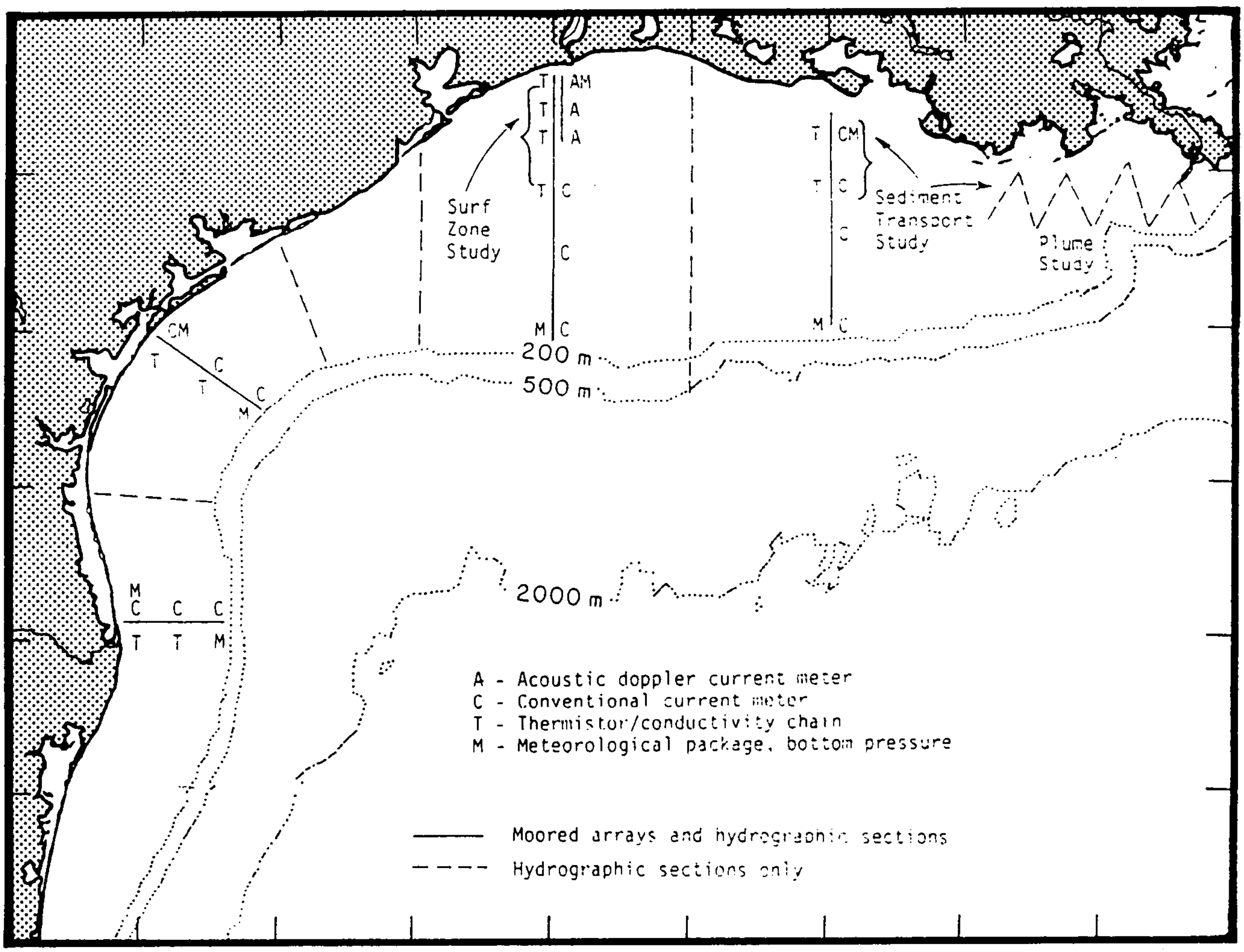
OCS Study
MMS 88-0065

Physical Oceanography of the Louisiana-Texas Continental Shelf

Proceedings of a Symposium Held in Galveston, Texas

May 24-26, 1988



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

OCS Study
MMS 88-0065

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Proceedings of a Symposium Held in Galveston, Texas

