediate assimilation into current models:

- Satellite-based SSH, SST, and ocean color at current observational rates (see Recommendation 2).
- Surface current data from newly procured and/or installed and operated HF radars on three oil/gas platforms in the western Gulf, and on land sites covering the inflow/outflow regions (see Recommendations 3, 10, and 11).
- Surface current and ocean surface meteorological data from various currents and more fully instrumented drifters (see Recommendation 1).
- Temperature, salinity, current vectors, and instrument pressure-depth from moorings that have surface communications capability (see Recommendation 7).
- Temperature, salinity, and current observations in the upper 1,000 meters of the LCS from gliders and profiling floats (see Recommendations 4 and 5).

Non–Real Time Observations

- Observations of near-bottom currents, bottom pressure, integrated water column currents, and temperature from bottom-moored instruments (e.g., inverted echo sounder and pressure type devices with current meters) and/or deep profiling instruments. The funding

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opportunity should encourage near-real-time data retrieval by acoustic communication networks or other methods that may become available within the realm of affordability (see Recommendation 6).

- Temperature, salinity, currents and instrument pressure-depth from moorings that do not have a surface communications capability (see Recommendation 9, 12, 13, and 14).
- Observations collected from full water column moorings and other bottom moored instruments from past field studies (e.g., the BOEM-supported field studies of 2009–2011 and Mexico's mooring and drifters programs in the LCS area) (see Recommendation 27).

Scientific Analyses

Understanding and predicting LCS behavior has been an open problem for decades, and despite enjoying some investment in observations, analysis, and theory, many questions regarding the dynamics of the LCS remain. While this campaign is expected to enable new near-real-time observations that should be directed for immediate assimilation into models, some data, especially archived and new data collected throughout the campaign, should be analyzed by scientific team(s) to gain a better understanding of LCS behaviors and processes. It is also time to consider new theories (e.g., in Chapter 2, the committee highlighted a new theory related to bathymetric/topographic influences). The campaign team should assemble a scientific team(s) to analyze archived and new observations and elevate new theories based on those observations, with a goal of recommending new physical expressions and new deep "climatology" for inclusion in numerical models (see Recommendations 8, 12, 22, 24, 27, and 28).

Technology Enhancements

The funding opportunity should strongly encourage and incentivize proposals that commit to the adoption of vehicle, sensor, and data communication technology enhancements. The LCS is an energetic system in that it follows that observational vehicles should have the capability to be as effective as possible when manuevering in such a system. As new theories emerge, there will be inevitable calls for new sensors and more robust sensors and vehicles with the volume and power to carry them. Near-real-time data from the deep LCS layer may prove to be valuable for assimilation into models, and new acoustic communications networks have promise in terms of accessing the deep layer data affordably (see Recommendations 16, 17, 18, 19, and 20).

Data Assimilation and Modeling

The funding opportunity should require that near-real-time observations be prepared for data assimilation. The campaign should include a team of ocean scientists and numerical modelers to enable the insertion of new modeling and assimilation techniques, new physics, and perhaps new deep "climatology" into models. Assuming new, near-term data are available (and possibly some new physics), a formal demonstration of real-time, operational data assimilative model forecasting (consisting of both short-term and long-range LCS prediction) should be conducted within approximately 3 years of the campaign'x initiation; this should help to inform any proposal made to extend the campaign. Likewise, a formal demonstration should be required in the 8- to 9-year timeframe. Workshops should be convened to discuss the impact of the campaign on model skill and the model forecasts' feedback on the observational program (see Recommendations 21, 23, 24, 25, and 26).

Encouragement of Cooperation, Collaboration, and Leveraging

While the LCS campaign will be initiated with GRP funding and oversight, the success of the campaign relies heavily on cooperation, collaboration, and leveraging with federal agencies,

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international agencies, public and private organizations and corporations, and academia. Opportunites for collaboration are highlighted in Box 4.1.

Box 4.1 LC Campaign Collaboration Opportunities

The GRP Funded LC campaign is a broad area, vertically integrated, long-term observation, analysis, and modeling effort with significant and reliable funding and open opportunites for collaboration, whether financial or in-kind.

- U.S. government agencies cannot directly receive GRP funding, yet collaboration is encouraged. For example:
    - Government funded private investigators may cooperate with the campaign
    - Government performers may cooperate with the campaign and *vice versa*
    - The campaign may charter observational time on vessels owned by the government yet bailed to institutions for operation, or use instruments procured with government funds yet operated by private institutions
- The campaign covers large parts of the Gulf of Mexico; close collaboration with scientific colleagues in Mexico and Cuba is strongly encouraged.
- The campaign presents opportunities for mutual leveraging of observations and observational infrastructure between the oil and gas industry and the campaign
- The campaign is largely a physical oceanography/ocean dynamics program, yet it provides observational opportunities for related fields (e.g., acoustics, biology, chemistry, etc.)

The campaign solicitation should reach out to talented ocean scientists and numerical modelers in:

- academia;
- other non-profit organizations that work in the ocean observing and modeling fields (e.g., Navy University Affiliated Research Centers [UARC], Federally Funded R&D Centers [FFRDC], National Science Foundation (NSF) national centers, and NOAA Cooperative Institutes and Regional Associations);
- oil/gas, geophysical observing, scientific, and ocean technology industries;
- international neighbors in the Gulf and its Straits; and
- government agencies, especially those that are invested in ocean or Gulf modeling (e.g., Navy [NRL and NAVOCEANO], NOAA [NCEP and OAR Cooperative Institutes], NSF [NCAR]).

Engaging the best talent is always a goal, but the funding opportunity should encourage collaboration with agencies and organizations that see the benefit of the GRP-funded observational and analyses efforts, and, therefore, realize there can be benefits to bringing their own funding or in-kind support to the campaign. This is particularly important in partnering with government-operated and -sponsored organizations, especially in leveraging data management systems (e.g., NOAA IOOS and NDBC), computational capacity (e.g., NAVOCEANO's Department of Defense Major Computer Center), and numerical modeling groups (e.g., NOAA's GFDL, NRL, NAVOCENO, and NCEP; NSF's NCAR and other federally supported programs). Furthermore, the oil/gas industry and its supporting ocean-practice contractors, to which the new observations and improved models will be immediately valuable, should be encouraged to join in substantially supporting this fuller Gulf and LCS observing system.

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The Gulf is not exclusively under the purview of the United States. We share the Gulf with Mexico and Cuba. We also share the Florida Straits with the Bahamas. While the campaign should encourage—to the point of funding—collaboration with our Gulf neighbors, the GRP should, in the near-term, begin discussions about data sharing and the furthering of moorings operations, HF radar installation, and other ocean observing plans. A near-term action for the GRP, and the eventual campaign leader, is to gain permits for ocean research (when a U.S. vehicle/instrument is the best option) in other nations' EEZs.

Recommendation 30: As the crafting of the funding opportunity matures, the GRP should engage stakeholders, including federally operated and sponsored organizations, Mexican and Cuban agencies, and private institutions and industry to discuss the campaign goals, explain the opportunities it supports, bring the ocean modeling community into the planning early, and explain the legal restrictions associated with the GRP funds.

Data Management Requirements

The GRP has published a data management policy[4] in previous funding opportunities; it should be referenced as a requirement in the solicitation and agreed on by any funding opportunity respondent in any formal proposal. Additionally, any funding opportunity should explicitly require a data manager or data management team to assure proper capacity for adhering to the data management policy. Regarding systems for data communications, quality control, archival and access, the funding opportunity should encourage the use of IOOS protocols and other existing, accessible, nationally accepted data management systems (e.g., those used by NDBC). Real-time or near-real-time data collected by this campaign should be made publicly available through recognized, established data sites. Results from GRP-sponsored, LCS campaign-specific scientific analyses should be made available to the data assimilation/modeling community as soon as possible and published within 1 year of analysis.

Campaign Solicitation Method and Campaign Management

There are several large ocean project management models (e.g., NOAA's Cooperative Agreements and Cooperative Institutes, Office of Naval Research's (ONR's) Defense Research Initiatives, NSF's recent Ocean Observing Initiative and National Ecological Observatory Network program). Each has a track record. Some models ask that funding opportunity respondents put together teams of performers and leaders. Another model is for the supporting agency to select what it thinks are its best performers and then a leader is picked from within the selectees. History shows that some technical respondents are not the best administrators. Other examples show that strong administrators are not necessarily technically skilled enough to manage a science enterprise. Still other examples show that the leadership regime, however chosen, may not have the administrative breadth to cover a complex project's requirements. Because most models of this scale use public monies, there are strict federal rules and audit requirements that must be followed. Moreover, there are varying degrees of management control over program execution by the government's program managers. This has led agencies to punctuate the importance of the selection of the nongovernment leader, also known as the principal investigator (PI), and the relationship between the government program manager and the lead PI. The GRP, while free of some specific contracting constraints, must also ensure sound, rigorous business practices and those expectations must be outlined in the funding opportunity. The committee believes that success in any model is dependent on the technical quality of the team selected and,

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[4] The Gulf Research Program's Data Management Policy can be found at: http://www.nationalacademies.org/cs/groups/gulfsite/documents/webpage/gulf_178879.pdf.

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especially, the quality of overall program leadership. The committee recommends that scientific/technical program principal investigators and science teams be selected based on track record, experience, and collaborative potential by a GRP selection panel. Separately, but at about the same time, the same GRP selection panel should pick a lead program manager and a team of subordinate administrators that he/she proposes. This will likely mean two RFAs, with one chosen for technical work and one for overall administration and management.

A strong leader with a technical reputation and demonstrated managerial excellence is critical. Because the GRP will likely outsource the campaign, the leader will need a management team to deal with sub-contracting, procurement, HR challenges, financial management/accounting/audits, legal matters, communications, reporting, international negotiations, and permitting, to name a few duties. The overall leader does not necessarily have to be a single person; it is, rather, a capability that will be needed to understand the science and broadly address management challenges. A self-assembled group of scientific persons may emerge (e.g., a new consortium of universities), as might an established non-profit group (e.g., an established consortium of partners like the Consortium for Ocean Leadership, University Corporation for Atmospheric Research, IOOS Regional Association, or a private institute), or a for-profit company with complex management experience. This is a critical decision and will take the best effort of a GRP selection panel.

The committee has recommended that the best scientists (observers, analysts, and numerical modelers) be chosen to execute the LCS campaign. Separately, not from within the science teams, a leader or leadership group should be selected. The “pro” in such a selection scheme is that the best are selected. The “con” is that there is always a chance that the top leadership team, while scientifically competent, will not be practicing scientists, but will have overall management authority. This can lead to interpersonal competition over authority, although this is admittedly personality dependent. Such models are normal in high-tech industries. A check and balance on such a management scheme is the appointment of an outside review board composed of experienced people from policy, science, and management backgrounds that can hear regularly from leadership and the science teams and advise the GRP Executive Director.

The GRP Executive Director should review the campaign leadership performance regularly and be empowered to replace the leadership regime if needed. This Executive Director’s authority should be explicitly mentioned in the funding opportunity. Likewise, all funding opportunities should explicitly describe the authorities of the overall leader.

ESTIMATED COSTS

The Statement of Task specifically asks for an estimate of the costs associated with the campaign components. The estimated costs described below do not consider contributions of outside funding or in-kind resources possibly contributed through collaborative leveraging.

