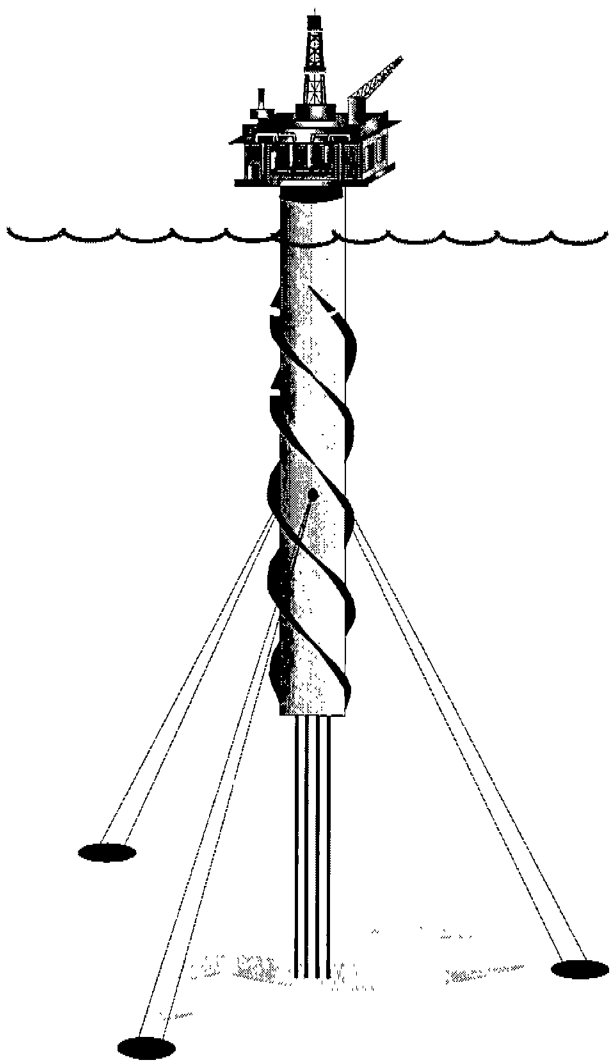
OCS Study
MMS 98-0022

Workshop on Environmental Issues Surrounding Deepwater Oil and Gas Development

Final Report



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

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Final Report

Editor

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Acknowledgments

Successful large workshops require the efforts of many behind-the-scenes people, and when the workshop must be set up and completed unusually fast, the efforts can be quite considerable. The exceptional work of the Minerals Management Service Gulf of Mexico Region staff must be noted, especially that of Ms. Debra Vigil. On the LSU campus the Office of Conferences Services responded to the challenge of setting up a meeting on budget and on time during one of the busiest hotel seasons in New Orleans. Ms. Lisa Leak headed this effort. The respective co-chairs for the sessions from LSU and MMS did an outstanding job, and the participation of those invited speakers who could fit the meeting into busy schedules on short notice is greatly appreciated. Bringing it all to closure, Ms. Jami Donley of LSU did the hard work of pulling this workshop report together.

1. Introduction: Meeting Information Needs for Deepwater Development

1.1. Emerging Deepwater Needs

With the passage of the Deepwater Royalty Relief Act and the development of technologies that allow for more cost-effective development beyond the continental shelf, leasing deeper than 1000 meters has proceeded at an unanticipated high rate. If predictions of ever larger reservoirs in deepwater prove true, then during the eight to ten year development period allowed on these deepwater leases the Gulf of Mexico will experience a profound change in the pattern of development. The Minerals Management Service (MMS), which is already charged with managing offshore oil and gas reserves, will bear the added burden of managing rapid expansion into a new and poorly understood environment in which evolving technologies will be used for the very first time.

Recognizing the magnitude of this task and the greatly accelerated pace of deepwater leasing, MMS contracted with the Coastal Marine Institute (CMI) program at LSU, an MMS-Louisiana cooperative undertaking to develop a workshop on deepwater issues under a short-lead-time. Serious talks about this workshop began at the December 1996 MMS-sponsored Information Transfer Meeting with the intent in having a workshop no later than the second quarter of calendar year 1997. The workshop was held April 22-24, 1997, in New Orleans, and was a success. The participants were a mixture of invited experts and people responding to a broad announcement. While there was a good mix of expertise at the workshop, the short notice made it impossible for many interested parties to participate. Similarly, the need to treat deep issues comprehensively limited participation in any given topic area. Therefore, the users of this report are cautioned to view these ideas and suggestions as a sample of what might be developed with more detailed consideration.

1.2. Meeting Structure

In keeping with its mandate, MMS must consider possible impacts of oil and gas development to both the natural and human socio-economic environments. Therefore, a workshop was convened that addressed socio-economic issues with a single working group and divided the natural environment three ways: physical oceanography, ecology, and sea floor geology. The reports of the four sessions herein reflect the different approaches associated with each discipline.

The socio-economic session had to address questions for which there is little prior knowledge and explored issues by means of open discussion. In contrast, there is appreciable information about the deepwater natural environment. A major part of addressing issues of the natural environment is figuring out who knows what, and of this information, what is most relevant. The session on sea floor geology approached this question by means of industry-academic discussions, while the physical oceanography session employed more formal input from its participants drawn from academia and industry. Lastly, the ecology session employed background presentations followed by a forum open to topics proposed from the floor.

Sociologists, physical oceanographers, marine geologists, and biological oceanographers (roughly the four divisions of the workshop) do not approach a problem from the same knowledge base, do not invoke similar paradigms in problem solving, and do not set priorities in the same manner. As a result, the sections of this report differ greatly from one another. There is, however, a simple underlying pattern of habitats and technologies. Deepwater development will employ new and old (existing) technologies that impact both new and old habitats in the sense of being newly or historically exposed to impact. Basically, MMS is highly experienced in dealing with old technologies in old coastal and shelf environments. In decreasing order of importance, the problems facing MMS may be presented as a simple list of two.

1. Identify those aspects of deepwater development for which the possibility of environmental or socioeconomic impact is no different than that now experienced in shallow water. Such activities may be evaluated and regulated largely within the current scope of knowledge, and MMS' needs for new information should be modest and easily met.

2. Identify those aspects of deepwater development for which the modes of development or the environments subject to impact possibly pose novel threats of impact. For such activities the adequacies of current knowledge for evaluation and regulation must be seriously questioned. In many cases, the absence of management information will be the result of major gaps in scientific understanding of the deep ocean. Obtaining necessary information may be so expensive as to require new partnerships and so far beyond what is already known as to require scientific creativity lying outside of MMS/ traditional procurement policy of best available technology.

2. Plenary Sessions: Establishing the Starting Place

2.1. Synopses of Plenary Presentations

2.1.1. MMS Perspective
Mr. Chris Oynes, Director MMS Gulf Region

The purpose of the workshop is to draw together a group of experts to determine what the knowledge baseline is, to identify missing information critical to MMS, and to establish priorities for meeting these needs. In doing so, three things need to be kept in mind.

a. Three days is obviously insufficient to consider all aspects of the impact of deepwater operations on the natural and socioeconomic environment. MMS views this as a starting place and recognizes that these initial discussions must be limited to be feasible.

b. There are many scientific questions that might be asked about deepwater. However, MMS is in need of applied research with close and obvious links to MMS decision making processes. During deliberations, assuring such an application linkage must be central.

c. Deepwater research is logistically expensive, and we are in an era of increasing fiscal restriction. Therefore, there is an extra burden placed on workshop participants. How are high priority needs to be met at lower costs?

The great increase of activity in deepwater began about two-and-a-half years ago in part because of the Deep Water Royalty Relief Act. It is not something that took MMS by surprise. The MMS has supported deep field programs since the 1980's. This workshop grew out of a need identified by the MMS Scientific Committee of the ACS Advisory Board, which had a deepwater subcommittee presence at the meeting.

The surge in deepwater (defined operationally as 1000 ft or greater) can be seen in a variety of statistics. In terms of leasing, total bids and tracts leased in 1995, 1996, and 1997 have seen previous records smashed. Each successive Central and Western lease sale has proven to be bigger than the past. Over 1000 tracts were leased in Sale 166, the most recent sale. The size of this single sale can be fully appreciated when compared to the fact that all sales prior to 1992 totaled only 1508 leases. The percent of deepwater leases in each successive sale has increased and moved progressivley deeper into the 200 to 400 m, 400 to 800 m, and 800+ (ultra deep) depth bands.

Deepwater operations are going to be different. A simple example is the effect on MMS inspections. Today inspection may involve offshore trips of 80 to 100 miles. In the near future, trips longer than 200 miles will be common. Because of cost considerations, operations will employ different technologies. Rigid structures spanning from the surface to the bottom are impractical much beyond 1500 ft. Subsurface systems tied back to shallow structures, spars, tension leg platforms, and other technologies will be used increasingly. Again related to costs, deepwater production will be high and employ horizontal segments in wells. Today, only a few shelf-depth platforms produce over 5,000 barrels per day. Shell's Auger, a tension leg platform in 872 m of water, which began operations in April 1994, produces at 13,000, and production as high as 25,000 barrels per day is anticipated. Currently, deepwater production is about 6% of total Gulf OCS activity, up from only 1% in 1992. By the end of the decade it is estimated that production may exceed 1.6 million barrels per day. A large fraction of this doubling will result from wells in deepwater.

At the conclusion of Mr. Oynes' talk, Drs. Ann Bull and Bob Avent of MMS narrated slides illustrating MMS's past and ongoing deepwater ecology work.

2.1.2 Industry Perspective
Mr. Paul Hays, Texaco, and Dr. James Ray, Shell

A good starting place to discuss deepwater operations is the Deepstar Program, a joint industry effort involving eighteen companies that began in 1992 and now is in its third phase. Through five committees, this program focuses on enabling development in the 3000 to 6000 ft range. Original emphasis upon seafloor systems tied back to shallower hosts has evolved to a larger number of options.

Deepwater development can be contrasted with shallow water development in four areas, drilling, production, processing, and transportation.

(a) <u>Drilling</u>. Shallow development employs fixed platforms with drilling and control usually on the platform. In deeper water these activities will migrate towards bottom. The safety concerns are the same for shallow and deepwater. Modular Offshore Development Units (MODU's) will increase in use, certainly in exploration activities.

(b) <u>Production</u>. Shallow and deepwater activities are actually quite similar with the former being a natural evolution of proven technologies from the latter. In production, workover, and abandonment, a major concern is keeping flow lines open. Subsea operations will see a shift in the location of hardware.

(c) <u>Processing and Separation</u>. Shallow and deepwater operations will be essentially the same.

(d) <u>Transportation of Fluids</u>. Deepwater operations may tie in to existing shallow pipeline systems connecting to existing infrastructure, thereby posing no new type of environmental risk. A newer technology under consideration for deep development is the use of tankers and floating production/storage and offloading facilities (FPSOs).

Any discussion of how deepwater operations might impact the natural environment can begin with a comparison of existing shallow water concerns and anticipated deep concerns. The physical disruption caused by deepwater drilling should be similar to shallow water in the sense that such things as anchoring and bottom founded structures will cause change in the benthic environment. However, operation costs mandate that deepwater development proceed with a lower density of structures than now on the shelf.

Operational discharges may be fundamentally the same for shallow and deepwater developments. Increased overall production rates in deepwataer will result in greater rates of produced water discharge, but the ratio of petroleum to water should be comparable to, or even less than now experienced, in shallow water. Traditionally, shallow well drilling has depended heavily upon water based drilling fluids. Deepwater wells will depend more upon newer synthetic drilling fluids, and it is expected that this same technology will be adopted at all depths. Multiple wells and horizontal drilling wells in deep water can be expected to produce a greater volume of cuttings. However, against this scenario of some increased discharge are two offsetting factors. First, overall operations density should be less. Second, the dilution capacity of a deeper water column should minimize impact.

2.1.3. Geologic Overview
Dr. Harry H. Roberts, LSU

Dr. Roberts chaired the Geology/Geohazards group, and the background document in section 3.3 contains a more detailed account.

Twenty-five years ago our knowledge of processes on the continental slope in the northern Gulf of Mexico was so limited that it was viewed simply as an accreting sedimentary structure. The Gulf of Mexico is now known to be extremely dynamic and is the international center of deepwater development and expertise. The slope is also marked by huge troughs or canyons cutting across the feature. These are conduits for sediment movement.

On the long-term, northern Gulf slope features are controlled by an interaction of rapid sedimentation and salt tectonics. On the shorter scale, this long-term complex is greatly modified by erosion, mass movement, and fluid expulsion. Both long- and short-term processes pose significant geohazards.

Shelf edge progradation is an interplay of rapid sedimentation and salt migration. In Pliocene and Pleistocene periods, sea level cycled, causing fluvial systems to prograde to the edge of the continental shelf depositing low sea level deltae. Thus, the edge of the shelf is stacked depocenters. The Mobile River delta off Alabama and the Brazos-Trinity complex off Texas are prime examples. The continued transport downslope today from these old shelf edge deltae pose considerable geotechnical problems to development. The number of processes carrying material to deepwater are numerous and poorly understood. Recent advances are the result of new methods of gathering and processing seismic data that allow geological structures under salt layers and other acoustic barriers to be studied in three dimensions.

Superimposed upon the regional continental margin topography is a complex of basins and major faults formed by the migration of salt sheets. Rapid loss of surface sediments, mass wasting, local faulting, and explulsion of entrapped fluids are the main processes of short term modification. Mass movements, such as localized slumping, are caused by slope instabilities that are relatively shallow in the sediment column. These layers of unstable sediment are proving to be far more common that originally thought. Even slowly accumulated mixtures of marine and terrigenous, hemipelagic sediments have caused thin skin slumping. Traditionally, hemipelagics have been considered highly stable. Faulting at all scales is intense over topographic highs.

Fluid expulsion areas, which include hydrocarbon seeps, contain a range of structures and processes that pose geohazards. These systems may be viewed as evolutionary in the sense that the feature spectrum can be related to an age and flux rate model. Expulsion areas may begin as mud-prone systems which then progress to mineral-prone.

2.1.4. Physical Oceanography Overview
Dr. Worth Nowlin, Texas A&M University

A written version of Dr. Nowlin's presentation is found in section 3.2.

The Gulf of Mexico is dominated by the Loop Current and its associated anticyclonic and cyclonic eddies. A convenient marker for studying this system is formed by the mixing of water masses. Circulation in the eastern Gulf is dominated by the Loop Current, which is a western boundary current in the Caribbean. Total transport in the Loop Current is approximately thirty million cubic meters per second with a variance of about ten percent. Speeds may exceed 150 cm/s at the surface with velocities as high as 5 cm/s still persistent at 1000 m. There are many studies of intrusion timing and eddy spawning.

To understand the fate of Loop rings, it is necessary to review western Gulf background circulation. A few synoptic studies have been undertaken, four in the 1960's, and each found a weak anticyclonic feature in the western Gulf with possibly an intensification along the Mexican coast. The mechanism is under debate: wind stress, loop eddies, and ring-slope-ring interaction have all been proposed. In the southwest Gulf there is a semi-permanent cyclonic gyre forced by winds.

Eddies pinch off from the Loop Current and migrate westward along a series of "preferred" paths. There has been considerable effort expended in modeling ring separation and movement. One weakness has been that the observed lifetime of rings exceeds that predicted in models. Deepwater current measurements have captured the influence of these eddies. Current meters at 500 m in the western Gulf showed velocity spikes to 30-40 cm/s.

There are three preferred paths. One goes down the central Gulf to the western border, then north. Another goes through the central Gulf, and a third skirts the continental slope off Louisiana. All three lead to the "eddy graveyard." These paths are caused by ring-slope interaction. Ring-slope interaction in this graveyard area can result in very strong offshore transport. (See Section 3.3 for a detailed discussion.)

Effects of atmospheric storms have also been captured in current meters. For example, during Hurricane Andrew currents at 100 m reached 20 cm/s and at 490 m about 5 cm/s was experienced. Hurricane effects in deepwater can be even more dramatic as in case of Hurricane Allen in 1980. At 700 m currents were 15 cm/s. Cyclones also have an effect giving rise to a characteristic current. Cold air outbreaks are a third phenomena with three to four a month, fall through spring. These force inertial oscillations. Thermal cycling causes some of the strongest surface currents seen in the MMS-sponsored Texas-Louisiana Shelf Physical Oceanography (LATEX) study. These are diurnal and associated with the summer.

2.1.5. Biology Overview
Dr. Gilbert Rowe, Texas A&M University

The deepwater Gulf of Mexico has been the site of an impressive amount of research, but it is work which has a unfortunate distinction. On the whole, deepwater Gulf work, except that associated with oil seeps, has not appeared in the peer-reviewed literature. Those data reflecting the soft bottom communities remain in relatively inaccessible archives or in the taxonomic literature. Therefore, as we anticipate meeting information needs, it is appropriate to begin by maximizing the value of early work, notably that of Pequegnat alone and in association with LGL Ecological Research Associates.

Willis Pequegnat was both pioneering and seminal in the deepwater Gulf, training many of the participants of this workshop. Although not ecological in a contemporary sense, his Gulf-wide sampling prior to EEZ limitations provides the descriptive and taxonomic foundation for current knowledge of megafauna. His data archives and specimens collected in the 1960s and 1970s remain at Texas A&M available for study. In the 1980s MMS placed emphasis on quantitative work with box corer samples. The Northern Gulf of Mexico Continental Slope Study (NGOMCS) established three transects downslope. The NGOMCS should be the main source of quantitative benthic biology. The results of this study suggest that the Gulf has a deep diversity pattern unlike that found in the Atlantic. Unfortunately, this is not a finding reported and debated in open literature. Beyond the 2600-2800 m limit of the NGOMCS Study, the structure of the deepwater Gulf community is virtually unknown.

While it certainly is possible to identify and remedy many specific omissions of Pequegnat's earlier work and the NGOMCS Study, the absence of any well-established ecosystem perspective must be considered the highest priority information need. Meeting this need requires two approaches for MMS.

a. The first step is to adopt an ecosystem model and then undertake field measurement of the important parameters. The model developed by Smith et al. (1983) for the deep Pacific is a good example of tracing energy from particle influx through various benthic components. Actual measurement is best accomplished by means of well-designed free vehicles. Rowe's GOMEX (Gulf of Mexico) lander is an example of such a system.

b. The second step is to adopt a sampling design which will allow studying the Gulf as a unified system. A simple SW to NE cross-Gulf transect mught be the least costly design. Restriction of ecological study ot the US EEZis artificial and may prove uninformative. A successful whole Gulf study will require collarboration iwth Mexican deepwatear ecologists, such as D. Elva Escobar.

2.1.6. Socioeconomic Overview
Dr. F. Larry Leistritz, North Dakota State University

During the energy crises of the 1970s, North Dakota and other northern plains states underwent rapid development of the fossil fuel industry. The lessons learned from this experience are applicable in the Gulf States as deepwater socioeconomic impacts are anticipated. Two traits characterized the boom associated with coal and coal-fired electric power plants. First, development was localized and extensive. Second, there was great uncertainty as to location, extent, and timing of development. An example of a possible impact might be a small community of a few hundred people faced with a peak transient construction population of over a thousand. Following this glut, a smaller but still substantial permanent cadre must be accommodated.

Realizing the planning needs, North Dakota established a four-year regional impact assessment program to identify issues and to implement impact management. The needs identified led to passage of a state coal severance and conversion tax. These revenues were returned to impacted communities to support infrastructure development. A highly informative contrast can be seen in the northern plains oil and gas development during the same era. This was allowed to progress unplanned. As a result, communities experienced deleterious boom and bust cycles. Ultimately, North Dakota made resources available to rectify some of the problems.

While the northern plains and the Gulf region are different, and the issues of deepwater oil are not dissimilar to those of coal, the procedure is still applicable. Issues can be identified, impact assessed, and impact management undertaken.

2.2. Common Themes

2.2.1. New Technologies in New Habitats

With the publication of NTL 96-4N, Deepwater Operations Plans, on August 19, 1996, the MMS began to receive conceptual, as well as actual information regarding deepwater development activities. These plans were concerned with engineering and safety analysis, but specifically omitted environmental information about the proposed activities.

The deep ocean habitat is so poorly understood that little more than conjecture about possible impacts are possible. Some concerns are actually a seaward extension of traditional resource conflict worries about fisheries and endangered species. Others, such as mesopelagic and deepwater benthic impacts, are relatively novel. MMS is in the unfortunate position of being one of the few federal agencies faced with needing to know a lot about deepwater ecology at a time when funds are limited and deepwater technologies are very expensive. Nevertheless, the knowledge base needs to be developed.

2.2.2. New Technologies in Old Habitats

The Gulf coastal states, most notably Louisiana and Texas, have a long history of inshore and shelf development. This has resulted in both a logistical and socioeconomic system that is impacted (positively and negatively) by OCS development. Deepwater development will, in effect, "plug into" these support systems. Old pipelines will carry more and new chemical mixtures as will new dedicated deepwater pipelines. Ports will experience new loads. The social system will experience new opportunities and costs, and the coastal wetlands will be impacted. Understanding these impacts requires more information about what industry will be doing in the future and less new information about the potentially impacted systems.

The common theme is that MMS must have better information on deepwater development and the environmental implications of these activities. With this in hand, more effective efforts can be designed to anticipate impacts in the new deepwater habitat and added impacts to the existing systems Studies of the deepwater habitats can be initiated by critically examining data currently archived prior to very expensive at-sea operations. Similarly, impacts upon onshore systems (environmental and socioeconomic) can proceed via information review and structuring of appropriate models.

3. Reports of the Working Groups

3.1 Socioeconomic Research Issues in Deepwater Oil and Gas Development

Co-Chairs: Harry Luton, MMS, and Charles Tolbert, LSU

3.1.1. Workshop Overview

More than 30 persons representing universities, state agencies, a local port authority, MMS staff, and present and past members of the Scientific Advisory Committee attended this workshop. Table 3.1.1 is a roster of presenters. The aim of the socioeconomic portion of the workshop was to identify information needs that—when filled—would improve assessment, prediction, and projection. This will provide a basis for better management information available in a timely manner.

During the first afternoon session, key issue areas were identified and breakout groups were formed. The groups worked throughout the second day until the late afternoon. Then the entire group was reconvened and terms of a summary report were discussed. Tolbert then developed a concluding report for a closing plenary on the following morning. Breakout groups were formed around three issue areas: industry, labor force, and infrastructure. Information needs for each issue area are outlined below. A detailed description of each group's work follows the discussion of socioeconomic challenges below.

Table 3.1.1. Roster of participants at the socioeconomic session.

Austin, Diane E.	Bureau of Anthropological Research	University of Arizona
Defenbaugh, Richard E.	Leasing and Environment	MMS
Endter-Wada, Joanna	Forest Resources	Utah State
Falgout, Ted	Greater Lafourche Port Commission	
Gramling, Bob	Sociology	USL
Greene, John	Leasing and Environment	MMS
Henry, Dan	Leasing and Environment	MMS
Landry, Connie	Leasing and Environment	MMS
Laurendine, Tommy	Field Operations	MMS
Leistritz, F. Larry	Agricultural Economics	North Dakota State U.
Luton, Harry	Leasing and Environment	MMS
Melancon, Archie	Environmental Assessment Branch	MMS
Murdock, Steve H.	Rural Sociology	Texas A&M
Ong, Michael E.	Field Operations	MMS
Richards, Carver		Phillips Petroleum
Seydlitz, Ruth	Sociology	UNO
Shah, Arvind	OSTS	MMS
Singelmann, Joachim	Rural Sociology	LSU
Tetley, Michele	Environmental Studies Branch	MMS
Thompson, Earl P.	Field Operations	MMS
Tolbert, Charles M.	Rural Sociology	LSU
Tootle, Deborah M.	Rural Sociology	LSU
Truxillo, Jon	Coastal Management Division	LA DNR
Zatarain, Vicki	Leasing and Environment	MMS

3.1.2. Framing Issues: Socioeconomic Challenges

There was a broad consensus among participants that we have entered a period of increased oil and gas industry activity on land and on the outer continental shelf. New technologies and price stability have sparked widespread, renewed interest in earlier discoveries and existing facilities. This has caused a skilled labor shortage, producing some historically low unemployment rates and tight labor markets in some areas. There may also be some resistance to reentering oil and gas work because of the large cohort of workers who experienced the last boom and bust episode in the GOM areas. These onshore and nearshore factors must be taken into account in any assessment of deepwater development activity.

Many in the socioeconomic workshop believed that a deepwater boom was also underway. At this time, the initial impacts appear to be concentrated in a few deep-port areas. One key feature of deepwater development appears to be an accelerated tempo of leasing, exploration, and production. In addition, there are important technological differences that will affect socioeconomic outcomes. These issues framed the work of the three breakout groups whose discussions are summarized in the next three sections.

3.1.3. Oil and Gas Industry Information Needs (Breakout Group I)

Breakout Group I addressed the key issue area of the industry. An industry survey is needed because data from currently available sources are not reported in appropriate levels of disaggregation to permit assessment or predictions with suitable levels of accuracy and timeliness. This information is particularly critical to addressing such issues as the direct effects of the industry on state and regional economies. Since these are driven by issues of industry employment and purchasing, an industrial labor survey would allow MMS to make more detailed and accurate projections and economic forecasts and to address issues of state and local benefits of deepwater development and/or exploration. This information is critical to addressing other issues, such as predicting future industry activities in deepwater and the socioeconomic consequences of these activities. Because this type of information is also useful to companies planning future business activities, the breakout group believes this research would be of considerable value to the industry.

3.1.3.1. Industry Survey The breakout group identified a number of information needs. This survey would collect data on individual players, such as what is produced and how it is produced. The survey would also collect information on the firm's material requirements and the sources of those materials. Information is also needed on how products are transported to market. Studies might also focus on industry behavior, such as alliances, joint ventures, and cooperative agreements. The firms would also be asked questions concerning the number of persons employed, training needs, and about their own training programs. Finally, this survey would gather information that would allow MMS to observe industry behavior from a historical perspective and to predict future behavior. Such information might include questions about the role of deepwater activities in overall business strategies, future outsourcing plans, unmet infrastructure and labor supply needs, and issues related to markets and transportation to markets. This information would be gathered in a survey of oil companies, construction firms, suppliers, vendors, and other support businesses.

The best way to gather these data is to develop a survey instrument, obtain OMB approval, test the instrument, and administer it on a regular schedule for tracking and monitoring purposes. Other approaches might include literature reviews, key informants, unstructured interviews, and work with trade associations. In developing this kind of information, MMS and the researchers would necessarily work in close cooperation with industry groups.

3.1.3.2. Industry Case Studies Another area of research discussed was industry case studies. Group I stated that industry case studies provide a typical and useful way to develop an understanding of how industries work and are changing. For example, major recent technological changes have led to deepwater oil activities, and these have had ramifications for engineering and labor usage. A case study that follows a deepwater project from conception through design, construction, and production would be extremely useful in understanding how the industry has changed with the advent of deepwater technology. The stages studied might include geology/geophysical data, lease purchase, exploration, economic evaluation, development of exploration plan, design team, fabrication team, installation team, connects to infrastructure (pipelines), maintenance/ production, offshore crews (helicopters, suppliers), inspection, logistics, and finally, removal/site clearance, all of which are critical to understanding where onshore effects are likely and for projecting the duration of onshore effects. The group also indicated case studies would be highly useful in regard to ports in both South Louisiana and across the Gulf of Mexico. Some ports become the locus of many onshore activities and effects due to the program and others do not. Information for a port study includes capacity, infrastructure problems, deepwater capacity, current and future deepwater impacts, diversity and expansion of ports, and community/regional impacts. Case studies of other industries would also provide important information for the assessment and regulation of the deepwater program. For example, the Louisiana Offshore Oil Port (LOOP) is currently important in the importing of foreign oil. It may, however, play an increasingly important role in moving oil from deepwater to market. For this reason, a study that looks at the capacity, maintenance, regulatory regime, and ability to handle deepwater production may be useful in developing future scenarios.

Another, less obvious example discussed by Group I was the shrimping industry. The decline of the Louisiana shrimping industry has been blamed on space conflicts and labor demands of offshore oil development, yet no study of this assertion has been conducted to prove whether this is true or false. Case studies of manufacturing industries and vendors would also be useful. Other issues discussed under the case study topic included waterways and pipelines (see Group Infrastructure II for elaboration).

3.1.3.3. Uncertainty Framing the entire discussion of oil and gas industry information needs are such uncertainty factors as (a) the price of oil, both current and future; (b) the development of new technologies; (c) the demands of relationship between traditional ways of doing business and the demands of deepwater exploration and extraction; and, (d) resources needed for profitable industry involvement in deepwater. Economic forecasts, time-series analyses, and company-directed policy research all might provide better insight into these critical but inherently uncertain issues.

3.1.4. Infrastructure Information Needs (Breakout Group II)

A second breakout group focused on the need for information about the effects of deepwater development on local infrastructure. At the community level, research should inventory effects on roads, water, waste disposal, public education, medical and health facilities, public safety, port facilities, and recreation. Similarly, research is needed on available facilities for supporting oil and gas development (e.g., shipyards, pipeyards, and terminals), and on local material and personnel requirements as they relate to deepwater development.

3.1.4.1. Capacity Analysis A key concern for Group II was the capacity of communities to handle rapid developments associated with deepwater activities. Deepwater impacts will be less diffuse than "routine" shelf activity/impacts. Moreover, deepwater impacts will occur faster than "routine" shelf activities. Studies should begin as soon as possible before communities are greatly impacted. This would allow MMS to identify stresses from a normal baseline in order to support informed planning (at state, local, and federal levels), monitoring, and mitigation actions. From the management perspective of MMS and from the perspective of the industry, it is important to be able to identify suitable port locations with existing capacity and the flexibility for expansion.

One major research issue is the definition of communities. While some social scientific work avoids this definitional issue, an effective community capacity analysis must define appropriate units of analysis. There is an advantage to have analysis units that make sense to communities involved, rather than be driven by Census data or similarly arbitrary sub-units, such as tax districts, municipalities, levee districts, high school districts, and port commissions. To define communities, Group II suggested a combination of surveys, ethnographies, and interviews with government officials. Among the issues to be resolved is the suitability of alternative spatial definitions of communities (e.g., Census places, tax districts, municipalities, levee districts, high school districts, and port commissions).

A second major research concern is gauging existing capacity and the flexibility of the community in responding to change. The methodology suggested is a community organization study that focuses on the local decision-making process.

A third research concern under this general topic is the scope of deepwater impact on community capacity. Research needs to address the numbers of impacted communities, the degree to which communities are impacted, aspects of impact, demands on communities and gaps between capacity and demands. Suggested methodological objectives include identifying ports with deep enough drafts for direct service to deepwater, facilities capable of constructing deepwater platforms and related structures, and business networks for construction and operation. The group also recommended that parish/county profiles available annually from the Louisiana Department of Economic Development be utilized. A survey was suggested that would include interviews with port commissioners, local/municipal planners, school superintendents, water boards, and medical administrators. It is also important to identify where these entities do not exist.

3.1.4.2. Study of Regional and Community Infrastructure To enable MMS and communities to prioritize needs and to plan for mitigation, there is a need for studies of regional and community infrastructures. Still, mitigation can occur only if problems are identified. Some issues are fundamental. For example, human safety could be at risk in the event f a hurricane evacuation if adequate egress routes are not available. Other issues include conflicts over infrastructure which will occur as demand rises. Changes will come quickly and communities must identify which infrastructure changes are needed and sustainable. Over the longer haul, it is important to identify the long term consequences of buildup of community infrastructure as well as to identify the long term consequences of buildup of oil and gas infrastructure.

Group II viewed such studies as important at two levels: regional and local. Important information needs at the regional level include the location of onshore deepwater activities disaggregated by location, race, ethnicity, gender and income levels. Definition of regional and community infrastructure requires information on roads, water, waste disposal, public education, higher education, medical/health, police/fire, local government, port facilities, civic centers, recreation facilities, libraries, and public social services. Information on oil and gas infrastructure information would include shipyards, pipeyards, terminals (these data may be available through the industry study outlined above). Regional information needs also include identifying material and personnel requirements of deepwater activity, such as drilling, production platforms, and service. This is important because labor requirements are likely to change as deepwater exploration shifts to production. The methodology for the regional infrastructure study includes historic baseline studies. Also recommended is a modeling effort to assess and project impacts on ports and other infrastructure that service deepwater oil and gas activity. The models can be based on data that are being collected (i.e., U.S. Customs provides weight for foreign cargo) and will provide some sense of the geographic scope of impacts.

Information needs for the local infrastructure studies parallel those recommended for the regional studies. Basic information on deepwater impacts needs to be disaggregated by location, race, ethnicity, gender, and income levels. Also needed are definitions of existing uses of infrastructure (e.g., use of roads, use of educational facilities). Research also needs to identify use conflicts and existing mechanisms to respond to them (e.g., hurricane evacuation routes for which plans and timing may be affected by oil and gas equipment and personnel on the road). Another example of adaptation is school curricula supportive of educational needs of workers nearshore and in deepwater. A fuller understanding requires the identification of infrastructure that is used to support deepwater activity and the entity responsible for that infrastructure. Suggested methodologies include surveys and interviews of port commissioners, local/municipal planners, school superintendents, water boards, medical administrators, higher education officials and industry representatives. Like the regional infrastructure studies, local studies can also be informed by historic baseline studies.

3.1.4.3. Planning for Good Times and Bad Group II also developed a set of information needs that could be used to assist communities facing expansions of deepwater activities. No GOM coastal communities have experienced a subsequent boom episode after the boom and bust of the 1980s. Thus, communities will need assistance in planning for the mitigation of impacts associated with the latest round of increased oil and gas industry activities. Data needs include projection of demand (intensity and longevity), trends in the oil industry, relevant decision-making processes at municipality, parish/county, and state levels, case studies of successful planning efforts, understanding the "boom/bust shadow" along different dimensions (banking business, oil and gas industry, contractors, service industries, individual workers), and opportunities/ability for communities to diversify their economies. Also needed are data on social disruption, such as crime rates, delinquency rates, suicide/homicide, substance abuse, mental health, and domestic abuse. Recommended methodologies include surveys or interviews with port commissioners, local/municipal planners, school superintendents, water boards, medical administrators, subject matter experts, and political entities, as well as industry (companies, drilling contractors). Quite useful would be a case study of successful planning based on results of survey/interview with planners.

3.1.4.4. Cultural Conflict The MMS, the industry, and impacted communities should recognize the inevitable cultural conflicts between various interest groups associated with deepwater development. The immigration response to deepwater development has been very strong. Communities presently lack bilingual (especially Spanish/English) capacities in business, government, and schools. Within certain indirectly related industries, potential conflicts among workers of different cultures possible. Deepwater activities can also affect traditional use areas. And, deepwater development affects income structure and may price individuals out of certain residential areas or recreational uses. It may also influence availability of workers to other industries.

One research issue is the current status of various cultural/ethnic groups at the regional and local levels. This involves a delineation of traditional cultural groups (i.e., Cajuns, Dalmatian Coast Yugoslavs), determining any newcomers (i.e., Mexican workers), and projecting ethnic compositions for the future. The ability of communities to respond to local and regional levels should also be assessed. Recommended methodologies are use of Census data, community ethnographies, and surveys or interviews with social service providers, educators, and others. Among the important issues to be resolved are the differential impacts of cultural conflict issues on public service needs and capabilities and how cultural conflict issues relate to stages of development.

Another research issue related to cultural conflict involves the analysis of traditional occupations by culture group (i.e., fishermen, oil), present occupations by culture group (related to stage of development), and future occupations by culture group (also related to stage of development). Methodologies might include use of Census data, community ethnographies, and surveys or interviews with social service providers, educators, and others in related professions.

Another research issue under the topic of cultural conflict is attachment to place. A better understanding is needed of how oil and gas development is affecting migration and levels of transient workers. Since conflict often occurs between locals and transients, this is also an important source of cultural conflict. Suggested methodologies are the same as those for other research issues under this topic.

3.1.4.5. Income Inequality and Public Assistance Coverage It is often necessary in socioeconomic impact research to rely on indirect measures of impact. Income inequality and public assistance coverage, however, are direct, concrete measures of community stress. Since deepwater poses potentially greater problems in this area than others due to geographic concentration, high capital needed, and differential skills required, Group II recommended that income inequality and public assistance be studied. Information needs include standard income inequality analyses. In addition, information is needed on local public assistance infrastructures. Existing resources—local and regional—should be inventoried. Clientele should be identified (past, present, future users; see cultural conflict) as should sources of funding (private, public: local, state, and federal dollars). Topics also include the capacity of public assistance agencies and facilities, whether deepwater poses new or different problems for public assistance resources (e.g., concentration of wealth), whether different phases of exploration/development place differential stresses on public assistance, and environmental justice issues (see infrastructure, cultural conflict above). Recommended methodologies include literature surveys, use of Census data, surveys and interviews with public and private service providers, and case studies in specific impacted communities.