May 24-26, 1988

Editor

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GALVESTON SYMPOSIUM

PHYSICAL OCEANOGRAPHY OF THE
LOUISIANA-TEXAS CONTINENTAL SHELF

EXECUTIVE SUMMARY

The Minerals Management Service (MMS), Gulf of Mexico Outer Continental Shelf Region sponsored a Symposium on the Physical Oceanography of the Louisiana-Texas Shelf in Galveston, Texas on May 24-26, 1988. The symposium brought together a number of physical oceanographers, meteorologists, and ecologists to discuss the state of knowledge and to begin the planning process for a long-term study of shelf circulation covering the region from the mouth of the Mississippi River to approximately 24° N latitude along the Mexican coast, and from the shore out to a depth of approximately 500 meters. The proposed study, to be a component of the ongoing MMS Environmental Studies Program, is expected to take place during the period 1989-1991. It is anticipated that the work will be done principally through contracts after a competitive procurement process. Specific charges to the participants were:

- Assess the current state of knowledge concerning the circulation on the Louisiana-Texas shelf;
- Identify significant gaps in that knowledge;
- Recommend a field measurement program to address these gaps;
- Recommend the development of a hierarchy of models of small to large scale processes and circulation features, from coastal plumes and fronts to shelf edge eddy exchange, etc.;
- Identify and initiate coordination mechanisms and data-sharing arrangements with other proposed research efforts.

A group of scientists with Gulf of Mexico research experience was invited to speak on physical processes relevant both to understanding and modeling shelf circulation offshore Louisiana and Texas. A second group of speakers was invited to review government and industry programs which may be conducted concurrently with the MMS program. These invited presentations occupied the first two days. On the third day, the participants divided into three working groups to define specific processes which need further study, and to discuss techniques to measure or model the processes. The groups and the chairman for each were:

- Inner shelf and Mississippi River plume processes:
  Dr. Gabriel T. Csanady, Old Dominion University
- Outer shelf and upper slope processes:
  Dr. George Z. Forristall, Shell Development Company

- o Modeling and model/observation comparisons:
  Dr. Dong-Ping Wang, State University of New York, Stony Brook

Following the working group sessions, the participants reconvened in plenary session to summarize their discussions and to present the outline of a measurement and modeling program which will accomplish the MMS' goals.

In an initial overview address on important shelf processes, Dr. Robert O. Reid, Texas A&M University, stated that "the forcing mechanisms important to shelf circulation in the Louisiana-Texas domain include: wind stress, buoyancy flux and mass flux (evaporation - precipitation) across the air-sea interface; influx of momentum/energy across the open seaward boundary; and influx of fresh water at the eastern lateral boundary." These processes were discussed and elaborated upon during the remainder of the symposium.

Loop Current eddies (LCEs) have been recognized as an important mechanism by which energy is transferred from the eastern Gulf toward the west, and from deep water onto the shelf, with significant impacts on shelf circulation and water-mass characteristics. Transient storm systems can create shelf wave energy which is effectively trapped by the Louisiana-Texas shelf.

The combined plume of the Mississippi and Atchafalaya rivers has a significant density contrast with the surrounding shelf water and can be traced to the Texas-Mexico border. The plume front could serve as a barrier to onshore movement of pollutants and as a "fast-lane" for pollutant transport down the Texas coast. Some of the boundary current appears to recirculate eastward along the outer shelf during the summer, resulting in significant amounts of relatively fresh water over the mid and outer shelf. In the vicinity of the Mississippi River Delta, the river plume reacts to strong winds and has been observed far east of its normal position.

