A Look at Currents in the Gulf of Mexico in 1999 - 2000


Abstract

Oceanographic conditions in the Gulf of Mexico have been extensively studied from the summer of 1999 through the fall of 2000. These studies included cradle to grave surveys of Juggernaut Eddy; surveys in the Caribbean by several consortia; oceanographic surveys in support of hurricane research in the Gulf; measurements of inflow/outflow through the Yucatan Strait; and regional nowcasts and hindcasts of circulation. Several interesting phenomena have been observed during this period, including energetic bottom currents in excess of 2 knots and bottom furrows on the continental slope; the intrusion of one of the strongest eddies in a decade into the north-central Gulf leases; and strong mid-water-column currents in SE Ewing Bank (~140 cm/s). This paper describes the observational data available and summarizes ongoing efforts to understand the oceanographic conditions during this period. Eventually, it is hoped that these efforts will lead to a better estimation of offshore structure design currents; an understanding of the dynamical causes of the strong mid-water-column currents; determining whether there is a link between the strong bottom currents at the base of the Sigsbee Escarpment and the Loop Current; and assessing the skill of the regional forecast/nowcast/hindcast oceanographic models.

Introduction

The importance of the Gulf to offshore mineral exploration and production is well known. But what may not be as well-appreciated is the fact that, because of the wealth of observational data and observational and modeling resources that have been brought to bear on the region in recent years, a better understanding and prediction of its circulation is more feasible today than ever before. In fact, the Gulf is an ideal test bed for exploring ideas on monitoring and predicting oceanographic conditions in a coastal/marginal sea.

The Gulf’s circulation is dominated by the Loop Current, an energetic current of warm subtropical water that enters the Gulf through the Yucatan Strait, extends northward, then loops around to the south and ultimately exits the Gulf through the Florida Strait. The position and strength of this Loop Current (LC) exhibits considerable variability. As first suggested by Ichiyé and later observed by Cochrane, the LC may extend so far north, often nearly to the Mississippi Delta, that the circulation closes off and a large warm-core (anticyclonic) eddy is shed. Like the LC, these Loop Current eddies (LCE) also have strong currents, but unlike the LC, they are not constrained to the eastern Gulf and typically drift westward at a few kilometers per day. Often, the westward drift can interfere with offshore operations. This happened in 1999 when British Borneo reported the shutdown of deepwater operations at Ewing Bank 965 due to the LC during August and September. This shutdown contributed to a $20 million increase in development costs for the Morpeth Field.

Currents in the LC and newly detached LCEs can be quite strong. Using an acoustic Doppler current profiler (ADCP), Cooper et al surveyed two LCEs in 1983 and recorded 223 cm/s (4.3 knot) surface currents. Measured currents during Fast Eddy were slightly lower reaching 180 cm/s (4.3 knot) surface currents. Measured currents during Fast Eddy were slightly lower reaching 180 cm/s (Forristall et al) After separation from the LC, the eddies decay and speeds slowly decrease. In the case of Fast Eddy, this slow evolution is described by Lewis et al.

On a smaller scale, shingles, filaments and small eddies may be formed by instabilities associated with the LC and LCE fronts. Vukovich et al found that some of these small-scale features were noticeable to 700 m depth and propagated along the Loop Current boundary at 28 km/day.

In the fall of 1999, the LC shed Juggernaut Eddy which traversed active lease sites in the northern Gulf before moving off to the southwest. A similar event occurred in 1989 when the LC moved into southeast Ewing Bank before shedding Nelson Eddy. As part of a long-term effort to better understand the Loop Current system and its variability and to develop the tools needed to accurately nowcast/forecast these
features, this eddy was extensively monitored and studied during its formation and transit.

Observations and Numerical Models

Due to a fortunate confluence of efforts by industry, government and university researchers, the Gulf was very well described in 1999 and 2000. Here we describe the comprehensive observations collected during this event and report on the current state of numerical circulation nowcast/forecast models for the Gulf.

NOPP Airborne Surveys. As part of the National Ocean Partnership Program (NOPP) Gulf of Mexico Ocean Monitoring System (GOMOMS) program, Naval Oceanographic Office (NAVOCEANO) undertook airborne expendable bathythermograph (XBT) surveys in the Gulf. Fig. 1 shows the survey tracks in 1998 and 2000.

