DEEP OCEAN CURRENT VARIABILITY NEAR THE MACONDO OIL SPILL SITE

An Undergraduate Research Scholars Thesis

by

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RESEARCH COMPLIANCE CERTIFICATION

Research activities involving the use of human subjects, vertebrate animals, and/or biohazards must be reviewed and approved by the appropriate Texas A&M University regulatory research committee (i.e., IRB, IACUC, IBC) before the activity can commence. This requirement applies to activities conducted at Texas A&M and to activities conducted at non-Texas A&M facilities or institutions. In both cases, students are responsible for working with the relevant Texas A&M research compliance program to ensure and document that all Texas A&M compliance obligations are met before the study begins.

I, Hannah Diaz, certify that all research compliance requirements related to this Undergraduate Research Scholars thesis have been addressed with my Research Faculty Advisor prior to the collection of any data used in this final thesis submission.

This project did not require approval from the Texas A&M University Research Compliance & Biosafety office.

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ABSTRACT

Deep Ocean Current Variability Near the Macondo Oil Spill Site

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After the Macondo (*Deepwater Horizon*; DWH) oil spill in 2010, an array of six deep ocean current moorings were deployed near the spill site for a period of two years in order to investigate the regional oceanic current variability and relate to oil spill transport predictions. In this analysis these mooring data were utilized to produce climatological maps of ocean current speed and direction in order to characterize how the ocean moves as a function of depth and season (i.e., time) throughout this region. Progressive vector diagrams, current magnitude profiles, and basic statistical metrics including mean, standard deviation, minimum, maximum, etc. were the principal data products used to analyze the variability between near-surface and near-bottom ocean currents throughout time. Results reveal the significance of time and location in oceanographic measurement making and analyses: variability in ocean currents were highly dependent upon when and where measurements were taken, both within the water column and along the continental slope itself. The variability due to these parameters ultimately describe the various transport and subsequent fates of the different DWH spill constituents that remained partially along the surface and partially subsurface. This analysis proves the necessity for

comprehensive temporal and spatial sampling programs in order to effectively capture/describe oceanographic variability, and thus will have important implications for future oil spill response and mitigation efforts in the deep ocean in addition to contributing to the general understanding of oceanic processes within the Gulf of Mexico itself.

DEDICATION

[To my incredible family and friends—I could not have done this without your unceasing support and love.]

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Contributors

First and foremost, I would like to thank my phenomenal faculty advisor, Dr. Steven F. DiMarco, for their continual guidance and encouragement throughout the entire course of this research. The completion of this project would not have been possible without such a remarkable mentor. Enormous thanks also go to my friends, colleagues and the department faculty and staff for their overwhelming support and for making my time at Texas A&M University such a memorable experience.

The data utilized throughout this study were obtained from the Gulf of Mexico Research Initiative Information and Data Cooperative (GRIIDC), a data management system developed by researchers and data specialists for the purpose of openly storing and distributing all Gulf research generated through the Gulf of Mexico Research Initiative (GoMRI).

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This undergraduate research analysis did not require or receive funding. However, this project utilizes data collected from a field program that was funded and developed by the Gulf of Mexico Integrated Spill Response Consortium (GISR) in conjunction with the Gulf of Mexico Research Initiative (GoMRI) after the 2010 Macondo *Deepwater Horizon* (DWH) oil spill event.

1. INTRODUCTION

The 2010 BP Macondo *Deepwater Horizon* (DWH) oil spill led to the release of approximately 4.4 million barrels of hydrocarbons into the deep Gulf of Mexico and thus became one of the worst oil spill events in US marine waters (Crone and Tolstoy, 2010). Surpassing the release of the 1989 Exxon *Valdez* oil spill by an order of magnitude, the unprecedented level and scope of the DWH spill forced a substantial mobilization of government resources and efforts, as well as extensive interagency cooperation between industry, academic, and government experts (Crone and Tolstoy, 2010; Lubchenco et al., 2012).

Prior to DWH, there had been minimal research dedicated to the investigation and understanding of the oceanographic systems that regulated the Gulf of Mexico. Following its aftermath, the spill event elucidated not only the need for such research in order to understand how Gulf systems would affect the mitigation efforts of this particular event, it also revealed the need for a more comprehensive understanding of Gulf processes in general so that future catastrophes such as this one may be proactively prevented. Thus, the Gulf of Mexico became a forefront within the oceanographic community, and a multitude of studies were launched after BP committed $500 million over a 10-year period for the specific purpose of investigating the environmental impacts of the DWH incident and cultivating Gulf research (GoMRI, 2010). Although 2020 marks the end of this specific ten-year research initiative (named the Gulf of Mexico Research Initiative; GoMRI), presently, the US National Academies are implementing a research plan in the Gulf of Mexico that will further advance the understanding of the major current behavior of the Gulf of Mexico (NASEM, 2018). Regardless of practical, mitigation or response-related motivations, it is nevertheless important to continue efforts to study oceans and the general processes that regulate them for the simple purpose of gaining a greater understanding of oceans in and of themselves.