The committee estimates, from the variety of its individual experiences, that the full three geographic component program can be funded for about \$100–\$125M over the course of a decade—an average of \$10–\$12 million per year, recognizing that some years involving new procurements will be higher and other years lower. The committee stresses that it would be counterproductive to recommend exact cost boundaries as such recommendations would stifle innovative proposals. The estimates below exist merely to give the GRP a rough order of magnitude for planning purposes. The funding opportunity(s) should not be constrained by the estimates provided in Tables 4.1 and 4.2.

TABLE 4.1 Near-Term (2018) Investments and 2-Year Operations

Observational Components	
HF radar procurements and/or installations	$2M

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• Installation and 2-year operation of two Mexican-owned HF radars measuring inflow • Procurement, installation, and 2-year operation of three HF radars measuring outflow from the Florida Keys and Bahamas • Procurement, installation, and 2-year operation of three HR radars to be located offshore in the main LCS active area	
Support the continued operation of Mexico’s mooring arrays (Campeche Bank, Yucatan Channel, and Florida Straits for 2 years)	$3M
Deploy a sparse bottom-moored pressure/current array for 2 years	$1.5M
Deploy a West Florida Shelf real-time “pressure point” mooring for 2 years	$1.5M
Studies and Analyses	
Conduct scientific analyses of inflow/outflow mooring data and Campeche Bank mooring data	$0.25M
Conduct a deep acoustic data communication network feasibility study	$0.25M
Conduct model comparisons, including comparison and process analyses during “active years”	$2–$3M
Conduct a desktop-style study to compile (and make accessible) physical oceanographic data of the Gulf of Mexico from 2002 to 2017	$0.15M
Total	**Approx. $10–$11M**

TABLE 4.2 Campaign Costs (for 10 years, listed in general order of priority within each section)

Decadal Observational Components		
Active LCS Area	Support HF Radar operations (three radars in LCS Active Area) Optional: Procure, install, and operate, initially as a demonstration, an HF Radar on a buoy	$1M $1M
	Procure and operate Gliders in the upper layer	$23M
	Procure and operate Surface Drifter program	$2.5M
	Deploy a full bottom-moored pressure/current array (approx. 60 kilometer spacing) Optional: selective near-real-time data sampling ($0.5 million per year) = $5M	$3M
	Real-time Mooring in the Central LCS Active Area	$3M
	Enhance Profiling Floats operation in upper layer	$2M
Inflow and Outflow Processes	Support HF Radar at Inflow and Outflow locations	$1M
	Support for the continued operation of Mexico’s Yucatan Channel array	$5M
	Support for the continued operation of Mexico’s Florida Straits array	$5M
Shelf Processes	Support for the continued operation of Mexico’s Campeche Bank arrays	$5M
	Support for the continued operation of the Pressure Point mooring for at least 3 additional years	$1.5M
	West Florida Shelf array Optional: Cross-shelf mooring west of Florida’s “Big Bend” Optional: Cross-shelf mooring west of the south Louisiana “Bird’s Foot”	$6.5M $6.5M $6.5M
Modeling and Analyses		
	Support scientific analysis and numerical modeling team(s)	$20–$30M
Program Managment		

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	Data management	$5M
	Program management	$10M
	Estimated Total	**Approx. $100–$125M**

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REFERENCES

Alvera-Azcarate, A., A. Barth, and R. Weisberg. "The Surface Circulation of the Caribbean Sea and the Gulf of Mexico as Inferred from Satellite Altimetry." *Journal of Physical Oceanolograpy* 39 (2009):640–657.

Austin, G. B. "Some recent oceanographic surveys of the Gulf of Mexico." *Eos, Transactions American Geophysical Union* 36, no. 5 (1955):885–892.

Badan, A., J. Candela, J. Sheinbaum, and J. Ochoa. *Upper-Layer Circulation in the Approaches to Yucatan Channel, in Circulation in the Gulf of Mexico: Observations and Models*. Edited by W. Sturges and A. Lugo-Fernandez. Washington, DC: American Geophysical Union, 2005: 57-69. doi: 10.1029/161GM05.

Barron, C. N., A. B. Kara, P. J. Martin, and R. C. Rhodes. "Formulation, implementation and examination of the vertical coordinate choices in the global Navy coastal ocean model (NCOM)." *Ocean Modell* 11, no. 3 (2006):347 –375.

Barth, A., A. Alvera-Azcárate, and R. H. Weisberg. "Benefit of nesting a regional model into a large-scale ocean model instead of climatology. Application to the West Florida Shelf." *Continental Shelf Research* 28, no. 4 (2008):561–573.

Carnes, M. R., W. J. Teague, and J. L. Mitchell. "Inference of Subsurface Thermohaline Strucure from Fields Mearuable by Satellite." *Journal of Atmospheric oceanic technology* (1994):551–566.

Chen, K., R. He, B. Powell, G. Gawarkiewicz, A. M. Moore, and H. G. Arango. "Data assimilative modeling investigation on Gulf Stream Warm Core Ring interaction with continental shelf and slope circulation." *Journal of Geophysical Research: Oceans*, 2014. doi: 10.1002/2014JC00989.

Chen, K., and R. He. "Mean circulation in the coastal ocean off northeastern North America from a regional-scale ocean model." *Ocean Science* 11, no. 4 (2015):503 –517. doi: 10.5194/os-11-503-2015.

Chen, S. S., and M. Curcic. "Ocean surface waves in Hurricane Ike (2008) and Superstorm Sandy (2012): Coupled model predictions and observations." *Ocean Modelling* 103 (2016):161–176.

Chérubin, L. M., W. Sturges, and E. P. Chassignet. "Deep flow variability in the vicinity of the Yucatan Straits from a high-resolution numerical simulation." *Journal of Geophysical Research* 110, no. C4 (2005).

Counillon, F., and L. Bertino. "High-resolution ensemble forcasting for the Gulf of Mexico eddies and fronts." *Ocean Dyanmics* 59, no. 1 (2009):83–95.

Cox, J., C. Coomes, S. DiMarco, K. Donohue, G. Z. Forristall, P. Hamilton, R. R. Leben, and D. R. Watts. Study of deepwater currents in the Eastern Gulf of Mexico. .S. Dept. of the Interior, Bureau of Ocean Energy Management, Regulation, and Enforcement, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study BOEMRE 2010-041. 473.

Cummings, J. A. "Operational multivariate ocean data assimilation." *Quarterly Journal of the Royal Meteorological* Society 131, no. 613 (2005):3583–3604.

Daley, R. *Atmospheric Data Analysis.* Cambridge, UK: Cambridge University Press, 1991. 457.

Debreu, L., and E. Blayo. "Special Issue on multi-scale modelling: nested grid and unstructured mesh approaches." *Ocean Dynamics* 58 (2008):415–428.

Debreu, L., P. Marchesiello, P. Penven, and G. Cambon. "Two-way nesting in split-explicit ocean models: Algorithms, implementation and validation." *Ocean Modelling* 49 (2012):1–21.

DeHaan, C. J., and W. Sturges. "Deep cyclonic circulation in the Gulf of Mexico." *Journal of Physical Oceanography* 35, no. 10 (2005):1801–1812.

Deleersnijder, E., and P. F. J. Lermusiaux. "Multi-scale modeling: nested-grid and unstructured-mesh approaches." *Ocean Dynamics* 58, no. 5 (2008):335–336.

Deleersnijder, E., V. Legat, and P. F. J. Lermusiaux. "Multi-scale modelling of coastal, shelf and global ocean dynamics." *Ocean Dynamics* 60 (2010):1357–1359.

Copyright National Academy of Sciences. All rights reserved.

Dietrich, G. "Die dynamische Bezugsfläche, ein Gegenwartsproblem der dynamischen Ozeanographie." *Annalen der Hydrographie u. Maritimen Meteorologie* (1937):506 –519.

DiMarco, S. F., W. D. Nowlin, and R. O. Reid. "A statistical description of the velocity fields from upper ocean drifters in the Gulf of Mexico." *Circulation in the Gulf of Mexico: Observations and Models* (2005):101–110.

Donohue, K. A., P. Hamilton, K. Leaman, R. Leben, M. Prater, D. R. Watts, and E. Waddell. *Exploratory study of deepwater currents in the Gulf of Mexico.* U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, 2006.

Donohue, K., P. Hamilton, R. Leben, R. Watts, and E. Waddell. 2008. Survey of deepwater currents in the northwestern Gulf of Mexico. Volume II: Technical Report. U.S. Dept. of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study MMS 2008-031. 364 pp.

Donohue, K. A., D. Randolph Watts, K. L. Tracey, A. D. Greene, and M. Kennelly. "Mapping circulation in the Kuroshio Extension with an array of current and pressure recording inverted echo sounders." *Journal of Atmospheric and Oceanic Technology* 27, no. 3 (2010):507–527.

Donohue, K. A., D. R. Watts, P. Hamilton, R. Leben, M. Kennelly, and A. Lugo-Fernandez. "Gulf of Mexico loop current path variability." *Dynamics of Atmospheres and Oceans* 76 (2016):174–194.

Donohue, K. A., D. R. Watts, P. Hamilton, R. Leben, and M. Kennelly. "Loop Current Eddy formation and baroclinic instability." *Dynamics of Atmospheres and Oceans* 76 (2016):195–216.

Edwards, C. A., A. M. Moore, I. Hoteit, and B. D. Cornuelle. "Regional ocean data assimilation." *Annual Review of Marine Science* 7 (2015):21–42.

Eriksen, C. C., T. J. Osse, R. D. Light, T. Wen, T. W. Lehman, P. L. Sabin, J. W. Ballard, and A. M. Chiodi. "Seaglider: A long-range autonomous underwater vehicle for oceanographic research." *IEEE Journal of Oceanic Engineering* 26, no. 4 (2001):424–436.

Evensen, G. "The ensemble Kalman filter: Theoretical formulation and practical implementation." *Ocean Dynamics* 53, no. 4 (2003):343–367.

Feppon, F., and P. F. J. Lermusiaux, 2017. *Dynamically orthogonal numerical schemes for efficient stochastic advection and Lagrangian transport.* SIAM Review.

Firing, Y. L., T. K. Chereskin, D. R. Watts, K. L. Tracey, and C. Provost. "Computation of geostrophic streamfunction, its derivatives, and error estimates from an array of CPIES in Drake Passage." *Journal of Atmospheric Oceanic Technology* 31, (2014):656–680.

Forristall, G. Z., K. J. Schaudt, and C. K. Cooper. "Evolution and kinematics of a Loop Current eddy in the Gulf of Mexico during 1985." *Journal of Geophysical Research: Oceans* 97, no. C2 (1992):2173–2184.

Glenn, S. M., G. Z. Forristall, P. Cornillon, and G. Milkowski. "Observations of Gulf Stream ring 83-E and their interpretation using feature models." *Journal of Geophysical Research: Oceans* 95, no. C8 (1990):13043–13063.

Glenn, S. M., and C. C. Ebbesmeyer. "Drifting buoy observations of a loop current anticyclonic eddy." *Journal of Geophysical Research: Oceans* 98, no. C11 (1993):20105–20119.