3.1.4.6. Voluntary Organizations One key form of existing social capital in a community is its voluntary organizations. These groups can serve as vehicles for conflict resolution or as potential sources of tremendous community conflict. Community-level research is needed to identify past, present and future local organizations. The analysis should include churches and nonprofit public assistance agencies (see income and public assistance above). The scope of the study should be large enough to encompass political, social, civic, and public interest organizations. The analysis should consider potential changes to and impacts on these organizations from deepwater activity. Lastly, such a study should identify informal coalitions that may serve the same functions as formal voluntary organizations. Recommended methodologies include surveys or interviews with key informants and community network analysis.

3.1.4.7. Sustainable Economic Development Group II's final research topic was sustainable economic development. There is a broad consensus among social scientists that sustainable, diversified local economies offer the brightest long-term prospects for communities. Through sustainable development, communities are able to buffer themselves from externalities such as declines or busts in industrial activity. This permits communities to maintain long-term involvement in oil and gas development. To research this issue, researchers would first define the economic structure of the region and community. This includes an inventory of non-oil and gas businesses. Also, the existence of a barter/subsistence economy would be considered. Other topics include the interaction among other economic activities (i.e., fishing, tourism) and oil and gas industries, opportunities for other industries to community development (e.g, shift port to handle produce or some other import or export), barriers to development of other industries, and community participation in alternate economic activities (i.e., lower pay). The recommended methodologies are case studies that are regional and extra regional (examples of communities that shifted from single industry dependent to diversified economies (Cook Inlet, Shetland Islands). Use of data from the Bureau of Economic Analysis is also suggested along with the development of regional histories and baseline studies.

3.1.5. Labor Force and Human Factors (Breakout Group III)

Breakout Group III addressed the key issue area of the labor force and human factors. The general topics of discussion included information needs relative to employers, workers, households, families, and communities. Topics included job searches, employer recruitment and retention strategies, migration, commuting, social disorganization (crime, delinquency, etc.), community organization and leadership, and labor supply issues. Five basic areas of information needs were identified by Group III. They are (1) understanding the characteristics of OCS-related work force and jobs (highest priority); (2) effects of OCS-related activities on households and workers; (3) OCS dependency and community integration; (4) community organizational capacity and OCS development; and, (5) work force availability (labor supply issues). These five areas are discussed in the following sections.

3.1.5.1. Offshore Labor Force and Jobs In this new period of increased oil and gas industry activity in the Gulf, there is considerable concern about matching qualified workers with employers. Several in Group III noted anecdotal accounts of labor shortages along coastal Louisiana. There is a potential for a breakdown in labor market efficiencies as firms attempt to recruit and retain workers. These factors point to a need for a more thorough understanding of the characteristics of the OCS-related work force and OCS-related job positions. Such a major study would provide basic data for environmental impact statements. Among the important issues is the relative concentration or dispersion of oil and gas industry employment among coastal communities. A better understanding of the offshore labor force and offshore job structures would be key data for assessing the distribution of benefits and costs across households, communities, and the region, one goal of the EIS process under NEPA.

Group III advocated surveying both workers and employers. The two-survey approach has proven very useful in other social scientific studies because the perspectives of workers and employers can be quite different. It is especially important that the surveys not be limited to cross-sectional research designs. Longitudinal data (especially panel designs) would permit ongoing monitoring as deepwater development accelerates. The group also advocated direct, face-to-face survey techniques, although other approaches, such as telephone or mailed surveys might prove useful. This type of research would require OMB approval of the survey instruments.

Data to be collected include number and location of workers (crucial to developing an adequate sampling frame), work histories (generational and personal), demographic characteristics of workers and families, residential and migration history, recruitment (training/retraining, job search strategies, skill requirements), exit from industry (reasons), and perceptions/assessment of work environment and scheduling. Key issues remaining to be resolved include obtaining a complete sampling frame (sufficient resources need to be allocated for this component), boundaries of the sample (geographical, affiliated industries), and distinguishing workers directly attributable to offshore activities (in general accounting).

3.1.5.2. Worker Households and Effects of Offshore Activities Another focus of Group III was on the impact of offshore oil and gas industry activities on the households and families of offshore workers. There is little available data on the location, magnitude, and characteristics of impacts on households. Yet, anecdotal evidence suggests that some households adapt quite well to the demands and scheduling of offshore work while other households do not. Simply put, household conditions affect the employment stability of workers. A household perspective on the consequences of offshore work scheduling is critical to an industry that has problems with labor force recruitment and retention. Moreover, understanding how households respond to the fluctuations of industry activity is key to understanding how communities (composed of households) adapt to the ups and downs of the industry. Studies of households are also critical to understanding the distribution of costs and benefits across places and across various population subgroups.

Once preliminary findings are in hand, survey methodology should be used to collect data on households and families. A sampling frame could be obtained from the worker/employer surveys households discussed above. Households should include persons employed directly and indirectly in oil and gas industries, suppliers, vendors, and/or other contractors. The research design should also take into account the variations in predictability/stability of employment that depend on direct or indirect household involvement.

Information needs at the household level include residential migration/commuting history and decisions/reasons for migration/commuting, effects of OCS work schedules on households, relationships between workers and other household members, household division of labor and decision-making, effects of OCS employment on job strategies of other household members (spouse, children), household networks and support systems (informal, familial, voluntary associations), household access to and utilization of community services, household integration into their communities, and purchasing patterns (economic multipliers and spatial distribution).

Issues remaining to be resolved include sample complexity and how best to capture the full range of effects on households.

3.1.5.3. Community Organizational Capacity and Deepwater Development To maximize community benefits and minimize undesirable consequences, it is important to identify strategies that communities can use to successfully manage offshore (especially deepwater) development impacts. Group III recommended the study of community organizational capacity through comparative case studies with extensive use of ethnographic methods. Special attention should be given to the criteria for selecting communities. One criterion might be the local history of managing oil and gas industry-related impacts in comparison to other types of development.

Consideration should be given to OCS/non-OCS developments and to GOM and other OCS places. Key information needs include local leadership structure, organizational bases, communication and other strategies for addressing community needs, economic development and planning capacity (beneficiaries might include local businesses, new businesses, local residents, immigrants, temporary workers), community access to information, assessment of human capital and resources, community connection with regional/state planning efforts, local ability to assess and monitor risks to local populations, capacity to negotiate operating procedures, and ability to exercise oversight though local zoning/other ordinances.

3.1.5.4. Work Force Availability Group III also discussed the tightness of national and regional labor markets. The situation could inhibit offshore employers from adequately staffing their operations. It is very important to understand the labor force limitations on industry expansion, the strategies employed by industry to overcome these limitation, and the effectiveness of these strategies. It is also important to assess the effects of deepwater expansion on other sectors of the regional economy. In doing so, researchers can be more accurate in their forecasts of labor force migration to the area and effects on local communities. Methods most suitable to this topic include assessment of current labor availability from secondary sources (state employment services) coupled with projections of future supply (labor being trained and entering workforce). Key information needs are size and skills of the pool of available labor as industry expands into deepwater, location of workforce (local vs. imported), displacement effect (being bid away from other sectors of the local/regional economy), and whether the existing OCS workforce is being expanded or being transferred from near shore to deepwater activities. Issues to be resolved include identifying labor mobility (geographic, skill transference) and coordinating with the companion industry survey to identify workforce needs.

3.1.6. Related Information Needs

Associated with these three key issue areas are a number of other information needs. These include enhanced projections and modeling procedures, elements of successful community planning, case study of deepwater projects, racial/ethnic diversity and culture conflict, new or different problems for public assistance, environmental justice, and dispersion of impacts and benefits across communities, states, and regions.

3.1.7. Suggested Action Plan

There was a broad consensus among those present that efforts to obtain industry and labor force information should begin immediately. In the process of fulfilling these information needs, researchers would necessarily collect data on infrastructure and community capacity. Such large-scale industry and labor force analyses are beyond the scope of CMI-type funding and should be solicited directly by MMS. Timing is critical; despite the recent upswing in industry activity, an opportunity exists to establish an early baseline of industry and labor force data. Most previous socioeconomic studies in the GOM region have necessarily been *post facto*. A timely addressing of these issues would enhance the caliber of GOM socioeconomic research.

3.2. The Physical Oceanography Group
Co-Chairs: Stephen P. Murray, LSU; Alexis Lugo-Fernandez, MMS

3.2.1. Background

In the last decade the oil and gas industry in the Gulf of Mexico has rapidly moved its operating area from depths of hundreds of meters on the continental shelf to the continental slope and continental rise where depths are in excess of 3000 m. Exploration and drilling there has far outrun our knowledge base of strength and variability of circulation and mixing processes that form the dynamic climatology of these deep water environments.

Accordingly, the goals of our section were (1) to develop a spirited discussion identifying the importance of physical oceanographic processes relevant to operating in the deep water of the U.S. central and western continental slopes in the Gulf of Mexico; (2) to review the state of knowledge and information available on these processes from all possible sources; (3) to identify and prioritize needs and data gaps; and (4) to outline experimental designs to fill in these gaps.

3.2.1.1. Focus Area We defined our area of interest as seaward of the 200 m isobath downslope to the EEZ line with Mexico (south 26° S) where depths are ~2500-3000 m. We restricted the domain of our interest to west of 89° W because of the ongoing study in the DeSoto canyon area. In order to facilitate and maintain discussion we chose a format of a mix of invited theme speakers (Table 3.2.1) interspersed with formal or informal comments and presentations from all participants in the audience. This approach appeared to work very well as active discussion continued unabated until the very end of our session.

Table 3.2.1. Roster of presenters at the physical oceanography session.

Presenter	Affiliation	Tittle
Hamilton, Peter	SAIC	"Gulf of Mexico Eddy Circulations"
Inoue, Masamichi	Louisiana State University	"Modeling Deepwater in the Gulf of Mexico"
Leben, Robert	University of Colorado	"Overview of Satellite Altimetry in the Gulf of Mexico"
Nowlin, Worth	Texas A&M	"Physical Oceanography of the Gulf of Mexico; an Overview"
Schaudt, Kent	Marathon Oil	"Industry Knowledge of Gulf of Mexico Eddies and Other Problems
Shay, Thomas J.	University of North Carolina	"Gulf Stream Rings and their Impact on the New England Slope"
Smith, Robert L.	Oregon State University	"Experience on the West Coast Slope"
Weatherly, Georges	Florida State University	"On Some Peculiarities of Bottom Boundary Layers on the Continental Slope"
Vogel, Michael	Shell Oil	"Industry Knowledge of Deepwater and Physical Oceanography/Current Data"

Appendix 3 consists of brief written contributions from (a) Dr. Worth Nowlin, providing an overview of important processes in the GOM; (b) Dr. Peter Hamilton, describing both the major Loop Current Eddies and the energetic field of smaller cyclonic and anticyclonic eddies (40-150 km) that appear ubiquitous on the northern slope region; (c) Dr. Robert Leben, describing recent results of satellite altimetry studies of GOM eddies; (d) Dr. Georges Weatherly on peculiarities to be expected in the bottom boundary layer on the continental slope; and (e) Drs. Masamichi Inoue and Susan Welch, providing a status report on numerical modeling in the GOM.

3.2.1.2. Industry Concerns The industry's list of processes important to operations included:

- eddy current variability (spatial/temporal gustiness)
- GOM cyclonic eddies, cold core eddies
- deep currents (below ~1000 meters)
- topographically influenced bottom currents, shelf/slope canyons, and effects of rough topography
- continue advancements in 3D numerical current modeling, and hindcasting/forecasting of Loop Current eddies
- real-time deepwater current profile measurements
- effects of super cloud clusters, squall lines and marine boundary layer regarding surface operations.

3.2.2. Consensus of Opinion

The dominant theme of these extensive discussions was that a broad consensus of opinion has emerged that this continental slope is populated by a complex melange of cyclonic and anticyclonic eddies of varying time and length scales. The 25 or more slope surveys from the LATEX-C and GULFCET programs appear to have established the horizontal eddy space scales reasonably well. However, their temporal and vertical scales are not established as well as the horizontal ones.

3.2.2.1. SYNOP Results The absence of data on the time scales and the necessity of a consistent mapping of the temporal variability of the eddy field on monthly-seasonal-interannual time scales require deployment of an extensive mooring array in key regions on the slope. It was clear from the presentation by Dr. Tom Shay on the results from the Synoptic Ocean Prediction (SYNOP) array in the Gulf Stream that the SYNOP central array has the scope and resolving capability that is required to decipher the complexities of the slope eddy field. Figure 1 (from Johns et al., 1995) shows the 25-30 member array, which consists of ADCP and conventional current meters and inverter echo sounders (IES). The center of gravity of a similar GOM slope array would, of course, be higher up the slope.

Suggestions were put forward by various participants that the array should be extremely flexible, perhaps able to relocate on short notice based on the evolving eddy field. Another prevalent point of view was that the array could and should be designed to resolve expected space scales of an eddy field without much adjustment. A fixed array has the advantage of consistent mapping and the generation of long time series at given locations, as evidenced by the notable success of the SYNOP fixed array. It was suggested that a few moorings be held in reserve that might be deployed to increase resolution of a specific feature found in an AXBT survey.

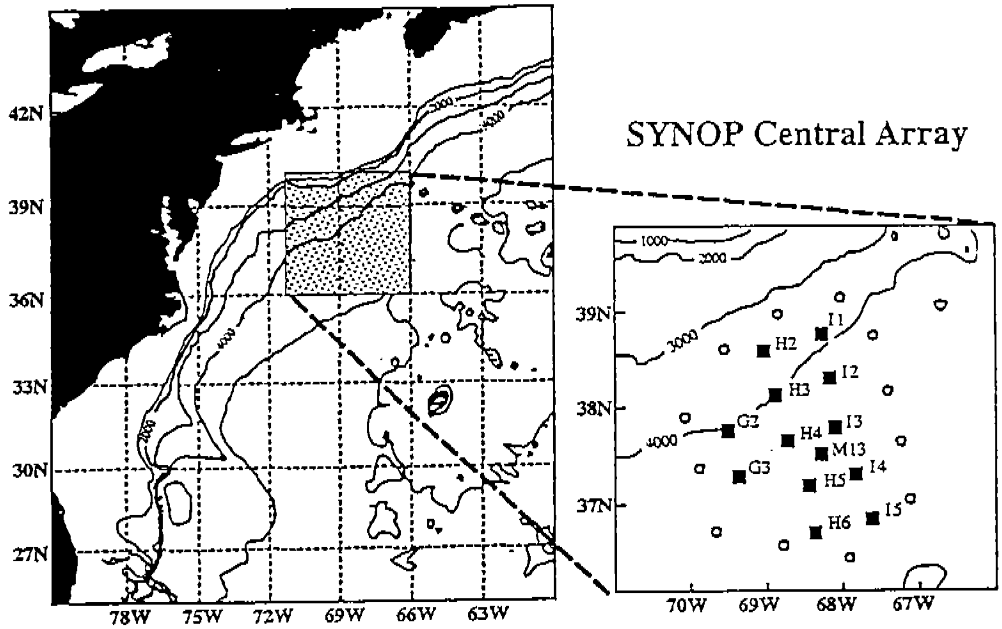

Figure 1. Location of the Synoptic Ocean Prediction (SYNOP) central array showing the array configuration (inset). The labeled sites (solid squares) indicate the location of current meter moorings and inverted echo sounders (IES); open circles are additional IES sites deployed around the perimeter of the currnt meter array. (From Johns et al., 1995).

3.2.2.2. Pilot Mooring Program Another idea put forward in the discussions was the advisability of a pilot mooring program. In addition to the added cost and shortening of the time that the main array would be in the water, there was pervasive opinion that the art of experimental array design was sufficiently advanced to preclude the necessity of a pilot mooring program. Post session written comments suggested employing mathematical or statistical anlyses to evaluate the resolving and detecting power of the mooring arrays.

3.2.2.3. Real Time Data Similarly, real time data transmission had its proponents and critics with the burden remaining on the proponents to show a compelling need for continuous mapping in real time sufficient to justify the increase in complexity, data loss risk, and diversion of assets to this end.

3.2.2.4. Suggested Sites The group concluded that two dynamically distinct sites should be investigated:

(a) the central GOM slope off western Louisiana, which is impacted by smaller scale cyclones and anticyclones that have arisen, presumably, from interactions with the slope of the much larger anticyclonic eddies shed by the Loop Current; and,
(b) the western GOM slope off south Texas, the "eddy graveyard" region where decay of Loop Current eddies leads to the generation of intensive cyclone-anticyclone pairs, referred to as modons. Extensive use of moored ADCPs, conventional current meters, IES (inverted echo sounder), temperature chains,

aerial XBT surveys, pressure gauges, and drifter deployments should be combined with ship-board hydrographic and ADCP surveys.

Simultaneous studies by satellite remote sensors of sea surface temperature, altimetry, and ocean are required.

3.2.2.5. Inverted Echo Sounder Array Another widely supported suggestion was that monitoring of the Loop current eddies as they pass south of the slope array is important. An inverted echo sounder (IES) array in depths of over ~2000 m would accomplish this purpose and allow the effects of the passage of LCEs on the slope eddy field to be documented.

3.2.2.6. Small-scale Studies The group, especially industry representation, strongly felt that embedded in the larger observational study must be smaller-scale studies aimed at characterizing the variability of the flow field in the numerous relatively narrow canyons that cut into the slope edge. These dynamically narrow canyons (with respect to the internal Rossby radius) will likely differ markedly from the dynamically wide DeSoto Canyon currently under investigation by MMS. Measurement of the thermal and dynamical properties of the slope bottom boundary layer are of extreme concern to benthic ecology/biology as the site of most direct impact of industry activity on the slope environment.

Thus, such a proposed study would successfully address critical processes such as (a) interaction of LCE with slope; (b) evolution and development of cyclones; (c) evolution and development of smaller anticyclones; (d) effects of energetic atmospheric events; (e) high frequency current questions; and (f) bottom currents.

In addition to the scientific understanding of the slope environment some more practical uses of these measurements include (a) evaluation of structural designs; (b) effects on drilling; (c) movement of drilling effluent; (d) effects on bottom fauna and sediment movements and geohazards; (e) oil/toxic spill response and remediation; and (f) model development/validation.

3.2.2.7. Historical Data Synthesis It was strongly recommended that the major observational study be preceded by an historical data synthesis. It was felt that a considerable body of data/information resides in MMS, university, and industry archives and reports that remain in an unsynthesized form. This historical data base on slope observations (e.g., current meters, drifters, CTD, XBT, IES) as well as numerical models outputs should be inventoried, compiled (on CD), and synthesized in a summary report.

3.2.2.8. Modeling The modeling community present recommended the development of a dynamical model/data synthesis system for interpretation of available data to identify important processes in the Gulf of Mexico. The use of a numerical model was proposed to hindcast the general circulation and to produce a synoptic climatology consistent with available remote sensing and field observations. The time period for the climatology would correspond to the period of intensive observations by MMS, which would facilitate skill assessment. An accurate climatology would provide useful geophysical information.

The incorporation of the most detailed up-to-date bathymetry recently compiled by the geology community (Bill Bryant, TAMU) is an absolute requirement.

3.2.3. Recommended Plan of Action

1. An historical data study should be initiated to inventory, compile on CD, and synthesize the data on the slope from all sources, e.g. industry, MMS, government laboratories, university and private companies.

2. A dynamical model/data synthesis system should be developed for interpretation of available data to identify important processes on the slope. This is, in essence, a numerical model capable of assimilating the satellite altimetry and other remote sensing and field observations. This will be used for a diagnostic tool to understand historical data sets and act as a guide for future intensive observations on the slope.

3. The third component of the proposed plan is an intensive observation plan to determine the characteristics of motions on the Louisiana-Texas slope. Two dynamically distinct sites should be investigated: (a) the central GOM slope off western Louisiana, which is impacted by smaller scale cyclones and anticyclones that have arisen, presumably, from interactions with the slope of the much larger anticyclonic eddies shed by the Loop Current, and (2) the western GOM slope off south Texas, the "eddy graveyard" region where decay of Loop Current eddies leads to generation of intensive cyclone-anticyclone pairs, referred to as modons. Extensive use of moored ADCPs, conventional current meters, IES, temperature chains, aerial XBT surveys, pressure gauges, and drifter deployments should be combined with ship-board hydrographic and ADCP surveys.

Embedded in this observation program must be smaller scale studies aimed at characterizing the flow fields associated with the rough topography (e.g., the ubiquitous narrow canyons that cut the outer slope) and measurements aimed at the thermal and dynamical properties of the bottom boundary layer, which is of extreme concern to benthic ecology/biology. While not directly discussed in the session, it is acknowledge that strong weather systems can affect the current regimes and oil and gas operations in deepwaters and should be addressed by modeling and field efforts.

3.3. Geology and Geohazards Subgroup
Chair: Dr. Harry H. Roberts, LSU

3.3.1. Geohazards Focus

The Geohazards Subgroup acknowledge that the northern-to-western Gulf of Mexico continental slope is perhaps the most complex continental slope environment in today's ocean. It is also the most active deepwater frontier for oil and gas production in the world and the production frontier is moving deeper at an alarming pace. Therefore, both operational and regulatory groups are presented with formidable challenges as hydrocarbon exploration and production proceeds in this little studied deepwater setting. Characteristics of the slope surface that present difficulties in both a geohazards and regulatory context are (a) steep local slopes; (b) variable sediment types; (c) complex faulting; (d) a variety of types of mass movement; (e) areas of lithified sea floor and mounded carbonates; (f) gas hydrates at or near the sea floor; (g) mudflows and mud volcanoes; and, (h) protected benthic communities (chemosynthetic communities) associated with a spectrum of hydrocarbon venting and seepage area. Within this complex matrix of surficial geologic features and conditions characterizing the deepwater slope environment, the Geohazards Subgroup tried to prioritize the subject areas for future MMS research support on the basis of (a) state of present knowledge and (b) risk to man's operations. Table 3.3.1. is a list of experts who participated in this workshop subgroup.

Table 3.3.1. Roster of expert participants in the geology and geohazards session.

Alan Balla	BHP Petroleum	Houston, Texas
Arnold Bouma	LSU Geology & Geophysics	Baton Rouge, Louisiana
William Bryant	Oceanography, Texas A&M	College Station, Texas
Kerry J. Campbell	Fugro-McClelland Marine Geoscience	Houston, Texas
James Coleman	LSU Office of the Chancellor	Baton Rouge, Louisiana
Doug J. Cook	BHP Petroleum	Houston, Texas
Wayne Dunlap	Offshore Technical Research	College Station, Texas
Andrew H. Hill	BP Exploration	Houston, Texas
Arlette Nunez	Shell Deepwater Development, Inc.	New Orleans, Louisiana
Charles E. Stilting	Chevron USA	New Orleans, Louisiana

3.3.2. Surficial Processes and Features

Under the general heading of "Surficial Processes and Features," the group identified three subject areas that present considerable risk to man's operations on the northern Gulf of Mexico continental slope. The categories of geohazards subject areas that pose the greatest risks were identified as (a) mass movement processes and resultant sediment transport and deformation features; (b) gas hydrates (both exposed and buried deposits); and, (c) sediment types and associated geotechnical characteristics.

3.3.3. Geologic Framework

In order to understand the geologic framework and stratigraphic architecture of the northern Gulf continental slope and resulting geohazards, an appreciation of the intraslope sedimentary basins is essential. Seismic profiles and well data (various types of well logs and associated micropaleontological data) provide the main elements for evaluating the evolving depositional environments, sedimentary facies, and salt characteristics. Bathymetric charts of the continental slope of the northwestern Gulf of Mexico alone

(Bryant et al. 1990) reveal the presence of over 105 intraslope basins with relief in excess of 150 m, 28 mounds, and 5 major and 3 minor submarine canyons. These basins occupy much of the area of the continental slope. Intraslope-interlobal and intraslope-supralobal basins occupy the upper (100 m to 2000 m) and lower (2000 m to 3200 m) continental slope, respectively. Intraslope-interlobal basins are formed by the coalescing of salt canopies and the supralobal basins by downbuilding into a salt nappe. These basins are sediment depocenters. The very upper continental slope areas have fewer basins and contain, in general, lower angled slopes. The structure of the uppermost slope area is less affected by the action of salt, except on a local scale, and influenced mostly by the seaward progradation of low sea-level Pleistocene deltas. The lower continental slope contains eight submarine canyons and a large escarpment, each feature evolving from, in part, the coalescing and migration of salt canopies, an unusual process for the formation of submarine canyons. Even though the salt-influenced basins and canyons in the Gulf of Mexico are considered unique, a number of passive continental margins of the world have similar features, such as the Nigerian margin where shale diapirs are common.

Some authors have produced sequential structural restorations for parts of the slope from available geophysical and well data sets (Worrall and Snelson 1989; Diegel et al. 1995; Peel et al. 1995; Rowan 1995; and McBride 1995). Such reconstructions help explain the evolution of salt structures coincident with input of sedimentation, especially at periods of lowered sea level. This new understanding of the dynamic changes that have taken place through time to give us the present slope configuration is possible because of improved seismic imaging technology (Ratcliff 1993), better physical modeling of salt-sediment systems (Vendeville and Jackson 1992), and the application of sequential restorations (McBride 1996). This new generation of work on the slope has shown that tabular allochthonous salt sheets and nappes are not new to the slope but have occurred previously and have undergone various stages of deformation and evacuation (Diegel and Cook 1990). The emplacement and eventual evacuation of allochthonous salt appears to vary spatially and temporally throughout the northern Gulf of Mexico basin. No single model for salt movement can explain the array of salt geometries presently imaged in the subsurface. However, it is clear that original salt geometries and the manner in which they interact dictate the positions of later minibasins, remnant salt diapirs, extensional growth faults, contractional structures, and strike-slip deformation (McBride 1996). In addition, it is clear that this framework provided by salt deformation and sediment loading is the template for understanding the complexities of the modern sea floor, including the variety of features and processes considered as geohazards.

3.3.3.1. Mass Movement Geologists and engineers have recognized the significance of slope instabilities as the economic significance of submarine environments has increased through the 1970s, 1980s, and now the 1990s. Lateral movement of sediments can be highly detrimental to pipelines, well heads, and platforms. Slope instability and mass movement have been recognized in a variety of offshore settings from shallow delta front instabilities (Prior and Coleman 1978), through massive shelf edge failures, (Coleman et al. 1986), to a variety of failure features on the continental slope (Doyle et al. 1992). Offshore surveys indicate that some of these features can occur on extremely low angle slopes (< 1°) where sediment strengths are very low and pore water and even pore gas pressures can be very high. In contrast, other areas with higher sediment strengths require much higher angle slopes to induce sediment failure. These conditions, however, are frequently met on the northern Gulf of Mexico continental slope where slopes are greatly steepened by faulting and salt diapirism.

Rapid deposition of sediment at the shelf edge faulting, and vertical migration of shallow salt create instabilities primarily by over steepening of slopes. A wide range of failure features results, from massive shelf edge evacuation features (Winker and Edwards

1983) to small-scale slumps creep along fault faces and on the side of diapirs. Depending on scale, massive volumes of sediment can be transported down slope in association with subaqueous mass movement processes (Coleman et al. 1986). These processes currently pose a considerable risk to man's activities on the northern Gulf's continental slope. Even thin deposits of hemipelagic highstand sediments that drape the topography of the slope display a tendency to fail (Doyle et al. 1992). Sediments displaced by slumps, submarine landslides, and other mass movement processes tend to have chaotic-to-acoustically opaque internal reflectors on high resolution seismic data and commonly produce small-scale irregular surface topography. Some intraslope basins contain fill-sequences of repeated and stacked chaotic units that are interpreted as the products of massive failures. These deposits likely originated at or near the shelf edge during periods of lowered sea level and failed during the loading process. The rugged surfaces of these deposits and chaotic internal reflectors mimic similar slumped units currently found at the sea floor in many places on the present continental slope.

The significance of slope instability processes has until recently been underestimated as a geologic sediment transport mechanism. However, with the development of better acoustic survey methods and increased data acquisition, it has become apparent that submarine slope instabilities are the dominant shallow-to-deep sediment transport mechanism and resulting sedimentary units account for a large part of the deepwater sedimentary column. Sea floor creep, slumps, and slides occur on many spatial and temporal scales.

At present the predictability of sediment failures is not sufficient to account for the spectrum of mass movement features that occur throughout the slope province. Although these gravity-driven processes depend on the geotechnical characteristics of slope sediments, slope gradient, and other conditions related to initiating processes such as fault movement, it is difficult to predict the timing, rates of movement, and return intervals for mass movement processes. More research attention and support needs to be focused on the processes and response features collectively grouped under the mass movement category. These mechanisms can have a negative impact on man's operations and structures in deepwater.

3.3.3.2. Gas Hydrates In the last decade, the science and applied science communities have recognized the global significance of naturally occurring gas hydrate deposits in deep water settings. Gas hydrates are solids composed of small gas molecules, usually methane crystal enclosed in a lattice of water molecules. These substances are termed clathrates, gas hydrates, and methane hydrates in the scientific literature, but the term "gas hydrate" is most used in the geosciences (Kvenvolden 1993). Such frozen mixtures of hydrocarbon gases and water occur under special conditions of temperature and pressure where the supply of hydrocarbon gas is sufficient to stabilize the molecular architecture of the hydrate. Stability conditions are met in two large-scale environmental setting: the high latitude where surface temperatures are very cold and the ocean where pressures are high. The latter environmental setting and its special hydrate-supporting conditions are met on the numerous and complex fault systems that function as transport pathways, nearly continuous fault adjustments related to salt tectonics, and a myriad of surface hydrocarbon seeps (McDonald et al. 1996) make the Louisiana continental slope an ideal setting for gas hydrate accumulation.

Gas hydrates are important for several different reasons. Firstly, they constitute an unconventional energy resource that occurs in vast quantities and on a global scale (Krason 1994). Secondly, natural gas hydrates have been implicated in global climate change by destabilization and release of large volumes of methane, a greenhouse gas, into the atmosphere thus enhancing the processes that cause global warming (Paull et al. 1992;

Kvenvolden 1993). Thirdly, the peculiar and largely unknown properties of hydrates make them hazards to man's installations and operations in the marine environment. Destabilization of gas hydrates is considered a potential major factor in slope instability (Kayen and Lee 1991). Regardless of whether Louisiana's hydrate accumulations are considered energy resources, the need to know more about the physical states and geotechnical properties of these accumulations is unquestionable.

A very practical problem related to gas hydrates deals with the stability of sediments that contain these substances. Because gas hydrates are metastable compounds that can be affected by slight changes in temperature and pressure, destabilization of hydrates at or beneath the sea floor can lead to changes in submarine soil properties that may result in mass wasting events such as slumps and slides. That is, in normal sediments water and gas pass through this porous media without disrupting the particle-to-particle contacts as progressive consolidation takes place with increasing overburden. When gas hydrates form in sediments, an ice-like solid fills available pore space and effectively prevents normal consolidation and stabilization by common mineral precipitation. With destabilization of the gas hydrate due to heating associated with progressive burial or short-term natural or man-made perturbations in the pressure or temperature field, sediment strength reduction and slope failure can occur. Kvenvolden and McMenamin (1980) summarizes many examples throughout the world of submarine failures that are thought to be gas hydrate related. In general, geotechnical problems associated with hydrate-prone areas are very similar to those of Arctic permafrost regions. Although the soil strength of hydrates may be quite high and seemingly adequate for foundations, their stability is highly dependent on stable environmental conditions, especially pressure-temperature equilibrium. Structures and pipelines change this equilibrium so the first stage in assessing any engineering project near hydrates is to assess their present-day stability on the sea floor (Briand and Chaouch 1997). Because of the complex sea floor of hydrate areas, remote geotechnical testing is simply inadequate to generate data sets necessary for developing realistic models of hydrate behavior under different natural environmental and man-induced conditions. Models are necessary, however, for confident decision-making about hydrate behavior in the context of engineering projects. At present, there are no successful testing systems to provide adequate environmental measurements to evaluate in situ stability of hydrate areas and for generating the data base on which modeling advances can be made. This situation emphasizes that present day knowledge is not adequate to fully evaluate risk of sediment failure. So, the present strategy is to simply avoid hydrate areas, sometimes at great expense. Problems of heat transfer with adjacent sediments, expansion-contraction properties of hydrates, the variability of hydrate properties over large complex areas, and simply the sizes and shape of hydrate deposits within sediments must all be considered. The overall role of gas hydrate in areas like the Gulf of Mexico where they occur at the sea floor and are more vulnerable to environmental change is still in question. Only detailed in situ data sets will answer the critical questions about their geotechnical properties and overall behavior. In addition, it is important to know how to predict where gas hydrates are located. With our present state of knowledge, we can guess based on acoustic wipeout zones on high resolution seismic, but we really have very poor predictability. In an engineering context, it is important to know how gas hydrates affect the geotechnical properties of surrounding sediments, and how changing thermal regimes introduced by man's installations will affect hydrate stability. Much more attention will have to be focused on this unusual bottom type as operations move deeper onto the slope.

3.3.3.3. Sediment Characteristics A fundamental starting point for understanding surficial geological processes and response features of the slope is sediment properties (Hooper and Dunlap 1989). Even though thousands of core samples have been taken in deepwater, it is still not possible to make a map of even small areas of the slope showing sediment types and characteristics. Sediment input to the slope during Late

Pleistocene periods of lowered sea level when fluvial systems migrated to the shelf edge introduced sands and gravels to many slope sectors (Suter and Berryhill 1985). Salt tectonics have caused some of these deposits to be exposed at the modern sea floor or in the very shallow subsurface. Oceanographic processes are also known to winnow fine sediments and concentrate coarse components, especially in the upper slope province. Diagenetic processes, especially where oil and gas are reaching the sea floor by way of faults, and cause crust, nodular masses, and even large mound-like buildup to occur. The predictability of all these sediment types as well as their geotechnical properties is poor. Shallow flow layers are layers in the sediment column near the sediment-water interface in which the sediments are unexpectedly fluid and geo-pressurized to such an extent that they flow upward into the drill bore.

A standard method of evaluating sea floor sediments and their geotechnical characteristics is to acquire piston cores of surficial sediments and run geotechnical tests on the cores in the laboratory. Unfortunately, because of the great pressure changes between in situ slope-depth settings and a laboratory onboard a survey ship, fundamental changes in sediment properties occur. As a result, new in situ systems are being designed that can be deployed from a ship or ROV. Other systems are simply dropped from a ship and the data are telemetered back to a surface receiving station (Orenberg et al. 1996). Improved acoustic systems are being devised that can rather rapidly survey large areas of the sea floor and classify surficial sediments on the basis of acoustic penetrability and backscatter characteristics (Pace and Gao 1988; Panda et al. 1994; and Uliana and Dune 1996).

The Geohazards Subgroup recognized the need for a better general understanding of sediment properties on the slope. Changes in slope sediment characteristics as a function of such variables as depth, topography, and relationships to salt and faults are presently not well understood. A systematic effort to define slope sediments and their properties is important to continued deepwater development.

3.3.4. Additional Concerns

Several other topics emerged from Geohazards Subgroup discussions that deserve special attention in this document. Those topics include (a) the state of bathymetric data on the slope; (b) instrumentation necessary to collect adequate data sets in deepwater for assessing geohazards; and, (c) the issue of information transfer between industry, government, and academia on subjects dealing with geohazards. Each of these topics is summarized below.

3.3.4.1. Bathymetry The most elemental parameter for describing the characteristics of the sea floor is its depth. The most elemental parameter for the description of a particular environment of an area is its bathymetry. The specific depth below the sea surface and the general bathymetry are the first concerns in any activity offshore, especially regarding engineering activities related to hydrocarbon production. Detailed bathymetry of specific areas offshore, however, is usually very difficult to obtain and up until very recently almost nonexistent. Hydrographic charts used by the public are very general and the nature of the sea floor is expressed in local depths and very general contours. More detailed maps of the sea floor have been generated by the National Ocean Service (NOS), a subsidiary of NOAA. The NOS is no longer in existence and the duty of producing detailed maps of the sea floor falls to the National Geophysical Data Center. The Naval Oceanographic Office maps the sea floor, but the data are usually proprietary. With the development of the multibeam echo sounding system, detailed deep water (200 meters or more) bathymetric surveys are for the first time economically feasible.

The engineering and geological constraints on the continental slope of Texas and Louisiana related to the hydrocarbon recovery are many in number and will require both novel geological and geophysical surveys and engineering methods to economically overcome. Significant sea floor engineering problems in deep waters include slope instabilities, both short-term (slump) and long-term (creep), pipeline spanning problems, mass transport from unknown causes, and unusual stiffness and strength conditions (Hooper and Dunlap 1989). The first and most fundamental requirement to the understanding of the parameters listed by Hooper and Dunlap is bathymetry.

In response to a 1983 presidential proclamation establishing the U.S. Exclusive Economic Zone (EEZ), which extends 200 nautical miles offshore of the United States and the U.S. Trust Territories, NOAA's Coast and Geodetic Survey commenced surveying this zone with multibeam swath sonar techniques. The surveys were undertaken for a variety of purposes which include the conservation and management of living and non-living resources and for various types of planning purposes and the interpretation of geological structures and processes, to help the U.S. in such diverse undertakings as the exploration for oil and gas and in understanding the dispersal of pollutants along the sea floor (NOAA). The data are also useful for teaching the physiographic nature of the continental margin and the techniques used in the construction of bathymetric charts, the art of contouring, and the generation of maps by computer graphics.