1.1 Circulation in the Gulf of Mexico

Previous research regarding Gulf currents and the processes that drive them have shown these forces to be numerous and varied (Ledwell et al., 2016). Foremost, the most dominant physical process in the surface waters of Gulf of Mexico is defined by the Loop Current (LC) (NASEM, 2018; Cox et al., 2010). Entering through the Yucatan Channel and exiting through the Florida Straits, the LC meanders through the Gulf and carries a large, deep mass of warm waters with strong, fast moving currents (NASEM, 2018). The position of the LC varies substantially and is characterized by two states: extended (i.e. intruding far into the northern and western Gulf before anticyclonically turning and exiting through the Florida Straits) and retracted (i.e. abruptly flowing directly to the east and exiting through the Florida Straights soon after entering through the Yucatan Channel) (NASEM, 2018; Schmitz et al., 2005; Schmitz, 2005). In its extended state, the LC may separate from the main flow and form large, energetic, anticyclonic eddies (LCEs) that slowly migrate westward (NASEM, 2018; Sturges and Leben, 2000; Schmitz et al., 2005; Schmitz, 2005). This extended state shedding of LCEs has significant implications on a number of anthropogenic and environmental affairs including hurricane intensities and intensity predictions, oil and gas operations/offshore safety, Gulf food chains, disaster mitigation efforts, shallow-water nutrient supply, and the Gulf fishing industry (NASEM, 2018). However, despite being the most dominant physical process in the Gulf of Mexico and despite its obvious influence, causes and predictions of extended state LC activity and subsequent LCE shedding are not fully understood, thus further reiterating the need for increased Gulf research endeavors (Sturges and Lugo-Fernández, 2005).

There is also evidence that LC and LCE activity also give rise to another physical process regarding deep-ocean circulation: topographic Rossby waves (TRWs) (Oey and Lee, 2002; Hamilton, 2009; Hamilton, 1990). Hamilton (2009) and Oey and Lee (2002) explain that while the upper 800-1200 m of the Gulf are generally dominated by the LC and LCEs, lower-layer current variability below 1000 m is generally dominated by TBWs produced from cross-isobathic motions above sloping topography. Furthermore, Hamiltion (2009) continues by relaying that due to the differences in the propagation speeds and periodicities between lower-layer Rossby waves and upper-layer eddies, flow between the upper and lower water column are "largely decoupled." However, research also shows that forcing by winds due to strong atmospheric processes including tropical storms and hurricanes drive inertial waves that can propagate deep into water depths (Shay et al., 1998; Oey et al., 2008; Jaimes and Shay, 2010).

In general, DiMarco et al. (2005) showed that the overall net circulation in Gulf surface waters generally follows a clockwise pattern around the ocean basin. Using tracers dispersed throughout the Gulf of Mexico, Ledwell et al. (2016) showed that circulation is "greatly enhanced" along the continental slope. Lastly, Wang et al. (2016) showed the significance of turbulence and its role in water mass exchange along the continental shelf and slope. While there are clear differences between surface and deep-water currents, variability is ultimately a result of when and where measurements are made due to the numerous, various, and complex processes that regulate the Gulf of Mexico.

1.2 Fate of the DWH oil spill remnants

Based on the existing literature that developed as a result of the spill, it is known that the substance released from the ruptured Macondo well was a 50/50 mixture of gas-phase methane and liquid petroleum (Kessler et al., 2011). The methane plume was observed to remain roughly

1200 m from the surface while the liquid component rose from the sea floor directly to the ocean surface (Kessler et al., 2011). Because of the separation of these components, knowledge of the full water column ocean current structure is vital in regards to transport prediction of all phases of the spill. Previous knowledge had determined clear differences between surface and deep ocean currents (Jochens and DiMarco, 2008). However, due to a lack of understanding on how these differences would affect the transportation of the methane and petroleum components of the spill, a field program was designed and deployed in order to quantify the ocean current variability at the DWH site. Thus, an array of six deep water current-meter moorings were placed near the Macondo spill site from 2012 to 2014 in order to investigate the regional ocean current variability with respect to time and depth. It is the data collected from this program that was analyzed within this study in order to contribute to filling the knowledge gap between surface and deep ocean current variability. This study will subsequently have important implications for future oil spill response and mitigation within the deep ocean, and will also contribute to the general understanding of oceanic processes within the Gulf of Mexico

