The National Academies of SCIENCES ENGINEERING MEDICINE

GULF RESEARCH PROGRAM

Healthy Ecosystems Grants 2 Final Report

Project Title: Synthesis of Historical Observations Using Novel Model Approaches to Improve Understanding and Predictability of Deep Gulf of Mexico Circulation
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Project Director: Steven Morey
Affiliation: Center for Ocean - Atmospheric Prediction Studies, Florida State University

Project Key Personnel:

- Amy Bower, Woods Hole Oceanographic Institution
- Eric Chassignet, Florida State University
- Bruce Cornuelle, Scripps Institution of Oceanography
- Kathleen Donohue, University of Rhode Island
- Dmitry Dukhovskoy, Florida State University
- Peter Hamilton, Leidos, Inc.
- Cathrine Hancock, Florida State University
- Joao Marcos Azevedo Correia De Souza, Centro de Investigacion Cientifica y de Educacion Superior de Ensenada (CICESE)
- Enric Pallas Sanz, Centro de Investigacion Cientifica y de Educacion Superior de Ensenada (CICESE)
- Ashwanth Srinivasan, Tendral LLC
- Ganesh Gopalakrishnan, Scripps Institution of Oceanography

I. PROJECT SUMMARY (from proposal)

This project has the overall goal of achieving a greater understanding of the physical processes that control the deep circulation in the Gulf of Mexico (GOM) through the synthesis of historical measurements with advanced data assimilative numerical models, and analysis of synthesized model and observational data. Previous observational and modeling studies indicate the deep GOM (below the main thermocline) is a surprisingly energetic environment, driven in part by strong dynamic coupling between the upper and deep layers near the Loop Current (LC), but little is known about the processes and pathways by which energy is transported through the rest of the deep Gulf. Smaller scale circulation features spawned by instability processes related to the LC, radiating through the Gulf, and dissipating through interaction with topography are hypothesized to play important roles. Understanding the physics of these processes is fundamental for improving the characterization and prediction of the deepwater environment that impacts oil and gas operations, as well as biological, sediment and pollutant transport.

A wealth of data has been collected in the deep GOM for academic, government, and industry studies over the past 15 years, spurred by an intensification of oil and gas exploration at greater depths and by discovery of unexpected energetic currents and diverse benthic ecosystems. These data include government and industry-funded measurements from moorings, Pressure Inverted Echo Sounders (PIES), and acoustically tracked (RAFOS) floats, almost none of which have previously been synthesized in models. Analyses of these data show that the deep GoM is a complex energetic system, with measured current speeds approaching 1 m/s near the seabed at 2000 m depth over the Sigsbee Escarpment, a region with several industry platforms, and deep acoustically tracked floats identifying a deep cyclonic boundary current extending along this escarpment toward the Perdido escarpment and Bay of Campeche. Such strong currents are atypical for the deep ocean and are hypothesized to be related to other energetic deep circulation features such as eddies and topographic Rossby waves (TRW) focused at these steep topographic boundaries.

This project has the specific objectives of determining: (1) mean and variability of circulation patterns in the deep GOM and their impact on material transport; (2) energy pathways throughout the deep GOM, including sources, radiation, and dissipation; and (3) impact of deep ocean forcing on the continental shelf slope, and exchanges between the deep ocean and slope. Historical observational data from MMS/BOEM-funded arrays of PIES and current meters, deep Lagrangian float experiments, current meter array deployments by GoMRI- and industry-funded projects, and other common public data will be synthesized into cutting-edge data assimilative models, which will provide new comprehensive state estimates for the GOM for analyses. Outcomes of this study will include: (1) new knowledge of deep GOM dynamics, including links with upper layer circulation and pathways for transport and energy propagation, (2) improvements in forecasting methodology critical for safe design and operation of oil and gas infrastructure, and (3) new circulation estimates that can be used to determine dispersal pathways for deep water organisms and contaminants.