Gopalakrishnan, G., B. D. Cornuelle, I. Hoteit, D. L. Rudnick, and W. Brechner Owens. "State estimates and forecasts of the loop current in the Gulf of Mexico using the MITgcm and its adjoint." *Journal of Geophysical Research: Oceans* 118, no. 7 (2013):3292–3314.

Guinehut, S., P. Y. Le Traon, G. Larnicol, and S. Philipps. "Combining Argo and remote-sensing data to estimate the ocean three-dimensional temperature fields—a first approach based on simulated observations." *Journal of Marine Systems* (2004):85–98.

Haley, P. J., and P. F.J. Lermusiaux. "Multiscale two-way embedding schemes for free-surface primitive equations in the 'Multidisciplinary Simulation, Estimation and Assimilation System.'" *Ocean Dynamics* 60, no. 6 (2010):1497–1537.

Copyright National Academy of Sciences. All rights reserved.

Haley, P. J., A. Agarwal, and P. F.J. Lermusiaux. “Optimizing velocities and transports for complex coastal regions and archipelagos.” *Ocean Modelling* 89 (2015):1–28.

Hall, C. A., and R. R. Leben. “Observational evidence of seasonality in the timing of loop current eddy separation.” *Dynamics of Atmospheres and Oceans* 76 (2016):240–267.

Halliwell, G. R., V. Kourafalou, M. Le Hénaff, L. K. Shay, and R. Atlas. “OSSE impact analysis of airborne ocean surveys for improving upper-ocean dynamic and thermodynamical forecasts in the Gulf of Mexico.” *Progress in Oceanography* 130 (2015):32–46.

Hamilton, P. “Deep currents in the Gulf of Mexico.” *Journal of Physical Oceanography* 20, no. 7 (1990):1087–1104.

Hamilton, P., T. J. Berger, and W. Johnson. “On the structure and motions of cyclones in the northern Gulf of Mexico.” *Journal of Geophysical Research: Oceans* 107, no. C12 (2002).

Hamilton, P., J. J. Singer, E. Waddell, and K. Donohue. 2003. Deepwater Observations in the Northern Gulf of Mexico from In-Situ Current Meters and PIES. Final report, Volume II: technical report. OCS Study MMS 2003-049, U.S. Dept. of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study MMS 2003-049. 95 pp.

Hamilton, P., J. C. Larsen, K. D. Leaman, T. N. Lee, and E. Waddell. “Transports through the Straits of Florida.” Journal of Physical Oceanography 35 (2005):308–322.

Hamilton, P. “Topographic Rossby Waves in the Gulf of Mexico.” *Progress in Oceanography* 82 (2009):1–31.

Hamilton, P., K. A. Donohue, R. R. Leben, A. Lugo-Fernández, and R. E. Green. “Loop Current observations during spring and summer of 2010: Description and historical perspective.” *Monitoring and Modeling the Deepwater Horizon Oil Spill: A Record-Breaking Enterprise, Geophys. Monogr. Ser* 195 (2011):117–130.

Hamilton, P., K. Donohue, C. Hall, R. R. Leben, H. Quian, J. Sheinbaum, and D. R. Watts. 2014. Observations and dynamics of the Loop Current. Hamilton, P., K. Donohue, C. Hall, R. R. Leben, H. Quian, J. Sheinbaum, and D. R. Watts. 2014. Observations and dynamics of the Loop Current. OCS Study BOEM 2015-006, U. S. Dept. of the Interior, Bureau of Ocean Energy Management, Gulf of Mexico OCS Region, New Orleans, LA, 417 pp.

Huang, H., N. D. Walker, Y. Hsueh, Y. Chao, and R. R. Leben. “An analysis of Loop Current frontal eddies in a ⅙ Atlantic ocean model simulation.” *Journal of Physical Oceanography* 43, no. 9 (2013):1924–1939.

Hoteit, I., T.Hoar, G. Gopalakrishnan, N. Collins, J. Anderson, B. Cornuelle, A. Köhl, and P. Heimbach. “A MITgcm/DART ensemble analysis and prediction system with application to the Gulf of Mexico.” *Dynamics of Atmospheres and Oceans* 63 (2013):1 –23.

Hsieh, W. W. *Machine learning methods in the environmental sciences: Neural networks and kernels.* Cambridge, UK: Cambridge University Press, 2001.

Hurlburt, H. E., and J. Dana Thompson. “A numerical study of Loop Current intrusions and eddy shedding.” *Journal of Physical Oceanography* 10, no. 10 (1980):1611–1651.

Jacobs, G. A., B. P. Bartels, D. J. Bogucki, F. J. Beron-Vera, S. S. Chen, E. F. Coelho, M. Curcic, A. Griffa, M. Gough, B. K. Haus, and A. C. Haza. “Data assimilation considerations for improved ocean predictability during the Gulf of Mexico Grand Lagrangian Deployment (GLAD).” *Ocean Modelling* 83 (2014):98–117.

Judt, F., S. S. Chen, and M. Curcic. “Atmospheric forcing of the upper ocean transport in the Gulf of Mexico: From seasonal to diurnal scales.” *Journal of Geophysical Research-Oceans* 121 (2016):4416–4433.

Kaiser, M. J., and Y. Yu. “The impact of Hurricanes Gustav and Ike on offshore oil and gas production in the Gulf of Mexico.” *Applied Energy* 87, no. 1 (2010):284–297.

Copyright National Academy of Sciences. All rights reserved.

Kuehl, J. J., and V. A. Sheremet. "Identification of a cusp catastrophe in a gap-leaping western boundary current." *Journal of Marine Research* 67, no. 1 (2009):25–42.

Kuehl, J. J., and V. A. Sheremet. "Two-layer gap-leaping oceanic boundary currents: Experimental investigation." *Journal of Fluid Mechanics* 740 (2014):97–113.

Le Hénaff, M., V. H. Kourafalou, R. Dussurget, and R. Lumpkin. "Cyclonic activity in the eastern Gulf of Mexico: Characterization from along-track altimetry and in situ drifter trajectories." *Progress in Oceanography* 120 (2014):120–138.

Leben, R. R., G. H. Born, and B. R. Engebreth. "Operational altimeter data processing for mesoscale monitoring." *Marine Geodesy* 25, no. 1-2 (2002):3–18.

Leben, R. R. "Altimeter-derived loop current metrics." *Circulation in the Gulf of Mexico: Observations and Models* (2005):181–201.

Leonard, N. E., D. A. Paley, F. Lekien, R. Sepulchre, D. M. Fratantoni, and R. E. Davis. "Collective motion, sensor networks, and ocean sampling." *Proceedings of the IEEE* 95, no. 1 (2007):48–74.

Lermusiaux, Pierre F. J. "Uncertainty Estimation and Prediction for Interdisciplinary Ocean Dynamics." *Journal of Computational Physics* 217, no. 1 (2006):176–199.

Lermusiaux, P. F. J., C. S. Chiu, G. G. Gawarkiewicz, P. Abbot, A. R. Robinson, R. N. Miller, P. J. Haley, W. G. Leslie, S. J. Majumdar, A. Pang, and F. Lekien. "Quantifying uncertainities in ocean predictions." *Oceanography* 19 no. 1 (2006):92–105.

Lermusiaux, P. F. J., P. Malanotte-Rizzoli, D. Stammer, J. Carton, J. Cummings, and A. M. Moore. "Progress and prospects of U.S. data assimilation in ocean research." *Oceanography* 19, no. 1 (2006):172–183.

Lermusiaux, P. F. J. "Adaptive modeling, adaptive data assimilation and adaptive sampling." *Physica D: Nonlinear Phenomena* 230, no. 1 (2007):172–196.

Lermusiaux, P. F. J., T. Lolla, P. J. Haley, Jr., K. Yigit, M. P. Ueckermann, T. Sondergaard, and W. G. Leslie. "Science of autonomy: Time-optimal path planning and adaptive sampling for swarms of ocean vehicles." In *Springer Handbook of Ocean Engineering*, 481–498. Springer International Publishing, 2016.

Lermusiaux, P. F. J., P. J. Haley, Jr., S. Jana, A. Gupta, C. S. Kulkarni, C. Mirabito, W. H. Ali, D. N. Subramani, A. Dutt, J. Lin, A. Y. Shcherbina, C. M. Lee, and A. Gangopadhyay. "Optimal Planning and Sampling Predictions for Autonomous and Lagrangian Platforms and Sensors in the Northern Arabian Sea." *Oceanography* 30, no. 2 (2017).

Lewis, J. K., A. D. Kirwan, and G. Z. Forristall. "Evolution of a warm-core ring in the Gulf of Mexico: Lagrangian observations." *Journal of Geophysical Research: Oceans* 94, no. C6 (1989):8163–8178.

Li, Y., R. He, K. Chen, and D. McGillicuddy. "Variational data assimilative modeling of the Gulf of Maine in spring and summer 2010." *Journal of Geophysical Research: Oceans* (2015): 3522–3541. doi: 10.1002/2014JC010492.

Liu, Y., R. H. Weisberg, J. M. Lenes, L. Zheng, K. Hubbard, and J. J. Walsh. "Offshore forcing on the 'pressure point' of the West Florida Shelf: Anomalous upwelling and its influence on harmful algal blooms." *Journal of Geophysical Research: Oceans* 121, no. 8 (2016):5501–5515.

Liu, Y., A. MacFadyen, Z.-G. Ji, and R. H. Weisberg. "Introduction to monitoring and modeling the Deepwater Horizon oil spill." *Monitoring and Modeling the Deepwater Horizon Oil Spill: A Record-Breaking Enterprise* (2011):1–7.

Lugo-Fernández, A. "Is the Loop Current a chaotic oscillator?" *Journal of Physical Oceanography* 37 (2007):1455–1469.

Lugo-Fernández, A., and P. Hamilton. "The Loop Current Dynamics Experiment (2009–2011) in the Gulf of Mexico." *Journal of Dynamics of Atmosphere and Oceans* 76, part 2 (2016):155.

Lugo-Fernández, A., and P. Hamilton, eds. "The Loop Current Dynamics Experiment." *Dynamics of Atmospheres and Oceans* 76, part 2 (December 2016):155 –344.

Copyright National Academy of Sciences. All rights reserved.

Maul, G. A. “The annual cycle of the Gulf Loop Current. Part I: Observations during a one-year time series.” *Journal of Marine Research* 35, no. 1 (1977):29–47.

Mayer, D. A., R. H. Weisberg, L. Zheng, and Y. Liu. “Winds on the West Florida Shelf: Regional comparisons between observations and model estimates.” *Journal of Geophyscial Research–Oceans* 122 (2017): 834–846. doi: 10.1002/2016JC012112.

Mooers, C. N. K., E. D. Zaron, and M. K. Howard, 2012: Final report for phase I: Gulf of Mexico 3-D Operational Ocean Forecast System Pilot Prediction Project (GOMEX-PPP). Final Rep. to Research Partnership to Secure Energy for America, 149 pp.

Moore, A. M., H. G. Arango, E. Di Lorenzo, A. J. Miller, and B. D. Cornuelle. “An adjoint sensitivity analysis of the Southern California Current circulation and ecosystem.” *Journal of Physical Oceanography* 39, no. 3 (2009):702 –720.