2. METHODS

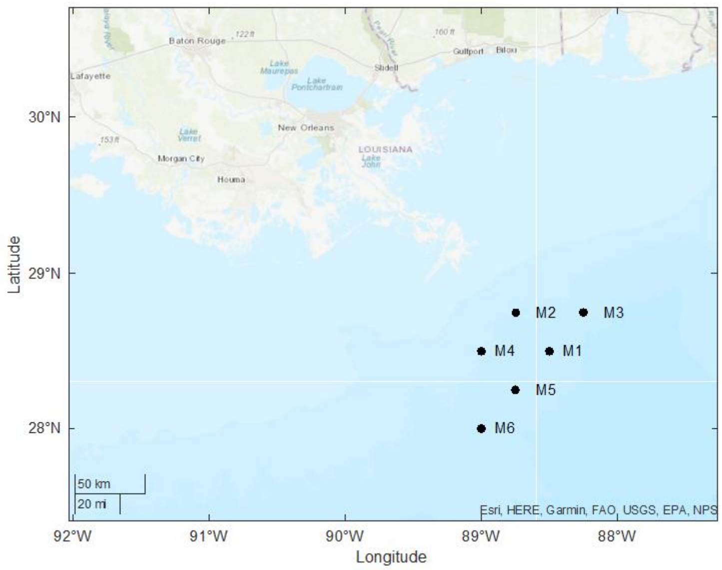

Figure 1 *Placement of mooring array in the Gulf of Mexico.*

This data utilized throughout this study were collected from a two-year mooring field program that was developed by the Gulf of Mexico Integrated Spill Response Consortium (GISR) in conjunction with the Gulf of Mexico Research Initiative (GoMRI) after the 2010 Macondo *Deepwater Horizon* (DWH) oil spill event. An array of six deep ocean moorings were deployed along the continental slope in the Mississippi fan region of the northern Gulf of Mexico (see Figure 1 for placement of mooring locations) on GISR Cruise G01 in July 2012, were recovered and redeployed on GISR Cruise G04 in July 2013, and were again recovered on GISR Cruise G06 in July 2014. Each mooring consisted of numerous oceanographic instruments to measure parameters including temperature, salinity, and current velocities, and the total water depth of each mooring varied from approximately 900 m to 1700 m along the water column (see Table 1 and Figure 2 for summary of instrumentation and vertical placement).

Table 1 *Mooring instrumentation and vertical placement.*

Mooring	***Latitude***	***Longitude***	***Total Water Depth***	***75kHz ADCP Depth***	***SBE-16 CTD Depth***	***InterOcean S4A Depth***	***StarMon Temp Depth***	***RCM-8 Depth***	***RCM-11 Depth***	***SBE-37 Microcat Depth***	***Benthos 685A Depth***
1	28.50 N	88.50 W	1690m	690m	692m	790m 890m 990m 1090m	1190m 1390m 1540m		1290m 1490m 1677m	1292m 1679m	1690m 1690m
2	28.75 N	88.75 W	1035m	535m			736m 837m		635m 835m 1020m	527m 1022m	1035m 1035m
3	28.75 N	88.25 W	1337m	837m			1037m 1187m		937m 1137m 1317m	839m 1319m	1337m 1337m
4	28.50 N	89.00 W	836m	336m			536m 686m		436m 636m 816m	338m 818m	836m 836m
5	28.25 N	88.75 W	1650m	1150m			1350m 1500m	1450m	1250m 1630m	1632m	1650m 1650m
6	28.00 N	89.00 W	1312m	812m			1012m 1162m 1299m	1112m	912m 1297m		1312m 1312m

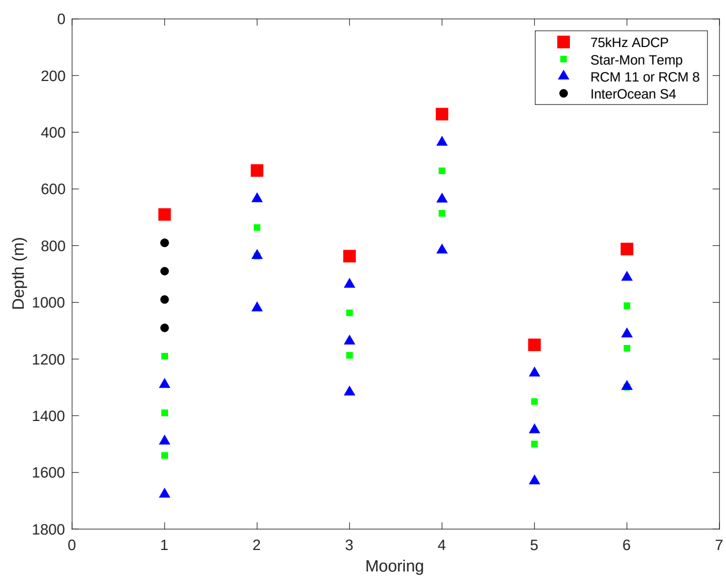

Figure 2 *Principal mooring instrumentation throughout the water column.*

These mooring data produced daily, half hourly and hourly, Eulerian time series measurements of current velocities, temperature, and salinity. For the purposes of this project, this study primarily focused on analyzing the current velocity data gathered from each of the six ADCPs over the two-year data collection period from July 2013 to July 2014. It is important to note that the ADCPs are unique oceanographic instruments in that they are able to measure current velocities over a range of depths using the Doppler effect (*ADCP Principles of Operation*, 2011). This principle is what is allows for the analyzation of variability *throughout* the water column, not simply the single, stationary location/depth the instrument is located (as is the case with most orthodox oceanographic instruments).