II. PROJECT SUMMARY (from final report)

Very little has been previously known about the general circulation in the deep Gulf of Mexico, including pathways by which organisms and pollutants are transported and how the abyssal and upper layers of the Gulf are dynamically connected. Recent large-scale observational programs have been undertaken in the Gulf that included high-density arrays of moored instruments as well as drifters that float with currents at deep levels. Though these experiments have provided exciting new depictions of certain aspects of the deep Gulf of Mexico circulation and dynamics, there are still limitations to the understanding we can get from these observations alone. Numerical models that assimilate these data provide us with a way to fill gaps both in space and time between observations as well as gaps in knowledge of the dynamical processes responsible for controlling the deep circulation. This project brought together researchers who study the Gulf using observations and numerical models to develop new understanding of the deep ocean circulation within the Gulf of Mexico, including identifying the sources of energy for the deep circulation and pathways by which organisms or pollutants may be transported through the deep Gulf. The project resulted in several numerical model data sets that synthesized the recent deep Gulf observations. These simulations were analyzed together with the observations to yield a more comprehensive understanding of the deep Gulf circulation and dynamics.

III. PROJECT RESULTS

Accomplishments

Introduction

Historically, little has been known about the circulation of the deep layer of the GoM, primarily due to challenges of collecting long-term measurements with good spatial sampling at these depths. The lack of Gulf-wide observations at depth has prevented adequate evaluation of numerical models, and certainly has provided nearly no data for constraining model analyses. Over the past two decades, though, interest in the deep Gulf has increased with the advancement of oil and gas operations off the continental shelf into waters deeper than 1000m. Industry measurements of strong current speeds near the seabed at 2,000m depth along the base of the Sigsbee escarpment motivated a number of studies of the deep Gulf to understand this potentially energetic environment. However, these studies were often very location-specific. In recent years, groundbreaking large-scale observational studies have been conducted for the deep Gulf of Mexico. These include: a Gulf-wide BOEM-funded Lagrangian study using 158 drifters at 1,500m and 2,500m from July 2011 – June 2015; a BOEM-funded array of 25 inverted echo sounders with pressure gauges (PIES), nine full-depth moorings, and seven near-bottom moorings deployed under the LC region from April 2009 – November 2011; and a number of full-depth moorings in the western Gulf of Mexico operated by Mexican institutions since 2008. Additionally, regional studies in the northern Gulf of Mexico have included a Lagrangian study using 20 RAFOS floats at 400m and moorings from the Shelf Energetics and Exchange (SEED) project in the DeSoto Canyon region.

The goal of this project is to improve our understanding of the deep Gulf of Mexico circulation and the physical processes that control it through synthesis of historical observations with advanced data assimilative numerical models. Specific scientific objectives include: (1) Determining the mean and variability of circulation patterns in the deep GOM and their impact on material transport; (2) Determining energy pathways throughout the deep GOM, including sources, radiation, and dissipation; and (3) Determining the role of deep ocean forcing on the continental shelf slope, and exchanges between the deep ocean and slope. To accomplish these objectives, this project brought together teams of modelers with expertise on simulating the Gulf of Mexico with teams of observationalists and dynamicists that have been involved in the above-mentioned recent observational programs. The modeling teams are from CICESE (Mexico), Scripps Institution of Oceanography (SIO), and Florida State University (FSU, assisted by a subcontractor, Tendral, LLC). The observational teams are from Woods Hole Oceanographic Institution (WHOI), the University of Rhode Island (URI), Leidos, Inc. (co-PI P. Hamilton retired mid-project from Leidos and continued to work as a private consultant and adjunct faculty member of North Carolina State University), and FSU.

