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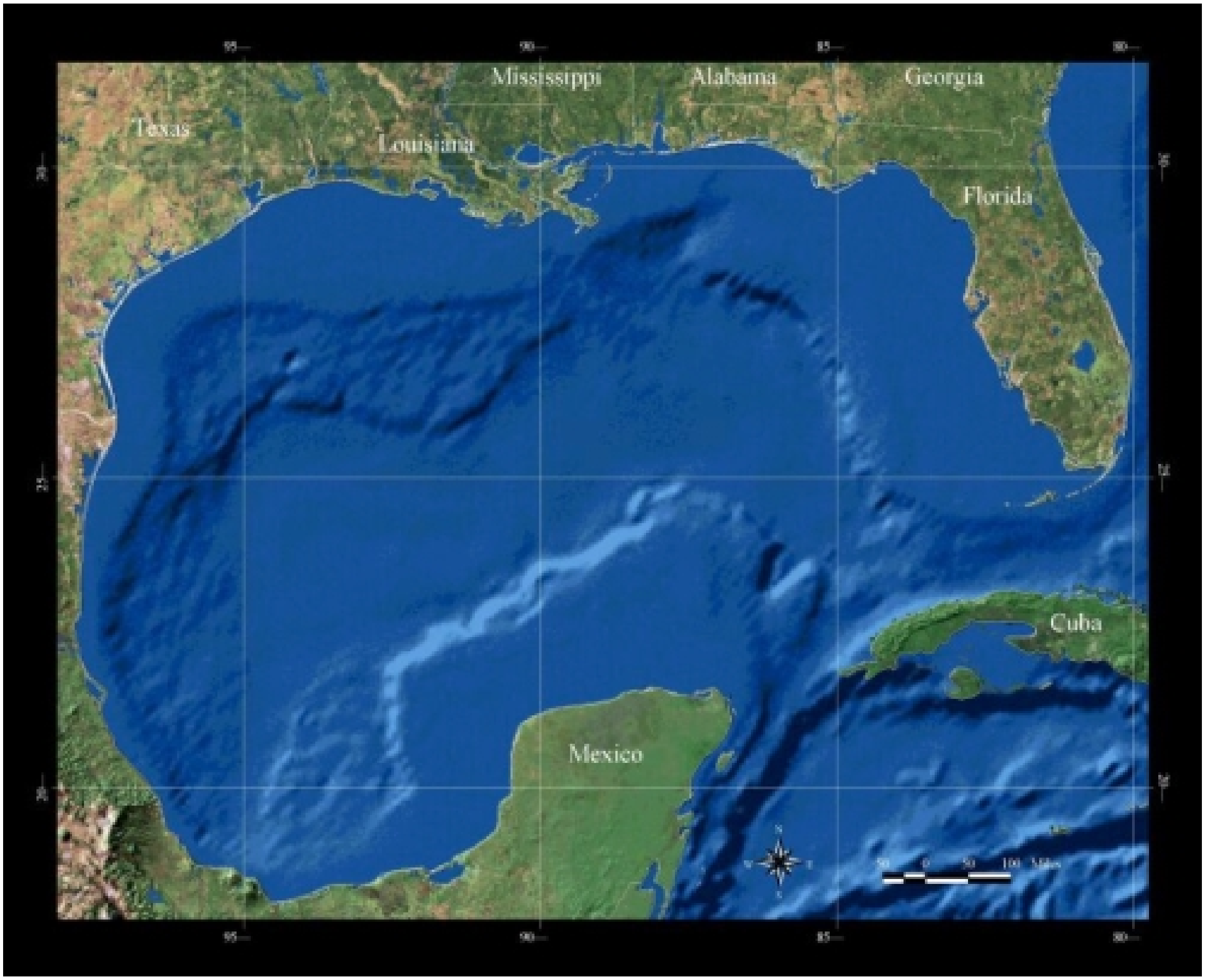
MMS 2001-021

Workshop on the Physical Oceanography Slope and Rise of the Gulf of Mexico

September 2000



U.S. Department of the Interior
Minerals Management Service
Gulf of Mexico OCS Region

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Workshop on the Physical Oceanography Slope and Rise of the Gulf of Mexico

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This workshop was a collaborative effort between Larry Atkinson, the University of New Orleans Office of Conference Services, and the Minerals Management Service. Much time and effort was spent in preparing for this workshop. The individuals and associations listed below are owed a debt of gratitude for their professional, dedicated efforts in the execution of this successful meeting.

Larry Atkinson – Program Chair

Alexis Lugo-Fernandez – MMS Program Chair

Debra Vigil – Program Coordinator, Contracting Officer’s Technical Representative

John Klinck, Craig Lee, Randy Watts – Invited Working Group Chairs

Darice Breeding, Carole Current, Jeff Ji – MMS Working Group Chairs

T.J. Broussard, Connie Landry, Michelle Morin, Todd Marse – Working Group Recorders

Joe Perryman – Computer Technical Support

University of New Orleans Office of Conference Services Staff

Employees of the New Orleans Airport Hilton

PHYSICAL OCEANOGRAPHY INFORMATION NEEDS IN THE SLOPE AND RISE REGION OF THE GULF OF MEXICO: WELCOME AND INTRODUCTION

Dr. Larry Atkinson
Old Dominion University

OPENING REMARKS

I would first like to mention briefly why we are here. There are high levels of oil and gas exploration, development, and production occurring in the deep waters of the Gulf of Mexico. Just a few years ago, little exploration was occurring outside the 300 m line.

Coincident with exploration and development in deeper waters, some preliminary observations of ocean currents in the deeper Gulf were made. Surprisingly, there were reports of strong currents at depths where currents are usually weak. As more measurements were reported, it was realized that there truly are strong currents in the very depths of the Gulf. In addition to direct observations of strong, deep currents, there were observations of wave-like features and scouring in the surficial sediments that compellingly suggested the presence of strong currents. Thus, there was a convergence of concern about environmental conditions in the deep Gulf of Mexico that might affect oil and gas operations.

The purpose of this workshop is to assess the state of our knowledge and to make recommendations for research that can improve our knowledge in areas of importance to the management of the oil and gas activities in the GOM. This process is very important because the recommendations coming from this group may result in new research directions for MMS. Also, the future of safe, efficient oil and gas production in the Gulf depends on good scientifically-based understanding of the Gulf. The assessments and recommendations you make here will assure that.

The presentations at this workshop set the stage and bring us up to date on the latest scientific findings. We will also gain a perspective on the issue from the MMS, the oil industry, and from the Deepwater Subcommittee of the MMS Science Advisory Committee.

When this workshop plan was being developed, we wanted to have working group leaders who could understand the science issues and coordinate the group efforts. But they also had to be outside the normal Gulf science community. The three people that met this task and accepted the challenge were:

Craig Lee, University of Washington and the Applied Physics Laboratory
Randy Watts, University of Rhode, Island Graduate School of Oceanography
John Klinck, Old Dominion University, Center for Coastal Physical Oceanography

The success of a meeting such as this requires a steering committee that understands the goals of the meeting, the scientific process, and can facilitate a consensus. The steering committee is composed of Craig, Randy, John, and Jim Coleman representing the deep-water subcommittee of the MMS Science Advisory Committee, and Alexis Lugo-Fernandez and Debra Vigil from MMS.

When MMS asked me to chair this workshop, my first concern was to assure that a good scientific exchange occurred and that the attendees learned something. This is especially important since the oceanographic processes that appear to be causing the strong currents are not well known, the observations are extremely limited, and the time needed to get adequate measurements is long. We also wanted new collaborations to form. To facilitate all this we asked people to bring poster and computer displays so they could share their results with their colleagues in the Gulf. We wanted the participants' conceptual model of the processes in the deep gulf to improve.

Several years ago I was a member, then the chair, of the MMS OCS Science Advisory Committee. I have many good memories of the experience. What I feel best about was that we worked with MMS staff to develop ways for MMS to do the best science possible. The product of that effort is here today. We see an excellent mix of scientists and managers from the private sector, universities, and federal agencies.

INTRODUCTION

In the last decade, the oil and gas industry has moved into ever deeper water in the Gulf of Mexico. The MMS has responded to this by focusing its studies into even deeper water. MMS determines what studies are needed through workshops to determine needs and priorities and studies to gather new information deemed necessary. This process has proved very effective in focusing limited funds on very difficult problems in relatively unknown areas of the ocean.

In 1997, a workshop was held that addressed the then emerging issues of knowledge gaps in the deep Gulf of Mexico (Carney, R.S. 1997. Workshop on environmental issues surrounding deepwater oil and gas development. Final report. OCS Study MMS 98-0022. U.S. Dept. of the Interior, Minerals Mgmt. Service, Gulf of Mexico OCS Region, New Orleans, La. 163 pp.). The statement from the physical oceanography section of the workshop is as follows:

> Present studies of physical processes, observational and numerical modeling, conducted in the Gulf focused on the shelf and shelf edge. A similar study in the slope region where industry activities are rapidly expanding has not been done. All previous efforts were essentially directed a producing gridded fields of currents for risk analyses. The available or anecdotal information suggests that the Loop Current and secondary eddies are very active and that strong near-bottom currents exist. The bottom relief on the slope and rise is extremely rough and can drive different physical processes that are little understood or studied. Known processes that need to be studied included the interaction of LC eddies with the bottom topography, generation and evolution eddy-like features, topographic steering of flows, mid-water jets; inertial currents, and wind-driven flows. Also, more information is needed concerning

> the currents near the Mississippi Canyon where newly separated eddies begin their westward voyage across the deep Gulf.

Based on this workshop, MMS proposed a field study with objectives, methods, and significance that are described below.

> 1) to deploy arrays of moorings to collect oceanographic observation across the entire water column; 2) to coordinate with a parallel numerical modeling effort; and 3) to analyze and interpret these measurements using existing theories relevant to the oceanographic processes identified. Among potential processes to be examined are: interaction of LC eddies with the topography; generation and evolution of cyclonic features; topographic steering of flows; and wind driven circulation.

The observational methods were:

> This effort will deploy mooring arrays and conduct oceanographic cruises at suitable time intervals to resolve relevant temporal and spatial scales. Remote sensing data will also be employed to examine the synoptic thermal and sea surface topography of the area. Detailed surveys of important features will be conducted to investigate their characteristics.

And, the significance of the effort would be:

> The results from this study will provide information regarding the interactions of LC eddies with the topography; generation and evolution of eddy-like features; topographic steering of flows; wind driven circulation; and mid-water column jets. The study will support other ongoing studies by identifying the physical processes away and increasing the understanding of them and their interactions, and by providing data for numerical model verification. These results should provide MMS with values of the seasonal and annual variability of the physical processes studied. The results will also be available for completing risk assessments used by MMS for preparation of NEPA documents.

Clearly the participants in the 1997 workshop foresaw the important issues. The physical oceanography group at that workshop recommended that two studies be completed: “A Deepwater Physical Oceanography Reanalysis and Synthesis of Historical Data” and “A Study of Physical Processes Over the Slope and Rise Using Numerical Models.” During the past year these projects were funded and work initiated.

Since 1997, the industry has gone into even deeper waters than anticipated. Furthermore, the energetic currents that were then near speculation are now reality. Because of the pressing information needs, the MMS felt it necessary to develop further plans to speed the process of information gathering. To that end, the workshop reported on here was conceived.

PURPOSE OF THE WORKSHOP

- Update the community consensus on our knowledge of physical processes in the slope and rise region of the GOM
- Recommend topics for exploratory studies in FY2001
- Provide background for a possible "Deepwater Environmental Planning Workshop" in 2002
- Provide the groundwork for a possible "Complete Study of Deepwater Physical Oceanography" in 2004
- Provide a forum for exchange of information between scientists working in the GOM.

WORKSHOP STRUCTURE

The workshop format was designed to reach our goals and yet provide an open forum among nearly 100 participants. To reach a consensus on any topic with that many participants requires considerable organization and considerable adaptability. The organizers were able to achieve consensus by having a diverse steering committee that represented all participants. The steering committee met formally at least twice per day and informally at each break. Many mid-course changes were made to accommodate new scientific findings or realizations of a better way to reach our goal.

The workshop was organized to first provide an overview. A scientific overview was provided by five scientists who have extensively studied the region from different viewpoints. An overview of the management needs was provided by a scientist who has served on many oversight committees for MMS and by an MMS manager with responsibility for all activities in the Gulf.

After the overviews, we broke into three groups to independently assess what we do know about physical processes over the slope and rise and what we do not know yet need to understand.

The second day was devoted to addressing the processes deemed important during the previous days' activities. We also addressed new technology, the importance of physical oceanographic studies, and ways to increase collaboration between federal agencies, academia, and industry.

The final morning we reached a consensus on the types of studies that would increase our knowledge of the processes deemed necessary to understand.

In addition to the meetings and discussions, we urged the participants to share their results by displaying posters and showing computer visualizations of results.

ENERGETIC CURRENT EVENTS IN THE DEEPWATER GULF OF MEXICO: DATA NEEDS AND RECOMMENDED SAMPLING STRATEGY

Dr. Worth D. Nowlin, Jr.
Dr. Steven F. DeMarco
Dr. Ann E. Jochens
Dr. Matthew K. Howard
Mr. Robert O. Reid
Dr. Yongxiang Li
Texas A&M University

Texas A&M University is undertaking the Deepwater Physical Oceanography Reanalysis and Synthesis of Historical Data for the Gulf of Mexico supported by the Minerals Management Service of the U.S. Department of the Interior. The goals of that program are to inventory the physical oceanographic data from the deepwater region of the Gulf of Mexico (water depths greater than 200 m); to acquire and quality control as much of that data as possible; to produce a CD-ROM with the resulting data set; to examine that data and create a climatology of energetic current events; to prioritize those events in terms of needs for additional data; and to recommend a strategy for obtaining the needed observations.

We are well advanced with this Deepwater Program. Our draft synthesis report and CD-ROM are scheduled to be completed by the end of calendar year 2000.

Our work has included a review of the literature of the physical oceanography of the Gulf of Mexico. We are engaged in a new examination of the general background circulation in the Gulf using surface drifters, current meter measurements, traditional hydrography, satellite altimetry, and numerical circulation model output. In addition to the general circulation, we have described examples of the various phenomena/processes responsible for energetic current events known, or inferred, to exist in the Gulf. These include:

- The Loop Current and surface-intensified rings
- Currents generated by energetic wind events, including tropical storms and hurricanes, winter cyclones, cold air outbreaks and other frontal passages.
- Deep barotropic and bottom-trapped motions, including consideration of near-bottom currents associated with mega-furrows
- Near-inertial motions induced by flow over a sloping sea bed
- Other subsurface, mid-water column motions

Much of the initial effort on the Deepwater Program was spent identifying and obtaining data sets. Although this effort has resulted in the accumulation of a great wealth of data, some data holders are reluctant to release data. Others have released data with the proviso that they be held as proprietary. We have searched the current records available to us for evidence of energetic current events and have isolated segments of those records containing such events. We are completing the climatology of such information. We have identified ten classes of processes and phenomena that produce energetic current events and a method for prioritizing each in terms of the need for additional data. Finally, based on the foregoing information and on experiments carried out using model output, we have a provisional plan for the next program of measurements needed to understand, simulate, and predict the highest priority processes.

For purposes of prioritization, these processes and phenomena are subdivided into the following ten classes:

1. General surface-intensified circulation due to local wind forcing (e.g., Sturges 1993; Vázquez de la Cerda 1993)

2. General deep circulation (e.g., Oey 1996; Welsh and Inoue 2000)

3. Loop Current (e.g., Molinari and Cochrane 1972; Molinari and Morrison 1988; Sturges and Evans 1983; Sturges and Leben 2000)

4. Surface-intensified eddy-induced currents, including mesoscale cyclonic and anticyclonic rings and Loop Current eddies (e.g., Cooper *et al.* 1990; Elliott 1982; Forristall *et al.* 1992; Hamilton *et al.* 1999; Hamilton 1992; Vukovich and Maul 1985)

5. Motions induced by hurricanes and tropical storms (Brooks 1983; Shay and Elsberry 1987; Sanford *et al.* 1987; Price *et al.* 1994; Qi *et al.* 1995)

6. Motions induced by winter cyclones, frontal passages, and other energetic wind events (Qi *et al.* 1995)

7. Deep barotropic and bottom-trapped motions, including topographic Rossby waves, deep cyclonic and anticyclonic eddies, and eddy-pairs (e.g., Hamilton 1990; Sturges *et al.* 1993; Welsh and Inoue 2000)

8. Currents associated with mega-furrows (e.g., Dzulynski 1965; Allen 1969)

9. Near-inertial motions induced by flow over a sloping sea bed (e.g., Thorpe 1996)

10. Other subsurface, mid-water column motions

Currents associated with these processes/phenomena may not be distinct. For example, class 2 or class 7 may in fact be responsible for mega-furrows (class 8).

Three major criteria were selected for use in determining the priority of the need to obtain additional data regarding these classes of physical processes and phenomena. These are: improved level of understanding, improved ability to simulate and predict, and ability to observe.

The first criterion is the need to improve our level of understanding of the process/phenomena. For this criterion, a numerical rating was determined by weighting five factors, consisting of the level of general knowledge of the process/phenomenon available and four event-specific physical characteristics. The first factor considers our present ability to provide a general description of the process/ phenomenon and its causation. The four event-specific physical factors are frequency of occurrence, energy level, duration, and spatial extent. The frequency of occurrence criterion considers how often an event occurs. The energy level is based on how strong the associated currents are. Duration considers the temporal extent or how long the motions typically last. The spatial extent considers the size of the area over which the motions occur. These five factors then identify the relative need to improve our understanding.

The second criterion is the need to improve our ability to simulate and/or predict the motion in numerical models. This criterion addresses the question of whether enhancements are needed in the data base to reasonably model the occurrence and nature of the motion. It does not address the issue of whether improvements are needed in the modeling code or computing hardware. Four factors were used to determine the ratings for this criterion. These are the importance of additional data for (1) improving skill assessments, (2) making accurate predictions of impacts to structures/vessels/other human activities (i.e., engineering), (3) making accurate assessments of pollutant transports (i.e., environmental assessment), and (4) enhancing the ability to parameterize the motion in a deterministic model.

The third criterion, ability to observe, also was considered. This criterion examined the issue of whether there are reasonable measurement systems that could be designed to capture the motion. Except for the mid-water column motions, it was determined that systems could be designed to measure the other identified events. It should be noted that, to capture the motion, costs associated with the deep- and bottom-water column motions (classes 6, 7, and 8) might be relatively expensive, and measurement of currents associated with tropical storms and hurricanes would depend on whether a storm occurred during the measurement period. It was determined that the weight of this criterion should be less than the first two. This factor was weighed as half that of each of the other factors.

The emphasis in the ratings has been on assessing the need for additional data to improve our ability to understand and simulate/predict the motions generated by the physical processes and phenomena. The motions with the highest ranking are those about which the least is known or which are relatively high in energy for periods lasting on the order of weeks to months. The top three priority classes were associated with deep and bottom currents (deep barotropic and bottom intensified motions, the general deep circulation, and currents associated with mega-furrows); ranked fourth and fifth are eddy-induced, surface-intensified currents and the Loop Current.

The following constraints were considered in the design of measurement systems to measure priority events.

1. Relevancy of array location to the needs of the MMS/petroleum industry in leasing and drilling and production operations.

2. Adequacy of resolution of horizontal and vertical scales of priority events to be detected by the measurement array (array configuration and extent).

3. Adequacy of temporal resolution and duration of measurements consistent with that of the priority events.

4. Capability of the array to detect propagation of priority event signals across the domain of the array (array configuration and extent).

5. Adequacy of the type of measurement (fluid velocity and scalar properties) for characterization of the priority event.

6. Adequate signal-to-noise ratio, where noise is all energy associated with all phenomena other than the priority event (including measurement errors).

7. Availability of concurrent ancillary data such as ship or aircraft surveys, satellite altimetry, satellite-tracked drifters, and meteorological data.

To apply these design criteria, certain critical background information is needed. This information includes estimates of spatial decorrelation scales for currents, dominant EOF model patterns (vertical and horizontal) and the spectra of modal sequences, and propagation speeds of events.

In our application we have used the following information:

- Spatial scales of fluctuating deep currents from model output

- spatial scales of surface-intensified currents from measurements and literature

- Scales and propagation speeds of deep eddies from model output and literature

- Our EOF results using model output and measured currents

- Estimated vertical profiles of maximum and mean currents and standard deviations based on measurements

- Distributions of mean currents and variability estimates from model outputs

- Examination of energetic events of various kinds from measurements

- Examination of literature, and
- Region of interest to the MMS/petroleum industry

The recommended elements of an initial measurement program are:

- Long-term exploratory/statistics arrays extending through the water column at a limited number of locations. These will explore the statistical characteristics of currents and so contribute to knowledge of both deep and surface general circulation as well as of any energetic events occurring during deployments. Initial array may be limited in scope.
- Clusters of bottom measurements to supplement geological measurements and understand currents associated with mega-furrows.
- Scale/physics arrays located in the north-central deepwater Gulf. Both along- and across-isobath arrays should be deployed simultaneously. These will establish scales and propagation speeds of energetic fluctuations in deep water, enable more complete description and understanding of surface-intensified eddies, and provide detailed information on other categories of events present.
- Lagrangian measurement component in the deep basin (2,500-3,000 m) as a complement to Eulerian measurements. This measurement will describe the mean and variability of deep circulation including correlation scales. Data can be used also for estimating dispersion and the study of deep features.

Improving the climatology of deepwater currents found in the Gulf is important. All elements will contribute to that objective.

The prudent approach to an effective measurement program is one that begins with and builds upon the basics. We are not yet sure of scales or of physics, and any program that launches without this knowledge will likely be ineffective. Therefore, a measurement program should begin with observations needed to confirm scales and better understand physics. Needed is the flexibility to adapt the sampling focus during the course of the program. For example, results from initial deployments of appropriately long duration should be used to develop follow-on deployments of resources. The design and its evolution should be based on all evidence, not just current measurements. Output of numerical circulation models and implications from geological studies should be used together with physical measurements.

SUMMARY

Texas A&M University is undertaking the Deepwater Physical Oceanography Reanalysis and Synthesis of Historical Data for the Gulf of Mexico supported by the Minerals Management Service of the U.S. Department of the Interior. Following examination of physical oceanographic information available to us, we selected ten classes of energetic processes and phenomena in the deepwater region of the Gulf:

- General surface-intensified circulation due to local wind forcing
- General deep circulation
- Loop Current
- Surface-intensified eddy-induced currents
- Motions induced by hurricanes and tropical storms
- Motions induced by winter cyclones, frontal passages, and other energetic wind events
- Deep barotropic and bottom-trapped motions
- Currents associated with mega-furrows
- Near-inertial motions induced by flow over a sloping sea bed
- Other subsurface, mid-water column motions

Three major criteria were used to determine the priority of the need for additional data regarding these classes: improved level of understanding; improved ability to simulate and predict; and ability to observe

The top five priority classes were first deep and bottom currents (deep barotropic and bottom intensified motions, the general deep circulation, and currents associated with mega-furrows) and second with eddy-induced, surface-intensified currents and the Loop Current.

A suite of design criteria were used in considering measurements needed for priority classes of events. To apply those criteria, critical background information is needed, including estimates of spatial decorrelation scales for currents, dominant EOF model patterns (vertical and horizontal) and the spectra of modal sequences, and propagation speeds of events. The recommended elements of an initial measurement program are long-term exploratory/statistics arrays extending through the water column at a limited number of locations; clusters of bottom measurements to supplement geological measurements and understand currents associated with mega-furrows; scale/physics arrays located in the north-central deepwater Gulf; and a Lagrangian measurement component in the deep basin. An effective measurement program must begin and build on the basics. Because we are yet unsure of scales and physics, the program should begin with observations needed to confirm scales and better understand physics. Needed is the flexibility to adapt the sampling focus during the course of the program. The design and its evolution should be based on all evidence, not just current measurements. Output of numerical circulation models and implications from geological studies should be used together with physical measurements.

REFERENCES

Allen, J.R.L. 1969. Erosional current marks of weakly cohesive mud beds. J. Sedentary Petrology 39:607-623.

Brooks, D. A. 1983. The wake of Hurricane Allen in the western Gulf of Mexico. J. Phys. Oceanogr. 13(1):117-129.

Cooper, C., G. Z. Forristall, and T. M. Joyce. 1990. Velocity and hydrographic structure of two Gulf of Mexico warm-core rings. J. Geophys. Res. 95(C2):1663–1679.

Dzulynski, S. 1965. New data on experimental production of sedimentary structures. J. Sedimentary Petrology 35:196–212.

Elliot, B. A. 1982. Anticyclonic rings in the Gulf of Mexico. J. Phys. Oceanogr. 12:1292–1309.

Forristall, G. Z., K. J. Schaudt, and C. K. Cooper. 1992. Evolution and kinematics of a loop current eddy in the Gulf of Mexico during 1985. J. Geophys. Res. 97(C2):2173–2184.

Hamilton, P. 1990. Deep currents in the Gulf of Mexico. J. Phys. Oceanogr. 20:1087-1104.

Hamilton, P. 1992. Lower continental slope cyclonic eddies in the central Gulf of Mexico. J. Geophys. Res. 97(C2):2185-2200.

Hamilton, P., G. S. Fargion, and D. C. Biggs. 1999. Loop Current eddy paths in the western Gulf of Mexico. J. Phys. Oceanogr. 29(6):1180-1207.

Molinari, R. L., and J. D. Cochrane. 1972. The effect of topography on the Yucatan Current, pp. 149-155. *In* L. R. A. Capurro, and J. L. Reid. Contributions on the Physical Oceanography of the Gulf of Mexico. Houston, TX: Gulf Publishing Co.

Molinari, R. L., and J. Morrison. 1988. The separation of the Yucatan Current from the Campeche Bank and the intrusion of the Loop Current into the Gulf of Mexico. J. Geophys. Res. 93(C9):10 645-10 654.

Oey, L.-Y. 1996. Simulation of mesoscale variability in the Gulf of Mexico: sensitivity studies, comparison with observations, and trapped wave propagation. J. Phys. Oceanogr. 26:145-175.

Price, J. F., T. B. Sanford, and G. Z. Forristall. 1994. Forced response to a moving hurricane. J. Phys. Oceanogr. 24:233-260.

Qi, H., R. A. DeSzoeke, and C. A. Paulson. 1995. The structure of near-inertial waves during ocean storms. J. Phys. Oceanogr. 25:2853-2871.

Sanford, T. B., P. G. Black, J. R. Haustein, J. W. Feeney, G. Z. Forristall, and J. F. Price. 1987. Ocean response to a hurricane. Part 1: Observations. J. Phys. Oceanog. 17:2065-2083.

Shay, L. K. and R. L. Elsberry. 1987. Near-inertial ocean current response to Hurricane Frederic. J. Phys. Oceanogr. 17:1249-1269.

Sturges, W. 1993. The annual cycle of the western boundary current in the Gulf of Mexico. J. Geophys. Res. 98(C10):18 053-18 068.

Sturges, W., and J. Evans. 1983. On the variability of the Loop Current in the Gulf of Mexico. J. Mar. Res. 41:639-653.

Sturges, W., J. Evans, S. Welsh, and W. Holland. 1993. Separation of warm-core rings in the Gulf of Mexico. J. Phys. Oceanogr. 23:250-268.

Sturges, W., and R. Leben. 2000. Frequency of ring separations from the Loop Current in the Gulf of Mexico: A revised estimate. Manuscript.

Thorpe, S. A. 1996. The cross-slope transport of momentum by internal waves generated by along-slope currents over topography. J. Phys. Oceanogr. 26:191-204.

Vázquez de la Cerda, A. M. 1993. Bay of Campeche cyclone. Ph.D. Dissertation. Texas A&M Univ., College Station, TX. 91 pp.

Vukovich, F. M., and G. A. Maul. 1985. Cyclonic eddies in the eastern Gulf of Mexico. J. Phys. Oceanogr. 15:105-117.

Welsh, S. E., and M. Inoue. 2000. Loop Current rings and the deep circulation in the Gulf of Mexico. J Geophys. Res. 105:16 951-16 959.

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WHAT DO MODELS TELL US ABOUT THE DEEP-FLOW ENERGETICS IN THE GULF OF MEXICO?

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ABSTRACT

Previous observations (Hamilton 1990) suggest the hypothesis that episodic subsurface current events in the Gulf of Mexico (GOM) are caused by topographic Rossby waves (TRWs) forced by Loop Current (LC) pulsation (north/south extrusion and retraction) and Loop Current eddy (LCE) shedding in the eastern Gulf. While this hypothesis is supported by model results such as those presented in Oey (1996), the existence of TRWs in the model has never been rigorously established. This paper analyses results from a ten-year simulation of LC and LCEs, with resolution double than that used by Oey, are analyzed in this paper to isolate the TRWs. It is shown that over 60% of the simulated subsurface energetics reside in the 20- to 100-day periods (within which observations indicate TRWs) along various narrow bands over the continental slope and rise. The locations of these bands coincide with regions of linear TRWs that can be supported (in the 20- to 100-day) by the topographic slope and stratification (i.e. Brunt-Vaisala frequency) used in the model. A detailed analysis of the east-to-west high-energy band over the 2,800m to 3,400m isobath (i.e. across the Gulf from Florida west slope to Texas/Mexico border) indicate significant (to 95% confidence level) correlation (~0.5) between a (fixed) station just under where the modeled LCE is shed and stations further west. Contours of lag-times suggest offshore (i.e. down-slope) propagation and westward elongated energy band indicating therefore up-slope (and westward) group wave energy propagation direction. Finally, bottom intensification exists in these high-energy bands. All these factors indicate the existence of TRWs in the simulated sub-surface currents. Though the precise mechanism(s) through which these TRWs derive their energy is not yet resolved, the model suggests generation via propagating LCEs.

INTRODUCTION

Most of the materials in this report are preliminary, incomplete results of a study to understand deep motions caused by topographic Rossby waves (TRWs) in the Gulf of Mexico (GOM), by me and my colleagues. Our research is sponsored by the Minerals Management Service (MMS), to whom we are grateful.

Given that recent observations (at admittedly limited mooring sites on the slope and rise) suggest that deep-flow energetics reside predominantly in periods of the TRWs, from 20 to 100 days, it is of interest, as a first step towards gaining a better understanding of deep-flow dynamics in GOM, to search for evidence of these waves in a three-dimensional simulation of the Loop Current (LC) and Loop Current Eddies (LCEs). Since models are generally dynamically self-consistent, in the sense that their behavior is constrained by a set of well-defined conservation laws, correct interpretations of the model results should lead to a more solid set of hypotheses that one can test from observations.

To the best of my knowledge, Hamilton (1990) presented the first observational evidence of TRWs in GOM. Based on deep moorings over the slope and rise around the Gulf, east from Florida to northern and western Gulf, he found energy spectral peaks at 25, 45 and 100 days that correspond to nearly barotropic motions for depths deeper than approximately 1,500m. The current ellipses tend to align along-isobath and amplitudes tend to intensify near the bottom. Analyses showed that these motions have wavelengths of about 150km, phase velocities that are offshore and energy propagation that are westward with speeds of approximately 9km/day. Given the topographic slope and stratification in the Gulf, these correspond closely to the properties of TRWs.

Hamilton's work motivated Oey (1996; henceforth O96) to attempt identifying TRWs from his numerical model of the LC and LCEs in the Gulf. He also found nearly barotropic motions for depths deeper than 1,500m at stations over the slope and rise around the Gulf, along-isobath motions that intensify near the bottom, spectral peaks at 25, 50, 80 and 100 days, and westward energy propagation with speeds of about 12km/day. While Oey's findings were potentially important, in that a direct link between LC/LCE variability and bottom energetics was established, several issues remain. The first is whether or not the bottom energetics he found, though possessing many TRW-like features, were indeed TRWs. The second is how these motions, if indeed they were TRWs, were produced by the LC/LCE variability. There is also the question of whether or not at horizontal grid sizes of 20km (used in O96), a 150km TRW wavelength can be adequately represented. This report, describes our attempts to improve Oey's model and his analyses.

METHODOLOGY

The Princeton Ocean Model (POM) is used in an orthogonal curvilinear grid system that covers the region west of 55°W in the Atlantic, including the Caribbean Sea and the Gulf of Mexico (Figure 1). Steady inflow and outflow transports are specified at 55°W. This open boundary specification is sufficiently removed from the Gulf that, as in O96, dynamic interaction between the Caribbean Sea and the Gulf through the Yucatan Channel is allowed to be free. There are 26 sigma layers in the vertical. The horizontal grid sizes vary from about 10km in the vicinity of the LC, 5km in the northern Gulf, and 20km in the southwestern Gulf. Overall, the grid resolution is about double that used by O96. To remove ambiguity when interpreting the origin of the forcing to deep flows, all surface fluxes are zero. Thus (c.f. O96) the energy source for deep energetics comes entirely from LC and LCE variability.

The model was integrated until a quasi-equilibrium state in which regular, nearly-periodic LCE shedding occurs. This integration took approximately 2.5 years and continued through 10 years. Figure 2 shows snapshot examples (every 90 days) of contours of speed near the surface. Various characteristics of the LC and LCEs are as follows. The shedding period is approximately 10 months and LCE diameters are about 300 km. Once shed, modeled eddies tend to traverse across the Gulf

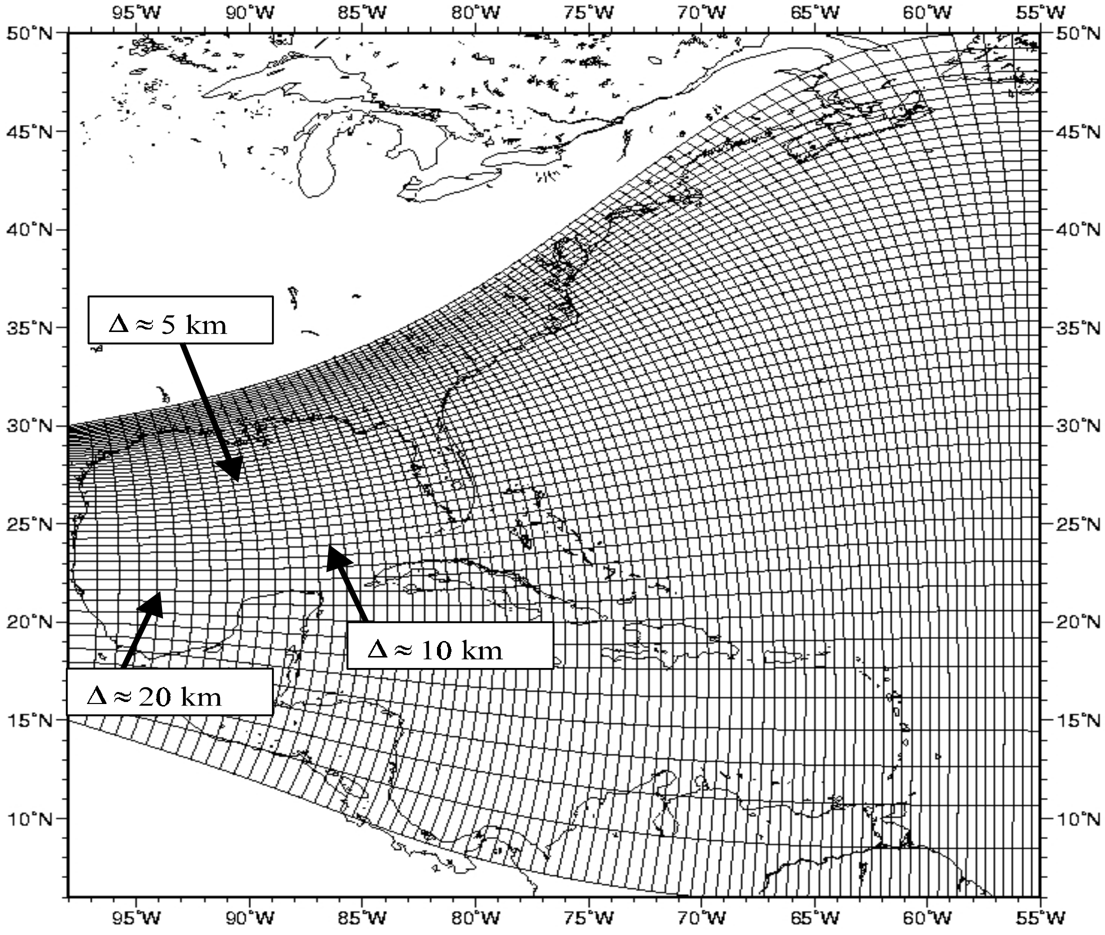

Figure 1. The model orthogonal curvilinear grid domain encompassing the entire Gulf of Mexico and Caribbean Sea, and portion of the Atlantic Ocean. Grid lines are shown at every seventh grid point. The approximate distribution of grid sizes in the Gulf is indicated and there are 26 sigma layers in the vertical, with vertical grid sizes less than 5m near the surface over the deepest region of the Gulf (~3500m). Time-independent inflow and outflow (total) transports are specified across the 55˚W, and surface fluxes are zero.

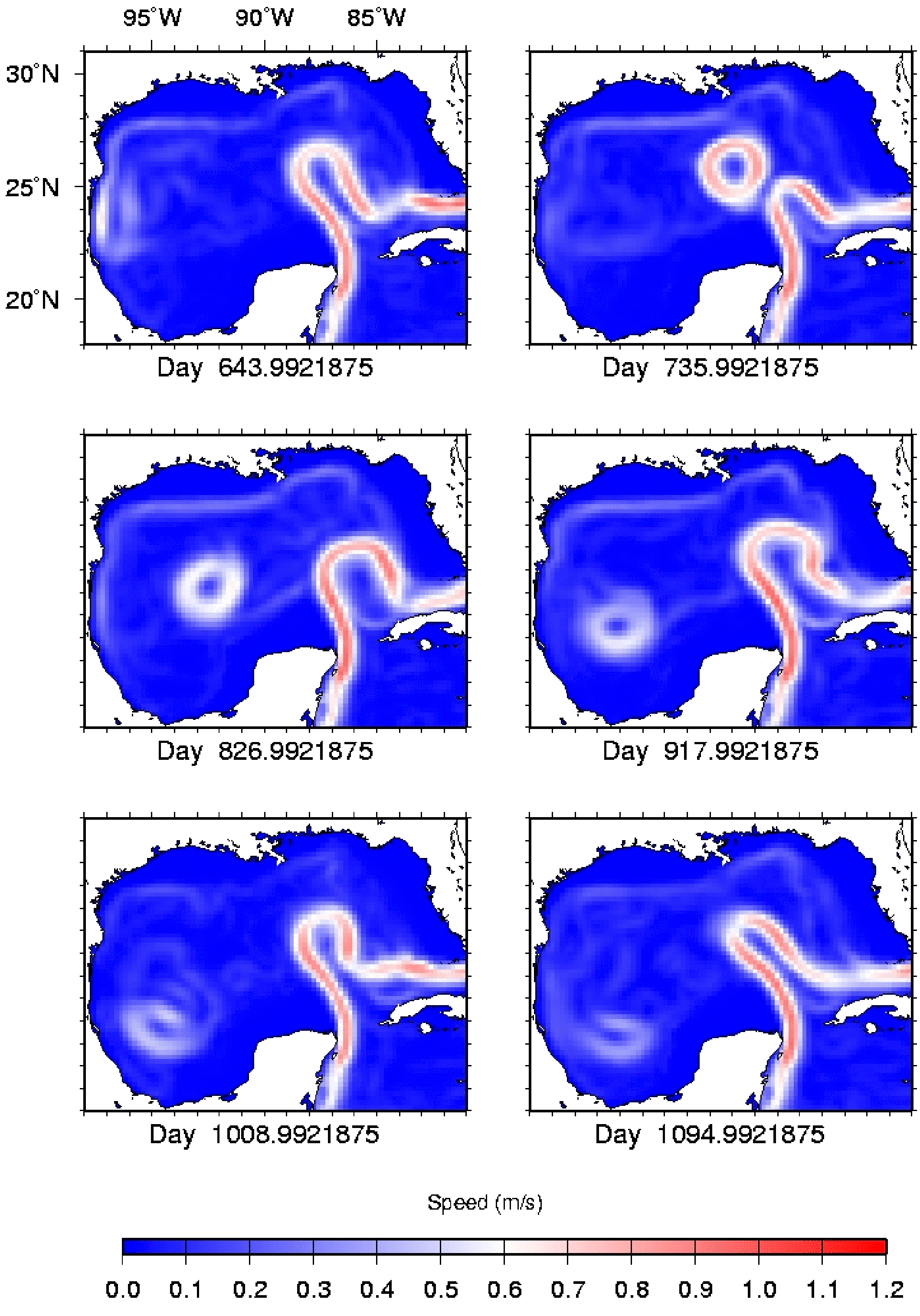

Figure 2. Sample speed images from the model at 90-day interval.

in a west/southwestward direction at speeds of approximately 4 to 5 km day^{-1}, and decay eventually in the southwestern corner of the Gulf (Figure 2). Typical swirl speeds and V/f (relative vorticity divided by local Coriolis parameter) around an eddy are 1.2 m s^{-1} and -0.4, respectively, while the corresponding values at the western edge of the LC in the Yucatan Channel are 1.5 m s^{-1} and 0.7. While the maximum swirl speeds are still lower than those typically observed, about 1.5 to 2 m s^{-1} (Kirwan *et al.* 1988; Forristal *et al.* 1992), they represent improvements over those found in O96, which gives values of 0.76 m s^{-1} (V/f » -0.25). Since the forcings are similar in the two calculations, improvements are a result of increased grid resolution (doubled) in the present case (c.f. Oey 1998).

For the purpose of identifying TRWs in the model, we find it useful to divide the model's results into four isopycnal layers, with layer 1 from surface to $27\sigma_t$ (~300 m thick), layer 2 from $27\sigma_t$ to $27.5\sigma_t$ (~500 m thick), layer 3 from $27.5\sigma_t$ to $27.7\sigma_t$ (~ 500 m thick), and layer 4 from $27.7\sigma_t$ to bottom. Since TRW motions are columnar and nearly barotropic at depths below about 1,000 to 1,500 m, we examine flow energetics in the fourth layer, i.e. below the $27.7\sigma_t$ surface (note that this lies approximately 1,000 to 1,500 m below the free surface). The modeled currents (daily averaged) are then depth-averaged in each layer. The depth-averaging in the fourth layer filters out non-columnar motions, as well as possible biases (of high energetics) that might occur in some region if a fixed level were used to search for TRWs. It also has the added advantage of filtering out any grid-point noise. The last 7 years of the 10-year run were then spectrally analyzed, and results in the 20- to 100-day, TRW band examined.

DEEP-FLOW ENERGETICS

Figure 3 compares the time series of lower-layer kinetic energy (LOKE) at a station just west of the LC (the 'X' point in Figure 4) with the corresponding 20-100 day band-passed LOKE (henceforth referred to as $LOKE|_{20\text{-}100d}$). It can be seen that at this station the band-passed series accounts for a major portion of the signal, in that amplitude and phase of the band-passed series generally match those of the total series. Thus the total LOKE consists primarily of fluctuating motions with periods from 20 to 100 days. From a series such as Figure 3, ratios of $LOKE|_{20\text{-}100d}$ to total LOKE at all grid points were computed and averaged over the last seven model years; contours are shown in Figure 4. It can be seen that there are banded regions in the Gulf where $LOKE|_{20\text{-}100d}$ accounts for over 60% of total LOKE. A conspicuous band extends from under the LC at (86^{o}W, 26^{o}N) to the west along the 3,000 m isobath. This is the band that we focus on.

To help ascertain that high $LOKE|_{20\text{-}100d}$ bands in Figure 4 are regions where TRWs might be prominent, we estimate regions in the (model) Gulf where TRWs with periods from 20 to 100 days and wavelengths ~ 150 km can be supported. The estimate is based on the following (linear quasigeostrophic) dispersion relation (Pickard 1995):

$$w.l_v.\tanh(l_v h) = N^2.(kh_y - lh_x)/f, \quad (1)$$

where $l_v = (k^2+l^2+bk/w)^{1/2}$ N/ f, *(k,l)* the wave number vector, *w* the period, h the water depth, *N* the Brunt-Vaisalla frequency, *b* the planetary beta and subscripts *'x'* and *'y'* represent partial derivatives. Setting k ~ l = 2p/150 km, and N = 10^{-3} s^{-1} (» averaged model value in the lower layer) we

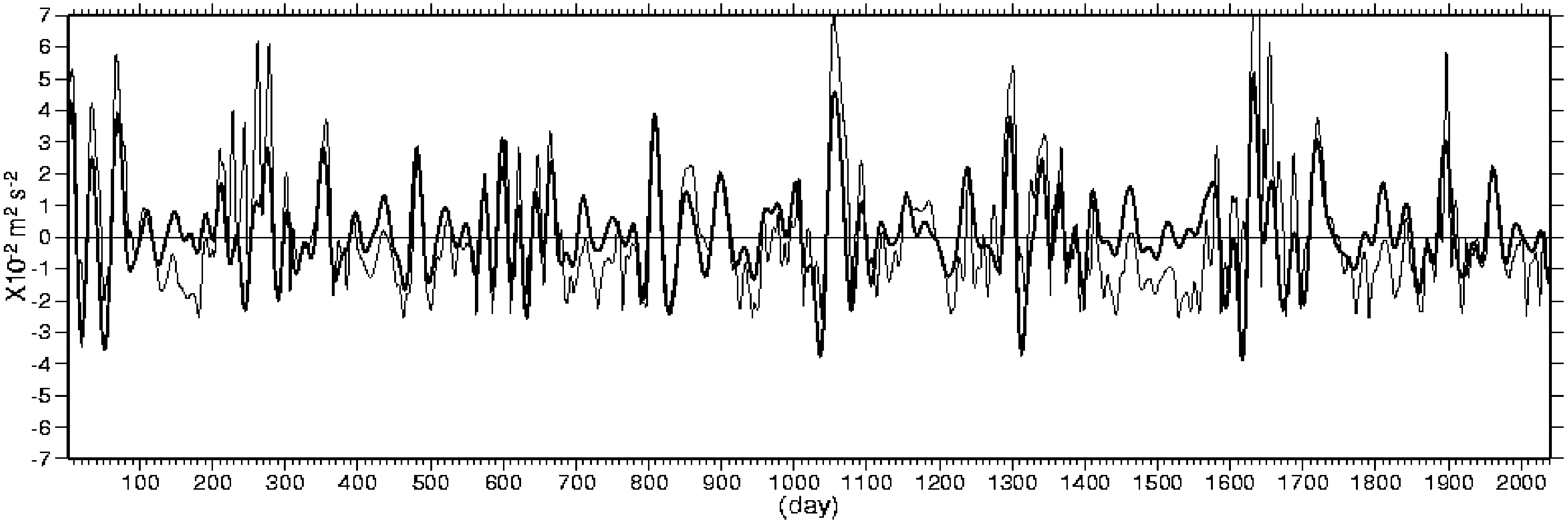

Figure 3. A comparison of the kinetic energy time series in the model's lowest-most (4th) layer, at the point indicated in Figure 4: band-passed, 20- to 100-day, series (thick curve), and total series (thin curve).