Within the statistical programming software, MATLAB, these data were utilized to calculate basic statistical metrics including mean, standard deviation, minimum, maximum, and histograms to create maps of ocean current velocity fields as a function of depth and location. These were then used to produce monthly progressive vector diagrams (PVDs) to display water movement throughout multiple depths on a monthly basis. The vectors displayed on the monthly progressive vector diagrams were calculated using Equation 1 so that East/West and North/South distance traveled is described by the cumulative summation of the velocity measurement (measured in cm/s) converted to units of km/hr.

$$Distance\ traveled = \frac{\sum_{i=1}^{n} X_i \ * 3600}{1000} \qquad \textit{(Eq. 1)}$$

3. RESULTS

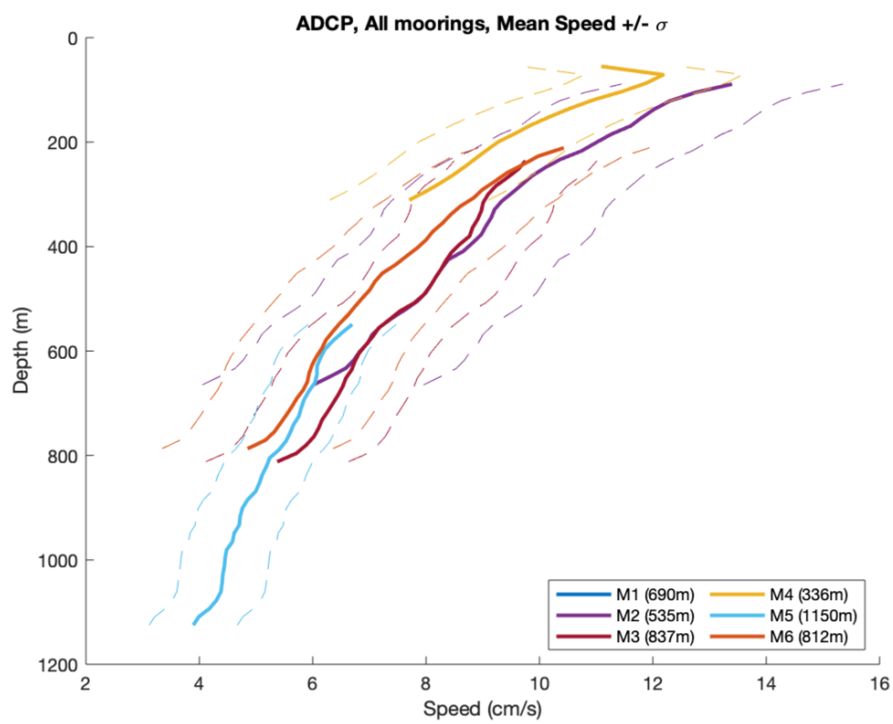

Figure 3 *All moorings' ADCP mean speed, +/- one standard deviation.*

Figure 3 describes all moorings' ADCP measured mean speed (the thicker, bolded colored lines) plus/minus one standard deviation (the lighter, dashed lines), and displays the fundamental essence regarding how variability along the water column progresses from near-surface to near-bottom depths. As shown throughout the figure, at the surface, the standard deviation lines are wider along the mean speed lines, and the mooring speeds encompass larger mean values. At the bottom depths, the mean speed drops drastically from approximately 13 cm/s at the surface to a comparatively minor 4 cm/s. This point is further elucidated when comparing Mooring 4 and Mooring 5: Mooring 4, which is displayed in yellow and captures near-surface velocities starting at 336 m, has standard deviations between 5.30 cm/s and 8.02

cm/s, whereas Mooring 5, which is displayed in light blue and captures near-bottom velocities starting at 1150 m, has standard deviations between only 2.45 cm/s and 4.71 cm/s, a much smaller range than compared to Mooring 4 at the surface. In a broader sense, this principle has further important implications because current speed is essentially a measure of kinetic energy—as expected, currents are more energetic at the surface then at the bottom, which is ultimately conveyed by the much larger mean speed values at the near-surface depths versus the much smaller mean speed values at the near-bottom depths displayed by all moorings.

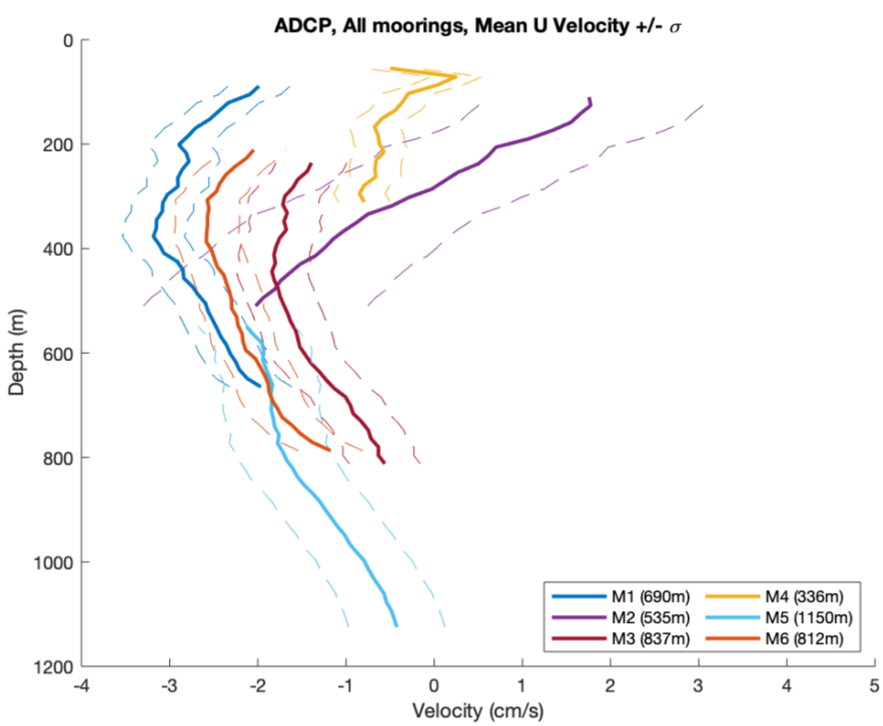

Figure 4 *All moorings' ADCP mean East/West velocity, +/- one standard deviation.*