Satellite images have revealed a highly complex frontal structure over and beyond the shelf. River fronts, the coastal boundary current front, turbidity fronts, remnant Loop Current eddies, and "squirts" and "jets" along the shelf break have all been observed and contribute to the complexity of measuring and modeling the circulation of this area.

Meteorological effects on shelf circulation can be significant. The general southeasterly wind flow during most of the year can be interrupted by severe tropical storms during summer and early fall, and by cold frontal outbreaks ("northers") during winter. Frontogenesis has been observed to shift from the coastline in fall to the shelf break during winter.

Since 1983, the MMS has supported the further development of the Gulf of Mexico circulation model of Hurlburt and Thompson. While providing accurate representations of deep water circulation, including Loop Current eddies, the model is not optimal for representing shelf circulation. Several presentations on the wide variety of models which have been applied to Gulf regions indicated that, although seldom noted in the literature, there have been notable successes in simulating specific regions or events, such as hurricanes.

The prospects for major physical measurement or modeling activities by any other agency in the northwestern Gulf of Mexico during the target period are slim, judging from the presentations by agency representatives. No significant new initiatives were described, but a number of operational efforts will take place, including modeling work in Galveston Bay by the National Ocean Service, an increase in offshore meteorological stations supplying data to the National Weather Service, and continued hydrographic survey work by Texas A & M University, the Mexican Navy, and the Mexican Institute of Electrical Investigations. (These latter two groups have long cooperated with MMS in physical studies emphasizing LCEs in the western Gulf.) MMS intends to share data and coordinate program activities with other agencies working in the area, mainly by means of rapid data-archiving at the National Oceanographic Data Center.

The participants in the workshop sessions addressed the process-oriented discussions of the previous two days (in which processes and features which needed study were identified) and each group formulated a set of recommendations to resolve the questions that had been raised. The MMS charge to the groups was to design a sound scientific program which would enhance the Service's oil spill modeling and risk assessment capability. The discussions of the inner and outer shelf groups resulted in recommendations to establish several current meter transects from shallow water to beyond the shelf break, with an appropriate admixture of thermistors, pressure sensors, conductivity sensors, and wave gauges. Existing offshore weather buoys (and a new network of meteorology stations supported by an industry consortium) may be augmented by additional buoys. Hydrographic cruises across the shelf and along the shelf break were recommended, along with special studies of the Mississippi and Atchafalaya rivers' near field plume, regional sediment transport, and near shore currents. Satellite imagery and drifting buoys will enable LCE-tracking during the program.

The modeling group recommended analyzing a hierarchy of models consisting of the following four components:

- o Basin-scale model for the Loop Current and eddies;
- o Basin/sub-basin scale shelf-edge eddy exchange models;
- o Shelf circulation models;
- o Coastal plume/front models.

Models should be nested to derive full benefit of the modeling hierarchy. Field data should be made available to the modelers as rapidly as possible for model validation, as well as to enhance feedback from the modelers to the field program design. The modeling group recommended establishing procedures for independent evaluation of model performance.

It was recommended that the MMS sponsor a synthesis of existing data, and publish the results of this study in a peer-reviewed book dedicated to Louisiana-Texas shelf circulation.

1.0 INTRODUCTION

1.0 INTRODUCTION

1.1 Background

The Minerals Management Service (MMS) of the Department of Interior is responsible for managing the activities of the Outer Continental Shelf (OCS) oil and gas industry and for assessing impacts of the industry on the environment. One aspect of managing the OCS Leasing Program is the assessment of risks associated with offshore development.

The MMS uses a numerical simulation model, the Oil Spill Risk Analysis (OSRA) model, to provide a quantitative basis (probabilities of contacts to various resources and areas) for assessing risks associated with various oil exploration, production, and transportation scenarios. The OSRA model is not used in a real-time (or real-case) prediction mode, but rather as a tool to develop statistical estimates of oil spill trajectories and the multiple effects of spilled oil on the environment. In using the OSRA model, a number of randomly occurring oil spills, from various potential sites and spill sources are input to the model. A large number of spills are started from each location, simulating oil spill occurrences. The start time of each spill is selected randomly in time with a given number of starts each season. The model then calculates the spill trajectories, based on winds and currents input from other sources.