NOPP Vessel Surveys. Two efforts are of interest here. As part of the NOPP GOMOMS program, Juggernaut Eddy was surveyed in late October 1999 as it separated from the Loop Current (Fig. 2). Oceanographic measurements were also collected across the Yucatan Strait in October 1999 to better understand the inflow conditions. Fig. 3 shows near-surface currents measured along the Yucatan Strait. Near surface flow was generally northward with speeds exceeding 100 cm/s over much of the section. There was also a significant backflow from the Gulf into the Caribbean on the Cuban side.

Hurricane Research Division. During the course of hurricane research, NOAA’s Atlantic Oceanographic Marine Laboratory conducted expendable bathythermograph (XBT) surveys of the Gulf of Mexico before, during and after the passage of hurricanes through the Gulf of Mexico in 1999 and 2000. The survey tracks in early October 1999 are typical of the coverage shown in Fig. 4.

Inflow/outflow surveys. In order to improve the skill of numerical nowcast/forecast modeling, the inflow region in the Yucatan Channel and the Caribbean was extensively studied by a coordinated effort between NOPP, Conoco’s Eddy Joint Industry Program (EJIP) and Texaco’s Deepstar project. Current meter moorings were deployed in the Yucatan Strait. The array spanned both the Mexican and Cuban sides of the Strait and the moorings had several current meters to sample the vertical structure of the inflow. ADCPs were also deployed on all of these moorings. ADCP and Conductivity/Temperature/Depth (CTD) surveys were made across the Strait during deployment and retrieval of the current meters. Also, airborne XBT (AXBT), airborne expendable CTD (AXCTD) and airborne expendable current profiler (AXCP) surveys were made in July 1999, March 2000 and July 2000. The surveys were conducted along the ground tracks of the TOPEX altimeter to enable using altimetry to provide conditions along the open southern boundary of numerical nowcast/forecast models of the Caribbean and the Gulf.

EJIP Surveys. Starting in October 1999, EJIP conducted a series of current and temperature surveys of Juggernaut Eddy from its formation in the central Gulf to its decay in Mexican waters.

Moorings and Rig Observations. Currents were measured at numerous locations in the Gulf, both from moorings and from fixed and mobile platforms. Many of the historical datasets and the numerical hindcast modeling are described in greater detail by Texas A&M’s work in the Deepwater Physical Oceanography Reanalysis and Synthesis of Historical Data (TAMU) project. This effort, funded by the MMS, is pooling and analyzing industry and public current data.

One of the most significant recent efforts is the three moorings deployed for the MMS at approximately the 2000 m isobath in the central Gulf in Atwater Valley 663, Green Canyon 744 and Atwater Valley 838 from August 1999 through August 2000 (TAMU). The MMS moorings and the location of representative industry moored, platform or drilling rig-based current measurements are shown in Fig. 5. Most of the industry sites used ADCPs deployed from drilling rigs for roughly 90-day periods.

In order to better understand the Topographic Rossby Waves, which are hypothesized to cause strong deepwater currents, Fugro GEOS’s Gulf Lower Layer (GULL) Current Measurement Project recently deployed 19 current meter moorings in water depths from 5,000 to 11,000 feet (Fig. 6).

CODAR Observations. Increasingly, CODARs (H/F RADAR systems for mapping currents) are being used to monitor and study near-coastal surface currents in the Gulf. Surface currents at the Morpeth platform (Fig. 5) were measured using a CODAR Seasonde. Testing of two long-range CODARS with the ability to map currents within a 300 to 400 km radius began in 2000. Assuming successful test results, long-range CODARS will be deployed to operationally map the currents in the Exclusive Economic Zone (EEZ) offshore Louisiana. Fig. 7 shows the overlapping region where hourly current vectors would be mapped at approximately a 6 km resolution and the large region with radial coverage.

Altimetry. Ready availability of real-time data streams from NASA/CNES TOPEX/Poseidon altimetric mission and the ESA ERS-2 has enabled continuous monitoring of the Gulf as well as provided input into nowcast/forecast models of the Gulf (see for example, http://www-ccar.colorado.edu/~leben/research.html). An example was shown in Fig. 2. Excellent altimetric coverage has existed since 1993 and is expected to continue well into this decade with the JASON-1, the successor to the TOPEX altimetric mission.