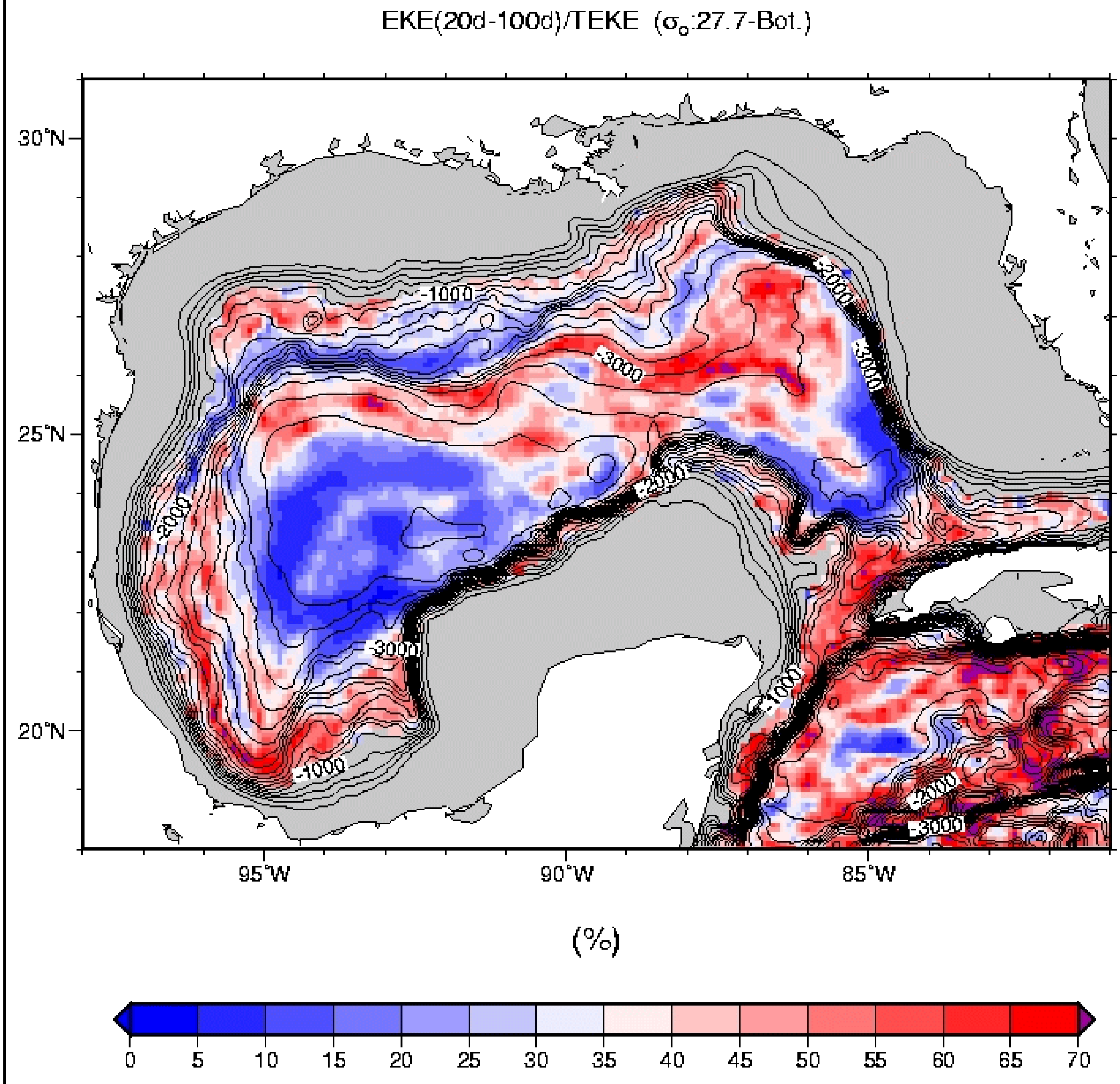

Figure 4. The lower-layer EKE in the 20- to 100-day period band, expressed as a ratio (%) to the lower-layer EKE in the entire spectral band.

superimpose on the contours of LOKE$|_{20\text{-}100d}$ in Figure 5 regions where 2p/w (from equation (1)) has values between 20 and 100 days (hatched). One sees that the aforementioned high LOKE$|_{20\text{-}100d}$ band along the 3,000 m isobath, for example, is indeed in region where TRWs with periods 20 to 100 days (and wavelengths ~ 150 km) can be supported by the model topography and stratification (i.e. N). There are also regions, however, where LOKE$|_{20\text{-}100d}$ is high but TRWs cannot be supported (i.e. under the LC). We will return to this point later.

The high LOKE$|_{20\text{-}100d}$ band along the 3,000 m isobath suggests a region where motions, *presumably* due to TRWs, might be related. A time-lagged correlation of the LOKE$|_{20\text{-}100d}$ time series (e.g. Figure 3) at the 'X' point in Figure 4 with all other grid points might therefore cast further insight into the nature of the TRWs in the model. The top panel of Figure 6 shows contours of the maximum lagged correlation (at 95% significance level) in the 3,000 m isobath, high LOKE$|_{20\text{-}100d}$ region, from 86^{o}W to 92^{o}W, and the second panel the lags in days. The third and fourth panels show LOKE$|_{20\text{-}100d}$ itself and LOKE$|_{20\text{-}100d}$ percent values (as in Figure 4), respectively. As expected, the high LOKE$|_{20\text{-}100d}$ band coincides with region of significant correlation, with values of about 0.4 at distances some 400 km west of the 'X' point (95% significance level is » 0.15 at this western point). The significant correlation does not imply, however, a simple east-to-west wave propagation. Indeed, in the vicinity of the 'X' point, the time-lag contours suggest a wave *phase* propagation from northeast to southwest[1]. Since isobaths are approximately east/west in this region, one can show, upon setting $h_x=0$ in equation (1) that, both ω/k and ω/l are < 0, and that $\partial\omega/\partial k < 0$ and $\partial\omega/\partial l > 0$. Thus phase velocity is westward and *offshore*, while group velocity is westward but *onshore*. The time-lag contours of Figure 6 thus give further credence to our claim that the high LOKE$|_{20\text{-}100d}$ regions of Figure 4 are bands of TRW activity. On the other hand, since wave group propagates onshore (and westward), why do high LOKE$|_{20\text{-}100d}$ and significant correlation persist hundreds of kilometers to the west despite TRW strong dispersion?

To understand the nature of TRW propagation in the model as exemplified by the question posed above, we first examine if the vertical structure of KE spectra in the 20- to 100-day at selected sample stations within the high LOKE$|_{20\text{-}100d}$ region show bottom intensification. This bottom intensification (or lack of it) will be taken as further eviidence for the existence (or nonexistence) of TRW at the selected stations. The selected stations are marked as 'O' in Figure 7, and results for five of the twelve stations are shown in Figure 8. Apart from the eastern-most station #1, all other stations are in the region where TRWs are supported (Figure 5). Bottom intensification exists at stations 4, 6 and 8[2] and is barely discernable at station #10. At station #1, the lack of bottom intensification *and* high LOKE$|_{20\text{-}100d}$ ratio (Figure 5) suggest that lower-layer energetics there are produced by direct LC and LCE shedding variability, rather than by TRWs; i.e. station #1 is near the source of TRWs. The weak bottom intensification at station #10 (and #11 and 12 also, not shown) suggests weak TRW activity in the western portion of the Gulf.

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[1] Strictly speaking, time-lag contours and phase lines are equivalent only for monochromatic waves. Further analyses are needed to confirm that this holds true (approximately) in the present case of assemblage of wave with periods from 20 to 100 days.

[2] Except for station #6, other stations in the figure show mild bottom intensification. However, bottom intensification is much more pronounced for individual TRW peaks, e.g. the 45-day period.

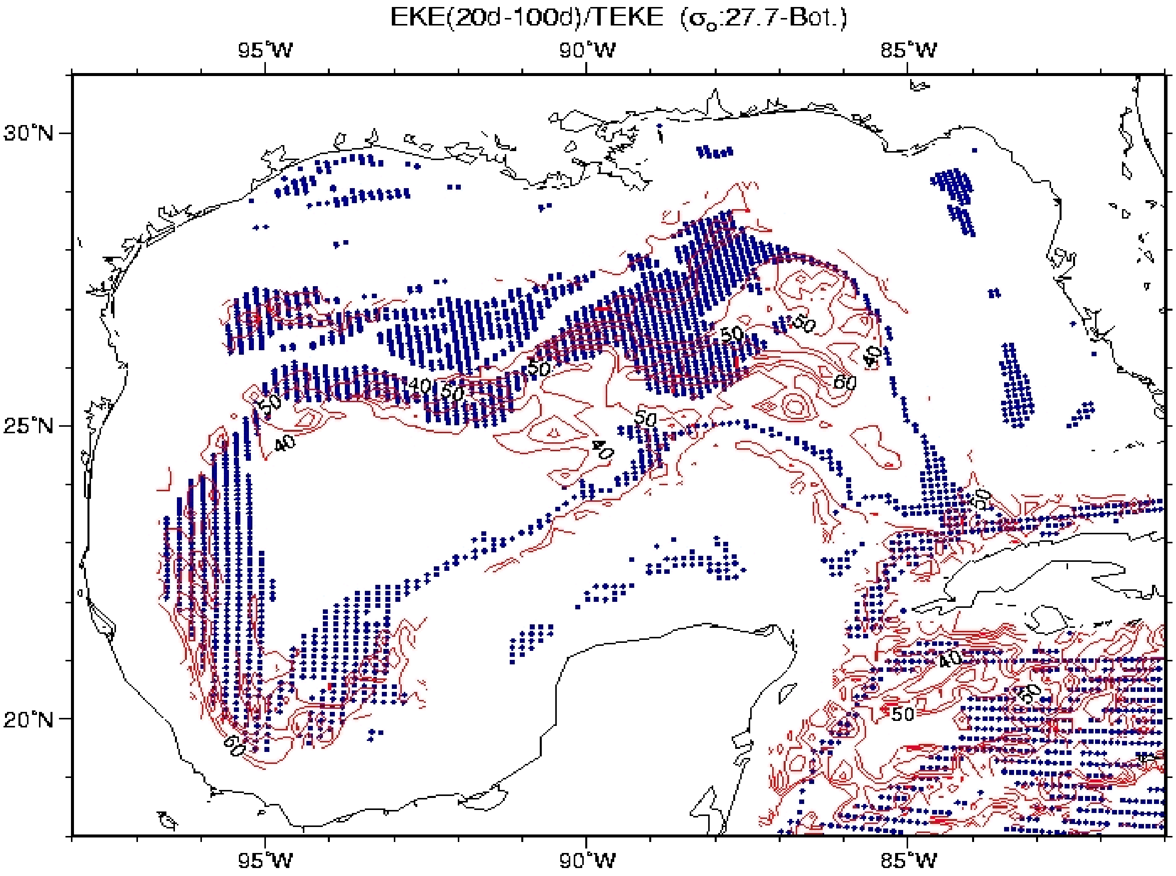

Figure 5. The hatched regions are where TRWs with periods of 20 to 100 days and wavelength = 150 km can be supported based on the model topography and stratification. Contours are ratios (expressed as %) of the lower-layer EKE in the 20- to 100-day period band to the lower-layer EKE in the entire spectral band. Only those values that exceed 40% are contoured.

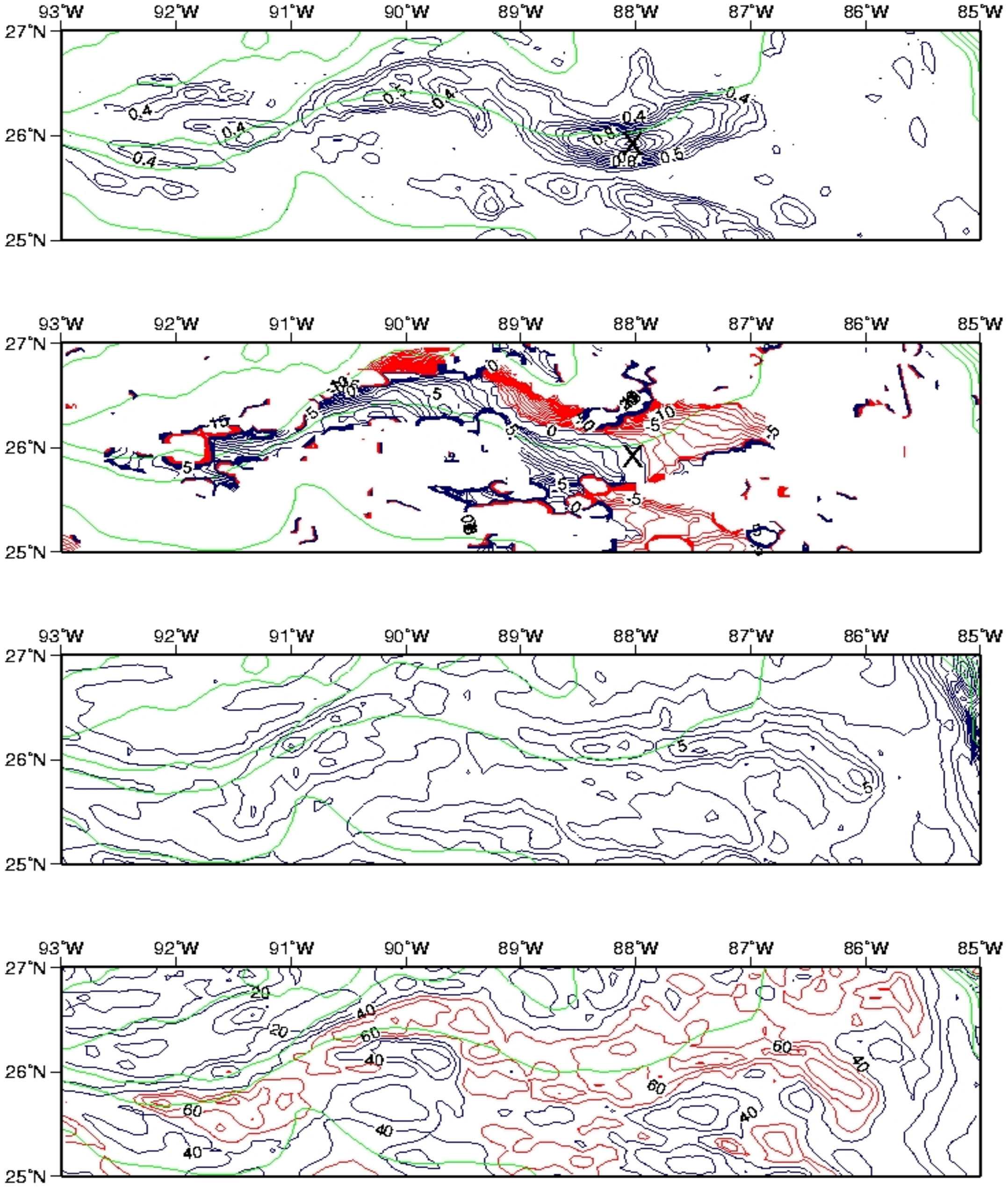

Figure 6. Top panel: contours of maximum lagged correlation (at 95% significance level) in the 3,000 m isobath, high LOKE$|_{20\text{-}100d}$ region, from 86˚W to 92˚W; second panel: the corresponding lags in days; the third and fourth panels show LOKE$|_{20\text{-}100d}$ itself and LOKE$|_{20\text{-}100d}$ percent values (as in Figure 4), respectively. Here LOKE$|_{20\text{-}100d}$ is the lower-layer EKE in the 20-100day spectral band.

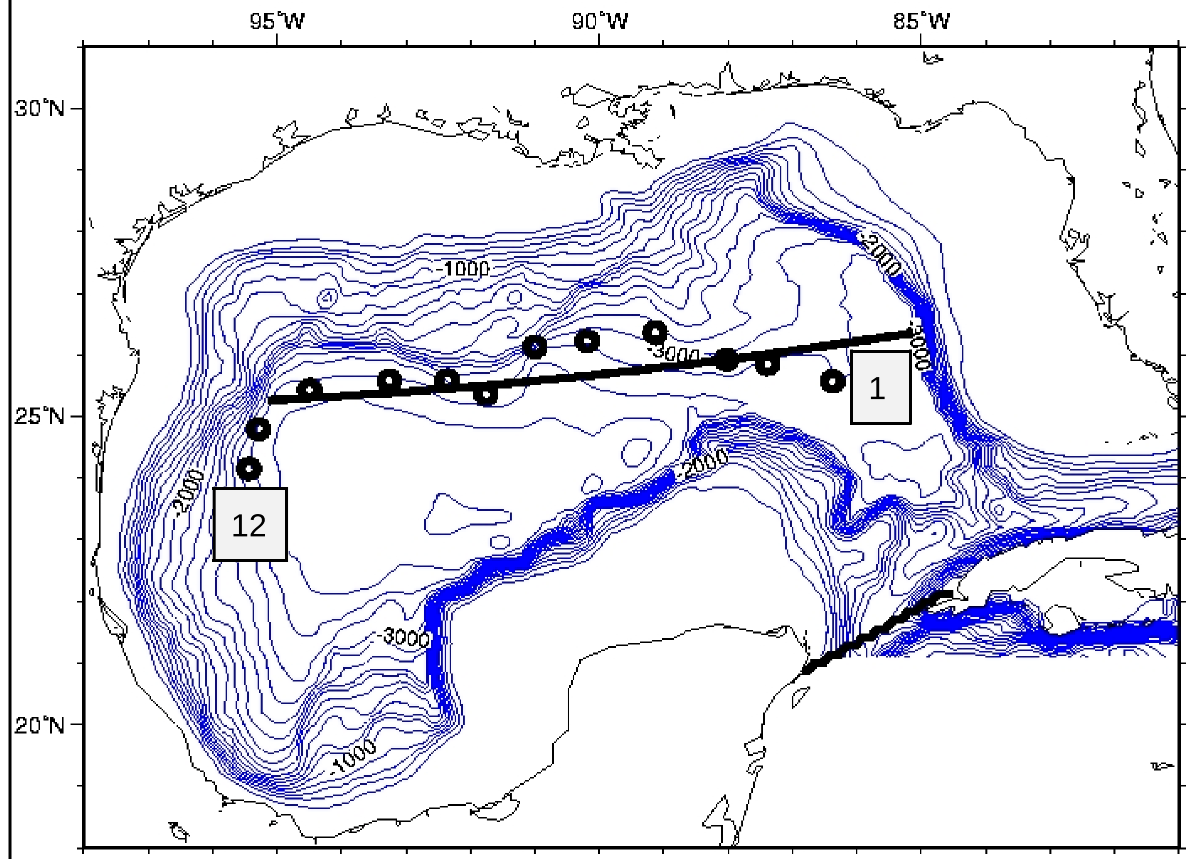

Figure 7. The selected 12 sample stations (marked as) within the high $\text{LOKE}|_{20\text{-}100d}$ region of Figure 4. Also shown is the east/west line through which vertical section contours of model's velocities will be shown in Figure 12.

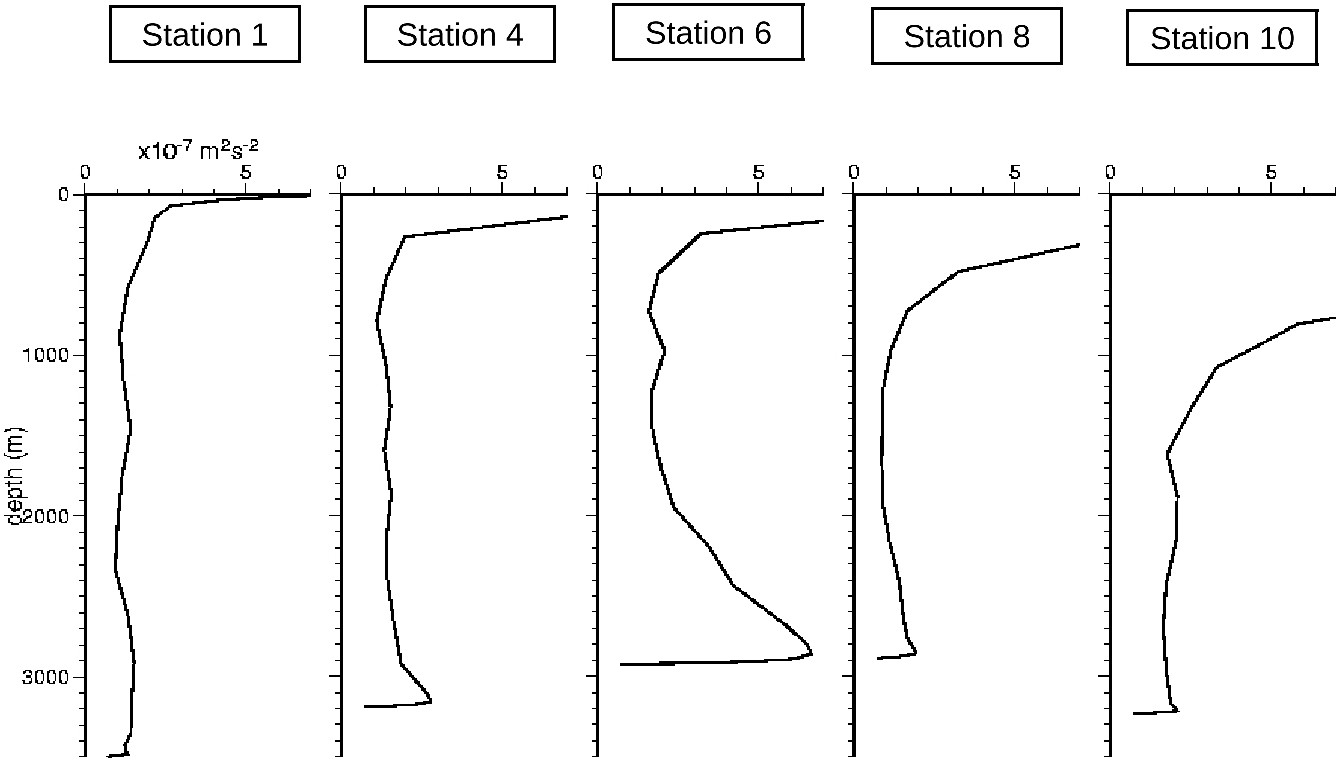

Figure 8. The vertical structure of KE spectra in the 20- to 100-day at 5 of the 12 selected stations shown in Figure 7.

In summary, there is strong evidence that the high LOKE$|_{20\text{-}100d}$ along the 3,000m isobath is related to TRWs. The energy source, at least for the eastern portion of the Gulf (from station 2 to approximately station 7), resides in variability due to the LC and LCE shedding at approximately (86^{o}W, 26^{o}N) under the LC. However, despite significant correlation along the 3,000m isobath from east to west, it is unlikely that the westward spread or propagation of this energy source in deep layers is entirely due to TRWs, since the latter are highly dispersive and energy propagates onshore as well as westward.

GENERATION OF DEEP FLOW ENERGETICS

We now offer *incomplete, tentative* explanations of how the high LOKE$|_{20\text{-}100d}$ band along the 3,000m isobath may be an imprint of energy emitted from LC vacilations, LCE sheddings and propagating LCEs. Research is ongoing to study the problem more completely.

Figures 9 and 10 show three year time-series plots of KE for the upper-most layer (layer 1; Figure 9) and the lower-most layer (layer 4; Figure 10) at the twelve stations shown in Figure 7. The period covers four LCE shedding events indicated by ‘E’ below the abscissa. The layer 1 KEs in the eastern stations (#1-3) show these events as peaks punctuated in between by peaks caused by LC vacillations (but no sheddings). While the dominant period is approximately 150 days (5 months)[3], episodically higher-frequency oscillations (periods » 10 to 20 days) precede LCE shedding. Such oscillationa are particularly clear at station 3 and are related to peripheral meanders that traverse around the LC. Further west, at stations 4 through 8, a clear signal of westward propagating LCE emerges, at a speed of approximately 4 to 5km day^{-1} (c.f. Oey 1996). The amplitude diminishes westward as propagating LCEs move away from the continental rise on their predominantly southwestward course. In Figure 11, 30-day snapshots of V/f at z=-50m show an example of this LCE path.

The layer 4 KE time series (Figure 10) shows strikingly different characteristics from its upper-layer counterpart. Most notable is the occurrence of higher-frequency motions dominated (of course) by energy in the 20- to 100-day band. The response can be further classified into three groups: 1) from stations 1 through 6 (near the energy source, either near the LC and LCE sheddings stations 1-3, or near the propagating LCE stations 4-6) at which shorter-period (<50 days) motions dominate; 2) from stations 7 through 10 at which longer-period motions (>50 days) appear; and 3) stations 11 and 12 at which motions with mixed periods exist[4]. In group 1, at station 3 in particular, there exist bursts of energy of short periods (10 to 20 days) caused by above-mentioned peripheral surface meanders around the LC (Figures 9 and 10). These short-period motions can be seen as far west as station 6, but one can barely see propagation of these motions along stations 3 through 6. In group 2, the short-period energy bursts of group 1 can no longer be seen, replaced by longer-period motions that similarly show only a slight trace of westward propagation. Motions in group 3 are even more

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[3] Why this is so, or for that matter why shedding period is approximately 10 months, is unclear. A detailed study that examines closely the LC path and sensitivity to model sensitivity is necessary.

[4] More exact analyses are clearly necessary to identify the various spectral peaks.

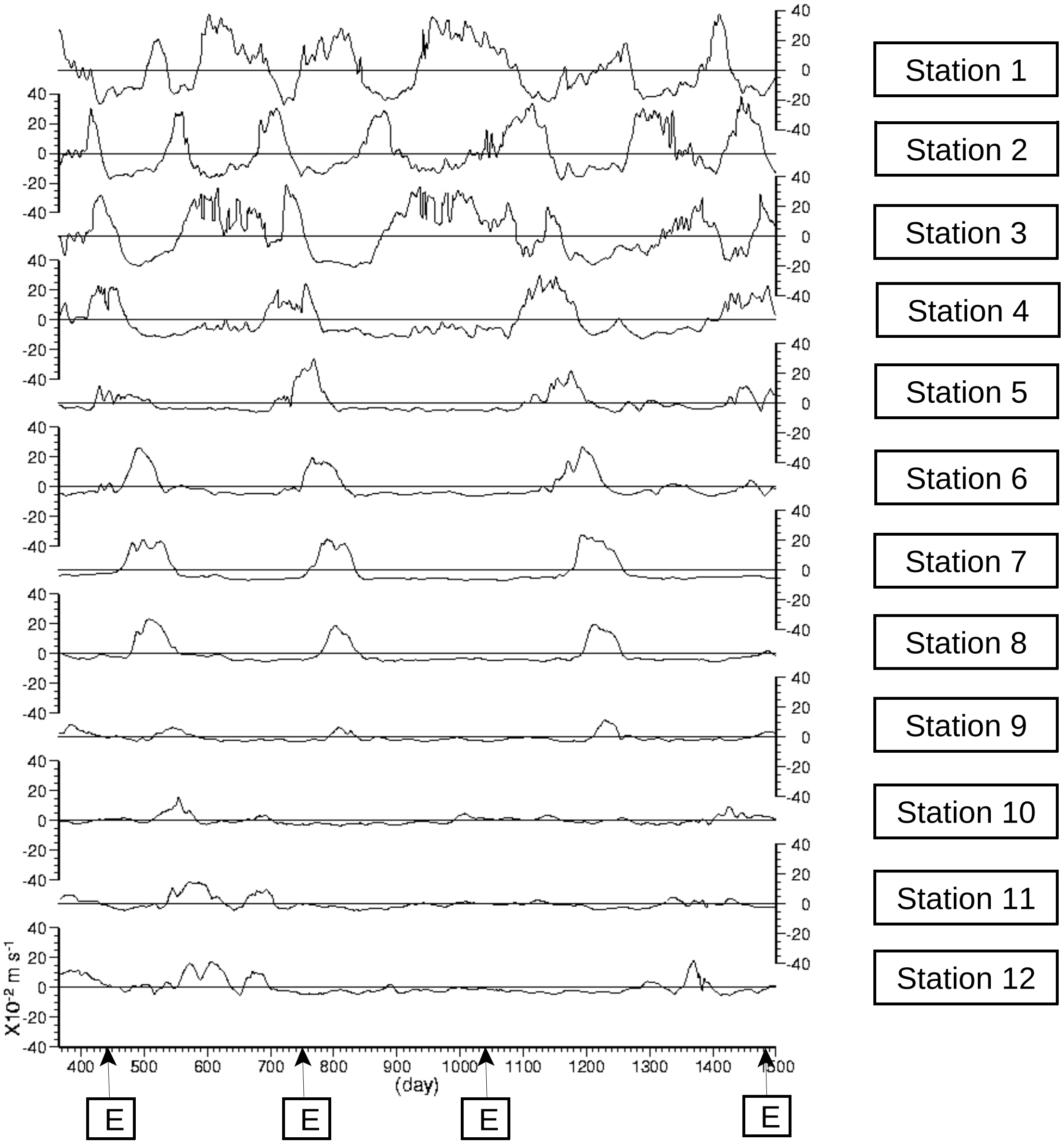

Figure 9. Three year time-series plots of KE for the upper-most layer (layer 1) at the twelve stations shown in Figure 7. The period covers four LCE shedding events indicated by below the abscissa.

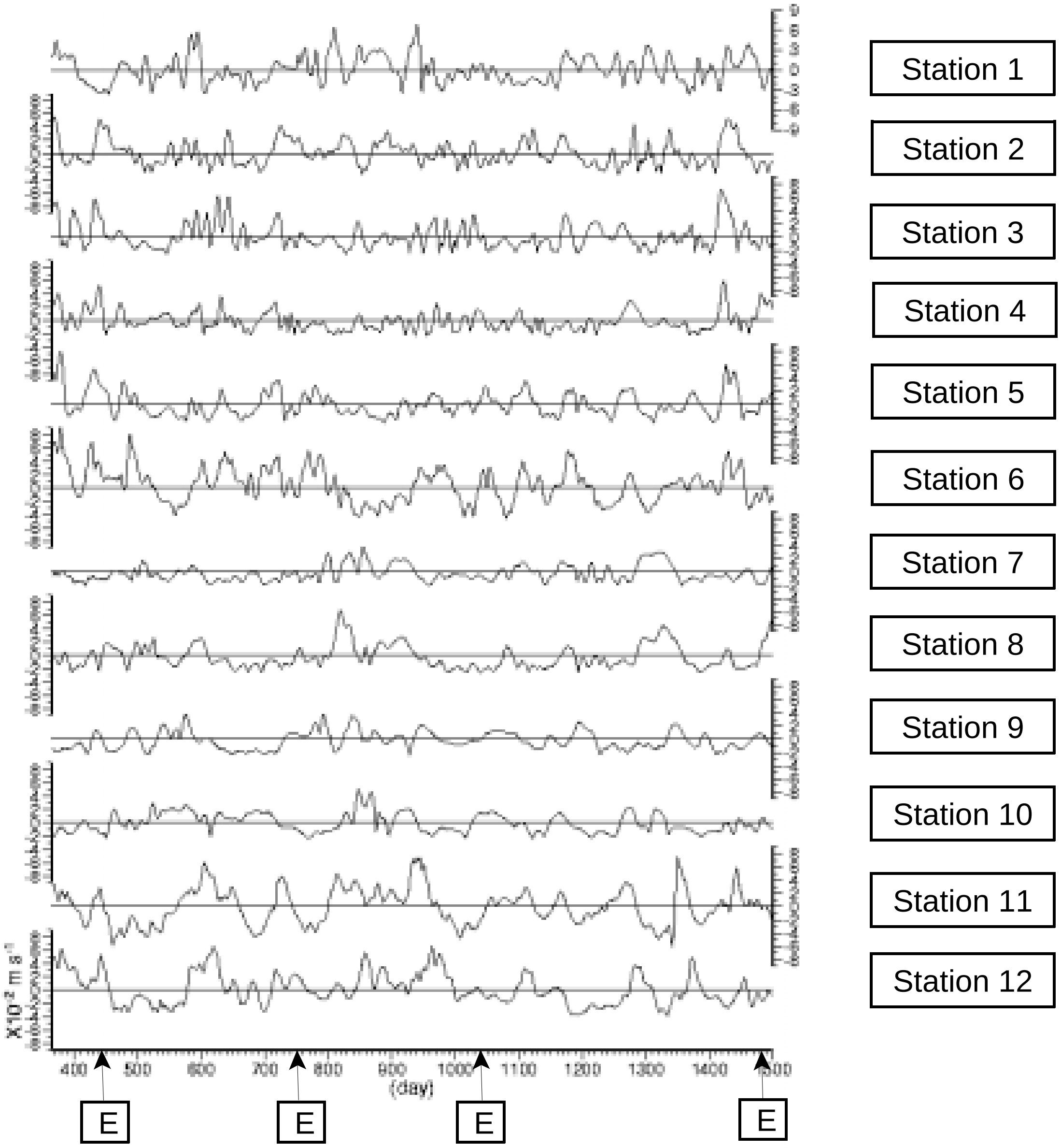

Figure 10. Three year time-series plots of KE for the lower-most layer (layer 4) at the twelve stations shown in Figure 7. The period covers four LCE shedding events indicated by below the abscissa.

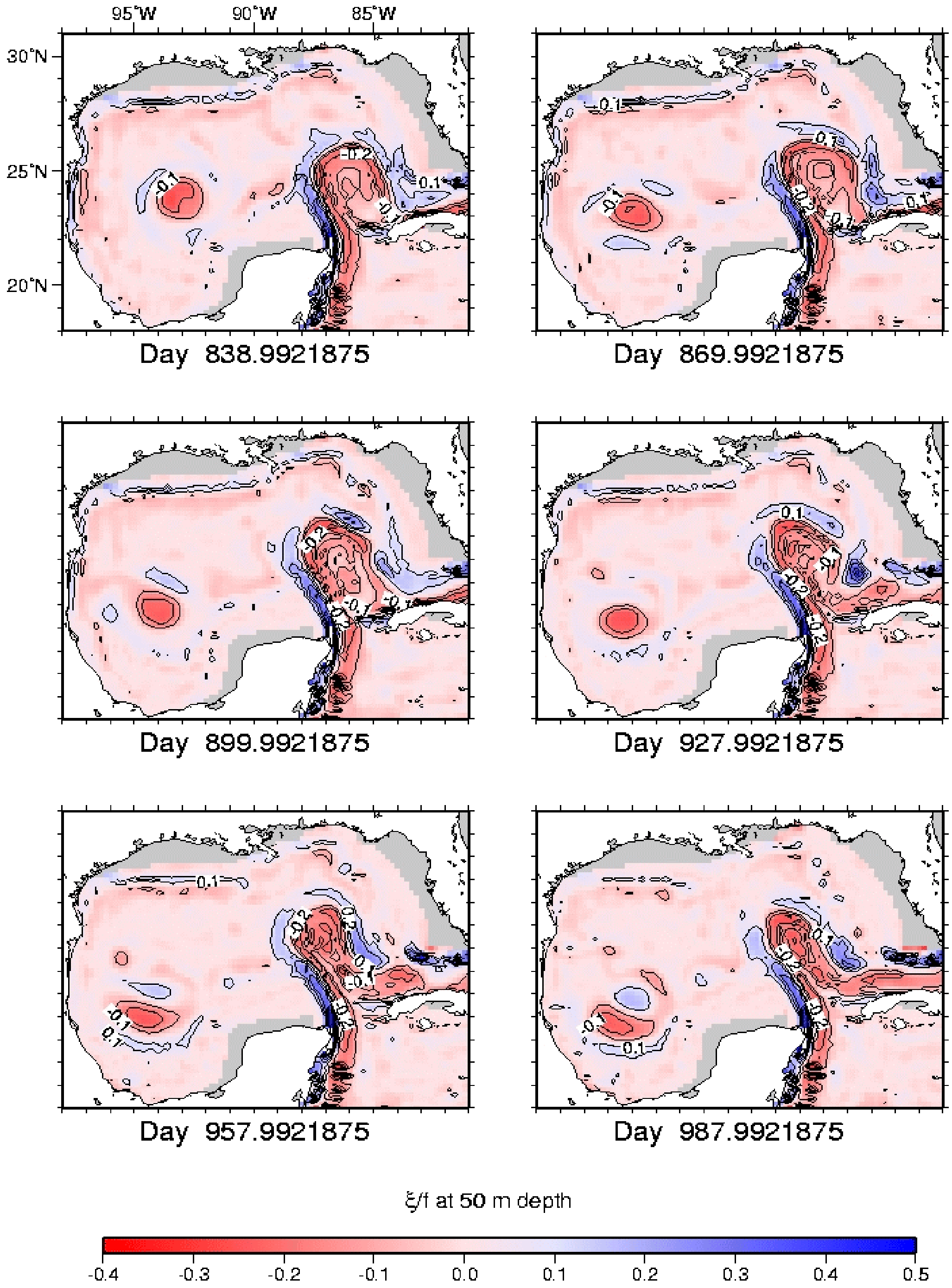

Figure 11. Thirty day snapshots of relative vorticity (ξ/f) at z=-50m showing LCE shedding and southwestward propagation. The LC north/south vacillations, LCE shedding and propagation excite bottom motions exemplified by vertical section contours of Figure 12.

complex and show no clear signal of TRWs, in that the two selected stations 11 and 12 are outside the high LOKE$|_{20\text{-}100d}$ region and show no bottom intensification (not shown).

We conclude from these time-series plots (Figures 9 and 10) that the surface- and bottom-layer motions have fundamentally different characteristics, in that the former have periods of about 150 days and longer, while the latter are shorter than 100 days. However, superimposed on the long-period surface motions are peripheral meanders that propagate around the LC. The meanders excite motions of 10-20 day periods that penetrate also to the bottom layer. Apart from these meander-related, directly-forced deep motions, the short-period bottom motions are most certainly topography-induced. Not only do these motions have short periods (20-100 day), their spatial structures are also quite distinct from those near the surface. Figure 12 shows 30-day snapshots of vertical sectional contours of the north/south velocity across the Gulf along the transact shown in Figure 7. In the upper 500m, one sees a structure dominated by the presence of LC and LCEs, particularly when the latter are near the transect (upper left panel). In the lower layer, and after the passage of a LCE, motions are columnar with peak-to-peak separating distances of about 100-200km. These short-period and short-wavelength motions are particularly unambiguous in far-west region away from direct LC influence (stations 6 through 10 of Figures 7, 9, and 10), where there is a clear separation of short-period bottom signals from those of longer period near the surface. In region of direct LC influence (stations 1 through 5), peripheral meanders around the LC have non-negligible effects on bottom motions.

Deep-flow motions produced in the model are unambiguously generated by LC and LCE variability, since these are the only significant variability that can be generated in the Gulf by the constant transport we specify at the 55^{o}W open boundary in the Atlantic. How these predominantly surface-trapped (z>-1,000m) variability excite deep motions is a scientific problem that we wish to address, at least in the model. Unfortunately, our analyses have not gone far enough to enable us to resolve the issue at present. Pedlosky (1977) suggested that propagating meanders can excite bottom motions if the meanders' phase velocity is in the same direction as the Rossby (planetary or topographic) wave phase velocity. It is conceivable that the model's surface motions comprising of LC fluctuations, peripheral meanders, and propagating LCEs can satisfy Pedlosky's conditions in certain instances. This would explain why there exists a significant and fairly high (0.4) correlation between east/west stations too far (~400km) apart for dispersive nature of TRWs to retain identity (Figure 6): they are related through a common forcing by the westward propagating LCE (see top-left panel of Figure 11). The details obviously require more in-depth analyses.

CONCLUSION

The ultimate goal is to understand the mechanism(s) by which bottom-trapped topographic Rossby waves (TRWs) over the continental slope and rise of the Gulf of Mexico (GOM) are generated by Loop Current (LC) and Loop Current Eddy (LCE) variability. As a first step, we report here our attempt in finding evidence for TRWs from a circulation model of the Gulf of Mexico. A ten-year, primitive-equation model simulation forced by constant transport from the Atlantic was conducted

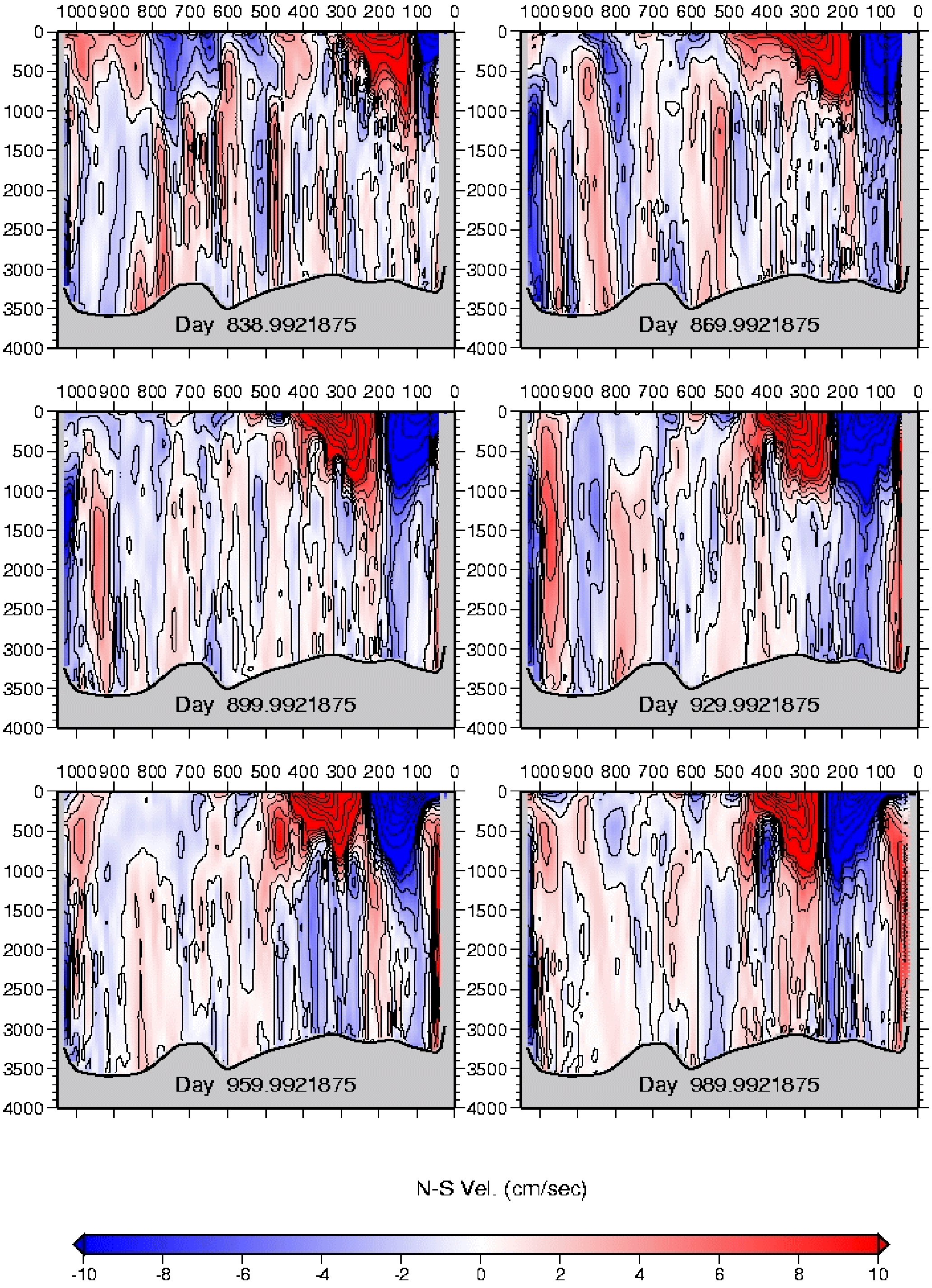

Figure 12. Thirty-day snapshots of contours of north/south velocity in the vertical sectional plane across the Gulf as shown in Figure 7. Note the columnar structures in deep layers with peak-to-peak separating distances of approximately 200km.

so that regular LCE sheddings occur. Deep-layer analyses were then performed to band-pass motions with 20- to 100-day periods, a range that corresponds to that found for the observed deep energetics at the few current-meter locations in the Gulf. We found that in certain well-defined regions, in a semi-circular loop over the 3,000m isobath around the Gulf in particular, the band-passed energetics account for over 60% of the deep motions (Figure 4). Moreover, we confirmed that, at least over the northern half (i.e. the U.S. side) of the loop, the high-energetics regions coincide with regions where, according to linear dispersion relation, TRWs in the 20-100 day periods can be supported by the model's topography and stratification. These regions are also where bottom-intensification of energetics occur, where there are significant correlations (at 95% confidence level) with locations near the LC (and LCE sheddings), and where time-lag contours suggest offshore and westward phase velocities. All these findings suggest that the high bottom-energetics over the 3,000m correspond to TRWs.

A number of possible sources for surface-to-bottom energy transfer in the model are given. The first is direct short-period (10-20 days) forcing by propagating peripheral meanders around the LC; the second is LC north/south vacillation and LCE sheding; the third is westward propagating LCE just offshore of the 3,000m isobath. The first and third of these might emit energy through coupling of the TRW and meander/eddy propagating phase velocities.

ACKNOWLEDGMENTS

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REFERENCES

Forristal, G.Z., K.J. Schaudt, and C.K. Cooper, 1992: Evolution and kinematics of a Loop Current eddy in the Gulf of Mexico during 1985. *J. Geophys. Res*., 97: 2173-2184.

Hamilton, P. 1990. Deep currents in the Gulf of Mexico. *J. Phys. Oceanogr*., 20: 1087-1104.

Kirwan, A.D., Jr., J.K.Lewis, A.W. Indest, P. Reinersman, and I. Quintero, 1988. Observed and Simulated Kinematic Properties of Loop Current Rings. *J. Geophys. Res.*, 93, 1189-1198.

Oey, L-Y., 1996. Simulation of mesoscale variability in the Gulf of Mexico, *J. Phys. Oceanogr.*, 26, 145-175.

Oey, L-Y. 1998. Eddy energetics in the Faroe-Shetland Channel, *Cont. Shelf Res*., 17: 1929-1944.

Pedlosky, J., 1977. On the radiation of meso-scale energy in the mid-ocean. *Deep Sea Res.*, 24, 591-600.

Pickart, R.S., 1995. Gulf Stream-generated topographic Rossby waves. *J. Phys. Oceanogr.* 25, 574-584.

DEEP CURRENTS OVER THE NORTHERN GULF OF MEXICO SLOPE: OBSERVATIONS AND DYNAMICS

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INTRODUCTION

Observations of the water column over the deeper waters in the Gulf of Mexico basin indicate that there is a basic two-layer structure. Above ~800- to 1,200-m depth, the circulation is dominated by the Loop Current in the east, anticyclones shed from the Loop Current in the central and western basin, and smaller-scale cyclones and anticyclones that are probably generated by the major eddies. This upper layer has vigorous flows that result from the eddies and interactions between the eddies. These flows often have strong vertical shears. Below ~1,000 m, limited measurements have shown that currents are nearly depth-independent with a tendency for bottom intensification. These lower-layer flows do not have a strong relationship to simultaneous current fluctuations in the upper layer. Hamilton (1990) suggested that these deep motions were the result of topographic Rossby waves (TRW) propagating westward across the slope and rise of the basin. Similar kinds of deep motions have been extensively studied in the Mid-Atlantic Bight where there is evidence that they are generated by meanders of the Gulf Stream (Pickart 1995). In the Gulf, it seems plausible that deep TRWs are generated by Loop Current (LC) fluctuations, Loop Current eddy (LCE) shedding events, and the propagation of LCEs across the Gulf. The latter could include the interaction of LCEs with topography and other eddies in the basin. However, the generation mechanisms are not presently well understood.