The Gulf of Mexico is a complex region, in the physical oceanographic sense. The MMS Gulf of Mexico OCS Region embarked on a five-year physical oceanographic program in 1982 to measure and model physical conditions in the Gulf. These programs concentrated on processes in the deep, open basin of the Gulf and have been quite successful in modeling features such as the Loop Current and eddies spun off from it. The MMS now desires to conduct a program to study physical oceanographic processes on the Louisiana-Texas shelf and to develop a circulation model of this region.

A symposium was held in Galveston, Texas on May 24-26, 1988 to assist MMS in developing a program to model the circulation on the Louisiana-Texas continental shelf. The symposium was organized by Geo-Marine, Inc., with the technical aspects of the program developed by the University of Southern Mississippi Center for Marine Science (USM/CMS).

1.2 Purposes

The purposes of the symposium were to bring together a group of physical oceanographers, meteorologists, ecologists, and modelers; to provide them a forum to assess the current state of knowledge of circulation on the Louisiana-Texas shelf; and to begin the planning process for a long-term study of shelf circulation off Louisiana and Texas. The area of interest extends along the shelf from the mouth of the Mississippi River in the east, to approximately 24°N latitude along the Mexican coast, and from the shore out to a depth of approximately 500 meters. Offshore processes which influence shelf circulation, such as eddies, also will be considered. Specific symposium goals were to:

- Assess the current state of knowledge concerning the circulation on the Louisiana-Texas shelf;

- Identify significant gaps in that knowledge;

- Recommend a field measurement program to address these gaps;

- Recommend the development of a hierarchy of models of small to large scale processes and circulation features, from coastal plumes and fronts to shelf edge eddy exchange, etc.;

- Identify and initiate coordination mechanisms and data-sharing arrangements with other proposed research efforts.

The proposed study will be a component of the ongoing MMS Environmental Studies Program, and will be conducted by the MMS Gulf of Mexico OCS Region, New Orleans, Louisiana. The study is expected to take place during the period 1989-1991. It is anticipated that the work will be done on a contractual basis, following a competitive procurement process.

1.3 Symposium Structure

An Advisory Panel was convened by the MMS to assist in: planning technical aspects of the symposium; determining presentation topics; and selecting appropriate speakers. Panel members conducted workshop sessions at the symposium and assisted in preparing the Proceedings. The panel members were:

- Dr. Gabriel T. Csanady
  Old Dominion University
  Norfolk, VA

- Dr. George Z. Forristall
  Shell Development Company
  Houston, TX

- Dr. Dong-Ping Wang
  State University of New York
  Stony Brook, NY

Dr. Thomas M. Mitchell, USM/CMS, coordinated preparations for the symposium, moderated the meeting, and edited and assembled the Proceedings. Dr. Murray Brown, MMS, oversaw and advised the panel and moderator on all aspects of preparation and conduct of the symposium. Mr. Ruben Garza, Geo-Marine, Inc., coordinated all logistical aspects for the symposium.

The symposium consisted of three distinct sessions:

- Invited technical presentations;

- Invited presentations to review government and industry programs which may be conducted concurrently with the MMS program;

- Workshop sessions and general discussion.

The first two days were devoted to the technical and government/industry program presentations. A group of scientists with research experience in the Gulf of Mexico was invited to speak on their various areas of expertise in order to set the stage for the workshop sessions and to bring all participants up to a minimum level of knowledge on the pertinent processes. The speakers were asked to summarize the state of current knowledge in each topic area, and not just relate results of their own research. A second group of speakers was asked to review programs which their agencies or industry may conduct during the time period 1989-1991, and which could either contribute to the MMS program, or benefit from its results. The MMS intends to coordinate program activities with other agencies working in this area, and to share data mainly by means of rapid data archiving at the National Oceanographic Data Center.