The continental slope off Texas and Louisiana was surveyed starting in 1988. By 1991 the survey was stopped after three fourths of the area was surveyed. Seven hundred survey days and over 100,000 nautical miles of detailed multibeam data were acquired. However, one quarter of the slope remains to be covered with multibeam swath sonar techniques. The workshop participants considered this remaining bathymetric data to be an important need as a consistent data base from which to start meaningful geohazards investigations.

3.3.4.2. Instrumentation The Geohazards Subgroup recognized that data-collection systems for acquiring remotely sensed acoustic data for the slope are changing rapidly and that different needs for exploration vs. operations should perhaps dictate different data types. It has been shown before that surface-tow high resolution tools produce data that are less and less useful as water depths increase beyond the shelf edge. With increased resolution and usefulness of 3D-seismic data, the group suggested that comparisons of these data sets be made with standard geohazard, data sets (surface-tow and deep-tow) to assess the benefits and shortcomings of presently used systems. Methods for upgrading our interpretation skills using combinations of data calibrated to "ground truth" observations and samples was also identified as a needed focus for further research.

Since the entire continental slope in the northern Gulf of Mexico will soon be covered with exploration-scale 3D-seismic, it is important to explore the usefulness of these data for geohazards assessments, especially in the middle and lower slope areas where surface tow high resolution data are of limited use. As pointed out by Hill (1996), using 3D-seismic data in screening potential well and platform locations can help ensure that inappropriate sites or even pipeline routes are not surveyed with higher resolution tools (e.g. deep tow systems), thus minimizing survey costs. Although it is acknowledged by most specialists who perform geohazards assessment that 3D-seismic does not have the resolution to answer many important questions about the sea floor, the potential for utilizing these new data sets for geohazards-scale evaluations of the sea floor has not yet been realized. The role of 3D-seismic data as well as other types of remotely sensed data sets in geohazards evaluations were considered topics of important inquiry by the Geohazards Subgroup.

3.3.4.3. Information Transfer It was recognized that slope data sets are held by numerous companies as well as academic groups and government agencies. More importantly, the understanding of slope environment resides in many groups and individual specialists. There is a need to identify available data sets, where these data sets reside, and their formats, plus instruments used, and overall data quality. The Geohazards Subgroup also recognized the need to digest, summarize, and transfer information about the slope between those who need or want to understand the sea floor of the continental slope environment. A system of information transfer centering on geohazards and slope geology issues was recommended.

3.4. Ecological Issues Working Group

Co-chairs: Dr. Robert Avent, MMS; Dr. Robert Carney, LSU

3.4.1. Overview of Working Group

The topic of impacts resulting from deepwater operations is exceedingly broad because it spans the water column far offshore, covers the continental slope where drilling development and production will occur, and stretches along the transportation route all the way to coastal wetlands. Each component of this potentially impacted system could be the focus of a major workshop. In many regards, the results reported here might be considered only an introduction to many broader topics. It should be especially noted that the topic of nekton and pelagic ecology was not represented.

Table 3.4.1. Roster of expert participants in the ecological working session.

Dr. Benny Gallaway	LGL Ecological Research Associates
Dr. Barbara Hecker	Consulting Oceanographer
Dr. John Lambshead	British Museum
Dr. Ian R. MacDonald	Texas A& M University
Dr. Gilbert Rowe	Texas A&M University
Dr. David Thistle	Florida State University

3.4.2. Background Information: A Primer on Deep Benthic Ecology

While the deep-sea floor has not been studied to the extent of the shallow ocean, there is a substantial amount known about it. Therefore, an initial task is to determine what is especially relevant to deepwater oil and gas operations. For this purpose, it is possible to categorize most deep ecological knowledge into four categories: faunal zonation; biomass; diversity; and, chemosynthetic communities. Following such an introduction, the state of knowledge in the Gulf of Mexico will be reviewed.

3.4.2.1. Faunal Change with Depth Bathymetric Zonation is the term applied to the progressive change of fauna with depth such that the fauna along isobaths over hundreds of kilometers may be more homogenous than fauna across a 1000 m depth over a few kilometers distance. The descriptive nature of zonation is reasonably well documented at several places in the ocean. However, the cause is not actually known. A description of zonation is the result of analysis of species inventory data based upon sampling, sample processing, specimen identification, and confirmation. As noted below, the results of zonation are highly dependent upon the method of analysis selected and interpretation can be highly subjective. Gage and Tyler (1991) provide an introductory review based in large part on Carney et al. (1983).

There is one major oil and gas relevant aspect of zonation. The "deep sea" can not be treated as an uniform environment. The community subject to impact changes with depth such that survey and monitoring programs must be depth stratified to prevent confounding natural change with impact or swamping a real local impact with great wide-depth range variation.

The fact that the species collected from the ocean beyond the shelf break are different from those in shallow water is one of the earliest observations about the deep ocean, and delineation of the global pattern of bathymetric change was a major aspect of deep trawling studies from the voyage of the HMS Challenger in 1872-76 till the end of expeditionary sampling in the early 1960's. With the popularization of multivariate analysis in the late 1960, bathymetric faunal patterns were easily described and discussed by methods such as cluster analysis. Since the review of Carney et al (1983) there has been relatively little progress in understanding the mechanisms causing zonation. It is widely accepted that it reflects adaptation to changing environmental conditions, but causal mechanisms remain speculative.

Identification of the factors that control vertical zonation is an elusive task since so many ocean parameters co-vary with depth in a manner that prevents separating causality from correlation. Prior to the 1960s, ocean distributions were usually attributed to abiotic factors, especially physiologically important ones, such as pressure, temperature, and salinity. Since pressure increases continuously with depth in the relatively isothermal and isohaline depths, it may be the most important physiological factor. In their review Seibenaller and Somero (1989) summarize the unequivocal evidence of enzyme pressure adaptation. Contemporary ecological explanations for zonation place greater emphasis upon biotic factor,s such as competition, and employ the term "species replacement" (Rex 1981). The strongest evidence that biotic factors are important is Rex's (1981) observation that depth range is related to feeding type. Ultimately, biotic control may be modulated by food availability, suggesting detritus influx rate gradients as the primary cause of zonation (Rowe and Pariente 1992). A new approach is that of Pineda (personal communication, 1933), who has begun the task of what part of zonation patterns may simply be random effects of artifacts versus which part reflects causation.

When deciphering published zonation schemes it is important to realize that the process of describing faunal patterns changed dramatically in the 1965-1970 time period. Prior to the 1960's biological oceanographers were greatly influenced by the geomorphology of the ocean basin and the physical conditions of the water column when dividing the ocean into zones. There was relatively little data, no convenient way of analyzing it, and it seemed quite reasonable to expect faunal zones to coincide with physical geological boundaries. A clear example of this is the zonation scheme for the Gulf of Mexico proposed by Pequegant (1983). It took into account the morphology of the basin, the thermal structure of the water, the water masses filling the Gulf of Mexico, and lastly the fauna. In the jargon of classification, this is a polythetic system employing several criteria.

With the popularization of multivariate analyses, traditional polythetic approaches were effectively replaced with monothetic analyses. The species inventory in samples became the sole criteria for describing faunal patterns. The most serious limitation of this approach lies in the analyses used. In order for all multivariate analyses to produce simple displays of complex patterns some underlying model must be applied, and these models impart certain distortions or easily misinterpreted results. Regretfully, highly meaningful scientific questions can be nearly lost in a debate over the relative merits of highly subjective analyses. For example, if cluster analysis is used to see if the fauna undergoes gradual change or marked zonation, then zonation will be found. Zonation is implicit in the model of inclusive clusters. If the same question was asked using some ordination procedure, gradual change would more likely be the conclusion.

3.4.2.2. Biomass Pattern Measured either in terms of dry/wet tissue weight, organic carbon or nitrogen, or counts per unit area biomass has a distinct depth pattern, decreasing exponentially with depth. In more contemporary oceanography, this static parameter is viewed as being somewhat uninformative by itself, and it is preferred to measure system components more fully. Therefore, biomass should be coupled with carbon influx and sediment community respiration studies. In this fuller systems view, biomass decrease with depth is attributed to reduced influx of labile carbon caused by bacterial consumption during sinking. The relevance to deepwater oil and gas activities are three.

a. At progressive depths, the community subject to impact may decrease in size.

b. At progressive depths, conflicts with biomass exploiting activities such as fishing should decrease.

c. Studies of the deep environment will be plagued by small sample sizes.

3.4.2.3. Diversity Pattern Diversity, either simply expressed as the number of species (species richness) in a sample or as an index based upon proportional abundances, is the most enigmatic general aspect of deep-sea biology because it is unexpected and complicated to explain. The unexpectedness is due to an apparent conflict with accepted ecological theory which predicts that homogenous environments have few niches and few species. The complication arises out of trying to explain the apparent contradiction between theory and observation. The deep sea is species rich, and in some regions there is a well defined species maximum on the lower continental slope. The consequences of high deep-sea diversity to the oil and gas industry are potentially considerable.

a. Regulatory policy specifying that biodiversity be preserved may treat the deep sea on a par with more "charismatic" high diversity habitats such as coral reefs, protected species, and tropical forests.

b. The fact that deep high diversity is poorly understood can be taken to mean that we do not know how the deep-sea ecosystems function and are unable to predict impacts.

c. Some of the diversity explanations suggest a far greater dependence upon subtle environmental variables than is found in shallow water. If true, this could imply a much greater sensitivity to perturbation.

d. As a practical matter, species inventory data is notoriously bad and getting worse as fewer and fewer taxonomic experts exist. In this regard high diversity samples are extremely hard to work. The possibility exists that low data quality could either mask a real environmental impact, or produce a false positive.

Diversity estimates are the result of analysis of species inventory data. Since the fauna sampled are highly subject to sampling effects, a beginning decision must be made about equipment and processing. For macro and meiofauna a 0.25 m^2 box core of the Sandia-Hessler design has become a de facto U.S. standard. Samples are sieved on a 250 micrometer screen. Sorting takes place under 10x magnification following staining. Due to the relative uniformity of deep sea sediments, bulk concentrating and separating techniques are seldom applied. Results are extremely dependent upon the effectiveness of sorting, the consistency of identification, and the correctness of identification if cross-study comparisons are intended. MMS normally specifies that H', the information statistic diversity measure, be reported. R, species richness, the number of species, is appealing because of its simplicity but dependent upon the number of specimens Therefore, when unequal samples are compared some correction must be considered. Expected Species shared provides such a correction, but the nature of the correction is such as to make it an index of equatability rather than diversity *per se.*

The theoretical explanations for high diversity in the deep sea are so complex that a useful account can not be presented here. Therefore, this account focuses upon ideas that are of particular relevance to oil and gas development. Phrased as a question, are there aspects of deep sea diversity which suggest that the fauna may be especially susceptible to impact? The simple answer is yes. Four of the most widely discussed explanations do imply greater sensitivity.

Time-Stability. Although now considered out of date because of increased understanding of the deep environment and progress in competition theory, the idea put forward by Sanders and colleagues (Sanders 1979) still merits consideration because it focuses upon organism-organism interactions. Basically it says that species somehow accommodate to each other and partition resources rather than compete in environments which are vast, old, and relatively stable. Such accommodation implies a fine and easily upset balance among species for a narrow range of resources.

Cropper Control. This explanation was a direct application of rocky intertidal and tropical vegetation ideas whereby competition among species lower on a food chain is minimized by cropping by higher level consumers. Originally proposed as random cropping by animals such as holothuroids, the idea was subsequently corrected to be directed cropping aimed specifically at species that were about to exclude competitively weaker species (Dayton and Hessler 1972). The idea still has merit and makes us realize that predator-prey interactions may be very important and "keystone" species may exist. Such keystone species may be subject to impact, which would then influence the larger community. Oddly, the notion of keystone predators seems to have no following in shallow water.

Grain Matching. This is an explanation originated by Jumars and his associates (Jumars and Eckmann 1983) from a series of studies looking at the spatial scale of diversity. In effect, the idea says that the deep-sea bottom is finely divided into many habitats, many of which are biogenic. Thus, the system is not as homogenous as human means of observation and scales of observation would suggest. The manager who tries to make use of these habitats must keep in mind that they are not rigorously tested ideas. If fine scale (centimeters and smaller) textural differences in the sediment-water interface are important to the fauna, then activities that physically alter this environment may have major impacts.

Contemporaneous Disequilibrium. This idea has been primarily advanced by Grassle and his associates (Grassle and Maciolek 1992) and produces a very dynamic picture of deep-sea diversity in which the broader sea floor is populated by species emigrating from many small and temporally varying centers of high competitive success. In effect, large areas never come to a low diversity equilibrium. The special importance of this idea is that some areas of the sea floor (source areas) are more important than others in diversity maintenance. But, we can not yet predict which parts. Thus management faces a dilemma, how can you protect that which you can not identify?

3.4.2.4. Sampling Methods for Deep Benthic Studies Deep-sea ecology is exceedingly equipment-limited, and results are strongly equipment biased.

Therefore choice of gear very much determines what can actually be achieved in the study. This section provides a discussion of gear, data types provided, and major limitations.

Submersibles and ROV. These platforms have the tremendous advantage of placing the scientist in the environment providing a direct and intimate view of what is otherwise an abstract place. They also allow discretionary sampling and very fine spatial scale control for both samples and experiments. However, there are severe limitations. They have a minimal sample payload, they are expensive, and in some cases have operation schedules that preclude desired time series. Except for specific habitats, such as chemosynthetic communities and other deep hard bottoms, ship-based studies are preferred.

Deployed Experiments. Submersibles and ROVs can deploy experimental microcosms. These can consist of defaunated deep sediments spiked with high levels of organics. Colonization over time can then be monitored. In the case of oil and gas applications, the microcosms could include potential discharged solids to test for impacts upon colonization.

Research Vessel. Sample payload, reliability, costs, and ease of utilization all argue in favor of ship-based surveys and monitoring. A ship equipped with 9/16 cable at least 3 times the maximum studied depth is adequate for all heavy wire work. Such a vessel is also well-suited for free vehicle and mooring deployment.

Box Corer. The box corer is the de facto standard for quantitative samples of macrofauna, meiofauna, and sediments. At this time the Sandia-Hessler 0.25 m^2 design is preferred and was employed for both the MMS Atlantic deep studies and the California Mapping Program. This is a partitioned corer that allows ease of subsample allocation and provides biological subsamples from the center area of minimal "bow wave" effects. In selecting coring devices, it is the hydrodynamic performance that must be considered, not the sample area alone. Therefore, it was unfortunate that the NGOMCS Study employed yoked Gulf of Mexico corers (Gray-O'Hara modifications of the J&O box corer). Together, a pair did sample approximately 0.25 m^2 of bottom, but the pattern of bottom disturbance must be very different.

Beam and Otter Trawls. In spite of efforts to make these devices quantitative, they must be viewed as qualitative with comparisons between samples being a catch per unit effort basis. Trawls provide ground truth specimens of megafauna which might be photographic or video surveys. They also provide tissue for analytical purposes. Use of otter trawls at depth requires a greater degree of familiarity with the technique since too great a speed over bottom and too much wire out may result in no bottom contact, while going too slow will cause the trawl boards and bridle to become tangled, although smaller beam trawls are more forgiving in operation.

Imaging Systems. There has been great progress in imaging systems in the past decade, notably digital photography, higher resolution small size video, and laser scanning. All have the advantage of surveying a greater area than trawling can accomplish. However, all have limitations. Laser line scanning lacks the resolution needed to record all but the largest of organisms with sufficient detail to make identifications. Very high resolution video, digital, and film images do allow for such identification. Choice among the three is somewhat arbitrary. Film, however, remains the highest resolution and most compact storage option compared to digital still picture. Video requires greater power for lighting, but does provide a continuous record and clearly shows organism responses. Combined photo/video systems are feasible.

Free Vehicles. These devices are deployed from ship, sink passively to the bottom, and deploy experimental systems on the sea floor. After a predetermined time, the experiments are terminated, and the vehicle surfaces for pickup. Most often, bottom respirometers, current meters, and various imaging systems are deployed. When properly designed, these devices provide a submersible's experiment capabilities without the attendant costs.

3.4.3. Previous Deep Studies in Gulf of Mexico

3.4.3.1. Pequegnat's Collecting The Office of naval Research (ONR) supported deep sampling in the Gulf by Willis Pequegnat (Pequegnat 1983) was carried out in the 1960s and 1970s very much along the lines of classical natural history surveying which was otherwise being replaced by process-oriented studies in the 1950s and 1960s. While it is easy to criticize the ecological failures of this work, it must be remembered that ecology was not the intent of the sampling. The primary achievement of the study was the providing of high quality taxonomic base for deep megafauna for entire Gulf, done prior to EEZ restrictions and at a time when Smithsonian curators actively involved in ongoing sampling programs. With respect to omissions, the study did not conduct quantitative sampling of macrofauna.

3.4.3.2. The Northern Gulf of Mexico Continental Slope Study MMS contracted a study of the continental slope fauna and environment between 1983 and 1987. The prime contractor was LGL Ecological Research Associates of Bryan, Texas, with subcontracts to Texas A&M University. Dr. Benny Gallaway presented a synopsis of the tasks undertaken. The objectives were:

a. provide an environmental and biological characterization;
b. compare patterns in the biotic and abiotic components of the environment;
c. consider meiofauna;
d. consider macrofauna;
e. consider megafauna;
f. consider chemosynthetic communities (an addendum);
g. develop a conceptual model of slope ecosystems.

Unfortunately little of the NGOMCS Study appeared in the open literature except for a general account (Pequegnat et al, 1990) and chemosynthetic components. Annual report year four (Gallaway 1988) remains the primary reference. Three areas were sampled in the Central, Western, and Eastern Planing Areas. Sampling consisted of various combinations of Neil-Brown Mark III CTD/rosettes/ transmissometer deployments, box cores, otter trawls, and benthic photography. Sample analyses consisted of descriptive sedimentology, carbon fractions, carbon isotopes, high molecular weight hydrocarbons and core faunal fractions. Trawl samples were also submitted for isotopic and hydrocarbon analysis. Interrelations among variables were sought with principal components analysis. Especially noteworthy findings were:

a. Chemosynthetic communities were discovered concurrent with the project.

b. Meiofauna densities appeared to be two to three times more abundant than in the western Atlantic, an observation attributed to such causes as organic enrichment at seep sites. While possible, increased surface productivity might also be the cause, if the difference in sampling devices does not invalidate the comparison.

c. Macrofauna were of both lower density and lower diversity than reported in the western Atlantic using different sampling techniques.

d. Three primary faunal zones were identified between 300-700 m, 700-1650 m (with a possible subdivision at 1300 m), and 2000-3000 m.

e. Correlations between fauna and abiotic parameters could be explained by spuriously high numbers during multiple testing. Thus, convincing relationships were not found.

f. Trawling operations were only marginally successful due to operational problems. Discussion of trawl results in quantitative terms is problematical. Nevertheless, biomass decreased with depth and there was some indication of mid-depth diversity maxima.

g. No conceptual model was developed.

3.4.3.3. Chemosynthetic Seep Communities Dr. Ian MacDonald of Texas A&M University's Geochemical and Environmental Research Group (GERG), leader of the ongoing seep work supported by MMS, gave a review and status report. Chemosynthetic seep communities were discovered in conjunction with research on thermogenic gas hydrates (Brooks et al. 1984) when trawling on bottoms with an acoustic "wipe out" signature produced chemosynthetic species (Kennicutt et al. 1985). This discovery was concurrent with the MMS supported Gulf of Mexico (Gallaway 1988) Northern Gulf of Mexico Continental Slope Study (NGOMCS), which was amended to include an initial submersible investigation of the seeps in 1986 (MacDonald et al. 1989). Subsequently, MMS supported a larger study completed in 1994 (MacDonald et al. 1996) and third MMS-supported investigation is now underway. The lead institution of the two larger studies is the Geochemical and Environmental Research Group (GERG) at Texas A&M. However, the projects have a remarkably broad participation (Texas A&M, Louisiana State University, Pennsylvania State University, Rutgers University, University of Virginia, University of Texas, University of California at Davis), and are especially noteworthy in peer-reviewed scientific publication. In addition to the larger studies, MMS is supporting seep-geomorphology correlation work by Roberts and seep radionuclide work by Aharon via the LSU Coastal Marine Institute program. In addition to MMS support, work at Gulf seeps has been supported by NOAA's National Undersea Research Program (NURP) and the National Science Foundation.

If one examines the duration of relatively uninterrupted funding (1986-1997), the recurrent cruises over the same period, the breadth of institutional participation, and the scientific productivity, the hydrocarbon seeps of the Gulf of Mexico emerge as arguably the best studied deep ecosystems. Therefore, management and industry have the relative luxury of being able to carefully review the knowledge base and narrowly define information needs. Obviously, since there is an ongoing project, critical assessment of the knowledge base is premature. However, it is possible to look at some of the previous findings and draw management-relevant conclusions.

<u>Widespread Seep Systems in Northern Gulf of Mexico</u>. Chemosynthetic fauna has been found along the northern Gulf slope between 95° and 88° W and approximately 300 and 2200 m. This generally coincides with the oil and gas rich areas of the Gulf but is biased by the geography of sampling (little to the east) and national boundaries (US studies stop at 26° N). The existence of chemosynthetic fauna at the far eastern edge of the Gulf (Hecker 1985) unrelated to hydrocarbons raises the possibility that such systems are even more widespread than presently known.

The primary management relevance is that if seep communities are common, the criteria of acceptable impact can be relaxed since damage to a few might be viewed as acceptable. The simple fact of being widespread is itself not adequate to make this decision. Rather, it is the ability of the undamaged to ultimately repopulate the impacted areas that must be known. Although repopulation following impact can only be conclusively known following a real impact, the potential to repopulate can be inferred from faunal and genetic similarity studies. The underlying supposition being that site-specific seepage may be intermittent, and existing communities reflect numerous repopulation events. Faunistically, we have mixed results. Above the 1000 m depth limit of the submersible Johnson Sealink, the sampled communities are quite monotonous, suggesting linkage. However at ALVIN-investigated deeper sites, the fauna is distinctive. Thus, there may be some zoning of connectedness. Exactly how genetically close these <1000 m sites are will be determined by molecular studies in the current project.

Habitat of Seep Communities Can Be Determined Remotely. Seep fauna is known to occur in some areas of acoustic wipeout, of authegenic carbonates, and of observable seepage.

There is an obvious cost advantage to industry to be able to extract a highly reliable "faunal likelihood index" from the information they routinely gather during exploration. However, no such index yet exists, and the only proof that communities exist at a particular site lies in directly sampling or observing that site. Industry's more common need, proof that a seep fauna does not exist is even more problematic since it is both very hard and very costly to prove that a community has not been overlooked during survey. Present efforts are remote detection centered around finding a community then exploring for correlates. Ultimately, these correlates (geophysical bottom signatures) must be used to predict the location of communities and the prediction tested. Such prediction and testing needs to be undertaken in the future.

Physiology and Growth of Chemosynthetic Species Have Been Characterized. Based on marking and monitoring of tube growth, cold seep vestimentiferan worms may be extremely old invertebrates with some individuals exceeding 100 years. This is in stark contrast to hot vents where related species grow at exceptionably fast rates. Seep mussels grow at site specific rates that approximate those of shallow water heterotrophic species. Large individuals may be as old as 50 years.

This information on species population structure is actually equivocal for predicting environmental impact. It is equally valid to conclude that a population of old animals exists because the population has survived natural environmental perturbation and is robust, or that it has not experienced perturbation and would be fragile in the face of disturbance. Good estimates of recruitment and mortality are needed to make use of the excellent information already obtained.

Fauna Partially Described at Sites Shallower than 1000 m. The species composition of chemosynthetic and heterotrophic fauna at sites above the 1000 m isobath are remarkably uniform. However, poorly studied deeper sites are known to be different. During operations in July 1997 discovery of dense hesionid worm populations on the surface of an exposed hydrate indicates that undiscovered microhabitats may still remain and can only be explored with new methodologies (C. Fisher, 1997, unpublished data). Foodweb tracing indicates that mobile megafauna from the surrounding mud bottoms do exploit the seeps as a food source.

Fauna similarity shallower than 1000 m suggests that a uniform set of rules may be applied. The geographic nature of the transition to deeper seep faunae must be determined prior to development of regulations for that region. Regulations that stress no impact should be adequate to assure protection of yet-to-be discovered microhabitats and populations. The trophic link to the surrounding fauna is problematic. MMS now seeks to afford protection to "lush communities." This is a standing stock description and may not reflect trophic dependence, which is based upon rate processes. Indeed, low standing stock communities may be the ones that are most heavily exploited by the surrounding fauna.

Taphonomic Studies Indicate Persistence Through Time. The methods employed are highly biased to infaunal bivalves, such as the lucinids, but are of especially great importance due to the temporal perspective provided. Seep areas were found to be persistent through time although experiencing transitions between seep and non-seep fauna. The composition of seep taphofacies is conservative and did not show succession.

On a 500-and-less year time frame, communities are obliterated and become reestablished. Regionally, seep communities may be resilient. Ideally, the generality of these results should be extended to hard substrate by means of a drilling program.

Summary of Seep Information Needs. If MMS takes the most conservative approach and proscribes disturbance, then remaining information needs are few to none. However, this may pose restrictions on industry that provide no environmental benefit. Alternately, some degree of impact might be deemed suitable, but this increases the information needs considerably. Rigorously determined recruitment and mortality rates for major species are needed. Informed conjecture about resilience and stability must be tested by well-designed experiment, and remote methods of inferring community presence tested against prediction. Future work should await completion of current research.

3.4.4. Major Remaining Questions

Chemosynthetic work is progressing, and remaining needs are best addressed at the completion of the current project. Pequegnat's work was pioneering and seminal, but its utility is really in fauna identification and not contemporary ecology. The NGOMCS study did an excellent job carrying out initial seep community studies, but was notably weaker with respect to soft bottom where species quality control may be an issue in box core samples and relatively few megafaunal trawl samples were successful. Therefore, it must be concluded that previous work can not meet information needs.

3.4.4.1. Soft Bottom System Consensus Studies MMS needs to know if the deep benthos with its dependence upon detrital influx, its poorly understood diversity, and its vertical zonation is especially more sensitive to impact than the shelf benthos. Pequegnat's collection and the NGOMCS study form a starting place from which to plan more effective and comprehensive surveys. By themselves, they are insufficient to meet information needs. Listed by priority are suggested studies.

Confirm and Maximize Utility of Previous Work. Pequegnat's data archives are not in accessible form and NGOMCS macrofauna data archives do not reflect the final resolution of polychaete identifications. Thus, the actual utility of previous work is not known. An appropriate starting place would be to have Pequegnat's data submitted to NODC and a taxonomic quality assurance program applied to the NGOMCS archives.

Produce an Ecosystem Model of the Gulf of Mexico via a Comprehensive Survey Including Process Measurements. The scope of such a program would include the following. Sampling should be Gulf-wide and stratified to examine topographic effects. Macrofauna studies could be focused on major groups, such as polychaetes. An improved meiofauna could be added by focusing on nematodes and harpacticoids. The increased numerical data may increase sensitivity of analyses. Taxonomic quality control is of paramount importance. Photographic surveys of megafauna would be included. Such surveys can provide information of physical conditions, soft bottom, and seep systems.

Video and laserline scan systems offer possible new technologies. Models should be structured around trophic relationships and include detritus influx and bottom respirometry.

Undertake Manipulative Experiments at Existing Development/Production Sites to Assess Impacts. Such work would require ingenuity in designing meaningful and rigorous experiments that might be deployed and monitored by ROV. It is anticipated that most work would involve the deployment of artificial substrates.

3.4.4.2. Individual Expert Comments on Soft Bottom Studies

Thistle. Focusing specifically on production effects, an experimental approach could be taken at new deepwater sites. Experimental systems could be deployed by ROV's working from platforms at a considerable cost savings over ship/submersible work. Such sea floor deployments afford opportunity for many experiments as well as time-series monitoring of the environment and flux rates.

Sampling design would be basic near-vs.-far as used in GOMEX with multiple platforms studied.

Rowe. Focusing more broadly, there needs to be a Gulf of Mexico Deepwater Ecosystem Structure and Function Study to provide an interpretive context for other site-specific work. This study would assess the environmental health of the GOM, including Mexican portions. Sampling could be along transects radiating from the Sigsbee Plain. Activities would include traditional mega-, macro-, and meio-fauna surveys, along with microbial and flux work needed to understand the trophic system. Shipboard box coring, trawling for megafauna ground truth, camera deployments, and free vehicles would accomplish the primary sampling. ROV's and/or submersibles would be employed in topographic feature specific sampling

Hecker. Rowe's basic Ecosystem Structure and Function approach is meritorious. By employing camera systems, special emphasis can be placed on exploring the relationship between topography, bottom currents and fauna. By camera survey of a variety of bottom types, subsequent coring programs can be more effectively developed.

3.4.4.3. Consensus Suggestions for Future Hydrocarbon Seep/Chemosynthetic Community Studies Chemosynthetic communities are currently being studied under MMS contract by a multi-institution team coordinated by the Geochemical and Environmental Research Group (GERG) at Texas A&M. Dr. Ian MacDonald, project manager and Co-Principal Investigator gave a presentation on the objectives and activities of that program. Since this project was just beginning, with initial field work in July 1997, effective planning to meet future information needs should wait on the results to be obtained in the next three years. However, discussion from the floor highlighted information needs which the current or future programs must meet.

Strengthening Biology Inference from Geological Evidence. Enforcement of NTL-88-11 is based upon industry providing MMS with geological/geochemical evidence concerning bottom habitat. MMS must then infer from that evidence if a seep community worthy of protection exists. Therefore, in order for NTL-88-11 to achieve its intended protection without being unnecessarily burdensome, the means of inferring both presence and extent of seep communities must be objective and highly reliable. Previous research has produced much information about how components of a few well-established seep communities function. And, informed speculation has been put forward as to how seepage on a larger regional scale may effect community establishment and demise. If the current study does not provide the necessary strong inference tool to management, then it will remain a high information priority.

Need for Population and Community Dynamic View of Seep Function. It is anticipated that seep community studies will parallel the advances seen in rocky intertidal systems with a progression from descriptive ecology and detailed organismal studies to experimental studies that estimate parameters such as recruitment rates, natural mortality rates, and post settlement competitive interactions. These populations and community parameters seem to offer a greater chance of answering central questions about resilience and persistence.

Is the "Competing for a Common Resource" Question Tractable? The fundamental question of whether oil and gas production may ultimately cause the demise of seep communities by shutting off the needed hydrocarbon supply remains unanswered. Simply put, the argument that this is a possibility is based upon the belief that the necessary surface seepage is driven by reservoir pressure that will be reduced during decades of production. Equally simplified, the argument that this is unlikely is based upon models of subsurface geology in which no such pressure-seepage linkage exists for the particular reservoirs targeted by industry. Unfortunately, testing of both may prove futile if the temporal lag between reduced pressure and surface seepage is on the order of hundreds to thousands of years.

3.4.4.4. Issues Put Forward by Dr. Ian MacDonald, Program Manager Chemo-II Study

Management of Ecological Resources: an Issue Extending Beyond MMS Responsibilities. It is necessary and timely that MMS initiate or participate in intra-and inter-agency planning to produce a comprehensive management and protection plan for deep hydrocarbon seeps analogous to the NOAA Sanctuaries program or the NSF-managed Antarctic Program. Participating agencies may include: MMS, NSF, ONR, NMFS, NOAA, BRD (USGS), and international participation.

The Gulf of Mexico hydrocarbon seeps and the associated biological communities have been studied for more than a decade. They are managerially unique in the deep-sea in that some degree of protection is afforded them through specific MMS policy, Notice to Leasors 88-11. In the nearly 10 years since issuance of NTL-88-11, the GOM seeps have become the most heavily studied cold seep systems due to the funding support of MMS and the NOAA National Undersea Research Program. It is the view of those scientists working on these systems that they continue to be an invaluable scientific resource and may have a broad ecological role. Ultimately, their study may provide valuable application in a broad range of applications from petroleum exploration to biotechnology. In this context of resource value, it is clear that MMS' mandate to avoid resource conflict can afford some protection but does not include the living resource management required for effective management. An appropriate management model must recognize economic value, existence value, and scientific value.

Increase the Geographic Coverage through Remote Surveying Techniques. Central questions are how many hydrocarbon seeps are there and to what extent are these colonized by chemosynthetic organisms? The present study will not provide broad geographic coverage. A comprehensive seep community inventory might effectively use remote sensing to identify surface slicks and then be complimented by geophysical survey methods.

Specifically Extend Bathymetric Range of Study Deeper Than 1000 m. Industry and chemosynthetic organisms have pursued hydrocarbons well below 1000 m, yet the bulk of our knowledge about GOM seeps comes from above that depth due to submersible restrictions. Work at the West Florida Escarpment and Alaminos Canyon sites indicates degrees of both similarity and difference between deeper and shallower communities (Carney, 1994). The need for a more comprehensive view is compelling. Greater coverage requires that deep submersible assets such as ALVIN be made available.

3.5. Adhoc Breakout Group on Fisheries Issues, April 22-24, 1997
Compiled by Dr. Ann Scarborough Bull, MMS

3.5.1. Issues

Five major issues were raised concerning oil and gas development in deepwater areas of the Gulf of Mexico and fisheries.

Table 3.5.1. Roster of participants in the ad hoc breakout group on fisheries.

Mr. Wally Adcox	MMS
Dr. Doug Biggs	Texas A&M University
Dr. Ann Bull	MMS
Dr. John Caruso	LUMCON Marine Center
Mr. Dennis Chew	MMS
Dr. Felecia Coleman	Florida State University
Dr. Benny Gallaway	LGL Ecological Research Associates
Dr. Churchill Grimes	
Mr. Rex Herron	NOAA
Dr. Jim Kendall	MMS
Dr. John Lamkin	National Marine Fisheries
Mr. Tom Lemming	National Marine Fisheries
Dr. Tom McIlwain	National Marine Fisheries
Dr. Bob Meyer	U.S. Geological Survey
Dr. Dave Stanley	Louisiana State University

3.5.1.1. Fisheries Conflicts The physical presence of oil- and gas-related structures and associated operations will likely conflict with fishing activity (both commercial and recreational) especially in, but not limited to, areas south and east of the Mississippi River delta.

Multimillion dollar fishing efforts in deepwater include (a) upper-ocean trolling for billfish; (b) mixed-depth long lining for yellowfin tuna and shark; and, (c) deep bottom trawling for royal red shrimp. The equipment for these types of fishing is significant in terms of size, weight, and expense. Interactions between oil and gas activity and fishing in deepwater may be costly, potentially environmentally hazardous, and possibly a human safety hazard.

3.5.1.2. Interference with Natural Movement As with other world-wide locations, the physical presence of large structures in deepwater will likely act as fish attracting devices (FAD's) that will seriously impact management of highly migratory fish species. Highly migratory species include yellowfin and bluefin tunas and broadbill swordfish.

Highly migratory species are managed by federal and international constraints. Any artificial concentration of these species will also concentrate fishing efforts into a novel and potentially detrimental situation for the Gulf of Mexico fish stocks.

3.5.1.3. Interference with Feeding and Spawning of Offshore Species As in many other world-wide locations, the physical presence of large structures in deepwater will likely act as fish attracting devices (FAD's) that will impact populations of highly migratory fish species through changes in their feeding and spawning behavior.

Spawning and feeding grounds for highly migratory species are thought to be limited to specific areas along the slope edge of the Gulf of Mexico. Potential geographic shifts in the location of spawning and feeding could impact these species on a population level.

3.5.1.4. New and Old Impacts in New Habitat Oil and gas development in deepwater will present both old and new environmental hazards to fish resources, e.g., oil spills that occur at the sea floor. Spills of hazardous materials do the most harm to larvae and juvenile stages of fish and shellfish. Scientific data indicate that larvae and/or juveniles and/or spawning aggregations of many species may be present in appreciable numbers in deepwater areas of the Gulf of Mexico. Some species examples include gag grouper, yellowedge grouper, yellowfin and bluefin tunas, oceanic sharks, broadbill swordfish, and marlin.

3.5.1.5. Future Abandonment Issues Oil and gas development in deepwater of the Gulf of Mexico will present unique site abandonment difficulties and raise questions concerning artificial reef planning.

Artificial reefs off Texas and Louisiana are routinely constructed of obsolete oil and gas platforms and associated materials. Long-range planning will facilitate the function and possible role that structures used in the development of deepwater prospects could play in Gulf State's artificial reef programs.

3.5.1.6. Threats to Endangered Turtles One major issue raised with regard to oil and gas development in deepwater in the Gulf of Mexico was endangered and threatened species of marine turtles. The slope edge of the Gulf of Mexico is a critical nursery ground for juvenile marine turtles. Development in deepwater areas of the Gulf may interact with, and further threaten, this endangered group of animals during their early life stages.