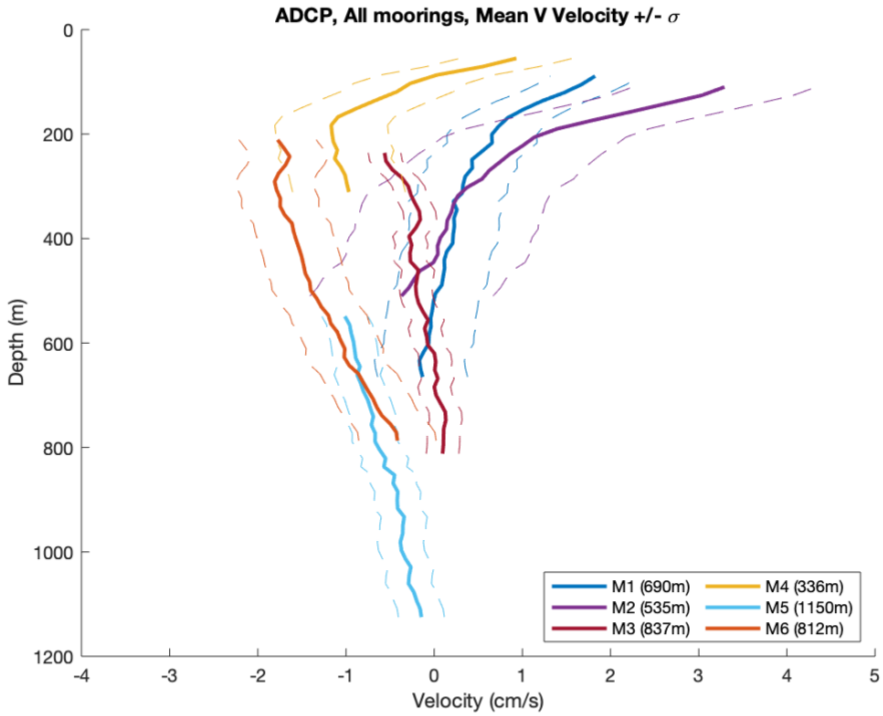

Figure 5 *All moorings' ADCP mean North/South velocity, +/- one standard deviation.*

Similar to Figure 3, Figures 4 and 5 describe all moorings' ADCP measured mean East/West velocities and North/South velocities (respectively) plus/minus one standard deviation. However, because velocity is a vector quantity (with both magnitude and direction) and speed is a scalar quantity (with only magnitude), these figures characterize ocean currents in a slightly different manner.

In Figure 4, positive values indicate eastward moving currents while negative values indicate westward moving currents. Moorings 1, 3, 5 and 6 are very similarly defined by primarily slow moving, westward currents, whereas Moorings 2 and 4 are instead characterized by slightly faster, partially eastward flowing currents. This consistency among Moorings 1, 3, 5 and 6 and their inconsistency with Moorings 2 and 4 displays the significance of location: location in regards to depth within the water column, and location in regards to placement along the actual continental slope as well. Regarding the former statement, Moorings 3 and 6 where placed at almost exactly the same water depth (1337 m and 1312 m, respectively), and their ADCPs captured extremely similar patterns of current variability throughout the water column—despite Mooring 3 conveying slightly faster mean velocities than Mooring 4, both moorings are characterized by the same "shape." Regarding the latter statement, Moorings 2 and 4 were located to the North of the remaining moorings and thus were higher along the continental shelf (refer Figure 1 for placement of moorings). In consequence, Moorings 2 and 4 were subsequently influenced by different oceanic processes than those that influenced Moorings 1, 3, 5, and 6, which ultimately revealed itself by capturing more eastward flowing currents.

In Figure 5, positive values indicate northward moving currents, while negative values indicate southward moving currents. In this case, when collectively analyzed together, all moorings display the same fundamental pattern of larger mean (specifically northward) velocities at the surface and smaller (essentially 0 cm/s) mean velocities at the bottom.