This paper discusses the observational evidence for deep TRW motions from the data used by Hamilton (1990) and some very recent deep current measurements which have some surprising characteristics. The paper also reviews the ability of the numerical model used by L-Y Oey (this volume) to reproduce some characteristics of the observations. Finally, the paper identifies major issues for the increased understanding of TRWs in the Gulf, along with some preliminary ideas for the design of field studies to begin to isolate the responsible processes.

OBSERVATIONS OF DEEP CURRENTS

Hamilton (1990) used moored current meter measurements under the LC in the eastern Gulf, along 92W in the central Gulf, and in the western Gulf, to show that 80 to 90% of the velocity variance deeper than 1,000 m could be explained by TRWs (Rhines 1970). Moreover, he found a significant correlation of the eastern and western velocities that implied a minimum propagation speed of 9 km/day. This finding agreed quite well with calculated group velocities for TRWs with 100- to 200-km wavelengths and periods of 20 to 30 days that dominated these current records. The westward propagation speed is higher than the typical translation speed of LCEs (3 to 6 km/day) and explains, in part, why in the central and western basins the upper and lower layer current fluctuations are generally unrelated.

The theory of TRW dynamics requires a bottom slope (α) and a stratified (lower) water column. Wave motions are rectilinear and at an angle to the general isobath trend. Phase propagation is perpendicular to the water particle motions and is directed such that the along-isobath component of phase has the shallower water on its right hand side. Thus, in the northern Gulf of Mexico the waves propagate to the west and are refracted by the changing bottom topography. The shortest period that is supported by these dynamics is given by $2\pi/N\alpha$, where N is the average Brunt-Vaisala frequency of the lower water column (Rhines 1970). These cut-off periods range from about 5 to 50 days in the deep Gulf, and there is usually a sharp reduction in spectral energy levels at this period compared to longer periods.

The source of deep current fluctuations is likely to be the energetic upper-layer circulation related to or derived from the LC. The dynamics of how and when this transfer occurs are not well developed. However, there is observational evidence from the North Atlantic Gulf Stream system that westward propagating TRWs can be generated from eastward propagating meanders if the magnitude and direction of the slope of the sea bed allow coupling of the waves (Pickart 1995). This evidence implies that TRWs are generated by upper-layer motions with similar time and space scales and has important consequences for deep water experimental studies that will be discussed below.

Standard deviation ellipses are given for representative lower water column current records for different areas of the Gulf (Figure 13a). The variance distribution is uneven with high kinetic energy (KE) under the LC (mooring G) and south of the Mississippi delta (near I1). Apart from the latter, the other records show an increase in variance from the base of the slope (2,000 m) toward the deeper water. The directions of the major principal axes of the fluctuations are consistent with topographic wave-like fluctuations propagating toward the west as discussed above. Moorings G and I1 have similar energy levels, but their KE spectra are quite different (Figures 13b and c). At G (Figure 13b), the most energetic fluctuations occur at 30 to 50 days with rapid decrease at periods shorter than ~16 days (the cut-off period). The spectra at G show clear evidence of bottom intensification between the 1,500- and 2,400-m levels. The bottom record at 3,175 m is only 25 m from the bottom and shows evidence of being affected by the bottom boundary layer. At I1, however, the spectral peak occurs at about the 10-day period, and the cut-off period is ~5 days (Figure 13c). The three lower records are nearly independent of depth at periods longer than 10 days, but show a small amount of bottom intensification at the higher frequencies. The current record at 1,000 m has an order-of-magnitude less variance than those from the lower layer. This is an indication of the transition zone between the energetic flows of the upper and lower layers. Analysis of the spectra of the currents from 92W and the far western Gulf are discussed in Hamilton (1990). For water depths greater than 3,000 m, the most energetic parts of the spectra were at ~20- to 30-day periods. If it can be assumed that these current records are representative of circulation processes, even though they were taken at widely different times, then the indications are that the highly energetic ~10-day waves at I1 could not have been generated from the region under the LC because the records at G contain little energy at these periods. At approximately 25-day periods where there were substantial energetic fluctuations at G, there was a relationship with the western Gulf currents over the 3,000-m isobath (Hamilton 1990). This relationship implies that TRWs of different periods have different origins (and propagation paths) in the eastern Gulf. It is likely that the longer period motions of > 20 days are related to the northward extension of the LC and the eddy-shedding process. Hamilton (1990) showed that large amplitude bottom-current fluctuations occurred at G when an anticyclone

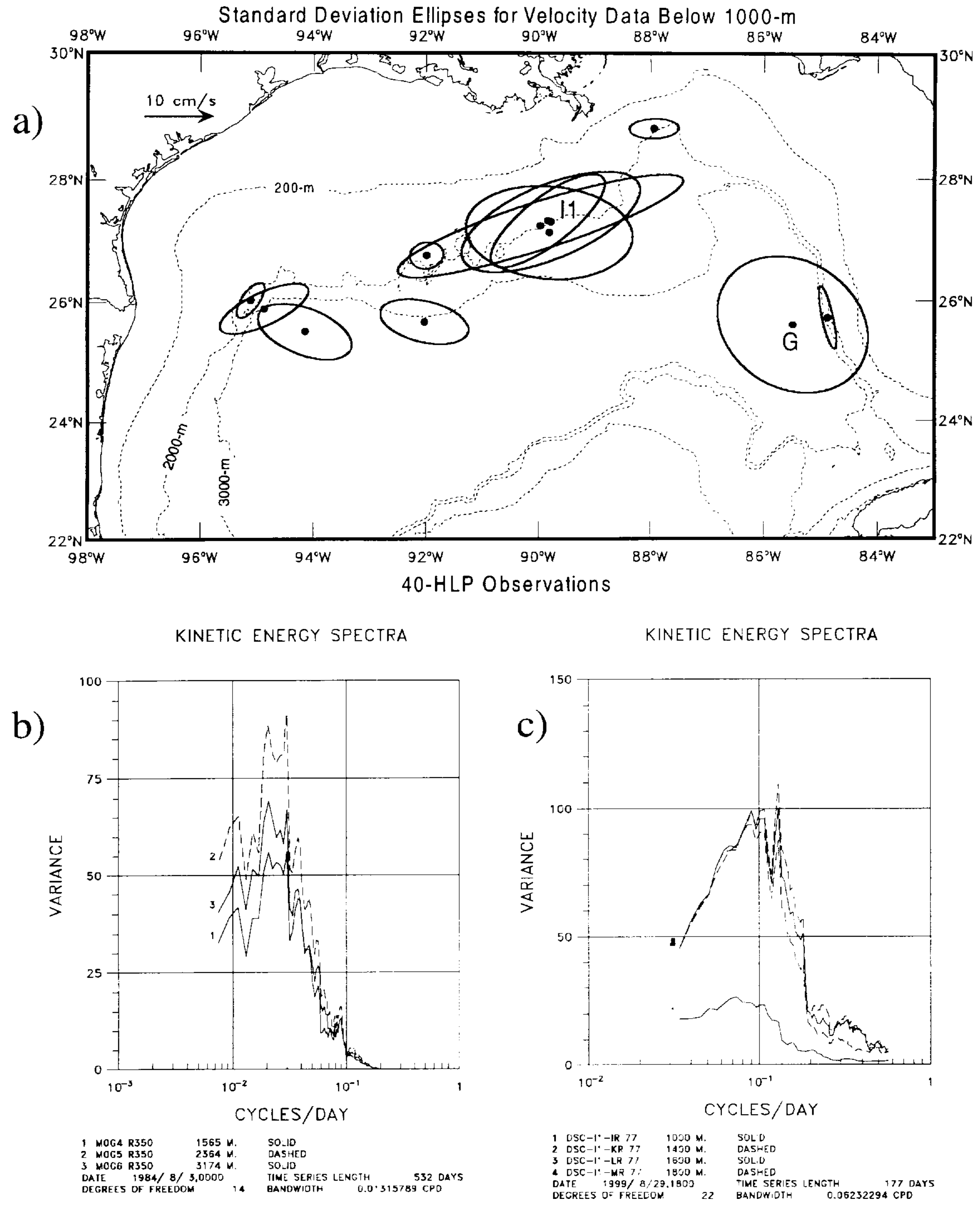

Figure 13. Standard deviation ellipses for deep current meter records longer than 6 months and within 200 m of the bottom (a). The major and minor axes of the ellipses represent the standard deviations of the principal velocity components. Kinetic energy spectra for the lower-layer velocity records at G (b) and I1 (c).

detached from the LC. However, the current records from the moorings in the central and western Gulf show relatively continuous TRW activity with no obvious increases in amplitude at the 6- to 14-month intervals of LC eddy shedding. Therefore, upper-layer events that lead to the genesis of TRWs must occur at more frequent intervals than those resulting from the shedding of large LC anticyclones.

RECENT MEASUREMENTS NEAR THE SIGSBEE ESCARPMENT

SAIC deployed three moorings, with funding from MMS, at the base of the continental slope. The mooring sites are due south of the Mississippi delta and close to the Sigsbee escarpment. These measurements documented events with exceptionally strong near-bottom current speeds (> 90 cm/s). The short periods of the fluctuations, compared to other deep-water (>2,000 m) current measurements, have been discussed for the full-depth mooring I1 in the previous section. The positions of the moorings (including a mooring (J1) deployed for BP) are shown in Figure 14. The moorings were initially deployed in August 1999 and will be retrieved in February 2001. Only observations from the first 6-month deployment will be discussed here. Moorings I2 and I3 are confined to the lower-layer with three instruments at 10, 200 and 400 m from the bottom. The three “I” moorings are in a general region where furrows have been found. The steep slope of the Sigsbee escarpment is between 1,500 and 2,000 m at 90W but becomes deeper further to the west. The recently discovered furrows in the sea bed are discussed in detail in other sections of this report. There is speculation that strong bottom currents may have a role in maintaining and/or creating these geological features.

Figure 15 shows the 40-HLP velocity vectors at selected depths through the water column at I1. The upper-layer (100-, 325-, 675-m levels; Figure 15) is dominated by the westward passage of the northern side of eddy J (for Juggernaut) through the site. The eddy currents have large vertical shears that correspond to the outer edge of a major anticyclone. The 1,000-m level had weak currents that show influences at different times of the upper-layer eddy or the lower-layer TRWs. Between 1,000 m and the bottom, currents increase in magnitude with maxima of order 50 cm/s near the sea bed. The fluctuations are quite continuous with the ~10-day periods noted above. The lower-layer events generally do not correspond to upper-layer flows with a few notable exceptions. At the beginning of the record, around 12 September, two cold cyclonic frontal eddies passed through the site. These events are characterized by low temperatures in the 95-m record and the counterclockwise rotating vectors of the upper-layer currents. There is evidence in the sea surface height map (Figure 15) of poorly resolved cyclonic flows on eddy J’s front, south and east of the mooring site. Eddy J is in the process of detaching from the LC at this time. The passage of the cyclonic frontal eddies produced westward currents through the whole water column (~8 and 20 September, Figure 15). This coupling of upper and lower layers suggests that LC/LCE frontal eddies may play a role in generating deep energetic disturbances which then propagate westward as TRWs. The first event corresponds to observed bottom speeds of greater than 70 cm/s at the I2 mooring,positioned 20 km west of I1 (Figure 14). The highest speed (95 cm/s) of all the bottom records occurred at I2 within the first few days of the deployment. This part of the record is not shown in Figure 15 because the ends of the record are lost by the 40-HLP filter.

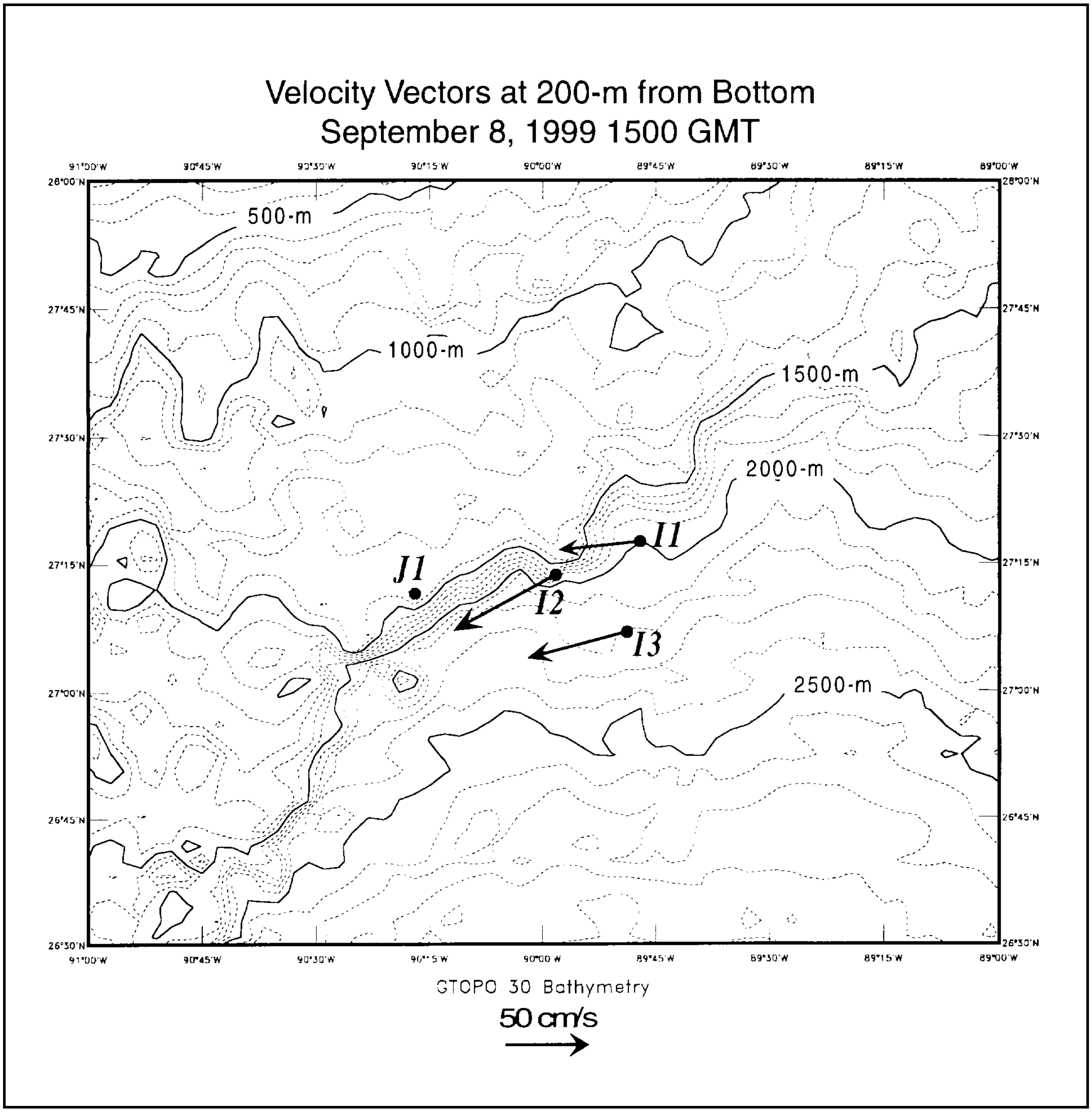

Figure 14. Detailed bathymetric map of the Sigsbee escarpment in the region south of the Mississippi delta. The positions of the MMS/SAIC (I1, I2 and I3) and the BP/SAIC (J1) moorings are shown. Maximum velocities at 200 m from the bottom are shown for the event on 8 September 1999.

Another event that produced coherent flows throughout the water column occurred around 18 December 1999. In this case, flows were eastward, and the center and northern front of eddy J were situated due south and just seaward of I1, respectively. There is no clear evidence of a cyclone in this position from the sea surface height and sea surface temperature maps (not shown) at this time. Thus, evidence for coupling of upper-layer circulation to TRWs is at present circumstantial. It is unlikely that further progress can be made in relating bottom events to upper-layer flows until spatial

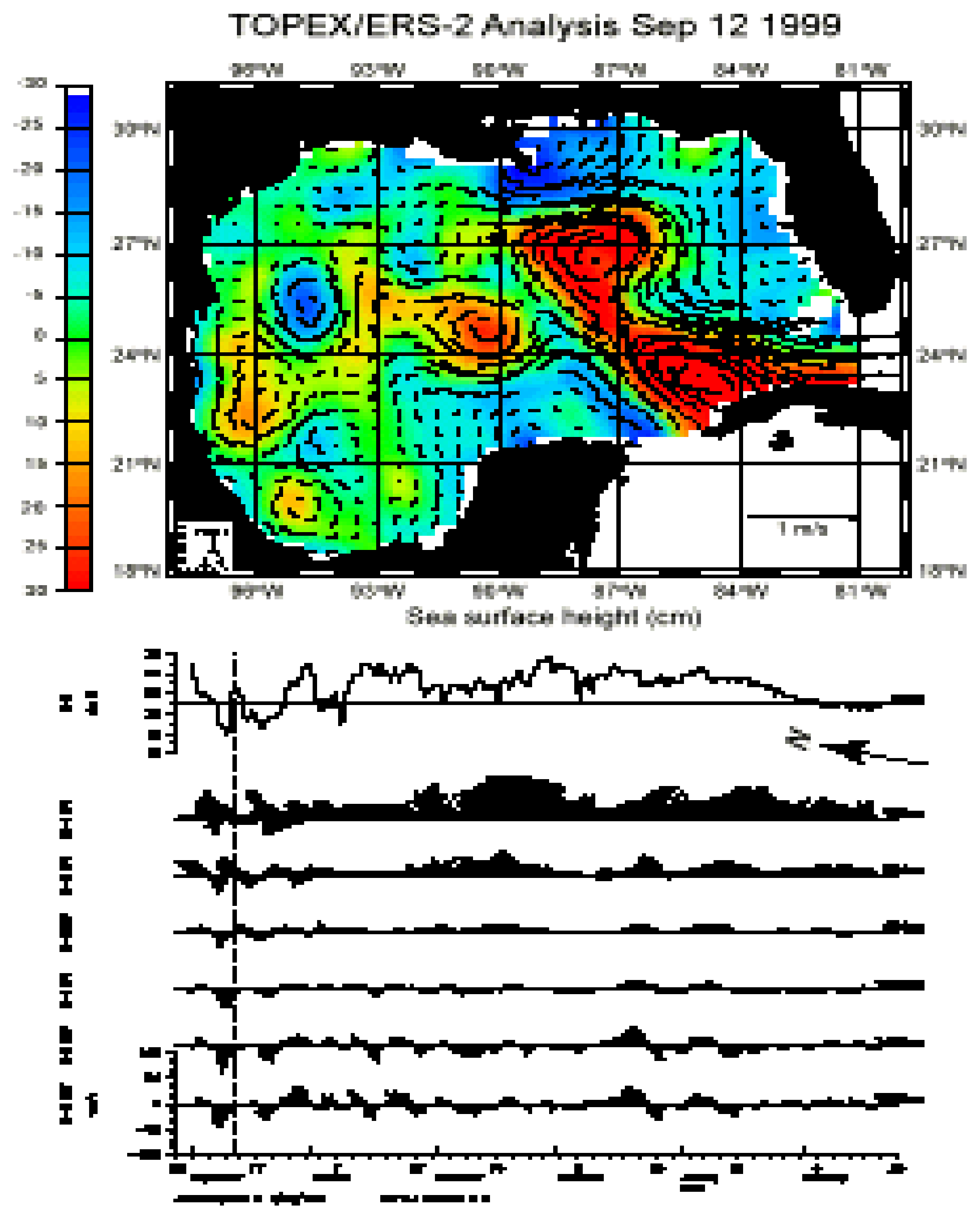

Figure 15. 40-HLP velocity vectors and upper layer temperature records for the first 6-month deployment of I1 (lower panel). The sea surface height map for 12 September 1999 corresponds to the dashed line. The mooring position is given by the dot (upper panel).

mapping arrays can resolve velocity and property gradients in both upper and lower layers at scales appropriate to LC/LCE frontal circulation.

A spatial analysis of the coherent lower-layer fluctuations at the three I moorings, using frequency domain EOFs (Hamilton 1990), showed that the first mode accounted for more than 82% of the total velocity variance of the records 200 m from the bottom for periods between 50 and 7 days. The results are given in Figure 16a using hodographs that are similar to the representation of tidal current ellipses (Foreman 1979). The ellipse traces out the velocity vector fluctuating at the central frequency of the analyzed spectral band (13 days). The arrowheads give the relative phase. It can be seen that I1 leads I2 by a small phase difference but I3 lags both I1 and I2 by about 45. This difference represents a signal propagating offshore and alongshore to the west, which is typical of TRW motions and represents energy propagating westward and up-slope (Hogg 1981). Performing a least-squares fit to the phase differences determines that the wavevector is directed due south with a wavelength of ~70 km. A surface layer feature with this diameter translating northwards at ~5 km/day results in ~13-day period motions. These scales are similar to those produced by a cyclonic frontal eddy propagating northwards through the site around the extended LC or LCE (e.g. eddy J; Figure 15). These rough calculations support the suggestion that small-scale (~50 to 100 km) features could be a primary source for the observed, large-amplitude bottom motions with periods of order 10 days.

The EOFs also show that the amplitudes of the TRW motions vary considerably over the 20-km distances between the moorings. I2 has the largest amplitude (~20 cm/s); this is not quite twice the amplitudes at I1 and I3 (Figure 16a). It is not clear whether the steep Sigsbee escarpment (Figure 14) is responsible for the westward amplification. Currents at J1 deployed north of the escarpment in ~1,400-m water depth are much weaker than at the I moorings. Near-bottom current measurements from three moorings on the 1,300-m isobath in the DeSoto canyon showed long-period (20 to 50 days) topographic wave motions of small amplitude (~3 to 5 cm/s) that decayed rapidly to the west (SAIC 2000). This is perhaps an indication that TRW motions dissipate on the middle slope and may account for the weak currents found near the bottom in this region.

The Sigsbee escarpment moorings (I1 to I3) have been shown to have exceptionally high-energy TRWs compared to other Gulf of Mexico current data in similar water depths (Figure 13). The dominant TRW periods are short (8 to 14 days) compared to those in deeper water, and there are large amplitude changes over short distances. There is some evidence of coupling to LC or LCE peripheral frontal eddies of similar length and time scales. At present, generation mechanisms, wave propagation paths, and decay processes have not been elucidated.

COMMENTS ON MODEL RESULTS

The numerical model used to examine TRWs has been described elsewhere (Oey, this volume). The simulations showed a band of coherent energy with periods of 20 to 100 days in depths of ~2,500 to 3,500 m on the northern side of the basin. It has been suggested that the LC and the propagation of LCEs westward across the basin could be responsible for generating these lower-layer topographic wave-like fluctuations. This discussion is concerned with how closely the simulations resemble the observations of lower-layer currents. Six years of daily-averaged velocity data were

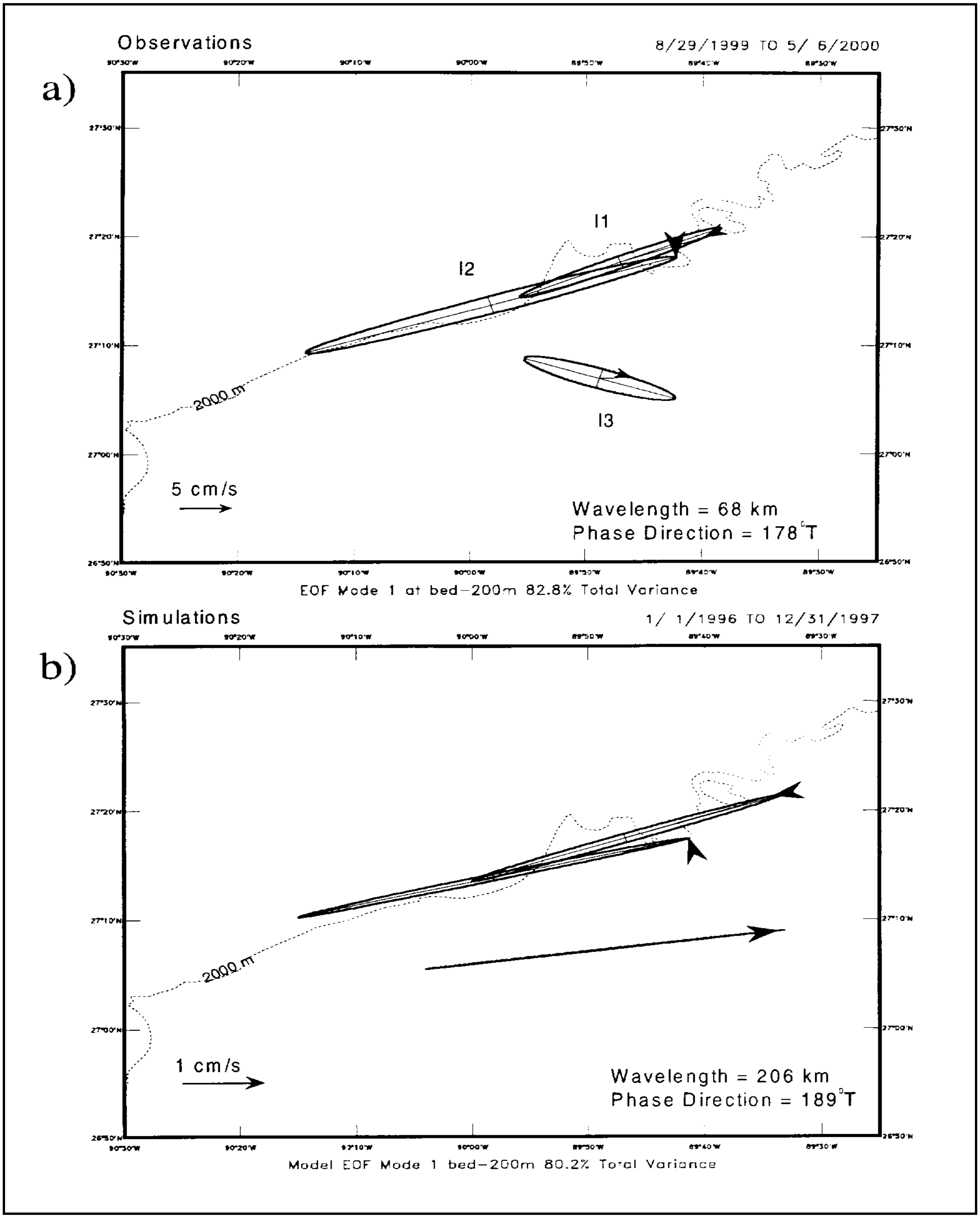

Figure 16. EOF analysis of 50- to 7-day period fluctuations from measurements (a), and numerical model simulations (b) of currents 200 m from the bottom. Note the change in velocity scales.

extracted from the model at positions corresponding to the deep-water mooring sites shown in Figure 13. The final two years of these time series were used to calculate statistics, spectra, and EOFs in exactly the same way as for the observations. Thus, the characteristics of the lower-layer fluctuations from the model can be examined and compared to the observed TRWs.

The standard deviation ellipses and KE spectra for sites G and I1, obtained from model simulated velocities, are given in Figure 17. These statistics can be directly compared to their observational equivalents in Figure 13. The variances from the model were relatively uniform with magnitudes similar to the lowest observed values (Figures 13a and 17a). The simulated fluctuations were more closely aligned to the isobaths than the observations, and there is almost no amplification seaward of the 2,000-m isobath. Therefore, the model lower-layer currents had considerably less energy than is indicated by the observations. The simulated KE spectra for sites G and I1 (Figures 17b and c) show much less energy at all frequencies than the observations (Figures 13b and c) along with decay with increasing depth. Bottom intensification of velocity fluctuations was largely absent from the model results. The spectra at G show peaks around 20 and 100 days but seem to miss the observed prominent peak at 30 to 50 days (Figure 13b). At I1, the KE was an order of magnitude less than observed, and the prominent 10-day peak of Figure 13c is not present in Figure 17c. This is not too surprising, if the arguments on the scales of the upper-layer motions required to generate 10-day TRWs are correct, because the model grids were unable to resolve properly surface-layer motions at ~50- to 100-km scales.

A characteristic of TRW motions and the observations, besides bottom intensification, is the high-level of coherence of the fluctuations through the lower half of the water column. Coherence squared and phase differences between pairs of velocity components, separated by approximately 1,500 m and 600 m at sites G and I1, respectively, are shown for the observations and equivalent model simulations in Figure 18. In both cases, the observations were more highly coherent where energy was present (see Figures 13 and 17) than the simulated velocities. Phase differences were not significantly different from zero in all cases, except the higher frequency bands of the simulated currents at I1 (Figure 18). This is a little unusual because models tend to generate smoother fields than are observed. The low vertical coherence of the model velocities may imply that there was noise in the calculated depth variability. This also implies that the coherent barotropic or bottom intensified motions explain the majority of the observations. Using the simulated velocities from the three I moorings, the EOF and the wavevector calculations were performed for the same 50- to 7-day period motions as the observations. The results are given in Figure 16b. Compared to the analysis on the observations (Figure 16a), the fluctuations were more rectilinear, had much smaller magnitudes, and had less clockwise rotation of the principal axes at the deeper site (I3). However, the phase propagation was offshore and the wavevector was in the correct quadrant for westward propagation of TRWs. The wavelength was more than twice that obtained from the measurements, but again this reflects the model's lack of resolution at short wavelengths, and therefore for short period, motions. It is reasonable to conclude that though this particular model produces lower-layer currents that have some similarity to observed TRWs, there is lots of room for improvement. Future studies with higher resolution models have a good chance of producing better agreement with the observation. They should be able to produce more lower-layer KE and generate the higher frequency, short wavelength topographic waves that will have better propagation and dissipation

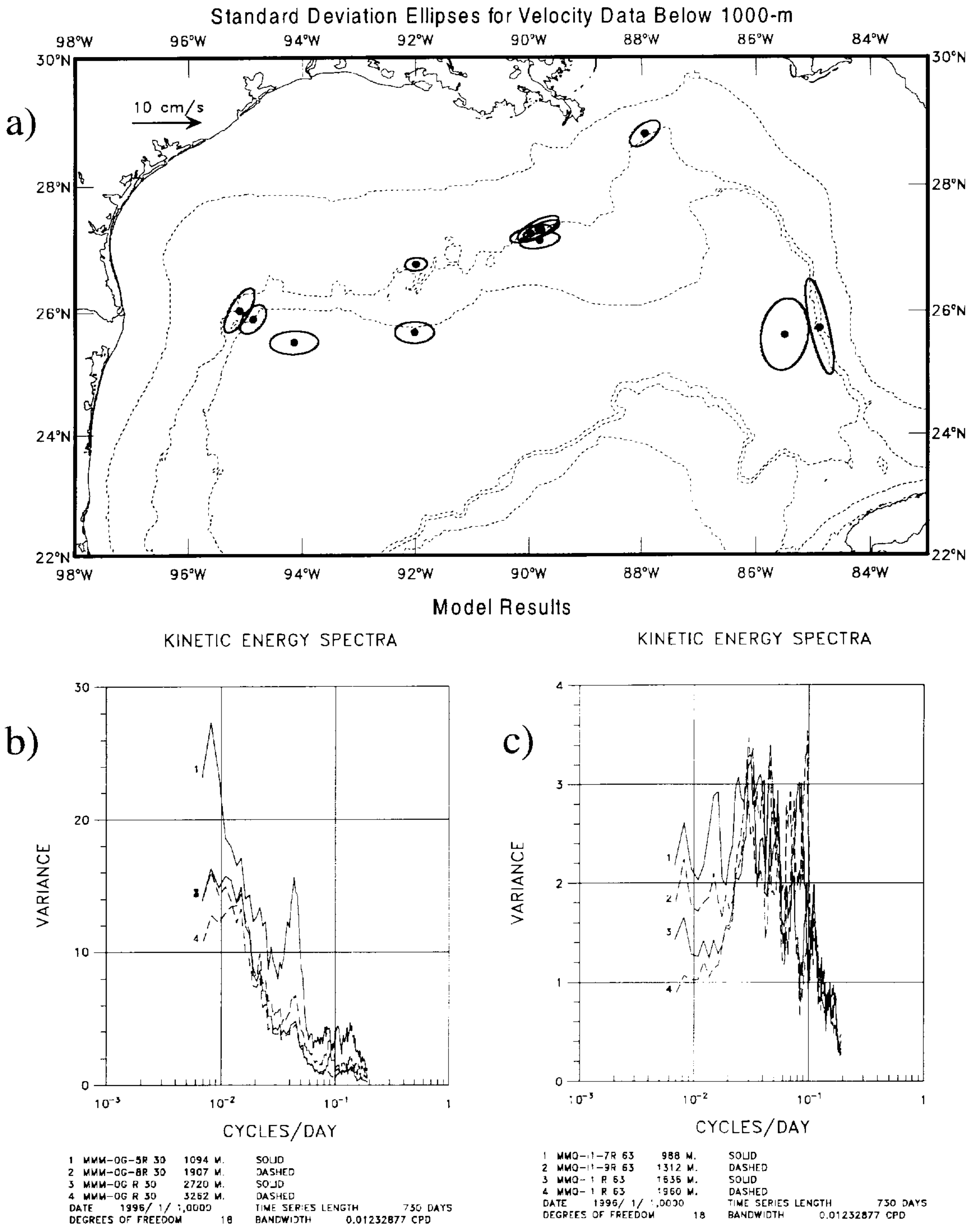

Figure 17. Standard deviation ellipses from 2 years of model simulations (see Oey, this volume) for the same positions and similar depths as the records in Figure 13 (a). Kinetic energy spectra for selected deep simulated currents at G (b) and I1 (c) (see Figure 13).

characteristics. However, this can only occur if the upper-layer eddy circulation at scales of 50 km and greater are correctly modeled.

The limited observational database of deep currents indicates that the TRW theory accounts for their basic characteristics. Model results (Oey, this volume) have indicated possible generation regions and propagation paths for the longer period motions. However, the model study of Welsh and Inoue (2000) suggests that deep-water eddies may also exist beneath Loop Current rings. Welsh and Inoue's (2000) model generates deep eddies that are formed during the eddy shedding process and translate westward with the LCE. At present, there are essentially no observational measurements in the center of the basin that can confirm the existence of these deep eddies.

SUGGESTIONS FOR EXPERIMENTAL STUDIES

The major issues identified in this paper concerning deep lower-layer circulation in the basin and over the slope are as follows:

1. There is a need to understand the generation mechanisms of TRWs and possible deep eddy flows. Progress in understanding the generation processes will improve the ability of models to simulate and predict high speed, near-bottom currents. This involves primarily studying the interactions of the LC, LCE shedding events, peripheral frontal eddies of the LC and LCEs with the lower-layer.

2. There is also a need to investigate the propagation characteristics of TRWs within the Gulf of Mexico. Such investigation should shed some light on why the KE distribution (e.g. Figure 13a) is inhomogeneous and why different period motions dominate in different parts of the basin. Observation of the propagation and refraction of wave packets over the complex topography of the Gulf will also aid the modeler's quest to simulate reality.

Experimental methods that could be used to design studies of these phenomena are discussed at length in other sections of this workshop report. Experimental design should consider the use of arrays of deep current meter moorings, inverted echo sounders equipped with bottom pressure (PIES), and deep Lagrangian floats. Because currents below 1,000 m are almost depth independent, the vertical dimension need only be sparsely instrumented. On the other hand, the short horizontal decorrelation scales of deep motions requires the use of closely spaced (~20 to 40 km) arrays, if the horizontal gradients are to be resolved adequately. Sketches of possible approaches to the two issues noted above follow.

The study of TRW generation mechanisms requires simultaneous mapping of both upper-layer eddies and the lower-layer flows at short enough spatial scales to resolve the important gradients of density, velocity and potential vorticity. Present ideas suggest that the LC, LC peripheral cyclones, and LCE shedding dynamics have an important role to play in generating deep circulation. The LC is a little easier to map with a stationary array than LCEs translating westward across the Gulf because the position of the LC front during an eddy shedding event is quite well known from several decade-long studies of SST images and, more recently, altimetry (e.g. Sturges 1994). The area covered by the fronts when the LC is extended or when an eddy detaches is relatively limited. If

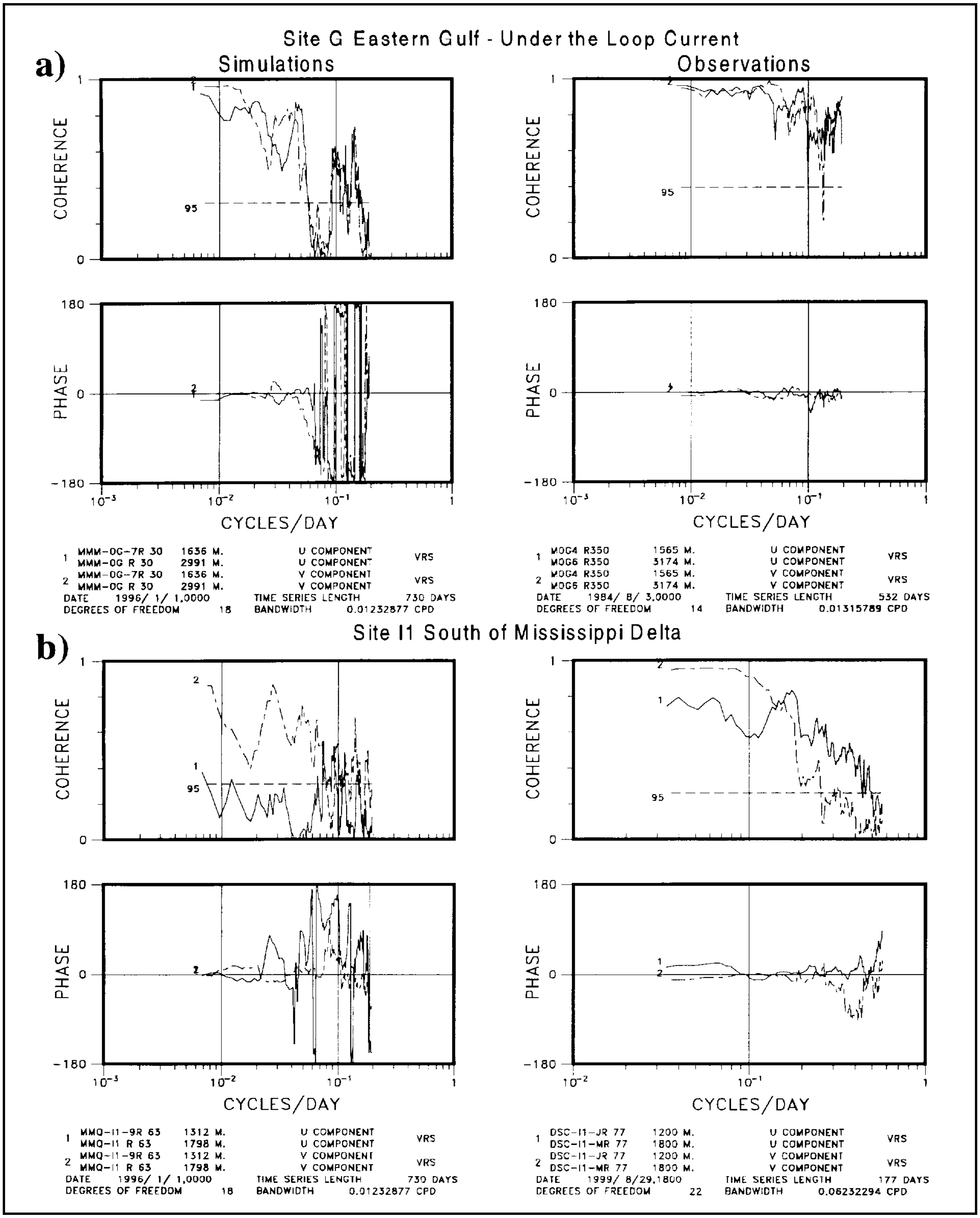

Figure 18. Coherence squared and phase differences between indicated depth levels for simulated and observed velocity components at G (a) and I1 (B), rotated to an along (v) and cross (u) isobath coordinate frame.

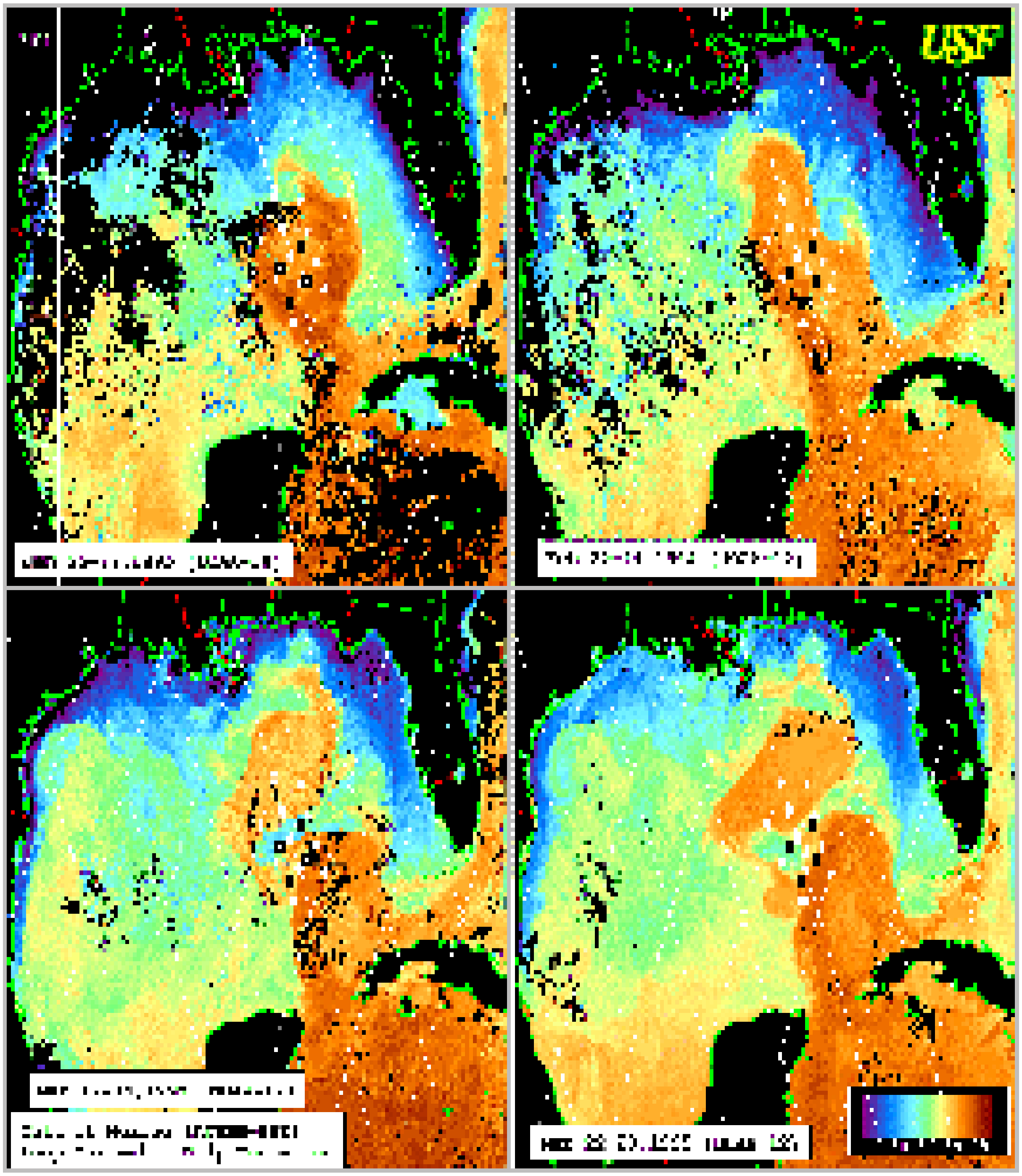

Figure 19. Four composite sea surface temperature maps (courtesy Frank Muller-Karger, University of South Florida) of a Loop Current eddy shedding event. The maps are overlaid with Topex/Poseidon altimeter tracks (white dashed lines) and a suggested mapping array of PIES (white dots) and bottom current meter moorings (black rectangles with white centers).

attention is restricted to the northwestern and northern part of an extended LC then mapping arrays can be deployed entirely within U.S. and international waters. An example of a basic minimal array of 10 PIES and 4 deep bottom moorings is given in Figure 19. It is overlaid on SST images of a typical eddy shedding event to show that even such a limited number of instruments can provide reasonable coverage of a process that has never been observed in any detail. Such an array would also capture some of the peripheral cyclones propagating around an extended LC front. PIES are well suited for this kind of mapping because they are economical, compared with full depth current meter moorings, and they are able to map density and geostrophic velocity fields in three space dimensions and time. Bottom moorings, with two or three current meters, are used to provide lower-layer flows that can be used to level the PIES so that absolute geostrophic velocities can be calculated (Tracey *et al.* 1997). Similar types of PIES and current meter arrays have been used to map Gulf Stream meanders, the Antarctic circumpolar current, the Kuroshio and other major current systems. A similar but more extensive approach to mapping the LC is discussed by Watts (this volume).

Mapping and local LC dynamics studies that use stationary arrays (Figure 19 or similar) can be combined with Lagrangian deep float deployments to investigate the propagation of eddies and TRWs into the western and southwestern Gulf. Such floats, deployed at depths between 1,500 and 2,000 m, will also provide descriptions of the deep circulation processes, having many spatial scales, throughout the entire Gulf. Investigating TRW propagation paths downstream of a source region-mapping array could also be accomplished by deployment of conventional deep current meter moorings. A suggested approach could use clusters of small arrays deployed along the Sigsbee escarpment and other regions of high energy suggested by model results. A minimum of three moorings (e.g. the I moorings in Figure 14) is needed in each cluster to resolve local wavevectors. This is the approach that is being used by Fugro/GEOS (this volume) who have deployed (in August 2000) 20 moorings along the lower slope between 89˚ and 92˚W to investigate the distribution of TRW energy and wave characteristics. All experimental studies of deep water should be at least two to three years in length to capture several eddy shedding cycles.

REFERENCES

Foreman, M.G.G., 1979. Manual for tidal currents analysis and prediction. Pacific Marine Sci. Rep. 78-6, Institute of Ocean Studies, Patricia Bay, Sydney BC, 70pp.

Hamilton, P., 1990. Deep Currents in the Gulf of Mexico. J. Phys. Oceanogr., 20, 1087-1104.

Hogg, N.G., 1981. Topographic waves along 70W on the continental rise. J. Mar. Res., 39,627-649.

Pickart, R.S., 1995. Gulf Stream-generated topographic Rossby waves. J. Phys. Oceanogr., 25,574-584.

Rhines, P.B., 1970. Edge-, bottom-, and Rossby waves in a rotating stratified fluid. Geophys. Fluid Dyn., 1, 273-302.