This project produced three new Gulf of Mexico ocean model simulations that assimilate data from recent large-scale observational programs for the deep Gulf of Mexico. The resulting simulations are the first model syntheses of these groundbreaking observational data sets. These simulations, as well as their free-running counterparts, were analyzed with the observational data to understand the state-of-the-art capability in simulating the deep Gulf circulation as well as to gain an improved understanding of the dynamics governing the deep circulation, specifically focusing on the project's scientific objectives. The model simulations are based on previously existing Gulf of Mexico simulations using the community ocean models: Regional Ocean Modeling System (ROMS) run at CICESE, the MIT General Circulation Model (MITgcm) run at SIO, and the Hybrid Coordinate Ocean Model (HYCOM) run by FSU and Tendral, LLC. These three models were selected to take advantage of their differing numerical and data assimilation capabilities and their extensive application to the Gulf of Mexico. This approach of using a suite of models not only yields information about the capability of the models for simulating the deep Gulf, but also allows for analysis of different model products for different objectives based on the models' capabilities.

<u>The Models</u>

ROMS - During this project a reanalysis of the ocean estate for the Gulf of Mexico (GoM) was developed using a 1/10° resolution ROMS configuration with a strong constraint, incremental, 4DVar data assimilation scheme. Special focus was on the deep circulation, and the evaluation of the reanalysis capability in representing it. A 5-year non-linear, non-assimilative version of the model simulation was used to provide the background estate for the assimilative model and to investigate the general patterns of the deep circulation. Two versions of the reanalysis were developed. The first one (reanalysis v1) includes the assimilation of datasets provided in near-real-time (satellite along-track SSH and SST, and argo float temperature and salinity profiles) to emulate an operational forecast system. This reanalysis covers the full year of 2011. A second version of the reanalysis (reanalysis v2) including the assimilation of deep moored velocity and temperature observations was run for the first 3 months of 2011. The results show that the assimilation of observations concentrated in the near surface region can generate perturbations of the deep circulation that degrade the solution. This is related to the lack of constraint for the deep portion of the domain. This is theme of a paper in preparation for submission. The assimilation of deep observations minimizes this problem, although the impact of the different observation types and locations is still to be determined. This will be dealt through another project under revision for funding.

MITgcm - The MITgcm simulation uses a telescopic grid with a horizontal resolution of 1/20° x 1/20° in the central GoM decreasing to 1/10° x 1/10° toward the boundaries, and has 80 vertical z-levels. This model configuration was used to produce an 8-year (2009–2016) forward model simulation with no data assimilation and a data assimilative 2010 hindcast. The hindcast assimilates satellite along-track SSH and mapped SST observations, and deep Gulf mooring observations (zonal/meridional currents from nine tall moorings) from the BOEM Loop Current study, using a 4-DVAR approach with non-overlapping two-month assimilation windows. For the first two-month experiment (May–June, 2010), four assimilation experiments were performed with data withholding in order to understand the impact of each type of observations on the two-month hindcasts and forecasts. Those experiments were: Exp-1: no data assimilation, Exp-2: SSH and SST data assimilation, Exp-3: SSH, SST and mooring data assimilation, and Exp-4: only mooring data assimilation. Based on the hindcast comparison with assimilated observations, Exp-3 produced an overall closest hindcast. Since the overarching goal of this project is to obtain a synthesis of all available observations, the Exp-3 assimilation was performed for the other two-month segments of 2010. The optimized states were compared with independent observations of estimated temperature and salinity data from the BOEM Loop Current Study PIES data.

HYCOM - A 3-km resolution HYCOM simulation, with domain covering the Gulf of Mexico and extending throughout the Intra-Americas Seas was run using the Tendral Statistical Interpolation System (TSIS). Unlike the assimilation methodologies for the ROMS and MITgcm, TSIS is a computationally efficient sequential assimilation method that is commonly used for operational forecasting. This simulation was run for 2009 through 2011, assimilating the typical satellite altimetry and surface temperature data as well as the three-dimensional 12-hourly mapped velocity fields from the BOEM Loop Current Study array. In addition, an existing multi-decadal (54-year) HYCOM Gulf of Mexico simulation that has the same 1/25° resolution used by the Navy Research Laboratory Gulf of Mexico Nowcast/Forecast System was analyzed. The new HYCOM-TSIS simulation has a higher horizontal and vertical resolution grid that better represents the steep bathymetry of the deep Gulf that is critical for deep energy radiation. Data from the new simulations developed under this project have been made available on publicly accessible data servers as detailed in the Data Management section of this proposal.