Drifters. Lagrangian drifters have enabled the circulation in the Gulf to be monitored since the eighties. Horizon Marine deploys drifters drogued at 50 m depth, as part of their Eddy Watch program. As part of NOPP sponsored research in the Gulf of Mexico, 18 temperature Profiling Autonomous
Lagrangian Circulation Explorer (PALACE) subsurface floats were deployed in the deep Gulf of Mexico basin in 1998 (http://www.cape.com/~profiles/general-info.html). Every seven days, each float surfaces and reports the temperature profile measured while suffering from depth, which is nominally 900 meters. Seventeen floats were still operational in the Gulf as of January 2001. In addition, WOCE-type drifter buoys (YOTO) were deployed in the Caribbean during 1999 and 2000 (http://drifters.doe.gov).

Numerical Hindcasts. Routine real-time nowcast/forecasts of the oceanic state in the Gulf have been made by Colorado University (CU) researchers under funding from Marathon's Climatology and Simulation of Eddies (CASE) project since 1998. The effort is described by Kantha et al\textsuperscript{10}. Briefly, the CU version of the Princeton Ocean Model is used for these nowcast/forecasts. Data from TOPEX and ERS-2 altimeters are assimilated into the model along with composite MCSST from NOAA AVHRR to produce a nowcast, from which 4-are assimilated into the model along with composite MCSST nowcast/forecasts. Data from TOPEX and ERS-2 altimeters version of the Princeton Ocean Model is used for these

Using the same data-assimilative model, hindcasts of the oceanic state in the Gulf have also been made from Colorado University (CU) researchers under funding from Marathon's Climatology and Simulation of Eddies (CASE) project since 1998. The effort is described by Kantha et al\textsuperscript{10}. Briefly, the CU version of the Princeton Ocean Model is used for these nowcast/forecasts. Data from TOPEX and ERS-2 altimeters are assimilated into the model along with composite MCSST from NOAA AVHRR to produce a nowcast, from which 4-week forecasts are made. The model has 1/12° resolution in the horizontal and 21 sigma levels. It is seen that altimetric SSH anomalies assimilated into the model define and fix the large-scale features such as the LC and LCEs, while the model dynamics fills in the small-scale features such as the cold-core cyclones around the LC. Nowcasts obtained in this manner are quite skillful, as can be seen from Fig. 8, which shows the nowcast on Dec 10, 1999 overlaid on top of the AVHRR image on that day. However, the lack of synoptic inflow conditions along the Yucatan Strait, the southern boundary of the circulation model, limits skillful forecasts to about a week or two. Extension beyond 2 weeks requires extending the model into the Caribbean and prescribing realistic time-varying inflow conditions there. This effort is being actively pursued at present.

The Gulf Eddy Model (GEM) is a descriptive model of the velocity field in an eddy. Eddies are described as translating ellipses. The input to the model is the eddy center position, major and minor axes lengths and orientations, solid body rotation rate of the interior of the eddy, and the eddy translation speed. The GEM models are a product of the Marathon's CASE project and are used for estimation of design and operating eddy currents. The newest version (GEM4) predicts the amplitudes of 3 empirical orthogonal functions (EOFs) which give current profiles as a function of position in the eddy.

Two surveys of Juggernaut Eddy were made in October and November 1999 using ADCPs mounted on the R.V. Gyre.

During the first two weeks after its formation, Juggernaut Eddy elongated along its north-south axis forming a more characteristic elliptical shape. It stretched from 25°N to 29°N with currents well in excess of 100 cm/s (2 knots). The LC by this time had retracted far to the southeast (Fig. 12). The eddy ellipse began to rotate clockwise (CW). By 11 November 1999, the major axis of the eddy was oriented east-west and the region of maximum currents were now south of 28°N. The eddy ellipse continued its slow CW rotation while an area of counterclockwise (CCW) circulation associated with a cold-core eddy formed on the northern edge on 2 December 1999 (Fig. 13). The CW rotation continued and on 1 January 2000, the major axis of the eddy was again aligned north-south. The small cold-core eddy had moved to the eastern side of Juggernaut. By 15 January 2000, Juggernaut assumed a southwest track while continuing its CW rotation and currents began to weaken. The eddy’s currents dropped below 75 cm/s (1.5 knots) by 3 February 2000 and its major axis was again aligned east-west (Fig. 14). Juggernaut continued its southwest track through spring and early summer of 2000. Maximum currents on the southeast side of the eddy were above 100 cm/s (2 knots) as its translation speed increased. During this time the LC migrated north again and in mid-June 2000, Eddy Kinetic formed. Juggernaut Eddy, however, continued to be tracked in the southwestern Gulf through the fall of 2000.