Science Applications International Corporation (SAIC), 2000. De Soto Canyon eddy intrusion study: Synthesis report, Volume II. Draft Technical Report: OCS Study MMS 2000-080. U.S. Dept. of Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA. 271pp.

Sturges, W., 1994. The frequency of ring separations from the Loop Current. J. Phys.Oceanogr., 24, 1647-1651.

Tracey, K.L., S.D. Howden, and D.R. Watts, 1997. IES calibration and mapping procedures. J. Atmos. Oceanic Technol., 14, 1483-1493.

Welsh, S.E., and M. Inoue, 2000. Loop Current rings and deep circulation in the Gulf of Mexico. J. Geophys. Res., 105, 16951-16960.

DEEP CURRENTS IN THE GULF OF MEXICO: COMPARISON WITH MODELS

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INTRODUCTION

This work is conducted in collaboration with several colleagues who are running numerical models: Ya Hsueh and Yury Golubev at Florida State, who are working with several different versions of the Brian-Cox (or MOM) model; Eric Chassignet and Anastasia Romanou at RSMAS, Miami, who are working with the MICOM; and Tal Ezer at Princeton, who is working with the Mellor model. All the model results described here are from model runs that include almost the full North Atlantic Ocean, so that questions about inflow boundary conditions at Yucatan are pushed as far away as possible.

We have studied the model output for some things that we expect to find, but that we lack adequate data to examine in the kind of detail that is so obvious in a model. We ran three different models because we are skeptical about some of the details that come out of models; if we can find general agreement in some major features of the flow among these different implementations, then we think that there may be some insight to be gained here.

And we DO see some of the things we had hoped to see.

VARIABILITY OF THE LOOP CURRENT INFLOW

As the Loop Current intrudes to the north, well before a ring detaches, the northern edge of the Loop Current front can move from a position just north of the Florida Keys to a position north of Tampa—an extent of perhaps 400 km—in only a couple of months. During this time, a volume of new fluid, roughly the size of a Loop Current ring, is introduced into the Gulf of Mexico. The questions we must ask are these:

1. What is the approximate rate of *additional* inflow between Cuba and Mexico in order to supply the fluid that will form the ring;

2. What additional fluid outflow must take place in order to accomplish the mass balance? That is, how does all this extra water leave the gulf? At the surface? How? Where?

As the LC intrudes, the area it displaces—or the area of a ring—is approximately the area of a circle with diameter of ~ 300 km. If the ring is ~ 1,000m deep, the volume has to be *of order* $7 * 10^{13}$ m^3. The time over which the intrusion takes place can vary from as little as one month to more than 3 months or longer. But for a brief time – if the Loop intrusion takes place in ~2 months, there is extra

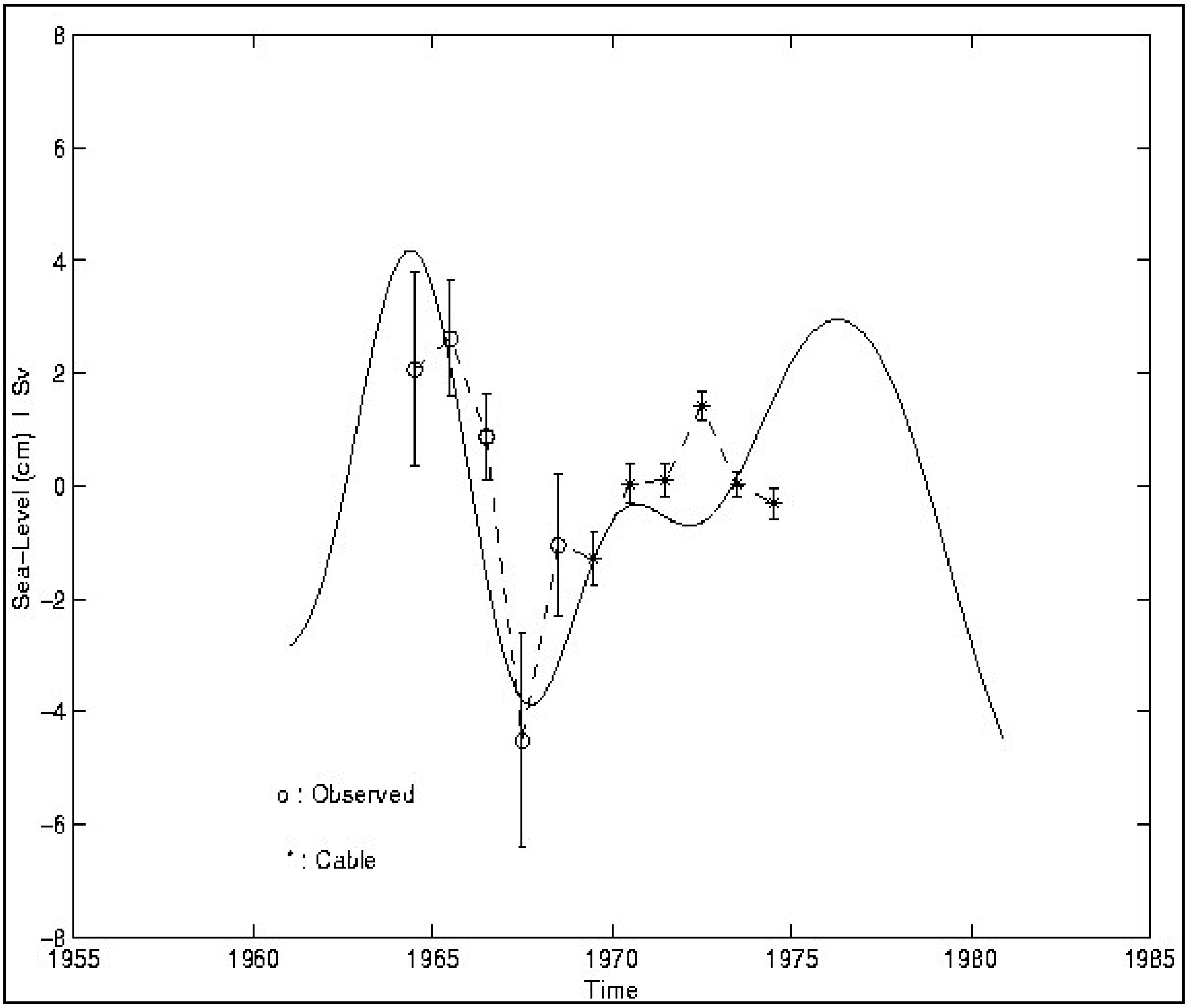


Figure 20. Transport variability in the Florida Straits. Data points from the 1960s are from W. Richardson's drop-sonde measurements. Data in the 1970s are from J. Larsen's cable voltage results. Full curve is from a model calculation, adapted from work of Sturges and Hong (to appear in Jour. Phys. Oceanography).

inflow, *on the order* of 14 Sv. We need to ask ourselves, how can the Gulf accommodate an extra inflow this large? And certainly there must be compensating outflow; where does it take place?

All the currents we deal with have large variability. We know that a great deal of variability exists at periods associated with the intrusion and shedding cycle of the Loop Current. There is also variability of the same order of magnitude on other time scales. We have a lot more measurements of the Gulf Stream than in Yucatan. We know that the variability of the Florida Current is roughly +/- 3 Sv in the annual cycle. In addition, Figure 20 shows the variability of transport in the Straits of Florida on much longer time scales.

We see that there is large variability on these longer time scales as well as on the scale of a few months. So the inflow and outflow can vary on time scales of a few months, at the annual period, and at periods of many years. And these are additive.

POSSIBILITY OF DEEP OUTFLOW?

The principal question is this: When the Loop Current is intruding, what about the mass balance? That is, to balance the extra inflow, what water goes back out of the Gulf? Figure 21 shows a snapshot of the flow field—a vertical section between Cuba and Mexico—taken from the Mellor model (Ezer), at a time when the Loop Current is intruding and there is large outflow back to the south. The original figure was in color; this black and white version does not show the distinctions between flow to the north and flow to the south; but in the original we see the usual flow to the north in the upper left, and (in the dark area in the lower left) a surprising amount of flow back to the south. The speeds in the southerly flow, below 1,000m, are over 16 cm/sec within a substantial region here. It is important to note that this is not a brief flow, caused by the presence of a transient eddy. Dr. Ezer performed a special calculation to determine where the outflowing water originated. This fluid comes from a region just to the north of Yucatan at about the 1,500 m isobath. In other words, the deep outflow is from the interior of the Gulf, west of the Loop Current.

From similar plots of the velocity field taken from the MICOM and from MOM we see a similar variability of the deep flow. The details, the absolute magnitudes, are different, but the same general pattern emerges. One of the most noticeable features in the MICOM is a deep inflow from the Caribbean to the Gulf on the Cuban side. This flow would be consistent with bottom topographic rectification, as is a flow to the south on the Mexican side. A region of southerly flow on the Mexican side is also present in the MICOM, but the amplitudes are not so great as in the Princeton model. The amplitudes are under 10 cm/sec in the MICOM, but the region of southerly flow seems to cover a large area of the deep section.

The deep flow suggested here should be compared with observations. The earlier observations of Maul and his colleagues at AOML found consistent southerly flow near the bottom in Yucatan Channel. Over a three-year period the flow was steadily to the south, with irregular variability. The deep flows in these model runs are certainly consistent with their observations.

Thus, these additional flows seem to consist of two parts. First, a large inflow in the surface layer that is balanced by a possible, surprising, and counter-intuitive southerly flow at depth, associated with the intrusions of the Loop Current. Second, we see a cyclonic deep flow in the whole basin, driven by topographic rectification, with deep inflow in Yucatan on the Cuban side and outflow on the Mexican side. The evidence for this flow is also elusive. Figure 22 shows a map of the depth of a deep density surface. The one here is near 1,500m, and is (somewhat arbitrarily) potential density relative to 1,000 m, at a value of 32.335. Near the center of the Gulf basin this surface is roughly 75 m deeper than near the edges. This deepening in the center is consistent with a mean cyclonic geostrophic flow, under the assumption that the flow at ~900 to 1,000m is much slower.

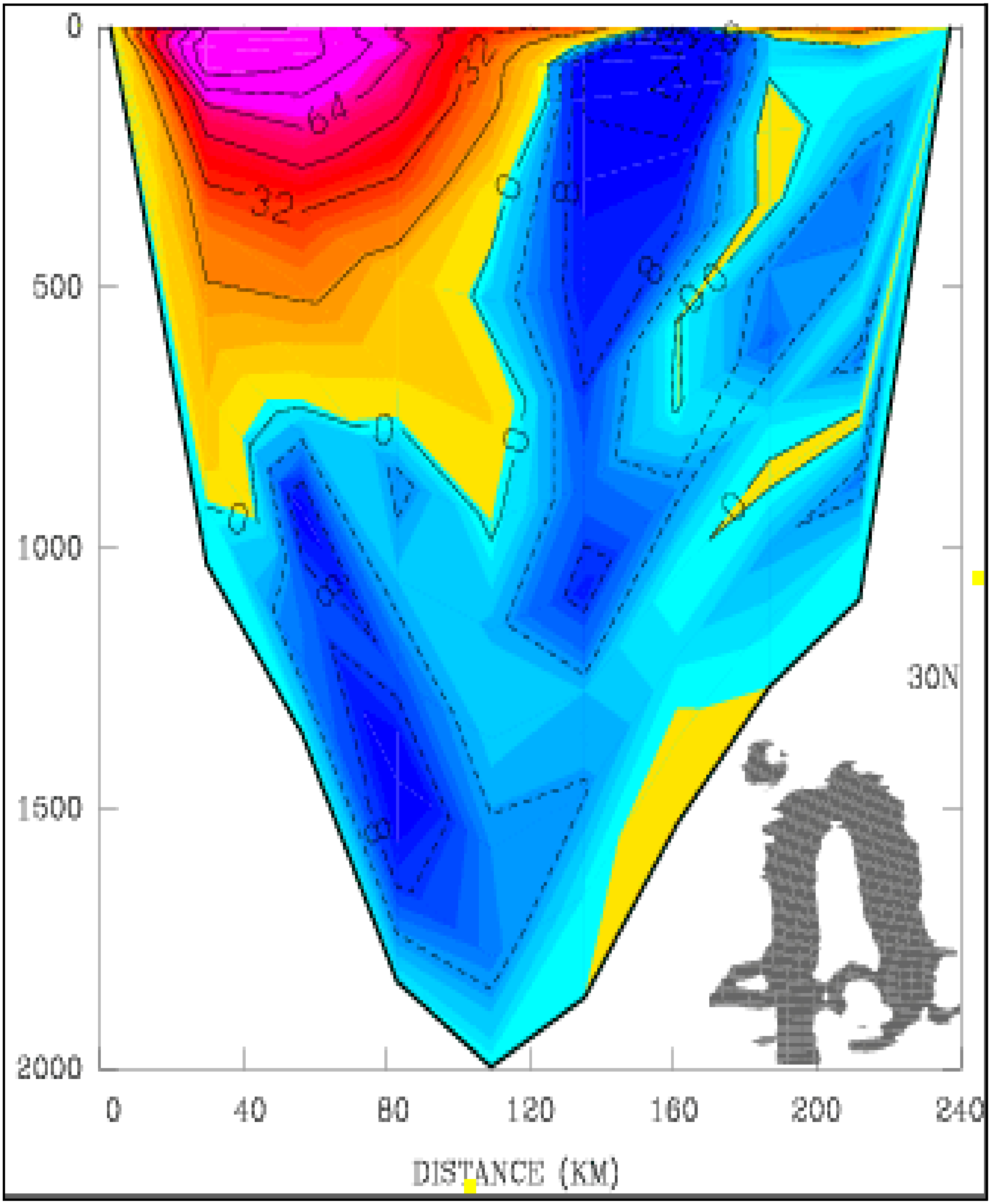


Figure 21. A velocity cross section in Yucatan Channel, with Mexico on the left, Cuba on the right. The contours are in cm/sec. From model output of the Princeton Ocean Model, full Atlantic, forced by the mean seasonal cycle of winds (Ezer).

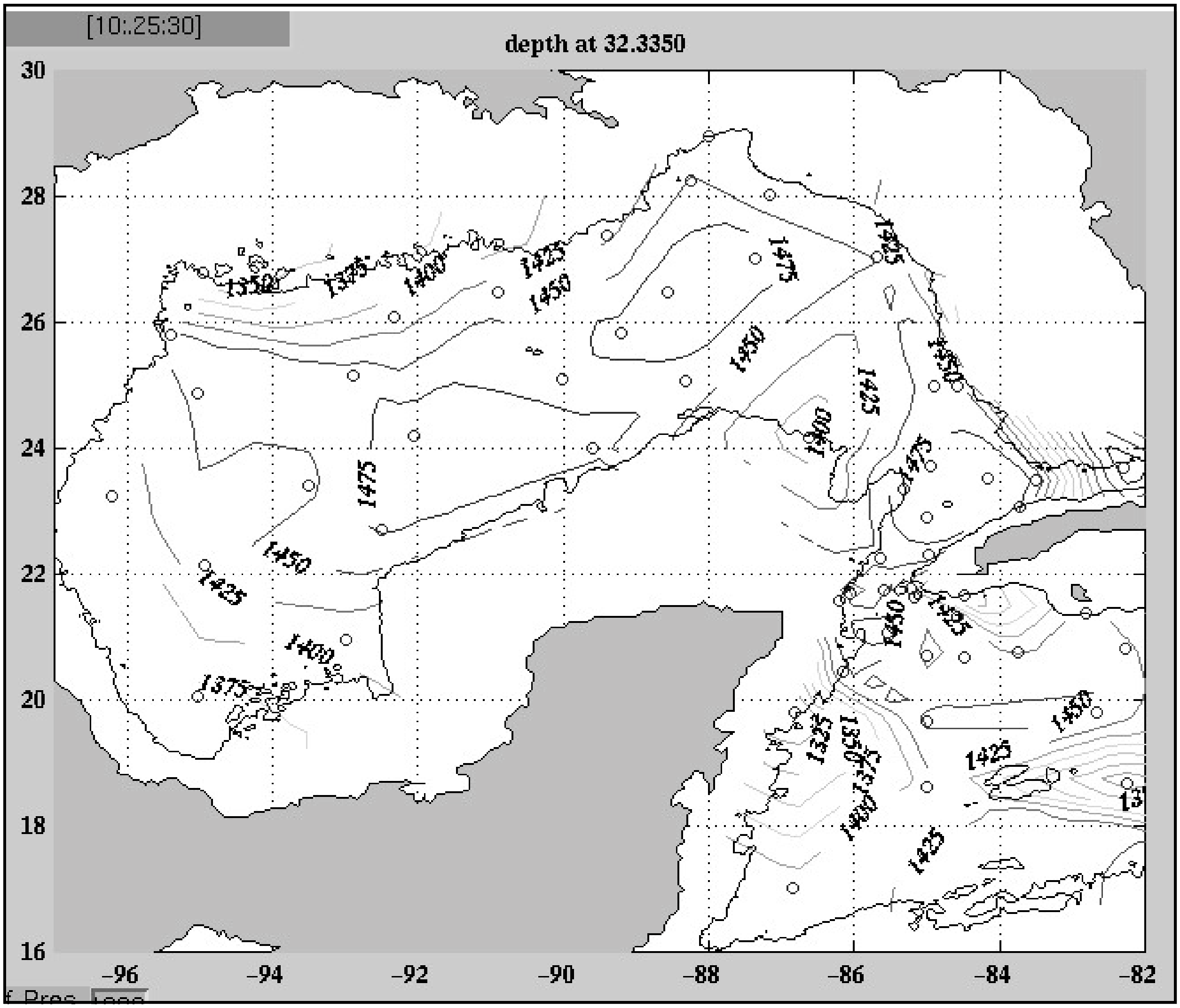


Figure 22. The depth of the potential density surface 32.335, relative to 1,000 db. The small circular data points show the positions of groups of hydrographic stations that were averaged. The data are from all available stations from the NODC archives. This figure is from results of J. Jimeian.

MEAN WINDS OVER THE GULF OF MEXICO

The mean wind field over the Gulf (based on the NCEP reanalysis winds) suggests a net convergence over the whole area. The Ekman pumping over the Gulf gives a net downward flux of ~ 2 Sv; this transport is consistent with the outflow necessary to balance the year-long mean transport of a single Loop Current ring.

SOME THOUGHTS ON THE NEED AND FOCUS FOR POSAR

Dr. Cortis Cooper
Chevron Petroleum Technology Co.

Mr. Kenneth J. Schaudt, CCM
Marathon Oil Co.

HOW WOULD THE INDUSTRY USE POSAR?

The Industry uses metocean (meteorological and oceanographic) data (Figure 23) in various ways. There are three types of metocean data: climatological, extreme, and real-time. Climatological data consist of long-term records and are used by engineers for fatigue and operability (downtime) analysis. From an environmental standpoint, climate data are used to determine the fates of pollutants, including noise. Extreme (storm) data are used by engineers to design drilling rigs and production facilities. Real-time data are needed to operate offshore facilities, and for tactical planning should there be an accidental spill.

Extreme data are used to design the major components of a deepwater productions facility, in this

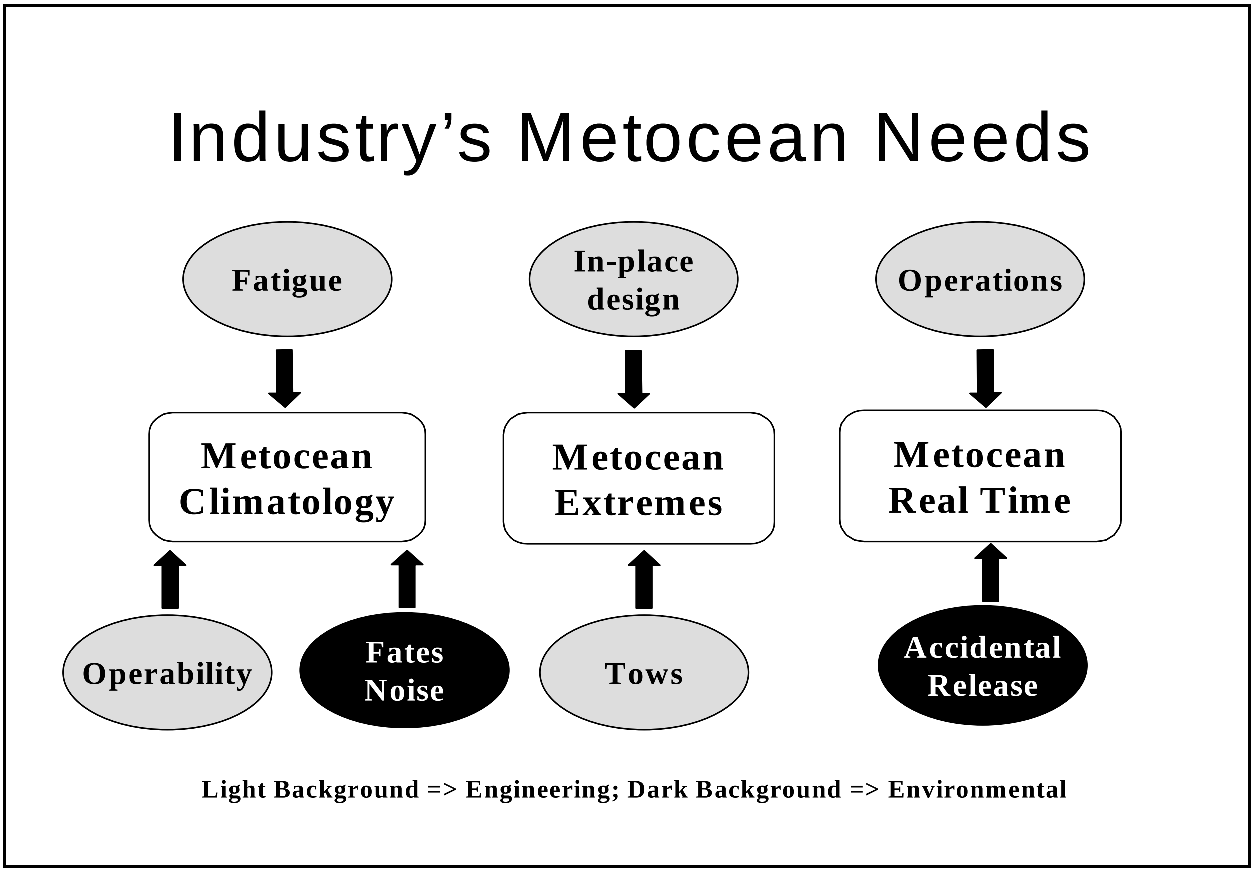


Figure 23. The Industry uses metocean (meteorological and oceanographic) data in various ways.

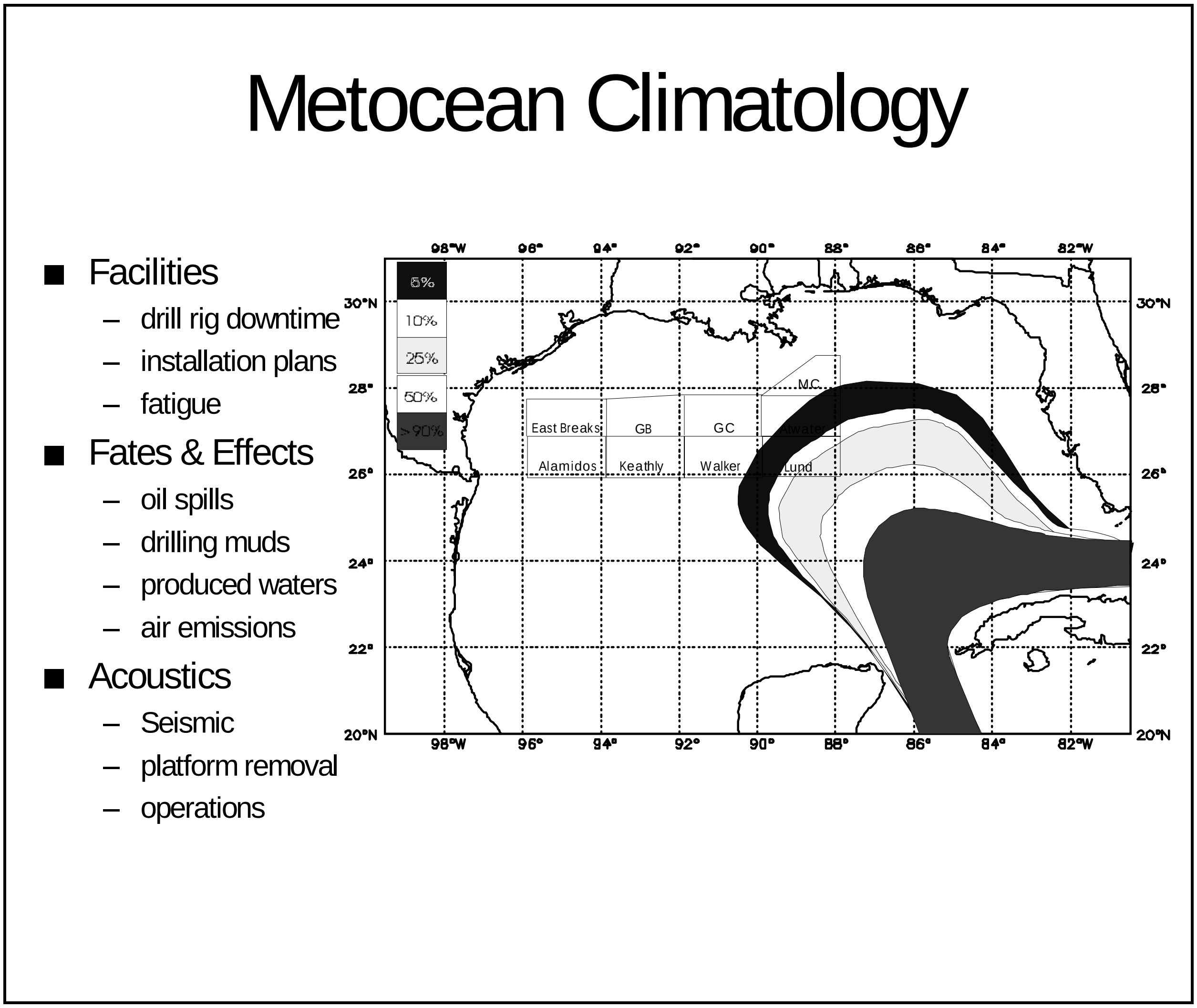
case, a spar (Figure 24). The major components of a spar are the deck facilities, mooring lines, risers, and pipelines. Each item lists the type of “storm” that might create the “design” condition. The term “storm” is used in a generic sense to mean an “extreme” event in the atmosphere or the ocean. For most components, the storm type that creates the design case will depend on the geographical location, water depth, and specifics of the facilities. The typical strength of the design current used in the Gulf of Mexico for each subsurface component varies. Processes that cause currents much less than these values are not of much interest. Estimates of extreme minimum water temperature are needed in deep water because of the impact it can have on hydrate formation, wax accumulation, etc.

Figure 24. Extreme data are used to design the major components of a deepwater productions facility.

We also use climatological data (Figure 25). One example of the type of climate data we need is a frequency contour map showing currents exceeding a given level (in this case 3 kt). Such information is needed by the drillers to select the appropriate drilling vessel and riser fairings. The same information is critical during the installation of things like TLP tendons or risers. Finally, climate-like data are needed to design risers against fatigue failure.

From an environmental standpoint, climate data are needed to develop contingency plans to deal with accidental pollutant releases and to calculate the fate of potential pollutants like drilling muds, produced waters, and acoustic noise from seismic surveys, platform removal, etc.

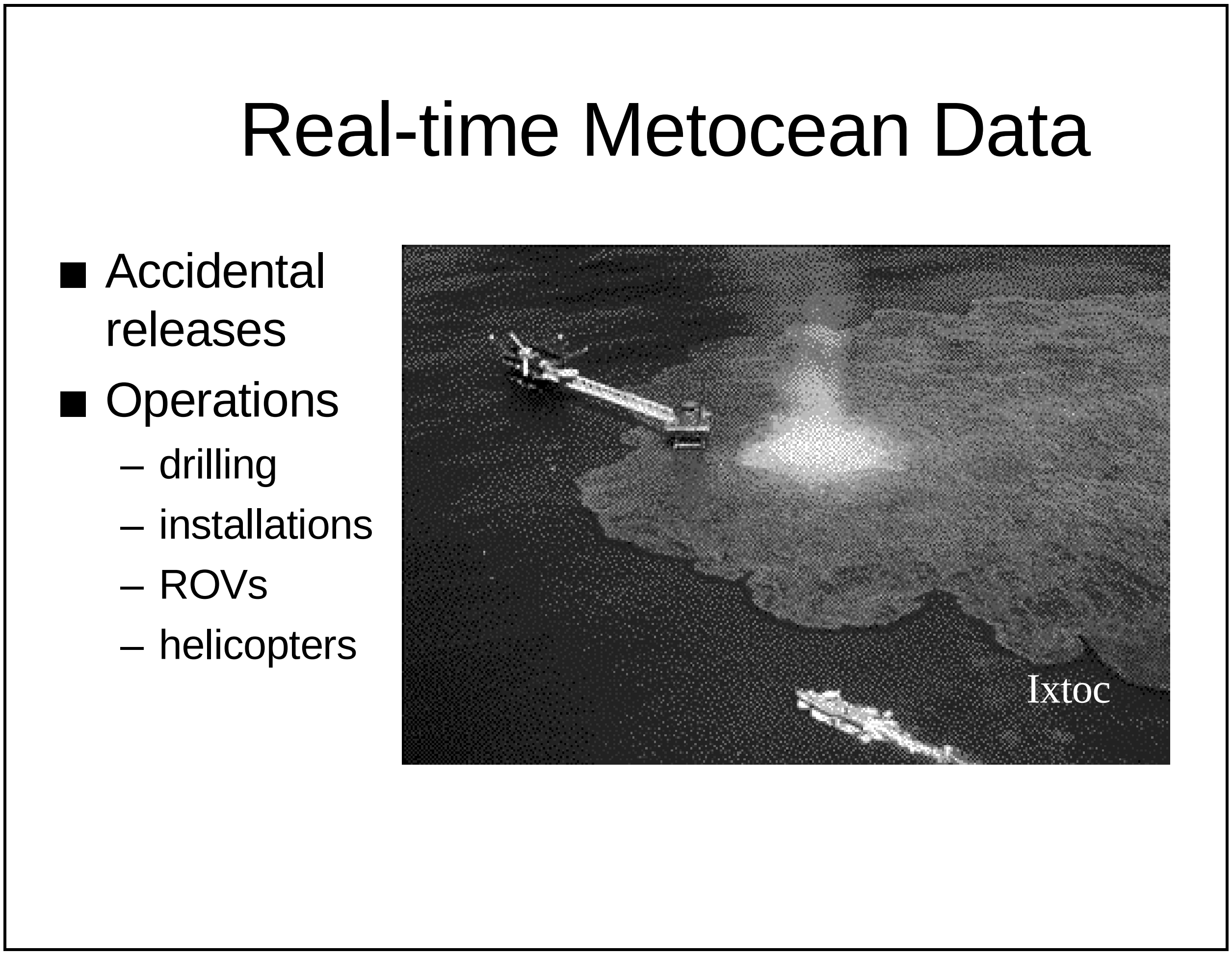
Some specific uses for real-time metocean data include guiding the tactical response to an accidental pollutant spill as well as operational needs (Figure 26). One of the more important uses is guiding drilling operations or installations since the Loop Current/eddy can cause costly delays. Real-time data can help minimize such losses.



Metocean Climatology

- Facilities
  - drill rig downtime
  - installation plans
  - fatigue
- Fates & Effects
  - oil spills
  - drilling muds
  - produced waters
  - air emissions
- Acoustics
  - Seismic
  - platform removal
  - operations

Figure 25. Types of climatological data used by designers, installers, drillers, and environmental contingency planners.



Real-time Metocean Data

- Accidental releases
- Operations
  - drilling
  - installations
  - ROVs
  - helicopters

Ixtoc

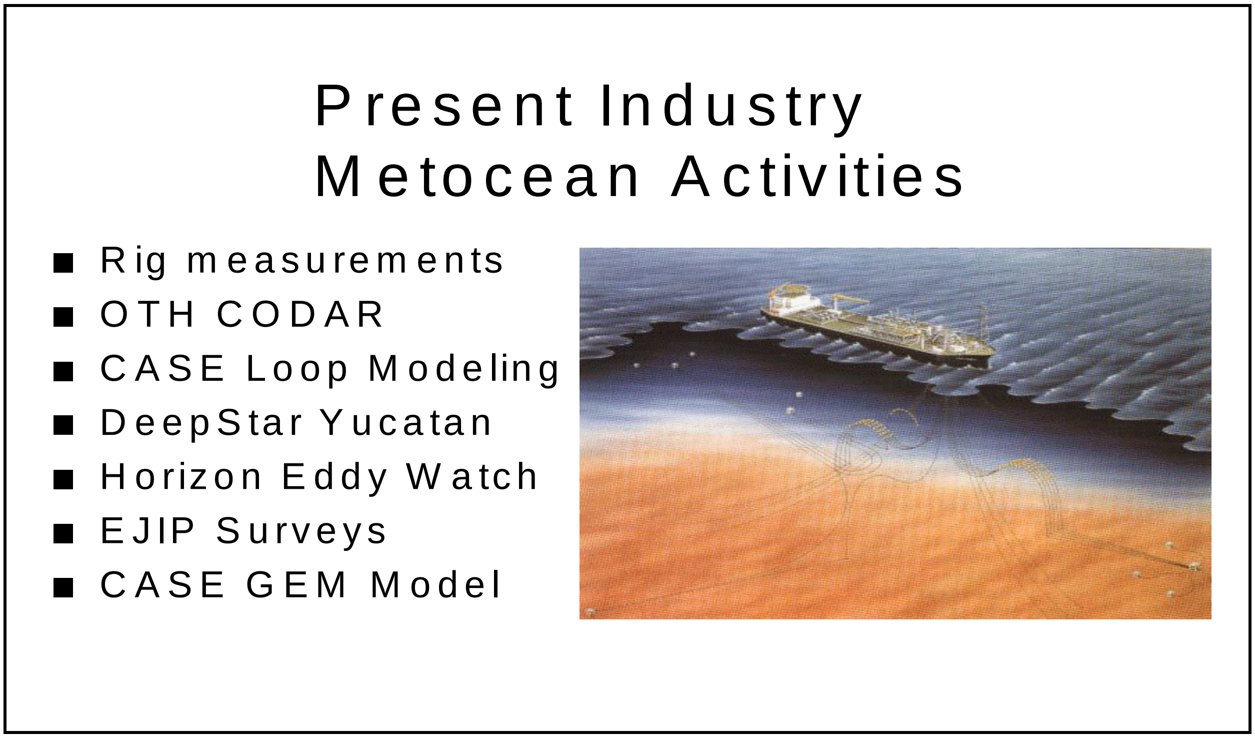
Figure 26. Some specific uses for real-time met ocean data include guiding the tactical response to an accidental pollutant spill as well as operational needs.

WHAT POSAR-LIKE ACTIVITIES IS THE INDUSTRY INVOLVED IN?

The oil industry is involved in seven major activities related to deepwater oceanography (Figure 27).

Figure 28 shows where we have been drilling in deepwater (dark dots) over the first six months of the year. It also shows the deepwater production platforms. The locations cover a broad swath over most of the northern slope of the Gulf.

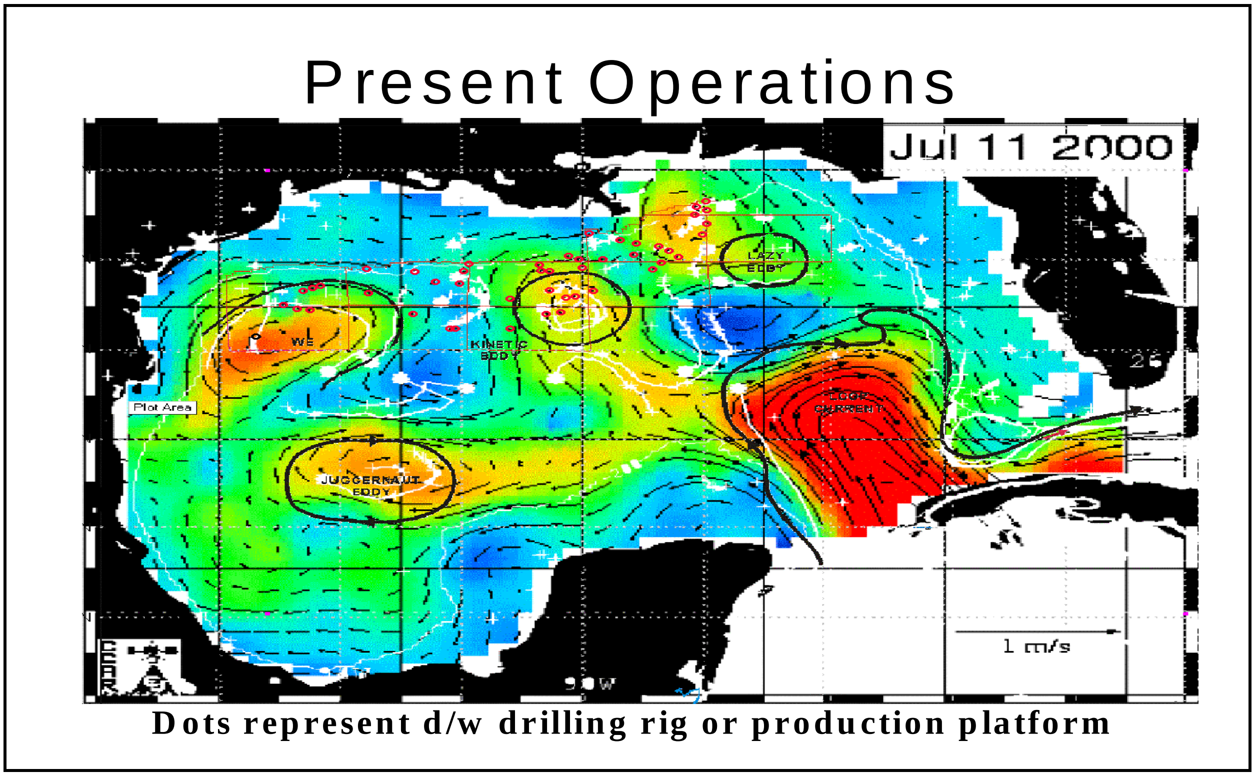
Figure 29 shows the location of on-going current measurements in deep water. Most of these involve ADCPs deployed from drilling rigs stay in place for about three months. These locations cover a substantial region and reflect the industry's most recent region of focus. Given this interest and the infrastructure provided by these facilities, it makes a lot of sense to try to utilize them as a component of POSAR.



Present Industry Metocean Activities

- Rig measurements
- OTH CODAR
- CASE Loop Modeling
- DeepStar Yucatan
- Horizon Eddy Watch
- EJIP Surveys
- CASE GEM Model

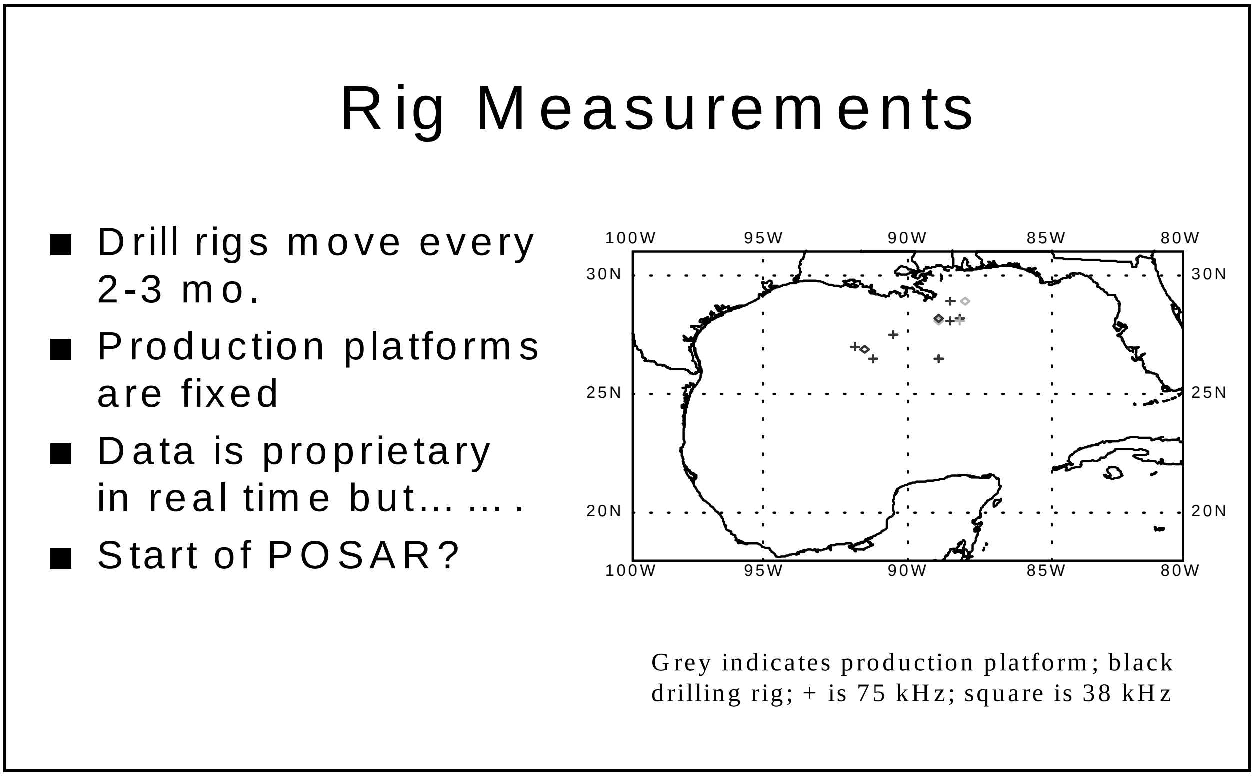
Figure 27. The seven major activities related to deepwater oceanography.



Present Operations

Dots represent d/w drilling rig or production platform

Figure 28. Locations of deepwater drilling rigs or production platforms.



Rig Measurements

- Drill rigs move every 2-3 mo.
- Production platforms are fixed
- Data is proprietary in real time but... … .
- Start of POSAR?

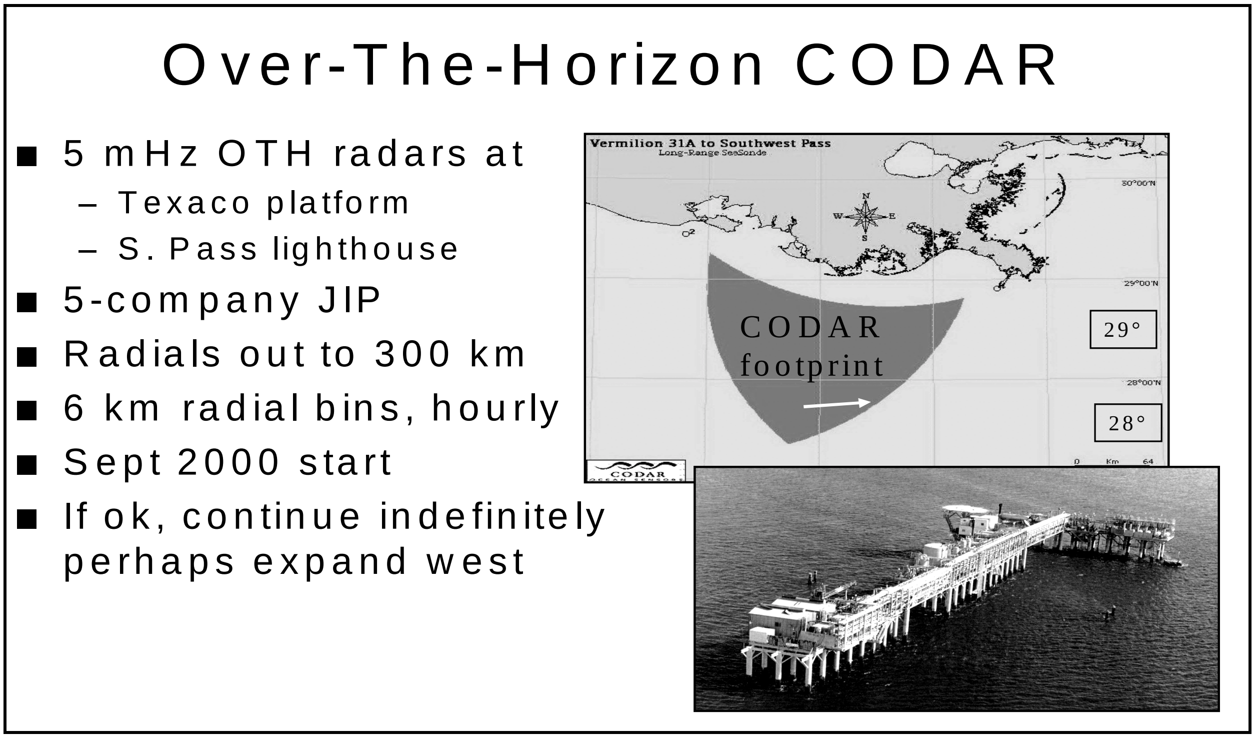
Grey indicates production platform; black drilling rig; + is 75 kHz; square is 38 kHz

Figure 29. Locations of on-going current measurements in deep water.

Figure 30 summarizes the CODAR JIP that the industry started early this year. It consists of two high-powered CODARS designed to reach out to 300 km from the source. The figure shows the overlapping region where we expect to get hourly current vectors at 6 km resolution. Of course, radial speeds will be available from a region about three times that size. The system is still being tested. If it proves viable, it will continue indefinitely, and a similar system may ultimately be installed in the western Gulf.

Figure 31 summarizes the modeling being conducted at the University of Colorado with funding from the CASE Joint Industry Project (JIP). This effort began in 1996 with the goal of developing a long-term climatology and a real-time forecast of the Loop/eddies. MMS has leveraged off this effort to produce the seven-year hindcast for the TAMU Reanalysis. Our present focus in on generating a monthly forecast, upgrading the inflow boundary condition, and quantifying model error. The latter is an especially important step that is conspicuously absent in previous efforts in the Gulf.