Munk, W. H. “On the wind-driven ocean circulation.” *Journal of Meteorology.* 7 (1950):79 –93.

Nof, D. “The momentum imbalance paradox revisited.” *Journal of Physical Oceanography* 35, no. 10 (2005):1928–1939.

Oey, L.-Y. “Simulation of mesoscale variability in the Gulf of Mexico: Sensitivity studies, comparison with observations, and trapped wave propagation.” *Journal of Physical Oceanography* 26, no. 2 (1996):145–175.

Oey, L. Y., and H. C. Lee. “Deep eddy energy and topographic Rossby waves in the Gulf of Mexico.” *Journal of Physical Oceanography* 32, no. 12 (2002):3499–3527.

Oey, L. Y., T. Ezer, G.Forristall, C. Cooper, S. DiMarco, and S. Fan. “An exercise in forecasting loop current and eddy frontal positions in the Gulf of Mexico.” *Geophysical Research Letters* 32, no. 12 (2005).

Oey, L. Y., T. Ezer, and H. C. Lee. “Loop Current, rings and related circulation in the Gulf of Mexico: A review of numerical models and future challenges.” *Circulation in the Gulf of Mexico: Observations and models* (2005):31–56.

Oey, L. Y. “Loop Current and deep eddies.” *Journal of Physical Oceanography* 38 (2008):1426 –1449.

Pichevin, T., and D. Nof. “The momentum imbalance paradox.” *Tellus A* 49, no. 2 (1997):298–319.

Prasad, T. G., and P. J. Hogan. “Upper-ocean response to Hurricane Ivan in a 1/25 nested Gulf of Mexico HYCOM.” *Journal of Geophysical Research:* Oceans 112, no. C4 (2007): 2156-2202.

Reid, R. O. “A simple dynamic model of the Loop Current.” *Contributions on the Physical Oceanography of the Gulf of Mexico* 2 (1972):157–159.

Ringler, T., M. Petersen, R. L. Higdon, D. Jacobsen, P. W. Jones, and M. Maltrud. “A multi-resolution approach to global ocean modeling.” *Ocean Modelling* 69 (2013):211 –232.

Robinson, A. R., and S. M. Glenn. “Adaptive sampling for ocean forecasting.” *Naval Research Reviews* 51 (1999):28 –38.

Rudnick, D. L., R. E. Davis, C. C. Eriksen, D. M. Frantantoni, and M. J. Perry. “Underwater gliders for ocean research.” *Marine Technological Society Journal* 38 (2004):48–59.

Rudnick, D. L., G. Gopalakrishnan, and B. D. Cornuelle. “Cyclonic eddies in the Gulf of Mexico: Observations by underwater gliders and simulations by numerical model.” *Journal of Physical Oceanography* 45 (2015):313–326.

Rudnick, D. L. “Ocean research enabled by underwater gliders.” Edited by C. A. Carlson and S. J. Giovannoni. *Annual Review of Marine Science* 8 (2016):519–541.

Sapsis, T. P., and P. F. Lermusiaux. “Dynamically orthogonal field equations for continuous stochastic dynamic systems.” *Physica D: Nonlinear Phenomena* 238 no. 23 (2009):2347 –2360.

Scharroo, R., W. H. F. Smith, and J. L. Lillibridge. “Satellite altimetry and the intensification of Hurricane Katrina” *Eos Transactions American Geophysical Union* 86 no. 40 (2005):366–366. doi: 10.1029/2005EO400004.

Schmitz, W. J. “Cyclones and westward propagation in the shedding of anticyclonic rings from the Loop Current.” *Circulation in the Gulf of Mexico: Observations and Models* (2005):241–261.

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Schofield, O., J. Kohut, D. Aragon, L. Creed, J. Graver, C. Haldeman, J. Kerfoot, H. Roarty, C. Jones, D. Webb, S. Glenn. "Slocum gliders: Robust and ready." *Journal of Field Robotics* 24, no. 6 (2007):473–485.

Schroeder, K., J. Chiggiato, A. C. Haza, A. Griffa, T. M. Özgökmen, P. Zanasca, A. Molcard, M. Borghini, P.M. Poulain, R. Gerin, E. Zambianchi, P. Falco, C. Trees. "Targeted Lagrangian sampling of submesoscale dispersion at a coastal frontal zone." *Geophysical Research Letters* 39, no. 11 (2012).

Sherman, J., R. E. Davis, W. B. Owens, and J. Valdes. "The autonomous underwater glider 'Spray.'" *IEEE Journal of Oceanic Engineering* 26, no. 4 (2001):437–446.

Sharma, N., J.S. Storie, K.M. Obenour, M.J. Leber, and A. Srinivasan. Loop Current Hyperactivity: Analysis of *In Situ* Measurements in the Gulf of Mexico (2016). Offshore Technology Conference. doi: 10.4043/27229-MS.

Shay, L. K., G. J. Goni, and P. G. Black. "Effects of a warm oceanic feature on Hurricane Opal." *Monthly Weather Review* 128, no. 5 (2000):1366–1383.

Shay, L. K., and E. Uhlhorn. "Loop current response to hurricanes Isidore and Lili." *Monthly Weater Review,* 137 (2007):3248 –3274.

Sheinbaum, J., J. Candela, A. Badan, and J. Ochoa. "Flow structure and transport in the Yucatan Channel." *Geophysical Research Letters* 29, no. 3 (2002): 10-1–10-4.

Sheinbaum, J., G. Athié, J. Candela, J. Ochoa, and A. Romero-Arteaga. "Structure and variability of the Yucatan and loop currents along the slope and shelf break of the Yucatan channel and Campeche bank." *Dynamics of Atmospheres and Oceans* 76 (2016):217–239.

Sheremet, V. A. "Hysteresis of a western boundary current leaping across a gap." *Journal of Physical Oceanography* 31, no. 5 (2001):1247–1259.

Sheremet, V. A., and J. Kuehl. "Gap-leaping western boundary current in a circular tank model." *Journal of Physical Oceanography* 37, no. 6 (2007):1488–1495.

Sturges, W., and R. Leben. "Frequency of ring separations from the Loop Current in the Gulf of Mexico: A revised estimate." *Journal of Physical Oceanography* 30, no. 7 (2000):1814–1819.

Sturges, W., and A. Lugo-Fernandez. "Circulation in the Gulf of Mexico: Observations and models." *Washington DC American Geophysical Union Geophysical Monograph Series* 161 (2005).

Sturges, W., N. G. Hoffmann, and R. R. Leben. "A trigger mechanism for Loop Current ring separations." *Journal of Physical Oceanography* 40, no. 5 (2010):900–913.

Talley, L. D., G. L. Pickard, W. J. Emery and J. H. Swift, 2011. Descriptive Physical Oceanography: An Introduction (Sixth Edition), Elsevier, Boston, 560 pp.

Thacker, W. C., and R. B. Long. "Fitting dynamics to data." *Journal of Geophysical Research: Oceans* 93, no. C2 (1988):1227–1240.

Thacker, W. C., A. Srinivasan, M. Iskandarani, O. M. Knio, and M. Le Henaff. "Propagating boundary uncertainties using polynomial expansions." *Ocean Modelling* 43 (2012):52–63.

Ueckermann, M. P., P. F. J. Lermusiaux, and T. P. Sapsis. "Numerical schemes for dynamically orthogonal equations of stochastic fluid and ocean flows." *Journal of Computational Physics* 233 (2013):272–294.

Storch, H. V., and F. W. Zwiers. Statistical analysis in climate research. Cambridge, UK: Cambridge University Press, 1999.

Walker, et al., (2011) – AGU Monograph Series 195, 10.1029/2011GM001120. 103-116, 2011.

Weatherly, G. L., N. Wienders, and A. Romanou. *Intermediate-Depth Circulation in the Gulf of Mexico Estimated from Direct Measurements, in Circulation in the Gulf of Mexico: Observations and Models*. Edited by W. Sturges and A. Lugo-Fernãndez. Washington, DC: American Geophysical Union, 2005. doi: 10.1029/161GM22.

Wei, M., G. Jacobs, C. Rowley, C. N. Barron, P. Hogan, P. Spence, O. M. Smedstad, P. Martin, P. Muscarella, and E. Coelho. "The performance of the US Navy's RELO ensemble, NCOM, HYCOM

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during the period of GLAD at-sea experiment in the Gulf of Mexico." *Deep Sea Research Part II: Topical Studies in Oceanography* 129 (2016):374–393.

Weisberg, R. H., and L. Yonggang. "On the Loop Current Penetration into the Gulf of Mexico." *Journal of Geophysical Research: Oceans* (2017): doi: 10.1002/2017JC013330.

Welsh, S. E., and M. Inoue. "Loop Current rings and the deep circulation in the Gulf of Mexico." *Journal of Geophysical Research: Oceans* 105, no. C7 (2000):16951–16959.

Wunsch, C. *Modern observational physical oceanography: Understanding the global ocean.* Princeton, NJ: Princeton University Press, 2015.

Xu, F. H., L. Y. Oey, Miyazawa, Y. Masa and P. Hamilton. "Hindcasts and forecasts of Loop Current and eddies in the Gulf of Mexico using local ensemble transform Kalman filter and optimum-interpolation assimilation schemes." *Ocean Modelling* 69 (2013):22–38.

Yin, X. Q., and L. Y. Oey. "Bred-ensemble ocean forecast of Loop Current and rings." *Ocean Modelling* 17, no. 4 (2007):300–326.

Zambon, J. B., R. He, and J. C. Warner. "Investigation of Hurricane Ivan using the Coupled Ocean-Atmosphere-Wave-Sediment Transport Model" *Ocean Dynamics* 64 no. 11 (2014):1535–1554. doi: 10.1007/s10236-014-0777-7.

Zamudio, L., and P. J. Hogan. "Nesting the Gulf of Mexico in Atlantic HYCOM: oceanographic processes generated by Hurricane Ivan." *Ocean Modelling* 21, no. 3 (2008):106–125.

Zeng, X., Y. Li, and R. He. "Predictability of the Loop Current variation and eddy shedding process in the Gulf of Mexico using an artificial neural network approach." *Journal of Atmospheric and Oceanic Technology* 32, no. 5 (2015):1098–1111.

Zeng, X., Y. Li, R. He, and Y. Yin. "Clustering of Loop Current patterns based on the satellite-observed sea surface height and self-organizing map." *Remote Sensing Letters* 6, no. 1 (2015):11–19.

Zeng, X., and R. He. "Diagnosing large Gulf Stream meanders in the South Atlantic Bight using adjoint sensitivity analysis." In American Geophysical Union, Ocean Sciences Meeting 2016, abstract# PO43B-01. 2016.