3.5.1.7. General Biodiversity Concern Another major issue raised concerned the biodiversity of fish and macroinvertebrates. Population densities and biodiversity of deepwater fish and macroinvertebrates is poorly understood. The potential effects of human intervention and activity in these geographic realms on biodiversity is unknown.

3.5.2. Information Needs Addressing the Above Concerns

a. What are the locations of longline, trawl, and troll fishing with reference to areas of oil and gas development in deepwater?

b. What should be done to minimize potential conflict situations between deepwater fishing and the development of deepwater prospects?

c. How might MMS interact with the oil and gas industry and Federal and International fisheries managers to resolve impacts on the management of highly migratory species from development in deepwater?

d. What and where are the prime spawning grounds for key species in deepwater areas across the Gulf?

e. What and where are the prime feeding grounds for key species in deepwater areas across the Gulf?

f. What are the spatial and temporal factors that comprise major influences on feeding, spawning, and larval transport for deepwater fish species? How will deepwater development affect these influences?

g. Data search and synthesis of the effects of large Fish Attracting Devices (FAD's) located world-wide on highly migratory fish species.

h. What are the new environmental hazards that may affect fishing and fish resources due to development of deepwater prospects?

i. Will there be a functional artificial reef effect from oil and gas structures located on the sea floor and within the water column in deepwater areas of the Gulf?

j. How can structures from deepwater development support Gulf State's artificial reef programs?

k. What are the new environmental hazards that may affect the juvenile stages of endangered and threatened species of marine turtles?

l. What are the population densities and biodiversity of deepwater fish and macroinvertebrates in deepwater areas of oil and gas development?

m. What are the potential effects of human intervention and activity in deepwater geographic realms on biodiversity?

3.5.3. Approach/Study Design To Fill Information Needs

Fisheries scientists and experts were unable to attend the entire workshop. The approach/study design to fill information needs was not attempted.

3.6. Ad Hoc Breakout Group on Deepwater Operational Process Issues Breakout Group, April 23, 1997
Moderated and Complied by Gail Rainey, MMS

3.6.1. Overview

The MMS has acquired considerable experience in the management of offshore oil and gas operations on the continental shelf. This experience and the largely traditional operational approaches undertaken by industry on the shelf have made it possible for MMS to efficiently and confidently fulfill the services compliance mandates. Industry's accelerated movement into water beyond the shelf break poses new problems; the greatest of which may be an overall uncertainty that is unavoidable with cutting edge technologies. Therefore, MMS and industry face a common problem, will the distance from shore, water depth, underlying reservoir geology, hydrocarbon geochemistry, and yet-to-be invented operations processes give rise to situations that are altogether different than what has been experienced on the shelf for more than 30 years? The first step in answering this question is to identify those areas where new information is most likely to be needed and then design appropriate reviews and studies.

3.6.2. Discharges: A Three-Phase Program of Modeling and Field Verification

Since deepwater operation must somehow span the thousands of meters between the surface and the bottom, and we know the physics of that expanse are different from shelf-depth oceanography, it is reasonable to assume that the fate and effect of deepwater discharges will also be different. Because of new technological approaches to drilling and production, we also know that the volumes and characteristics of the discharged materials may be different. Knowledge of discharge pattern is, therefore, an easily identified need. Such knowledge can be gained in a three-phase approach as outlined below.

3.6.2.1. Model Fates This approach employs appropriate physical models and predicts the fate of various hypothetical discharges (composition, rates depths varying).

3.6.2.2. Establish Chemical Markers So that the predictions may be tested, reliable chemical and/or isotopic markers could be identified in the discharge stream. These markers could also serve as long-term monitoring tools to assess transport of discharge material.

3.6.2.3. Field Study of Discharge In cooperation with actual deepwater operations, a field study could be undertaken to use the distribution of markers (discharge footprint) to test the initial models and allow for refinement.

3.6.3. Spill Concerns, Generic and Habitat Specific

3.6.3.1. Generic Although spills by nature are unforeseeable events, in the mature development areas of the Gulf of Mexico, the MMS can rely on past experiences to predict may factors regarding spill behavior. As industry rapidly expands operations into deeper waters, more information is needed on risks, fate and effects, and response capabilities, if a spill were to occur. The breadth of concern suggests that an appropriate start would be to conduct a study of environmental risk and a partitioning assessment of spill risk from deepwater surface facility types, subsea completions, flexible riser use, and deepwater pipeline transport.

Sources New potential sources that could result in larger spill sizes are expected. These sources include the extended well testing procedures that may occur, different oil storage, new types of production facilities, and new methods of transporting the oil from the well site to the surface facility and from the surface facility to shore. Traditional sea bottom-supported platforms handling oil from a few wells may be replaced by subsea well complexes or by large central processing and storage facilities in deepwater. Floating production facilities will function as a hub for production from other floating facilities and from multiple subsea well locations. The produced well stream may be carried from the subsea well to the surface vessel though the water column a great distance by risers (flexible gathering lines that must remain suspended in the water column) rather than trenched on the seafloor in order to allow for movement of the floating structures above. Very little is known about their risk of oil spillage. Shuttle tankers are expected to be used to service some floating production systems.

Subsea Blowouts/Pipeline Ruptures A deepwater spill may occur at the seafloor thousands of feet below the surface of the Gulf because of a blowout or large pipeline rupture. There is very little understood about how the slick would behave and change over time as the result of the transport processes acting on the spilled oil. Wheat are the countermeasures for subsea well blowouts in deepwater? If the oil were to reach the sea surface, it may consist of oil droplets that would form a very thin surface slick spread out over a larger area requiring a very different cleanup approach. This slick may dissipate rapidly. Not all of the oil originally released may reach the surface in the form of a surface slick. A significant question is the areal extent and length of time water column organisms will be exposed to spills occurring on the seabed prior to the spilled oil forming a slick on the surface of the water.

High Flow Rates Industry anticipates high levels of production and much higher rates of pumping when pipelines are used. This implies that spill volumes may be higher as well. What are the appropriate spill response plans and engineering countermeasures?

New Crude Oil Characteristics Crude oil composition from deepwater fields may be different from crude oil generated on the shelf. Preliminary data show some crudes having very different weathering and buoyancy characteristics, and there may be differences in the fate and effects of these crudes once spilled. The weathering pattern of the deepwater spill will govern the residentce times that a slick will remain on the surface of the water and potentially be transported to shore and how easily they can be cleaned up. Characterization studies must be undertaken in order to determine which resources will be at risk and what response strategies would be most appropriate.

Flowline Enhancers In order for infrastructure systems to safely and economically produce in the severe, remote environment of deepwater, a wide range of specialty chemicals is needed to ensure well performance and resource recovery. Uses can include production treatment chemicals, gas processing chemicals, stimulation and workover chemicals, and flow enhancers. Subsea systems are expected to require more extensive and frequent use of chemical products to maintain multiphase flow and inhibit the formation of waxes, hydrates, corrosion, and asphaltene buildup in the flowlines. these chemicals may be stored at shoreline facilities, transported by vessel or pipe for long distances, and stored on offshore surface structures prior to usage. These chemical products may contain hazardous or toxic substances and could generate hazardous wastes. Of concern is the risk of spills occurring, especially spills of significant volume, the environmental impact caused by spills that could occur, and the ability of industry to respond. Research is needed on the risk of spillage of these compounds, including mixtures of these compounds and oils, on their fate and effects in the marine environment, and in response strategies.

Increase In Pipeline Landfalls Will increased flow and possibility of new pipeline contents increase the risk of spills in the coastal wetlands and barrier islands.

3.6.4. Abandonment: Anticipating Future Regulation

Presumably abandonment of deepwater structures is still decades in the future. However, as it becomes increasingly hard to work on the sea floor, it is reasonable that industry will prefer abandonment to removal. Presumably navigational and fisheries restrictions will be less in deepwater. A central issue in abandonment is whether some reef benefit is achieved. It is well established that artificial reefs in the photic zone give rise to diverse and highly productive communities. Even at poorly lighted shelf depths there is a fish attracting benefit for disposed material. However, is there any real benefit for disposal at 1000 m or 2000 m in an aphotic environment with no sport fish? The question is, in part, semantic. It is, however, possible to assess secondary productivity and fish attraction of deep structures.

4. Setting Priorities on Future Studies

4.1. A Warning on Limitations

Whenever a list of priorities is made there is always a danger that the contents will be remembered but the limitations forgotten. The projects suggested here reflect the ideas and discussion of a limited number of people who had to restrict their focus in order to fit activities into two-and-a-half days. Therefore, there are omissions. Most notably, the ecology of the offshore upper ocean and mesopelagic region received scant attention. Similarly, the issue of new toxicological problems with deep oil and produced water was poorly discussed.

It is recommended that MMS continue the discussions begun in the ad hoc breakout groups on fisheries (Section 3.5) and operations (Section 3.6). Development of white papers on these two areas addressing the list of topics in this workshop report could serve as a good starting place for additional workshops or discussion groups. Since upper ocean fisheries are the most likely to be impacted, the topic of water column ecology could be addressed simultaneously.

4.2. The Three-tiered Cost Step Function

While priorities should always be first assigned on the basis of information needs, cost must be considered. The costs of meeting deepwater information needs will have three levels.

4.2.1. Level One

Collection of socioeconomic data, and the collection and synthesis of archived physical, geological, and biological oceanography data are activities that are free of offshore logistical costs. Labor and indirect charges should be the primary cost items. Therefore, the highest cost/benefit tasks will probably be found in this category.

4.2.2. Level Two

This is a rather gray area that includes offshore data gathering in which operational costs are shared with or entirely covered by a partner. Piggyback projects with vessel operating organizations such as industry, NOAA, NSF, and ONR are possibilities. Setting up level two projects will require considerable effort on the part of MMS and potential investigators. Examples of projects that might be put in this level are MMS-industry geology and ecology of specific lease blocks and experimental studies of impact at development sites using platform-based ROV's.

4.2.3. Level Three

Offshore vessel-based research has high and unavoidable logistical costs. Large scale ecological, geological, and physical studies will fall into this category.

When budgets are constrained and the information needs broad, then level one activities are the most attractive options. However, the need for MMS to be at sea with industry studying the deep environment is absolutely unavoidable if the service's mandates are to be taken seriously. Therefore, there is considerable benefit in identifying high need level three projects and partnering to make them level two. A serious obstacle that must be resolved in such partnerships is that most potential partners who might share logistical costs lack deepwater expertise. In the case of federal partners, the increasing focus inshore runs counter to MMS and industry's movement in the opposite direction.

4.3. Top Priority Tasks by Discipline

4.3.1. Socioeconomic Studies

Initiate large scale industry and labor force analysis. Starting immediately will miss the earliest effects of deepwater development now underway, but it is not to late to precede larger effects. (Cost Level One)

4.3.2. Physical Oceanography

Inventory, apply QA/QC procedures, compile, make accessible, and summarize existing data at MMS, industry, and academic archives. (Cost Level One)

Initiate development of a dynamic model that can assimilate both in-the-sea and remote sensing data. This is a necessary tool for interpretation for archived and new data. (Cost Level One)

Undertake intensive observation to determine characteristics of motions on the Louisiana-Texas slope focusing upon two dynamically distinct areas, the central GOM slope and the "eddy graveyard" off south Texas. (Cost Level Three)

4.3.3. Geology/Geohazards

Inventory, apply QA/QC procedures, compile, make accessible, and summarize existing data at MMS, industry, and academic archives. This information transfer activity must overcome proprietary concerns. (Cost Level One)

Assure that highest resolution possible bathymetry is available. This is a necessary prelude to additional studies. (Cost Level One)

Explore use of 3D seismic data for geohazard identification. (Cost Level One)

4.3.4. Ecology

Inventory, apply QA/QC procedures, compile, make accessible, and summarize existing data from Pequegnat and NGMCS. QA/QC activity must focus upon high likelihood of taxonomic error in NGMCS. (Cost Level One)

Seek opportunities for MMS-Industry use of manipulative experiments at existing deepwater development sites. (Cost Level Two)

Initiate Gulf-scale characterization of Deep Gulf benthos employing comprehensive survey and trophic function measurement. This assumes Mexican collaboration. (Cost Level Three)

4.4. Second Priority Tasks by Discipline

4.4.1. Physical Oceanography

Embed within larger scale study, characterize flow fields associated with bottom topography.

4.4.2. Geological/Geohazards

Undertake surface sediment surveys focusing upon geotechnical properties. The scope must be determined from gaps not filled by industry. (Cost Level Three)

4.4.3. Ecology

Expand geographic scope of chemosynthetic community study focusing on population dynamics of the community. (Cost Level Three).

5. References

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APPENDIX I. Workshop Agenda

MINERALS MANAGEMENT SERVICE
GULF OF MEXICO OCS REGION
ENVIRONMENTAL DEEPWATER WORKSHOP
APRIL 22-24, 1997

TUESDAY MORNING, APRIL 22 -- PLENARY SESSION

Ballroom C -- Second Floor

8:30 a.m.	Welcome	Dr. Robert Carney, Louisiana State University
8:40 a.m.	MMS Perspective	Mr. Chris Oynes, Regional Director, Gulf of Mexico OCS Region
9:10 a.m.	Industry Perspective	Mr. Paul Hays, Texaco
9:40 a.m.	Geologic Overview	Dr. Harry Roberts, Louisiana State University
10:10 a.m.	Break	
10:30 a.m.	Physical Oceanography Overview	Dr. Worth D. Nowlin, Texas A&M University
11:00 a.m.	Biologic Overview	Dr. Gilbert Rowe, Texas A&M University
11:30 a.m.	Socioeconomic Overview	Dr. F. Larry Leistritz, North Dakota State University
12:00 p.m.	Work Group Instructions and Ground Rules	Dr. Robert Carney, Louisiana State University
12:10 p.m.	Lunch Break	

TUESDAY AFTERNOON, APRIL 22 -- CONCURRENT WORKING GROUPS

1:30 p.m. **ENVIRONMENTAL/GEOHAZARD Working Group Convenes**

Ballroom C -- Second Floor

Chairs: Dr. Robert Carney, Louisiana State University
Dr. Robert Avent, Minerals Management Service
Dr. Harry Roberts, Louisiana State University

Overview, Instructions, Ground Rules.
Identification of Ecological, Geological, and Overlap Issues.
Structuring and Scheduling of Ecology and Geology.

3:00 p.m. Break
3:20 p.m. Reconvene
5:00 p.m. Adjourn

1:30 p.m. **SOCIOECONOMIC Working Group Convenes**
Audubon D -- Sixth Floor
Chairs: Dr. Charles Tolbert, Louisiana State University
Dr. Harry Luton, Minerals Management Service
Overview, Instructions, Ground Rules.

1:45 p.m. Deepwater Scenarios
3:00 p.m. Break
3:20 p.m. Reconvene/Invited and audience responses, identification of key issues, formation of breakout groups.
5:00 p.m. Adjourn

1:30 p.m. **PHYSICAL OCEANOGRAPHY Working Group Convenes**
Audubon E -- Sixth Floor
Chairs: Dr. Steve Murray, Louisiana State University
Dr. Alexis Lugo-Fernandez, Minerals Management Service
Overview, Instructions, Ground Rules.

1:45 p.m. Mr. Michael Vogel, Shell
Industry Knowledge of Deepwater and Physical Oceanography/Current Data Needs
Discussion and Individual Short Presentations on Research Ideas and Plans

3:00 p.m. Break
3:20 p.m. Reconvene

Dr. Peter Hamilton, SAIC
Eddies in the Northern Gulf of Mexico Velocity Structure, Kinematics, etc.
Discussion and Individual Short Presentations on Research Ideas and Plans

Dr. Robert Leben, University of Colorado
Altimetry and Eddies: Implications to Circulation
Discussion and Individual Short Presentations on Research Ideas and Plans

5:00 p.m. Adjourn

WEDNESDAY, APRIL 23 -- CONCURRENT WORKING GROUPS

8:30 a.m. **ENVIRONMENTAL/GEOHAZARDS Working Group Reconvenes**
Ballroom C -- Second Floor
Chairs: Dr. Robert Carney, Louisiana State University
Dr. Robert Avent, Minerals Management Service
Dr. Harry Roberts, Louisiana State University
Subgroups meet jointly to review progress and confirm schedule then breakout for continued discussions.

10:00 a.m.	Break
10:20 a.m.	Reconvene
12:00 p.m.	Lunch Break
1:30 p.m.	Reconvene
3:00 p.m.	Break
3:20 p.m.	Reconvene/Subgroups reconvene jointly to assemble report
5:00 p.m.	Adjourn

8:30 a.m. **SOCIOECONOMIC Working Group Reconvenes**
Audubon D -- Sixth Floor
Chairs: Dr. Charles Tolbert, Louisiana State University
Dr. Harry Luton, Minerals Management Service
Group Instructions.

8:45 a.m.	Breakout Groups (as identified during previous afternoon)
10:00 a.m.	Break
10:20 a.m.	Reconvene
12:00 p.m.	Lunch Break
1:30 p.m.	Reconvene/Breakout Groups
3:30 p.m.	Break
3:45 p.m.	Reconvene/Group Reports and Discussion
5:00 p.m.	Adjourn

8:30 a.m. **PHYSICAL OCEANOGRAPHY Working Group Reconvenes**
Audubon E -- Sixth Floor
Chairs: Dr. Stephen Murray, Louisiana State University
Dr. Alexis Lugo-Fernandez, Minerals Management Service

Mr. Kent Schaudt, Marathon Oil
Industry Knowledge of Gulf of Mexico Eddies and Other Problems
Discussion and Individual Short Presentations on Research Ideas and Plans

Dr. Robert L. Smith, Oregon State University
Experience On The West Coast Slope
Discussion and Individual Short Presentations on Research Ideas and Plans

10:00 a.m.	Break
10:20 a.m.	Reconvene

Dr. Thomas J. Shay, University of North Carolina
Gulf Stream Rings and Their Impact on the New England Slope
Discussion and Individual Short Presentations on Research Ideas and Plans

Dr. Georges Weatherly, Florida State University
Near Bottom Currents and the Bottom Boundary Layer
Discussion and Individual Short Presentations on Research Ideas and Plans

12:00 p.m.	Lunch Break
1:30 p.m.	Reconvene

Dr. Masamichi Inoue, Louisiana State University
Numerical Modeling Deepwater Results
Discussion and Individual Short Presentations on Research Ideas and Plans

3:00 p.m.	Break
3:20 p.m.	Reconvene/Design of Strawman Experimental Plans - Group
5:00 p.m.	Adjourn

THURSDAY MORNING, APRIL 24 -- PLENARY SESSION
Ballroom C -- Second Floor

8:30 a.m.	Introduction	Dr. Robert Carney
8:40 a.m.	Session Reports	Respective Chairs
10:00 a.m.	Break	
10:20 a.m.	Reconvene/Conclusion/ Discussion	Dr. Robert Carney
11:20 a.m.	Adjourn Chairs meet to plan report	

APPENDIX II. Attendance List

LSU SHORT COURSES AND CONFERENCES

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APPENDIX III.
Papers Presented at the Physical Oceanography Session

Physical Oceanography of the Gulf of Mexico; an Overview

by

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My objective is to briefly review or mention physical phenomena or processes in the Gulf of Mexico that may significantly impact the current regimes.

1. Water Masses of the Gulf of Mexico

We show in Table 1 the names, depth ranges, densities, and identifying characteristics of the remnants of the principal water masses found in the Gulf of Mexico, excluding the highly variable surface waters. Figure 1 shows plots of dissolved nitrate, phosphate, silicate, and oxygen *versus* potential density anomaly from a survey of the Caribbean Sea. The association of extrema in water mass properties with specific density surfaces is clearly seen. These waters enter the Gulf of Mexico from the Caribbean Sea through the Yucatan Strait, with a sill depth of approximately 1600 m. Below that depth, horizontal distributions of temperature and salinity within the Gulf are essentially uniform.

The T-S plots shown in Figure 2 illustrate two principal characteristics in the upper layers. Caribbean type water has a high maximum salinity marking the core of the Subtropical Underwater; this water is found within the region enclosed by the Loop Current that flows through the eastern Gulf. The second T-S distribution is characteristic of open Gulf waters outside of the Loop Current and of Loop Current rings that separate therefrom; the salinity maximum at the Subtropical Underwater core is much reduced by vertical mixing. Note the uniformity of the T-S relation below the level of the Subtropical Underwater.

2. The Loop Current and Ring Detachment

The circulation of the eastern Gulf of Mexico is dominated by the Loop Current. This is a western boundary current formed along the Caribbean coasts of Honduras and Mexico, and entering the Gulf through the Yucatan Strait between Mexico and Cuba. It is westward intensified along the eastern edge of the Campeche shelf. The current exits the Gulf through the Florida Straits. The total transport of the Loop Current is approximately 30×10^6 $m^3 \cdot s^{-1}$ with a variance of less than 10%. The sill depth of the Yucatan Strait is approximately 1600 m, and based on property distributions the current extends well below 1000 m.

The Loop Current may be confined to the southeastern Gulf of Mexico or it may extend well into the northeastern Gulf, with intrusions of Loop Current water over the DeSoto Canyon and even to the shelf edge of the Florida panhandle. The case of extension well into the Gulf is illustrated in Figure 3. This AVHRR image from 18 April 1993 shows Loop Current intrusions extending toward the continental margin in the northeast Gulf. The configuration of the Loop Current can be followed using such passive satellite retrievals unless the surface is masked by cloud cover or the Gulf waters into which the warm waters of the Loop Current are flowing are sufficiently warmed that no significant contrast is to be seen.

Figure 4 illustrates a time (20 March 1995) during which the Loop Current was confined to the southeastern Gulf. An anticyclonic current ring (Eddy Z) had almost completely separated from the Loop Current and was located to its northwest. In Figure 5 we picture the Loop Current and a newly separated ring based on Geomagnetic Electrokinetograph measurements of surface currents and geopotential anomaly of the sea surface relative to 1350 db based on a cruise during June 1967. Maximum surface speeds exceeded 125 $cm \cdot s^{-1}$ in both the ring and Loop Current. Vertical sections through both current and ring are shown in Figure 6. A deep reference near sill depth was used to should give reasonable estimates of the vertical speed distributions. It is seen that speeds up to 20 $cm \cdot s^{-1}$ extend down to 500 m and to 5 $cm \cdot s^{-1}$ down to 1000 m.

There are studies on the frequency of Loop Current intrusions into the eastern Gulf and of the frequency of Loop Current ring separation. These are clearly nonlinear processes, and the shedding of rings is chaotic with a bimodal frequency distribution. Suggested references include Sturges (1992, 1994), Sturges et al. (1993), and Vukovich (1995).

3. Background Circulation of Western Gulf

There have been only a few hydrographic surveys of the entire Gulf of Mexico made during relatively short times so that the data could be combined to obtain quasi-synoptic descriptions of the general circulation (through geopotential anomaly fields or distributions on isopycnals or core surfaces). Examples are *Hidalgo* 62-H-3, *Geronimo* cruises in the 1960s, and *Kane* 1969. The resulting patterns are similar, showing as in Figure 7, a large anticyclonic cell oriented southwest-northeast over the central western Gulf with indications of western intensification near the Mexican coast.

There has been debate in the literature regarding the mechanism for this anticyclonic circulation, and particularly the possible western boundary current along the coast of Mexico. Elliott (1979) attributed Loop Current rings as the primary source of energy for the anticyclonic circulation feature. Sturges (1993) argues that wind stress curl over the western Gulf is adequate to drive an anticyclonic circulation with a western boundary current. Moreover, he argues that there is annual variability in the wind stress curl corresponding to the strongest observed boundary current in July and the weakest in October. He reasons that the contribution of Loop Current rings to the western boundary current is relatively small. Others have attributed the presence of a northward flow along the western Gulf boundary to ring-slope-ring interactions.

There is a semi-permanent cyclonic circulation within the Gulf of Campeche which is pictured in Figure 8 (Vazquez de la Cerda 1993). A series of 13 cruises surveyed the Bay of Campeche, covering all seasons with a total of 247 CTD stations. The vertical structure of dynamic heights relative to several reference levels were decomposed using EOFs. More than 90% of the variance was accounted for by the first modes. The figure shows the average field of EOF mode 1 for dynamic height (in dynamic cm) of the sea surface relative to 425 db based on all data. Based on ADCP measurements during some of the surveys, maximum speeds of order 20 $cm \cdot s^{-1}$ are associated with this gyre. The average transport of this gyre was estimated to be 3.3×10^6 $m^3 \cdot s^{-1}$. It is suggested, based on study of climatological winds, that this cyclonic gyre is forced by the cyclonic wind stress curl; both fields have seasonal cycles.

4. Eddies

Sea surface height anomalies are being produced by removing the long-term mean sea surface height field from altimetric measures of surface height from one or more satellites. The fields being produced by Robert Leben and co-workers at the University of Colorado give very good representations of size and surface elevation for both cyclones and anticyclones in the western Gulf, as judged by statistical comparisons with geopotential anomaly fields.

Adding the mean sea surface height field can be added to interpolated sea surface height anomalies to produce a total sea surface height distribution. The Loop Current may be seen clearly, as are series of anticyclonic rings of decreasing intensity moving toward the western boundary. Such sequences of anticyclones might be compared with the anticyclone in Figure 7, which could be the result of such a sequence. Also to be seen in such representations are numerous cyclonic circulation features and some weak anticyclones. The Gulf of Campeche cyclone is a common feature.

Description and movements of Loop Current Rings

Descriptive studies of the fate of Loop Current rings after separation include two in-depth investigations: one by Elliott (1979) is based on in situ data from 1965 through 1972, the other by Vukovich and Crissman (1986) is based on satellite infrared and ship-of-opportunity data from 1973 through 1984. Based on those studies, Table 2 was prepared as a summary of pertinent information regarding translation speeds, dimensions, energy, and decay modes. There has been considerable effort expended in the modeling of the separation and subsequent behavior of warm core rings from the Loop Current. The observed lifetimes of rings are longer than simulations by most models. Lakshmi Kantha and co-workers at the University of Colorado have had considerable success in overcoming this difficulty by assimilating sea surface height anomalies from satellite altimetry into numerical forward models of the Gulf circulation to constrain them toward reality.

There are several examples of current measurements at deep water locations in the Gulf. Some of these have captured the influence of eddies. In Figure 9 are shown eastward current components measured during 1980-81 at depths between 200 and 700 m at two locations on the continental slope off south Texas (Brooks 1984). Both moorings were in water depths of approximately 730 m; mooring S was located at 26°N, mooring C at 26.5°N. The 200-m current speeds exceeded 30 $cm \cdot s^{-1}$ during 40% of the record and 50 $cm \cdot s^{-1}$ during 19% of the record. The persistent high speed event observed during October and November at mooring S was the response to a Loop Current ring that arrived in the region during September 1980. The center of that ring was located south of mooring S, but made two excursions northward in late October and early November, which caused large eastward flows at mooring C. Another anticyclone was known to have been centered south of mooring S in July—its effects are seen in eastward speeds at the beginning of the record.

Vukovich and Crissman (1986) were able to identify three preferred paths of movement of Loop Current rings across the central and western Gulf (Figure 10). Path 2 is across the open Gulf to the northwestern deep water region near 93° to 96°W and 25° to 28°N, sometimes called the eddy graveyard. Other paths place the rings into contact with the continental slope—either off Texas and Louisiana or off Mexico. Path 3 apparently occurs only when the ring shedding occurs at high latitudes in the eastern Gulf.

Eddy-slope and eddy-eddy interactions

Because of eddy-slope interactions we may expect the pattern of ring movements described by Vukovich and Crissman. Rings that propagate to the western slope off Mexico will propagate northward along the slope by nonlinear processes (self advection); this is path 1 in Figure 10. Rings that move northwestward and interact with the Louisiana and Texas continental slopes will be trapped in this waveguide and propagate linearly westward, as shown by path 3 in Figure 130 Thus, one might expect rings that endure long enough to eventually end up in the eddy graveyard off south Texas. Interactions between rings, resulting in blocking or transformation/decay may prevent many rings from following these paths and ultimately reaching the graveyard region. Suggested references include Oey (1995), Kirwan et al. (1984), Kirwan et al. (1988), Lewis et al. (1989), and Vukovich and Waddell (1991).

One instance of a Loop Current ring interacting with the continental margin in the eddy graveyard region is pictured in Figure 11. Shown are surface geopotential anomaly (dyn cm) relative to 400 m for cruises A-H05, C-F08, and C-F09 (26 April - 18 May 1993) and 10-m gridded currents ($cm \cdot s^{-1}$) averaged for two weeks before and during the cruise period. At that time a large Loop Current ring, Eddy Vazquez, was centered at about 27°N, 95°W where it interacted with the continental slope. Near-surface currents at the shelf edge north of the eddy were strongly eastward. A cyclone was located over the continental slope just west of Eddy Vazquez. Based on sea surface height anomaly data, that cyclone spun up as Eddy Vazquez began to encroach on the shelf. The combined influence of the cyclone-anticyclone pair on the continental margin was significant. Onshelf flow was observed between them and off shelf flow on either flank of the pair.

When eddies (cyclonic or anticyclonic) and wave-like oscillations of current propagate as free waves counterclockwise along the continental slope wave guide, they tend to have kinetic energy trapped near the bottom at the upper and mid-slope region (Hamilton 1990).

5. Effects of Atmospheric Storms

Hurricanes

The dramatic effects of a hurricane on currents at the shelf edge and upper slope are illustrated in Figure 12. Moorings 12 and 13 were located on the 500-m and 200-m isobaths approximately 100 km south of the location in Louisiana where Hurricane Andrew made landfall late on 26 August. Near surface currents at the shelf edge exceeded 150 $cm \cdot s^{-1}$. The storm passage appears to have triggered a near-inertial oscillation superimposed on a strong offshelf flow. In this situation, the current response seemed to decrease rapidly with depth over the upper slope: currents at 100 m did not exceed 50 $cm \cdot s^{-1}$; those near the bottom at 490 m were generally less than 5 $cm \cdot s^{-1}$.

Another example of the effects of a hurricane on the continental slope can be seen in Figure 9. In that case the moorings were located in 730 m water depths. The path of Hurricane Allen passed northwestward approximately 60 km southwest of mooring S on 9 August 1980. The along-shore surge that occurred with the storm passage gave current speeds in excess of 90 $cm \cdot s^{-1}$ at 200 m, decreasing to 15 $cm \cdot s^{-1}$ 32 m above the bottom. The ensuing inertial oscillations were elliptical with along-shore currents that reached a maximum range of 50 $cm \cdot s^{-1}$ within 3 days and decayed with a time scale of about 5 days (Brooks 1983).

Other cases of tropical storm effects on measured currents over the continental slope are given by Molinari and Mayer (1982) for the northeastern Gulf of Mexico.

Cyclones

There are on average some ten cyclones generated annually over the northwest Gulf of Mexico (Saucier 1949), most of which are formed from November through May. Based on experience during LATEX, these atmospheric storms can greatly affect ocean currents over the continental shelf and slope.

Currents at 12 and 100 m from a mooring at the 500-m isobath on the slope south of the Texas-Louisiana border are shown in Figure 13 for 5-25 March 1993. At about 1300 UTC on 12 March, the eye of a developing cyclone moved from over land in Mexico to the Texas continental margin. The storm rapidly deepened, moved eastward, made landfall over the Florida panhandle at 0900 UTC 13 March, and, after causing havoc along the eastern U.S., became known as the "storm of the century".

Following the storm's passage from the region there was a net northeastward flow at 12 m and an eastward flow at 100 m which lasted about five days. Superimposed were inertial oscillations that continued for about ten days; the maximum range of those oscillations at 12 m was near 50 $cm \cdot s^{-1}$. Currents are much diminished at 100 m, but still show a maximum range of oscillation greater than 20 $cm \cdot s^{-1}$.

Cold air outbreaks

Passages of cold air from the continent to the Gulf of Mexico are quite common. They occur with frequencies of four to nine per month during fall, winter, and early spring months. Some of these fronts do not reach the outer edge of the continental shelves, but many do. During LATEX, numerous cold air outbreaks were evident in the current records.

Figure 14 shows an example of effects at a mooring in 500 m of water off the south Texas shelf. A weak cold front passed over this shelf on 1-2 November 1992 setting up inertial oscillations at all three sampled depths (12, 100, and 490 m). These were greatly enhanced at the two upper levels by the passage of a strong, fast-moving cold front on 4 November. The range of inertial oscillations at 12 and 100 m were comparable: 20-30 $cm \cdot s^{-1}$. They continued for three to four days after the second frontal passage. Oscillations at 490 m were mainly cross-shelf, with maximum range of 20 $cm \cdot s^{-1}$.

The effects of cold air outbreaks on currents over the lower continental slope off Mobile, at the head of DeSoto Canyon, and off Tampa have been reported by Molinari and Mayer (1982). Measurements were made at depths between 90 and 980 m with record lengths to 358 days. At depths of 90 and 150 m the currents generated by cold fronts were comparable to those measured by LATEX A. Also seen were effects of a Loop Current intrusion and both a tropical storm and a hurricane in the Gulf.

6. Currents in Submarine Canyons

Submarine canyons are common features of the world's oceanic margins. They are known to be conduits through which sediments on the shelf transit to the deep ocean and are suspected to be conduits through which deep waters may be brought to the shelf. Theoretical studies suggest that currents in submarine canyons with characteristic widths that are wide relative to the baroclinic Rossby radius follow the bathymetry while flows in narrow canyons have a strong ageostrophic component and move down the pressure gradient. As a canyon becomes narrow shoreward it constricts the flow and currents, including tidal currents, may be intensified. While there have been several current meter studies designed to investigate currents in submarine canyons along the Pacific and Atlantic coasts (Monterey, Lydonia, and Baltimore Canyons), and numerous ancillary current records exist for other canyons, public studies in the Gulf of Mexico seem limited, though industry may have records in their archives. The MMS sponsored study of DeSoto Canyon will be the most comprehensive canyon study in the Gulf to date. However, because DeSoto is a wide canyon (relative to the Rossby radius), results from this study may not be applicable to other narrower Gulf canyons such as the Mississippi, Alaminos, or Keathy canyons.

7. Deep and Bottom Currents

During 1967-1969 a series of short current measurements were made in the bottom 10 m of the water column at stations clustered around 25.5°N, 86°W in the eastern Gulf of Mexico (Pequegnat 1972). Water depths ranged from 3074 to 3286 m. The results showed currents toward differing directions with speeds ranging from 6 to 19 $cm \cdot s^{-1}$. At the time, those measurements raised a few eyebrows. Since then, the few deep and near-bottom measurements available from the Gulf have substantiated the occurrence of such episodic deep currents.

Examples of near-bottom current measurements include those from the MMS-sponsored Physical Oceanography Program mooring G (25° 36.2'N, 85° 29.8'W in 3200 m water depth). Instruments produced records at 2364 and 3174 m for the latter half of 1984 and for 1985. Episodic events with currents as large as 10-20 $cm \cdot s^{-1}$ were observed and related to Loop Current movements and other activities.

In Figure 15 are shown vector time series of 40-hr, low-passed currents recorded at Mooring R, located in water depth of 3505 m at 25° 29.5'N, 94° 09.6'W. These 1985 measurements were part of the MMS-sponsored Gulf of Mexico Physical Oceanography Program. Effects of episodic events are seen to extend at least down to 3000 m, and essentially to the bottom, based on evidence at mooring G from the eastern Gulf. The effects seem nearly the same from 1000 m downward—especially at 1500 and 3000 m. This is in agreement with the expected barotropic response for waters near or greater than the sill depth of the Gulf, below which density is essentially horizontally uniform. The large currents beginning in August (Julian day 229) are associated with mesoscale cyclonic and anticyclonic features; the large response beginning in October and extending to the end of the record was due to the arrival of a Loop Current ring at the western boundary. It is interesting that the response to the Loop Current ring is almost opposite in direction below and above 1000 m.

8. Surface layers

Ekman flows

During recent years there has been renewed interest in measurements of currents and transports (volume and temperature) in the surface Ekman layers (e.g., Weller and Plueddemann 1996). Although these observational programs have been mainly in the North Atlantic and Pacific oceans, the results should be applicable to the surface layer of the Gulf of Mexico.

Thermal cycling

For surface waters with large stratification diurnal heating can give rise to diurnal oscillations (Price et al. 1986). Some of the stronger currents observed by the LATEX program resulted from this diurnal cycling. An example is shown in Figure 16 from a depth of 3 m at the 50-m isobath south of the Texas-Louisiana border. Only the along-shelf components are shown because the diurnal cycling is essentially circular. Currents for March 1994 are shown in the upper panel. There is little evidence of diurnal cycling except perhaps toward the end of the month with increasing solar radiation. The phenomena is fully developed by June (lower panel). The decrease in amplitudes around 20 June was due to a frontal passage which decreased the vertical stratification. In Figure 17 are shown amplitudes of 24 hr signals from complex demodulation of along-shelf and cross-shelf currents at 14-m depth over the inner shelf south of the Texas-Louisiana border for the 32-month LATEX A measurement period. The annual cycle of the diurnal cycling is clear. This cycling is also seen at the shelf edge. However, upper instrument depths there were ≥ 10 m. At those depths the amplitudes reached approximately 10 $cm \cdot s^{-1}$. However, they could be considerably larger nearer the surface. This phenomena may occur over the open Gulf as well.