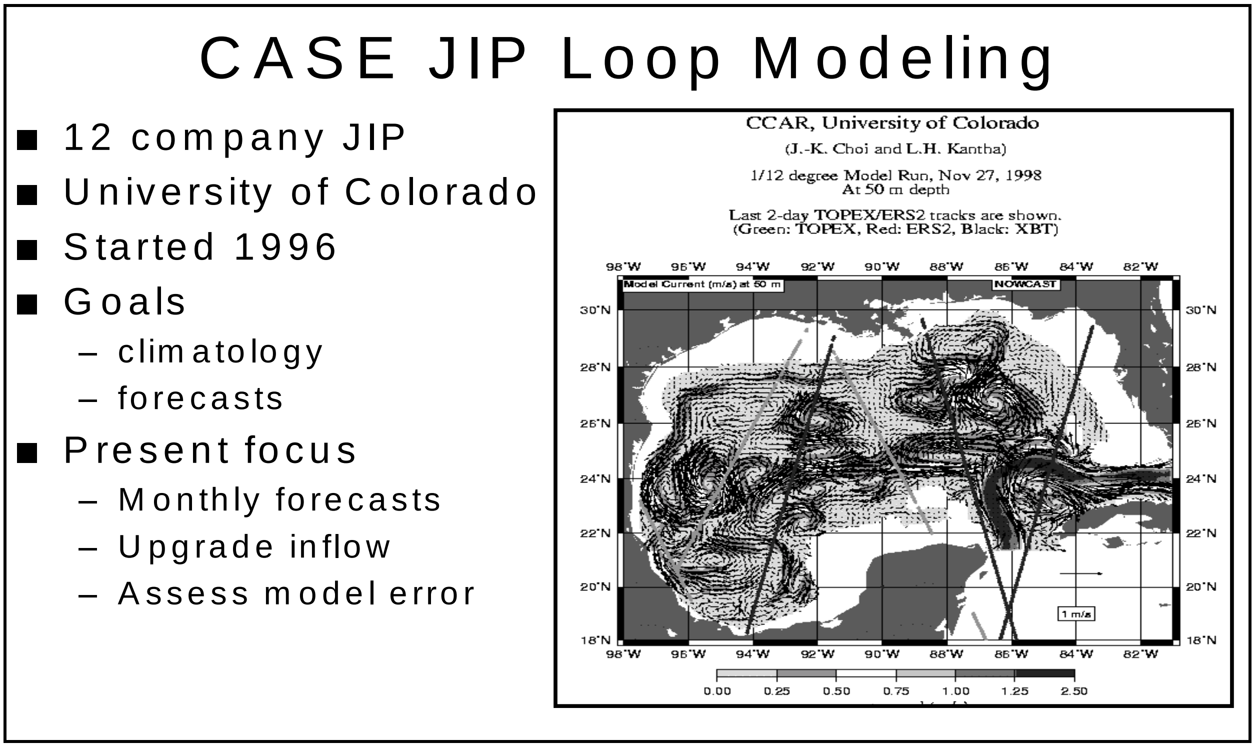
Figure 32 shows the mooring array that was deployed in the Yucatan Channel in August 1999 with funding from the DeepStar JIP and meters provided by the Navy. The meters were pulled in August 2000 with roughly a 90% data return, and redeployed for another six months. In addition to the moorings, several detailed synoptic surveys have been done across the Yucatan and the Topex Line 65 in the Caribbean. The primary driver for these efforts is to develop a realistic boundary condition for the modeling effort described earlier.



Over-The-Horizon CODAR

- 5 mHz OTH radars at
  - Texaco platform
  - S. Pass lighthouse
- 5-company JIP
- Radials out to 300 km
- 6 km radial bins, hourly
- Sept 2000 start
- If ok, continue indefinitely perhaps expand west

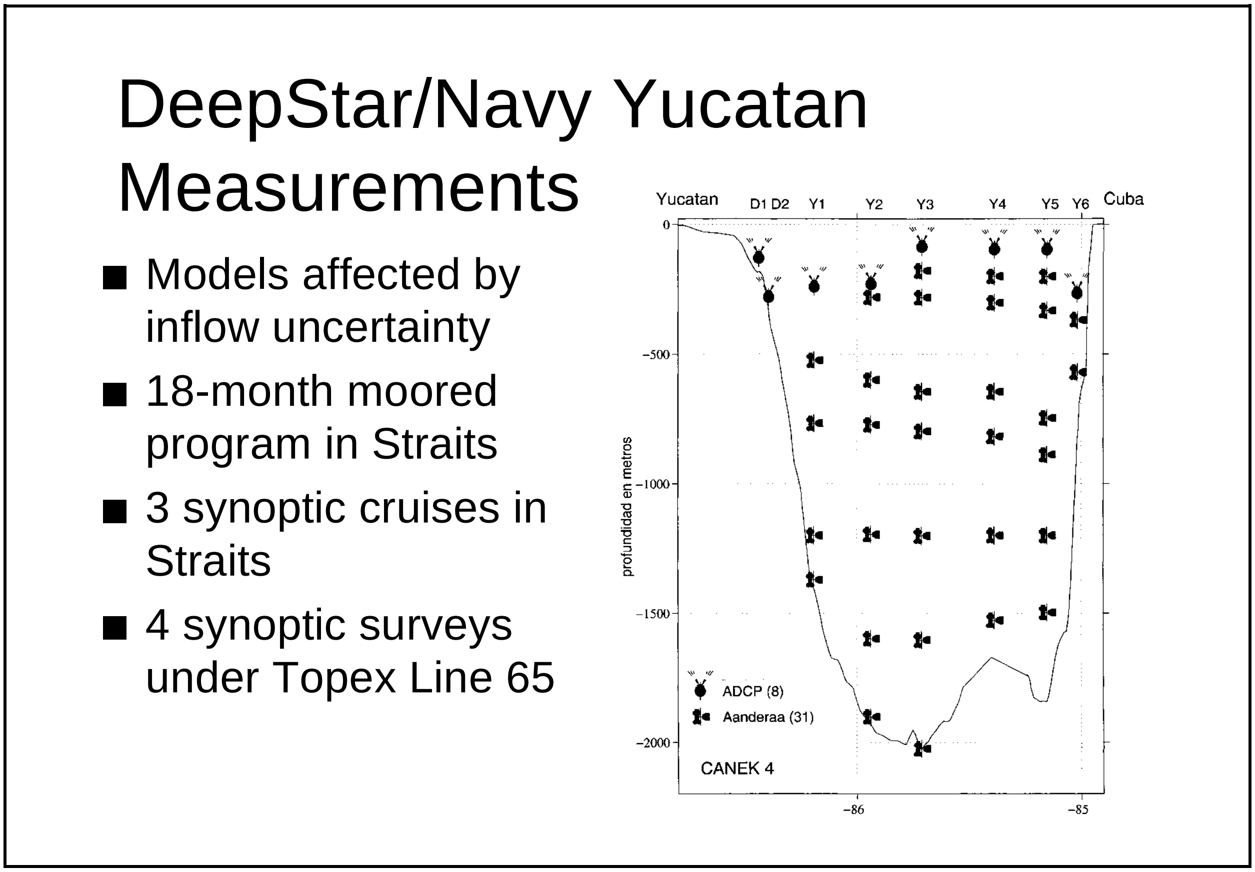
Figure 30. Summary of the CODAR JIP.



CASE JIP Loop Modeling

- 12 company JIP
- University of Colorado
- Started 1996
- Goals
  - climatology
  - forecasts
- Present focus
  - Monthly forecasts
  - Upgrade inflow
  - Assess model error

Figure 31. Summary of the modeling being conducted at the University of Colorado.



DeepStar/Navy Yucatan Measurements

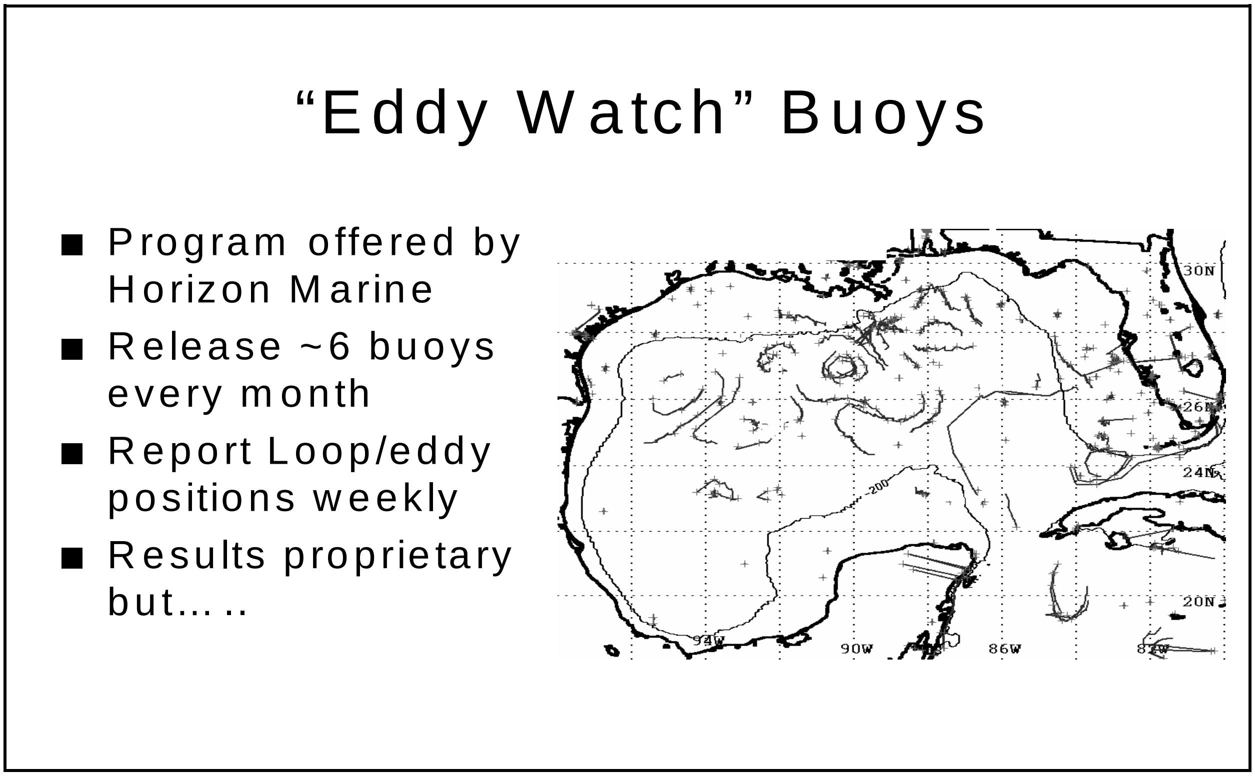
- Models affected by inflow uncertainty
- 18-month moored program in Straits
- 3 synoptic cruises in Straits
- 4 synoptic surveys under Topex Line 65

Figure 32. The mooring array deployed in the Yucatan Channel in August 1999.

Figure 33 summarizes Horizon Marine's Eddy Watch program. This is a commercial operation that deploys roughly six surface drifting buoys in the Gulf each month and develops a weekly summary of eddy/Loop position and strengths. This effort started in the late 1980s and represents a nearly continuous record of the eddy/Loop status during the entire year.

Figure 34 summarizes EJIP, a JIP focused on collecting baseline data in the deepwater Gulf primarily for engineering purposes. Started in1983, the JIP has funded surveys of many of the major eddies. Most recently it has done three synoptic surveys of Eddy Juggernaut covering its birth and death.

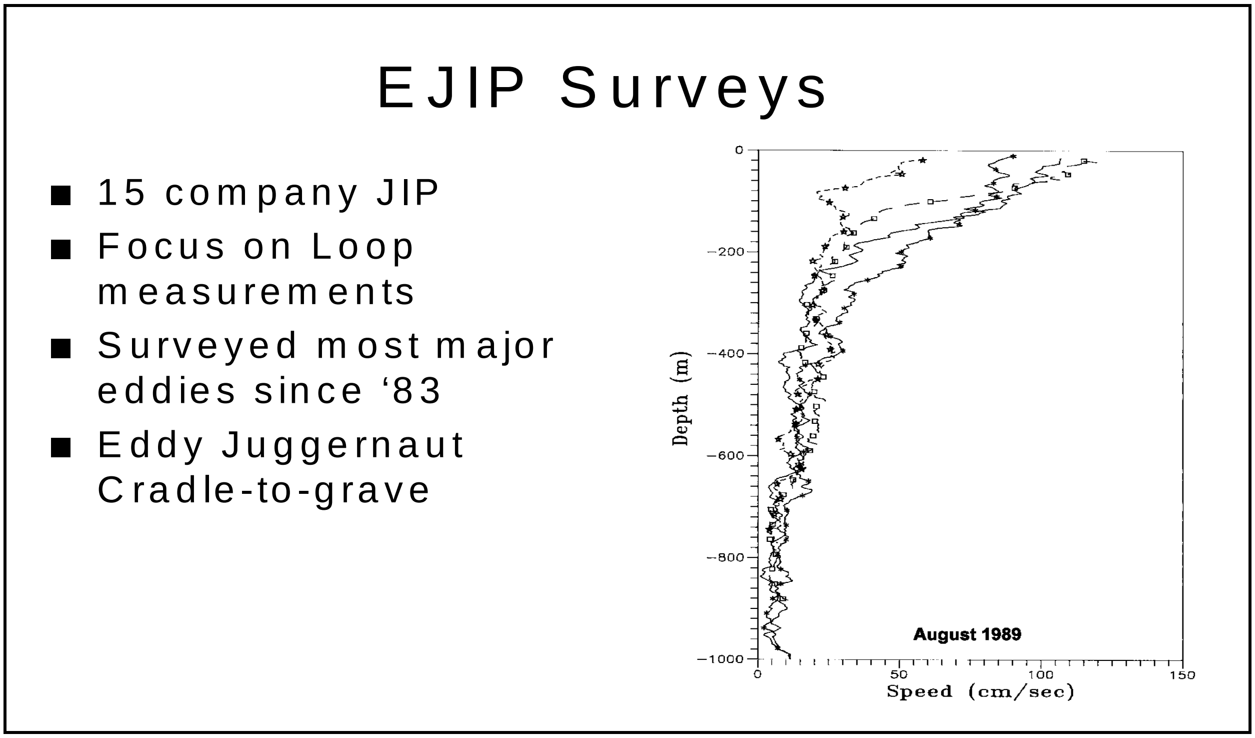
Figure 35 summarizes the Gulf Eddy Model (GEM) developed by the CASE JIP. This is a simple historical model that includes a database of eddy tracks and radii. Using this database and a simple parametric model, GEM can provide estimates of 3-D velocity fields generated by the historical eddies. CASE is presently upgrading GEM in three ways: using EOF analysis on data to enhance the profiles in the parametric model, extending GEM into the Western Gulf, and adding the most recent eight years to the track/radius database.



“Eddy Watch” Buoys

- Program offered by Horizon Marine
- Release ~6 buoys every month
- Report Loop/eddy positions weekly
- Results proprietary but… ..

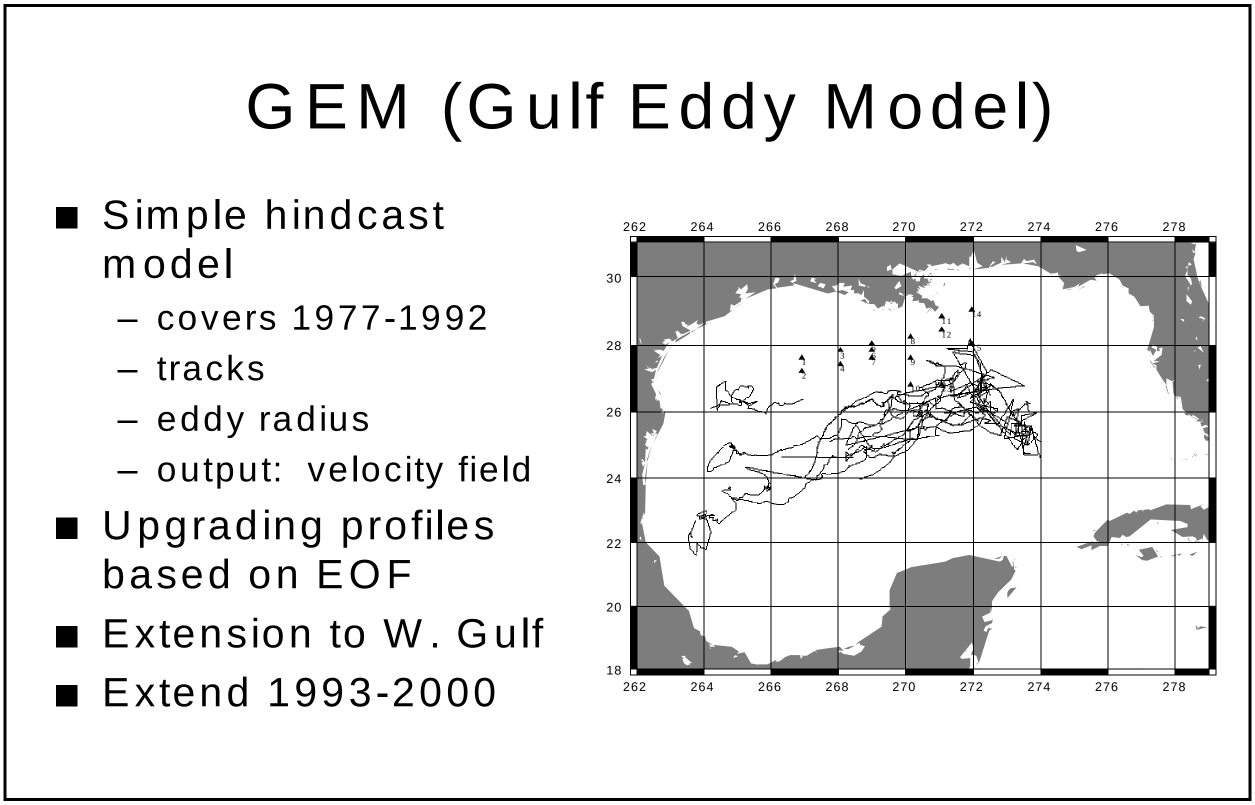
Figure 33. Horizon Marine’s Eddy Watch program.



EJIP Surveys

- 15 company JIP
- Focus on Loop measurements
- Surveyed most major eddies since ‘83
- Eddy Juggernaut Cradle-to-grave

Figure 34. A summary of EJIP.



GEM (Gulf Eddy Model)

- Simple hindcast model
  - covers 1977-1992
  - tracks
  - eddy radius
  - output: velocity field
- Upgrading profiles based on EOF
- Extension to W. Gulf
- Extend 1993-2000

Figure 35. The Gulf Eddy Model (GEM) developed by the CASE JIP.

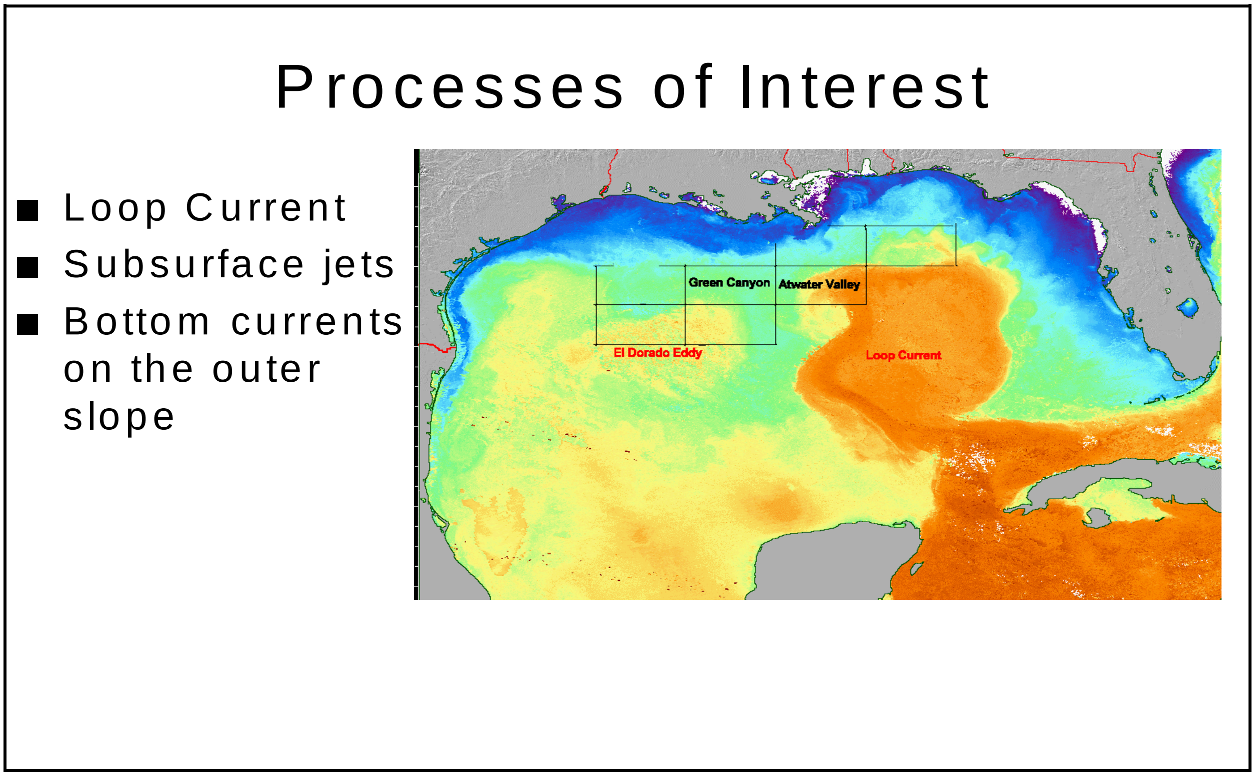
WHAT KINDS OF THINGS SHOULD POSAR MEASURE?

Figure 36 summarizes three topics of interest: some lingering mysteries regarding the Loop Current and associated eddies, subsurface jets, and bottom-intensified currents on the outer slope.

Figure 37 summarizes some of the questions that remain concerning the Loop and why they are important. The figure illustrates how powerful Loop currents can rapidly advect a hypothetical spill large distances from the source in a relatively short time. Despite our collecting data for nearly 20 years, there is still insufficient data on diurnal energy, profiles, and Western Gulf eddies.

Figure 38 shows the major features of subsurface jets. These have been briefly observed by the oil industry during the drilling of perhaps a half dozen wells. Subsurface jets are characterized by pulses of up to 3 kt 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.

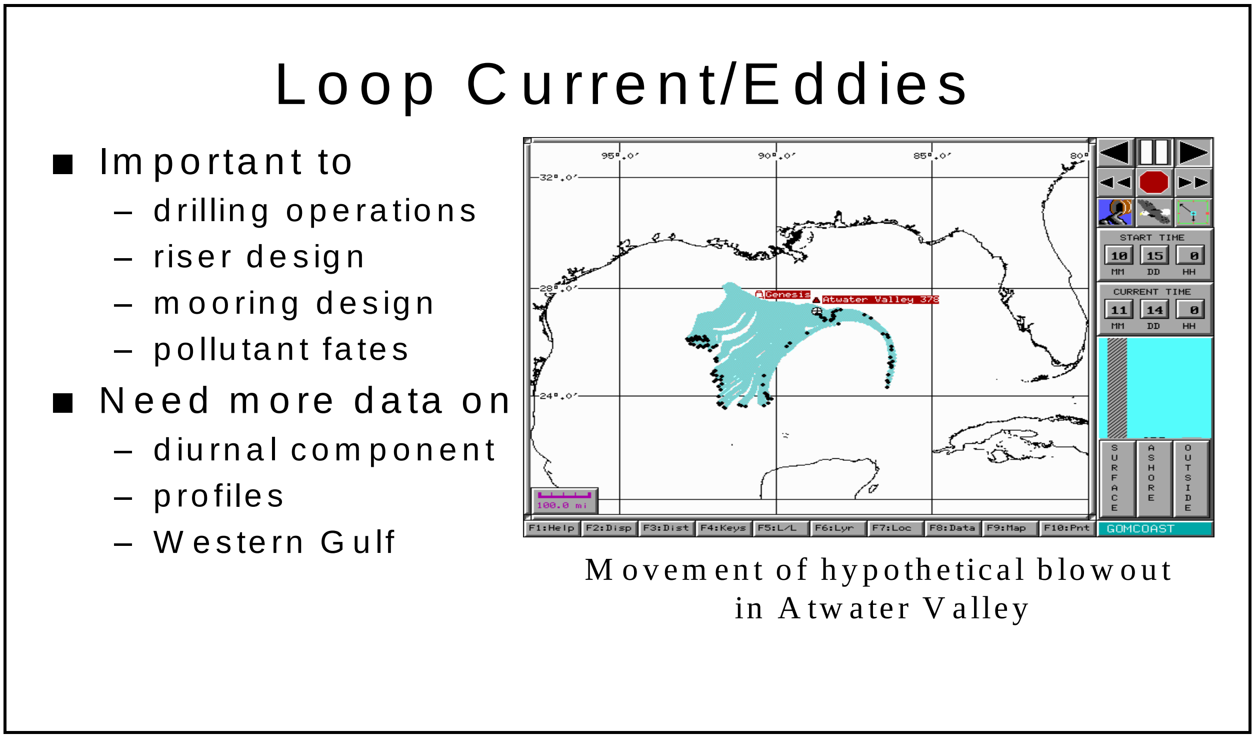
Figure 39 shows the major features of strong bottom currents recently documented in the measurements by MMS shown in the figure. There is strong evidence to suggest that these currents generate the furrows (10 m wide by 10 m deep trenches) found along the Sigsby Escarpment. Such currents will be important for pipeline design and risers as well as pollutant transport.



Processes of Interest

- Loop Current
- Subsurface jets
- Bottom currents on the outer slope

Figure 36. Three topics of interest.

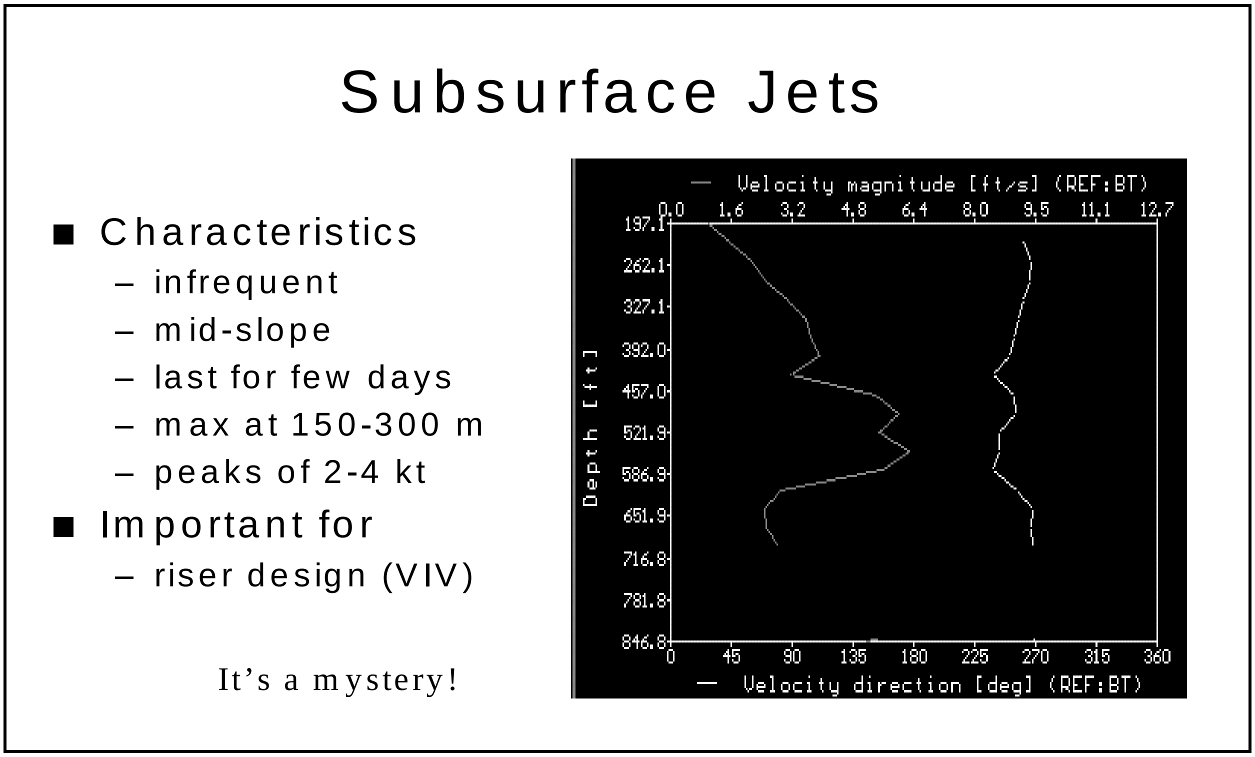


Loop Current/Eddies

- Important to
  - drilling operations
  - riser design
  - mooring design
  - pollutant fates
- Need more data on
  - diurnal component
  - profiles
  - Western Gulf

Movement of hypothetical blowout in Atwater Valley

Figure 37. Questions that remain concerning the Loop.

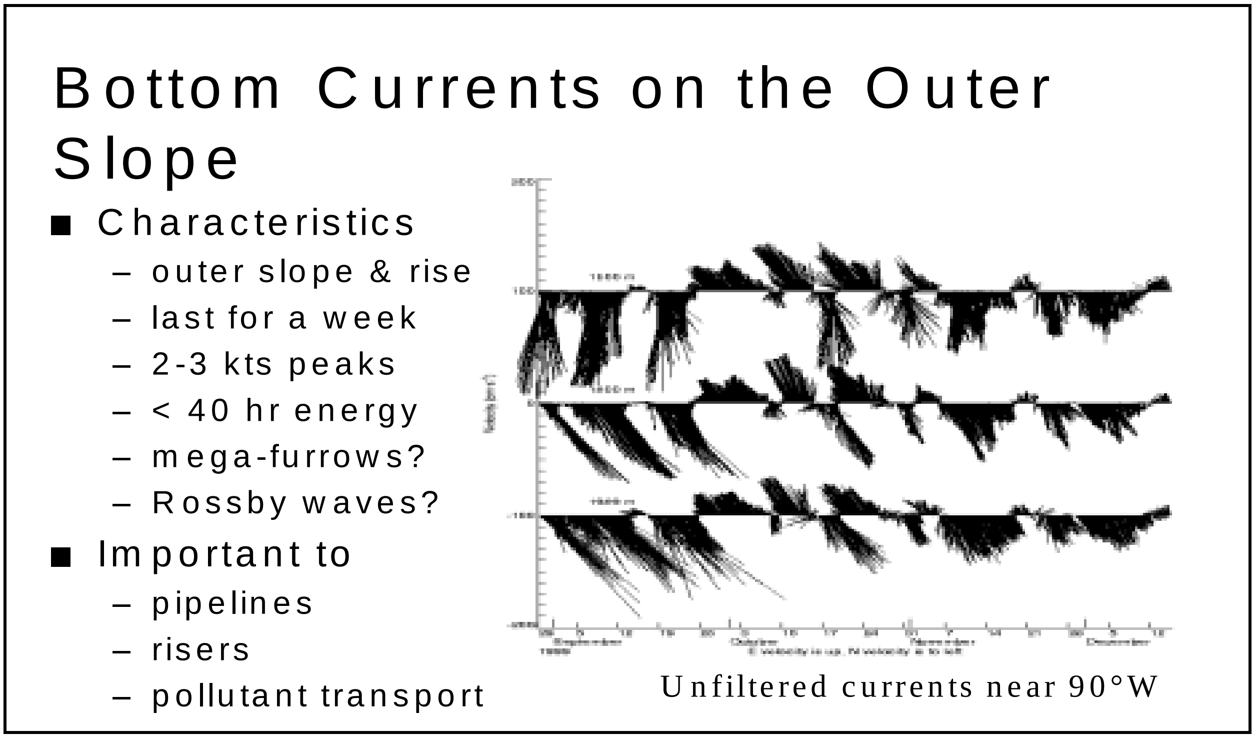


Subsurface Jets

- Characteristics
  - infrequent
  - mid-slope
  - last for few days
  - max at 150-300 m
  - peaks of 2-4 kt
- Important for
  - riser design (VIV)

It's a mystery!

Figure 38. The major figures of subsurface jets.

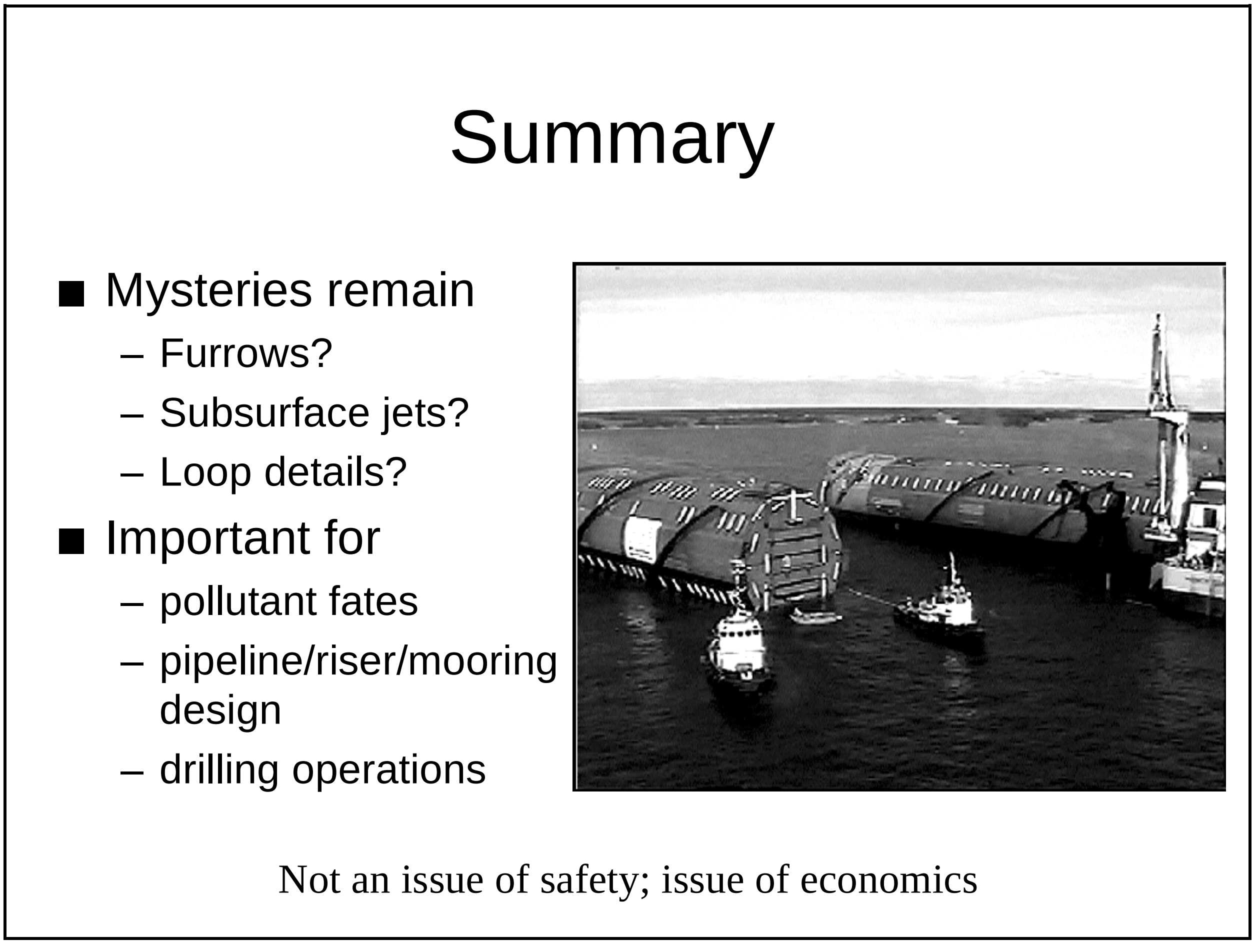


Bottom Currents on the Outer Slope

- Characteristics
  - outer slope & rise
  - last for a week
  - 2-3 kts peaks
  - < 40 hr energy
  - mega-furrows?
  - Rossby waves?
- Important to
  - pipelines
  - risers
  - pollutant transport

Unfiltered currents near 90°W

Figure 39. The major features of strong bottom currents.



Summary

- ■ Mysteries remain
  - – Furrows?
  - – Subsurface jets?
  - – Loop details?
- ■ Important for
  - – pollutant fates
  - – pipeline/riser/mooring design
  - – drilling operations

Not an issue of safety; issue of economics

Figure 40. A summary of the main points.

SUMMARY

Figure 40 summarizes the main points. A number of important oceanographic mysteries remain in the deepwater Gulf. These include the bottom-intensified currents likely causing furrows on the outer slope, subsurface jets, and several aspects of the Loop and associated eddies. Answering these questions is important so that we may be able to estimate fates and economically design and operate pipelines, risers, and moorings.

WORKING GROUPS SESSION INTRODUCTION:
TUESDAY AFTERNOON, 12 SEPTEMBER 2000

Dr. Larry Atkinson
Old Dominion University

Initial discussion focused on our knowledge of physical oceanographic processes in the Gulf, with emphasis on information presented that morning by the MMS management, the MMS advisory council, and oil industry representatives. The groups were specifically asked to consider the following:

- What processes do we now understand (recent findings)?
- What processes appear to be both important to the MMS and industry and not well enough understood?
- What are the critical observations that must be made?
- What monitoring should be done? For how long?
- What process study should be done? How can a sufficient number of process events be covered?
- What role should numerical modeling and tracers play?

The groups were reminded that Dr. Nowlin's presentation represented a potential sample design that required consideration in parallel with the workshop discussions.

Although the three groups diverged in their discussions, they maintained their focus on the deep energetic currents, what causes them, and how they could be best sampled. They discussed the theoretical basis for the currents, the ways that numerical models might aid in understanding them, and the relative merits of Eularian (fixed) and Lagrangian (drifting) measuring systems.

ISSUES REGARDING THE DESIGN OF THE POSAR PROGRAM

Working Group 1: Tuesday Afternoon, 12 September 2000

Dr. John M. Klinck
Discussion Leader
Old Dominion University

A variety of issues were discussed regarding the design of the POSAR program. The discussion ranged over all the topics below and in many cases returned to topics discussed at an earlier time. The order of discussion has been rearranged to make this summary coherent.

After considerable discussion, the TAMU sampling program was used as the focus. The four points of climatology, energetic deep flows, flow near megafurrows and Lagrangian measurements were discussed in turn.

Mean properties, which are also termed climatology, are more than just time averages of flow, but are rather descriptive statistics of the circulation. Given that the Loop Current Eddy (LCE) shedding interval is 10 months, 4 to 10 years of observations were thought to be the minimum required for stable statistics. At present, such long time series do not exist. Mean properties can be calculated from numerical simulations; in fact, such analyses are easy from numerical simulations. An important question is the realism of the numerical models and the reliability of model statistics.

There was considerable interest in the energetic deep flows around 2,500m isobath, which are called TRW (topographic Rossby waves). There was general agreement that the likely source of these energetic deep motions was the interaction of the LCE with topography in the northeastern Gulf of Mexico (GOM). The details of LCE shedding are related to details of the velocity structure in Yucatan Channel. Thus, these deep motions are not simply a local effect but are driven by other, remote, processes. Finally, the suggestion was made that higher frequency variability of surface currents have an effect on LCEs and eddy shedding.

Flow over and in megafurrows generated considerable discussion. This discussion expanded to consider not just the furrows but all sorts of smaller scale topographic features. A cautionary comment was made that other experiments in the Atlantic showed that bottom boundary layer dynamics are different on slope compared to the relatively flat continental shelf. The study of dynamic influences of small (>10km) horizontal scale bathymetry is missing in existing studies. In particular, the Sigsbee Escarpment was not included in most numerical simulations, which raised doubts about the accuracy of the model results. Some discussion considered the issue of having MMS buy the speculative, commercial current meter data available over the GOM. No conclusions were reached on this issue.

Also briefly discussed was the value of Lagrangian measurements compared to Eulerian. It was noted that drifter measurements are useful in identifying eddies in the flow. Specifically, surface drifters are critical in detecting small cyclones are attached to LCE. The larger LCE are clearly evident in satellite altimetry and do not require drifters to locate. The nature and size of deep eddies has not been determined, and midwater floats (RAFOS floats) were thought to be an effective tool in describing these motions. The initial thought was that floats were cheaper, but given the number needed for a good coverage, it was not clear that this was the case. It was clear that Eulerian measurements (moorings) can address issues of dynamics and correlation scale which are harder to analyze with drifters. A fleet of drifters is better at sampling over the whole GOM, which would be difficult with only moored sensors. The value of Lagrangian measurements was seen to be equal to Eulerian measurements at this point in the program.

A number of other study topics or issues were discussed or presented. The acoustic environment of the GOM and its effect on marine mammals was seen as an important topic. Water property climatologies, which exist, would be useful in a first study of acoustics. Midwater jets were interesting for engineering studies. However, the rare appearance of these events in existing records made it difficult to design a program to detect and study them.

Data needs and policies were discussed. This issue regards privately-held data by companies. It was generally agreed that lack of data is limiting our understanding of GOM processes. A part of the group called for observations to be made public, after some time span. So time was taken to consider large scale or long-term measurements that MMS might pursue. For example, the observations of flow in Yucatan Channel (DeepStar-like) are considered to be important for forcing and verifying models. Discussion questioned whether MMS/POSAR should continue these short-term industry-supported observations. The question of MMS support for real time observations was also aired. While both were considered to be valuable, the relative merit of these observational measurements versus more exploratory or targeted measurements was not explored.

Strong statements were made that other global and regional simulations, with high resolution grids, include GOM and should be analyzed. These model simulations exist and are available for free. For example, the Los Alamos Parallel Ocean Model results are global with 1/10 degree (5 to 10 km) grid spacing; they should be analyzed along with existing numerical simulations supported by MMS.

Model validation was identified as a critical activity for MMS as part of the POSAR program. It is important for studies to determine a variety of descriptive statistics for the GOM (LCE frequency, LCE path, LCE size, KE variability due to LCE, phase lag, spatial correlation scales). These should be estimated from measurements wherever possible and compared to similar estimates from numerical simulations. It was also thought to be useful to derive data from models for analysis. These data should have similar characteristics (number, time interval, locations, etc) to those of observations. Are the models giving similar answers as the observations? Can the models be used to design measurement programs? Can the models be used to extrapolate mean properties to regions devoid of measurements?

PROCESSES REQUIRING STUDY IN THE GULF OF MEXICO SLOPE AND RISE REGION

Working Group 2: Tuesday Afternoon, 12 September 2000

Dr. Randy Watts
Discussion Leader
Professor of Oceanography
University of Rhode Island

For this first breakout session on Tuesday afternoon, each of three Working Groups was asked to discuss “what processes require study in the Gulf of Mexico Slope and Rise region relevant to the MMS mission?” An appendix at the end of this subsection lists the attendees for Working Group 2 and the items suggested to all working groups for discussion.

We began by asking each participant to write for themselves a short list of topics for discussion. Next, we compiled a list by asking participants sequentially around the room to add one topic or modify the wording of an already-suggested topic, repeating until inputs were exhausted from all the participant’s. We focused the ensuing discussion on strong current processes and observational issues, but we also reserved time to discuss issues involving computer modeling of these processes. In both cases, we also began initial discussion of methods needed to address the questions.

Our group determined that the largest gap in data and knowledge of currents in the Gulf of Mexico is in the deep slope and rise waters. Basic exploratory field measurements are needed to determine the time scales and horizontal spatial scales of the deep water eddies and circulation in water depths greater than 1,000 m. Process-studies are also needed to analyze the coupling of deep eddies with baroclinic surface currents.

There is observational and theoretical reason to believe that the mesoscale eddy and the slowly-varying mean or background currents are only weakly dependent on depth below 1,000 m. Strong current shear exists at shallower depths than 1,000 m, within and above the main thermocline. Some degree of bottom-intensification is expected and observed for topographic Rossby waves (TRWs), dependent upon their horizontal wavelength. Nevertheless, over the sloped bathymetry, higher order vertical structure exists and may contain substantial variance (see discussion below of episodic observed submerged jets), particularly in association with periodicities of approximately 30 hours or less (inertial and internal-wave currents). It was pointed out that in some energetic events, the inertial and higher-frequency currents contributed an additional half of the total variance.

Thus, because the mean and low-frequency eddy currents have weak depth dependence below the thermocline (i.e. below about 1,000 m depth), much can be learned about the deep eddies and circulation from current measurements or floats at any one sub-thermocline depth. Nevertheless, it was suggested that additional field measurements should be taken at some subset of sites to study the detailed vertical structure of the deep currents, particularly those associated with higher frequency events.

It is of interest to study dynamic interactions between shallow (slope/ shelf) and deep waters. Numerical models are needed to address this 3-D general circulation problem and conduct Oil Spill Risk Analysis (OSRA). Additional field observations will greatly support OSRA modeling skills — which is viewed as a major motivation behind sponsoring new observational studies.

Benthic boundary layer (BBL) processes are of great interest. These currents are responsible for generating furrows and other bathymetric features, and the BBL processes link physical, biological, and geological processes. It was suggested that some proposals address such cross-disciplinary studies.

Powerful submerged jets have been observed at 200- 400 m depths. A few (5 – 6) episodic events have been observed in ~ 5 million hours of current records. In these episodes, the oscillation period is about a day (several hours) in bursts lasting a few days. These submerged current jets would be particularly effective at causing fatigue in oil-drilling and platform risers. We need to understand what causes them, whether they are steered or intensified by bathymetry, how long they last, and how often they might return at various sites. It could be very instructive to know if they are associated with a temperature or salinity anomaly (such as Subtropical Underwater, as in a submesoscale coherent vortex). Because they have thus far been so infrequently observed, it is difficult to design a dedicated experiment to study them. Nevertheless, it would be desirable to add upward-looking ADCPs at 300-400m depth on moorings that are deployed for other purposes. They might also be detected on shipboard ADCP transects taken for other purposes. We need to share current records from existing oil platforms or proprietary moorings, to seek a physical understanding of the processes responsible for these jets.

More observations are also needed of surface-intensified currents, particularly in the Loop Current and Loop Current Eddies (LCEs). We should not lose sight of the fact that much information is still needed in order to characterize, quantify, and understand these highly energetic processes. The LCEs are accompanied by strong smaller scale eddies around their periphery, and accompanied by strong abyssal eddies with current speeds exceeding 1 kt (nearly depth-independent). They are manifestations of instability processes as well as manifestations of interactions between the LCEs and the slope and rise topography. High frequency and better spatially resolved current measurements are required in the loop current and LCEs. We need to study the vertical coupling of upper and deep currents and variability from mesoscale to smaller scale features and to examine the higher frequency variability, which may arise as the LCEs interact with topography.

It is highly likely that strong TRW currents obtain their energy from the highly energetic loop current and LCEs. No other driving sources with appropriate spatial and temporal scales and sufficient energy are present in the GOM. It is important to characterize and quantify this generation process and how it is affected by topographic interactions. This process could lead to improved prediction of currents and improved understanding of pollutant dispersion.

We also need to promote the timely sharing of data. This statement applies to data sharing among scientists, among industry and consulting groups, and among international partners around the Gulf of Mexico. By appropriate sharing agreements, an "economy of scale" may result, because projects can be designed to benefit industry, government, and science. Deep-water drilling and production structures may be outfitted with current-measuring instruments; some discussion was devoted to the fact that this approach is *not* cost-effective *unless* the sampling design (e.g. location, horizontal array design, and duration) is suitable to elucidate the processes being studied and *unless* data quality is suitably high. Greater efforts are required if the latter quality control is to be achieved.

Considerable discussion was devoted to the desirability of assimilating data into dynamical models to understand physical processes. Assimilation is an important tool for dynamic interpolation between the observation sites, and understanding of the measurements can be improved using assimilation. Models are correspondingly improved – for example, most present models do not yet generate deep eddies that are nearly as strong as those observed. Model performance has been greatly improved and may be expected to improve much further still as computer power increases, enabling higher resolution. Much data-assimilation modeling-development effort is ongoing and required in the near future. We need to learn how best to assimilate a variety of new observational data into models.