On the third day, the participants divided into three working groups (of their own choosing) to define specific processes which need further study, and to discuss techniques to measure or model the processes. The groups and the chairman for each were:

- Inner shelf and Mississippi River plume processes:
  Dr. Gabriel T. Csanady

- Outer shelf and upper slope processes:
  Dr. George Z. Forristall

- Modeling and model/observation comparisons:
  Dr. Dong-Ping Wang

These groups were chosen to address the three principal areas needing the most emphasis and study. Following the workshop sessions, the participants reconvened in plenary session. Each workshop chairman presented the recommendations of his workshop group. A final discussion was held in which the participants developed the basis of a program of measurements and modeling to accomplish the MMS's goals.

Each speaker prepared an abstract of his/her presentation. These are presented in Section 2.0. The workshop chairmen prepared written summaries of their groups' discussions and recommendations, which are included in Section 3.0. The recommendations of the workshop groups and the general discussion which followed are synthesized into a coherent total measurement and modeling program designed to upgrade the OSRA model and provide accurate simulations of ocean circulation on the Louisiana-Texas shelf. These recommendations are presented in Section 4.0.

2.0 INVITED PRESENTATIONS

2.0 INVITED PRESENTATIONS

Two groups of speakers presented papers at the symposium. These were invited technical papers dealing with different oceanographic processes, and invited government/industry papers which dealt with programs that may be conducted concurrently with the MMS program by either other government agencies or industry. The MMS would like to initiate coordination mechanisms and data-sharing arrangements with such programs. Two introductory papers were given by MMS personnel.

Abstracts of the MMS introductory papers are included in subsection 2.1. Abstracts of the technical papers are presented in subsection 2.2, while abstracts of the government/industry program papers are presented in subsection 2.3. The papers appear in the order in which they were presented, within each category.

2.1 Minerals Management Service Presentations

2.1.1 WHY THE MINERALS MANAGEMENT SERVICE CONDUCTS PHYSICAL OCEANOGRAPHIC STUDIES

Mr. J. Kenneth Adams
Minerals Management Service
Gulf of Mexico OCS Region

The Minerals Management Service is a customer in the market for physical oceanographic information. As providers of this science you should be aware of the importance of understanding the customer's motives, concerns, and needs. A lesson can be learned about this from one of the major airline companies. They set as their goal complete customer satisfaction - no resources spared to make the customer happy. A distraught elderly lady was attempting to board one of their flights with her beloved pet dog in an animal container and was engaged in an argument with the gate attendant. The supervisor was summoned and gave his personal assurance that the dog would be perfectly safe as checked baggage. She conceded, but as luck would have it, the container did not show up at the destination baggage claim. The airline people responded immediately and tracked down the cage in a distant city. But when the cage was opened the dog was dead. In a panic this supervisor put out a search for an exact duplicate of the dog and paid an exorbitant price. He phoned the lady to tell her that her dog had been found and that he was personally delivering it. He arrived at the lady's house hoping that his ruse would be successful and that this customer would never know of the dog's demise. He was much relieved when the replacement dog bounded out of the cage and into the lady's lap. With tear-filled eyes she gazed up and said, "I do not know how to tell you this but this is not my dog." "Are you sure," he said? "This dog looks exactly like yours." "Yes", she said, "but, you see, my dog was dead."

So beware of assuming that you know the customer's needs. We are interested in physical oceanography for very practical reasons, primarily related to risk analysis.