Wind waves

Observational and hindcast data The NOAA/NWS National Data Buoy Center (NDBC) currently operates ten environmental data buoys in the Gulf of Mexico. Five measure wave heights, four also measure directional wave components. NDBC reports dominant wave period, significant height, and direction—for both local seas and swell, and an overall significant height for sea and swell combined. Data are transmitted to shore hourly via the Geostationary Operational Environmental Satellites and made available via the Global Telecommunication System and on NDBC's web site.

The U.S. Army Corps of Engineers' Coastal Engineering Research Center (CERC) Wave Information Study program developed wave hindcasts in all coastal areas of the United States for the period 1956 to 1994. These data are used by Corps district offices and authorized users to determine wave climates for coastal projects, to estimate extreme wave conditions for engineering designs, and to evaluate waves during specific storm events. Software developed by CERC allows users to access the hindcast database over the internet.

Wave Forecasts/Nowcasts Products Wave nowcast/forecasts are made by several government and private agencies. The National Center for Environmental Prediction (NCEP) Ocean Modeling Branch produces wave forecasts for the Gulf of Mexico on an experimental basis and posts these on a web site. The forecasts are based on the cycle-4 version of the WAM model using 10-m winds from the NCEP's mesoscale ETA model (ETA-29). Forecasts are made for 6 hr intervals out to 36 hours. The Fleet Numerical Meteorology and Oceanography Center (FNMOC) posts unclassified global wave forecasts at 12 hr intervals (out to 120 hr) on their web site. FNMOC uses a 1/4 degree resolution WAM model forced with surface wind stress fields from the Navy Operational Global Atmospheric Prediction System. Model output is directional wave spectra, at each grid point. Significant wave height, peak period, and peak direction are derived from the spectra. Oceanweather Inc., a private company, provides daily wind and sea state forecasts using a variety of global and regional spectral wave models including the WAM model. Forecasts are generated out to 72 hr and are produced primarily in support of offshore operations. The Weather Research Center, a non-profit research and education center located in Houston, TX, posts wind and wave forecasts for the LATEX Shelf on their web site. The center operates a worldwide forecast operation center as well as a Weather Museum and Education Center.

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Biographical Sketch

Worth D. Nowlin, Jr. is a Distinguished Professor at Texas A&M University affiliated with the Department of Oceanography. He is a Fellow of the American Geophysical Union, charter member of The Oceanography Society, and member of the Sigma Xi and American Meteorological Society. His BA and MS are in mathematics; his Ph.D. in Oceanography. His principal research interests are in meso- and large-scale oceanic distributions of properties, shelf circulation, dynamics of ocean circulation, long-term and systematic ocean observations for climate studies, research planning and management. His publications are focused mostly on the Antarctic Circumpolar Current, relationships between the Southern Ocean and the global ocean, and the American Mediterranean.

Table 1. Water Masses in the Gulf of Mexico and Associated Property Extrema and Potential Densities

Water Mass	~ Depth Range (m)	Identifying Feature(s)	Sigma-theta (mg cm^{-3})
Subtropical Underwater	50-250	salinity maximum	25.40
18°C Sargasso Sea Water	150-250	oxygen maximum	26.50
Tropical Atlantic Central Water	250-500	oxygen minimum	27.15
Antarctic Intermediate Water	500-900	salinity minimum; nitrate, phosphate, and silicate maxima	27.30-27.50
Upper North Atlantic Deep Water	> 1000	salinity maximum	≥ 27.70

Table 2. Loop Current Ring Properties

Translation speeds	Vary over speeds of 1-14 km per day Average speed of 5 km per day
Diameters	Initially usually $\geq$ 250 km; typical value near 350 km Decrease by 45% within 150 days; 70% within 300 days
Swirl Speeds	60-80 $cm \cdot s^{-1}$ at surface 20 $cm \cdot s^{-1}$ down to 500 m; 5 $cm \cdot s^{-1}$ to 1000 m for new rings
Depths	Property distributions and motions extend to > 1000 m for new rings Filaments are likely confined to the upper 50-300 m
Energy	Available potential energy for typical new ring is $15 x 10^4$ $J \cdot m^{-2}$ Ratio of available potential energy to kinetic energy ~ 4.5 for new rings
Decay modes	Interactions with boundaries—formation of filaments Ring shedding; ring-ring interactions

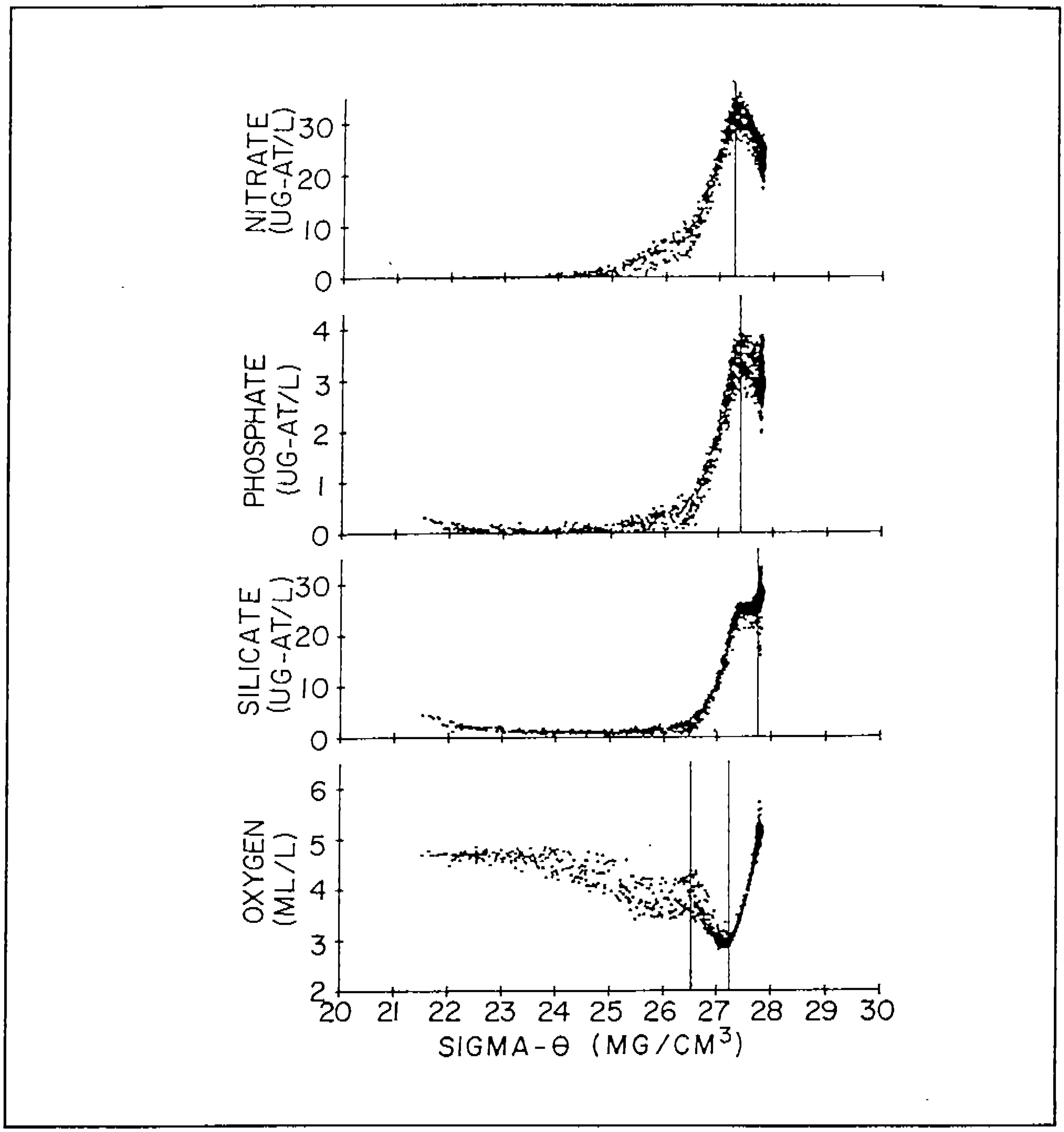

Figure 1. Systematic relationships of dissolved nitrate, dissolved phosphate, dissolved silicate, and dissolved oxygen versus sigma-theta from data collected in the Caribbean Sea. Vertical lines represent the potential density surfaces associated with the major subsurface water masses present.

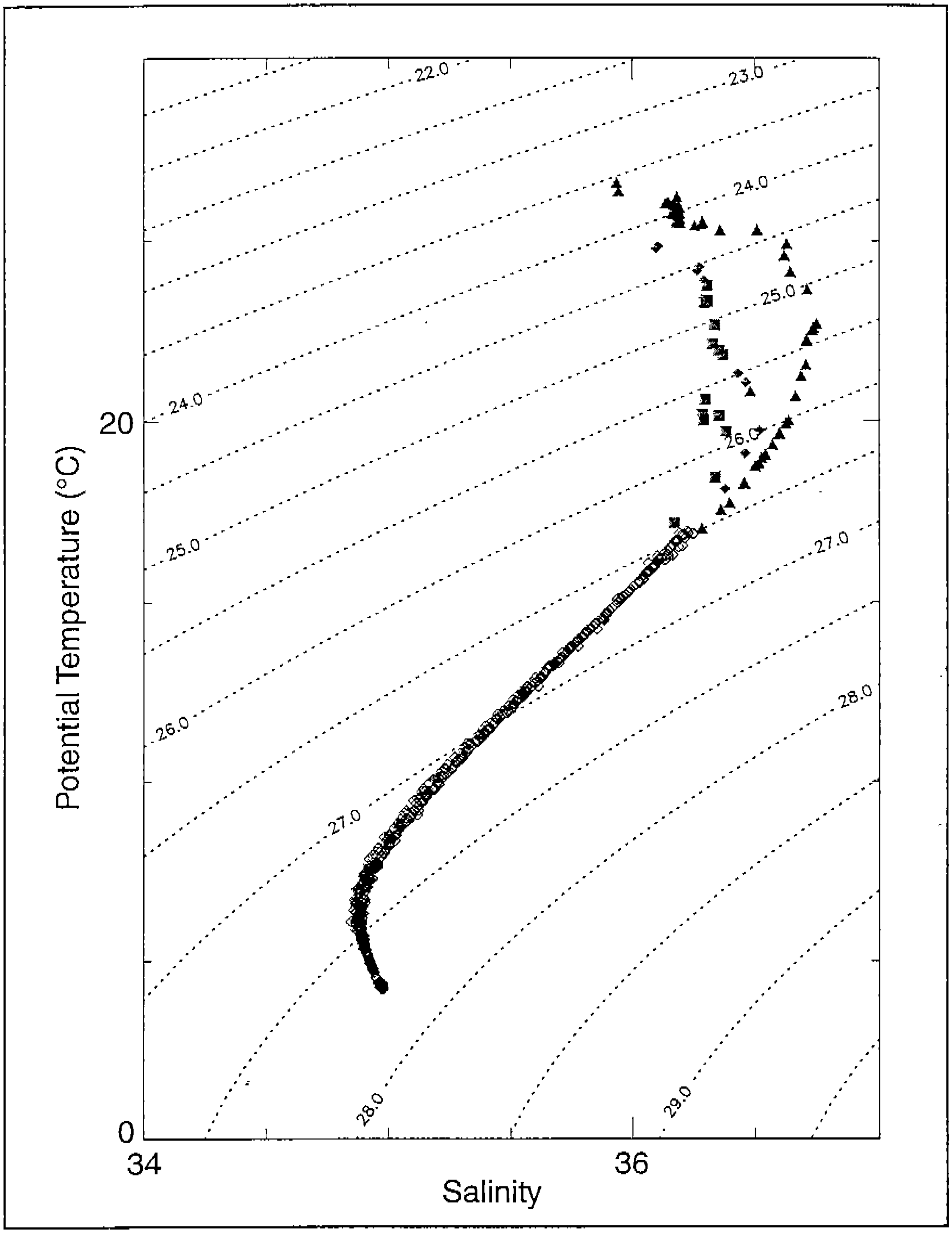

Figure 2. Example temperature-salinity relationships for the open Gulf of Mexico illustrating difference within the upper layers between Caribbean type water (solid triangles) and waters found outside the Loop Current and Loop Current Eddies in the Gulf of Mexico (filled boxes). The latter water mass is a result of vertical mixing of Caribbean type water.

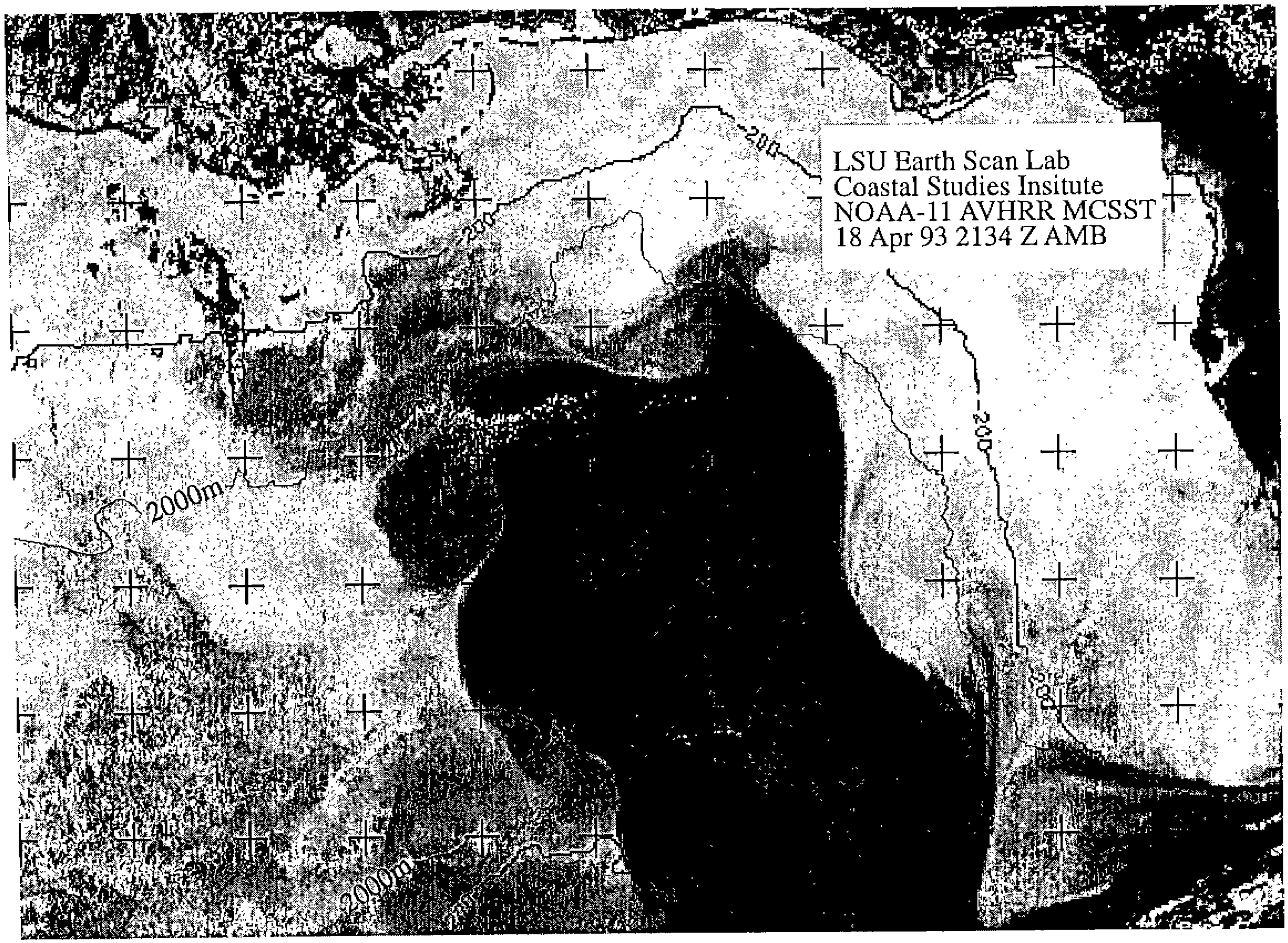

Figure 3. AVHRR image (18 April 1993) showing Loop Current extending well into the Gulf of Mexico (courtesy of Nan Walker, Louisiana State University).

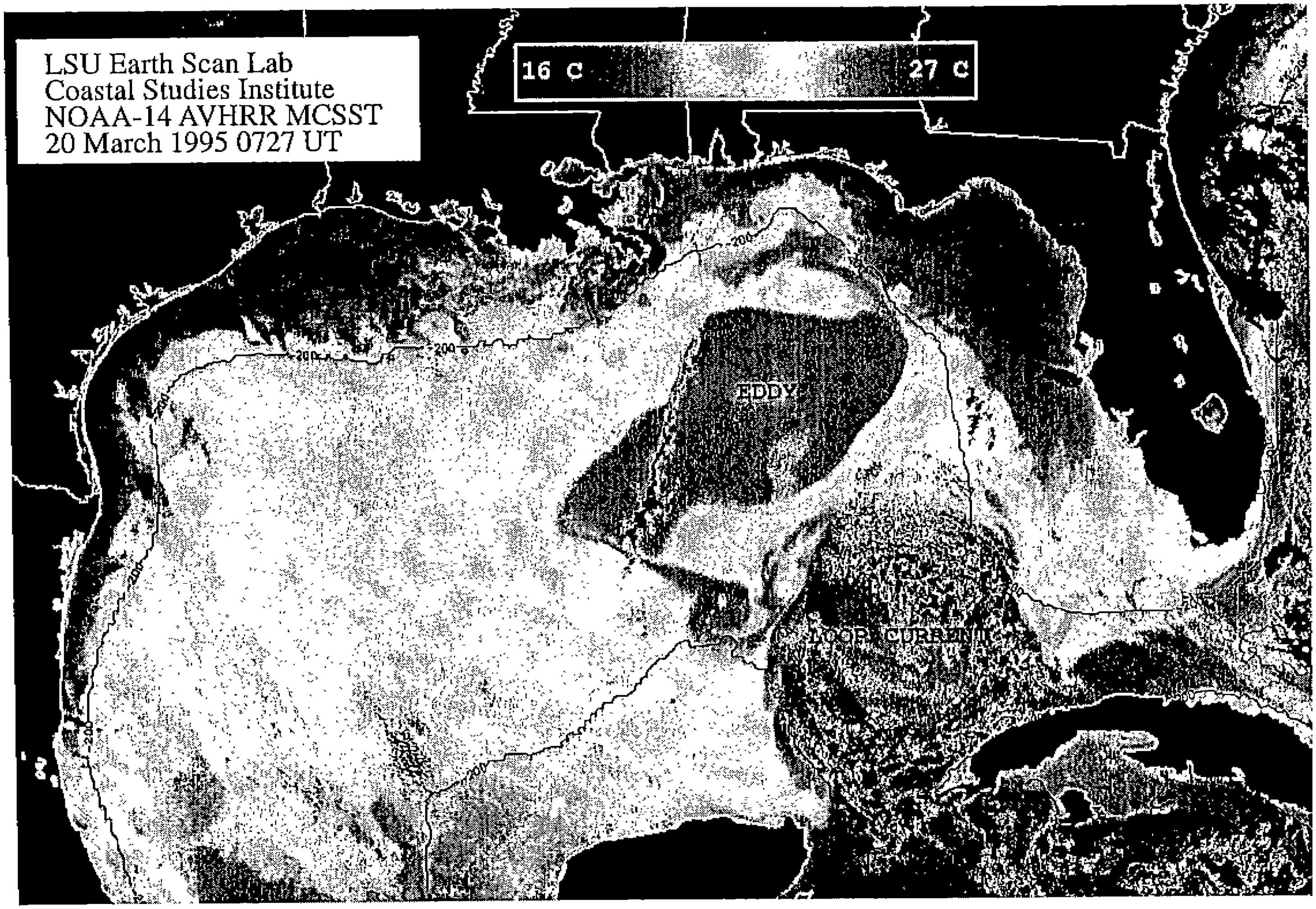

Figure 4. AVHRR image (20 March 1995) showing Loop Current extending into the southeastern Gulf with newly detached Eddy Z (courtesy of Nan Walker, Louisiana State University).

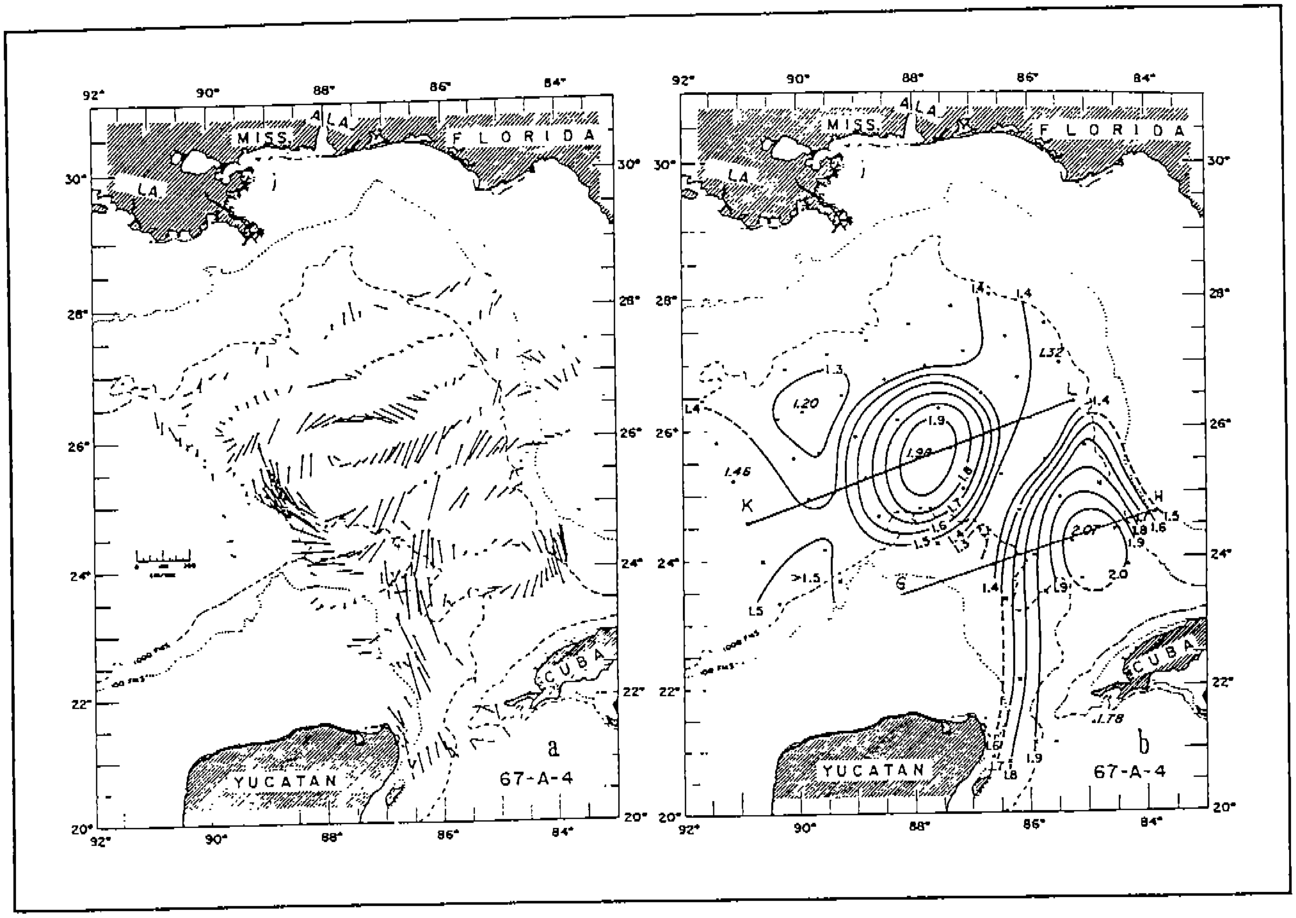

Figure 5. GEK vectors and geopotential anomaly (dynamic m) of the sea surface relative to 1350 db for *Alaminos* cruise 67-A-4 during June 1967. Station positions are shown. A newly separated anticyclonic ring is seen northwest of the Loop Current.

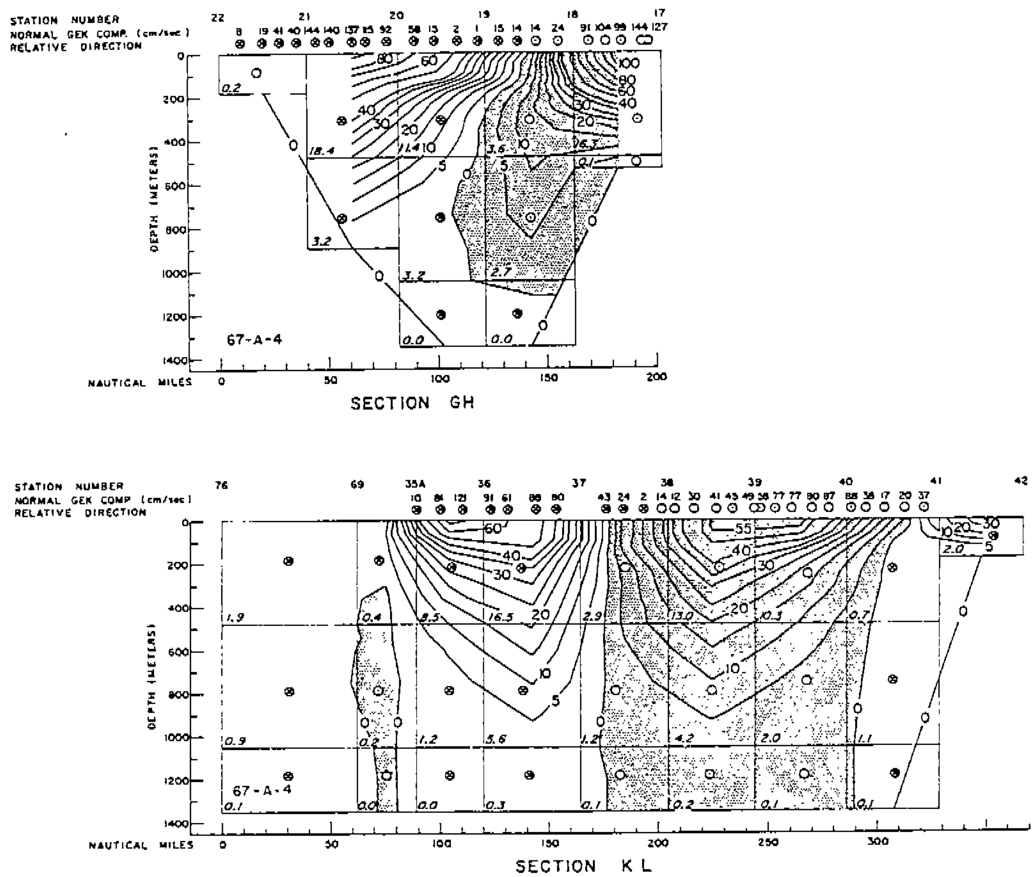

Figure 6. Isotachs of geostrophic speed ($cm \cdot s^{-1}$) relative to 1350 db, normal to section GH which passes southwest-northeast through both limbs of the Loop Current and section KL which passes southwest-northeast through the ring center. Also shown are normal components of GEK surface velocities measured along each section and relative volume transport ($10^6\ m^3 \cdot s^{-1}$) for indicated depth intervals between adjacent stations. A circled dot indicates flow toward the reader. Data are from *Alaminos* 67-A-4, June 1967.

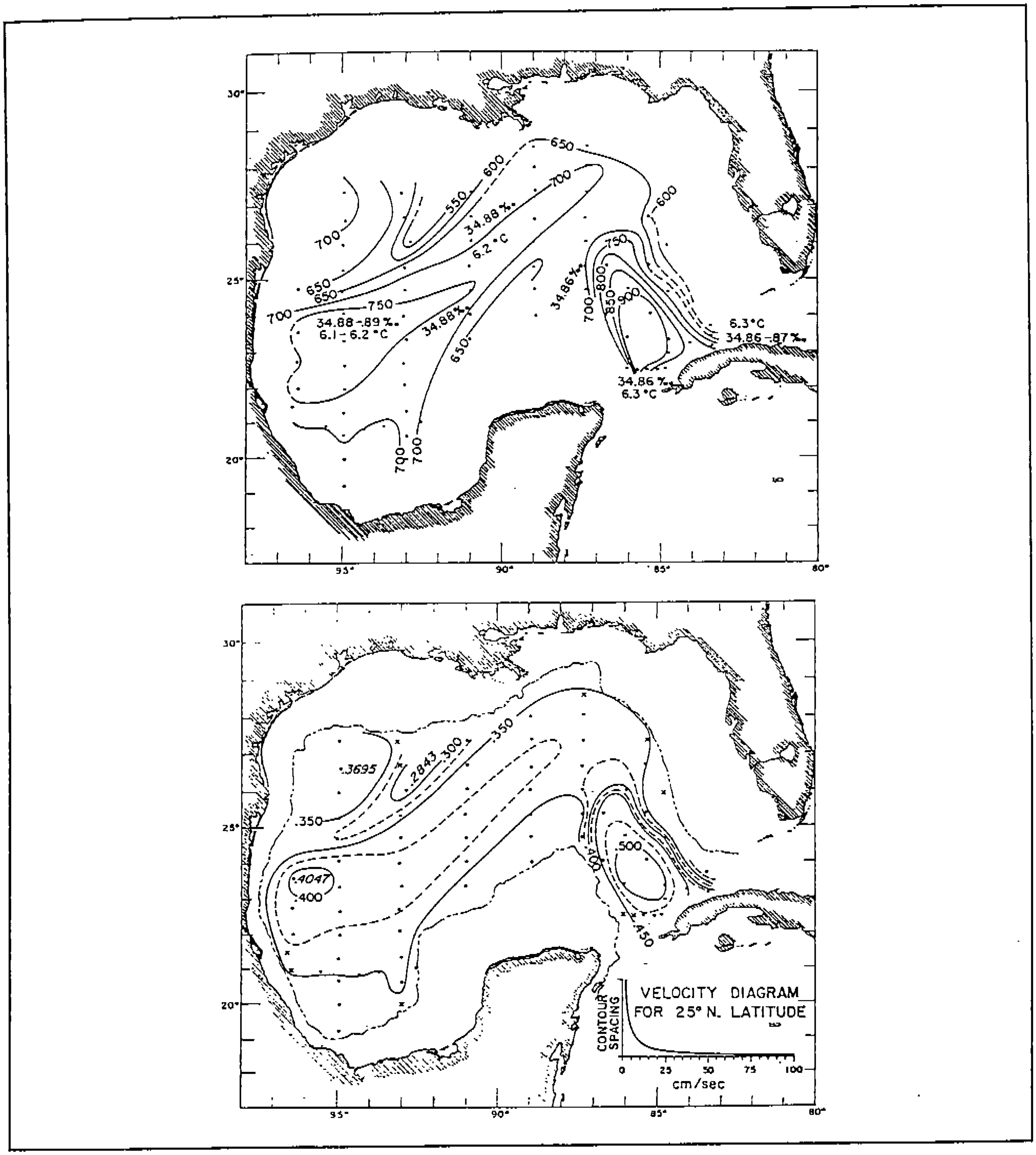

Figure 7. (Upper) Depth (50-m intervals) of salinity minimum of Antarctic Intermediate Water remnant. Selected values of temperature and salinity at the core are shown. (Lower) Geopotential anomaly of 500-db surface relative to 1000 db. Contour interval is 0.025 dynamic meters. Both based on data from *Hidalgo* cruise 62-H-3.

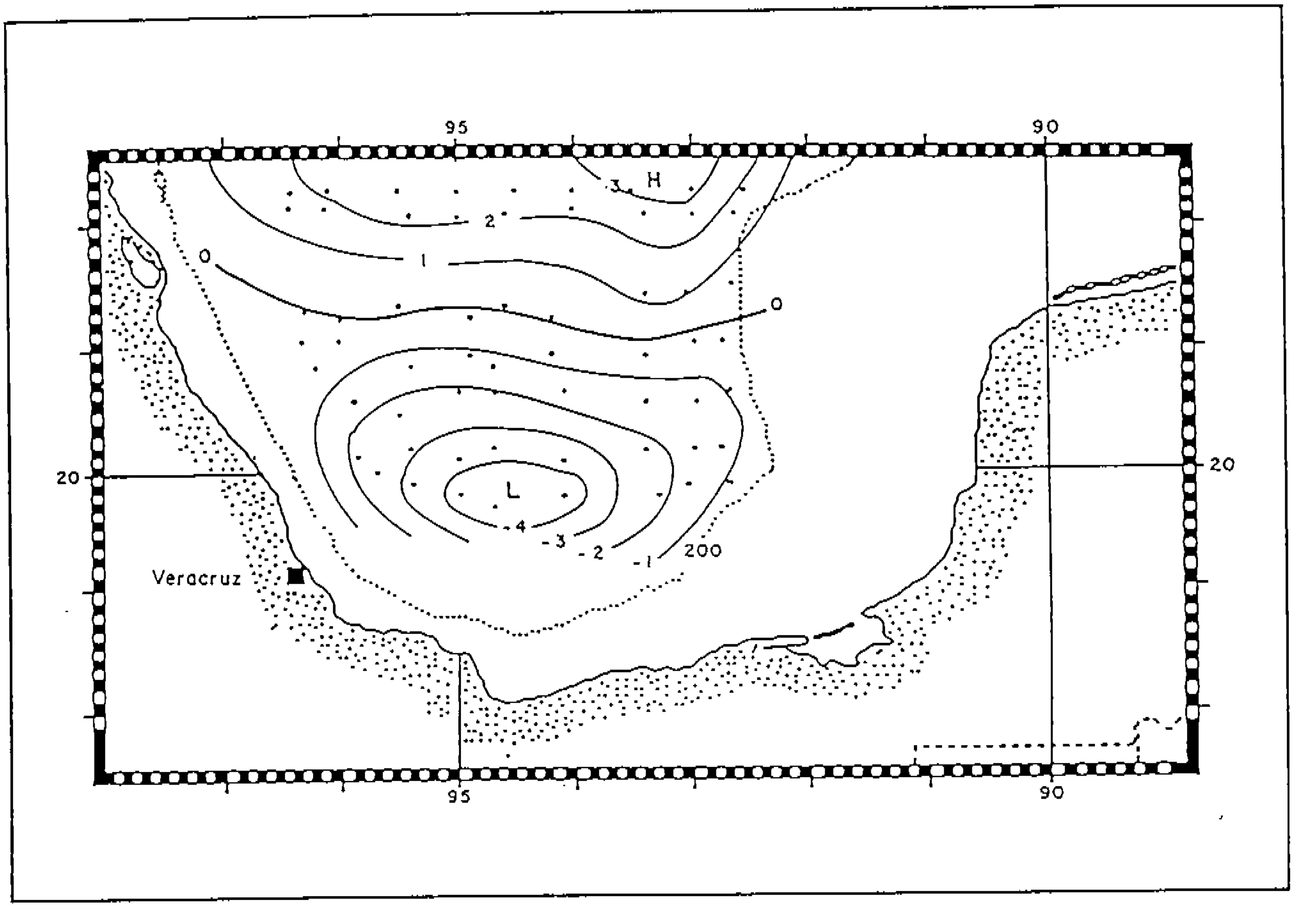

Figure 8. Contours of the average field of EOF mode 1 dynamic height (in dynamic cm) of the sea surface relative to 425 db based on 247 stations from 13 cruises covering all seasons (from Vazquez de la Cerda 1993).