We identified some important issues for numerical modeling development. Process models are needed as well as general circulation models. Particular questions of relevance to the Gulf of Mexico slope and rise region were noted: How fine a resolution of bathymetry is needed for models? For example, the escarpment south of Louisiana is a sharp feature that rises obliquely along the slope, thus occurring at different depths at different locations. Model focus on the benthic boundary layer is also needed.

Model skill must be assessed relative to the specific processes being modeled. "Metrics" must be generated to assess how well a model describes a process. The criteria of assessment may differ for different purposes, such as estimating mean and variability fields, or generating now-casts, or for predictive purposes.

A few additional topics were mentioned but received little further discussion in our group:

(a) the important role that the loop current and LCEs play in ventilating deep waters within the Gulf

(b) the operation of vertical transport mechanisms

(c) the role that mesoscale features in the Caribbean play in affecting the structure in the Yucatan Channel and in affecting the Loop Current and how / when it pinches off to form eddies

(d) the balance and relative importance of local wind curl forces and loop current effects upon the currents and variability within the Gulf.

APPENDIX: ATTENDEES AND ISSUES ASSIGNED FOR INITIAL DISCUSSION

Working Group 2 Attendees

Randy Watts, Chair
Jeff Ji, MMS, Co-Chair
Robert Avent
Douglas Biggs
John Blaha
Donald Davis
David Driver
Norman Guinasso, Jr.
H. James Herring
Ann Jochens
Carliane Johnson
A.D. Kirwan
Ronald Lai
Tom Meyer
Worth Nowlin
William Schroeder
Tony Sturges
Georgi Sutyrin
Dong-Ping Wang
Susan Welsh
Huijun Yang

Initial Issues Suggested for Discussion

- What processes do we now understand (recent findings)?
- What processes appear to be both important to the MMS and industry and are not well enough understood?
- What are the critical observations that must be made?
- What should be done in a monitoring mode for a long time? State time period.
- What should be done in a process study mode covering a sufficient number of proceeds events?
- What should be done with numerical modeling?
- What should be done with the use of tracers?

IDENTIFYING AND SUMMARIZING PHYSICAL PROCESSES RELEVANT TO MMS CONCERNS

Working Group 3: Tuesday Afternoon, 12 September 2000

Dr. Craig Lee
Discussion Leader
Applied Physics Lab
University of Washington

OVERVIEW

Working Group Three convened following the first plenary session with the goal of identifying and summarizing physical processes relevant to MMS concerns (e.g. processes that could modulate the environmental impact of oil/gas exploration and production activities or affect MMS safety assessments). For each process, the group:

- Assessed whether our present level of understanding was sufficient to meet MMS needs.

- In cases where the present state of knowledge was considered inadequate, worked to define the elements of a study that could produce significant advances.

The participants were (relatively) evenly distributed between MMS, industry and academia, contributing a variety of perspectives to this initial attempt at identifying the processes of interest.

At the start of the session, each participant identified a small number of processes and/or environmental concerns that they viewed as important and provided a short statement judging whether additional research was required. The compiled results from this 'survey' (presented below) guided further discussion directed at refining scientific questions that could provide the framework for upcoming research programs. The participants spent the balance of the session examining the merits of the various proposed research areas, considering both applicability to MMS missions and scientific merit. Industry representatives identified environmental phenomenon, such as episodic bursts of strong currents at depth, that they considered to be important subjects for any upcoming research efforts. The group avoided detailed consideration of the implementation issues (i.e. observational/modeling approaches, hardware and logistical requirements and budgetary needs) surrounding proposed studies, deferring these discussions to later working groups.

SURVEY OF RESEARCH TOPICS

Well Understood

- Dynamics associated with currents on the shelf (R. Patchen, S. DiMarco)

- Wind-driven circulation over the inner shelf (D. Brooks)
- Morphology of both Loop Current and Loop Current Eddies (LCEs) (F. Vukovich)
- Near surface currents over the slope and deep Gulf (J. Coleman, S. DiMarco)

Increased Understanding Required

- Geology of ‘mega-furrows’ (in hope that furrow characteristics could be used as a proxy for the long-term variability of episodic, strong, near-bottom currents (K. Schaudt, B. Bryant, S. DiMarco)
- Deep flow associated with mega-furrows (L. Yongxiang, S. DiMarco)
- Variability in the region between the deep basin and the shelf (R. Patchen)
- Processes involved in exchanges between the shelf, slope and deep basin (R. Patchen, C. Dehaan)
- Processes driving deep currents at the base of the continental slope (D. Brooks, V. Waddell, C. Dehaan, D. Gisclair)
- Processes driving strong, deep, episodic events over the slope (M. Inoue)
- Processes controlling LCE formation. Eddy shedding processes in the region of Yucatan Channel (D. Brooks, V. Waddell, F. Vukovich)
- Dynamics of deep rectified flows and deep western boundary currents, particularly given the absence of significant thermohaline forcing (K. Lehman)
- General circulation of deep water (S. DiMarco)
- Variability of barotropic motions over deep water (L. Yongxiang and S. DiMarco)
- Dynamics governing the translation, evolution and eventual dissipation of LCEs. What determines LCE pathway into the western Gulf of Mexico? How do LCEs interact with the boundaries?(V. Waddell, F. Vukovich, S. Murray, D. Rowe)
- Temporal and spatial variability of the LC and LCEs (L. Rouse)
- Eddy interactions with topography (topographic steering) (D. Rowe, L. Rouse)
- Processes linking upper and lower (above and below 1,000 m) water column dynamics (V. Waddell, D. Rowe)

- Particle (Lagrangian) dynamics within the deep (below 1,000 m) layer (V. Waddell)

- Use of both existing and new observations to refine numerical modeling efforts (F. Vukovich).

- Dynamics of low-frequency motions in both shallow and deep water (C. Dehaan)

- Role of currents in determining the pathways followed by deep and shallow water pollutant releases (D. Gisclair)

- Variations in bottom temperature and their effect on hydrate stability (J. Coleman)

- Geological features in the deep Gulf and their interactions with bottom currents (J. Coleman)

- Three-dimensional current variability over the Gulf (W. Teague)

- Validation and improvement of numerical models for both hindcast and forecast capability. Enhanced data assimilation schemes (W. Teague, D. Rowe)

- Sub-mesoscale eddies: vertical structure, dynamics, role in vertical energy transfer (C. Ebbesmeyer, L. Rouse)

- Vertical mixing over rough bottom topography on the slope (M. Inoue)

DISCUSSION

Discussions focused on motivating and refining the recommended research areas. Several participants emphasized the need to demonstrate the environmental relevance of all proposed research. Ultimately, any MMS-supported physical oceanography program must make a clear contribution to understanding the potential environmental impacts of exploration and extraction activities in the Gulf of Mexico. The role played by subsurface currents in determining the distribution of deep contaminant releases was offered as a specific example. The group's consensus was that this meant tying physical variability and dynamics to their effects on relevant biological systems. An investigator suggested that biological observations be undertaken in conjunction with any physical measurements.

Industry representatives expressed their desire to use a better understanding of the dynamics of the shelf and slope to aid in developing safe, efficient platform designs. Participants noted that this was not an indication that present platforms were unsafe, but rather a hope that better environmental data could be used to optimize designs to minimize both the probability of occurrence and the potential impacts of accidents. Particular issues mentioned included the effects of episodic, energetic events on fatigue cycles and the effects of strong currents at the slope base and over 'mega-furrows' in producing pipeline scouring problems. Several people noted that short-lived, strong events could greatly accelerate platform fatigue. The group indicated that while producers believe that they can safely design and operate systems, MMS is responsible for minimizing the risk of accidents.

Several of the episodic processes suggested for further study generated discussion about the challenges associated with observing event-driven systems. For example, the deep and mid-water strong current events were believed to have horizontal scales of O(5 km), limited vertical extents and durations of several days. All agreed that the probability of sampling such an event using traditional techniques was small, and that collecting enough realizations to gain any degree of statistical confidence was a daunting challenge. Several technologies, including instrumented moorings, arrays of inverted echo sounders, Lagrangian floats and long-range autonomous vehicles were briefly discussed as possible solutions. The idea of using prominent natural features, such as the 'mega-furrows,' as proxies to study the long-term, integrated effects of many short-lived, episodic events was also discussed. Given an understanding of furrow generation processes, furrow variability might be used to infer the distribution and frequency of episodic strong bottom currents.

The group considered the possibility that 'mega-furrows' could steer and/or accelerate near-bottom currents. Strong flow over the furrows could also generate internal waves, which might elevate near-bottom shear and lead to enhanced vertical mixing. Current acceleration and steering could affect both platform safety/design and pollutant transport, while wave generation and mixing could influence pollutant dispersal. Participants noted that furrows are not unique to the Gulf of Mexico, but also occur in other regions of the world's oceans. The small scales of the furrows prevents easy detection using multi-beam techniques, though they can be resolved in three-dimensional seismic mapping. Present formation theories invoke dynamics similar to those of Langmuir cells in the upper ocean. Some concern was expressed about whether the dynamics associated with the furrows were relevant to MMS goals.

Eddy dynamics and the vertical transport of energy occupied much of the discussion. Several participants noted that while we have a great deal of knowledge concerning surface features, the vertical structure of the eddies is poorly understood. Eddy variability includes Loop Current Eddies (LCEs) and smaller, sub-mesoscale features that occur in association with LCEs and also independently over the slope. These features may have prominent surface expressions, or they may be subsurface eddies with limited vertical extents. Interactions between shallow and deep eddies may be a mechanism for efficient transfer of energy into the interior and thus represent a possible source of energy driving strong, deep currents in the Gulf of Mexico. The roles played by topographic steering and eddy-eddy interaations in determining eddy translation pathways was also considered.

Participants expressed concern over the present state of knowledge of deepwater transport pathways, watermass formation mechanisms and the processes governing exchanges between the shelf, slope and deep basin. Several investigators indicated the need for a study to characterize watermass variability and trace origins and pathways in the Gulf. Likewise, participants voiced concerns that the measurement suite be extended to include other signals (e.g. dissolved oxygen) that might be useful as watermass tracers. Eddy interactions with the slope and the upward transport of deep water in up-canyon flows were discussed as a possible mechanisms driving exchanges between the shelf, slope and deep Gulf of Mexico.

SUMMARY OF RECOMMENDED RESEARCH TOPICS

General

- Vertical transfer of energy
- Shelf-slope-open basin interactions – processes that drive exchange
- Energy transfer between scales – eddy interactions
- Processes that control near-bottom temperature variability
- Interactions with topography → how bathymetry effects pathways of Loop Current and eddy propagation
- Consideration of what is needed to improve modeling/assimilation predictive capability
- Investigation of whether the geological record be used as a long-time scale integrator?

Eddies

- Formation, generation, mechanisms
- Propagation
- Influence on vertical energy propagation
- Scales of variability: what controls them?

Bottom Boundary Layer

- Furrow formation
- Furrow effects on near-bottom flows
- Internal wave generation by flow over rough bathymetry—enhanced mixing?
- Other mechanisms for generating strong near-bottom flows (turbidity currents dense down-slope flows…)

Water Mass Formation

- Formation of deep or intermediate waters: do they appear as subsurface lenses?

WORKING GROUPS SESSION INTRODUCTION: WEDNESDAY MORNING, 13 SEPTEMBER 2000

Dr. Larry Atkinson
Old Dominion University

Wednesday morning, the group met in Plenary to hear the reports from the previous afternoon. Following the plenary session, the groups were assigned new topics developed by the steering committee overnight. The topics selected and the rationale were as follows:

- Eddy Interaction with Topography—this topic was based on the fact that the energetic currents may be generated with Loop Current Eddies interacting with the continental slope and other features in the northern Gulf of Mexico.
- Effects of Small-Scale Topography—this topic focused on roughness features such as the “mega-furrows.”
- Eddy-Mean Flow and Eddy-Eddy Interaction—this topic addressed the eddy field associated with the large-scale flow patterns in the Gulf.

Although these topics are obviously related, each group came up with a different viewpoint on the topic. Such diverse views and approaches should be useful to managers trying to prioritize research goals.

During the discussions Tuesday evening, it became obvious that any research would require significant partnerships between the federal and state government, industry and academia. For this reason, we created a fourth discussion group for Wednesday morning to focus on:

- Partnerships for Future Studies—Industry-Federal/State Agencies-Academia

This groups’s report noted that several partnerships already exist although none yet are of the level needed to facilitate the research described in this report.

EDDY INTERACTIONS WITH TOPOGRAPHY

Working Group 1: Wednesday Morning, 13 September 2000

Dr. Craig Lee
Discussion Leader
Applied Physics Lab
University of Washington

OVERVIEW

Participants worked to define research programs focused on eddy interactions with topography, a broad range of topics identified by the previous afternoon's working groups. The session began with an open discussion about eddy variability and the various eddy-related processes active in the Gulf.

After a short period, two interest groups emerged, focusing on different classes of eddies:

- Generation, propagation and dissipation of larger (200 km) Loop Current Eddies (LCEs)
- The distribution and dynamics of sub-mesoscale eddies (specifically not LCEs), arbitrarily defined as having horizontal scales smaller than 100 km.

The participants divided into two groups, each working to address the following questions:

- Which topics should be chosen for additional study?
- What modeling and observational approaches might be critical to advancing our understanding of these processes?
- What would define a successful study?
- What motivates our need to understand these processes (e.g. the potential impacts of oil and gas spills on the environment)?

The two working groups met separately to choose specific research questions and outline strawman programs from the broader topics defined above. Due to lively discussion, these group activities occupied the majority of the session. Participants focused on defining specific topics for research, discussing the motivation and relevance of proposed studies and exploring the merits of various approaches. Both groups expressed strong reservations about explicitly prescribing the work to be done. Most participants felt that investigators responding to the Request for Proposals should be allowed latitude to optimize their efforts as they see fit. This may involve innovative approaches that the working group could not anticipate. A strong overall program should be built by choosing the best proposals that address relevant areas of research. The entire group reconvened during the last third of the session to exchange results, explore the proposed approaches for potential overlap and generate summary report.

PRELUDE

The group began by examining the importance of eddies to MMS goals. Participants noted that eddies (of various sizes) are energetic and ubiquitous in the Gulf of Mexico. Eddies can drive lateral transports of water, biology and pollutants, may influence the vertical propagation of energy (and thus the nature of episodic, strong subsurface currents) and can interact with the shelf and slope to effect significant exchanges of deep-basin water. Likewise, strong currents associated with eddies can influence platform design decisions when optimizing for safety and long-term durability. Bathymetry within the deep Gulf of Mexico influences the Loop Current path (and thus the location of the LCE generation region), steers eddies as they translate and impacts the role eddies play in exchanges between deep basin and shelf/slope waters.

The episodic nature of eddy events makes them difficult subjects for *in situ* observation. A common approach is to deploy long-term, fixed-location instruments in regions having historically high eddy activity in hope of catching passing eddies in the resulting time series. An alternative involves opportunistic sampling of eddies previously located by other means (e.g. satellite remote sensing) using techniques such as ship-based surveys and rapidly deployed, short-term moorings. The first approach cannot guarantee that a significant number of events will be observed, while the second requires very large commitments of both human and hardware resources. Relatively new technology that might be employed includes profiling (RAFOS, PALACE or MAVOR) floats, large arrays of inverted echo sounders and long-range, profiling autonomous underwater vehicles (AUVs). All participants agreed on the need to sample multiple realizations of eddies and on the importance of sampling vertically over the entire water column.

Two broad classifications were applied to eddies within the Gulf of Mexico. Several investigators identified Loop Current Eddies as important, prominent features. Smaller eddies accompany larger features such as LCEs, though these were considered to be part of the system which included the larger, central eddy. Likewise, LCEs are associated with complex vertical structures which include smaller, subsurface eddies. These smaller features play critical roles in affecting vertical and horizontal energy transfer and in linking the larger, overlying eddy to the bathymetry. Other investigators noted that although LCEs were certainly the most prominent features in the Gulf, the majority of observed eddies are smaller and more short-lived. There was general agreement that the dynamics of LCEs probably differed from those of the smaller, ‘sub-mesoscale’ eddies, and discussion branched into two separate groups, each focusing on issues specific to one class of eddy.

BREAKOUT GROUP SUMMARIES

Sub-Mesoscale (10-100 Km) Eddies

Research Focus

- Develop a climatology of eddy variability focusing on the continental slope and rise

- Understand generation and dissipation mechanisms (e.g. interactions with topography and flow instabilities)

Historical Data

- Compile climatology of eddy variability from pre-existing data, Data availability may limit this to surface features

- Develop a characterization of sub-mesoscale eddy vertical and horizontal structure using archived observations

Loop Current Eddies

Research Focus: Dynamics of LCE generation, propagation and dissipation. Specific issues include:

- Topographic steering of LCEs

- Cross-shelf exchange driven by LCEs

- Role played by associated sub-mesoscale features in coupling LCEs to underlying, deep bathymetry and in LCE dissipation

- Interactions between LCEs and the background mesoscale eddy field

- Role of loop current variability in determining formation location of LCEs. This is important because it influences subsequent propagation and the eventual fate of the eddy

Historical Data

- Relative to the sub-mesoscale eddies, far more research has been done on LCEs

- Both the vertical structure and characteristics and dynamics of the associated small-scale eddy field are poorly understood

Approaches

Possible New Observations

- Synoptic surveys (CODAR, ship-based ADCP, towed, SeaSoar towed undulating profilers)
- Floats and/or AUVs. Participants noted that the current generation of PALACE floats do not provide sufficient horizontal resolution to sample these sub-mesoscale features. Float sampling would rely on RAFOS floats or a new PALACE-RAFOS hybrid known as MAVOR.
- Dye release studies over rough topography. Several investigators noted that industry has already performed dye release work in selected areas.
- Mooring studies in regions of strong eddy variability
- Inverted echo sounder arrays

Possible Uses for Models

- Use model results to form testable hypotheses
- Model interpolation of sparse observations
- Model studies of dispersion associated with sub-mesoscale eddy fields
- Model evaluation and refinement

DISCUSSION

After reconvening and sharing results, participants agreed that much of the interest in both classes of eddies centered around their role in driving deep, large scale circulation in the Gulf of Mexico. This led to some debate over the scope of the proposed research program. All agreed that the Loop Current variability plays a critical role in eddy generation and translation. Several investigators noted that the pathways followed by LCEs were often roughly predictable and that they depended strongly on the where the eddies were formed. Because this influences whether the eddies propagate onto the shelf to drive exchanges with deep water, generation processes may be relevant to MMS goals. A study that included Loop Current variability would require an increased commitment of resources driven by the need to encompass the eastern Gulf of Mexico. Many opinions were expressed on whether a study covering the eastern Gulf of Mexico was appropriate for an MMS-supported program, but the group reached no conclusions.

Finally, a few members of the group expressed concern that research efforts appear to lag behind exploration and extraction activity. New research programs should be designed both to support ongoing activities and to anticipate future requirements. Participants suggested that MMS and industry activities could be projected on a five-year time scale to help guide new research efforts.

EFFECTS OF SMALL-SCALE TOPOGRAPHY

Working Group 2: Wednesday Morning, 13 September 2000

Dr. John Klinck
Discussion Leader
Old Dominion University
Norfolk, Virginia

The importance of small-scale topography was initiated by observations of megafurrows in the deep Gulf of Mexico (GOM). However, other issues regarding escarpments and small-scale features on the bottom were identified as being important to flow in the GOM, and thus, in the designation of small topography effects, as topics for discussion.

The first order of business was to clarify the meaning of “small.” This term meant different things to different participants. A general discussion about scales occupied some time at the beginning.

The result of the discussion was the agreement that small-scale topography in this context was a feature with horizontal scales (widths, diameters, decay scales) of 10 km or smaller down to scales of 1 m (although 10 m might be a more appropriate smallest scale).

Three influences of small-scale bottom topography on flow were topographic steering, sediment transport and bottom roughness. Topographic steering was taken to be the effect of the bottom when the strength or direction of flow changes in response to the bottom. Strength changes might be an increase due to the formation of a jet along the escarpment or a decrease due to slowing as flow splits to avoid a blocking hill. The effect of topography on sediment processes was the enhancement of scour or sediment working due to furrows, dunes or other features. This effect is really a feedback mechanism in which the flow is influenced by the bottom topography, which acts on the sediments to change the shape of the bottom. Finally, the term “roughness” is used in the most general sense to include not only very small bottom variations (roughness elements that cause skin friction), but also larger variations that produce bottom pressure variations that act to change the speed of the flow (form drag).

SCALES OF MOTION AND DYNAMICS

The following discussion considered the various processes associated with different horizontal length scales. We originally tried to use terms like “synoptic,” “mesoscale,” and “microscale,” but these were not consistently applied. Instead, and with little originality, we used the power of ten scale and identified processes associated with each power. This scale also has a natural interpretation in terms of ocean dynamics, which will be presented below. Keep in mind that these lengths are used as a general indicator and that a particular flow feature in that scale class might be half or two to three times the base scale.

The largest scale in the GOM is 100 km, which is not considered small but is included here for completeness. This scale is associated with the diameter of the loop current eddies (LCE) and with the width of the straits supplying and removing water from the Gulf. In geometrical terms, this length is the scale of variation of bottom topography from the shelf to the abyss as well as an indicator of the size of the Gulf. Finally, the wave length of the flow variability along isobaths (topographic vorticity waves, also known as TRW) is of this order. At these large horizontal scales, the flow is essentially geostrophic, which non-geostrophic processes being only a few percent of the dominant forces.

The largest "small" scale is about 10 km, which characterizes dense water blobs on the bottom, midwater eddies and attached cyclones on the bigger anticyclonic LCEs. The width of flow driven by bottom topography, like the escarpments, is a few 10s of km (an internal radius of deformation or so). Finally, the across slope length scale associated with topographic vorticity waves is a few 10s of km. Motions at these horizontal scales are still largely in geostrophic balance, but the flows tend more down pressure gradients than is the case at larger scales. That is, the ageostrophic forces may be up to 10% of those in the geostrophic balance.

At 1 km, lateral variations in the structure of the bottom mixed layer appear. These differences might be the thickness of the layer or KE of the flow in the layer. Additionally, flow variations on this scale are created as flow reacts to mounds or furrows on the bottom, which have this as a lateral size. The vertical scale of variation of bottom trapped flow is about 1 km. At these scales, flow is driven largely by pressure gradients due to density variations (internal waves) and are only weakly affected by Coriolis acceleration.

The size of dunes and anti-dunes, as well as the spacing between megafurrows is about 100 m. There is a clear coupling between dunes and the flow, which means that the dunes modify the flow in such a way as to preserve and move the dunes (and anti-dunes). Several suggestions were made that megafurrows are created and maintained by bottom flow, although the time scale for formation or moving is not known, nor is it known which if any of the observed furrows are active today. The vertical scale of baroclinic currents is of order 100 m, which is also the suspected vertical scale of the occasionally observed mid-water jets. At 100 m, the dynamics are almost entirely pressure gradient driven, and the vertical density gradients are not always sufficient to maintain the flow, which is mainly horizontal.

The size of individual furrows (width and depth) is of order 10 m. These individual bottom features affect the bottom boundary layer flow, which has a vertical scale of about this size. Individual bumps on the bottom can have vertical and horizontal scale of a few tens of meters, and these provide bottom roughness elements that mainly affect the flow through form drag (pressure acting on topography) rather than skin friction. These scales can also cause small-scale flow variations, which lead to energetic turbulence (which occurs on scales of centimeters). It is possible at these scales that the flow exists as horizontal rotors aligned with the flow and with elongated bottom features. The driving force at these scales is a mixture of pressure gradients due to density gradients and inertia (tendency for water to remain in motion once started).

At 1 m scales, we approach the thickness of the transition layer between skin friction and form drag. The largest turbulent (3d) eddies near the bottom are thought to be of this size. Laboratory experiments with laminar and viscous flow over rough bottoms provide information on the interaction of overlying flow with the bottom, be it planar or undulating, rough or smooth. This scale is taken to be too small to be investigated directly in the context of the MMS program but does produce effects on larger scale flow. These effects are usually parameterized in terms of drag laws, and these scale are rarely resolved explicitly, in measurements or models.

POTENTIAL STUDIES

Given the discussion on scales, three studies were discussed to assess the importance of dynamics at small (10 km or less) scales in the GOM. A fourth discussion considered satellite data sources and how they might help MMS physical oceanographic studies (this topic did not specifically focus on results of small-scale topography, but was part of our discussion).

BOTTOM BOUNDARY LAYER STUDY

The bottom boundary layer was identified as a physical oceanographic feature in the GOM that would be affected by bottom topography at scales of 10 km or less. Specifically, the bottom boundary layer was thought to be a few 10s to a 100 m thick with vertical scales as small as 1 m. Thus, measurements would be required at vertical intervals of 1 m or less, at least within 10 to 20 m of the bottom, with larger intervals above the bottom.

Different bedforms (furrows, ridges, walls, bumps, dunes, anti-dunes, etc) would affect the flow differently, so different areas should be sampled. This would require that a description of the bottom morphology be a preliminary study to a large scale BBL measurement program. Siting decisions for each study would be made after the preliminary bottom morphology study.

The measurement program would be designed around a small number of bottom instrument packages (say, tripods) on which were sensors for temperature, salinity, flow speed and direction, transmissivity and perhaps other properties. There might be an upward looking ADCP to measure the overlying currents and perhaps a mooring extending a few 100 m above the bottom. It was even discussed that an ADCP could be mounted sideways to get the structure of the flow in the BBL with horizontal resolution of 10 m over a range of a few 100 m. The importance of water property measurements was emphasized so that water types could be identified, particularly to detect dense water boluses descending the slope.

Because of the large number of locations that might be sampled, the group considered that two or three sampling platforms would be created with one located in a single site for a long-term study. The other two sensor packages would be put in place for a short time (a few months) after which they would be moved to another location. We thought that such a combination of short samples at several places with a long measurement program at one place would help identify the appropriate processes active in the deep GOM.

SCALE AND PHYSICS EXPERIMENT

A second measurement program that focuses on small-scale topography is based on the Texas A&M University experiment that analyzes energetic bottom trapped motions. The length scales to be sampled range from 1 to 100 km in the along-slope direction with resolution on the order of 5 to 10 km in the across-slope direction (these distances are smaller than those proposed by TAMU). This small-scale sampling is necessary to identify the reaction of flow to small-scale bathymetry and to make sure that measurements at different locations are correlated. The effect of bottom features such as furrows and the escarpment on flows would be detected by such an array. It is also important that the sampling extend at least 1 km above the bottom in order to capture the structure of the overlying flow since smaller features (cyclones) are known to occur with LCE as well as the seldom-observed midwater jets which are thought to have small horizontal scales.

The dynamics of topographic Rossby waves (TRW) should be used to design this sampling array. However, it is important to recognize that TRW theory identifies 3-D structure for these waves that can be exploited in designing the moorings. In particular, the different length scales of these motions in the along-, across-shore and vertical directions should be useful in a proper design. Antenna theory from electrical engineering should be useful in such designs. Finally, several numerical solutions should be investigated as means for testing the sampling design to make sure that meaningful measurements can be obtained. In this program, as in the BBL experiment, it was thought prudent to have two arrays; one that stays in place for several years and a second that samples a few different places (for six months to a year). This would allow sampling of a few locations to see the spatial variability that occurs. One of these arrays should be placed with sensors across that escarpment to see the effect of this bottom feature on flow.

NUMERICAL MODEL STUDIES

Three dimensional primitive equation numerical models are a commonly used tool in analyzing ocean circulation processes. Some of these simulations are being pursued now, but there was considerable concern that the grid spacing of these simulations is too large to properly represent most of the prominent features on the bottom of the GOM. A study should be considered with one or more models (or existing global high resolution simulations) with horizontal grid spacing of order a km or so. This would allow the model to include important, but smaller, bottom features. This resolution is not sufficient to represent the megafurrows, but some way might be used to parameterize this roughness and see its effect on the flow.

These models may also include nested grids to represent localized small-scale features, such as the megafurrow fields. There was some debate on the importance of sophisticated bottom boundary layer models as part of the overall simulation. Most 3D models have some sort of BBL submodel, but it was agreed that this should be a topic of discussion. The necessity of a sediment suspension and transport model was also discussed. The consensus was that it is too early to worry about sediment processes until the overlying flow dynamics are better understood.

These simulations should be analyzed to determine the vertical structure of the flow and the properties of the deep flow. These features could be compared to existing and planned observations. Other model products, such as LCE shedding interval; eddy size, strength, path; and mean and eddy kinetic energy would be useful in model verification and in identifying regions that might be the focus of measurement programs. These statistics, if verified by observations, could be used to extend to other regions the small number of direct determinations of such processes by measurement programs.

Finally, the geological record contains the net effect of bottom currents over an extended period of time and so should be used to determine mean flow patterns.

SATELLITES

NASA provides useful information to the MMS program. Several comments were made that the planned Synthetic Aperture Radar (SAR) satellite would provide surface currents over the GOM with horizontal resolution of a km or so. Additional altimetric satellites, also being discussed, will provide more closely spaced measurements of surface elevations. Both of these satellites provide useful information to the MMS program; therefore, MMS should encourage and support these missions.

EDDY-MEAN FLOW AND EDDY-EDDY INTERACTION

Working Group 3: Wednesday Morning, 13 September 2000

Dr. Randy Watts
Discussion Leader
Professor of Oceanography
University of Rhode Island

The steering committee suggested a set of general topics for discussion on Wednesday morning by this Working Group session. We projected that list on the front screen, and our group tailored the topics to be most relevant to eddy-mean flow and eddy-eddy interactions. That tailored list, along with a list of attendees, is given in an appendix.

THE PROBLEM OF EDDY-MEAN FLOW INTERACTION AND EDDY-EDDY INTERACTION

We devoted the first half of the discussion to stating succinctly the problem of eddy-mean flow interaction and eddy-eddy interaction and the relevance of the problem to the mission of MMS. Our discussion yielded the following key points:

- The deepwater region of the Gulf of Mexico is filled with strong currents that vary tremendously in both space and time, associated with energetic eddies. Mesoscale eddies account for the most energetic processes; mesoscale variability has time scales of days to months and space scales of 10s to 100s of kilometers. This eddy variability dominates the circulation on the slope and rise, and in particular this eddy field can couple shelf and deepwater circulation.

- The main source of energy for mesoscale eddies is the Gulf of Mexico Loop Current (LC) and the Loop Current Eddies (LCEs or Rings) that pinch off from steep loops north of Yucatan Channel. The LCEs propagate westward and slightly southward across the Gulf, often brushing the slope bathymetry along the north. The energy feeds into eddies from instability processes, which intrinsically involve the whole water column. The time-varying background currents concentrated in the upper jet of the LC and LCEs drive both deep and upper mesoscale eddies (including topographic Rossby waves, TRWs), which propagate to other locations where they can, in turn, create mean currents through rectification processes. Thus, there are two-way interactions between mesoscale eddies and both larger and smaller scale currents and eddy processes.

Several issues are involved in explaining the eddies, determining where and why they may be strong, and in analyzing their interactions with the mean flows and with other eddies:

- What is the spatial distribution and strength of the eddy currents? Is there a westward-intensified component of variable circulation?

- What is the vertical structure of the eddy currents—*e.g.*, in addition to surface intensification resembling the parent LCEs, how strong are the barotropic eddies induced nearby, and is there in addition bottom intensification?

- Can we quantify the relationship between the rather coarse detection of eddies by satellite altimetry and better-resolved *in situ* measurements – for example, if we can understand the eddy process and identify it as TRWs, can the eddy propagation be modeled and predicted?

- What non-linear mechanisms set the energy and momentum exchanges between the highly energetic mesoscale variability and larger- or smaller-scale as well lower- or higher-frequency variability.

In addition, we need to quantify the mass and vorticity fluxes that accompany these eddy processes.

RELEVANCE TO OIL AND GAS SPILLS

Our group also considered the question, "Why must we understand this process (relevant to how oil and gas spills may damage the environment)?"

Figures 41 and 42 illustrate the Gulf of Mexico and Loop Current using satellite sea-surface temperature (SST). An animation of SST images showing LC growth and eddy interactions can be found at the following websites: *http://sss-ccar.colorado.edu/~lebengulfmex_sceince* and *http://www.esl.lsu.edu/demos/goes/comploop3.gif* (5.5Mb).

Currents in eddies disperse oil spills and pollutants. Oil and pollutant dispersion in turn affects biological processes ranging from recruitment to marine mammal distribution and abundance. These wide-ranging biological processes are sensitive to a correspondingly wide range of space and time scales of physical processes in the ocean. Oil spills and pollutants, such as drilling muds, affect any and all parts of the water column. Moreover, eddy currents are now recognized to be strong in deep as well as shallow portions of the water column in the slope and rise region. Thus eddy-driven dispersion of pollutants occurs throughout the water column.

Understanding eddy strengths and variability is important to estimating oil spill and pollutant dispersion. For example, a better understanding of the eddy strengths, their correlation scales, and dispersion could allow us to better understand the evolution of an oil spill and indicate how susceptible one location is to a spill at an adjacent location. The highly energetic mesoscale eddies are known to interact with larger scale (or mean) currents and with smaller scale eddies. There is a critical need for better understanding of eddy-mean and eddy-eddy interactions to obtain better prediction of the location, frequency, and magnitude of strong current events along the Gulf of Mexico slope and rise.

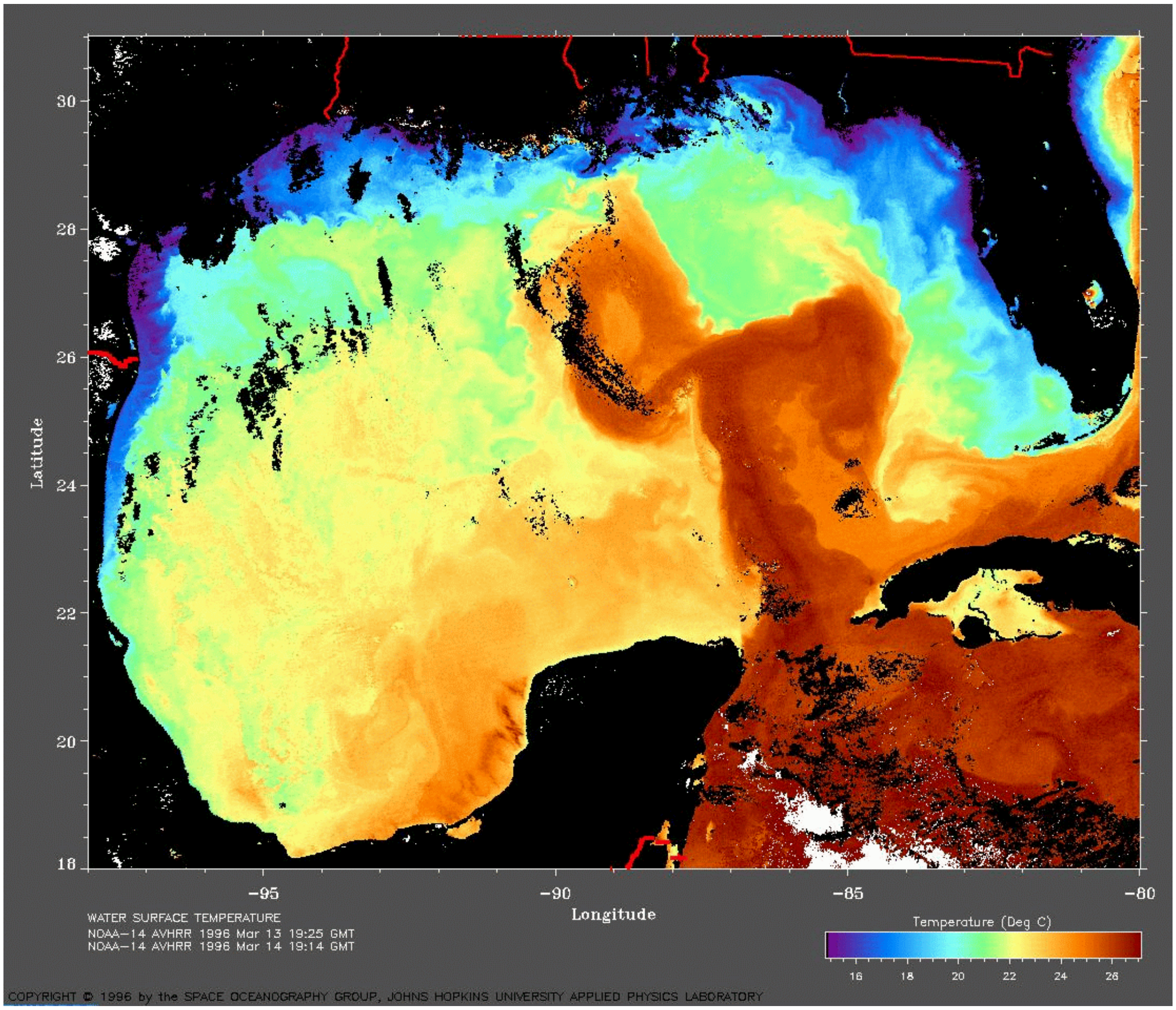


Figure 41. The whole Gulf of Mexico in a 7-day composite for 1 April 2000, from Johns Hopkins University APL Space Department web page, *http://srbdata.jhuapl.edu/d0043/avhrr/gm/averages/00apr/index.html*. The LC extends far northward into the Gulf and interacts with a separated LCE south of Louisiana. Smaller scale frontal eddies and meanders can be seen around both major features.

Ultimately, it is the strong effect of eddies upon biological processes and upon the dispersion of oil spills and pollutants that demands understanding of eddies and their interactions. Only with this improved physical understanding can we assess how oil and gas operations may affect the environment at the sea surface, through the deep water column, and near the sea floor.

DEFINITION OF A SUCCESSFUL PROGRAM OF STUDY

Our group next discussed "What would define a successful program of study" [of the physical oceanography of the slope and rise in the Gulf of Mexico]?

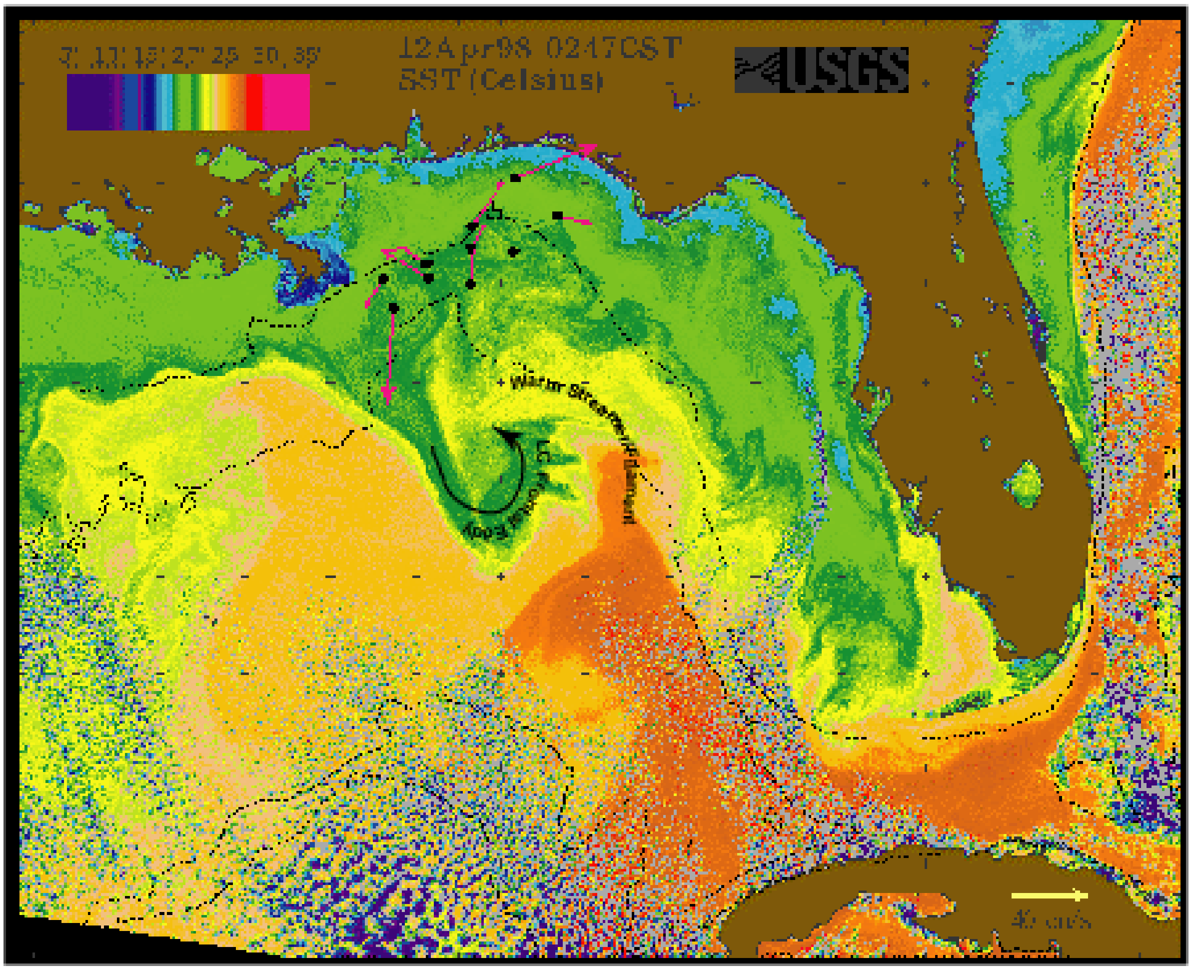


Figure 42. This figure zooms in on another extended LC event in the eastern GOM for 28 April 1998, from a USGS analysis with labels added by SAIC. It illustrates the strong cross-slope motions associated with LC frontal eddies, driving warm and cold streamers.

A successful program to explain and predict ocean circulation on the energetic eddy scales requires more observations and the use of models. The present database of observations is inadequate to approach this understanding, and models require substantial development, particularly to resolve and treat eddies properly. We proceeded to discuss in turn the observation program and model configurations to meet these needs.

OBSERVATIONAL DESIGN ISSUES

Understanding the eddy motions and interactions in the Gulf of Mexico requires synoptic pictures of the flow field – near-surface and deep. We need to determine the large-scale circulation throughout the Gulf of Mexico, and mesoscale or finer resolution arrays of measurements are needed for eddy process-studies in target areas. We need to determine particle pathways as influenced by eddy and mean circulation. Several types of measurements are required to meet these broad objectives. Our group discussed the recommendations from the preliminary design study that had been commissioned by MMS and presented at this meeting by Nowlin *et al.* (this volume), and by Hamilton (this volume), as well as other suggestions.

A Lagrangian measurement element was recommended in the deep basin, and received much favorable discussion. The floats should have a RAFOS capability (acoustically tracked while *in situ* subsurface) to measure position at intervals of six to eight hours, thus resolving important eddy motions. A desirable capability that can be incorporated into floats is to profile the temperature, or temperature and salinity, from the float's resident depth up to the sea surface at selected time intervals. However, their trajectories at resident depth should span at least several tens of days between vertical profiles, which would otherwise interrupt their Lagrangian pathways. The overall duration of these observations should be at least two years; it may be desirable to receive some of the data at more frequent intervals (after several months). It would be desirable to deploy floats at depths below the sill depth entering the Gulf of Mexico (about 2,000m, thus retaining them within the study region), and it is also desirable to explore more than one deep level.

For surface Lagrangian measurements, cooperation was recommended with oil industry studies (such as the joint industry project, Eddy Watch).

Moored arrays to study the scale and physics of eddy currents were recommended in north-central slope and rise regions of the deep Gulf of Mexico. The focus of this scale/ physics study is horizontal coverage, and a relatively coarse vertical coverage is acceptable. (See the complementary focus of the exploratory / statistics array.) Two-dimensional coverage, along and across isobaths, is needed to understand eddy motions and interactions. It was suggested that this array should combine PIES and moored current meters. The 2D array of PIES would provide a synoptic mapping capability of the barotropic and baroclinic currents of the mesoscale eddies. It was recommended that a cross shaped array of current meter moorings for this scale/physics study be spaced, for example, at 10, 30, 50, 70, and 150 km laterally along an isobath, and at some mix of spacings at various bathymetric depths across slope. Current measurements on these moorings would occur at relatively few, primarily deep levels. The purpose of the combined arrays would be to establish the scales, structure, and propagation of energetic fluctuations in deep water, to understand their coupling and relationship to surface-intensified eddies, and to characterize other events.

Long-term exploratory / statistics arrays were recommended, with moored current observations at several levels throughout the water column, at several sites. (This well-resolved vertical coverage extending into the upper water column and near-bottom has a complementary focus to that of the scale/ physics array, but at fewer sites with coarse horizontal spacing.) Somewhat in contradiction to the objective to obtain "long term" statistics, it was also suggested that the sites should change adaptively as other data in this study come available. Some of these current moorings can serve dual purposes of the exploratory/ statistics and the scale/ physics arrays.

A moored array of 12-15 PIES plus several deep current meters was recommended in the eastern-central deep Gulf of Mexico to study LC and LCE shedding events and the expected generation of TRWs and energetic peripheral upper and deep eddies. This combination of measurements is well suited for observing the deep eddies and TRWs, which exhibit weak variation with depth below the thermocline, and the strong surface-intensified eddy currents to which they are coupled. Hamilton's report (this volume) motivates and shows a minimal exploratory array, coordinated along TOPEX altimeter groundtracks. Discussion identified the desirability of embedding these observations within a broader 2D synoptic mapping array, which would require about twice as many PIES. Watts sketched a strawman 2D array for this purpose and suggested that some coordination might be possible with a scale/physics array such as described above.

The duration for all of the deep Gulf of Mexico measurements should be at least two to three years so that several eddy-shedding cycles may be captures. These cycles are expected to be the major source of highly energetic mesoscale deep current fluctuations.

MODEL CONFIGURATION ISSUES

A valuable objective of models is to help us to better understand eddy-eddy interaction and eddy-mean flow interaction. The numerical grid configuration must be oriented toward these process studies, including appropriate bathymetric representation, sufficient deep eddy energies, appropriate vertical, lateral, and temporal resolution to capture the small scale processes (e.g., frontal eddies and TRWs). Within the models one can investigate energy, momentum, and vorticity exchanges. An important role for process-oriented models is to test theoretical concepts.

The models can be "tuned" or "calibrated" to the observations (particularly new deep observations) relative to particular locations and particular processes. Then it is generally asserted that the model allows us to extrapolate our understanding to other regions of the GOM where observations are lacking. The models can help predict tracer distribution and Lagrangian pathways. Models can offer opportunities to study linkages between physical processes and biological processes in the Gulf of Mexico.

Models may also assist in our experimental design. Models can guide the placement of moorings and guide the choices of vertical and along / across-slope spacing.

Metrics should be developed with the help of the whole community to assess model performance.

Data assimilation can provide dynamic interpolation of the limited set of observations and improve our physical understanding of eddy processes. We need new modeling efforts to learn how best to assimilate remote sensing data, moored data from current meters and PIES, or Lagrangian float data.

Because a number of other funded modeling efforts exist today in the GOM, it will be important to coordinate and cooperate with those studies.