Objective 1: Deep Circulation Mean and Variability and Transport Pathways

Recent publications from the BOEM-sponsored observational programs listed above provided the opportunity to synthesize results from model experiments with analyses from the Lagrangian and moored measurements. The free-running ROMS, MITgcm, and HYCOM simulations described above were analyzed similarly to the observational data to provide for the first time an assessment of models' abilities to simulate basic characteristics of the deep Gulf circulation. The multi-decadal HYCOM simulation was also analyzed in non-overlapping segments to gain an understanding of the uncertainty in estimates of statistical properties from the limited-length (2 ½ or 4 years) observational programs. Major features of the mean deep layer circulation in the Gulf identified from the Lagrangian observations are: a cyclonic flow around the continental slope surrounding the deep Gulf, a deep cyclonic gyre (termed the Sigsbee Abyssal Gyre) in the southwestern Gulf, and a dipole of counter-rotating cells under the Loop Current region with a cyclonic circulation to the south of this dipole. The Loop Current Study moorings also show the dipole feature. Each model generally simulates these major features of the mean deep circulation.

Analysis of the multi-decadal model suggests that these features are representative of the long-term mean. These results have been synthesized into a schematic depicting the major upper and deep circulations features (Figure 1, uploaded as Figure1.png).

Analyses of the observed mean and eddy kinetic energy (EKE) show clear distinction of the eastern and western parts of the basin, with higher EKE in the east and higher mean kinetic energy in the west. The three models all simulate lower EKE values than determined from observations. Assimilation of the deep observations generally improves the deep EKE to more closely match observations. These results are detailed in a journal manuscript presently in preparation.

The free-running ROMS simulation was also analyzed along with the Lagrangian observations to improve the understanding of transport and connectivity throughout the deep Gulf. The Lagrangian observational dataset was complemented with a large number of virtual particles advected off-line by the validated ROMS velocity field. The findings emphasize the role of the deep western cyclonic gyre limiting the connectivity of GoM deep waters. The transport between the eastern and western GoM is mainly restricted to the cyclonic boundary currents around its outer edges (Figure 2). These results are the theme of a paper under review for publication in the journal Deep Sea Research.
The Lagrangian observations were further analysed to understand the role of small scale eddies in the deep Gulf transport. Wavelet analysis is used to identify coherent eddies in the float trajectories, leading to a census of the basin-wide eddy field including statistics of their kinematic properties. The eddy census reveals a formation region for anticyclones off the Campeche Escarpment, located northwest of the Yucatan Peninsula. These eddies appear to form locally, with no apparent direct connection to the upper layer. Once formed, the eddies drift westward and are incorporated into the Sigsbee Abyssal Gyre located in the southwestern Gulf of Mexico over the abyssal plain (Figure 3). This formation region and the eddy pathway are highlighted by a local maximum in the mean EKE field derived from the Lagrangian velocities. This local maximum is not evident in the coarser resolution ROMS and MITgcm model reanalyses, Inspection of the 3-km resolution HYCOM reanalysis does, however, show elevated EKE in the genesis region, suggesting that higher resolution is necessary to simulate these features. The observational data suggest that eddy formation is ultimately linked to the collision of a Loop Current eddy with the western boundary of the Gulf. Specifically, disintegration of a deep dipole under the Loop Current eddy Kraken over the western continental slope caused an acceleration of the deep boundary current in the Bay of Campeche and an the deep Gyre, leading to anticyclonic eddy formation. These results are highlighted in an article under review in the Journal of Geophysical Research and a second article in preparation.