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APPENDIX A

DESCRIPTION OF THE LOOP CURRENT

Dietrich (1937) provided perhaps the first comprehensive depiction of the surface circulation in the Gulf of Mexico, which shows the major circulation features now known as the LC in the eastern Gulf and a detached mesoscale anticyclonic eddy in the western Gulf. Austin (1955) provided the first use of the term “loop” to refer to the behavior of the current as it passes from the Yucatan Channel to the Florida Straits. DiMarco et al. (2005) provide a 10-year climatology of the mean surface circulation based on nearly 1,400 near-surface drifter records. The LC arrives in the Gulf through the Yucatan Channel, mostly above 800 meters (Sheinbaum et al., 2002), at a rate of approximately 23–27 Sv (1 Sv = 10^6 m^3/s) and brings warm (25–26°C) and salty (36.7–36.8 ppt) waters into the Gulf (Badan et al., 2005; Hamilton et al., 2005). Once in the Gulf, the LC and associated surface flows remain an upper ocean feature (i.e., approximately 800–1,200 meters and above) in the eastern Gulf (Hamilton, 2009; Oey, 2008). The degree of LC intrusion into the Gulf varies from between about 24°N to 28°N on time scales of 0.5–18.5 months without a clear annual signal (Alvera-Azcarate et al., 2009; Hamilton et al., 2011; Sturges et al., 2005; Zeng et al., 2015). The lowest degree of intrusion (i.e., 24°N) is often called a “port-to-port” position where the LC extends into the Gulf only minimally; the “average” position marks a northward position of approximately 26°N, roughly equivalent to the middle of the Gulf; and the “fully extended” position (approximately 28°N) of the LC abuts the Louisiana-Texas Shelf (e.g., Gopalakrishnan et al., 2013b). In each of the LC extension phases, the western side of the LC closely follows the eastern side of the Campeche Bank (the continental shelf extending north of the Yucatan Peninsula).

In general, the greater the LC extension, the greater the likelihood that the LC will form an anticyclonic warm-core eddy that separates from the main LC flow and propagates westward (e.g., Schmitz, 2005). When separation events do occur, they are not quick (i.e., taking several months) and often, an eddy will re-attach to the main LC before separating for good (Sturges and Leben, 2000); after a separation, the main LC intrusion retreats significantly. These eddies are very large (approximately 300 kilometers in diameter), spin at about 3–4 knots, and move at speeds of a few centimeters per day (approximately 0.1 knot) (Sturges et al., 2005). The interval at which an LCE separates varies considerably (approximately 0.5–19 months), but it averages about every 8 to 9 months (Leben, 2005). There is some evidence of a higher probability of separation during the spring and fall (Hall and Leben, 2016), but there is clearly much variability in the timing of separations. In terms of mechanisms, Sturges et al. (2010) suggested that these separation events may be influenced by 20- to 30-day signals propagating upstream into the Gulf from the Carribbean Sea. This is based on observations of increased eastward transport through the Florida Straits, as well as increases in sea level on the offshore side of the LC flow in the weeks prior to a separation, and builds on earlier work by Maul (1977). There is also evidence that cyclonic eddies along the LC front influence both LC extension and eddy separation (Gopapakrishnan et al., 2013b; Schmitz, 2005). Bottom flows out of the Yucatan are also linked to eddy separation (Oey, 1996). Additionally, bottom topography is likely to have a role in LCS dynamics (e.g., Cherubin et al., 2005).

At any given time, the LC and potentially associated large anticyclonic eddies exist within a larger eddy field containing many smaller eddies (approximately 40–150 kilometers in diameter), including both anticyclones and cyclones (Hamilton et al., 2002). At the northern edge of the LC penetration, pairs of counter-rotating eddies may be a major mechanism for transporting material on

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and off the Louisiana and Texas continental shelves (Hamilton et al., 2002). In addition, cold core cyclonic eddies (approximately 80–200 kilometers in diameter) that move downstream along the outside edges of the LC have also been observed (Huang et al., 2013; Le Hénaff et al., 2014, Rudnick et al., 2015). These eddies may be present on the western, northern, or eastern (i.e., West Florida Shelf side) edge of the LC and may play a significant role in the transportation of particles (e.g., Hamilton et al., 2002). The especially intense cyclonic eddies form near the Dry Tortugas and are called simply Tortuga eddies (Huang et al., 2013). Understanding the origin of cyclonic eddies, as well as their physics, interaction with the LC, and effect on Gulf biology, marine mammals (Biggs et al., 2005), and chemistry, require further observations and analyses.

Much of the work performed over the last several decades has focused on surface flows in the Gulf largely because surface measurements are more accessible. There is a long and rich history of energy industry-sponsored studies of the LC and LCE system dating back to the 1980s (e.g., Lewis et al., 1989). Many of these studies focused on limited surface drifter, shipboard, and aircraft observations of the horizontal and vertical structure of the currents in the upper 1,000 meters of the water column associated with long extensions of the LC into the Gulf, and with the LCEs that detach and propagate westward, some of which propagate along the central Gulf of Mexico escarpment where oil and gas exploration and production occurs. The general deepwater LCE current structure increases steadily from the center out to a radius of maximum velocity, then decays rapidly toward the outer edge. Vertically, the maximum currents often occur in the upper 100 meters, and often decay steadily down to a depth approaching 1,000 meters, below which the slower and relatively low sheared deep flow is observed. A kinematic feature model for the most critical design features of an LCE, specifically the horizontal structure and the current shear in the upper 1,000 meters of the inner core, was developed (e.g., Forristall et al., 1992; Glenn et al., 1990) and has been used as a design tool for establishing LCE eddy climatologies based on satellite and drifter observations of the eddy track and average swirl velocity. But kinematic LCE models, while useful for historical studies along past LCE trajectories, are not forecast models. They do not forecast LC growth or LCE separation and subsequent propagation. They assume the eddies are isolated in deepwater, do not include LCE interactions with the LC or topography, and they use a best fit symmetric elliptical shape to represent the actual complex LCE horizontal structure. Even individual LCEs have been observed to exhibit a range of different asymmetries over their lifetime, including asymmetries consistent with LC interactions, Topographic Rossby Wave (TRW) dispersion, and planetary Rossby wave dispersion (Glenn and Ebbesmeyer, 1993).

Weatherly et al. (2005) utilized data from 17 Argo (PALACE variety) Floats set in the Gulf that sampled the intermediate-depth (approximately 900 meter) flow from April 1998 to February 2002. Their analysis revealed a mean cyclonic circulation along the northern, western, and southwestern edges of the Gulf. This flow intensified into an approximately 0.10 m/s current in the western and southern Bay of Campeche and was deflected around a bathymetric feature, called here the "Campeche Bay Bump," in the southern Bay of Campeche. Associated with this intensified flow was a small cyclonic gyre in the southwestern Bay of Campeche. Floats launched in the eastern Gulf of Mexico tended to stay there and those launched in the western Gulf tended to stay in the western Gulf, suggesting a restricted connection at depths between the eastern and western Gulf. While this conclusion derived from a field study is not the final answer in unraveling the behavior of deep currents, it does demonstrate the complexity of deep Gulf circulation, and how it is heretofore not well observed or understood.

Our knowledge of the deep (greater than 1,000 meter) Gulf flows is driven primarily by data from Lagrangian floats and current meters/moorings, as well as numerical models (DeHaan and Sturges, 2005; Schmitz et al., 2005). The mean deep flow is thought to be opposite in direction from the main surface LC flows (i.e., cyclonic) in both the eastern and western Gulf and to move more slowly (e.g., approximately 1–2 cm/s at 2,000 meters) (DeHaan and Sturges, 2005). While slower than near-surface LCS currents, deep eddy currents are much stronger than the mean, with speeds that frequently grow to

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20–30 cm/s (approximately 1/2 kt). They extend nearly independent of depth through the full water column (Hamilton, 2009). These have been observed on numerous moorings in water depths from 2,000 to 3,500 meters south of Alabama to Texas. These deep currents are thought to be associated, at least in part, with TRWs that have periods of 10 to 100 days and wavelengths of 50 to 200 kilometers (Hamilton, 2009). The TRWs appear to be generated by stretching and squashing of the lower water column (potential vorticity adjustments) when the sloped thermocline of the LC shifts across the sloped sea floor. Deep cyclonic circulation is in part driven in the mean when TRWs approach the more steeply sloped upper continental slope and reflect (Hamilton, 2009). Some modeling work suggests that the deep cyclonic circulation observed may also be related to the formation of a deep cyclone-anticyclone eddy pair under the LC, of which the anticyclone dissipates much more quickly (Welsh and Inuoe, 2000). There is also evidence for the role of the Campeche Bank coupled with the baroclinic instability of the LC in the formation of these eddies (Oey et al., 2008; Weatherly et al., 2005). The deep cyclones in a numerical model by Oey (2008) have swirl speeds of approximately 0.3 cm/s and are approximately 100–200 kilometers across with vertical scales of 1,000–2,000 meters.

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APPENDIX B

FUNDAMENTAL UNDERSTANDING OF THE LOOP CURRENT SYSTEM

The Gulf LC is known to affect all of the oceanographic and meteorological phenomena of the Gulf and the adjacent continental land masses, including the moisture flux into the United States heartland. Thus, understanding the LC's behavior as it enters through the Yucatan Channel and exits through the Florida Straits is important for maritime commerce, fisheries, oil and gas operations, farming, and weather prediction. Observations, particularly the nearly continuous ones, over the recent era of satellite altimetry measurements show a complex set of behaviors, including periods of time when the LC is confined to the region of inflow and outflow, versus other times when the LC extends far into the Gulf of Mexico. Accompanying the large intrusion is the shedding of an anticyclonic eddy, upon which the LC tends to (but not always) retract back to its more direct inflow-outflow pathway. Numerous studies describe these behaviors along with some satellite altimetry era examples, which include Alvera-Azcarate et al. (2009), Leben (2005), Liu et al. (2016), Sturges and Leben (2000), and Zeng et al. (2015).

The most vexing theoretical issues regarding the behavior of the LC remain twofold. First, what controls the penetration of the LCS into the Gulf of Mexico, and second, what determines the shedding of an anticyclonic eddy and the retraction of the LC back into its more southern inflow-outflow position.

The theories begin with the work of Reid (1972), who argued that the LC loses its topographic control when heading north upon leaving the vicinity of the Campeche Bank, where the water depth increases abruptly from about 1,000 meters deep to the abyss at about 3,500 meters deep. As a result of this rapid depth transition, the LC flow field is largely limited to the upper 1,000 meters of the water column. Thus, a reduced gravity model was argued as being appropriate for considering subsequent LC evolution. By virtue of the planetary beta effect (due to the gradient in the Coriolis parameter $\beta = \partial f / \partial y$), further northward translation of the LC results in an increase of negative relative vorticity. Negative relative vorticity (or clockwise spin) tends to turn the LC to the right, causing it to eventually loop around and head back toward the south before exiting through the Florida Straits as the Gulf Stream, hence the name Loop Current. Hurlburt and Thompson (1980) built on this work with a series of idealized numerical model simulations using barotropic, reduced gravity, and two layered models, with and without planetary beta. The basic argument of Reid (1972) was demonstrated, the shedding of eddies were further shown to be a result of planetary beta, and both bathymetry and dissipation were argued to also be important. A corollary to this work is that eddy shedding and subsequent westward movement are intrinsic properties of the LCS. Triggering by time dependent inflows is not necessary for eddy generation, but as with any instability, further forcing may hasten the process.

A requirement for eddy shedding was identified by Pichevin and Nof (1997), who argued on analytical grounds that the northward inflow and eastward outflow resulted in a momentum imbalance paradox. By considering the area as an integrated, steady, inviscid, zonal momentum equation, they found that such a flow configuration was not possible to balance the zonal momentum outflow through the Florida Straits without eddies being shed to the west. Eddy size, speed, and shedding period estimates resulting from this theory appeared to be in reasonable agreement with the observed LC statistics. This theory was extended by Nof (2005), who used a multiple time scale approach to show that the integrated Coriolis force on a growing eddy is also able to provide momentum closure.