APPENDIX: ATTENDEES AND ISSUES ASSIGNED FOR INITIAL DISCUSSION

Working Group 3 Attendees

Randy Watts, Chair
Bob Avent, MMS
Doug Biggs, TAMU
John Blaha, NAVOCEANO
Dagmar Fertyl, GEO-Env
H. James Herring, DYNALYSIS
Jeff Ji, MMS
Ann Jochens, TAMU
Walt Johnson, MMS
A. D. Kirwan, University of Delaware
William Teague, NRL
Kevin Leaman, University of Miami / RSMAS
Tom Meyer, MMS
Lew Rothstein, AEF
Wensu Wang, Fugro GEOS

Initial Topics Suggested for Discussion

- Define the Eddy-Mean Flow / Eddy-Eddy Interaction in a few sentences…have a good schematic.

- Why must we understand this process (relevant to how oil and gas spills may damage the environment)?

- What would define a successful program?

- What are the appropriate observations?

- How can models be configured to help us better understand eddy-eddy interaction and eddy mean flow description? How do we best assess the skill of any model?

PARTNERSHIPS FOR FUTURE STUDIES: INDUSTRY-FEDERAL/STATE AGENCIES-ACADEMIA

Working Group 4: Wednesday Morning, 13 September 2000

Exploration and production activities in the deep Gulf of Mexico by the oil industry necessitate complementary research activities. The research must focus on a variety of phenomena ranging from methane hydrates to strong deep currents. The need for research to complement oil industry activities is not new. What is new, however, is the region. The deep Gulf of Mexico is, like most deeper parts of the ocean, relatively unknown. We know there are strong currents and we think they are related to topographic Rossby waves (TRWs), energetic currents that are generated by the Loop Current interacting with topography in the northern Gulf.

The research required to understand these strong currents and other processes not even yet discovered will require commitment of assets that may fall beyond what is available from the Federal government. To this end, the workshop felt it was necessary to address the need for better collaboration or partnerships between the industry, federal and state governments, and academic researchers. Only through such collaboration and partnership will the research be done in a timely and efficient manner. The main need is, of course, to raise the level of funding since deep water work is much more expensive than shallow water research. Thus, the group also explored and recommended new funding mechanisms. Although some of the ideas may be naive or unrealistic, we, felt nevertheless, that they needed to be articulated.

The following list captures the issues touched on in this session by the small group of representatives from industry, federal agencies, state agencies, and academia.

POTENTIAL FUNDING PARTNERSHIPS

- Industry
  - EJIP
  - OOC
  - Northstar

- Navy

- National Ocean Partnership Program
  - Suggested that Navy be involved via this 13-agency program

- Investment Community
  - Suggested that industry work with liability insurance interests to establish that 1%, for example, of investment capital can result in decreased liability. Set aside this 1% (1% of 1 billion for 1 DW platform = 10 million?) gathered from the investment community in a trust fund, using interest to fund study. Return principal when completed.

- Research Tax
  - Cited use in Norway to win leases

- Royalty Relief
  - Proposed restructured Royalty Relief to support deepwater studies
    - N Suggested that industry be involved in the planning of the studies
    - N Proposed royalty relief from shallower DW to fund research for ultra DW (proportionally more fair to all the industry players)
    - N Envisioned a trust fund

- MMS pays for it like any other study
  - Observed that this would be a good time to make new proposals because MMS is in five year planning process

- Recommended legislative action to establish funding for such a study

- Discussed NTL (Notice To Lessees) requiring that industry provide data but has a large impact on small operators and it becomes adversarial

LIMITATIONS/COMMENTS

- Competitive disadvantage to paying for research if their company can get it for free from public studies

- “A view” that industry is operating under that environment and they should pay for it

- Limited industry funding for long-term project support

- DEEPSTAR is an example but is small scale, order of magnitude difference

- Large sum of money—which exceeds historical MMS studies funding—required

SECONDARY INITIATIVES

- Limited, less costly initiatives that do not provide the breadth of data needed but add to available data

- Use of drilling and production rigs to obtain data with support from MMS and industry (very high priority)
- MMS purchase of eddy watch information
- Methods of the public release of GULL data
- Methods of the public release of CODAR GIP

WORKING GROUPS SESSION INTRODUCTION:
WEDNESDAY AFTERNOON, 13 SEPTEMBER 2000

Dr. Larry Atkinson
Old Dominion University

The Steering Committee and the group in general felt that three additional topics also needed consideration. They were as follows:

- Mean Currents and Climatology—this information is needed for basic knowledge and for model initialization.

- New Technology—any research must use the latest technology. This is especially true in this case, where the latest Lagrangian techniques may be both the best scientifically and most cost-effective.

- Environmental Justification for Physical Oceanographic Studies—some felt physical oceanographic studies were not needed although even the non-physical types in the group knew this to not be true. This group recorded what many of the participants were thinking on the topic.

MEAN CURRENTS AND CLIMATOLOGY REPORT

Working Group 1: Wednesday Afternoon, 13 September 2000

Dr. John M. Klinck
Discussion Leader
Old Dominion University

The discussion began with three questions: what do we mean by climatology; what information can we get about it; what scales, depths, locations are desired in studying it.

Initial discussion focused on what details were desired. The literal meaning of mean currents, as a time mean of the flow at different locations, was thought too restrictive. Instead, the more general term "descriptive statistics" was used as the focus of the discussion. Examples of desired characteristics are loop current eddy (LCE) shedding interval, path of detached LCEs, size and swirl velocity in eddies, kinetic energy (KE) as well as eddy kinetic energy (EKE), (a measure of velocity variability at different locations). Other descriptors, such as the maximum current speed and the frequency of occurrence of currents above some value, were critical to engineering issues.

Many of the above statistics are useful in testing results from numerical models. They may also be used for environmental assessment, simple models of tracer advection, and engineering design studies, among others.

The focus of the meeting is on deep flow in the Gulf of Mexico (GOM), so some discussion considered how to partition the waters between surface and deep. By general agreement, the depth horizon 800 to 1,000 m was thought to divide the upper from the lower water column. This horizon can be applied throughout the GOM, as there is no large scale tilt of the density surfaces.

Given the deep focus of the meeting, no consideration was given to flow statistics over the shelf. MMS defines deep water to be deeper than 300 m, while the physical oceanographic horizon is 800-1,000 m. The shelf break in the GOM is near 100 m, so both definitions involve sites along the continental slope or over the abyss. Therefore, these different definitions of deep do not cause any practical differences in the part of the GOM being evaluated.

There was general agreement that the surface flow climatology was known with some precision, although there was no agreement on the degree of precision. Some thought there was a reasonable climatology of near-surface flow due to the large number of surface drifters as well as satellite derived measurements of surface temperature, color and sea surface elevation. Others thought the climatology was only marginally well known. Nevertheless, there was agreement that almost nothing was known of the character of deep flow, which is based on about 10 deep current time series and no known deep drifters.

Two potential studies were identified as being useful in beginning to construct a deep flow climatology. One was a direct study of the deep eddy characteristics, similar to the surface flow analysis. A second useful study would look at the coupling (or linkage) between surface flows and deep flows, which would allow the surface flow climatology to be useful in a study of the deep flow. In particular, this study would consider the nature of the deep eddy flow under detached LCEs. Limited existing information shows that the vertical gradients of the deep flow, especially along the slope, are weak. Therefore, current measurements at almost any depth below 1000m could be used, without regard to depth, in constructing a flow climatology.

Some discussion by the group considered the design of a measurement program to begin a deep flow climatology. A GOM wide deep drifter program was clearly useful in illuminating the character of the deep flow. Moored current measurements are better at detecting spatial scales and extreme events, but suffer from the limited coverage due to expense. From the point of view of a climatology, the deep drifter program would be more useful, but engineering issues are more clearly addressed with current meter moorings. No conclusions were reached about which sort of study would be more useful or would receive a higher priority.

Although no numerical model has been calibrated for the GOM, several offer simulations that could be used to estimate various statistics. Existing numerical models should be used to construct deep flow climatologies. Agreement among climatologies from disparate models would be encouraging, but not conclusive. These model-derived products could be compared to the increasing set of deep measurements over the coming years, for the purpose of verification of models. The models, assuming some level of agreement, could be used to extrapolate flow characteristics from regions of measurements to other areas.

NEW TECHNOLOGIES

Working Group 2: Wednesday Afternoon, 13 September 2000

Dr. Craig Lee
University of Washington

Dr. Randy Watts
University of Rhode Island

Discussion Leaders

SATELLITE REMOTE SENSING

- New generation Synthetic Aperture Radar (SAR) may provide high resolution measurements of surface currents.

- Satellite based sea surface salinity sensors. Early versions of these sensors have been used successfully from aircraft. One investigator noted that a space-based salinity sensor is currently operating from a Japanese satellite. Other participants indicated that another sensor is currently scheduled for deployment (nationality and launch date unknown).

- Tropical Rain Measuring Mission (TRMM). Although sensor's primary mission is low latitude precipitation measurement, it also makes observations of sea surface temperature (SST). Cloud cover, which often causes severe contamination in AVHRR sea surface temperature measurements, does not hinder TRMM. Thus, TRMM offers extensive sea surface temperature observations that include areas normally obscured by clouds in AVHRR imagery.

- Eddies and other prominent mesoscale features often have chlorophyll signatures delineating their shape. Ocean color (e.g. SeaWiFS) sensors offer a measure of surface chlorophyll concentration that may be used to develop climatologies of eddy variability in the Gulf of Mexico.

FLOATS

- Profiling Autonomous Lagrangian Current Explorer (PALACE) floats drift at a preset density level, executing vertical profiles with an on-board CTD at user-specified time intervals. Profiles interrupt the Lagrangian trajectory. While at the sea surface, the floats obtain GPS fixes and telemeter data to shore. Net displacements at the normal resident drift-density level and velocities at the ocean surface are estimated from GPS fixes. Power limitations and desired mission duration restrict the profiling interval to be too coarse to resolve sub-mesoscale eddy variability in the Gulf of Mexico.

- The MAVOR float may offer an alternative. MAVOR is a hybrid PALACE float that has been enhanced to include RAFOS tracking capabilities. Mission profiles would be similar to those of a normal PALACE float, but acoustic tracking provides enhanced (8 hour) position information, allowing subsurface velocity estimates at much finer temporal and spatial scales. These floats could resolve deep, sub-mesoscale eddy activity. MAVOR floats must be deployed in conjunction with moored sound sources, which represent an additional expense above that needed for PALACE float deployments.

ASSIMILATION TECHNIQUES

- Following up on suggestions in the Tuesday PM Working Group, which noted that data assimilation into numerical models is beneficial for dynamical interpolation of the measurements, some investigators stated that much development effort is needed to assimilate the many types of measurements that may occur in the Gulf of Mexico. It was noted that observations of currents are relatively easy to assimilate.

- Sources of data, for which assimilation development efforts may be particularly useful, include satellite SSH and SST data, PIES data, and CODAR. It would be particularly useful to estimate subsurface structure of currents and density stratification from these data for assimilation.

TELEMETRY

- Several investigators expressed a need for real-time telemetry from sensors mounted on deep-water moorings. Two wireless technologies were discussed. Acoustic time-delay telemetry (currently implemented for inverted echo sounder moorings) offers a low-power method of transmitting a limited data stream through the water. Transmissions are received by shore- or mooring-based receiving stations that can service multiple instruments. Tradeoffs between sampling interval and installation lifetime can permit extremely long (5 year) deployments. Inductive modems offer an alternative technology presently under development for transmitting higher bandwidth data up mooring lines.

- Satellite telephone and paging (short text messaging) services will soon offer high bandwidth, low-power communications that can be exploited for data telemetry and remote platform control. Presently, some AUVs (long-range gliders) use shore-based cell phone and satellite text messaging services to upload data and download new mission profiles. Satellite systems will extend the offshore range of these vehicles and permit flexible, adaptive sampling strategies.

TOWED ADCP AND TOWED PROFILERS

- Towed ADCP/profilers allow sampling from a variety of vessels, including smaller workboats and ships of opportunity. This offers significant savings over the use of dedicated research vessels and permits greater flexibility in sampling.

- Towed ADCP/profiling can provide quasi-synoptic, three-dimensional surveys of mesoscale features. Surveys can be targeted at specific features using remotely sensed imagery or other real time data.

- Several different models of ADCP exist, offering vertical resolutions from 1-20 m and depth ranges from 20-400 m.

- Towed profiling vehicles (e.g. SeaSoar and Scanfish) are sensor platforms that use active control surfaces to profile through the water column while being towed at speeds up to 8 knots. These vehicles can be outfitted with a wide variety of physical and biological sensors. The tow cable provides telemetry for real-time data display and acquisition. These vehicles achieve excellent along-track horizontal resolution (1-3 km) while profiling from the surface to 100-450 m.

FULL WATER COLUMN REAL-TIME DATA TRANSMISSION AT DEEP (2,000 M) SITES

- This was identified as a required technology to provide needed information for oil industry drilling and platform operations. One method is to take advantage of drill ships outfitted with ADCPs; ADCPs with suitable low frequency can profile current to 700 – 1,000 m range. Another method to retrieve current data is to run a data line down to subsurface moored instrumentation.

AUTONOMOUS UNDERWATER VEHICLES (AUV)

Two classes of vehicles were discussed:

- Fast, short range AUVs use active propulsion to provide quasi synoptic sampling over a limited spatial range, but typically have endurance shorter than one day. Data may be stored on-board and retrieved on recovery.

- Long-range AUVs operate in a manner analogous to atmospheric gliders. These energy efficient vehicles propel themselves by altering their buoyancy such that they sink or rise. Fixed control surfaces combined with active vehicle attitude control permit the AUV to project vertical motion (rising and sinking) into lateral motions used to alter its horizontal position. Presently, gliders carry temperature, salinity and pressure sensors. Dissolved oxygen, chlorophyll fluorescence and volume scattering function sensors have also been added to glider payloads. Gliders can be programmed to run fixed survey patterns, to profile in place (acting as a virtual mooring) or to follow specific features. These vehicles move at speeds of up to 0.25 m/s and can operate for periods up to one year while profiling between the surface and 2,000 m. . Two-way telemetry via satellite- or shore-based cellular phone allows for near-real-time data acquisition and permits the downloading of updated mission profiles and operating parameters. This enables the design of highly responsive, adaptive sampling strategies.

MOBILE ARRAYS AND ADAPTIVE SAMPLING ARRAYS

- This approach has been used by industry researchers to obtain high resolution measurements of episodic events such as mesoscale eddies. Moorings designed for rapid deployment are kept ready for use. Short-term deployments are then executed whenever interesting features are identified. This permits the direct sampling of specific features by arrays that are tailored to the particulars of each event. However, extensive personnel, hardware and ship resources may be required to support these kinds of efforts.

CODAR

- This is a method employing radio-frequency transmissions reflected off water waves on the sea surface. Investigators explained that it uses two separated antennae, and the method can estimate synoptic surface currents, wave heights, and surface winds.

- Different ranges (40- 300 km) and resolutions (1 – 6 km) are possible, depending upon the radio frequency employed and the height of the antennae.

- Usually line-of sight (LOS); but over-the horizon (OTH) capability exists.

- A network of shore-based HF stations is planned along the entire Gulf Coast.

- Shipboard CODAR will eventually be available (using bow and stern antennae).

INSTRUMENTATION TO MONITOR INFLOW BOUNDARY CONDITIONS

Investigators involved in numerical efforts expressed a need for real-time monitoring of the Gulf's open boundary to constrain their models. Full velocity profiles would be best, though depth-integrated transport would also be a useful constraint.

Several participants also noted the desirability of moving the inflow boundary from Yucatan Channel into the Caribbean Sea. Doing so would reduce the influence of the open boundary condition on the region of interest (central and northern Gulf of Mexico).

PIES AND DEEP CURRENT METERS (DCMS)

- A PIES is a combination of Pressure sensor and Inverted Echo Sounder, which sits moored on the ocean bottom. The pressure sensor is stable and accurate enough to observe not just the tidal pressure fluctuations (~ 1 m water) but also the small pressure fluctuations (~ 1 cm water) associated with deep geostrophic currents. The vertical acoustic travel time (VATT) measurement provides an estimate of the temperature and density structure in the full water column. These density profiles are estimated *via* look-up tables (as a function of VATT) generated from historical hydrographic data for a region.

- The barotropic (BT) current and the baroclinic (BC) current profile may be estimated accurately using horizontally separated PIES, from the horizontal gradients in BT and BC pressure measured between them; the BC pressure profile is calculated as a function of depth above each PIES from the density profile above it and the measured (time-varying) reference pressure. An array of laterally separated PIES can thus map the absolute current structure and density and temperature structure in a region.

- Deep current measurements provide an absolute leveling for a bottom pressure array, so it can map absolute (not just time-varying) barotropic currents.

- An acoustic telemetry capability allows either daily retrieval of the array data from a moored receiving hydrophone capable of receiving from many PIES, or shipboard retrieval of the data whenever a ship interrogates a PIES.

MOORED PROFILERS

- Moored profiling instruments (e.g. MVP, Dr. John Toole, WHOI) offer a cost-effective means to collect time series over the entire water column. These instruments crawl up and down a fixed mooring line, executing profiles at user-specified time intervals. They may also be instructed to linger for specified periods at individual depths to collect more intensive time series. The profilers carry temperature, salinity, depth and velocity sensors and are capable of deployments lasting up to one year.

A NOTE ON COMBINED CAPABILITIES

- Both traditional (e.g. ship-based CTD surveys and long-term current meter moorings) and the new approaches outlined above have obvious strengths and shortcomings. Traditionally, there has been a trade-off when optimizing sampling for temporal and spatial resolution in addition to difficulties obtaining sufficient breadth in temporal and spatial coverage. Used in carefully considered combinations, many of these technologies offer complementary coverage. Mixing older and newer, emerging technologies could produce observational systems capable of making high-resolution, long-term measurements of the mesoscale processes targeted during the workshop.

NEW MODEL TECHNOLOGY

- Investigators involved in numerical modeling mentioned the development of nested grid techniques as a method to achieve high resolution yet avoid the artificial influence of open boundary conditions too near the region or process of interest.

- The nested grid model region can have 2-way dynamical interaction with the surrounding coarser-grid region. One application would be to use finely resolved bathymetry in a nested region; in another example the nested region could be instructed to move to follow a feature of interest (e.g., follow a strong eddy or a packet of TRWs).

- Data assimilation could occur within a fine nested region.

- It would be possible to couple ecosystem and physical models using nested grid structures. In this manner the coupling strategy could adapt locally to the fine-scale requirements of a biological process study.

APPENDIX: ATTENDEES

Craig Lee, Chair
Randy Watts, Chair
Cort Cooper, Chevron
Dave Driver, BP
H. James Herring, DYNALYSIS
Jeff Ji, MMS
A.D. Kirwan, University of Deleware
R. Lai, MMS
William Teague, NRL
Kevin Leaman, UM/RSMAS
Pongxiang Li, TAMU
Lew Rothstein, AEF
Dave Szabo, Furgo GEOS
Wensu Wang, Furgo GEOS

ENVIRONMENTAL JUSTIFICATION FOR PHYSICAL OCEANOGRAPHY STUDIES

Working Group 3: Wednesday Afternoon, 13 September 2000

Dr. Larry Atkinson
Old Dominion University

Dr. James M. Coleman
Coastal Studies Institute
Louisiana State University
Representing OCS Scientific Deepwater Subcommittee

Discussion Leaders

Physical oceanographic studies in the MMS programs are often solely justified in terms of the importance of knowing where currents will take spilled material such as oil. This is unfortunate, because all aspects of oceanography are interrelated, and it is recognized by almost all non-physical oceanographers that understanding the physical oceanographic setting is vital if they are to effectively do their own studies. During the early part of the workshop, these issues were discussed. To address this issue, a working group was formed to pursue the topic. Topics discussed are as follows:

- Effects of physical oceanographic phenomena on biological communities or local and regional habitats
- Scouring removal of fine sediments; changes in grain size profile
- Direct forces: interference with feeding of suspension feeders
- Larval transport
- Distribution of food (prey species) for large migratory fishes (swordfish, tuna) and cetaceans
- Sweeping clear of hardground B by currents B only substrate for fauna
- Redistribution of sediments in benthic storms (short term)
- Redistribution of sediments in mass wasting (long-term effects)
- Coastal upwelling, e.g. off Southwest Florida
- Previous MMS-sponsored studies in shallow water, with emphasis on the shelf and upper slope

- Examples of MMS physical oceanography studies addressing a biological/socioeconomic problem

There are many types of examples. A few were discussed:

- Mississippi River water is entrained and pushed eastward towards the western Florida Panhandle shelf region. This process has biological and socioeconomic implications.

- GulfCet studies of the distributions of whales in the GOM have found that sperm whales have an affinity for cyclonic eddies. Cyclonic eddies are of course one of the main topics of study for the MMS physical oceanography studies and POSAR. Increased understanding of the physics of the eddies will complement the studies of whales and their distribution in the GOM.

Understanding oil spill movements and changes is impossible without physical oceanographic knowledge. Examples are as follows:

- Dispersal timing, and dispersal of pollutants, cuttings and turbidity

- Controling distribution of water masses

- Instability of hydrates via temperature increases causing massive failures (slumps?)

- Health and robustness of benthic and chemo communities

- Major role of development of hypoxia on the Louisiana shelf

- Conduits for noise that impact marine mammals

- Bottom Boundary Layer (BBL) currents B unknown in detail, but critical to understand as an erosive agent that leads to a variety of geohazards

- Control of marine weather by surface currents and water temperature

- Safety considerations for long pipelines from deep water production sites.

The proposed POSAR fieldwork and modeling effort offers opportunity to study deepwater linkages between physical oceanographic and biological oceanography. Examples include:

- Ability to measure the teleconnection of larvae, between shelf and slope, or across the basin

- Opportunity to describe deepwater mean field and variability of ambient noise that sperm whales and other protected species are exposed to

INTRODUCTION TO POSAR WORKSHOP SHORT-TERM RECOMMENDATIONS: THURSDAY MORNING, 14 SEPTEMBER 2000

Dr. Larry Atkinson
Old Dominion University

The reports that came from the various working groups during the meeting provide a broad view of the topic from the perspective of many physical oceanographers. Since the goal of the meeting was to provide a consensus statement for MMS on what research might be done, we asked Dr. Worth Nowlin and others to develop as that consensus statement. Dr. Nowlin was asked to do this because he was funded by MMS to assess the recent data coming from observational efforts in the Gulf. Thus, he had already spent considerable time considering the issue.

The group heard the following report by Dr. Nowlin Thursday morning; the report led to considerable discussion. Those in attendance (most of the oil industry representatives had left by then) were in general agreement that his statement reflected fairly the thoughts of the group.

It may help readers to realize that discussions on observational strategy focus on mainly the relative merits of current meters and drifters. The discussions include what is essentially a cost-benefit analysis of the issue.

One of the most innovative parts of the discussions was the possible advantage of new Lagrangian drifters. These discussions are summarized in several of the reports.

Following is Dr. Nowlin’s report. Many people assisted him in the writing, including Dr. Wilton Sturges.

POSAR WORKSHOP SHORT-TERM RECOMMENDATIONS

Thursday Morning, 14 September 2000

Dr. Worth D. Nowlin, Jr.
Texas A&M University

Workshop participants discussed the many deepwater environmental issues in the Gulf of Mexico related to physical oceanography. They then recommended a program of field observations and modeling to clarify those issues. This recommended program would likely cost $10-15 million per year over a period of 5-10 years. A scientifically well-focused program of this scale can be justified and is believed necessary to obtain satisfactory answers to the unanswered questions that are before us.

Such a program is a small investment in comparison with the price of a dozen drilling rigs and production platforms, and is also small in comparison with the potential long-term damage to the economy of the coastal areas and the fishing/shrimping industry if something should go badly awry. The workshop participants did not predict disasters; but they felt that it is the charge of the community to investigate the scientific issues adequately so as to be able to provide to the decision-makers good information of adequate quality and depth.

Because we expect that adequate support is not yet available, the workshop participants planned a series of pilot projects that would build on available knowledge and add information beneficial to the solution of environmental problems in the deepwater Gulf, as well as helping to define a future major program (POSAR). Each of these pilot programs could be carried out within an envelope of $1 million.

During the final workshop session, participants endorsed four pilot field projects. All seem important, well justified, and essential to the long-term needs of the continued strength of the MMS program. In addition, participants focused on the need for further comparisons of numerical circulation models applied to the Gulf. The four pilot programs recommended are

1. Limited observations, numerical simulations, and theoretical considerations tell us that topographic Rossby waves (TRWs) (very energetic motions extending through the water column below the main thermocline with periods of 10 d or greater) are excited in the eastern Gulf and propagate westward along the continental slope and rise, passing the region of most intense oil and gas development in the north-central Gulf. Therefore, we propose a moored current meter array to describe scales and propagation of TRWs along the rise and slope of the north-central Gulf. This array also would capture other energetic events in the region below the main thermocline.

2. We know that large, very energetic eddies propagate all across the deep Gulf to the western boundary. The numerical models tell us that there are energetic deep motions associated with these large eddies, but we have almost no data to verify this, or to tell us what the levels of energy are. Therefore, we propose a moored current meter array in the abyssal plain of the Gulf to verify and describe the deep eddies.

3. Numerical model simulations indicate that the deep flow regime is complex and energetic, with boundary intensification and major bathymetric effects on both mean flow and variability, but observations are inadequate for verification. Rudimentary current measurements and general physical considerations suggest that the deep flow between the Gulf and the Caribbean Sea in extremely energetic and variable in direction, with transports of the same order as the surface-intensified Loop Current. Proposed is a Lagrangian float experiment in the deep basin designed to obtain statistics about the deep circulation and its variability and to give indications of deep flowthrough the Yucatan Channel. This would provide for the first time information regarding the the interchange of deep organisms between the Gulf and the Caribbean.

4. Although there are some current measurements from slope and rise of the north-central Gulf, the region of most active petroleum exploration and recovery, most records are short (months) and few moorings cover the vertical extent of the water column. Consequently, in this critical region the environment, we have inadequate observations to describe statistically the energetic current events known to exist. To help remedy this situation, a program is proposed to enhance the environmental observations obtained on the drill vessels and production platforms of the petroleum industry. Data gathered from exploratory drill vessels can be used to advance knowledge at sites of future production platforms. This program should be implemented first.

These pilot field programs are discussed in the paragraphs that follow.

A. In Figure 43 are shown the suggested (approximate) locations of the preliminary scale/physics arrays of pilot project 1. (Note that it is suggested that the present MMS current meter mooring located near 27.3N, 90W be continued.) The locations of the three cross-isobath scale arrays could be adjusted in longitude based on theoretical and model considerations of TRW propagation in this region. These arrays may be composed in a triangular configuration rather than the linear configuration shown schematically. The numbers and spacing of each array should be determined on the basis of the best available information. At this time, model results indicate that cross-isobath scales of energetic currents vary from 50 to several hundred km, but smaller scales may prove to be important.

B. Knowledge of currents over the abyssal plain in the Gulf of Mexico is based essentially on output of circulation models and theoretical conjecture. Measurements are missing, as seen in Figure 43. Shown in Figure 43 are the suggested locations of six moorings in the central Gulf to describe for the first time the propagation of deep eddies into the western Gulf. The MMS mooring now in place north of the Campeche Shelf should be continued and used as

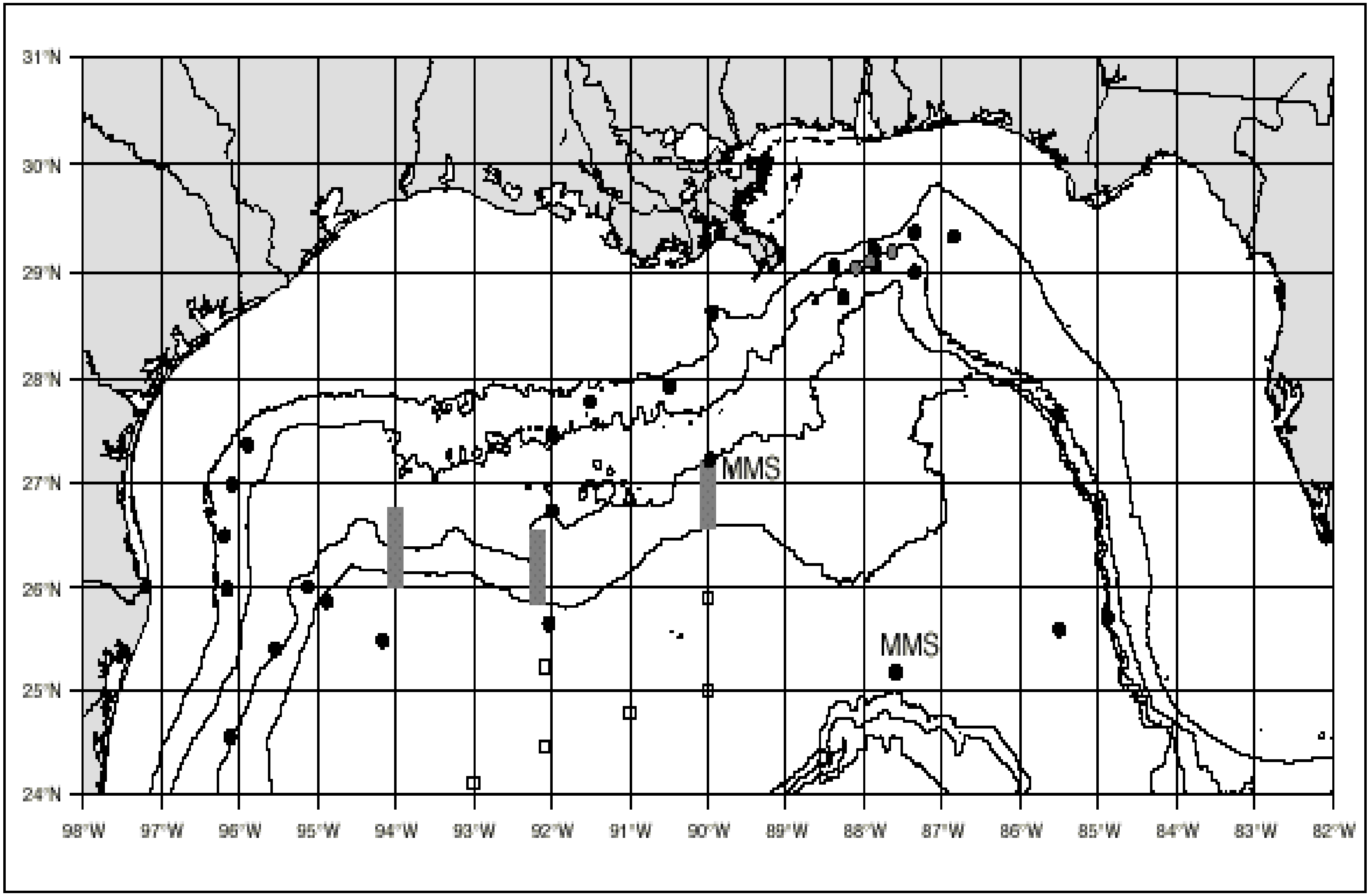


Figure 43. Mooring locations of public current measurements (•). MMS moorings proposed for extension are shown. Shaded lines over north-central slope and rise represent topographic Rossby wave (TRW) array of current meters. Boxes over central Gulf abyssal plain represent current meter array to observe deep eddies. The 200, 1,000, 2,000 and 3,000-isobaths are shown.

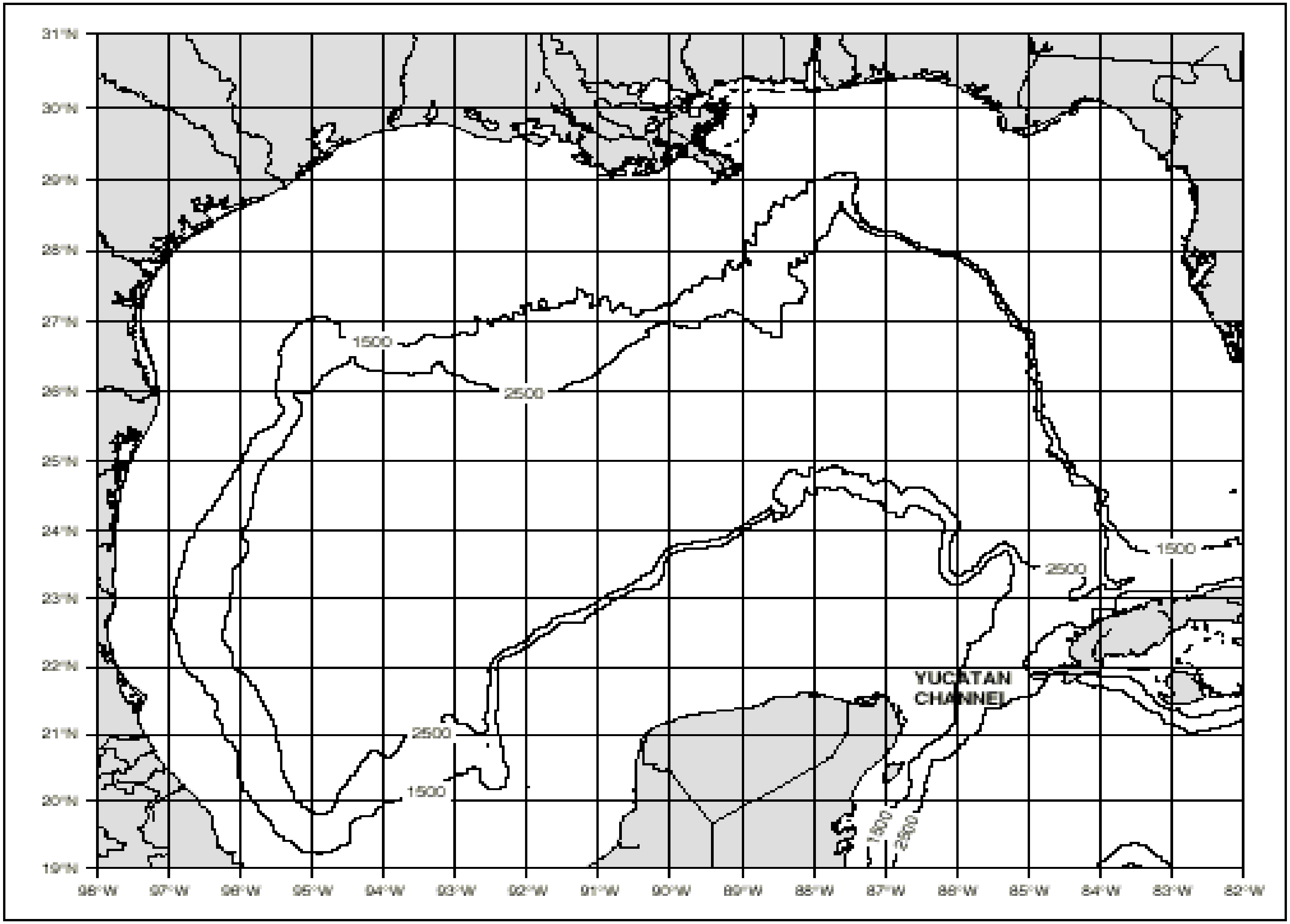


Figure 44. Area of 1,500-m and 2,500-m Lagrangian RAFOS float experiment.

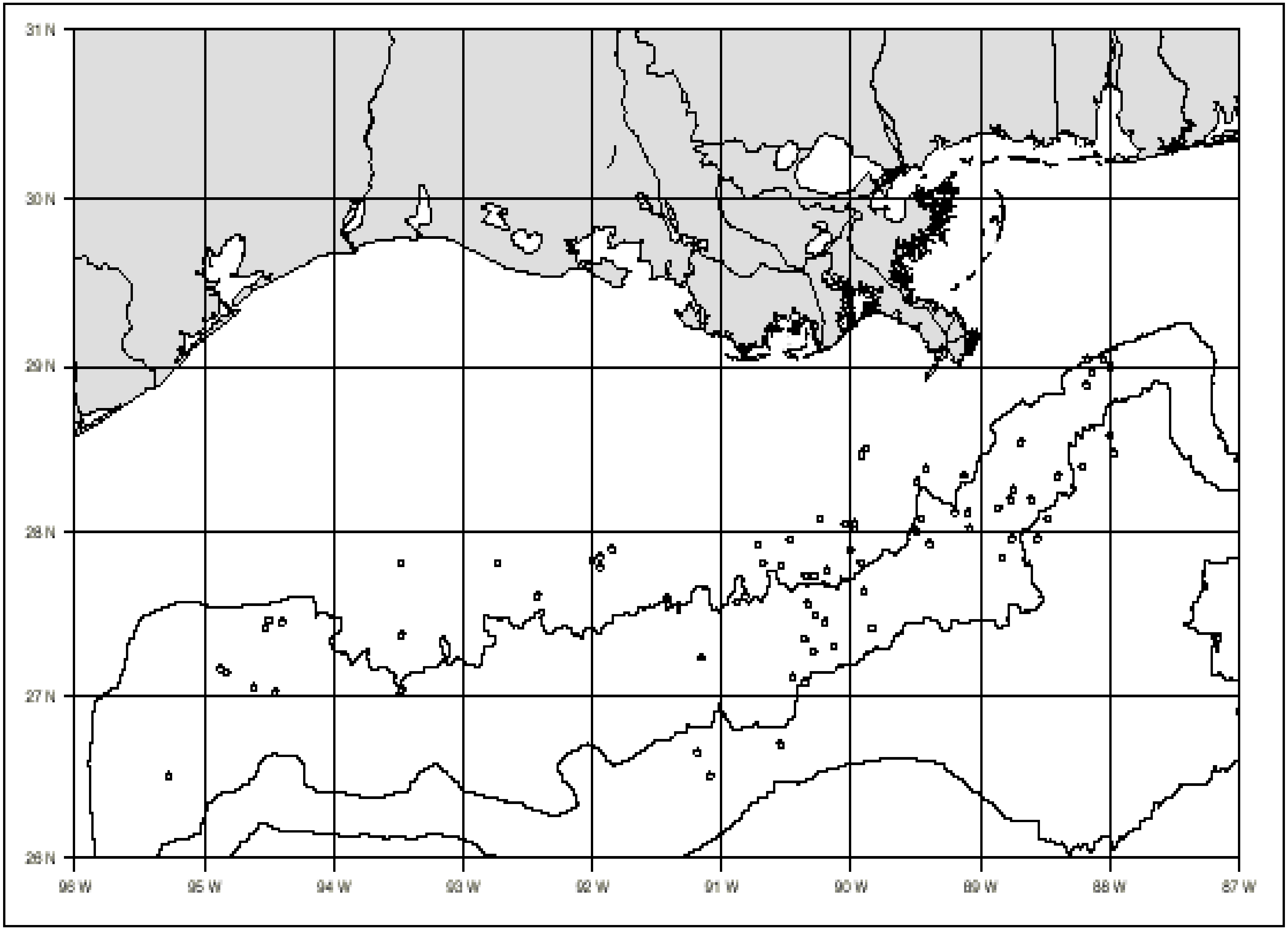


Figure 45. Locations of present and proposed drill rigs and production platforms.

a part of this array. These locations are schematic; they are subject to refinement based on further study of model output and observations. Measurements from these moorings also will capture other energetic current events in the deep central Gulf and, combined with the Lagrangian observations proposed as project 3, will contribute to deep flow climatology. They will contribute to our first substantial dataset concerning deep flow climatology, here considered to include not only mean fields but a variety of measures of the variability.

C. Shown in Figure 44 are isobaths in the region of the recommended Lagrangian float deployment. Suggested is a deployment for two years of approximately 60 RAFOS floats distributed between the 2,500-m and 1,500-m levels. Floats at 2,500 m would be confined within the Gulf basin, because the deepest sill depth (at Yucatan Channel) is approximately 2,000 m. Floats at1,500 m would be free to move through the Yucatan Channel. Sound sources must be positioned in the Cayman Sea as well as in the Gulf, and some of the floats should be deployed south of Yucatan Channel. Seven to eight sound sources would be needed.

D. At any given time there are 10-20 drilling or production platforms in the deepwater region of the north-central Gulf. The locations of present and proposed operations are indicated in Figure 45 (Courtesy of EJIP). Electricity and personnel are available to power and service instruments. These platforms regularly acquire current measurements from downward looking ADCPs suspended near the surface. However, the data are not necessarily quality controlled or saved. With modest additional expenditures, one could add additional instruments to obtain vertical resolution of currents, tides at platforms, and perhaps biogeochemical measurements as well, and could ensure equality control of the observations. Clearly, this is a potentially cost effective method of building a climatology of energetic current events over the continental slope and rise—including both barotropic deep and surface-intensified motions. Moreover, such data should be transmitted in use in monitoring and simulations.

Because the Gulf contains such a wide variety of energetic events, many of which are of relatively small scale, it is likely that needed environmental information will be obtained in considerable measure from numerical circulation models, constrained by a thin suite of observations. There are some half dozen models configured for the Gulf that have/are produced outputs. These outputs do not always agree, even on main issues such as whether deep barotropic eddies are “locked” to surface-intensified Loop Current eddies as they move into the western Gulf. It was suggested by the workshop that a careful comparison be made between results of these various models, corroborated by available observations.