Finally, a new analysis was performed on the hydrographic data collected from the seven Argo profiling floats deployed with the BOEM Lagrangian Study along with additional floats available during that time to map the water mass climatology basin-wide down to 1500m. Thus, water masses such as high salinity Subtropical Underwater (SUW) found in the core of the Loop Current at ~ 150-200 m depth, and low salinity Antarctic Intermediate Water (AAIW), also originating in the Yucatan Channel ~ 700 - 800 m, could be statistically tracked across the Gulf to the western slope. The effects of upper-layer cyclones and anticyclones on T/S profiles were also documented. This analysis is important for assessment of ocean models and the results can be compared with predictions of the dispersion of these water masses by numerical models. A paper based on these results is in press with the Journal of Physical Oceanography.

Objective 2: Energy Pathways Throughout the Deep Gulf of Mexico

The numerical models provide a framework for understanding the mechanisms that facilitate Loop Current Eddy formation and the subsequent generation of deep energy. Analysis of the MITgcm model reveals a similar pattern of deep energy during the Loop Current separation as seen in the Loop Current mooring data (a HYCOM simulation was previously analyzed with results published near the beginning of this project). As the Loop Current advances into the central Gulf, a deep anticyclone leads the Loop Current, presumably driving by vortex squashing ahead of the Loop Current In almost all Loop Current cycles, a deep cyclone develops off the west Florida shelf near 24N associated with vortex stretching as the LC moves off the shelf (Figure 4). A meander develops along the eastern periphery of the Loop Current deep eddy kinetic and deep energy intensifies. A train of upper-deep eddies both cyclonic and anticyclonic develop together with deep eddies. The pattern of upper-deep interaction is consistent with baroclinic instability – deep eddies lead upper eddies by approximately ¼ wavelength. Joint intensification is intermittent, generally lasting tens of days. In model and observations, a preferred frequency band, 100-30 days, for the upper deep coupling emerges. This train of upper-deep interaction always precedes separations.

The BOEM Loop Current study emphasized the transfer of energy from the upper layer Loop Current to the lower layer, and the role of topography, particularly the constraining effect of the Campeche Bank. Analysis of the Lagrangian observations together with the Loop Current mooring data has added to the description and characterization of energetic deep eddies under the LC and their relation to meander crests and troughs and LC eddy detachments. Besides the generation of deep eddies through baroclinic instability, anticyclones were observed forming under the northern front of an extending LC. These can be explained as a consequence of the conservation of potential vorticity of a compressing lower layer. Strong evidence was found for the deep eddies that cross the neck of the LC transforming into topographic Rossby waves (TRWs) that propagate to the northwest towards the Sigsbee escarpment. These TRWs are an important mechanism for transferring energy through the deep Gulf. Rectification of TRWs by shoaling topography along the escarpment is thought to be a mechanism contributing to the westward flowing mean boundary current. Float trajectories over the Mississippi Fan show rectilinear fluctuations with a cross isobaths component that had little or no westward mean flow that are characteristic of planetary Rossby waves. A paper describing the energy pathways from the Loop Current to deep eddies and TRWs is in preparation. The analysis provides a basis for evaluating the realism of Loop Current physical processes in numerical models.

Objective 3: Deep Ocean Forcing on the Continental Shelf Slope and Cross-Slope Exchange

The 400m De Soto Canyon RAFOS floats (deployed in 2012) were analyzed jointly with simulated particle trajectories from the ROMS free-running simulation to investigate major subsurface flow patterns along and across the continental slope in the northern Gulf of Mexico. Three main pathways can be seen from the RAFOS float trajectories: (a) westward along the 500m isobath, (b) southwestward down the axis of De Soto Canyon and (c) eastward along the 500m isobath. Float movement between 88˚W -91˚W and 1000-2000m water depth is mostly due to (a) entrainment by eddies (88˚W-89.5˚W) and (b) the turning and eastward movement of several floats at 90.5˚W. Movement along the 500m isobath is not symmetrical about De Soto Canyon, where floats moved 4˚ and 1˚ of longitude west and east, respectively, from deployment location. This motion is partly due to bathymetry along the West Florida Shelf, and partly due to the specific flow pattern during the observations of 2012.