Being that eddy shedding occurs aperiodically (e.g., Sturges and Leben, 2000), Lugo-Fernandez (2007) chose a nonlinear time series approach to determine if the LC behaved as a chaotic oscillator.

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Despite the limited available data, such analysis suggested that the LC is not chaotic, but instead acts as a nonlinear oscillator responding to variations in forcing conditions.

The next emergent line of thought was by Sheremet (2001), who considered the conditions under which a western boundary current in Munk (1950) balance (i.e., horizontal friction dissipating planetary vorticity advection) would either penetrate a gap (i.e., intrude into the Gulf of Mexico), versus leap across that gap (proceed directly from the inflow to the outflow). For narrow gaps (less than twice the Munk boundary layer scale defined by a horizontal friction parameter and the planetary beta), it was found that the current leaps over the gap, except for a small portion that leaks through, bends around and then exits the gap. For larger gap widths, the boundary current enters the gap and flows west as a zonal jet eventually returns as an oppositely directed zonal jet exits the gaps and flows north. Nonlinear effects modified the linear solution, as did an increasing Reynolds number (increasing turbulence) that further facilitated eddy shedding. Given that the distance is several hundred kilometers between the 1,000 meter isobaths on the Campeche Bank and the West Florida Shelf, the gap across which the LC must leap is large (according to the original values used by Munk in his seminal paper on western boundary currents), and consequently, an LC penetration into the Gulf of Mexico was a reasonable expectation according to this Sheremet gap leaping theory.

These ideas were then expanded on by Sheremet and Kuehl (2007, 2009) through a series of elegant rotating tank experiments viewed in light of the theory. Fluid inertia was found to promote a leaping state, planetary beta a penetrating state, and the flow state was also found to depend on prior evolution, i.e., a hysteresis. The strength of the current was also found to be important, suggesting that variations in volume transport might play a role in LC intrusion. This may be important given that analyses of altimetry observations in the Caribbean (Alvera-Azcarate et al., 2009) suggested an interannual variation in volume transport that was correlated with the zonal component of wind stress and a wind stress curl dipole on the northern and southern side of the Caribbean that tilted the thermocline, changing the circulation, and that these interannual findings were further related to the *El Niño* Southern Oscillation (ENSO) index. Zeng et al. (2015) subsequently argued for a similar teleconnection.

Stratification was added to both the analytical and laboratory treatments by Kuehl and Sheremet (2014), allowing for a more complete set of boundary layer scaling (inertia, bottom friction, horizontal friction) findings. They conclude that the system admits three distinct states: a steady gap-leaping state (retracted LC state), a steady gap-penetrating, extended LC state, and an eddy-shedding LC state. The transition between the latter two appears to be due to the relative strengths of vorticity advection into the gap and vorticity dissipation due to friction (predominantly Ekman friction). If friction is strong enough to balance vorticity advection, the system will assume a steady LC state. Once vorticity advection overcomes friction, the excess vorticity is dissipated by eddy shedding.

With LCE shedding shown by these previous works to be a consequence of planetary beta (due to relative vorticity becoming increasingly anticyclonic as the LC moves northward) and with the mechanism of energy conversion being either barotropic or baroclinic instability depending on the model set up (e.g., Hurlburt and Thompson, 1980), it remained to actually demonstrate the mechanism of instability observationally. This was accomplished recently by Donohue et al. (2016) who argued for baroclinic instability being the primary mechanism. Known to be shed aperiodically and taking on different sizes, there remains a need to determine under what conditions LCEs may, or may not, be shed. For instance, a Hovmuller plot for sea surface height anomalies across the central Caribbean, the Nicaraguan Basin, and the Gulf of Mexico shows differing frequencies of occurrences from region to region (Alvera-Azcarate et al., 2009), suggesting that triggering is not a simple matter (recall the Hurlburt and Thompson finding of a trigger not being a necessary condition for eddy shedding).

Whereas the LC may depend primarily on planetary beta once freed from topography, the Gulf is enclosed by steep escarpments that are also known to be important (Hurlburt and Thompson, 1980).

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These escarpments result in a topographic beta effect ($\beta_H = \frac{f}{H}\nabla H$, f being the Coriolis parameter and H the water depth) that may exceed the planetary beta effect [equal to about 2 x 10^{-11} m/s] by an order of magnitude along the escarpments). Thus, regions of steep bathymetric topography will result in the flow field tending to be oriented parallel to the isobaths and in the propagation of TRWs away from regions where the flow may be temporarily perturbed to go across the isobaths. Such energy loss through TRW propagation may carry energy away from the LC, thereby reducing the ability of the LC to penetrate further into the Gulf and also reducing the energy available for eddy shedding, thus providing a stabilizing influence on the LCS.

In the search for simplicity in advancing LCS theory, an important knowledge gap may be the role of bathymetric topography. DeHaan and Sturges (2005) argued for a deep Gulf cyclonic circulation on the basis of the escarpments, and direct observations by Hamilton (1990, 2009) confirmed this. Oey and Lee (2002) and Hamilton (2009) considered TRWs to be implied in numerical model simulations and *in situ* observations, but only in the deeper portions of the Gulf of Mexico due to their model resolution. TRWs may also occur along the escarpments, and, with TRWs propagating with shallow isobaths to the right (in the northern hemisphere), an important point of origination is the West Florida Shelf, a region that remains relatively unobserved because of the absence of oil and gas exploration or operations there.

This absence of simplicity becomes clear when contrasting LCS behaviors between different years. For instance (and as described in Chapter 1), during 2014 through 2015, the Gulf witnessed an uncharacteristically active LCS behavior with the far northward penetration of the LC and subsequent eddy shedding repeating for some 18 months. In contrast, during 2017, the LC remained retracted and fairly stable for several months before settling into another state in which it extended partially northward with cyclonic and then anticyclonic features seeming to block it from further translation (see Figure B-1). These differing behaviors suggest that planetary beta effects, topographic beta effects, and the three-dimensional linkages between the LC and its sequential eddy structures must all be considered when improving on predictive capabilities.

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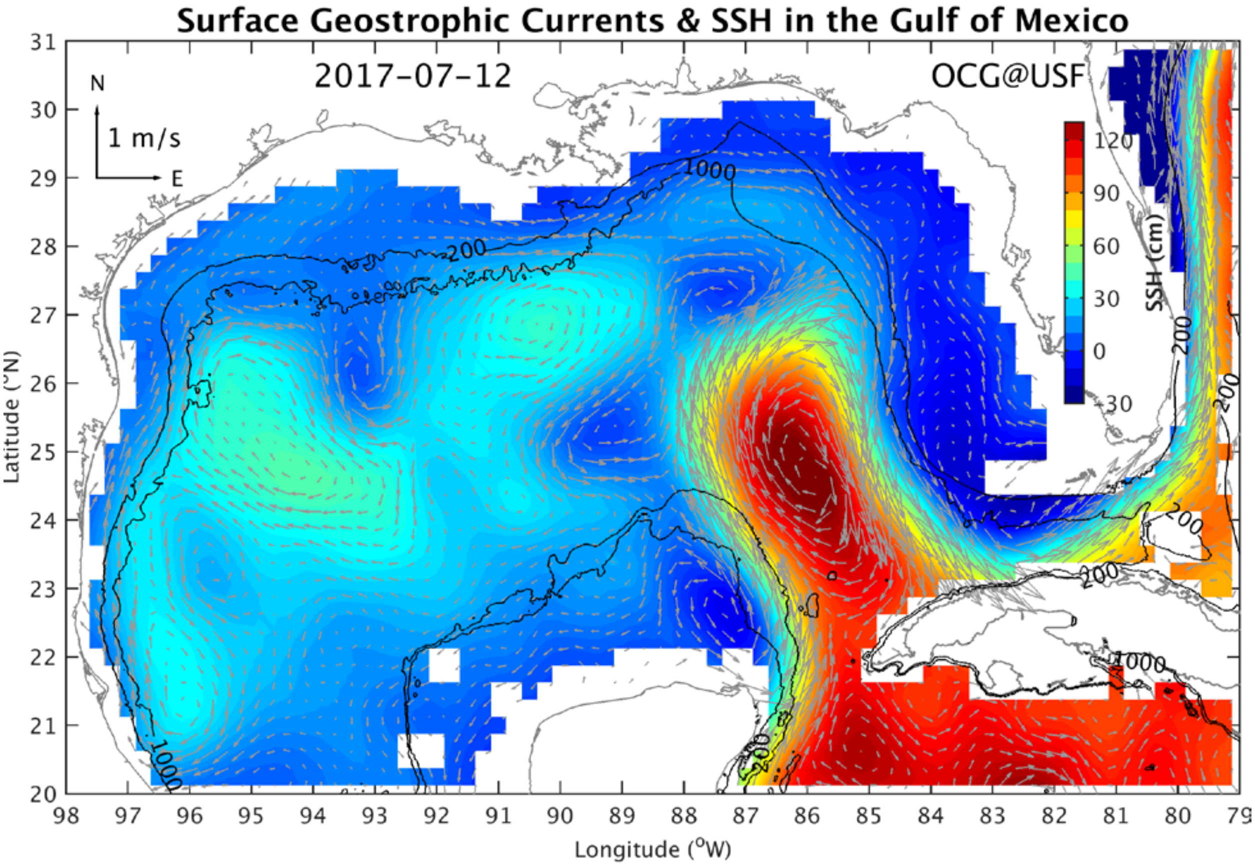

FIGURE B-1 Satellite altimetry (AVISO) derived SSH and associated estimated surface geostrophic currents for the eastern Gulf of Mexico showing a partially intruded Loop Current followed by a cyclonic and an anticyclonic feature.

SOURCE: Vonggang Liu and Robert Weisberg, College of Marine Science-University of South Florida. The observations derive from AVISO+ satellite sea level anomaly data produced by the Ssalto/Duacs with support from the Cnes, and distributed by the CM EMS, plus the mean dynamic topography MDT CNES-CLS13. Further analyses include subtracting the domain average and estimating surface geostrophic currents from the sea level gradient.

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APPENDIX C

COMMITTEE BIOGRAPHIES

Paul G. Gaffney, II (*Chair*) is a retired Navy vice admiral and president emeritus of Monmouth University, having served as president from 2003 to 2013. He was president of the National Defense University from 2000 to 2003. Prior to assuming those duties, Admiral Gaffney was the chief of naval research with responsibility for the Department of the Navy's science and technology investment. He commanded the Navy's Meteorology and Oceanography program headquartered in St. Louis, Missouri, and was the commanding officer of the Naval Research Laboratory. He was appointed to the U.S. Ocean Policy Commission in July 2001 and served during its full tenure from 2001 to 2004. His distinguished naval career spanned over three decades, including duty at sea, overseas, and ashore in six executive and command positions. Admiral Gaffney was assigned to duties in Indonesia, Japan, Spain, and Vietnam. He is a 1968 graduate of the U.S. Naval Academy and upon graduation he was selected for immediate graduate education and received a master's degree in ocean engineering from The Catholic University of America, where he is honored on its engineering "Wall of Fame." He attended the Naval War College, graduating with highest distinction. He completed an M.B.A. at Jacksonville University. The University of South Carolina, Jacksonville University, and Catholic University have awarded him honorary doctorates. He has been recognized with a number of military decorations and the Naval War College's J. William Middendorf Prize for Strategic Research. Admiral Gaffney is a member of the National Academy of Engineering. He chaired the federal Ocean Research/Resources Advisory Panel (ORRAP) and chaired the federal Ocean Exploration Advisory Board (OEAB). He is a member of the Steering Committee of the Joint Ocean Commission Initiative, a fellow in the Urban Coast Institute at Monmouth University, and a director of Diamond Offshore Drilling, Inc. He is currently chairing a National Academies of Sciences, Engineering, and Medicine's Transporation Research Board study on the domestic transportation of energy fluids.