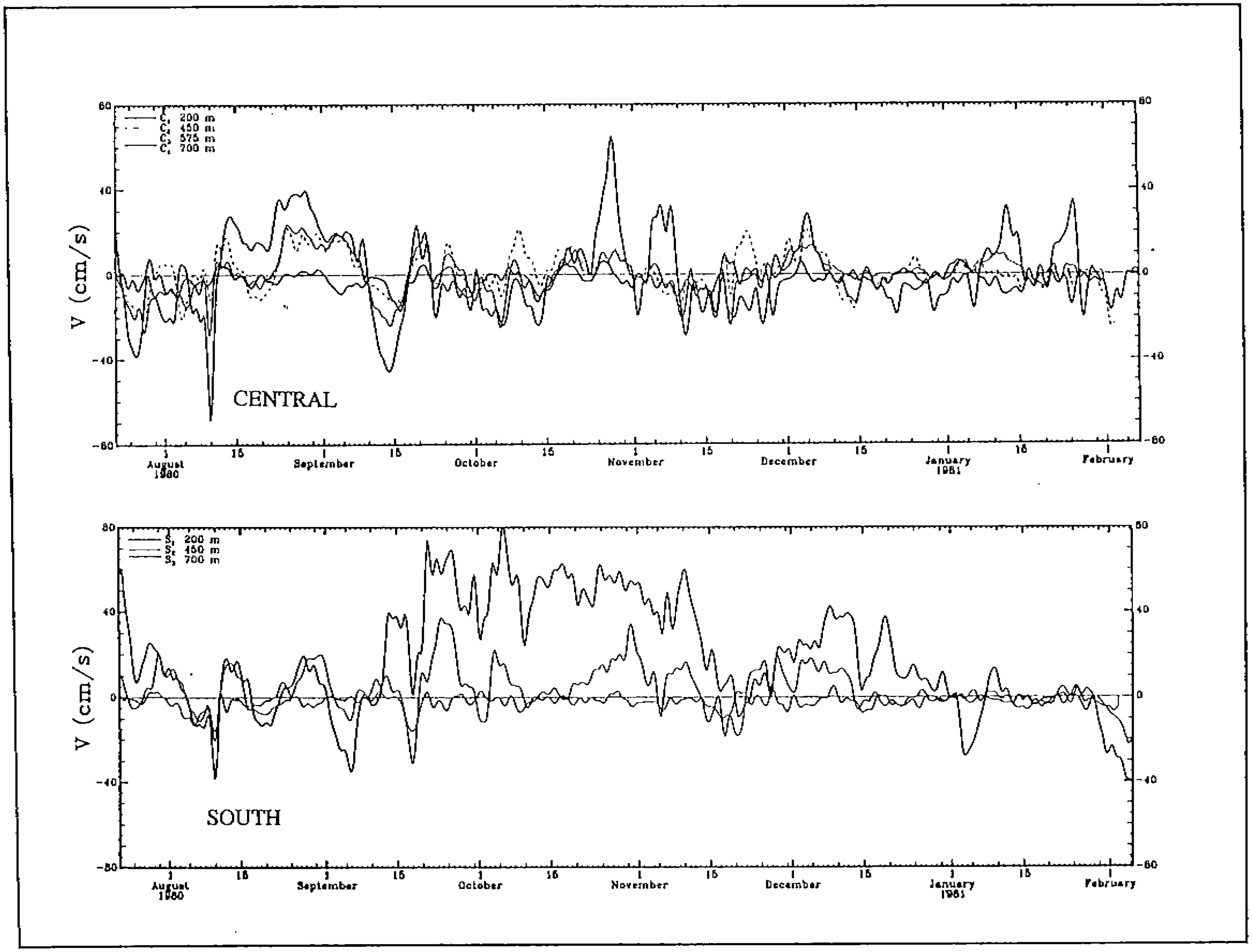

Figure 9. Eastward current components measured during 1980-1981 at depths between 200 and 700 m at two locations on the continental slope off south Texas. Both moorings were in water depths of approximately 730 m; mooring S was located at 26°N, mooring C at 26.5°N. (After Brooks 1984.)

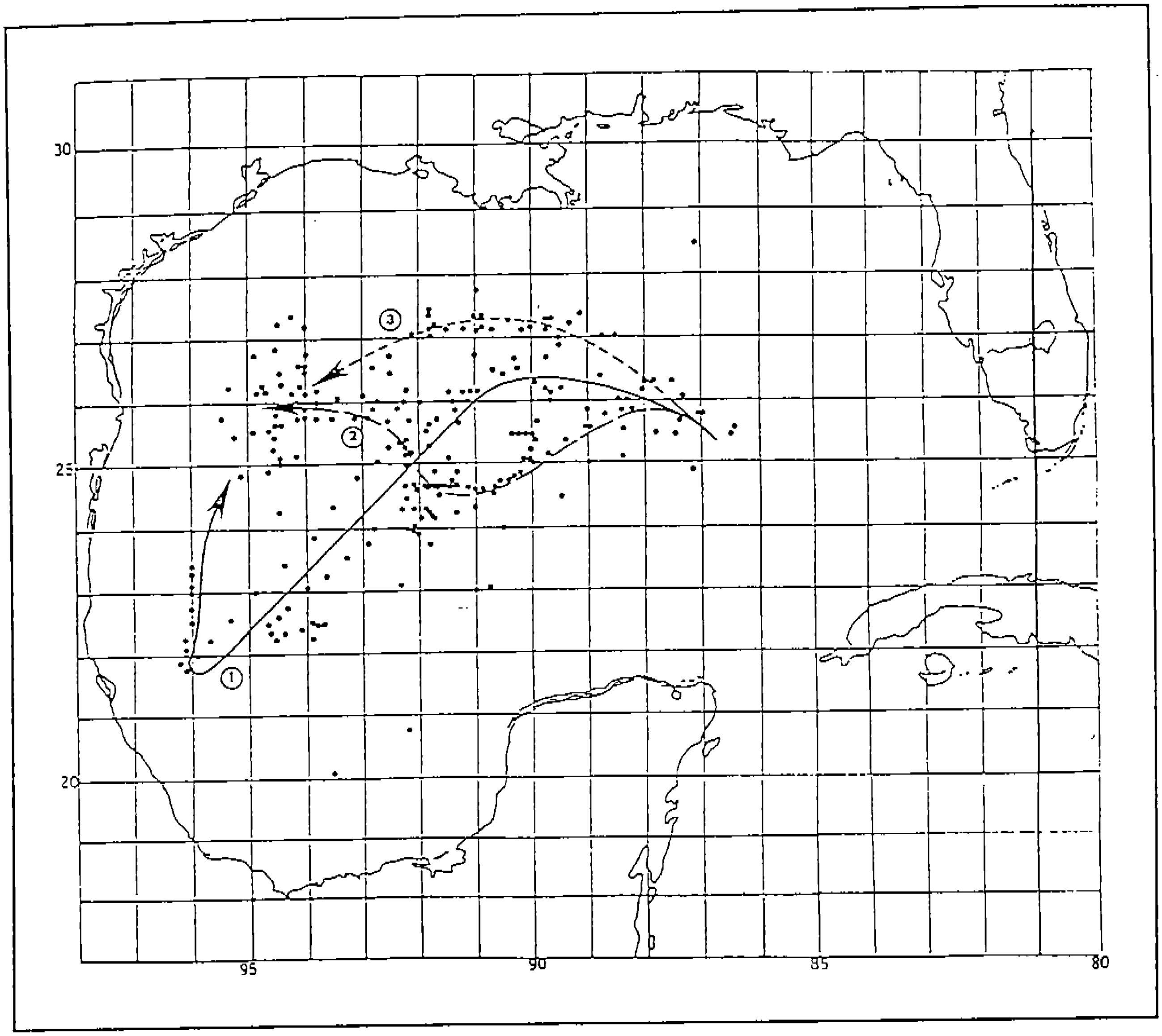

Figure 10. Positions of Loop Current rings obtained using GOES and NOAA satellite data for the period 1973-1984 and characteristic paths of such rings in the Gulf of Mexico (after Vukovich and Crissman 1986).

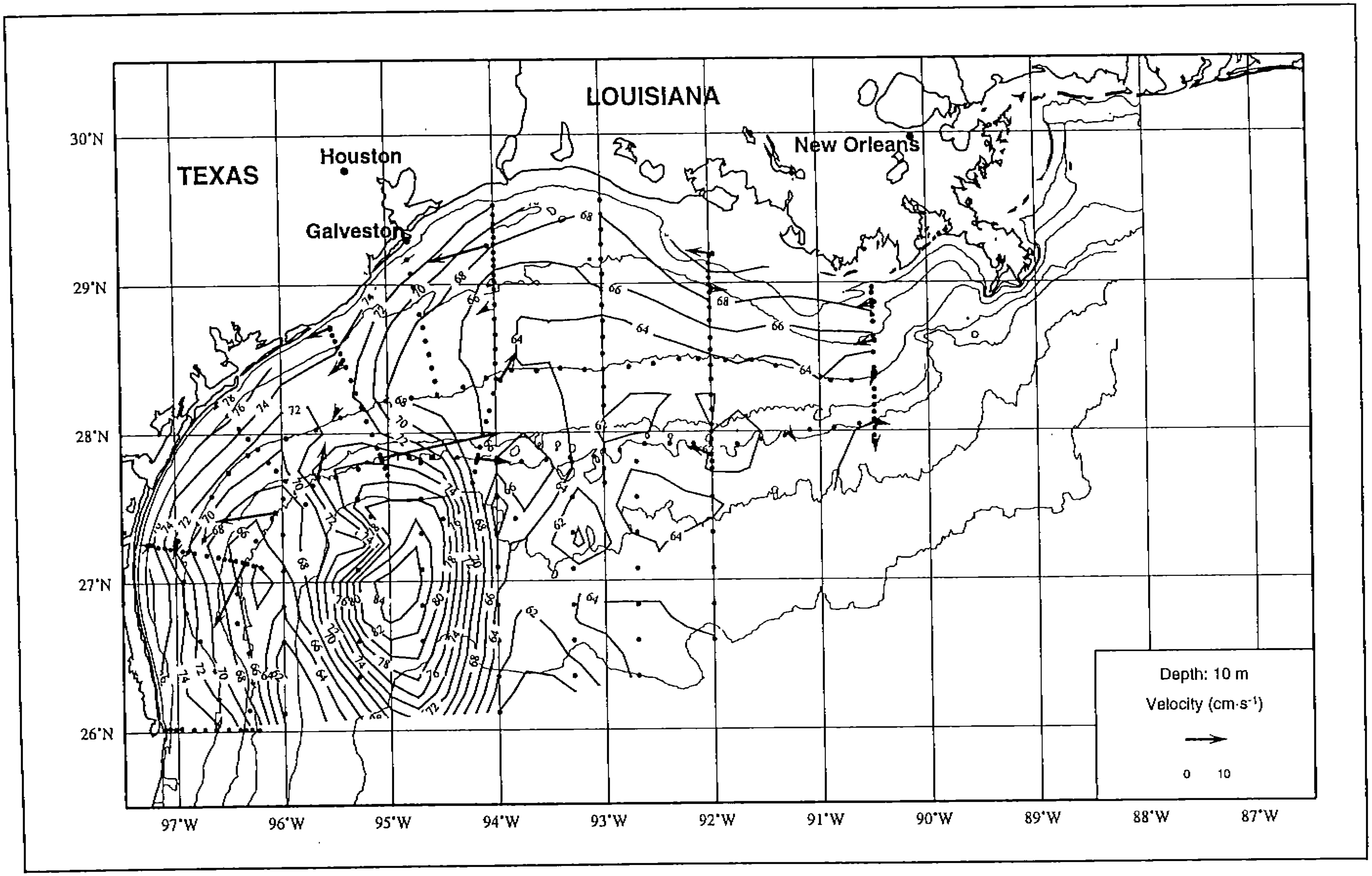

Figure 11. Surface geopotential anomaly (dyn cm) relative to 400 m for cruises A-H05, C-F08, and C-F09 (26 April - 18 May 1993) and 10-m currents (cm·s^{-1}) averaged for two weeks before and during the cruise period.

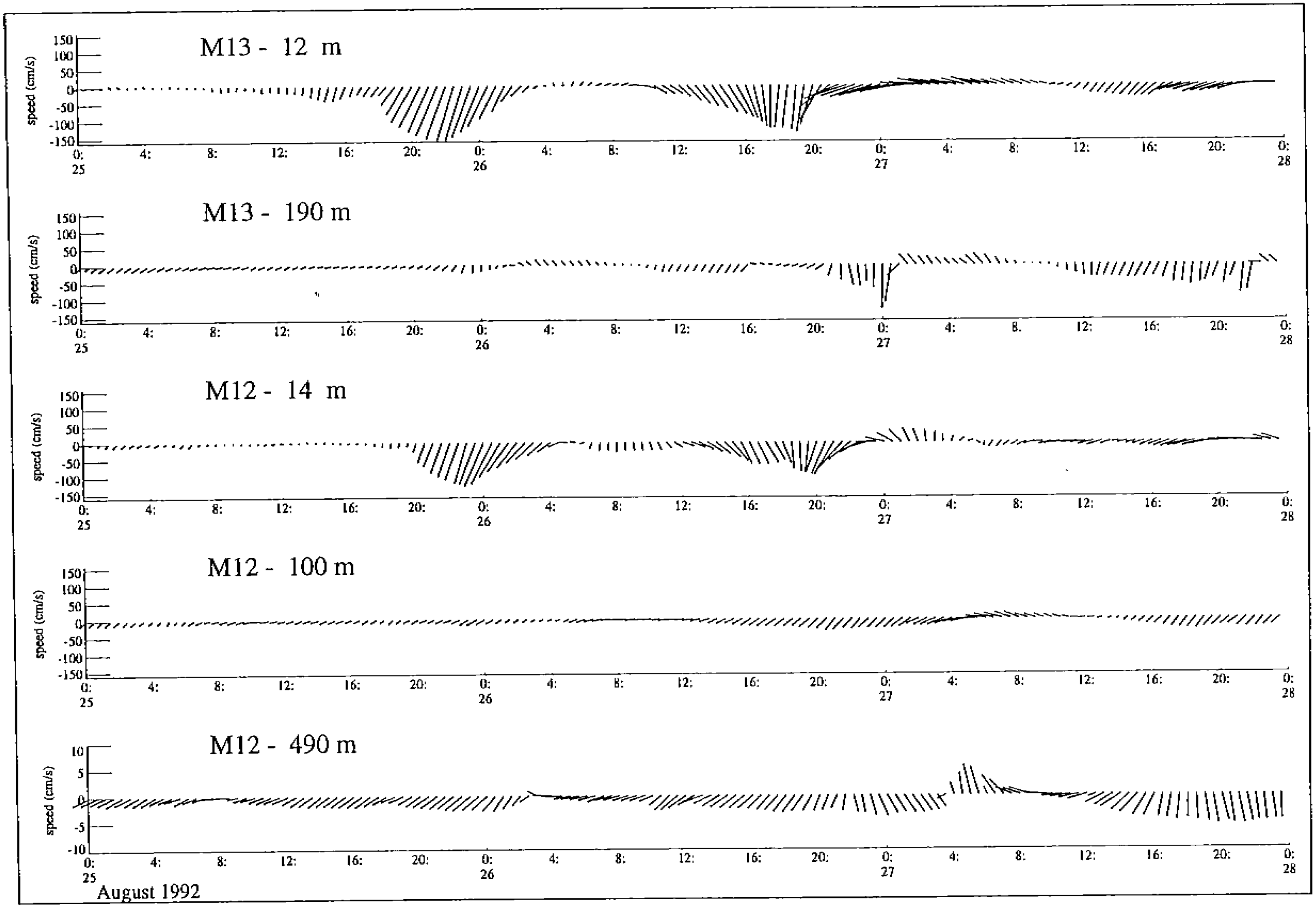

Figure 12. Currents at LATEX A mooring 12 on the 500-m isobath at 27.93°N, 90.50°W and mooring 13 on the 200-m isobath at 28.05°N, 90.50°W for the period 25-27 August 1992. Hurricane Andrew entered the Gulf of Mexico approximately 1300 UTC on 25 August and made landfall near Cypremort Point, LA approximately 0900 UTC on 26 August.

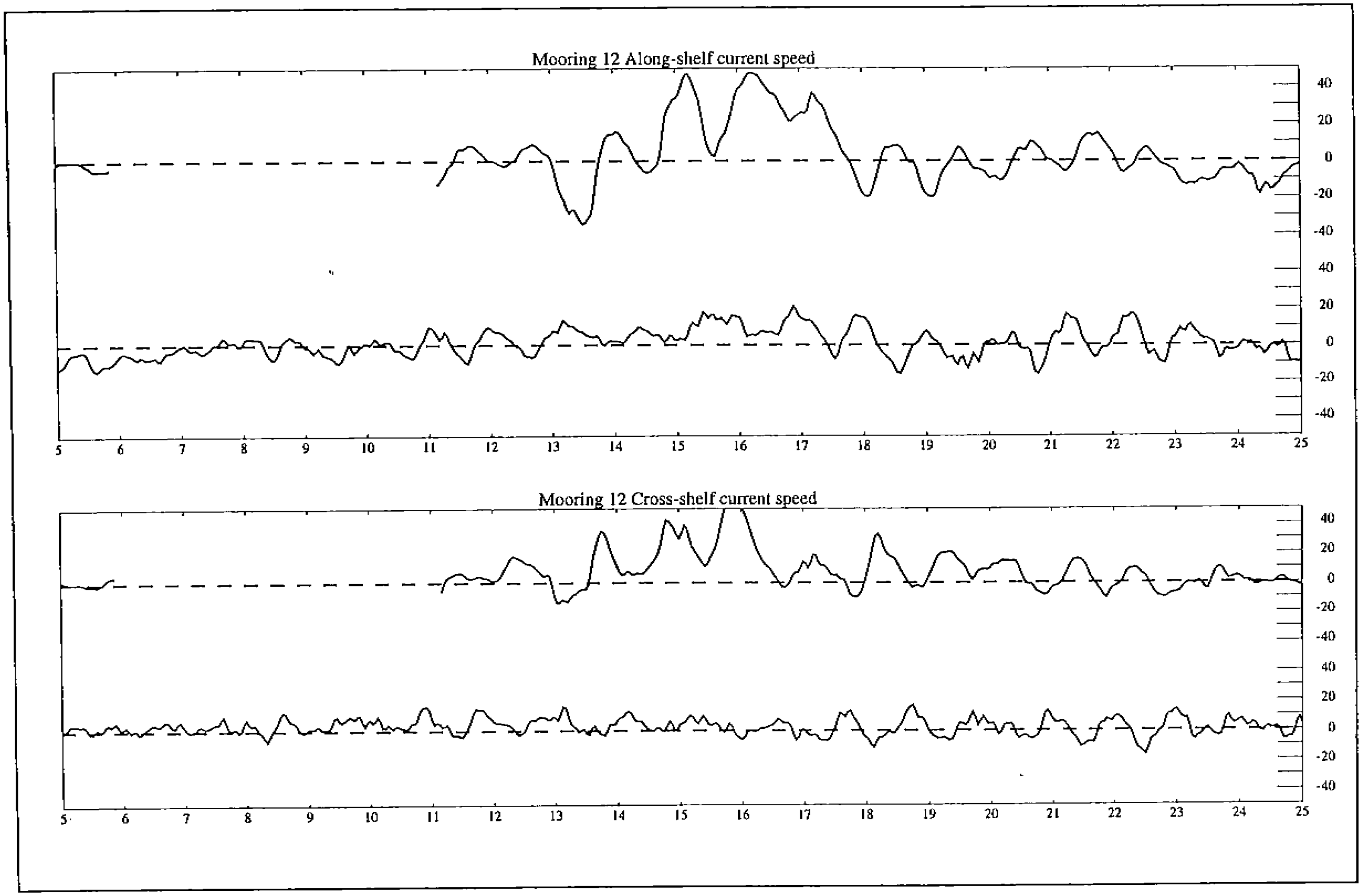

Figure 13. Currents at LATEX A mooring 12 on the 500-m isobath at 27.93°N, 90.50°W for the period 5-25 March 1993. Instrument depths were 12 and 100 m. The center of a cyclone, known later as the 'Storm of the century', moved from Mexico over the Texas continental margin about 1300 UTC 12 March 1993.

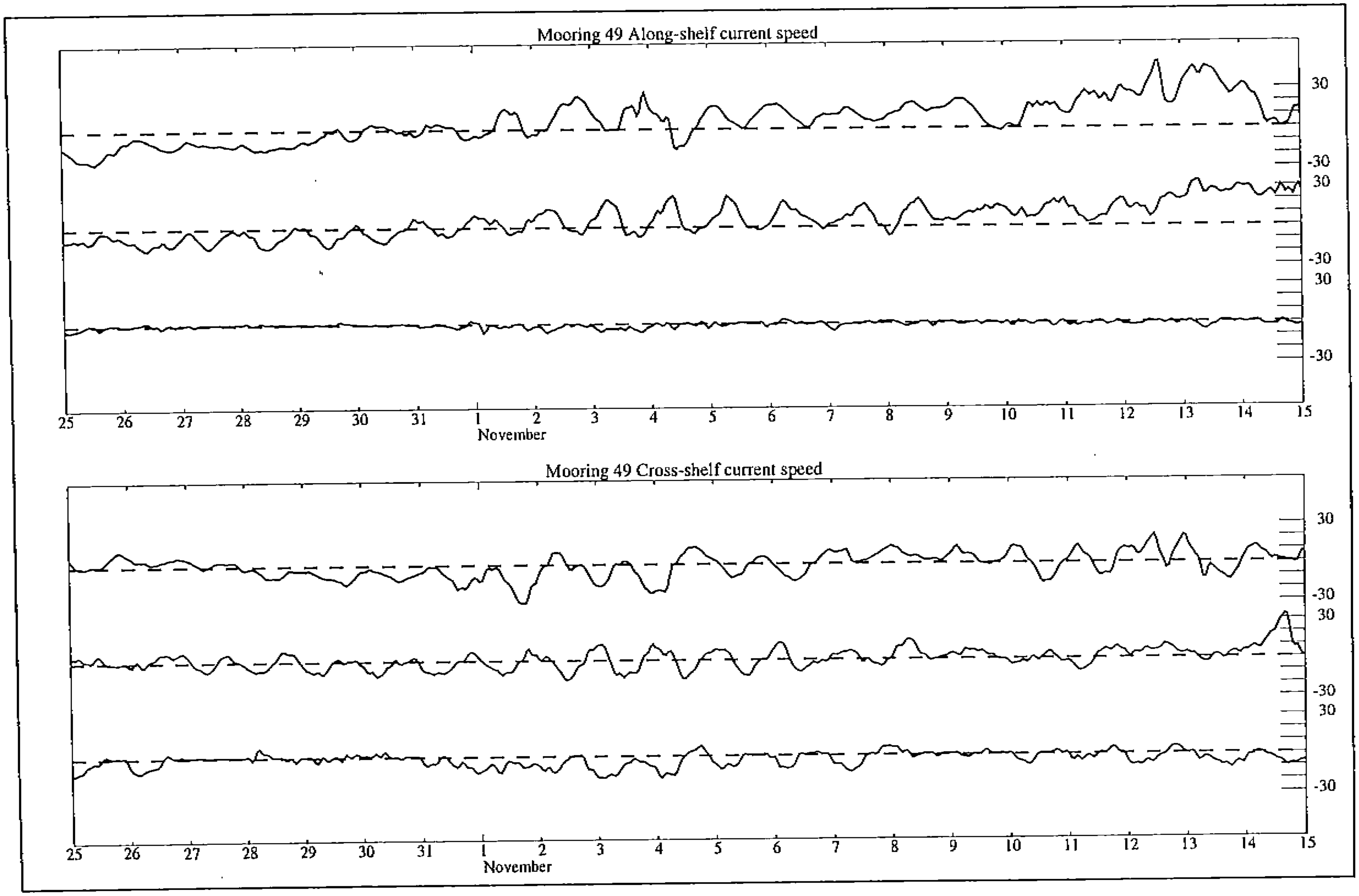

Figure 14. Currents at LATEX A mooring 49 on the 500-m isobath at 27.38°N, 95.90°W for the period 25 October to 15 November 1992. Instrument depths were 12, 100, and 490 m. A weak cold air outbreak passed over the shelf between midday on 1 November and the end of 2 November; a strong cold air outbreak passed over the region on 4 November.

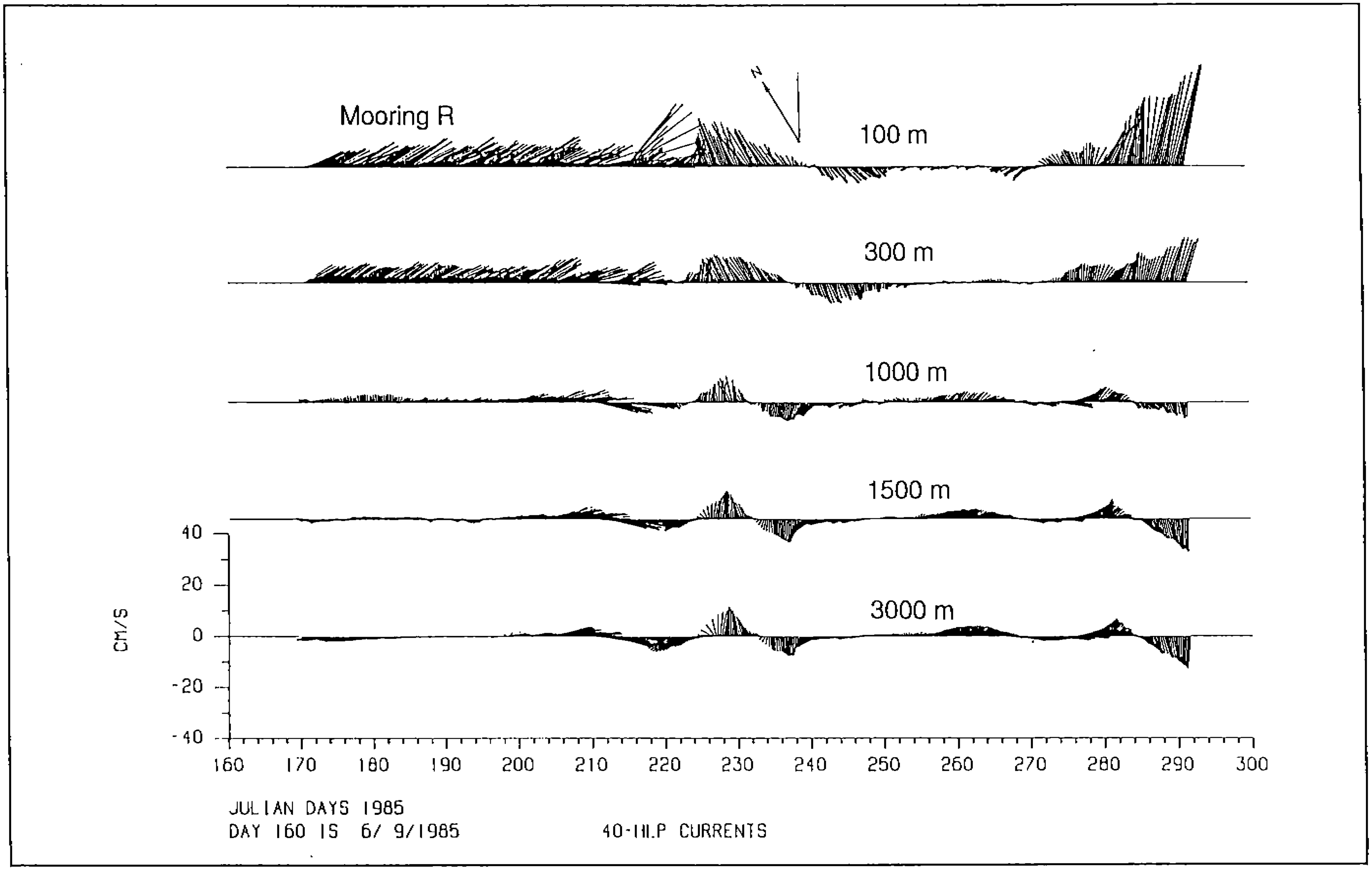

Figure 15. Vector time series of 40-hr, low-passed currents recorded at Mooring R, located in water depth of 3505 m at 25°29.5'N, 94°09.6'W. Measurements were part of MMS-sponsored Gulf of Mexico Physical Oceanography Program.

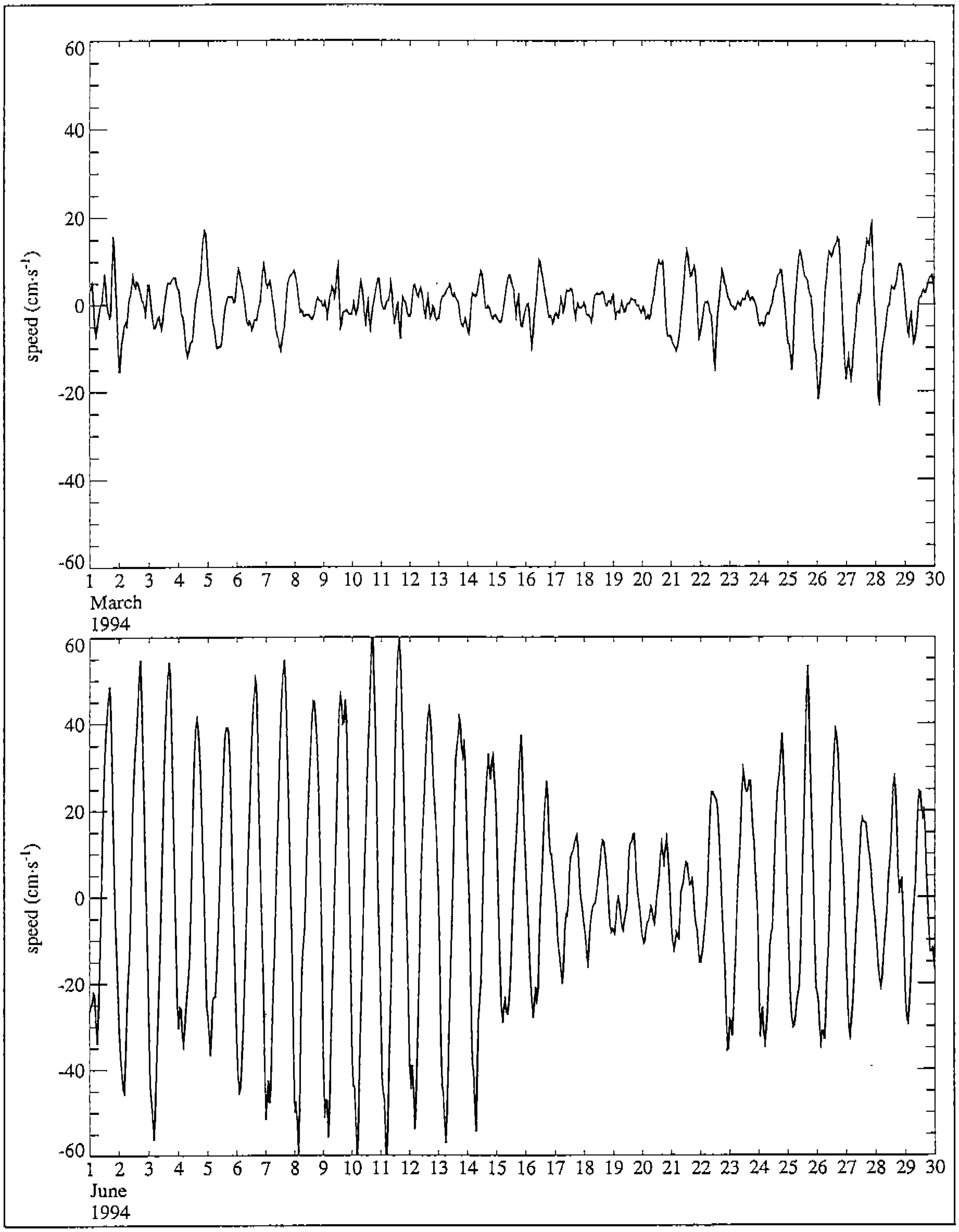

Figure 16. Time sequences in March 1994 (upper) and June 1994 (lower) of 3-40 hr band passed along-shelf current at 3-m depth on LATEX A mooring 22 located on the 50-m isobath at 28.35°N, 93.96°W.

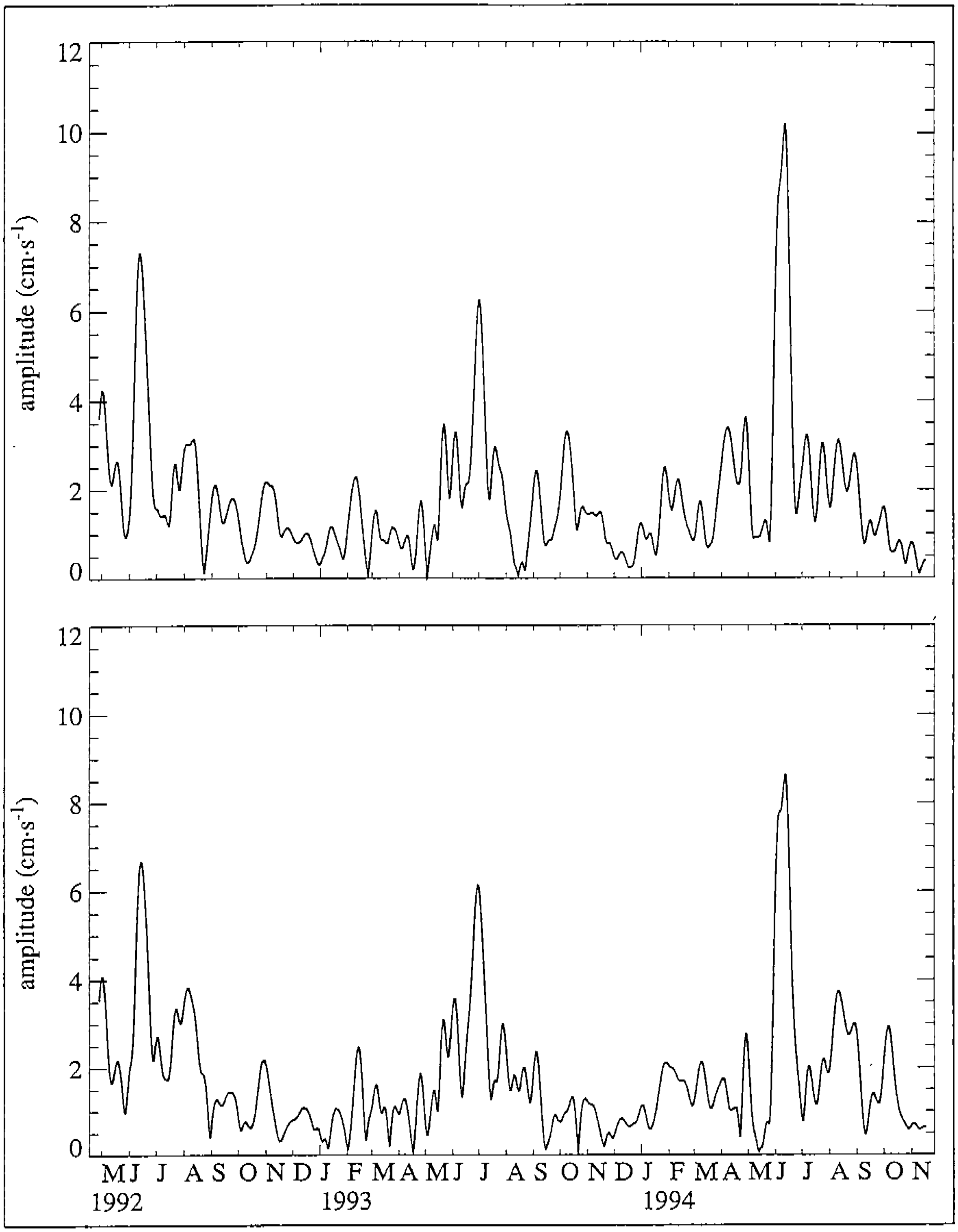

Figure 17. Amplitude of 24 hr signal from complex demodulation of along-shelf (upper) and cross-shelf (lower) current at 10-m depth on mooring 21 (located on the 20-m isobath at 28.83°N, 94.08°W) for the entire 32 months of the LATEX A field measurements.

Gulf of Mexico Eddy Circulations

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Loop Current Eddies

The major source of energy for the eddy field in the Gulf of Mexico is the fluctuations of the Loop Current (LC) and the periodic shedding of large (200-300 km diameter) warm anticyclonic eddies (LC eddies) which propagate into the western basin. It is now fairly well established from analysis of the northward excursion of the LC from SST maps and XBT transects (Sturges, 1992; 1994) and altimetry (Berger et al., 1996) that the fundamental periodicity is about 8 1/2 to 9 months. Variability of the periods between LC eddy detachments ranges from about 6 to 15 months.

LC eddies propagate across the deep western basin at between 3 and 6 km/day. The decay time scale for these eddies (Elliot, 1982) is greater than one year, and thus, vigorous LC anticyclones encounter the topography of the steep Mexican - South Texas slope as well as older eddies. The interaction with Mexican slope can generate cyclonic circulations by at least two mechanisms. Lewis et. al., (1989) describe the generation of a companion cyclone on the north side of eddy B ("Fast Eddy") in 1985 and 1986. The numerical study of Smith(1986) attributes this to instabilities and vortex stretching by the topography. Alternatively, LC anticyclones adjacent to the western wall can transfer momentum to cyclonic circulations on their southern sides (Vidal et al., 1994) and is explained by a wall effect model (Shi and Nof, 1993).