Virtual particles were seeded at the RAFOS deployment locations and tracked at 400m depth in the ROMS flow field. Deployments were repeated for eight model years to understand the variability in slope currents associated with different offshore forcing conditions. Analysis of the simulated trajectories reveals the same three main pathways identified from the observations, but with an additional pathway directed southeastward, likely due to entrainment in the Loop Current or anticyclonic eddies. Subsampling particles based on their existence within a particular region during specific months allows the trajectory maps to be analyzed as a time series using EOF analysis to identify specific spatial patterns. The first two dominant modes show the southwestward movement along De Soto Canyon, and some eastward and westward spreading along the slope. Mode 3 reveals the main exit point for floats in the northeastern region to the deep Gulf of Mexico. Particularly interesting is the principal components of these three modes, which shows a striking difference between years. Model years 2010 and large periods of 2011 show all three modes correlated with small to midrange amplitudes, whereas these same modes become uncorrelated with drastic amplitude increases during 2012 and 2013.

The results of the Lagrangian analysis were also interpreted along with analysis of velocity time series from the SEED moorings. Inspection of the mooring time series reveals that flow is dominantly along-isobath with the direction being 50%/32% and 37%/46% eastward/westward, for May-November 2004 (SEED-1) and November-May 2005 (SEED-2) respectively. Similarly, both time series show a mixed flow pattern 18% and 17% of the time, for SEED-1 and SEED-2 respectively. Model time series reveal similar traits, with along-isobath flow dominating and flow direction being 52% and 36% eastward and westward respectively. Again a mixed flow pattern occurs 12% of the time. The mooring and model time series are further analyzed using Self-Organizing Maps (SOM) an artificial neural network based on unsupervised learning. SOM maps high-dimensional input data onto a low-dimensional space, all while preserving topological relationships between the input data. The SOM analysis reveals three main features that combine to make distinctive flow patterns. These features are: (1) flow along the West Florida Shelf (referred to as the eastern side of DeSoto Canyon from hereon), (2) flow along the western side of DeSoto Canyon and (3) an eddy over DeSoto Canyon. From these, nine regimes of flow over the slope are identified as: (a) eastward flow, (b) westward flow, (c) eastward flow with a cyclone, (d) eastward flow with an anticyclone, (e) westward with a cyclone, (f) westward with an anticyclone, (g) bifurcation, (h) convergence and (i) a cyclone (Figure 5). Only two flow patterns, bifurcation and convergence, have opposing flows on the eastern and western side of De Soto Canyon. The results of this work are in preparation for submission as a journal article.

Implications

This project provided a novel opportunity to bring together teams with modeling and observational expertise who are on the cutting edge of Gulf of Mexico physical oceanography research to synthesize results from historical and recent groundbreaking observational campaigns with the latest in numerical modeling methods. The results of this project and collaboration with investigators leading the recent observational campaigns provide a wealth of new understanding of the deep Gulf of Mexico circulation and dynamics. Previously, the oceanographic community had only rudimentary understanding of the deep Gulf from inferences from limited historical observations. A consequence of this was that it was not possible to ascertain the realism of simulations of the deep Gulf, even those these model simulations were being used for research and forecasting purposes. Additionally, following the 2010 Deepwater Horizon oil spill, it became clear that there was a general lack of understanding of deep transport pathways. We now have a quantitative description of the primary circulation features of the deep Gulf and estimates of the variability, as well as a suite of improved model simulations and understanding of the impacts of deep observations on constraining the model dynamics.