Discussion

During 1999 and 2000, a wealth of information was collected in the Gulf of Mexico. As this information becomes available, there is a significant opportunity to improve our knowledge of the Gulf and to improve the tools used for analysis and prediction. Some of the initial results are discussed below.

Parametric Modeling. The Gulf Eddy Model (GEM) is a descriptive model of the velocity field in an eddy. Eddies are described as translating ellipses. The input to the model is the eddy center position, major and minor axes lengths and orientations, solid body rotation rate of the interior of the eddy, and the eddy translation speed. The GEM models are a product of the Marathon's CASE project and are used for estimation of design and operating eddy currents. The newest version (GEM4) predicts the amplitudes of 3 empirical orthogonal functions (EOFs) which give current profiles as a function of position in the eddy.

Two surveys of Juggernaut Eddy were made in October and November 1999 using ADCPs mounted on the R.V. Gyre.
Oceanography Reanalysis Project, Howard et al. report that observations completed in the Deepwater Physical tracks are consistent with model-indicated currents. Generally speaking, the buoy and 10-day forecast currents at 50 m depth overlaid on NOAA AVHRR imagery and Horizon Marine drifter buoy Validation of the model results was through comparison with currents at locations of interest to the offshore industry. Forecasts up to 4 weeks in advance; and hourly time series of week delay. The results included the nowcast (current time); (www-ccar.colorado.edu/~jkchoi/gomforecast.html) after a 6 industry sponsor. The results are posted to a public website posted on a password-protected website for use by CASE, the more frequent intervals when neccessary. The results were 1999 and 2000. These were updated every 4 weeks and at making routinely by Colorado University researchers during numerical modeling. Real-time nowcast/forecasts were made routinely by Colorado University researchers during 1999 and 2000. These were updated every 4 weeks and at more frequent intervals when neccessary. The results were posted on a password-protected website for use by CASE, the industry sponsor. The results are posted to a public website [www-ccar.colorado.edu/~jkchoi/gomforecast.html] after a 6 week delay. The results included the nowcast (current time); forecasts up to 4 weeks in advance; and hourly time series of currents at locations of interest to the offshore industry. Validation of the model results was through comparison with NOAA AVHRR imagery and Horizon Marine drifter buoy tracks. Fig. 17 and Fig. 18 show sample results: the nowcast and 10-day forecast currents at 50 m depth overlaid on Horizon Marine buoy tracks. Generally speaking, the buoy tracks are consistent with model-indicated currents.

Based on detailed comparisons of the model and observations completed in the Deepwater Physical Oceanography Reanalysis Project, Howard et al. report that the Colorado/CASE model well represents the general circulation of the Gulf. Further, Dimarco et al. report that the model well represents the vertical structure of the Gulf. In the Gulf, the LC and LCE signatures are quite strong and hence it is possible to use altimetric SSH anomalies alone to delineate circulation features (see Fig. 2) providing a powerful diagnostic capability. Since the nowcast/hindcast model assimilates altimetry SSH anomalies, it is not very surprising that the model SSH is in close agreement with that indicated by altimetry alone. CU researchers have used the 1993-1999 model hindcasts and the altimetry archives for that period to better delineate the dynamical circulation features in the Gulf during this period. An example was presented in Fig. 9.

Altimetry. In the Gulf, the LC and LCE signatures are quite strong and hence it is possible to use altimetric SSH anomalies alone to delineate circulation features (see Fig. 2) providing a powerful diagnostic capability. Since the nowcast/hindcast model assimilates altimetry SSH anomalies, it is not very surprising that the model SSH is in close agreement with that indicated by altimetry alone. CU researchers have used the 1993-1999 model hindcasts and the altimetry archives for that period to better delineate the dynamical circulation features in the Gulf during this period. An example was presented in Fig. 9.

Moorings and Rig Measurements. The intrusion of Juggernaut Eddy into SE Ewing Bank and NE Green Canyon brought with it strong currents. Although the current measurement system came online too late to catch the peaks, approximately 140 cm/sec (~3 knot) currents were recorded at the Morpeth platform (see Fig. 5 for location) as Juggernaut Eddy moved away from the site (Fig. 19).