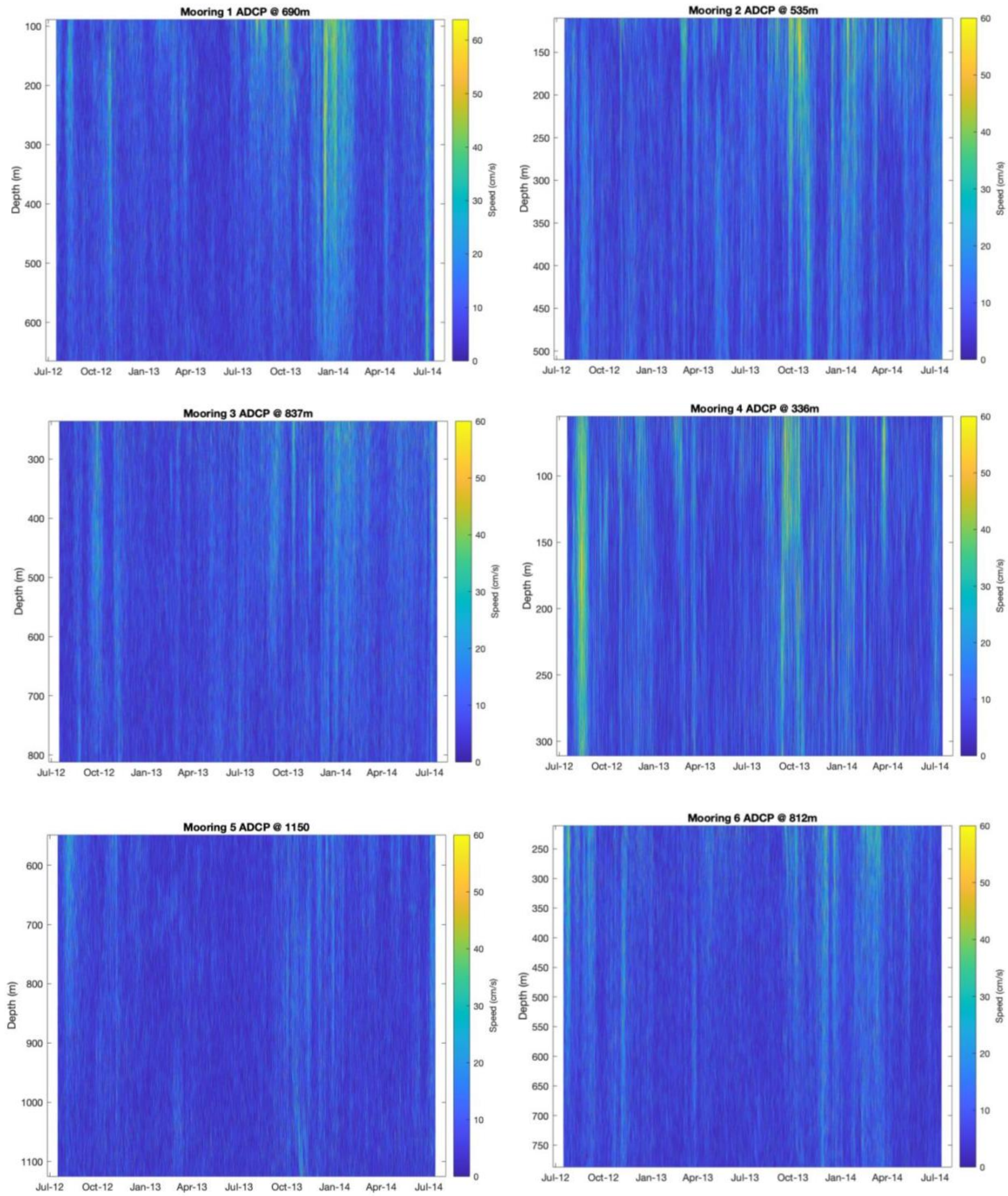

Figure 6 *Individual ADCP speed profile for all moorings.*

Figure 6 displays the individual speed profiles for all mooring ADCPs as a function of time over the two-year data collection period. Darker blue colors correlate to smaller, slow moving current speeds, whereas lighter yellow colors correlate to larger, fast moving current speeds. Important implications about current movements along the water column can be drawn from analyzing the graphs both individually and collectively. Analyzed individually, it is important to note that processes that occurred at the surface are not always exclusive to the surface: they can be resonated throughout a range of depths within the water column. This is shown by the vertical yellow "streaks" representing fast moving current speeds between 50 cm/s and 60 cm/s that are present in instances such as January 2014 in Mooring 1, October 2013 in Mooring 2, and August 2012 in Mooring 4. These vertical yellow "streaks" do not only occur at the surface and then abruptly end after reaching a certain depth; instead, they influence and persist throughout the water column until they lose energy and fade gradually. Analyzed collectively, it is important to note the difference in the abundance of yellow and blue between each graph. Moorings 1, 2 and 4 with ADCPs at 690 m, 535 m, and 336 m, respectively, have more instances of yellow than Moorings 5 and 6 with ADCPs at 1150 m and 812 m, respectively. This difference is directly correlated to depth and location, and further reiterates the difference between surface and deep currents and the processes that influence them.