The results of this project will guide future research in physical oceanography, forecasting, and deepwater ecosystems in the Gulf of Mexico. The comprehensive depiction of the deep Gulf circulation will provide a much-needed tool for assessment of numerical models. This work also highlighted aspects of numerical models that need improvement for forecasting and application to studies of Gulf dynamics. Importantly, this project was timely in that the results will serve as a guide for the upcoming studies funded by the NAS Gulf Research Program Understanding Gulf Ocean Systems.

The new understanding of the abyssal circulation of the Gulf of Mexico is relevant to a number of problems of scientific and societal importance. A major topic of research for application in the Gulf of Mexico is forecasting the Loop Current and eddies. These features are of particular importance to the oil and gas industry. Forecast models are primarily constrained by satellite observations with various methods used to project the observable surface variables to constrain the model fields at depth. Improved understanding of the coupling between the upper layer circulation and the abyssal circulation will lead to new research in improving methods of assimilating observations from both satellites and in situ observations to improve forecasting capability. Finally, this project has led to a new understanding of deep Gulf transport pathways and connectivity, which are important for predicting the impacts of future deepwater releases of oil on deep Gulf ecosystems, as well as understanding the ecological connectivity throughout the basin.

Unexpected Results

N/A

Project Relevance

The following audiences would be most interested in the results of this project:

- Researchers
- Federal Government Officials
- Non-Profit Private Sector
- For-Profit Private Sector

The results of this work will guide future research in the deep Gulf of Mexico for academic and federal government scientists. The results also have direct application to the oil and gas industry, including federal, non-profit, and private sector interests.

Education and Training

Number of students, postdoctoral scholars, or educational components involved in the project:

- Undergraduate students: 1
- Graduate students: 1
- Postdoctoral scholars: 2
- Other educational components: 0

IV. DATA AND INFORMATION PRODUCTS

This project produced data and information products of the following types:

- Data
- Scholarly publications, reports or monographs, workshop summaries or conference proceedings
- GIS applications
- Software packages or digital tools, or other interactive media

DATA

See attached Data Report.

Relationships Between Data Sets:

The three data products are related in that they are all numerical model hindcasts of the Gulf of Mexico.

Additional Documentation About Data:

The data sets generated by the numerical model simulations are all archived together with descriptions of the simulations.

Other Activities to Make Data Discoverable:
The model syntheses are based on other larger modeling programs, including the HYCOM Consortium and the ECCO Consortium. The simulations run for this project are linked to from the respective Consortia web pages.

INFORMATION PRODUCTS

See attached Information Products Report.

Citations for Project Publications, Reports and Monographs, and Workshop and Conference Proceedings:

Publications

- Hamilton, P., R. R. Leben, A. S. Bower, H. Furey, and P. Perez-Brunius, 2018. Hydrography of the Gulf of Mexico from autonomous floats. J. Phys. Oceanogr. doi:10.1175/JPO-D-17-0205.1
- Furey, H., A. Bower, P. Perez-Brunius, P. Hamilton, and R. Leben, 2018. Deep Eddies in the Gulf of Mexico observed with Floats. Journal of Geophysical Research-Oceans, In Review.
- Maslo, Aljaz; J M. A.C. Souza; P. P. Brunius; F. A. Canto, 2018. Connectivity of deep waters in the Gulf of Mexico. Deep Sea Research, In Review.
- Angeles B. G. Lucero. Analysis and correlation of the Loop Current indicators from satellite and ROMS simulation. The influence of the Yucatan channel at different model resolutions. Bachelor Thesis.
- Benemerita Universidad Autonoma de Puebla, April 2017.
- Four additional manuscripts are in preparation to be submitted to peer-reviewed journals.