APPENDIX A

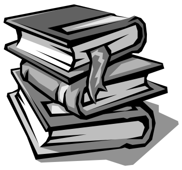
MMS ENVIRONMENTAL STUDIES PROGRAM

“STUDIES IN SUPPORT OF DEEPWATER DEVELOPMENT”

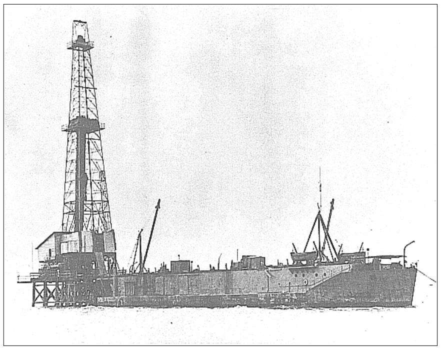
James M. Coleman
Coastal Studies Institute
Louisiana State University

ENVIRONMENTAL STUDIES PROGRAM

MISSION: **“To provide the environmental information necessary for informed decisions on OCS energy and nonenergy mineral planning and development activities.”**



- Advises MMS on feasibility, appropriateness, and scientific value of ESP
- Reviews information produced by ESP and recommends changes in scope, direction or emphasis
- Ensure that ESP contracts meet the needs of Regional offices
- Assure that the environmental studies conducted are of the highest scientific quality possible



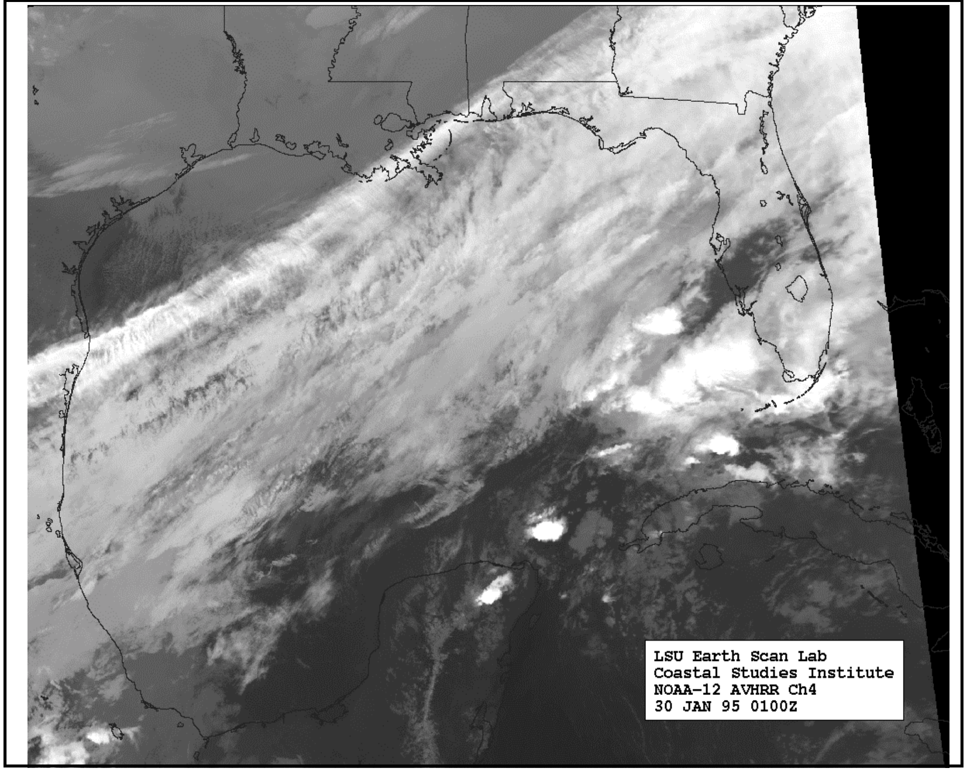
1947
$ ~230,000
18’ WD

2000
Several million $
2,700’ WD

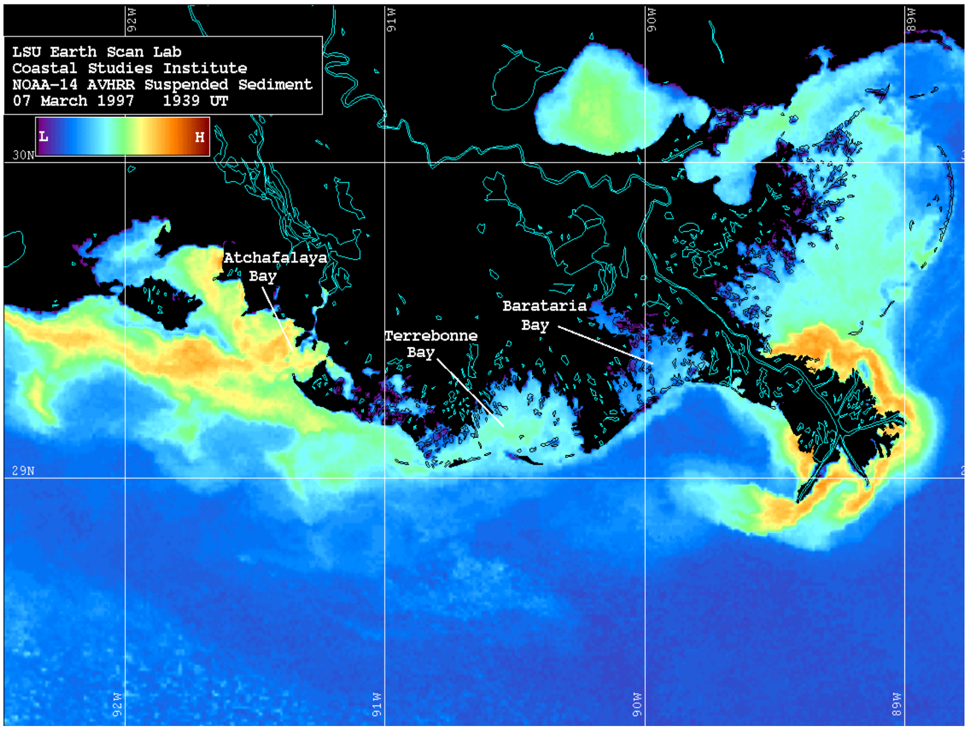
PREVIOUS STUDIES

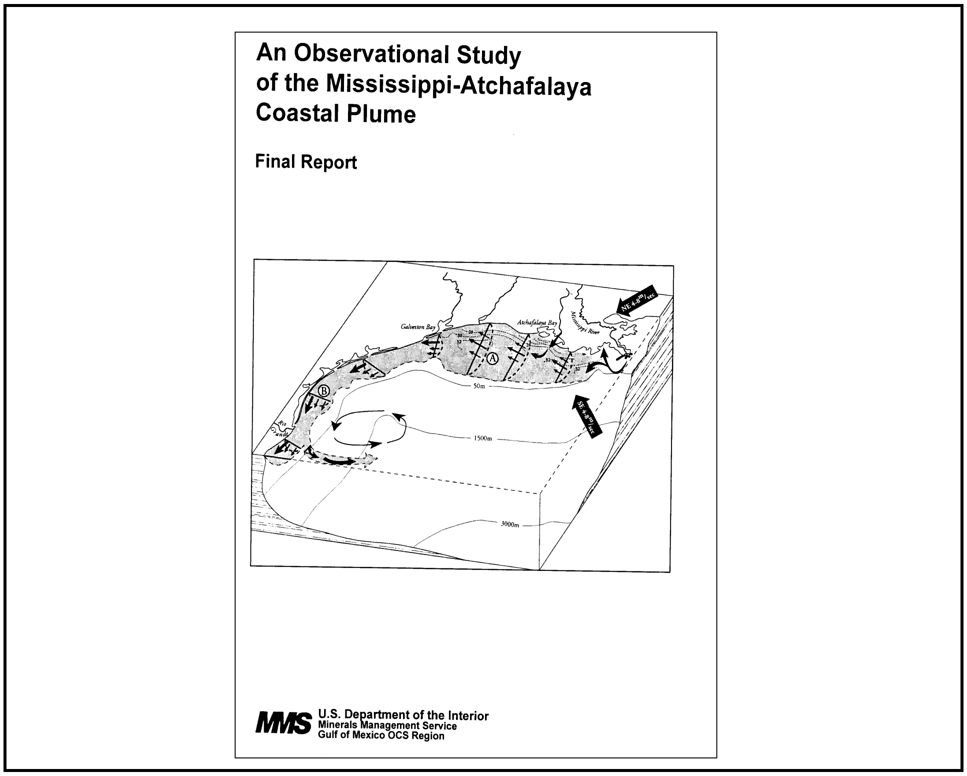
Physical Oceanography:

* Ambient Pollutants & Air Quality
* Numerical Simulation of GOM Circulation
* Coastal Currents & Sediment Transport
* Eddy Circulation



LSU Earth Scan Lab
Coastal Studies Institute
NOAA-12 AVHRR Ch4
30 JAN 95 0100Z

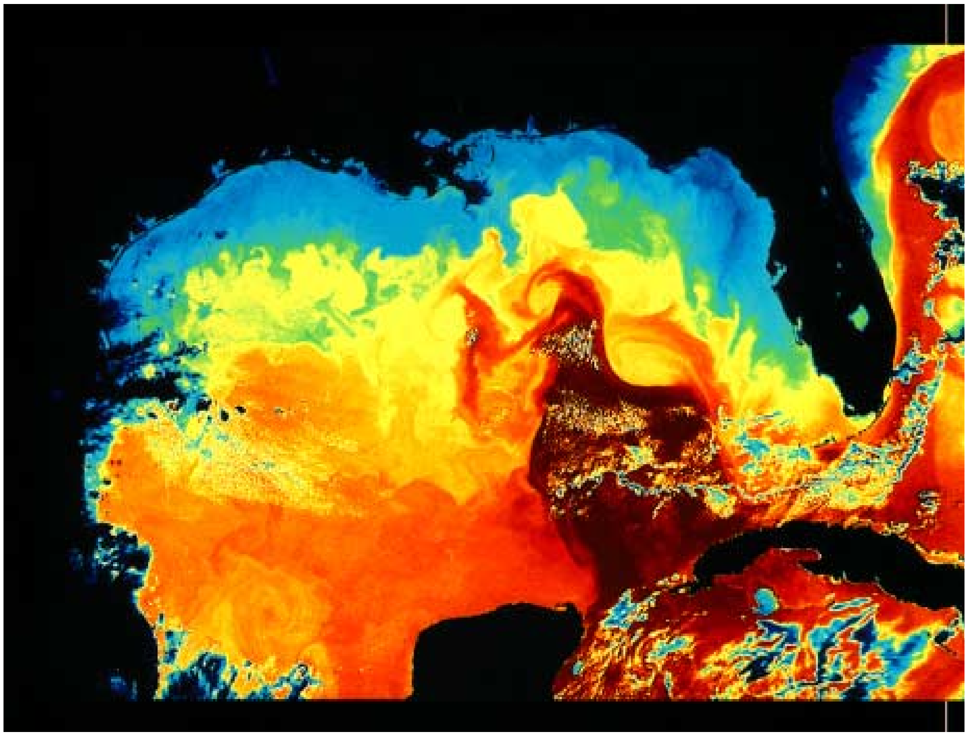


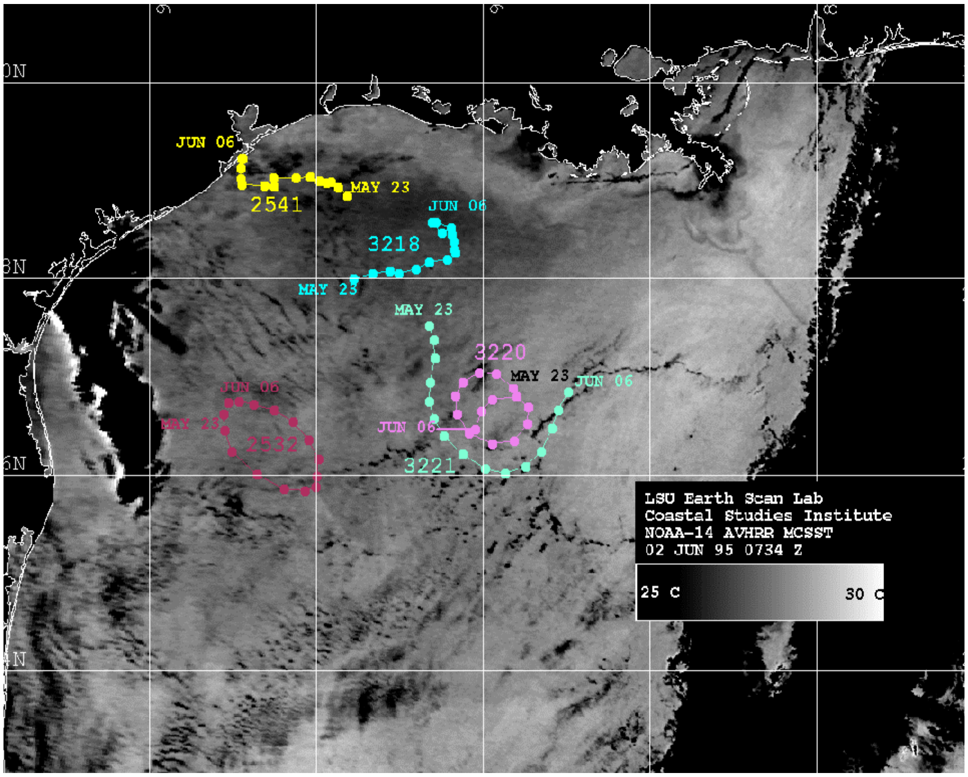


An Observational Study
of the Mississippi-Atchafalaya
Coastal Plume

Final Report

MMS U.S. Department of the Interior
Minerals Management Service
Gulf of Mexico OCS Region




0N
8N
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MAY 23
JUN 06
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LSU Earth Scan Lab
Coastal Studies Institute
NOAA-14 AVHRR MCSST
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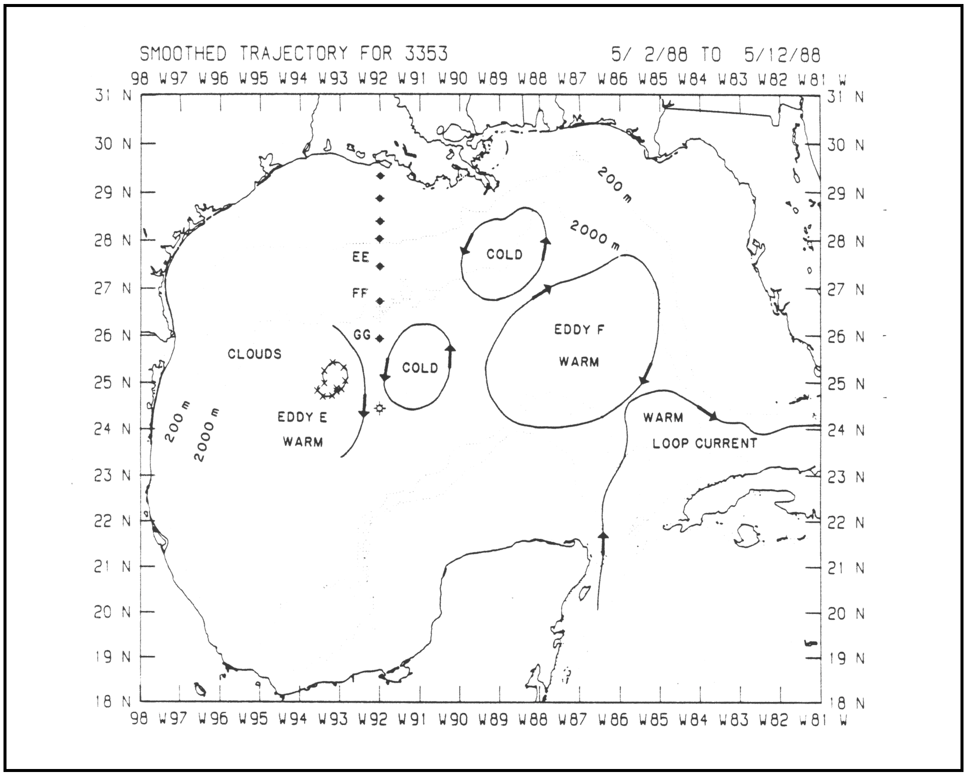
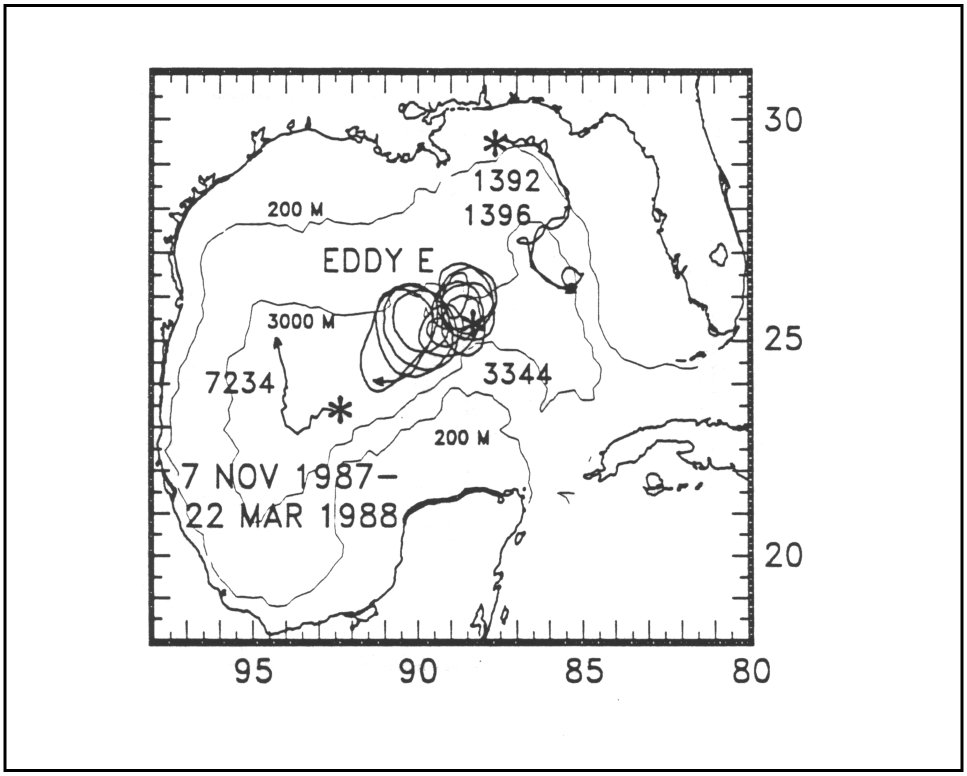
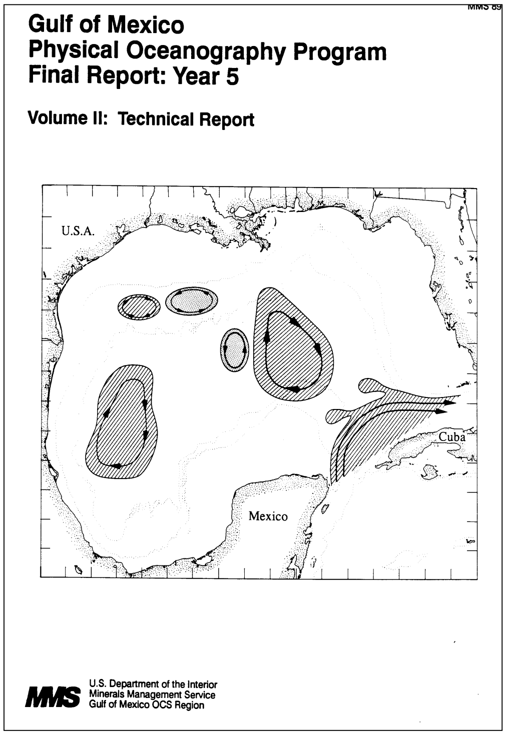

SMOOTHED TRAJECTORY FOR 3353
5/ 2/88 TO 5/12/88
98 W97 W96 W95 W94 W93 W92 W91 W90 W89 W88 W87 W86 W85 W84 W83 W82 W81 W
31 N
30 N
29 N
28 N
27 N
26 N
25 N
24 N
23 N
22 N
21 N
20 N
19 N
18 N
200 m
2000 m
EE
FF
GG
COLD
COLD
CLOUDS
EDDY F
WARM
EDDY E
WARM
200 m
2000 m
WARM
LOOP CURRENT


1392
1396
200 M
EDDY E
3000 M
7234
3344
200 M
7 NOV 1987–
22 MAR 1988
30
25
20
95
90
85
80



MMS 89

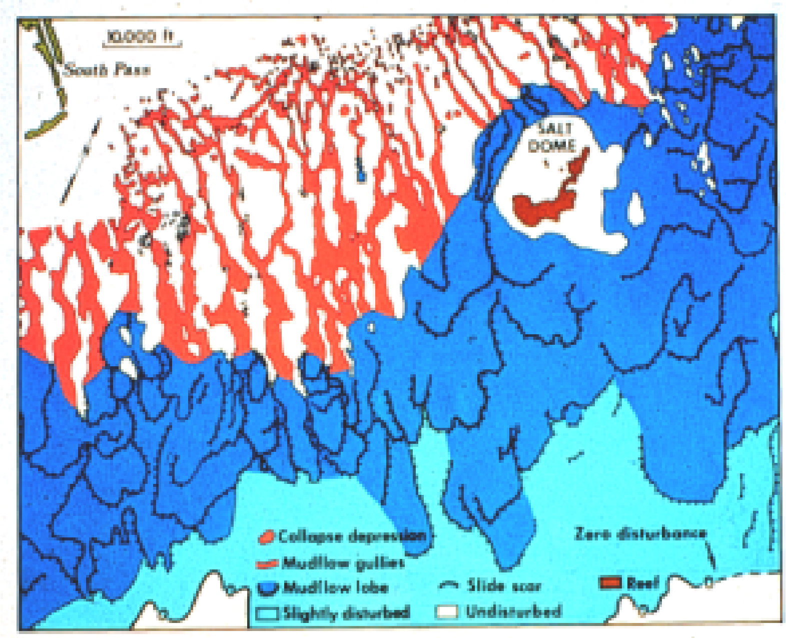
Gulf of Mexico
Physical Oceanography Program
Final Report: Year 5

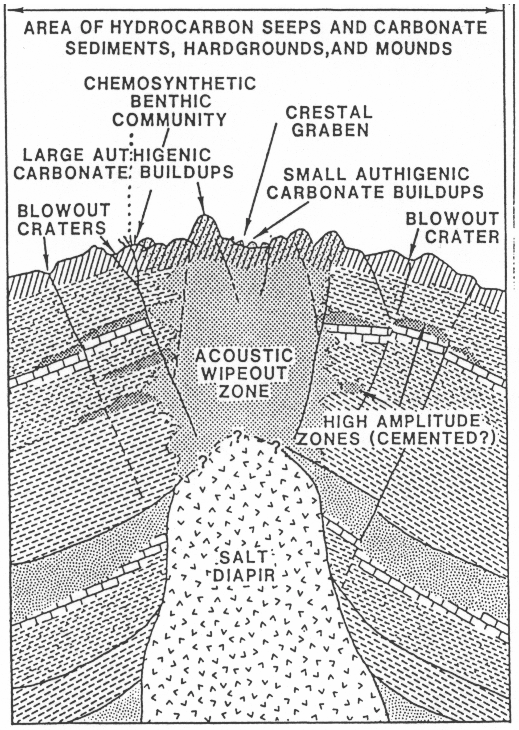
Volume II: Technical Report

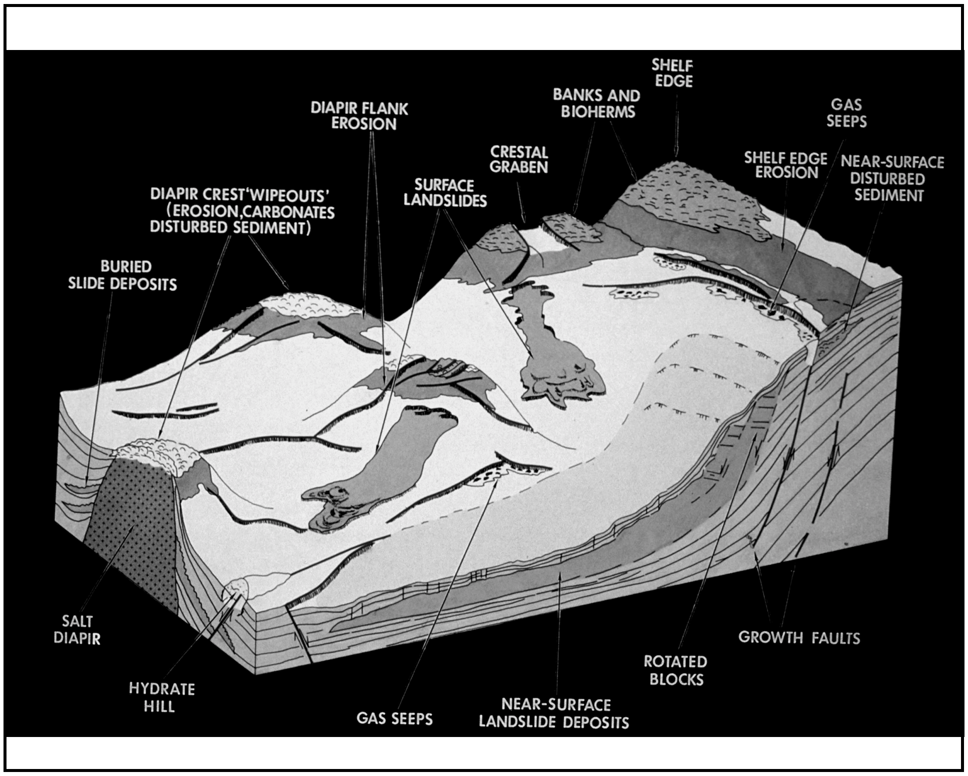
MMS U.S. Department of the Interior
Minerals Management Service
Gulf of Mexico OCS Region

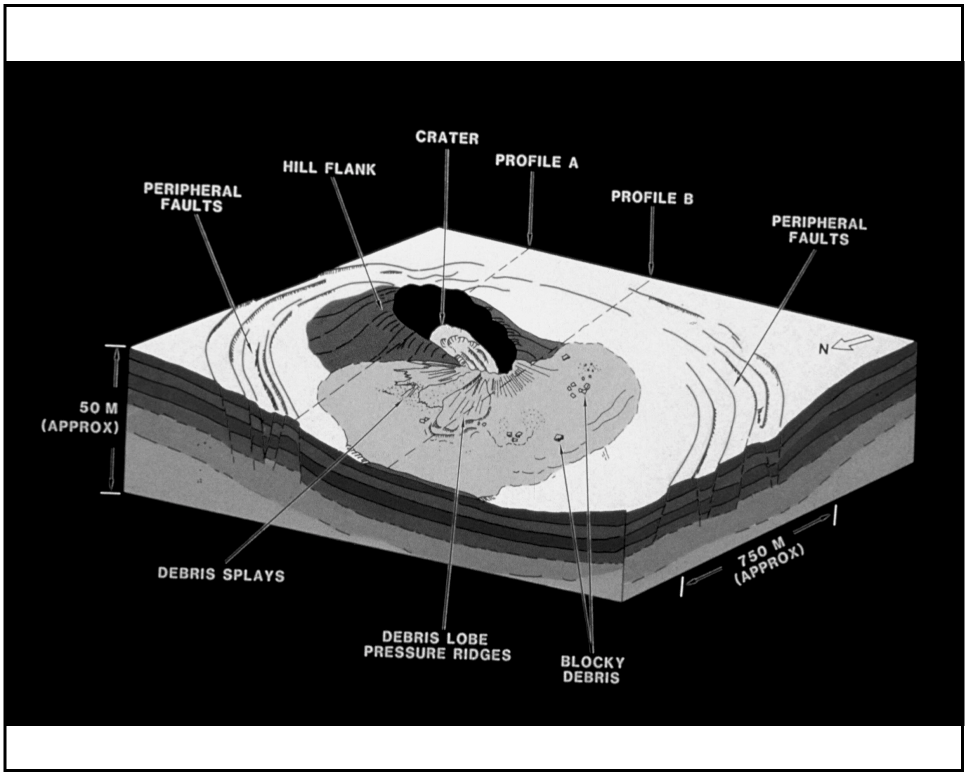
GEOHAZARDS

- **Mississippi Delta Mudslides**
- **Shelf-edge Hardgrounds**
- **Seeps & Mud Volcanoes**
- **Upper Slope Landslides**


10,000 ft
South Pass
SALT DOME
Collapse depression
Mudflow gullies
Mudflow lobe
Slightly disturbed
Slide scar
Undisturbed
Reef
Zero disturbance

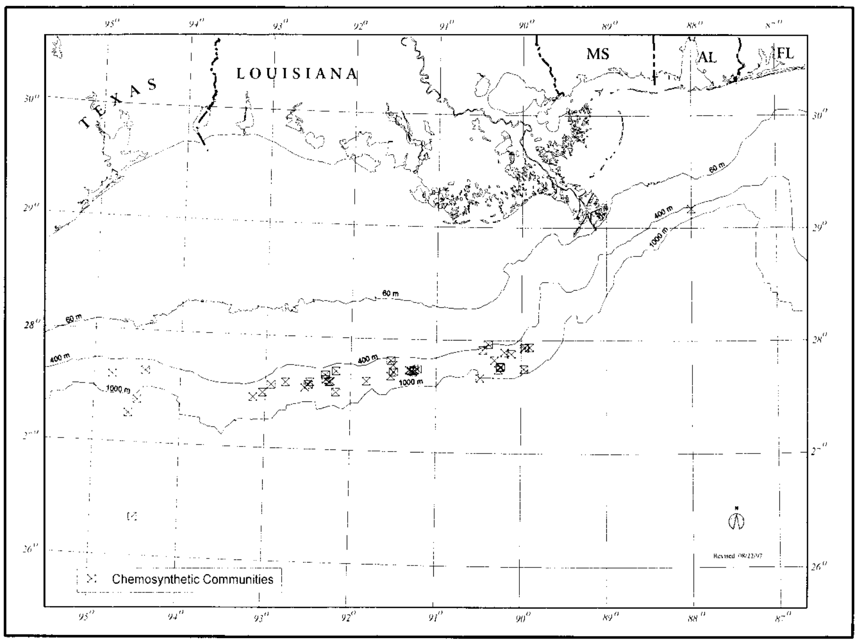

AREA OF HYDROCARBON SEEPS AND CARBONATE SEDIMENTS, HARDGROUNDS, AND MOUNDS
CHEMOSYNTHETIC BENTHIC COMMUNITY
CRESTAL GRABEN
LARGE AUTHIGENIC CARBONATE BUILDUPS
SMALL AUTHIGENIC CARBONATE BUILDUPS
BLOWOUT CRATERS
BLOWOUT CRATER
ACOUSTIC WIPEOUT ZONE
HIGH AMPLITUDE ZONES (CEMENTED?)
SALT DIAPIR


SHELF EDGE
BANKS AND BIOHERMS
DIAPIR FLANK EROSION
GAS SEEPS
CRESTAL GRABEN
SHELF EDGE EROSION
NEAR-SURFACE DISTURBED SEDIMENT
SURFACE LANDSLIDES
DIAPIR CREST'WIPEOUTS' (EROSION,CARBONATES DISTURBED SEDIMENT)
BURIED SLIDE DEPOSITS
SALT DIAPIR
HYDRATE HILL
GAS SEEPS
NEAR-SURFACE LANDSLIDE DEPOSITS
ROTATED BLOCKS
GROWTH FAULTS


CRATER
PROFILE A
HILL FLANK
PROFILE B
PERIPHERAL FAULTS
PERIPHERAL FAULTS
N
50 M (APPROX)
DEBRIS SPLAYS
750 M (APPROX)
DEBRIS LOBE PRESSURE RIDGES
BLOCKY DEBRIS

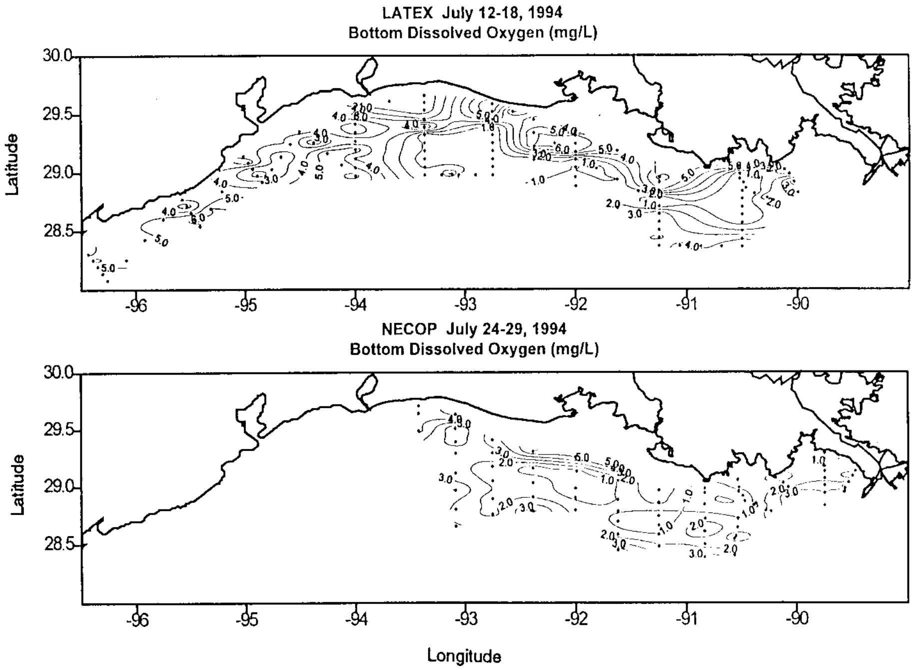
BIOLOGICAL/ECOLOGICAL

- Fisheries Habitat
- Marine Mammals
- Rigs-to-Reefs
- Continental Shelf Ecosystems
- GOOMEX
- Chemosynthetic Ecosystems
- Hypoxia



CHEMOSYNTHETIC COMMUNITIES

- **Slow growth rate**
- **Communities change rapidly over short distances**
- **No “typical” communities**
- **Levels of natural Oil & Gas seepage is great**
- **Mussel communities are short-lived**
- **Structure of chemosynthetic communities are similar world-wide (major type species are common.**



LATEX July 12-18, 1994
Bottom Dissolved Oxygen (mg/L)

NECOP July 24-29, 1994
Bottom Dissolved Oxygen (mg/L)

SOCIOECONOMIC ISSUES

- Impacts of restructured OCS oil & gas industry
- Economic & social consequences of oil spills
- Social & economic impacts of “Boom & Bust” cycles
- Oil & gas development & coastal income inequality

ESP STUDIES – FY 2000

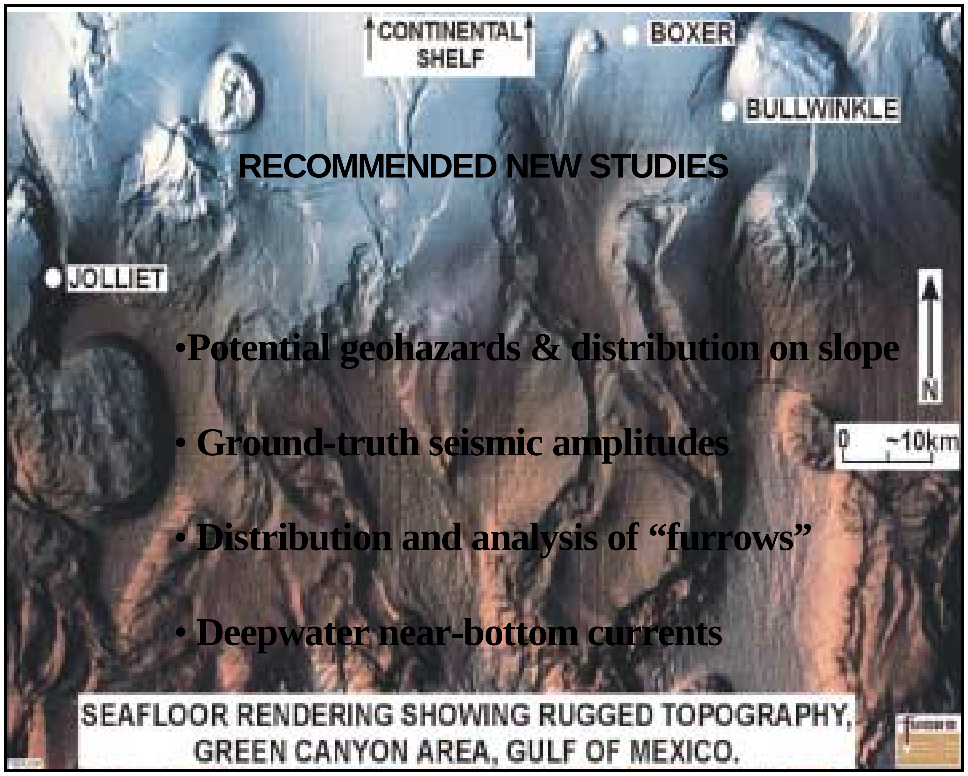
- Effects on Local Communities of OCS Frontier Areas
- Data search & synthesis on highly migratory fish and evaluation of FAD’s
- Summary of Northern GOM Continental Slope Studies
- Sperm Whale Studies
- Effects of O&G exploration at selected sites

ESP STUDIES – FY 2001

- Development of integrated oil spill trajectory model
- NE Gulf integrated study of physical & biological processes
- OCS regulated use of navigation channels
- GOM ozone modeling analysis
- Hydrate outcrops & associated chemo communities
- GOM deepwater protected species
- POSAR

ESP STUDIES – FY 2002

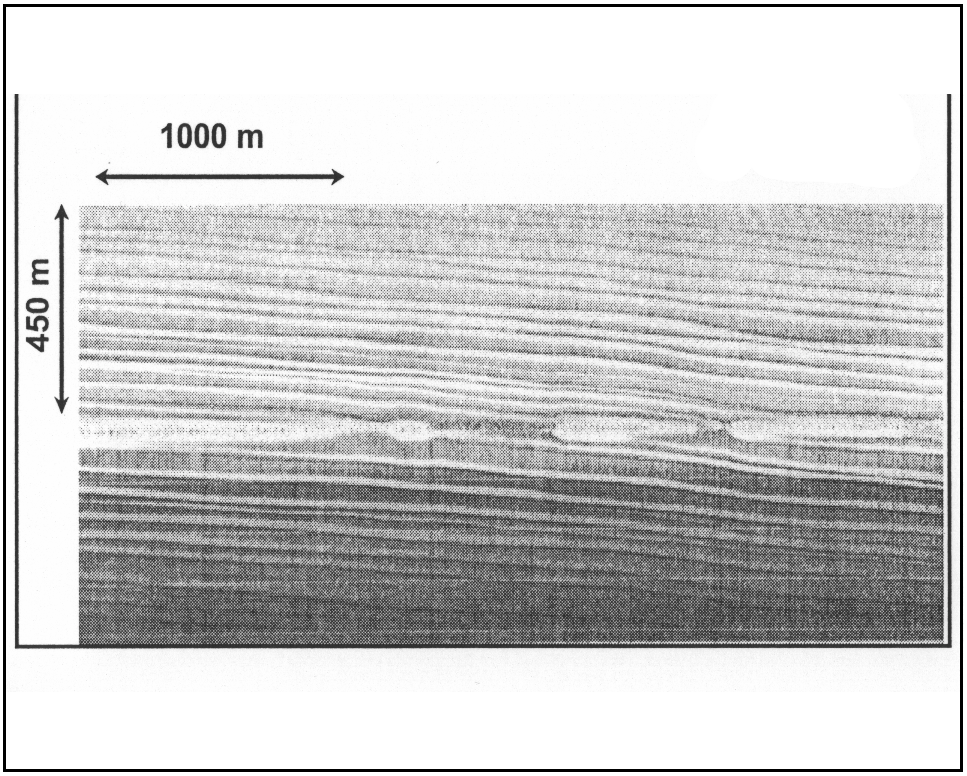
- Platform removal
- Air quality
- Seismic activity in GOM
- Invasive species
- Fates & effects of Oil
- Gas hydrates
- Environmental justice

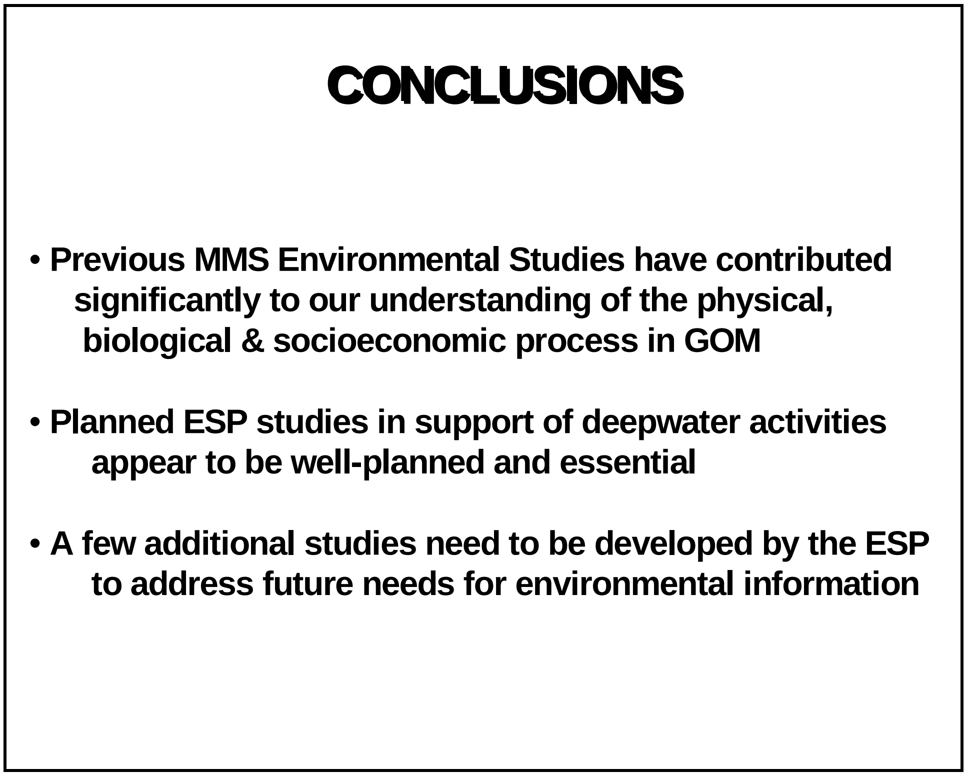


RECOMMENDED NEW STUDIES

- Potential geohazards & distribution on slope
- Ground-truth seismic amplitudes
- Distribution and analysis of “furrows”
- Deepwater near-bottom currents

SEAFLOOR RENDERING SHOWING RUGGED TOPOGRAPHY, GREEN CANYON AREA, GULF OF MEXICO.





CONCLUSIONS

- **Previous MMS Environmental Studies have contributed significantly to our understanding of the physical, biological & socioeconomic process in GOM**
- **Planned ESP studies in support of deepwater activities appear to be well-planned and essential**
- **A few additional studies need to be developed by the ESP to address future needs for environmental information**

APPENDIX B

Deepwater Physical Oceanography at the Minerals Management Service

September 12, 2000

by Chris C. Oynes

Regional Director
Minerals Management Service
Gulf of Mexico OCS Region

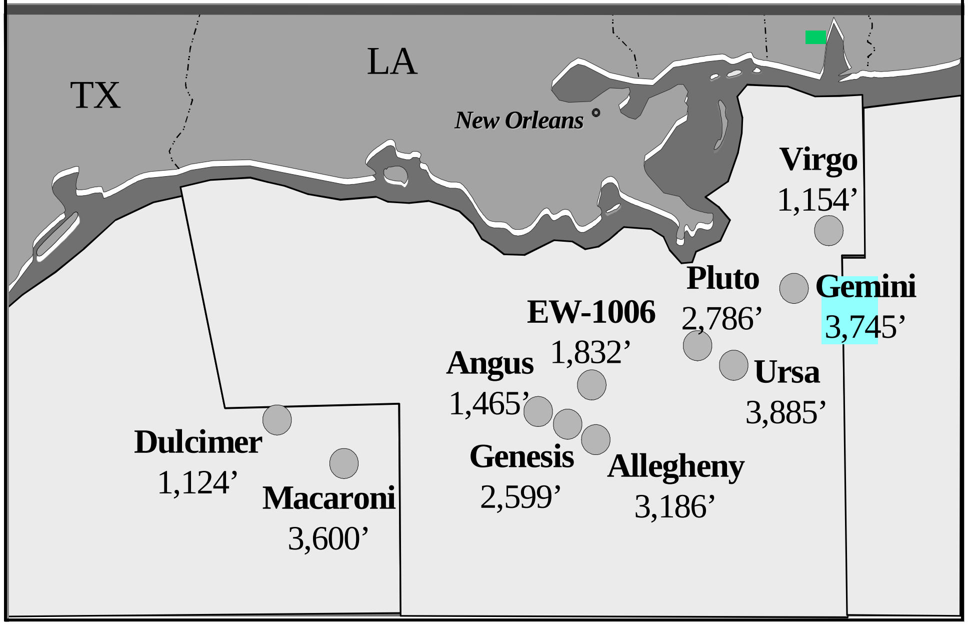
Context for the Workshop

Purpose of the Workshop

Progress in Deepwater in the Gulf

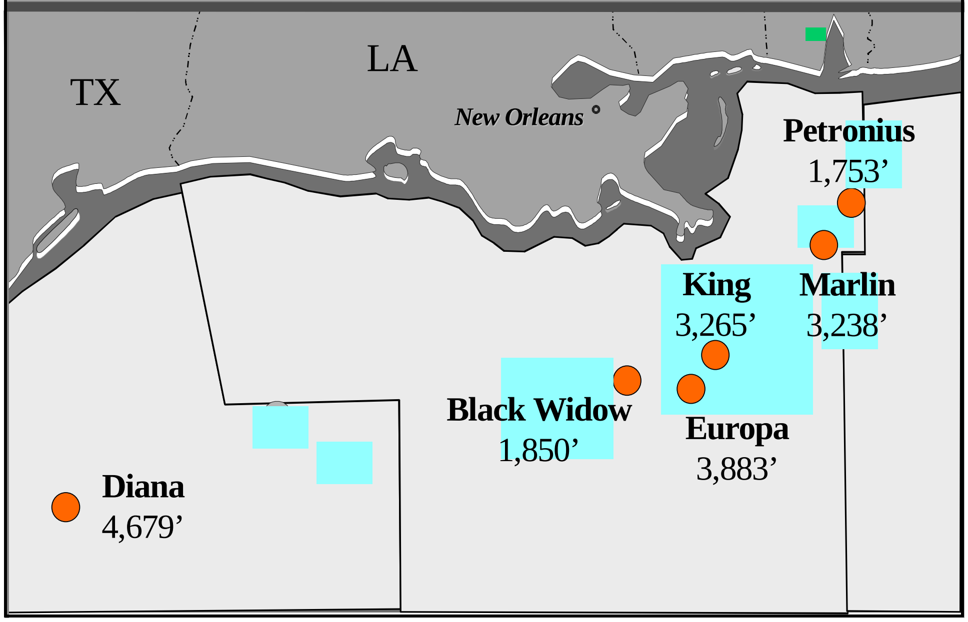
- Since 1996, industry has leased about 3,300 blocks beyond 200 meters water depth
- Exploration activity has accelerated
- More than 100 deepwater discoveries have been made; 35 deepwater fields have gone on production

Deepwater Startups 1999

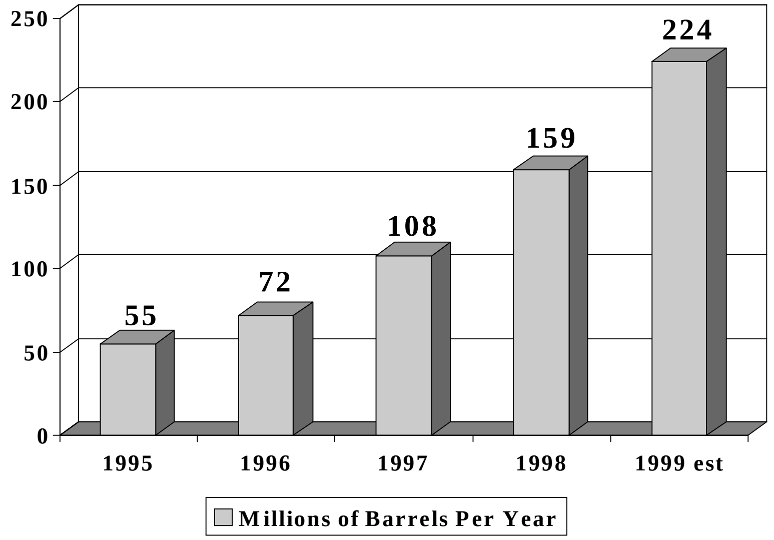


Deepwater Startups 2000

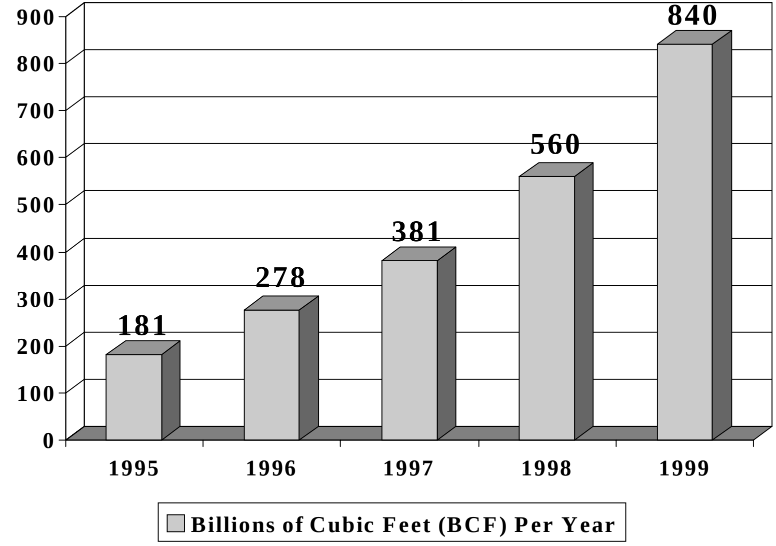
Expected



Gulf of Mexico Deepwater Oil Production

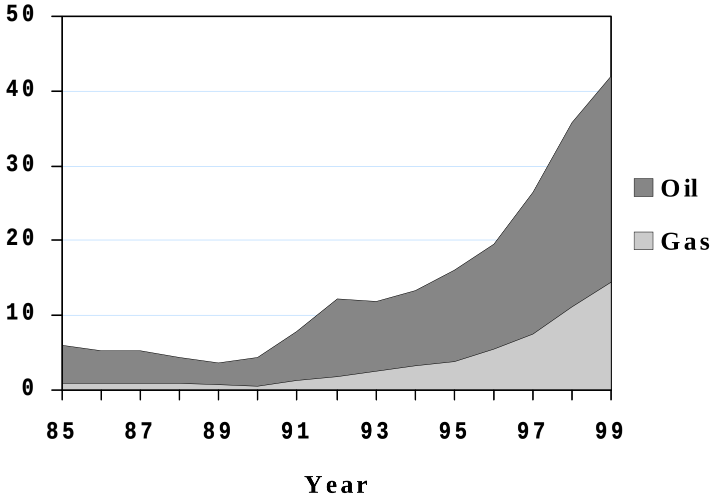


Gulf of Mexico Deepwater Gas Production



GOM OCS Deepwater Production

(% of Total)



Purpose

- Gather views and ideas about deepwater circulation in Gulf
- Prioritize these ideas and views
- Suggest field study or studies

Result of this workshop could lead to a study or studies, but that is not a foregone conclusion

What Has Led Us to This Workshop

- The 1997 Deepwater Workshop began serious discussion of deepwater physical oceanography in the Gulf
- Following this are recent significant deepwater current findings

Recent Significant Events in Deepwater Oceanography

- January 1999 MMS obtains data corroborating ~1 knot currents in deepwater
- Gulf of Mexico OCS issues safety alert of strong currents in deepwater
- Mega furrows on the rise off Louisiana suggest strong currents
- December 1999, MMS data corroborates ~ 2 knots currents in 2,000 m (6,000 ft.) deep

Expected Outcomes

- Workshop proceedings will be used by MMS in considering next steps
- Ultimately, MMS will make its decision based on your input, input from the Scientific Advisory Committee, industry, States, and other stakeholders

---

- MMS is planning for 2001, an exploratory study of the currents in the slope and rise that will provide important information for the refinement of a possible future and more complete field study
- MMS is planning a Deepwater Environmental Studies Planning Workshop for 2002
- MMS is considering requiring the startup of a Complete Study of Deepwater Physical Oceanography as early as 2004

APPENDIX C

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The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS), collect revenue from the Federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the **Offshore Minerals Management Program** administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil and other mineral resources. The MMS **Minerals Revenue Management** meets its responsibilities by ensuring the efficient, timely and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States and the U.S. Treasury.

The MMS strives to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic development and environmental protection.