Deep Mysteries
Surprises still occur in the Gulf despite more than 15 years of deepwater operations; and countless hours of current measurements by industry, government and university researchers.

Midwater Events. Strong mid-water-column 125 to 200 cm/s (2.5 to 4 knot) currents were observed in Ewing Banks along the 240 m (800 ft) contour as Juggernaut Eddy moved northward towards the area (Fig. 20). Over the last 10 years, such jets have been observed by the oil industry during the drilling of perhaps a half dozen wells. A similar event in deeper water is described by Nowlin et al. The jets appear to be characterized by pulses of up to 150 cm/s (3 knots) lasting for only a few hours or days and occurring in the mid-slope sites at 100-200 m beneath the surface. The origin of these sub-surface jets remains a mystery.

Bottom Currents. In Atwater Valley, the MMS mooring at the base of the Sigsbee Escarpment observed strong bottom currents (~2 knot) in the fall of 1999 (Fig. 21). The strong current events deep in the water column appear to be quite episodic. Although the physical cause is as yet unknown, the CU hindcast results indicate a local intensification of the deep currents at the base of the Escarpment (TAMU).

Conclusions
Clearly, a massive observational and modeling database exists for the Gulf during 1999 and 2000. Most of it has not been fully analyzed, nor is all of it available in the public domain. Nevertheless, it is a testimony to the increasing attention and resources being brought to bear on this region. Consequently, it is very likely that the Gulf is one of the very few regions in the world that can serve as a meaningful test bed for assessing the feasibility and the degree of success in monitoring and predicting the coastal ocean (Kantha).

Acknowledgments
The field measurements were supported by Conoco’s Eddy Joint Industry project, the NOPP GOMMOS, and Texaco’s Deepstar Project. Marathon’s CASE project sponsored the CU numerical modeling. Alexis Lugo-Fernandez of the MMS granted access to information from the Deepwater Reanalysis Project and again demonstrated the value of cooperation between government and industry. Our thanks are gratefully extended to David Tubbs of Burlington Resources and Michael Spillane for access to the rig measurements in Ewing Banks and to Thomas Mitchell of Texaco, Dave Szabo of Fugro-Geos, and John Blaha of the Naval Oceanographic Office for information about their programs.

References
Fig. 4--AOML HRD October survey tracks and CU model 20° isotherm nowcast.

Fig. 5--Location of current measurements in NE Gulf; MMS moorings indicated by bullets and industry data by boxes.

Fig. 6--Study area for GULL moorings.

Fig. 7--Proposed coverage of operational CODAR.

Fig. 8--Three-day composite MCSST image from NOAA AVHRR (courtesy of Johns Hopkins Applied Physics Lab) overlaid with model SSH (contour interval 10 cm) from Dec. 10, 1999.
Fig. 9-Time series of the maximum northward and westward penetration of the Loop Current, as well as the area encompassed by it, from the 1993-1999 hindcast run of the Gulf of Mexico circulation model. The thin vertical bars show LCE sheddings. Note the rapid retreat of the Loop Current once it sheds a strong eddy. The panels on the left hand side show corresponding histograms.

Fig. 10--Detail for period ending 12 August, 1999.

Fig. 11--Major features on 07 October 1999.

Fig. 12--Major features on 21 October 1999.

Fig. 13--Major features on 02 December 1999.
Fig. 14--Major features on 10 February 2000.

Fig. 15--Juggernaut Eddy - October Gyre NOPP Cruise.

Fig. 16--Juggernaut Eddy - GEM4 model.

Fig. 17--Nowcast currents at 50 m depth on April 13, 2000 from the Gulf nowcast/forecast run. Only one in two grid points are plotted in each direction. The green line shows the TOPEX and the red one, ERS-2 overpass during that day. Eight day Horizon Marine drifter buoy tracks are also shown with dots denoting the end point.
Fig. 18--Ten-day forecast currents at 50 m depth on April 23, 2000 from the Gulf nowcast/forecast run. Only one in two grid points are plotted in each direction. Eight day Horizon Marine drifter buoy tracks are also shown with dots denoting the end point.

Fig. 19--Currents observed at Morpeth platform. See Fig. 5 for location.

Fig. 20--Observed currents at Ewing Bank 913 at ~800 ft depth. See Fig. 5 for location.

Fig. 21--Currents from MMS Atwater Valley mooring I2 on 1998 m isobath. See Fig. 5 for location.