Conference Presentations

- Furey, H., A. Bower, Perez-Brunius, P., P. Hamiton, R. Leben, 2018. RS34B-1992: Deep Eddies in the Gulf of Mexico Observed with Floats. 2018 AGU Ocean Sciences Meeting, Portland, OR.
- Perez-Brunius, P., H. Furey, A. Bower, P. Hamiton, R. Leben, J. Candela, P. Garcia-Carrillo, J. Outerelo, M. Piedeleu, L. Zavala Sanson, F. Beron-Vera, A. Malso, D. Balwada, 2018. RS34B-1991: Research Highlights of the BOEM Funded Lagrangian Program “Deep Circulation in the Gulf of Mexico” (Invited). 2018 AGU Ocean Sciences Meeting, Portland, OR.
- Hamilton, P. R. Leben, A. Bower, H Furey, P Perez-Brunius, 2018. RS33A-05: Hydrography of the Gulf of Mexico using Autonomous Floats. 2018 AGU Ocean Sciences Meeting, Portland, OR.
- Donohue, K., B. Cornuelle, and G. Gopalakrishnan, 2018. RS33A-06: Generation of deep energy in the central Gulf of Mexico. 2018 AGU Ocean Sciences Meeting, Portland, OR.

- Maslo, A., J. Marcos Souza, P Perez-Brunius, and F. Andrade Canto, 2018. Connectivity of deep waters in the Gulf of Mexico. 2018 AGU Ocean Sciences Meeting, Portland, OR.
- Morey, S.L., A.S. Bower, B.D. Cornuelle, K.A. Donohue, D.S. Dukhovskoy, G. Gopalakrishnan, P. Hamilton,
- J. Marcos Souza, and P. Perez-Brunius, 2018. RS34B-1993: Coomparison of model estimates of deep circulation and variability in the Gulf of Mexico. 2018 AGU Ocean Sciences Meeting, Portland, OR.
- M. Mercedes Montano, 2018. RS34B-1995: Development and evaluation of Lagrangian predictability model in the deep Gulf of Mexico. 2018 AGU Ocean Sciences Meeting, Portland, OR.
- Marcos Souza, J., A. Maslo, and J. Sheinbaum, 2018. RS34B-1996: A Gulf of Mexico regional reanalysis – impact on the deep circulation. 2018 AGU Ocean Sciences Meeting, Portland, OR.

Additional Documentation About Information Products:
N/A

Other Activities to Ensure Access to Information Products:
N/A

V. PUBLIC INTEREST AND COMMUNICATIONS

Most Unique or Innovative Aspect of the Project

A significant outcome of our project was to provide new understanding of how the upper and deep layers of the Gulf interact and exchange energy. This new knowledge will be important to future efforts focused on improving ocean forecasting in the Gulf of Mexico.

Most Exciting or Surprising Thing Learned During the Project

For the first time, we now have a complete quantitative description of the Gulf-wide circulation in the abyssal layer that can be used to assess numerical simulations. Previously, numerical models were used for studies related to pollutant and biota transport in the deep Gulf, yet with little knowledge of whether the models were actually correctly simulating the deep circulation correctly. The outcomes of this project now allow models to be used with much more confidence on studies of the deep Gulf of Mexico.

Most Important Outcome or Benefit of Project

This project has resulted in a number of published and upcoming scientific papers that will provide a fundamental new understanding of the deep Gulf of Mexico circulation with significant impact to future scientific studies. Research that will be impacted by this project will include studies of deep Gulf ecosystems and development of improved ocean forecasting methodologies.

Communications, Outreach, and Dissemination Activities of Project

Press Releases and Media Coverage:

https://scripps.ucsd.edu/news/scripps-oceanography-researcher-receives-nas-gulf-research-program-award

http://news.fsu.edu/news/science-technology/2015/12/10/fsu-researchers-win-grants-study-gulf-mexico- currents-oil-spill-movement/

http://myemail.constantcontact.com/Winter-2016-Newsletter-from-the-FSU-Center-for-Ocean-Atmospheric-Prediction-Studies--COAPS-.html?soid=1104107396812&aid=-dmHhznOUiU