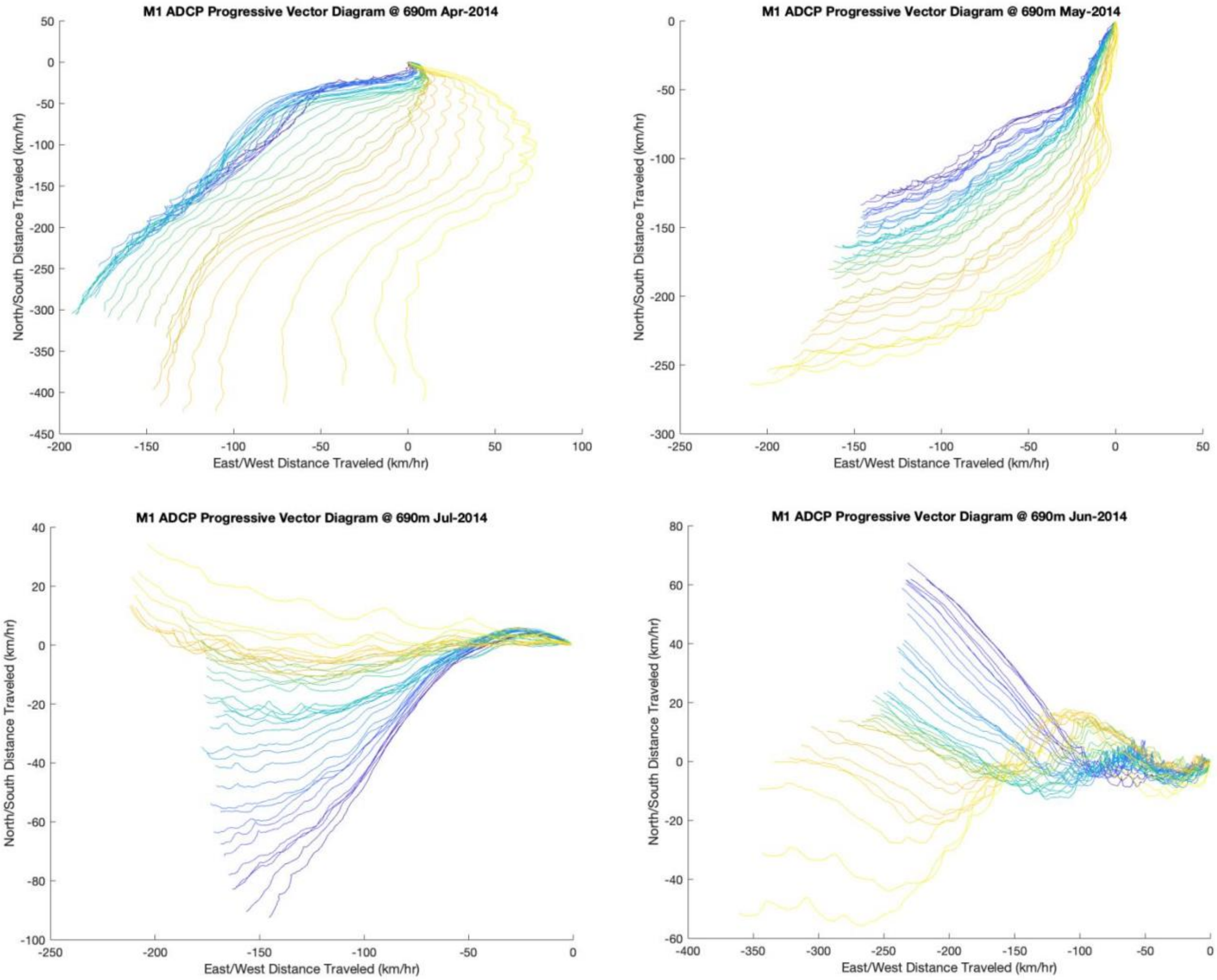

Figure 7 *Selected progressive vector diagrams from M1 ADCP.*

Figure 7 displays selected progressive vector diagrams from Mooring 1's ADCP for the months of April, May, June, and July of 2014. Light vectors shown in yellows are indicative of surface depths while dark vectors shown in blues are indicative of deeper depths. These graphics are important for a number of reasons, one being that they show the similarities and/or differences in the vertical coherency between surface and bottom currents as they relate to time. For the month of April 2014, there was strong vertical coherency in that all depths followed essentially the same pattern of flowing south and to the west. This theme of strong vertical coherency is also displayed in the month of May 2014, where all depths similarly flow southwest. However, this ideal is broken in the month of June 2014. In this case, surface currents flow east and to the north, whereas bottom currents conversely flow east and to the south. In this month there is relatively weak vertical coherency throughout the water column.

In addition to the directional pattern of the vectors, it is also important to note the relative magnitude of the vector distance traveled. In all four of the graphics, surface currents traveled farther and faster than their corresponding deeper currents. These graphics further reiterate the variability patterns seen throughout Figures 1-3: near-surface currents are generally more energetic than near-bottom currents. Furthermore, there is also variability between each month itself and the magnitude of distance traveled. The East/West scale for the month of June 2014 is much larger than the remaining months, and similarly the North/South scale for the month of April 2014 is also much larger than the remaining months.

4. CONCLUSION

Mean profiles of speed, North/South and East/West velocities showed general variability patterns of faster, more energic surface currents as opposed to deep currents. PVDs and current magnitude profiles of speed showed the influence of strong and weak vertical coherency throughout the water column. Taken together, overall results reveal the significance of both time and location in oceanographic measurement making and analyses: variability in ocean currents were highly dependent upon when and where measurements were taken due to the highly variable, complex nature of the Gulf of Mexico. There will be numerous different processes and systems that affect different locations (both within the water column and along continental slope itself) at different times (whether seasonally, monthly, yearly, or even daily). The variability due to these parameters ultimately describe the various transport and subsequent fates of the different DWH spill constituents that remained partially along the surface and partially subsurface. This analysis proves the necessity for comprehensive temporal and spatial sampling programs in order to effectively capture/describe oceanographic variability, and thus will have important implications for future oil spill response and mitigation efforts in the deep ocean.