- We must assure structure and equipment reliability on the continental slope and in areas of unstable bottom;

- We must predict pollutant transport

  The movement of spilled oil:
  - as a surface slick;
  - as an emulsion - as in the Ixtoc spill; and
  - as physically or chemically dispersed droplets in the water column;

- We must predict the dispersal of drilling fluids and produced formation waters;

- We must estimate recruitment and recolonization rates for areas depopulated by spilled oil;

- We must devise workable oil spill contingency plans to manage and decrease the risk associated with OCS development; and

- We must describe and define physically driven biotopes such as upwelling and stagnation zones.

These needs are simple to state but difficult to satisfy and we need your help. If you would like to know more about our interest in physical oceanography, please see any of the MMS associates here between seminars. We will be glad to discuss our concerns with you.

2.1.2 USE OF APPLIED OCEANOGRAPHY IN STOCHASTIC MODELING OF OIL SPILLS ON THE OUTER CONTINENTAL SHELF

Mr. Robert P. LaBelle
Minerals Management Service
Branch of Environmental Modeling

The Department of the Interior analyzes the likelihood and potential impacts of oil spills associated with production and transportation of oil in Federal waters of the Outer Continental Shelf (OCS). A computerized simulation model, the Oil Spill Risk Analysis (OSRA), is used to provide the quantitative basis for oil spill risk assessment in the preparation of Environmental Impact Statements as part of the offshore leasing process.

The oceanographic research program which supports the OSRA model is outlined below with emphasis on the application of study results for the Gulf of Mexico OCS Region. The representation of winds and surface currents used to simulate the transport of spilled oil (as modeled by OSRA) is discussed, including circulation models currently in use and planned for the Gulf of Mexico Region.

Introduction

In managing the Outer Continental Shelf (OCS) Leasing Program, the Minerals Management Service (MMS) of the Department of the Interior uses computer simulation modeling to assist in analyzing the potential effects of oil spills on the marine and coastal environment. The Oil Spill Risk Analysis (OSRA) model is used to estimate the likelihood of spill occurrence and contact with ecological or economic resources located throughout the U.S. OCS. Because oil spills are a major concern associated with offshore oil development in all Federal lease areas, quantitative assessments of risks are needed to describe and analyze the effects of alternative leasing proposals. The OSRA model is not designed to simulate a particular real-time event, but rather to model a series of randomly occurring spill events from many potential spill sites and sources. This allows projection of contact probabilities estimated over the 15- to 25-year lifetimes of OCS leases. Therefore, a wide array of seasonal surface current and wind conditions in each region is needed to simulate trajectories that are then used to calculate the statistics of potential contact. Since OSRA does not calculate winds and currents directly, input data for a quantification of such features are derived from a combination of direct measurements and mathematical modeling. The model is supported by an oceanographic research program maintained by the OCS Environmental Studies Program of the MMS. The relationship between OSRA and this program, as well as the major oceanographic study efforts currently used to provide inputs to the oil spill model, have been described in a recent publication. The present paper will outline several circulation models that are projected to be used in future modeling of oil spill trajectories in the Gulf of Mexico OCS Region.

Gulf of Mexico Region

Ongoing and planned studies sponsored by MMS support a 4-year program in numerical ocean circulation modeling for the Gulf of Mexico. The aim of the program is to progressively upgrade in modest increments an existing numerical ocean circulation model of the Gulf developed by the Naval Ocean Research and Development Activity (NORDA). The final model should have a horizontal resolution of about 10 km and vertical resolution approaching 1 to 10 m in the mixed layer, 10 m at the thermocline, and 100 m in deep water. Throughout the program, the validity of the upgraded model will be continuously tested, and velocity field time series delivered periodically based on the most realistic simulation of Gulf circulation available.

Experiments in the first year with a two-layer hydrodynamic primitive equation model on a 0.2° grid concentrated on correctly specifying the coastline and bottom topography for maximum realism in circulation simulation. In the second year the grid was increased to 0.1° and simulations were generated by wind forcing, port forcing, and wind plus port forcing. An example of the Loop Current-driven circulation is presented in Figure 1 as a model simulation of surface currents on a specific day from a 10-year simulation. A new large anticyclonic Loop Current eddy is shown reaching the coast of Mexico and moving northward as it dissipates. The remainder of the 4-year program will further develop the capability for diagnostic and prognostic circulation modeling, including improved simulation of shelf and slope circulation features.