Shuyi S. Chen is a professor of Atmospheric Sciences at the University of Washington. Her research interests include observations and modeling of the tropical atmosphere and the ocean with a focus on air–sea interaction from weather to subseasonal time scales, development of coupled atmosphere–wave–ocean–land models, and prediction of extreme weather events, including hurricanes and winter storms, the Madden-Julian Oscillation, and the upper ocean circulation and transport over the Gulf of Mexico. Dr. Chen has led and participated in many major field campaigns, including CBLAST, RAINEX, ITOP, DYNAMO, GLAD, LASER, SPLASH, and CPEX-2017. Dr. Chen received the National Aeronautics and Space Administration (NASA) Group Achievement Award for tropical cloud systems and processes and is a member of the NASA Ocean Vector Wind and Precipitation Measurement Missions science teams. She was an editor of AMS's *Weather and Forecasting*. Currently, she serves as the vice chair of the National Academies of Sciences, Engineering, and Medicine's Board on Atmospheric Sciences and Climate (BASC), the Decadal Survey for Earth Science and Applications from Space (ESAS 2017) Steering Committee, and the University Corporation for Atmospheric Research (UCAR) Board of Trustees. Dr. Chen is a fellow of American Meteorological Society. She received her Ph.D. in meteorology in 1990 from The Pennsylvania State University.

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Steven F. DiMarco is a professor in the Department of Oceanography and Ocean Observing Team leader in the Geochemical and Environmental Research Group at Texas A&M University (TAMU). Prior to this position, Dr. DiMarco served as an associate professor, an associate research scientist, and an assistant research scientist in the Department of Oceanography at TAMU. He is a charter member of the National Science Foundation—University National Oceanographic Laboratory System (UNOLS) Ocean Observing Science Committee and has previously served on the UNOLS Regional Class Research Vessel Science Oversight Committee. Dr. DiMarco is an observational oceanographer whose research has focused on interdisciplinary studies in which physical and biogeochemical processes overlap. He is deeply involved in regional, national, and international programs focused on implementing new technologies and methodologies associated with ocean observing systems and involve applied problems associated with societal concerns of human impact on the marine environment. The results of his research have been used to guide management policies and drive agency decisions in the United States and abroad. In 2013, Dr. DiMarco was honored with the Dean's Distinguished Achievement Award for Research and was recognized as a leader in the Gulf of Mexico physical oceanography community for his important contributions to understanding basic physical processes in the Gulf. He has authored or co-authored more than 50 peer-reviewed journal publications, 20 technical reports, and more than 130 conference abstracts. He obtained his master's degree in physics in 1988 and his Ph.D. in physics in 1991 from The University of Texas at Dallas.

Scott Glenn is a distinguished professor in the Department of Marine and Coastal Sciences at Rutgers University and co-director of the Center for Ocean Observing Leadeship. His research interests include the development of new autonomous ocean observing technologies, their application to scientific research in remote and extreme environments, and the demonstration of new educational paradigms. His technology development work focuses on autonomous systems that can be operated remotely as distributed networks to improve the spatial sampling of complex environments. A major scientific focus of his is extreme events, including storms, hurricanes, and typhoons, investigating with observations and numerical models the linkages among the ocean, the atmosphere above, and the seabed below. Dr. Glenn's educational activities are designed to better prepare students to meet the challenges of a changing environment using modern observatories to explore the global ocean. After graduating from the Massachusetts Institute of Technology and Woods Hole Oceanographic Institution Joint Program in 1983 with an Sc.D. in ocean engineering, he began a more than 30-year research career of implementing sustained real-time ocean observation and forecast systems for offshore oil exploration at the Shell Development Company (1983–1986), then for the Naval Oceanography Command supporting fleet operations while at Harvard University (1986–1990), and, since 1990, for a wide range of scientific and societal applications at Rutgers University. In the only U.S. national program to recognize excellence in undergraduate teaching, he was named one of the U.S. Professors of the Year representing the State of New Jersey by the Carnegie Foundation for the Advancement of Teaching and the Council for Advancement and Support of Education. He recently received the international Society for Underwater Technology's Oceanography Award for outstanding contributions to the field of oceanography.

Ruoying He is a distinguished professor in the Department of Marine, Earth, and Atmospheric Sciences at North Carolina State University. His research expertise includes coastal circulation dynamics, air–sea interaction, and biophysical interactions. As the director of the Ocean Observing and Modeling Group in the Department of Marine, Earth, and Atmospheric Sciences, he conducts coastal ocean observations, remote sensing data analyses, and leads the development of prediction models of ocean circulation, air–sea-wave interactions, physical–biogeochemical couplings, and data assimilation. Dr. He served as an associate editor for the *Journal of Geophysical Research-Oceans*, and as a guest editor for *Ocean*

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Dynamics. He also serves on the editorial boards of several other scientific journals and on the organizing committees of several major international science meetings. Dr. He has served as a reviewer for 20 journals, including the *Journal of Atmospheric and Oceanic Technology*, *Journal of Geophysical Research*, *Journal of Physical Oceanography*, *Nature*, *Ocean Modelling*, *Oceanography*, and *Science*. He was the vice chair of the Gordon Research Conference on Coastal Ocean Modeling in 2015 and co-chaired the Cordon Research Conference on Coastal Ocean Dynamics in 2017. He is presently a member of the UNOLS Ocean Observing Science Committee, a member of Integrated Ocean Observing System-National Modeling Steering Team, and a science team member of International GODAE OceanView project. His honors and awards include Distinguished Professor, North Carolina State University (2014); National Aeronautics and Space Administration (NASA) Young Investigator Award (2006); the Sears Collaboration Award (2006); the Coastal Ocean Research Award (2005); the Green Innovative Technology Award (2004) from the Woods Hole Oceanographic Institution; and the Sackett Innovative Research Award (2004) from the University of South Florida. He was inducted into the Phi Kappa Phi Honor Society in 2000. Dr. He holds a Ph.D. in physical oceanography from the University of South Florida (2002).

Joseph Kuehl is an assistant professor in the Department of Mechanical Engineering at the University of Delaware. He is also an Air Force Office of Scientific Research Young Investigator; a member of the NATO working group STO/AVT-240 Hypersonic Transition; and a board member and fellow of The Institute of Ecological, Earth and Environmental Science (TIEEES), a fellow of the Center for Spatial Research (CSR), and an adjunct faculty member at The University of Texas Marine Science Institute. Dr. Kuehl conducts cutting-edge research in three different fields of study: hypersonic boundary-layer stability and transition, geophysical fluid dynamics, and nonlinear vibrations. His current research in the area of geophysical fluid dynamics focuses on Loop Current systems, bottom boundary-layer processes, and the influence of topography on fate and transport modeling. Dr. Kuehl has been invited to give talks at several universities and conferences/meetings, including the Michigan Technological Institute (2016), the NATO STO-AVT-240 Meeting (2016), the University of Rhode Island (2016, 2012), The University of Texas Marine Science Institute (2015), Gulf of Mexico Oil Spill & Ecosystem Science Conference (2015), The University of Texas Dallas (2015), the University of Delaware (2013), The University of Texas at Austin (2012), and Texas A&M University (2009). Dr. Kuehl holds a Ph.D. in mechanical engineering and applied mechanics and a Ph.D. in physical oceanography, both of which were obtained in 2009 from the University of Rhode Island.

Robert Leben is a research professor in the Department of Aerospace Engineering Sciences at the University of Colorado Boulder and a member of the Colorado Center for Astrodynamics Research (CCAR). His primary area of expertise is satellite altimetry and its application to ocean circulation monitoring. He has published more than 50 peer-reviewed publications in this area. He is currently a principal investigator (PI) on the OSTM/Jason-2 satellite altimeter mission, and was a co-investigator on the TOPEX/POSEIDON, Jason-1, and Envisat missions. He has also made significant contributions to oceanographic research in the Gulf of Mexico. He has been a PI or co-PI on research programs in the Gulf, including the Minerals Management Service/Bureau of Ocean Energy Management (U.S. Department of the Interior) funded programs such as the Louisiana/Texas Shelf Physical Oceanography Program Eddy Circulation Study; GulfCet II-Cetaceans, Sea Turtles and Seabirds in the Northern Gulf of Mexico: Distribution, Abundance and Habitat Associations; Desoto Canyon Eddy Intrusion Study; Exploratory Study of Deepwater Currents in the Gulf of Mexico; Survey of Deepwater Currents in the Northwestern Gulf of Mexico; Survey of Deepwater Currents in the Eastern Gulf of Mexico; Gulf of Mexico Loop Current Study; A Lagrangian Approach to Study the Gulf of Mexico's Deep Circulation; and the National Science Foundation Collaborative Research Program: Why does the Loop Current have such

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an irregular eddy shedding cycle? He has also assisted in the development and skill assessment of ocean circulation nowcast/forecast systems for the offshore oil and gas industry working in the Gulf of Mexico and off the southeast Brazilian coast. He received his Ph.D. in aerospace engineering sciences from the University of Colorado.

Pierre F. Lermusiaux is a professor of mechanical engineering and ocean science and engineering at the Massachusetts Institute of Technology (MIT). His research thrusts include understanding and modeling complex physical and interdisciplinary oceanic dynamics and processes. With his group, he creates, develops, and utilizes new mathematical models and computational methods for ocean predictions and dynamic diagnostics, optimization and control of autonomous ocean systems, uncertainty quantification and prediction, and data assimilation and data-model comparisons. Dr. Lermusiaux received a Fulbright Foundation Fellowship in 1992, the Wallace Prize at Harvard in 1993, the Ogilvie Young Investigator Lecture in Ocean Engineering at MIT in 1998, and the MIT Doherty Chair in Ocean Utilization from 2009–2011. In 2010, the School of Engineering at MIT awarded him with the Ruth and Joel Spira Award for Distinguished Teaching. He is on the editorial board of the *International Journal of Ocean & Oceanography* (2005–present), and serves as associate editor for *Ocean Dynamics and Ocean Modeling* (2008–present). He has served on numerous committees and boards, including the Advisory Board, European Coastal-shelf Sea Operational System (ECOOP) from 2007–2010, the IMUM (International workshop on Multiscale (Un)-structured mesh numerical ocean Modeling) 2010 Scientific Committee (chair, 2009–2010), and the National Science Foundation (NSF) Physical Oceanography Review Panel, NSF PIONEER Array MIT-Rep. (2011). He served on the Advisory Board of the European Stochastic Assimilation (SANGOMA) and Maritime Integrated Surveillance Awareness (MARISA), and was a member of the National Academies of Sciences, Engineering, and Medicine's Committee on U.S. Research Agenda to Advance Subseasonal to Seasonal Forecasting. Dr. Lermusiaux has more than 100 refereed publications. He obtained a master's in applied physics in 1993 from Harvard University–DEAS and a Ph.D. in engineering sciences in 1997 from the same university.