REFERENCES

Cox, J., C. Coomes, S. DiMarco, K. Donohue, G.Z. Forristall, P. Hamilton, R.R. Leben, and D.R. Watts (2010). Study of Deepwater currents in the Eastern Gulf of Mexico. U.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

Crone, T. J., and M. Tolstoy (2010). Magnitude of the 2010 Gulf of Mexico Oil Leak. *Science*. 330, 634, *JSTOR*, www.jstor.org/stable/40931710

DiMarco, S.F., W.D. Nowlin, Jr., and R.O. Reid (2005). A statistical description of the velocity fields from upper ocean drifters in the Gulf of Mexico. In: Sturges, W. and A. Lugo-Fernandez. *Circulation in the Gulf of Mexico: observations and models*. Washington, DC.: American Geophysical Union. Pp. 101-110.

Gulf of Mexico Research Initiative (2010). BP Releases Long-Awaited Plan for $500 Million for Gulf Research. https://gulfresearchinitiative.org/bp-releases-long-awaited-plan-for-500-million-for-gulf-research.

Hamilton, P. (2009). Topographic Rossby waves in the Gulf of Mexico. *Progress in Oceanography*, 82, 1–31. doi:10.1016/j.pocean.2009.04.019

Hamilton, P. (1990). Deep currents in the Gulf of Mexico. *J. Phys. Oceanogr.* 20, 1087– 1104.

Jaimes, B., and L. K. Shay (2010), Near-inertial wave wake of hurricanes Katrina and Rita over mesoscale oceanic eddies, *J. Phys. Oceanogr.,* 40, 1320–1337.

Jochens, A. E., S. F. DiMarco (2008). Physical oceanographic conditions in the deepwater Gulf of Mexico in summer 2000–2002. *Deep Sea Research Part II: Topical Studies in Oceanography*. Vol. 55, 2541-2554. https://doi.org/10.1016/j.dsr2.2008.07.003.

Kessler, J. D., D. L. Valentine, M. C. Redmond, M. Du, E. W. Chan, S. D. Mendes, E. W. Quiroz, C. J. Villanueva, S. S. Shusta, L. M. Werra, S. A. Yvon-Lewis, T. C. Weber

(2011). A Persistent Oxygen Anomaly Reveals the Fate of Spilled Methane in the Deep Gulf of Mexico. *Science*. Vol. 331, 312—315. doi: 10.1126/science.1199697.

Ledwell, J. R., R. He, Z. Xue, S. F. DiMarco, L. Spencer, and P. Chapman (2016). Dispersion of a tracer in the deep Gulf of Mexico. *Journal of Geophysical Research: Oceans*. Vol. 121, 1110– 1132. doi:10.1002/2015JC011405.

Lubchenco, J., M. K. McNuttb, G. Dreyfusa, S. A. Murawskia, D. M. Kennedya, P. T. Anastasc, S. Chud, and T. Hunter (2012) Science in support of the Deepwater Horizon Response. *PNAS*. Vol. 109, 20212—20221. https://doi.org/10.1073/pnas.1204729109

NASEM (2018). Understanding and Predicting the Gulf of Mexico Loop Current: Critical Gaps and Recommendations. Washington, DC: The National Academies Press. https://doi.org/10.17226/24823.

Oey, L.-Y., and H.-C. Lee (2002), Deep eddy energy and topographic Rossby waves in the Gulf of Mexico, J. Phys. Oceanogr., 32(12), 3499–3527.

Oey, L.-Y., M. Inoue, R. Lai, X.-H. Xin, S. E. Welsh, and L. J. Rouse (2008), Stalling of near-inertial waves in a cyclone, *Geophys. Res. Lett*., 35, L12604, doi:10.1029/2008GL034273.

Shay, L. K., A. J. Mariano, S. D. Jacob, and E. H. Ryan (1998), Mean and near-inertial ocean current response to Hurricane Gilbert, *J. Phys. Oceanogr.*, 28, 858–889.

Schmitz, W. J., Jr. (2005), Cyclones and westward propagation in the shedding of anticyclonic rings from the Loop Current, in *Circulation in the Gulf of Mexico: Observations and Models*, *Geophys. Monogr. Ser.*, vol. 161, edited by W. Sturges III and A. Lugo-Fernandez, pp. 241–261, AGU, Washington, D. C.

Schmitz, W. J., Jr., D. C. Biggs, A. Lugo-Fernandez, L.-Y. Oey, and W. Sturges (2005), A synopsis of the circulation in the Gulf of Mexico and on its continental margins, in *Circulation in the Gulf of Mexico: Observations and Models*, *Geophys. Monogr. Ser.*, vol. 161, edited by W. Sturges III and A. Lugo-Fernandez, pp. 11–29, AGU, Washington, D. C.

Sturges, W., and R. Leben (2000), Frequency of ring separations from the loop current in the Gulf of Mexico: A revised estimate, *J. Phys. Oceanography*, 30, 1814–1819.

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

Teledyne RD Instruments (2011). Acoustic Doppler Current Profiler Principles of Operation A Practical Primer. https://www.comm-tec.com/Docs/Manuali/RDI/BBPRIME.pdf

Wang, Z., S. F. DiMarco, S. A. Socolofsky (2016). Turbulence measurements in the Northern Gulf of Mexico: Application to the Deepwater Horizon oil spill on droplet dynamics. *Deep Sea Research Part I: Oceanographic Research Papers*. Vol. 109, 40—50. http://dx.doi.org/10.1016/dsr.2015.12.013.