Though cyclones have been observed along the Mexican slope, there is increasing evidence that cold eddies can be found anywhere in the deep basin and over the northern slope (Hamilton, 1992; Vidal et al., 1994; Berger et al., 1996). The origin of these cyclones is at present uncertain or unknown. In particular, it is now evident that LC eddies do not propagate across the western basin as isolated vortices but interact with other anticyclones and cyclones. These interactions cause perturbations of the circulations and paths of the LC eddies. Biggs et al., (1996) observed the splitting, in 1992, of eddy T by a large cyclone, and there is evidence that anticyclones can merge (Lewis et al., 1989; Berger et al., 1996). An example of the displacements of the orbital circulations and the track of the center of eddy Y by a cyclone on the lower slope to its northwest is given in Figure 1. The orbit parameters were found from the application of the translating ellipse feature model of (Glenn et al., 1990) to satellite tracked drifters.

Using the drifter data from a number of programs, statistics on eddy paths in the central and western Gulf were assembled from 10 eddies (1985-1995). There is a general west-southwestward trend to the paths which occupying a broad band of 2 to 3 degrees of latitude in width in the central and western basins. One important result from the statistics of the paths west of 94 °W is that the net northward translation velocity is not significantly different from zero.

Therefore, the eddies have equal tendencies to move both north and south along Mexican slope in this data set. Vukovich and Crissman (1986), using sea-surface temperature (SST) image analyses, consider that northward movement is the norm for eddies encountering the slope between 23 and 24 °N.

Eddies on the Northern Slope

The Latex C and GulfCet studies produced over 25 surveys of the northern slope region between 1992 and 1994. They showed that an energetic eddy field of both cyclones and anticyclones, with diameters ranging from 40 to 150 km, is almost always present with no evident preferential position for eddies of either sign. The lower slope is more influenced by the passage of LC eddies to the south of the slope. On the upper slope and shelf break, the smaller scale circulations tend to be dominant. An example of a typical slope eddy field, from a LATEX C survey in May 1994, is given by the dynamic height and observed velocities from AXCP's, drifters and current meters in Figure 2. There is a prominent cyclone, centered at about 26.5 °N, 94 °W, with two small warm eddies on its northern side. This eddy field produces complex flows, and there is some indication that current velocities are enhanced in the region between the cyclone and the anticyclone on its northeastern side.

Figure 3 shows the temperature, east component of velocity, and geostrophic velocity for a north to south AXCP/AXBT section through the cyclone along 94 °W. The cyclone is characterized by large upward displacement of the deep compared with the level upper-layer isotherms. The latter show that there is little surface expression for this cyclone, and thus, these type of cyclonic circulations are unlikely to be directly observed by SST imagery. Measured velocities show a signal down to about 1000 m with little shear in the central region of solid body rotation which has a diameter of less than 50 km. There is a subsurface maximum, at a depths 150 - 200 m, of about 40 cm/s, and the outer region of anticyclonic horizontal shear extends out to about 75 km from the center. The geostrophic velocity field shows similar features to the direct velocity observations. The expanded depth scale plot of the upper layer temperatures (Figure 3d) shows that there is a slight depression of the isotherms over the center of the cyclone. The dynamical cause of this feature, which has been observed for other slope cyclones, is not clear at present.

Limited information in the subsequent movement of the cyclone is provided by the LATEX C and SCULP I drifters for May through July 1994 (Figure 4). The cyclone is peripheral to a large weak warm eddy, centered at 25 °N, 95 °W, which may be a remnant of LC eddy X. The cyclone moves southwestward off the slope under the influence of the clockwise swirl velocities of X. The presence of the small anticyclones on the upper slope provide transport pathways to the outer shelf for a number of drifters from the lower slope. This illustrates the effect of the eddy field on shelf-slope exchange.

These small scale upper slope eddies can mask the influence of larger eddies on the lower slope on shelf break currents. Consequently, there is little continuity of the flows along the shelf break and thus, usually poor coherence between current meters with 50 km, or less, separation. Therefore, speculation on eastward jet-like flows along the shelf break (Oey, 1995) are not born out by direct measurement or the analysis of the hydrographic fields.

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Biographical Sketch

Dr. Peter Hamilton is a Senior Oceanographer with Science Applications International Corporation. He has served as a Principal Investigator on many MMS programs. He received his Ph.D from the University of Liverpool (U.K.) in 1973.

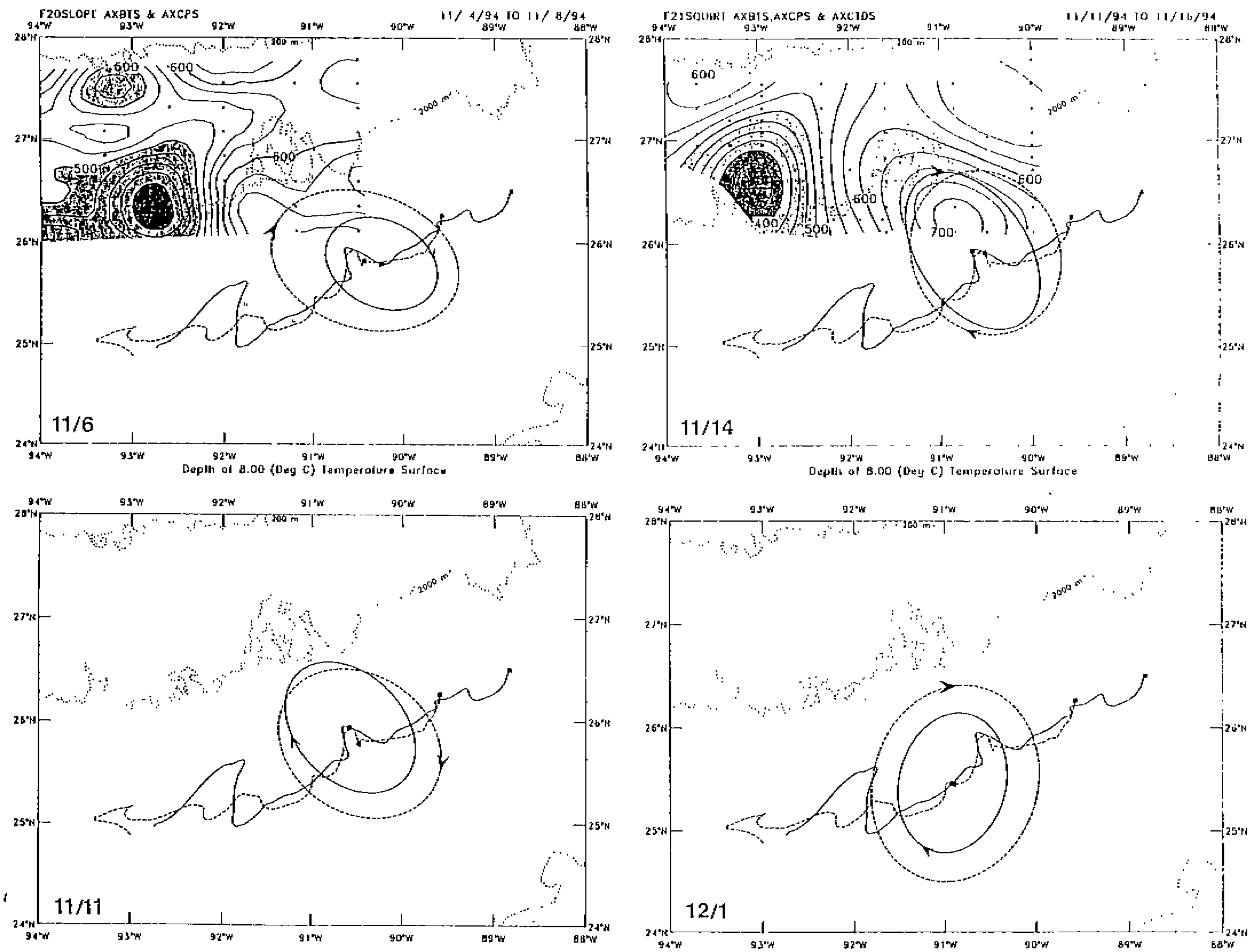

Figure 1. Orbits and center paths of LATEX C drifters 12376 (solid) and 12377 (dashed), drogued at 100 m, deployed in eddy Y and obtained from the translating ellipse feature model of Glenn et al., (1990), are given for four dates (00 H, GMT) in 1994. On the panels for November 6 and 14, the depth of the 8 °C isotherm is given for the F20SLOPE and F21SQUIRT AXBT surveys, respectively. Areas (cyclones) above 500 m depth are shaded.

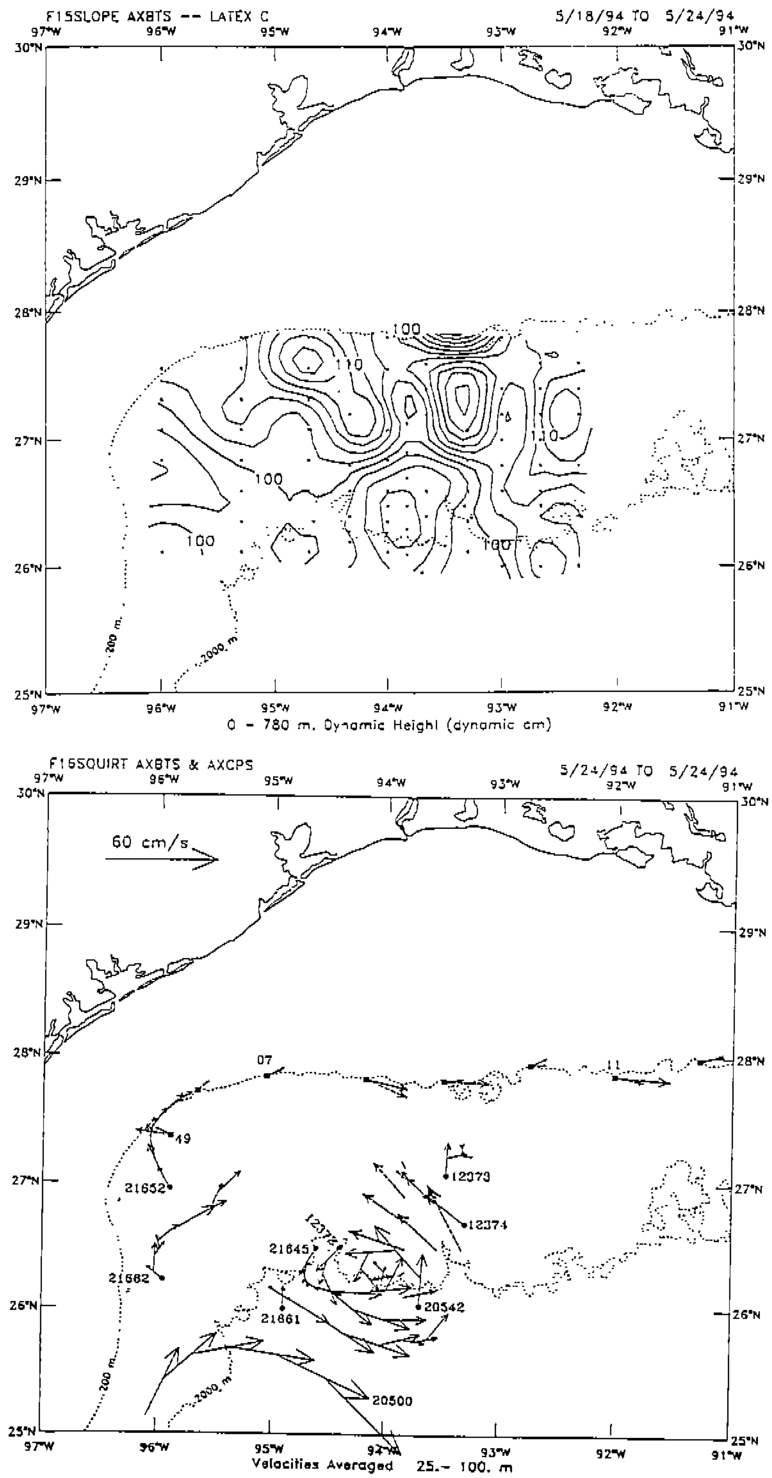

Figure 2. Upper panel - Dynamic height from the F15SLOPE and F16SQUIRT AXBT surveys; Lower panel - Daily averaged velocity vectors for May 25,1994 from LATEX A shelf break moorings (solid squares) (dashed and solid arrows at 12 and 100 m, respectively), LATEX C and SCULP I (id's > 20000) drifters (thin solid arrows), and AXCP stations (thick dashed arrows). The latter are smoothed and averaged between 25 and 100 m.

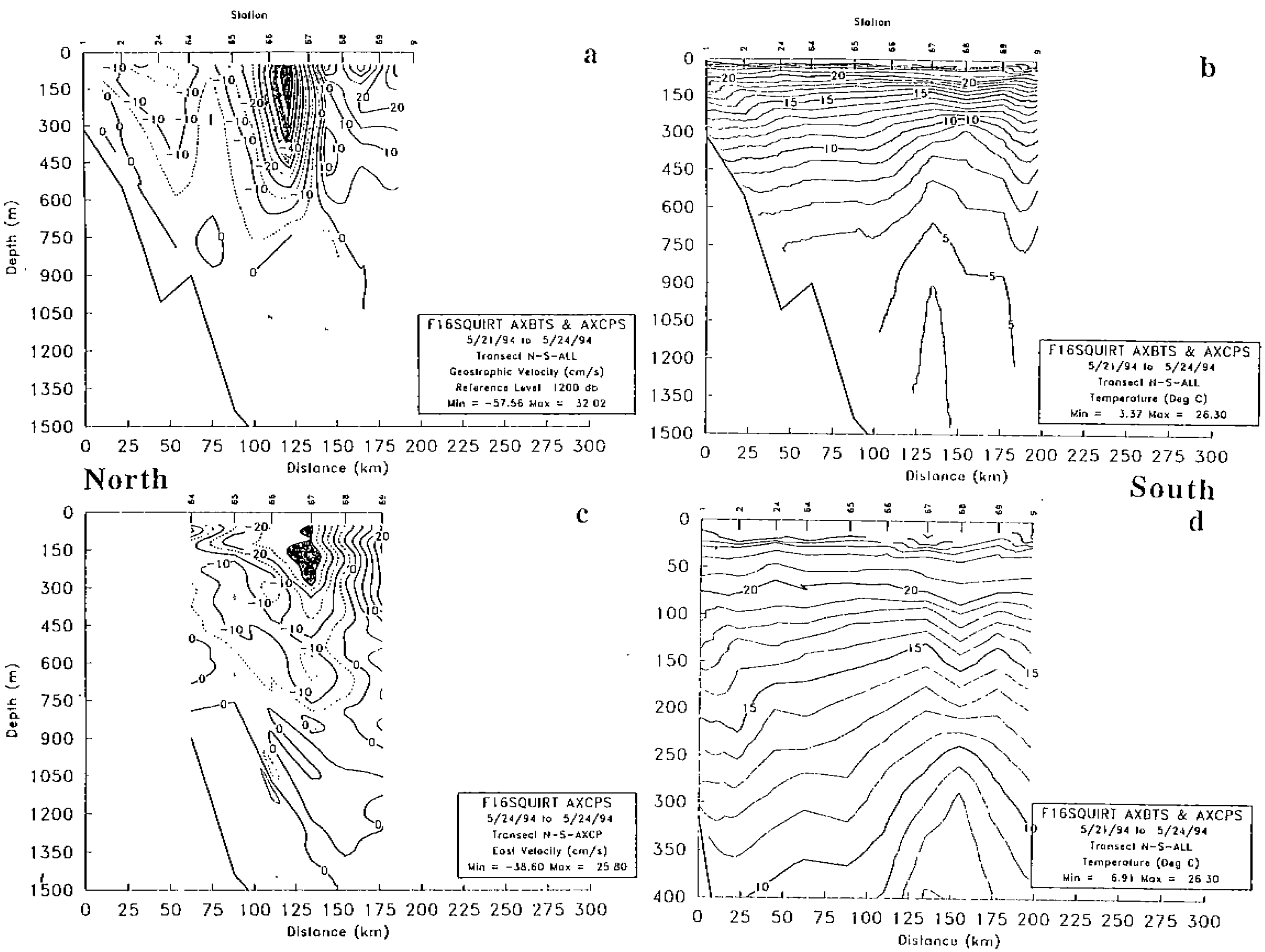

Figure 3. Vertical transects along 94 °W from F15SLOPE and F16SQUIRT AXBT & AXCP surveys. (a) Geostrophic velocity (east velocities are positive), (b) Temperature, (c) East component of smoothed AXCP velocities, and (d) Upper layer temperature.

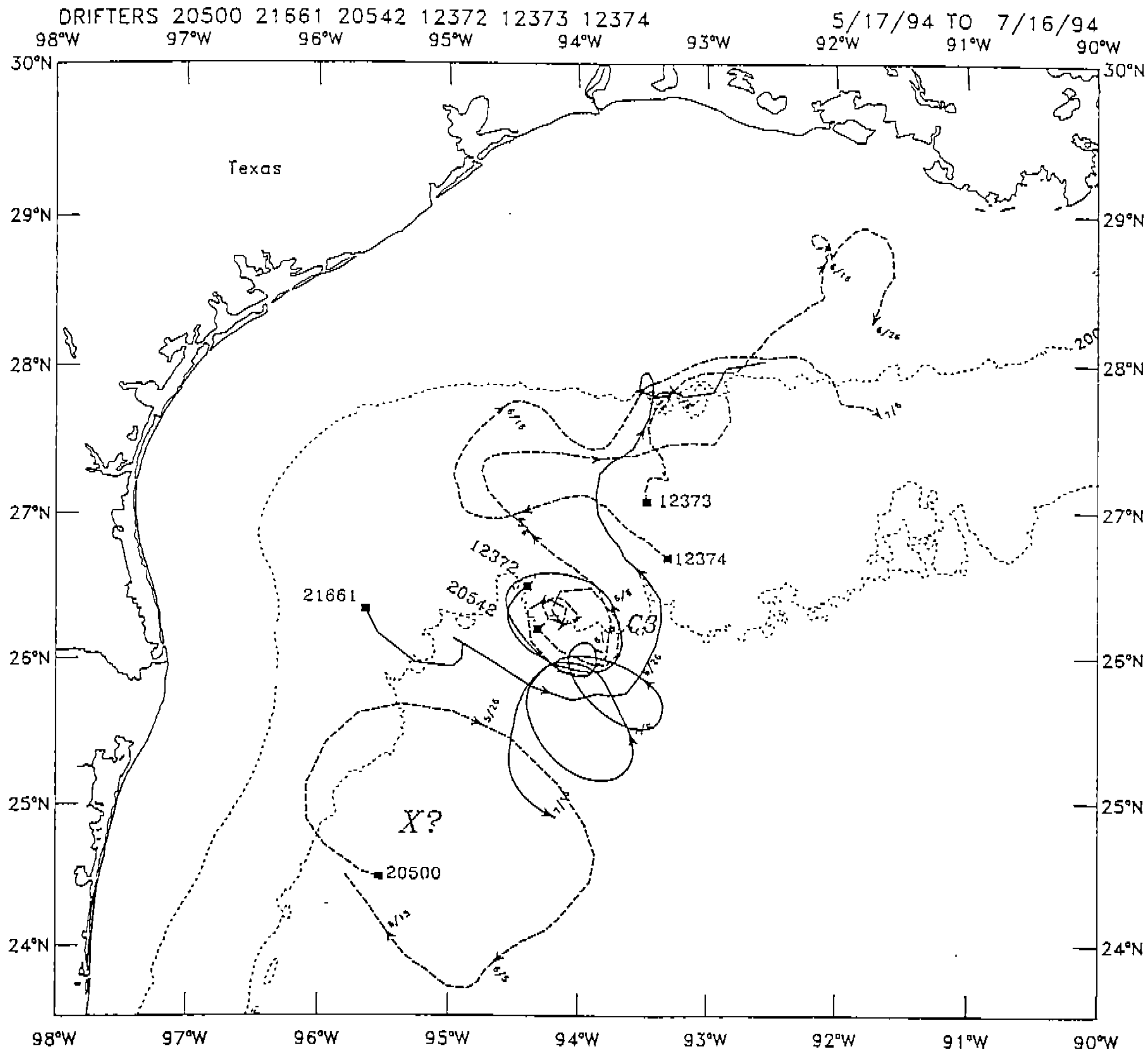

Figure 4. Drifter paths for the indicated period from SCULP I (Near surface Davis drifters with id's > 20000; daily averaged positions), and LATEX C (drogued at 50 or 100 m; positions are smoothed and given at 6 hour intervals). Arrow heads are at 10 day intervals.

On Some Peculiarities of Bottom Boundary Layers on the Continental Slope

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Abstract. The bottom boundary layer (BBL) on the continental slope has recently been recognized as being very different from the BBL on continental shelves and on the abyssal plains. Why this is so is reviewed, and some measurements are presented to illustrate its peculiarities.

The bottom boundary layer (BBL) over the continental slope and rise appears to be quite different from the standard BBL. By standard BBL, I mean those found on the continental shelf and over the abyssal plain. The standard BBL is very similar to the bottom Ekman layer described in many physical oceanography textbooks. Because of its Ekman spiral behavior, there is net flow in the standard BBL at right angles to the free-stream current above the BBL. However, as I will try to explain below, the Ekman transport (i.e., the Ekman spiral) is usually absent in BBLs over the slope.

What makes the BBL on the continental slope and rise so different from the standard Ekman BBL results from three things. One is that currents along the slope flow along constant depth contours. The second is that the water is stratified with denser water below and lighter water above. The third is that the bottom is not level but is inclined. Once a current starts on the slope or rise, its BBL tries to act like a standard BBL and transport water perpendicular to the free-stream current. Because the current is along depth contours and the water is stratified, this means the BBL tries to transport either dense water up slope or lighter water down slope. (Whether it is up slope or down slope depends on the current direction. For the northern hemisphere up slope transport occurs if the deep water is to the right, and down slope if shallow water is to the right.) However, the BBL cannot continually push dense water up slope or light water down slope; eventually the buoyancy restoring force becomes too great. For conditions found on the slope the resulting buoyancy forces are sufficiently strong after a day or so after the current has started to shut down completely the up or down slope BBL transport.

Why this shut-down should not occur over level bottoms but should occur over sloping bottoms is illustrated in Fig. 1. The upper two panels show conditions representative for the shelf in winter (upper left) when the water is well-mixed and the shelf in summer and abyssal plain (upper right) where the water is vertically stratified. In both of these cases the bottom for all practical purposes is level. There is net movement of water in the BBL perpendicular to the overlying current but nothing acts to restrain it. However, when the bottom is inclined, as on the continental slope and rise, such motion results in either an up slope or down slope net transport in the BBL of either denser or lighter water. This is illustrated in the lower panels of Fig. 1. Buoyancy forces result to restrict such up slope or down slope BBL transport, and for conditions encountered on the slope or rise the resulting buoyancy forces are often strong enough after several days to effectively terminate the cross-slope BBL transport.

Two other important consequences arise for BBLs over inclined bottoms. The cross - slope BBL advection always results in tilted or inclined isopycnals in the BBL. This is illustrated in Figure 2. Physical oceanographers have long known that tilted isopycnals result in vertical shear in horizontal currents, the so-called thermal-wind shear (named by the meteorologists who first identified the effect). What is particularly interesting is that this effect is non-trivial for BBLs on the continental rise. After several days the isopycnals are often sufficiently tilted to bring the current to zero at the bottom! Thus, after several days of cross-slope BBL transport, thermal wind effects rather than bottom friction are often sufficient to bring the current to zero at the bottom! For this reason BBLs on the slope are sometimes called slippery bottom layers, because bottom friction is often unimportant in bringing currents to zero across the BBL (Garrett *et al.*, 1991). A second consequence is an asymmetric behavior in the BBL thickness and temperature depending on whether conditions are favorable for down welling or up welling (Weatherly and Martin, 1978; Trowbridge and Lentz, 1995). For the former, the BBL can be two or three times thicker than a level-bottom Ekman layer. (It will be a little warmer too, but usually this effect is negligible.) However, for the upwelling case, the BBL will be considerably thinner than a level-bottom one and can be several degrees colder than the overlying water. The asymmetric behavior in BBL temperature is illustrated in Figure 3 which shows near-bottom temperatures measured on the upper rise in the Gulf of Mexico. For times < 84 hours conditions were favorable for downwelling in the BBL, and after they were favorable for upwelling. The upwelled BBL is seen to be about 5 °C colder than the overlying water (compare the 2.5 m and 31.5 m above bottom temperature curves at time = 120 hr), while the downwelled BBL is only about 2 °C colder (compare the 2.5 m and 31.5 m above bottom temperature curves at times < 96 hr).

The above curious behavior of the BBL on the rise and slope is pretty well understood theoretically. However, not all is understood. Some new results indicate features which are as yet unaccounted for. In some places on the rise where the mean currents are relatively weak, there appears to be a net down-slope BBL transport even though the overlying flow is along depth contours. This is illustrated in Figure 4 which shows some current meter data from about the continental rise off the coast of Brazil in water of depth 1700 m. The progressive vector diagram at 120 m above the bottom show the flow going approximately northward - which is approximately along depth contours here. However, at 7 m above the bottom the flow is going predominately eastward - which is downslope here. Such behavior has been observed elsewhere on other rises (off of Virginia and in the Gulf of Mexico) which appear to be regions of relatively weak flows.

Summary. Recent studies of the BBL on the continental slope show this BBL to be quite different from the BBL on the shelf and on the abyssal plain. The latter BBLs appear to be very much like the standard bottom Ekman layer found in the texts. The former are not; the Ekman spiral or BBL transport is usually terminated a few days after the current starts. Although the Ekman cross slope BBL transport is short lived it none the less results in very thick and somewhat warm BBLs (when down welling is favored), or in very thin and quite cold BBLs (when up welling is favored). Bottom friction is also greatly reduced as a consequence. Some very recent studies indicate that in some regions of the slope, which appear to be in regions of weak mean flows, a persistent and pronounced downslope transport occurs in the BBL. Why, in some regions on the slope, all cross-slope BBL transport is quickly turned off while in others it down slope transport is enhanced is, as yet, unknown.

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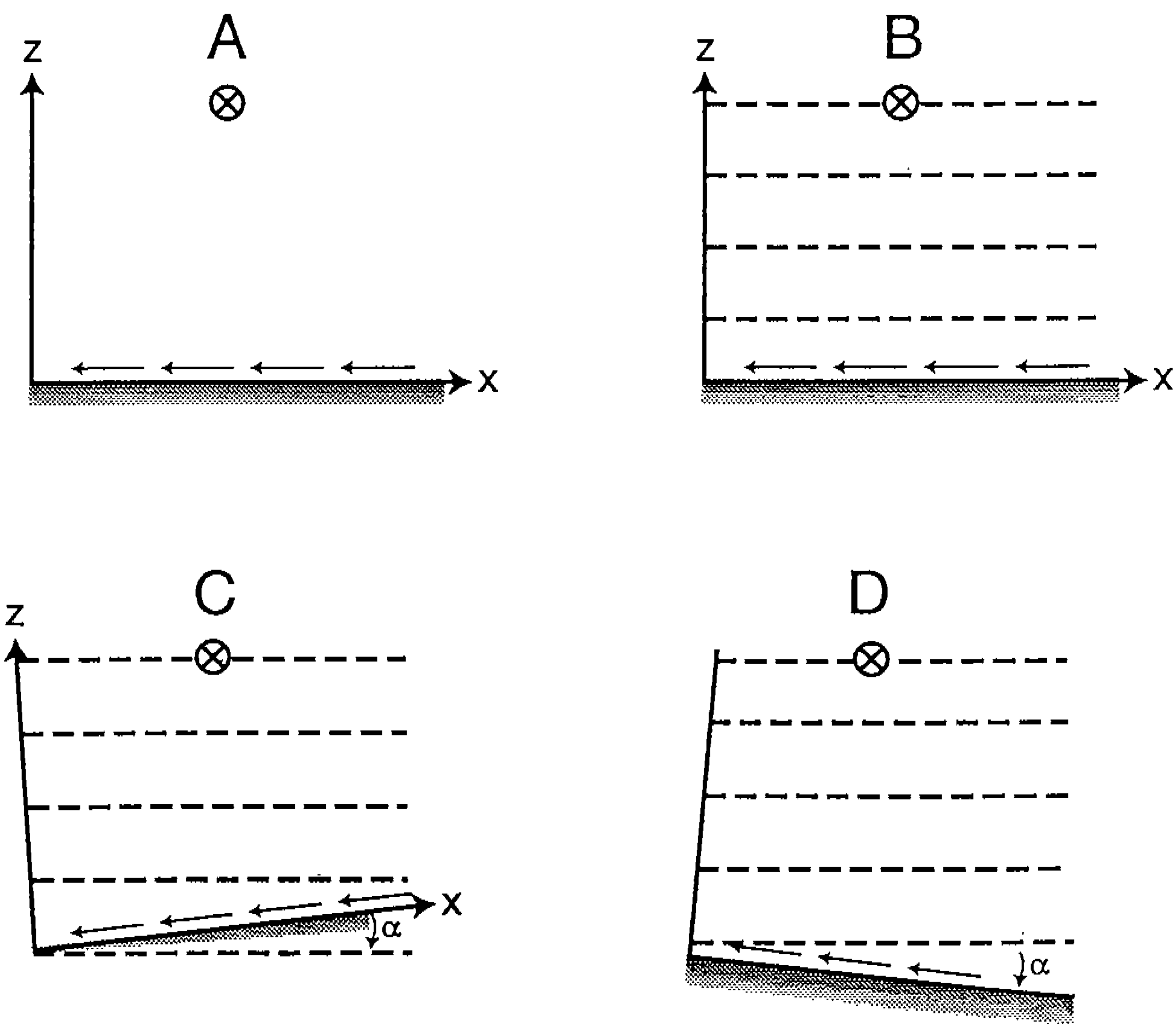

Fig. 1. Schematic of bottom boundary layer (BBL) flow over a level bottom (a) and (b) and over an inclined bottom (c) and (d). Isopycnals are indicated by dotted lines (none are in (a) which represents well-mixed conditions on the continental shelf in winter). The current above the BBL is into the plane of the figure (indicated by a circled X), the BBL transport is given by arrows, and α is the bottom slope angle. Note that for the sloping bottom cases, the BBL either pumps lighter fluid down slope (c) or heavier fluid up slope (d). However, as pointed out in the text such cross slope BBL transport is short-lived on the continental slope. Figure is from Weatherly and Martin (1978).

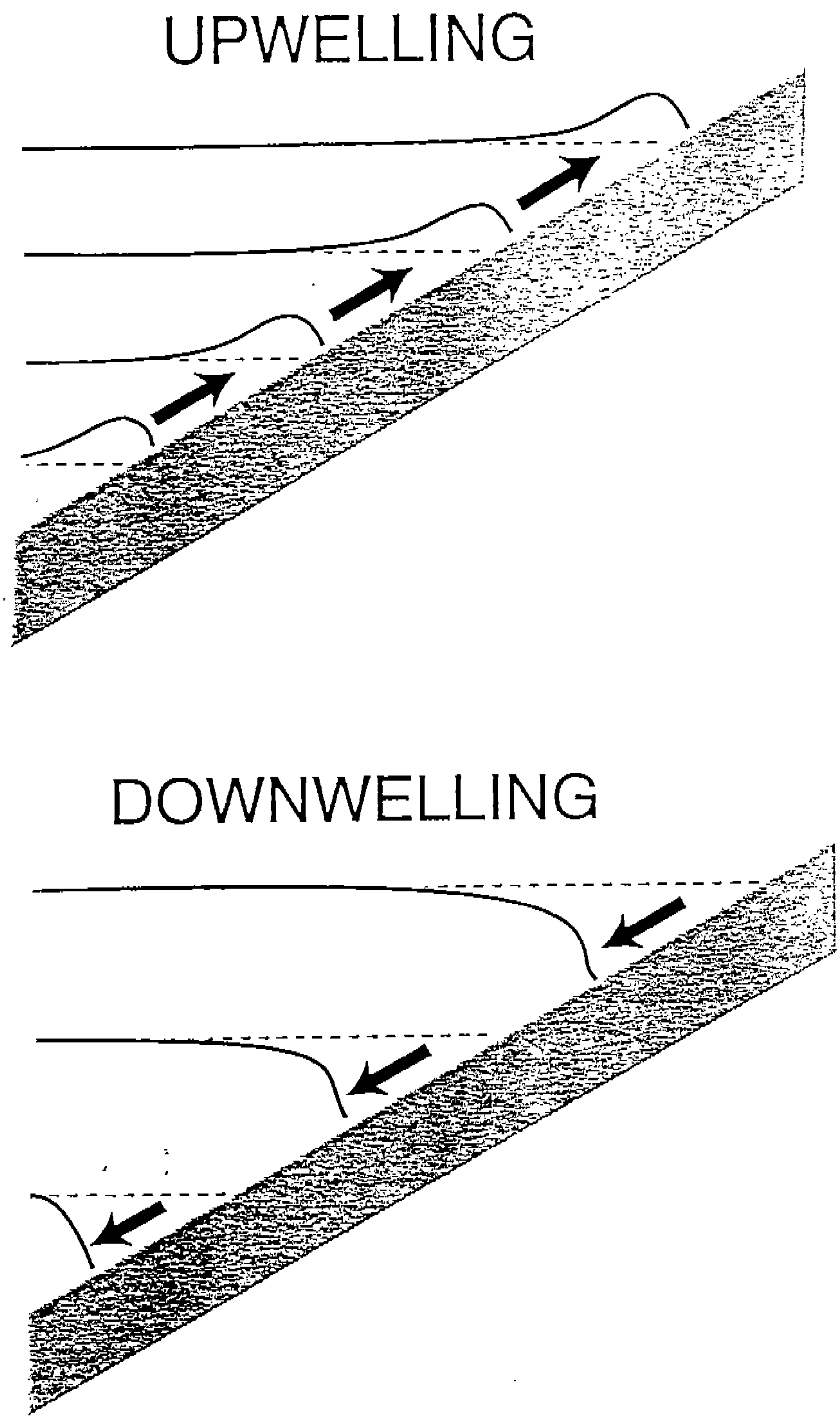

Fig. 2 Schematic showing how cross slope BBL transport (indicated by arrows) tilts isopycnals (indicated by solid lines). The resulting tilting is usually sufficient to bring the current to zero across the BBL by thermal wind effects a few days after the transport starts. Figure is from Trowbridge and Lentz (1995).

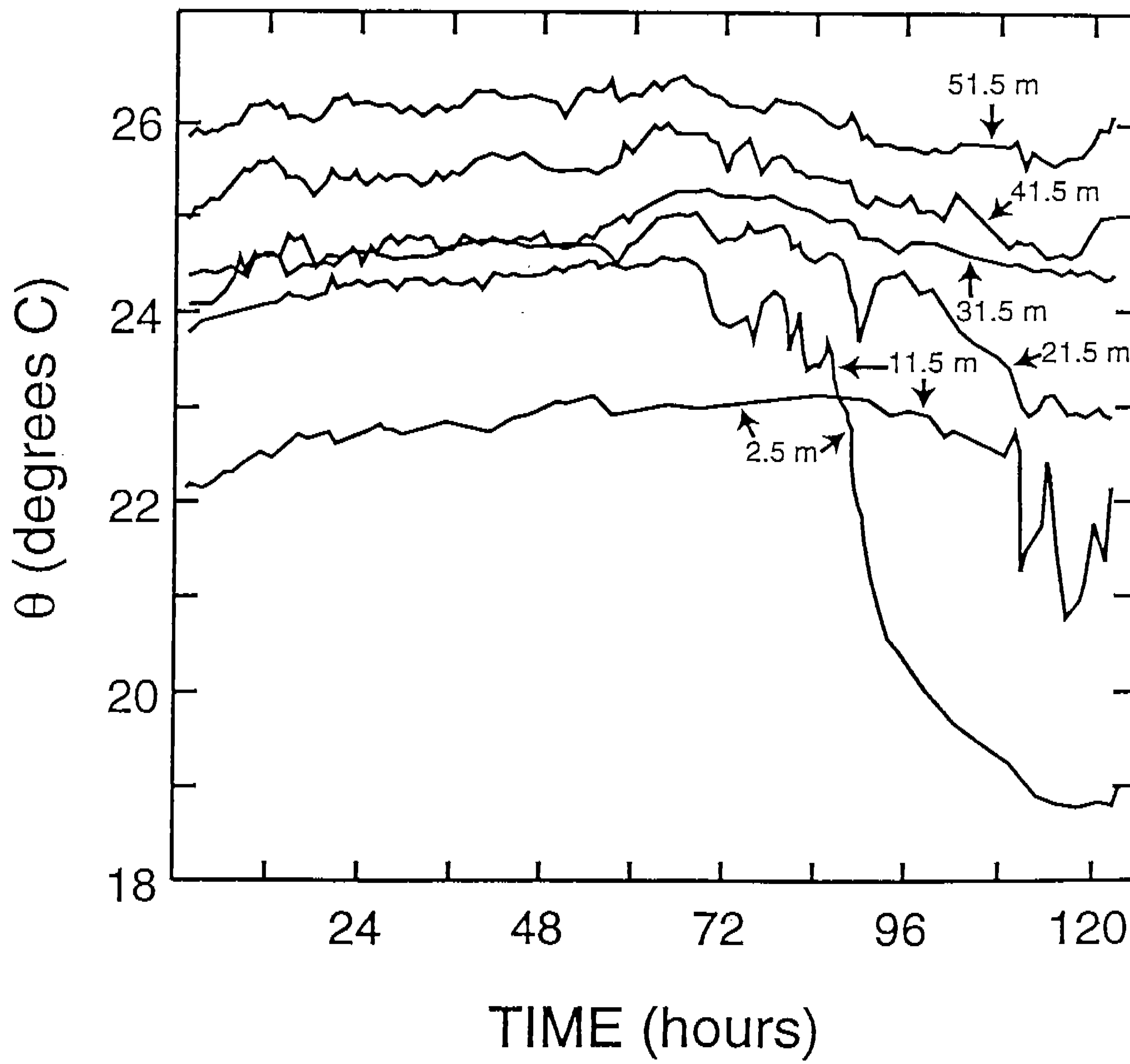

Fig. 3. Time series of temperature from the upper slope in the eastern Gulf of Mexico from Weatherly and Martin (1978). Height above bottom is indicated by each curve. Consider the 2.5 m and 31.5 m curves which are respectively from the BBL and above the BBL. For time < about 84 hours down welling conditions were favored in the BBL, and the BBL slowly warmed while the interior temperature remained relatively constant. For time > about 84 hours up welling conditions occurred and the BBL quickly cooled (by about 4 °C) while the interior temperature changed relatively little.