Ruth L. Perry is a marine scientist and regulatory policy specialist responsible for offshore marine environmental regulations and policy for the Shell Exploration and Production Company. In this capacity, Dr. Perry integrates marine science and ocean technology into regulatory policy advocacy and decision making in the areas of oceanography, marine sound, marine resources, ocean observing, and marine mammal and life science, primarily in the Gulf of Mexico. She is also responsible for helping Shell develop public–private science collaborations, such as real-time ocean monitoring programs, to improve industry and community knowledge of the offshore marine environment. Her recent projects with Shell include working with the National Oceanic and Atmospheric Administration (NOAA) and the University of Southern Mississippi to deploy autonomous underwater vehicles to better understand the Gulf of Mexico's physical environment relative to improving storm and hurricane intensity predictions and Loop Current forecasting. Near the Shell Stones field, she and her colleagues are establishing a long-term metocean station to collect surface and water column data down to 3,000 meters. Prior to joining Shell, Dr. Perry was a research scientist with NOAA's Integrated Ocean Observing System (IOOS), specifically the Gulf of Mexico Coastal Ocean Observing System, and the Geochemical and Environmental Research Group at Texas A&M University. While there, she worked on many diverse projects, including the implementation of a regional glider network; ocean science education and outreach campaigns; incorporating geospatial techniques with remote sensing and ocean observing to study Gulf environmental hazards, such as hypoxia; and the effects of physical ocean processes on marine mammal distributions. Dr. Perry has more than 10 years of national and international experience in oceanographic project management, research, and fieldwork in the areas of ocean observing technology,

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physical oceanography, ocean policy analysis, and marine mammal observational studies. She earned her Ph.D. in oceanography from Texas A&M University in 2013.

Daniel L. Rudnick is currently a professor and director of the Climate Ocean Atmosphere Program and formerly the deputy director of Education at Scripps Institution of Oceanography. Dr. Rudnick is an observational oceanographer whose research focuses on processes in the upper ocean. His particular interests include fronts and eddies, air–sea interaction, the stirring and mixing of physical and biological tracers, the effect of oceanic structure on acoustic propagation, boundary currents, and coastal circulation. He is interested in observational instrumentation, having been involved in the use and/or development of moorings, towed and underway profilers, autonomous underwater gliders, and profiling floats. Dr. Rudnick has sailed on more than 25 oceanographic cruises, more than half as chief scientist. He has authored more than 80 peer-reviewed publications. He was a member of the Ocean Studies Board of the National Academies of Sciences, Engineering, and Medicine and has served on various panels and committees for the National Science Foundation, National Oceanographic and Atmospheric Administration, and the Office of Naval Research. Dr. Rudnick is Chair of the Executive Steering Committee of the Southern California Coastal Ocean Observing System (SCCOOS), a component of the Integrated Ocean Observing System (IOOS), and is a member of the OceanGliders international steering team and the U.S. Interagency Ocean Observation Committee Glider Task Team. He earned his Ph.D. in oceanography from the Scripps Institution of Oceanography in 1987.

Neha Sharma is currently the vice president of operations at Horizon Marine, Inc. She has been with the company since 2007, serving as physical oceanographer and EddyWatch analyst (2007–2010), physical oceanographer and team leader (2010), EddyWatch operations manager (2010–2012), EddyWatch program manager (2012–2015), and EddyWatch and SurveyWatch program manager (2015), with the primary responsibility of conducting research and compilation/analysis of oceanographic data for the purpose of providing real-time ocean current monitoring and forecasting for the offshore oil and gas industry in the Gulf of Mexico; offshore Australia, Brazil, East Africa, India, Trinidad, West Africa, and other regions impacted by strong ocean currents. Ms. Sharma holds a B.E. in electronics and telecommunications engineering from Maharashtra Institute of Technology WEC, Pune University (2005) and a master's degree in physical oceanography and remote sensing from Louisiana State University (2007). Among her interests are public speaking, computer programming, marketing, and business strategy.

Randolph Watts is a professor of oceanography at the Graduate School of Oceanography of the University of Rhode Island. He holds a Ph.D. in physics from Cornell University (1973) and a B.A. in physics from the University of California, Riverside. From 1972 to 1974, he was a postdoc in the Department of Geology and Geophysics of Yale University, working with Dr. Tom Rossby. In 1974, he joined the faculty of the Graduate School of Oceanography of the University of Rhode Island as an assistant professor. Dr. Watts was granted tenure in 1980 and promoted to full professor in 1988. Dr. Watts's research has focused on understanding mesoscale dynamics of major ocean currents using moored instrumentation. For many years, his field programs were concentrated on the Gulf Stream in the region downstream of Cape Hatteras in order to develop observational and analytical methodology to understand the dynamics and energetics of that current system. More recent field experiments have been conducted in the Kuroshio Extension east of Japan, Gulf of Mexico, Japan/East Sea, the Agulhas Current off South Africa, and the Antarctic Circumpolar Current. These programs included observations made by inverted echo sounders, pressure gauges, current meters, and hydrography. Dr. Watts has been actively involved with the development of the inverted echo sounder since it was first used to

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make scientific measurements in the mid-1970s. During the 1980s, he oversaw modifications to the inverted echo sounders to incorporate additional sensors for measuring pressure, temperature, and ambient noise. At present, Dr. Watts is overseeing the latest improvements to the Model 6.2C inverted echo sounder which permits current measurements and data telemetry. This instrumentation is now being used by more than 20 research groups at major oceanographic institutions in Asia, Europe, South America, and the United States.

Robert H. Weisberg is a distinguished university professor at the University of South Florida (USF). As an experimental physical oceanographer, he conducts ocean circulation and ocean–atmosphere interaction studies in the tropics, on continental shelves, and in estuaries. His current research emphasizes the West Florida Continental Shelf (WFS) and the interactions occurring between the shelf and the deep ocean and between the shelf and the estuaries. He maintains a coordinated program of real-time *in situ* observations, analyses, and numerical circulation models aimed at describing and understanding the processes that determine WFS water properties. Dr. Weisberg is on the Board of Directors for the Southeast Coastal Ocean Observing Regional Association (SECOORA) and is a fellow of the Southeastern Universities Research Association (SURA) engaged in the Coastal and Environmental Research Program (CERP). He served on the Committee on New Orleans Regional Hurricane Protection Projects of the National Research Council from 2005 to 2009, and he led the Naval Research Lab (Stennis, Mississippi) Battlespace Environments site review in 2009. He received the Phi Kappa Phi Honor Society and USF Chapter Scholar of the Year Award in 2011, the National Oceanographic Partnership Program Excellence in Partnering Award in 2008, the President's Award for Excellence in 2003, the Professorial Excellence Award in 1998 from USF, and the American Geophysical Union Editor's citation for excellence in refereeing for *Geophysical Research Letters* in 1995. Dr. Weisberg is a member of the Oceanography Society, the American Geophysical Union, the American Meteorological Society, and Sigma Xi. He obtained his master's degree and Ph.D. in physical oceanography in 1972 and 1975, respectively, from the University of Rhode Island.

Dana R. Yoerger is a senior scientist at the Woods Hole Oceanographic Institution and a researcher in robotics and unmanned vehicles. He supervises the research and academic program of graduate students studying oceanographic engineering through the Massachussets Intitute of Technology / Woods Hole Oceanographic Institute Joint Program in the areas of control, robotics, and design. Dr. Yoerger has been a key contributor to the remotely operated vehicle JASON; the Autonomous Benthic Explorer known as ABE; and most recently, the autonomous underwater vehicle, SENTRY and the hybrid remotely operated vehicle NEREUS, which reached the bottom of the Marianas Trench in 2009. Dr. Yoerger has gone to sea on more than 80 oceanographic expeditions exploring the Mid-Ocean Ridge, mapping underwater seamounts and volcanoes, surveying ancient and modern shipwrecks, studying the environmental effects of the *Deepwater Horizon* oil spill, and the recent effort that located the Voyage Data Recorder from the merchant vessel El Faro. His current research focuses on robots for exploring the midwater regions of the world's oceans. Dr. Yoerger has served on several National Academies of Sciences, Engineering, and Medicine committees, including the Committee on Undersea Vehicles and National Needs, the Committee on Evolution of the National Oceanographic Research Fleet, and the Committee on Distributed Remote Sensing for Naval Undersea Warfare. He has a Ph.D. in mechanical engineering from the Massachusetts Institute of Technology.

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APPENDIX D

ACRONYMS AND ABBREVIATIONS

ADCP	acoustic Doppler current profiler
ANN	artificial neural network
ASV	autonomous surface vehicle
AUV	autonomous underwater vehicle
AVISO	Archiving, Validation and Interpretation of Satellite Oceanographic data
AXBT	Airborne Expendable BathyThermograph
BOEM	Bureau of Ocean Energy Management
BSEE	Bureau of Safety and Environmental Enforcement
CARTHE	Consortium for Advanced Research on Transport of Hydrocarbon Environment
CICESE	Centro de Investigación Científica y de Educación Superior de Ensenada
C-IMAGE	Center for the Integrated Modeling and Analysis of the Gulf Ecosystem
CPIES	current pressure induced echo sounder
DAC	data assembly center
DEEP-C	Deep Sea to Coast Connectivity in the Eastern Gulf of Mexico
DOI	Department of Interior
EEZ	exclusive economic zone
EOF	empirical orthogonal function
FFRDC	Federally Funded R&D Centers
GFDL	Geophysical Fluid Dynamics Laboratory
GLAD	Grand LAgrangian Deployment
GOMEX-PPP	Gulf of Mexico Pilot Prediction Project
GoMRI	Gulf of Mexico Research Initiative
GRP	Gulf Research Program
HF	high frequency
HMI	Horizon Marine, Inc.
HYCOM	HYbrid Coordinate Ocean Model
IOOS	Integrated Ocean Observing System
ISOP	Improved Synthetic Ocean Profile
LC	Loop Current
LCE	Loop Current eddy
LCS	Loop Current System
MMS	Minerals Management Service

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MODAS	Modular Ocean Data Assimilation System
NAVOCEANO	Naval Oceanographic Office
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NCODA	Navy Coupled Ocean Data Assimilation
NCOM	Navy Coastal Ocean Model
NDBC	National Data Buoy Center
NOAA	National Oceanic and Atmospheric Administration
NRL	Naval Research Laboratory
NSF	National Science Foundation
NTL	Notice to Lessees and Operators
OSSE	Observing System System Simulation Experiment
PI	principal investigator
PIES	pressure-recording inverted echo sounder
POM	Princeton Ocean Model
ROV	remotely operated vehicle
SSH	sea surface height
SST	sea surface temperature
SWOT	Surface Water and Ocean Toporgaphy
TRW	topographic Rossby wave
T/S	temperature/salinity
UARC	University Affiliated Research Centers
URI	University of Rhode Island

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