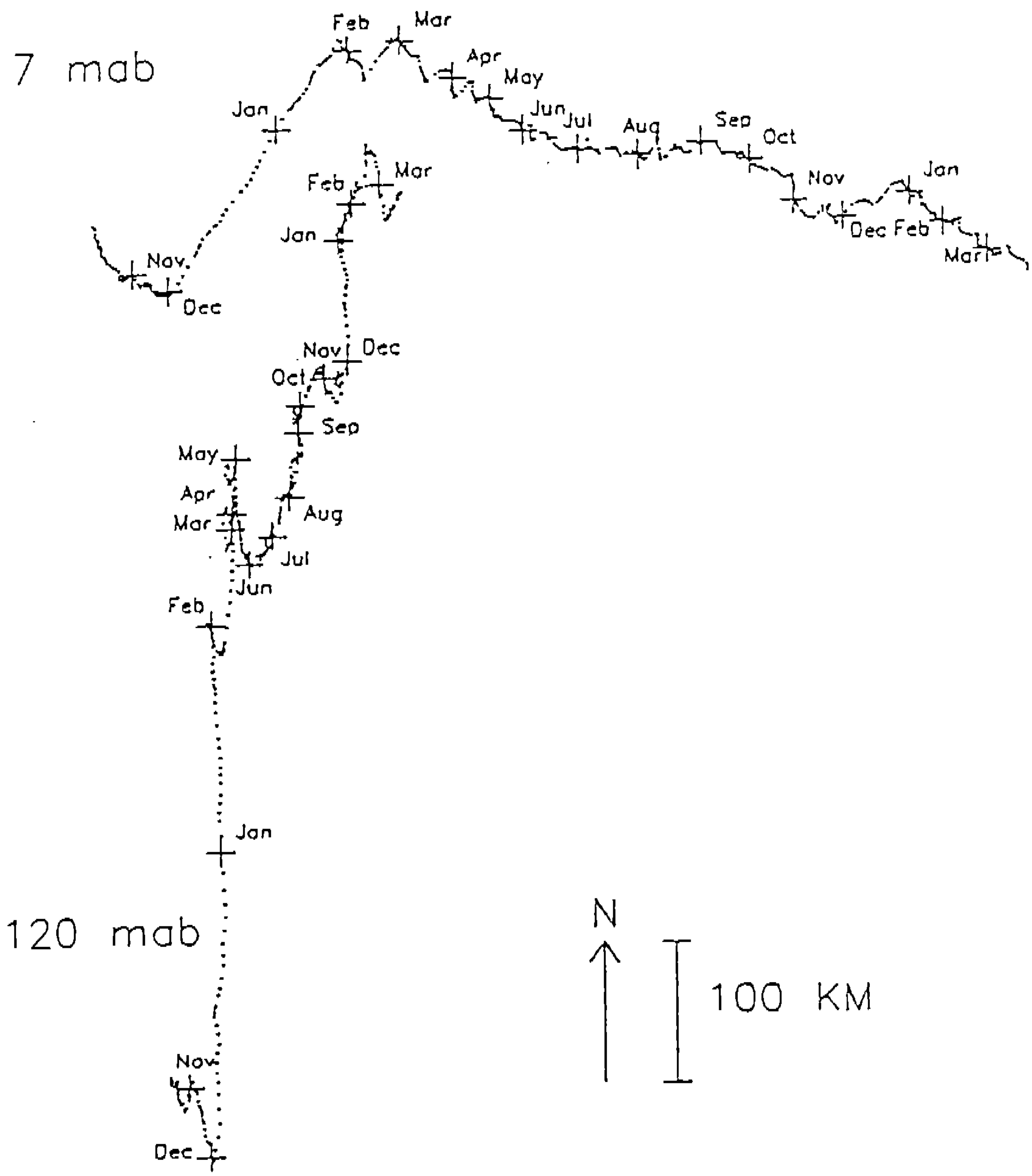

Fig. 4. Two progressive vector diagrams (PVDs) obtained on the slope off of Brazil in water 1700 m deep. The PVD from 120 m above the bottom (the lower one) indicates the water above the BBL flowed approximately northward which is the direction of the depth contours. However, the PVD from 7 m above the bottom (the upper one) indicated that the flow in the BBL was approximately across the depth contours towards deeper water. Figure is from Harkema and Weatherly (1996).

Overview of Satellite Altimetry in the Gulf of Mexico

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INTRODUCTION

The primary benefit of satellite altimetry is that it is an all-weather/all-season data source that can be used to continuously monitor the deep basin circulation in the Gulf of Mexico, barring data outages. This is a significant advantage over remote monitoring with visible or infrared imagery, which is often hampered by cloudy conditions over the gulf. Historically, altimeter data have been routinely available only in a delayed mode and have been primarily used in retrospective analyses to augment field observations (Berger et al., 1996a; Biggs et al., 1996). Recently, near-real-time data have become available from the TOPEX/Poseidon and ERS-2 satellites (Lillibridge et al., 1997). This near-real-time availability has resulted in altimeter observations playing an essential part in the operational monitoring of the Loop Current and its associated eddies, supplementing infrared images and ARGOS tracked drifting buoy observations. In this paper a brief overview of climatological and near-real-time applications of satellite altimetry in the Gulf of Mexico will be given.

METHODS AND RESULTS

A climatology of Gulf of Mexico sea surface height (Berger et al., 1996b) has been produced using the complete GEOSAT altimeter time series (April 1985 to December 1989), including declassified along-track data from the Geodetic Mission released in the summer of 1995. All along-track data are referenced relative to an accurate high resolution mean surface based on altimeter data collected from the TOPEX/Poseidon, ERS-1 and GEOSAT Exact Repeat missions (Yi 1995). Analysis of this historical GEOSAT data set showed that altimetry referenced to an accurate mean surface can provide accurate observations of individual features and basin-wide circulation in the Gulf of Mexico (Berger et al., 1996a).

This climatology was used to track five out of the six Loop Current eddies detected during the GEOSAT time period over their life span and to compare statistics with similar measures from drifter tracks and survey data. Excellent agreement is found between altimetric-derived eddy dimension and kinematic parameters and similar estimates derived from drifter tracks or cited in the literature. Observations of the life histories of individual eddies and their interactions with the Mexican slope, other Loop Current eddies and with smaller cyclones and anticyclones provide new insight into those interactions. For example, the merger of two Loop Current eddies in May-July 1986 was well observed. This merging event apparently conserved mass and circulation with the required energy input coming from an adjacent cyclone. The climatology provides some evidence that the historically observed southwestward Loop Current eddy path in the western gulf is the typical path in the absence of external forcing. Deviations from that path are likely a result of eddy-eddy interactions.

Retrospective studies are in progress using data collected during the 1990s by altimeters aboard the TOPEX/Poseidon and ERS-1/2 satellites. Operational applications of satellite altimetry in the gulf are also being investigated. In early 1996, a pilot project began at the Colorado Center for Astrodynamics Research (CCAR) to develop a "real-time" altimeter data processing capability to monitor Loop Current eddies and other circulation variability in the Gulf of Mexico. This project was initiated based on the availability of "real-time" data from both the ERS-1/2 and TOPEX/Poseidon satellites. Since November 1995, NOAA has been generating "Real-time Geophysical Data Records" (RGDRs) for ERS-1 and ERS-2. ESA's Fast-Delivery altimeter data arrive at NOAA within 6 hours of acquisition, are combined with JGM-3 orbits produced by the Delft Univ.

of Technology, and are enhanced with several environmental corrections. The operationally computed orbits are generated with a 2-3 day lag and have errors of ~10cm. To create the RGDRs within 12 hours of acquisition, predicted extensions to the operationally computed orbits are generated for each orbit solution. The RGDRs, thus, contain orbit errors of ~50 cm, so are most useful for short-arc mesoscale studies such as have been historically used to monitor Loop Current eddies. In early February 1996, the Naval Oceanographic Office (NAVOCEANO) at Stennis Space Center, Miss. began providing real-time GDRs (RGDRs) from TOPEX/Poseidon. NAVOCEANO obtains the data directly from the TOPEX/Poseidon Project at the Jet Propulsion Laboratory and uses predicted orbits computed by the JPL Earth Orbiter Systems Group, based on tracking data from the Global Positioning System. The accuracy of these orbits are comparable to the predicted ERS orbits. Additional corrections for the dry tropospheric refraction, and tidal elevations are applied to the data at NAVOCEANO.

Because of the substantial orbit error present in the RGDRs, further treatment of the sea height data is required to derive accurate maps of sea surface topography. The procedure used at CCAR blends ERS-2 and TOPEX altimetry, treating both data sets in a consistent fashion:

1. All TOPEX and ERS-2 data are referenced to the Ohio State University Mean Sea Surface 1995 (Yi 1995). The data are treated as nonrepeat tracks and are referenced directly to the mean sea surface. This saves a significant amount of computation in the near-real-time processing.

2. Along-track "loess" filtering is used to remove orbit and environmental correction errors. Loess filtering is a running least squares fit of a tilt plus bias, within a sliding window. The window width is approximately 15 degrees of latitude, to retain mesoscale signals.

3. A fast, multigrid preconditioned Cressman analysis is used for interpolation to a quarter-degree grid (Hendricks et al., 1996).

4. Finally, a model mean is added to the sea surface height anomaly to produce an estimate of the total dynamic height.

An example of the sea surface height topography derived using this method is presented in Figures 1 and 2. Here clear images of sea surface temperature in the Gulf of Mexico (courtesy of Frank Muller-Karger, Univ. of S. Florida) are shown with overlaid contours of sea surface height based on the TOPEX/ERS-2 analysis. A large meander in the Loop Current, in the southest corner of the gulf, is well mapped by the altimeter derived sea surface. Even less energetic cyclones and anti-cyclones are clear in the surface topography maps, in excellent agreement with the surface temperature fields. Maps of sea surface height in the Gulf of Mexico are produced daily based on the most recent 10 days of TOPEX and 17 days of ERS-2 data. These are usually available within 18 hours of overflight. The maps can be accessed from the CCAR Gulf of Mexico home page at http://www-ccar.colorado.edu/gom.html.

CONCLUSIONS

Retrospective analysis and synthesis of satellite altimetry with field observations will continue to improve our understanding of the circulation in the Gulf of Mexico. With the launch of GEOSAT Follow-On (GFO) in September 1997, three altimeter satellites will be on orbit. The GEOSAT Follow-On program is the U.S. Navy's initiative to develop an operational series of radar altimeter satellites to maintain continuous ocean observation from the GEOSAT Exact Repeat Orbit. The additional sampling along the GEOSAT 17-day repeat orbit ground tracks, added to the current TOPEX/Poseidon 10-day and ERS-2 35-day repeat orbit sampling, will increase the spatial and temporal resolution afforded by altimetry. All of these data streams will be delivered in near-real-time and should be available for operational remote sensing in support of field programs in the deep waters of the Gulf of Mexico.

ACKNOWLEDGEMENTS

Near-real-time altimetry requires the concerted effort of a large number of individuals and organizations. I thank the European Space Agency (ESA) for providing the ERS-2 radar altimeter fast-delivery data, Delft University of Technology for providing predicted orbits, and John Lillibridge and Bob Cheney of the NOAA Satellite and Ocean Dynamics Branch for enhancing the ESA product and producing the NOAA Real-time Geophysical Data Records. I thank the Jet Propulsion Laboratory (JPL) for providing the TOPEX fast-delivery data, the JPL Earth Orbiter Systems Group for providing predicted T/P orbits, and John Blaha and Ronnie Vaughn of the NAVO Altimetry Data Fusion Center for enhancing the JPL product and producing TOPEX/Poseidon Real-Time Geophysical Data Records

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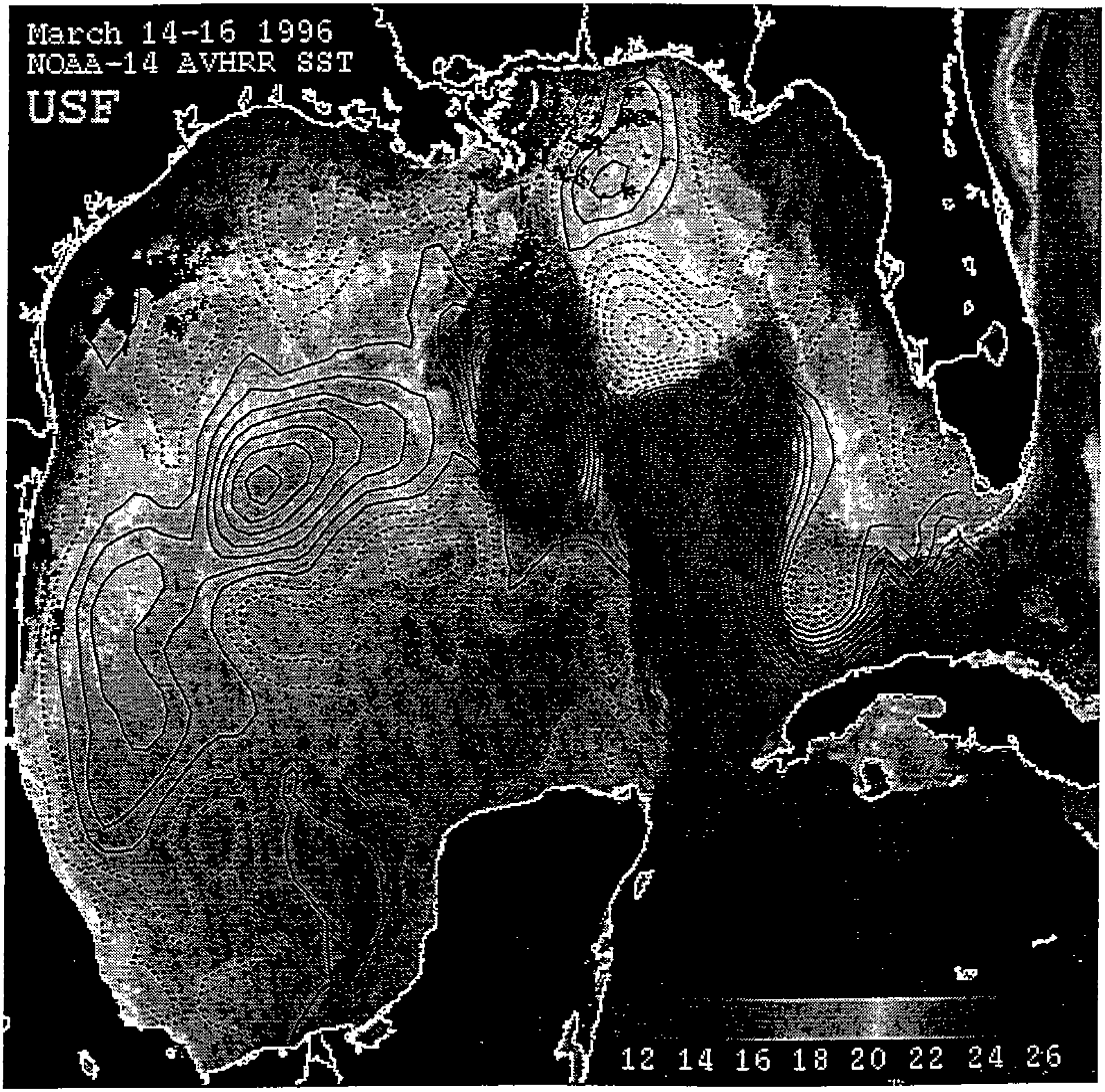
FIGURE LEGENDS

Figure 1. Composite of sea surface temperature images from the Gulf of Mexico for March 14-16, 1996 with overlaid contours of sea surface height from TOPEX and ERS-2 (5 cm interval). The shedding of Eddy Biloxi from the Loop Current is clearly seen.

Figure 2. Composite of sea surface temperature images from the Gulf of Mexico for April 20-22, 1996 with overlaid contours of sea surface height from TOPEX and ERS-2 (5 cm interval). This is approximately one month after previous image. Eddy Biloxi now clearly has a companion cyclone to the northwest.

BIOGRAPHY

Robert R. Leben received the B.S., M.S. and Ph.D. in aerospace engineering sciences from the University of Colorado, Boulder in 1981, 1982 and 1986, respectively. Since 1986, he has been employed at the Colorado Center for Astrodynamics Research at the University of Colorado, Boulder, where he is currently an Associate Research Professor. Dr. Leben's research interests include satellite altimetry and its application to ocean circulation monitoring.



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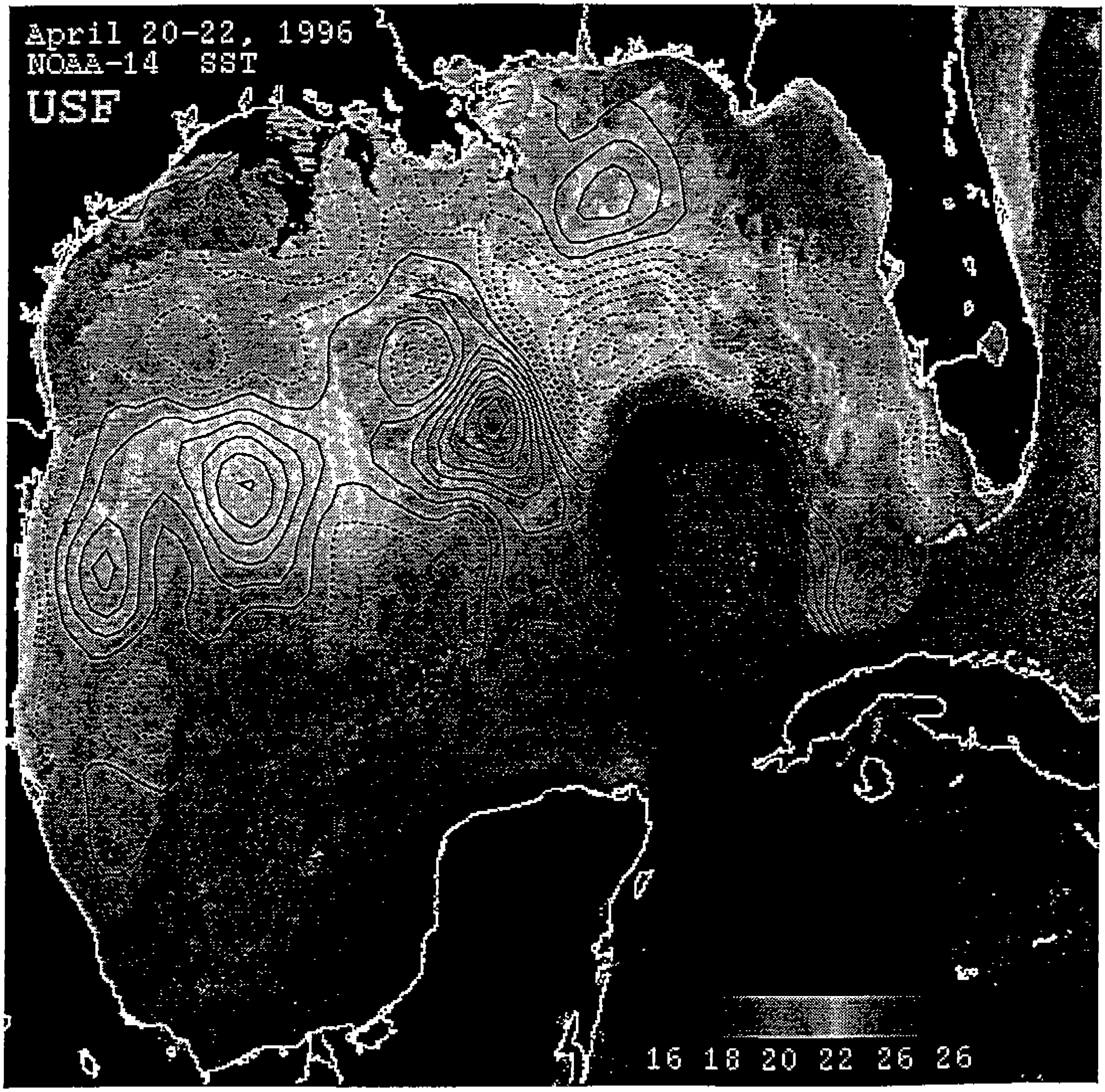

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Modeling Deepwater in the Gulf of Mexico

by

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Introduction

In this presentation, a brief summary of the previous and on-going modeling studies of the Gulf of Mexico (GOM) is presented with a discussion of some relevant issues. Since the pioneering work of Hurlburt and Thompson (1980), ocean circulation in GOM, in particular, the dominant Loop Current (LC) and the Loop Current Eddies (LCE) have attracted the interests of modelers . In recent years, significant efforts (e. g., models by DYNALYSIS and Kantha, et al.) have been exerted toward verifying the models of GOM within the framework of simulating the dynamics of LC and LCE. In addition, model verification over the Louisiana-Texas shelf has been a notable objective of the recent model study funded by MMS (DYNALYSIS). It is well known that the upper layer circulation (i. e., top several hundred meters) in GOM is dominated by LC and LCE. In contrast, very little is known about the circulation below 1000 m. Direct current measurements have been rare (e. g., Pequegnut, 1972; Hamilton, 1990). Similarly, limited attention has been focused on deep circulation in GOM by the modeling community. Recent surge of interest regarding offshore leases for oil exploration and production beyond the shelf break and well into the upper slope in the northern GOM is accompanied by the strong interest in understanding the deep circulation in GOM.

Bottom bathymetry in GOM

The abyssal plain within the GOM has depths exceeding 3600 m while the sill depths in Yucatan Strait (approximately 1700 m) and in Florida Strait (approximately 800 m) are significantly shallower. This suggests that water within GOM below the sill depth in Yucatan Strait (1700 m) must be ventilated through vertical mixing. There is some evidence based on radioactive tracer data, suggesting relatively short residence time for the deepwater in GOM (Buerkert, 1997), i. e., fairly efficient ventilation below the sill depth. Ubiquitous energetic eddies observed in GOM through their interaction with bottom topography could be at least partially responsible for the efficient vertical mixing in deepwater (e. g., Vidal et al., 1994). Another interesting feature is the very rough bottom topography over the continental slope in the northern GOM. The complex bottom topographic features range in many spatial scales ranging from tens of meters (carbonate mounds and salt domes) to several kilometers (mud volcanic craters and submarine canyons) (Roberts, personal communication). The presence of the rough bottom topography implies possible topographically-induced current instability and enhanced vertical mixing (e. g., Polzin et al., 1997). Most of those topographic features are too small to be represented in the models that are presently used. This suggests that if enhanced mixing could result, somehow, this has to be accounted for in the model, perhaps through judicious parameterization in the model.

Previous and ongoing model studies

Since the pioneering model study of circulation in GOM by Hurlburt and Thompson (1980, 1982), several different types of numerical models have been used to model circulation in GOM (Tables 1 and 2). They include Princeton Ocean Model (POM), Modular Ocean Model (MOM), NRL (Naval Research Laboratory) global layer-model, Miami Isopycnic Coordinate Model (MICOM), Dietrich/Center for Air Sea Technology (DieCAST) and Sandia Ocean Modeling System (SOMS), Sigma/Z-level Ocean Model (SZM), and a nonhydrostatic mesoscale ocean model (Mahadevan et al., 1996).

In modeling GOM, two types of model domains are commonly used, namely, a limited-domain and as part of a larger-domain. The most common type of model domain is a limited-domain which limits model domain to GOM. Often, this type of model domain extends into the neighboring basins of Caribbean Sea and even part of the North Atlantic. The use of a limited-domain usually requires the specification of inflow as well as outflow representing the LC and the Florida Current, respectively. Under a larger-domain, circulation within GOM is modeled as part of a much larger model domain, such as the entire North Atlantic, or even a global circulation model. The use of a larger-domain alleviates the need to specify flow into and out of GOM.

Features of physical oceanographic importance in GOM encompass many scales in both time and space. Many satellite imageries of GOM reveal the dominance of the LC and the LCEs in the eastern gulf, while the central and the western gulf is dominated by older LCEs. Previous model studies indicate that in order to simulate realistic LC and LCE dynamics, it is necessary to use model grid resolution of 10-15 km. Additionally, if one is interested in smaller-scale features such as parasitic eddies, frontal waves that develop along the outer boundaries of LC and LCEs, frontal instabilities that develop along the shelf and coastal fronts, squirts and jets, it would be necessary to use even smaller model grid resolution, perhaps as small as a few kilometers or less. Moreover, if current-topography interaction in the rough slope water region is of primary importance, even smaller horizontal as well as vertical grids are needed in order to resolve 'rough' texture over the slope region. In fact, this poses a formidable challenge to the modeling community, considering that many of the prominent bottom bathymetric features are the size of salt domes with length scales of tens of meters. Owing to the dominant role played by the LCEs in providing energy input to the western gulf, realistic simulation of westward migration and decay of LCEs is of paramount importance. In order to faithfully simulate formation, subsequent westward migration and decay of LCEs, it appears that the use of small horizontal friction coefficients are necessary (less than 100 m^2 s^{-1}) (e. g., Dietrich and Lin, 1994; Welsh, 1996; Dietrich et al., 1997).

Modons (Anticyclone-cyclone pairs) in deep GOM

In studying LC and LCE dynamics, main focus has always been directed to the top several hundred meters of water column where LC and LCEs are so prominent. In contrast, deepwater, below the top several hundred meters, has not received mush attention, except for a very limited number of observations made (e. g., Pequegnut, 1971; Hamilton, 1990). There have been a few model studies which examined deepwater circulation in GOM (Hurlburt and Thompson, 1980, 1982; Sturges et al., 1991; Indest, 1992; Welsh, 1996). Hurlburt and Thompson (1980 and 1982) (hereafter referred to as H&T) simulated distinct features in deepwater GOM, which also appear in more recent model studies with more realistic model bottom bathymetry.

Pioneering model study by H & T revealed the dominant role of anticyclone-cyclone pairs in deep GOM which are associated with upper-layer LCEs. H&T refer to those anticyclone-cyclone pairs as "modons" following Stern (1975). According to H&T, in their two-layer experiment, when LC begins to form an eddy in the upper layer, a modon is formed in the lower layer. The modon intensity tends to follow that of the generating eddy in the upper layer. The axis of the modon is oriented close to the direction of propagation by the upper layer vortex with the anticyclone member leading and the cyclonic member trailing. The westward propagation speed of the modon slightly exceeds that of the upper layer vortex. Thus the flow actually becomes more baroclinic and the anticyclonic eddy in the upper layer situated over the cyclonic member of the modon. The modon tends to follow bottom topography. Apparently, the back interaction from the modon to the upper layer is sufficient that the trajectory of the upper layer vortex is also modified by the ,bottom topography. The presence of those anticyclone-cyclone pairs in deep water have been confirmed by more recent model studies (Indest, 1992) including those with more vertical resolution (Sturges et al., 1993; Welsh, 1996) than the two-layer model used by H&T. Those modons appear to be vertically coherent below the upper layer (top several hundred meters) all the way to the bottom, suggesting that the basic dynamics within GOM can be represented by a two-layer ocean.

The sequence by which a modon is formed in the lower layer can be understood by invoking an explanation proposed by Cushman-Roisen et al. (1990) to understand the formation of a anticyclone-cyclone pair underneath an upper-layer anticyclone in a two-layer ocean. When a Loop Current eddy is formed in the upper-layer, usually, a newly-formed LCE separates from LC and moves northwestward or westward direction. In the process, the lower layer below the eddy is being squeezed, while the trailing lower layer behind the eddy is stretched. This generates a nonuniform distribution of relative vorticity in the lower layer, anticyclone under the eddy and cyclone behind the eddy. This is indeed what is observed in the recent model study by Welsh (1996) (Fig. 1). Note that the center of the upper-layer eddy remains in the middle of anticyclone-cyclone pair in the deeper layer as the pair propagates more or less westward following the deepest part of the gulf. As the deep modons migrate westward with the upper-layer LCEs, the deep cyclone strengthens relative to the leading anticyclone and dominate the eddy field in the western GOM (Welsh, 1996). Those deepwater anticyclone-cyclone pairs appear to have a lifespan slightly less than those of upper-layer LCEs. Currents associated with those eddies in deepwater could reach 15~20 cm s^{-1} even at the deepest parts of GOM (Welsh, 1996). Interestingly, the only deepwater current meter measurements available (Hamilton, 1990) could be interpreted as features associated with those deepwater eddies (Welsh, 1996). In addition, a deep cyclone underneath the upper-layer anticyclone in the western GOM often appears along a hydrographic section (e. g., Hoffman and Worley (1986)).

Conclusions

Previous model studies of GOM indicate the presence of anticyclone-cyclone pairs that are associated with the upper-layer LCEs. Many features revealed by the limited previous observations available in deepwater appear to be consistent with the interpretation that deepwater in GOM below 1000 m is dominated by those eddies. Deepwater eddies are formed at the time of the formation of LCEs in the eastern Gulf, and migrate westward following the westward migration of the upper-layer LCEs. Those deep eddies are vertically coherent and give rise to significant deep currents even in the deepest parts of GOM. It appears that their interaction with rough slope topography in the northern slopewater region could be significant in dominating deep currents and circulation over the region.

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Biography

Masamichi Inoue had worked at the Florida State University and at Australian Institute of Marine Science. He has been at Louisiana State University for the past 10 years and is Associate Professor at the Coastal Studies Institute and in the Department of Oceanography & Coastal Sciences. His research interests include modeling ocean circulatiuon and transport processes. Dr. Inoue received his Bachelor of Engineering in naval architecture from Tokai University in Japan, his M. S. in ocean engineering from the University of Rhode island, his Master of Engineering in civil engineering and his Ph. D. in oceanography from Texas A&M University.

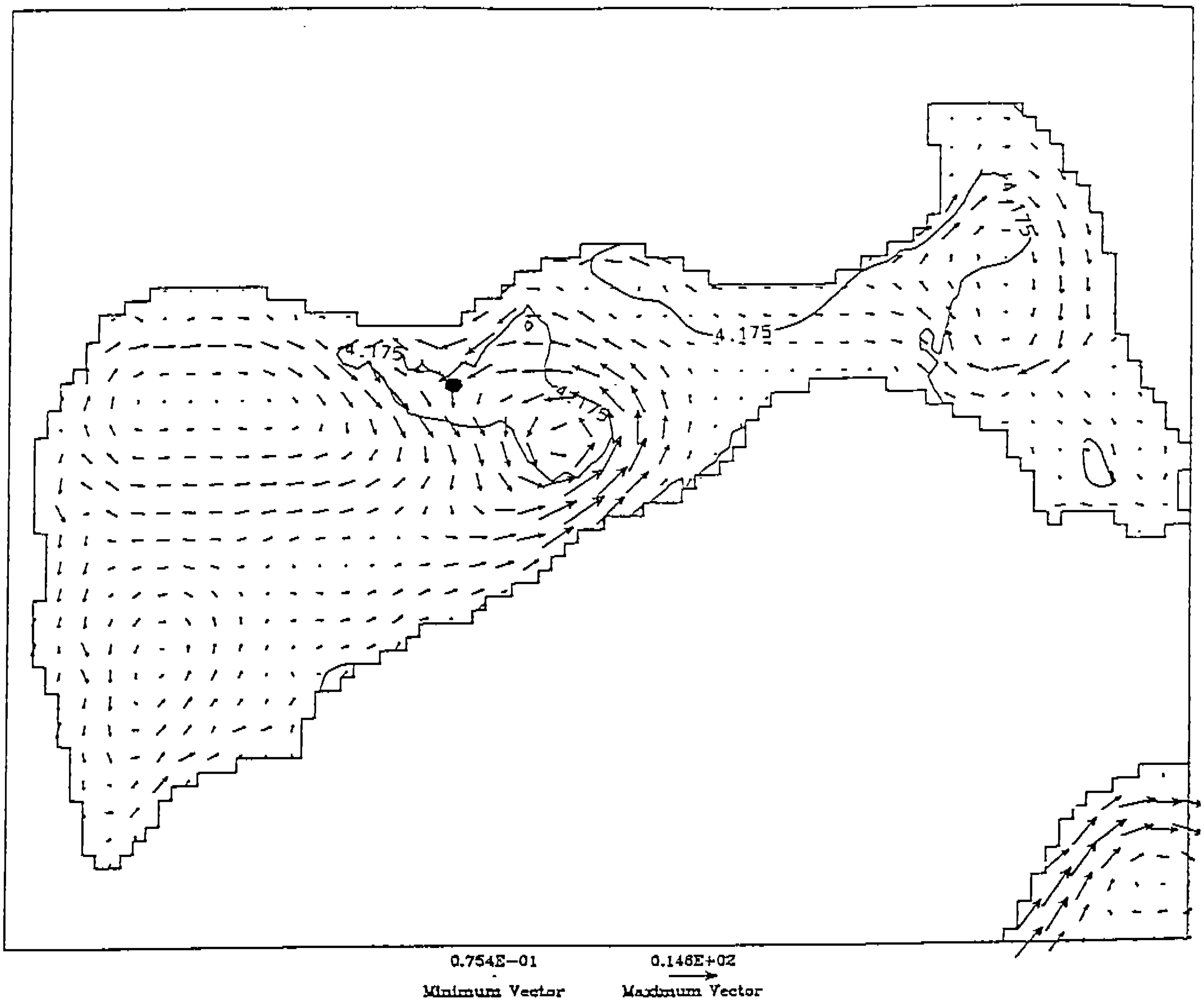

Figure 1. A snapshot of model temperature (°C) and velocity (cm/s) at 3150 m in the Gulf of Mexico. A closed-circle indicates the location of the center of the upper-layer Loop Current Eddy (LCE). Note that an anticylone is located to the west and a cyclone is located to the east of the LCE. The numerical model is based on the Modular Ocean Model on a 1/8 ° grid with 15 vertical levels. The model domain extends from 97.75°W to 72.875°W and from 16°N to 30.875°N. The model is forced by the inflow in the central Caribbean Sea and the Hellerman and Rosenstein climatological monthly wind stress (1983). (Welsh, personal communication).

Table 1. List of previous model studies of the Gulf of Mexico.

Hurlburt and Thompson (1980, 1982), 2-layer model.
Wallcraft (1986), NRL layer model.

Blumberg and Mellor (1985), DYNALYSIS, Oey (1995), Kantha, POM.

Arango and Reid (1991), a generalized reduced gravity model.

Sturges et al. (1993), MOM.

Welsh (1996), MOM.

Dietrich and Lin (1994), SOMS, Dietrich and Ko (1994), SOMS and DieCAST.

Mahadevan et al. (1996), a nonhydrostatic model.

Table 2. List of ongoing model studies of the Gulf of Mexico. It should be noted that the list may not be comprehensive.

NRL Group:
- Hurlburt & Murphy, NRL Global & N. Atlantic Models, Impact of Caribbean eddies.
- Johnson, POM.
- Martin, Comparison between POM & SZM.
- Barron, Comparison of different models.
- Keen, POM applied to several bays.

DYNALYSIS, POM with an emphasis on LATEX Shelf.

Kantha (U. of Colorado), U. of Colorado POM, data assimilation.

Mooers (U. of Miami), POM applied to Intra-Americas Sea.

Peggion (Center for Ocean & Atmospheric Modeling at U. Southern Mississippi), POM, GOM model nested with a coastal model.

Weisberg (U. South Florida), POM applied to west Florida continental shelf.

Hsueh (Florida State U.), MOM, study of DeSoto Canyon area.

Chao (Jet Propulsion Lab.), MOM, part of North Atlantic Model.

Dietrich and Mehra (Mississippi State U.), SOMS and DieCAST.

Bleck (U. of Miami), MICOM, GOM model driven by a global model.

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 **Royalty Management Program** 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.

Minerals Management Service
Gulf of Mexico Region

Managing America's offshore energy resources

Protecting America's coastal and marine environments