For the purposes of this workshop, it is necessary to consider the need for joint development of field studies and circulation models. When evaluating the appropriateness of circulation models, the Branch of Environmental Modeling uses the decision tree illustrated in Figure 2 as a guideline. Identification of the processes characteristic to a certain region, as well as those that affect the fate and transport of pollutants, is the first step in evaluating or designing a candidate model. The field studies should have the objective of identifying, characterizing and parameterizing processes that are critical in this region. Some of the following processes may dominate this region or act in concert and it is important to properly represent these in the modeling efforts:

- The wind-driven shelf circulation;
- Air-sea interaction;
- Fronts, stratification, and the inner shelf circulation;
- Riverine input, turbid plumes;
- Effects of eddies on the slope and outer shelf with resultant induced circulation on the inner shelf.

The field studies should also have the objective of comparing specific field measurements and results with existing model products so that we can learn from past experience and quantify the quality of the model products. Finally, the field studies will provide very valuable data for calibration and verification of models in the development phase. In turn, the results of modeling efforts can be used to "fine-tune" the observational programs.

References

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Hurlburt, H.E. and J.D. Thompson. 1980. A numerical study of Loop Current intrusions and eddy shedding. J. Phys. Ocean. 10:1611-1651.

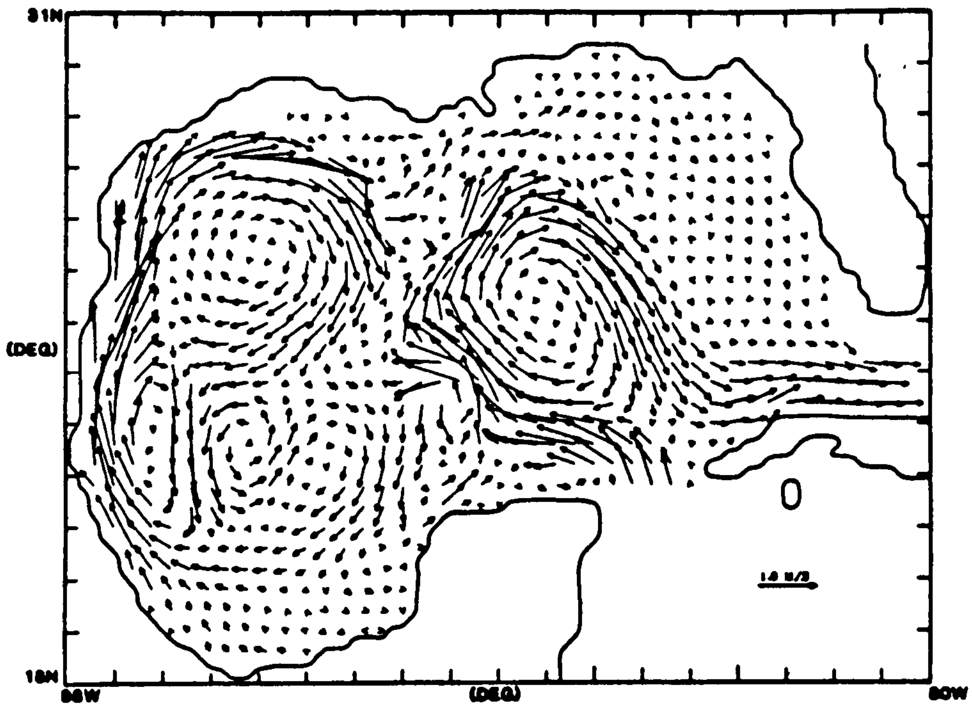

Figure 1. NORDA/Jaycor model simulation of surface currents for a specific day from a 10-year simulation.

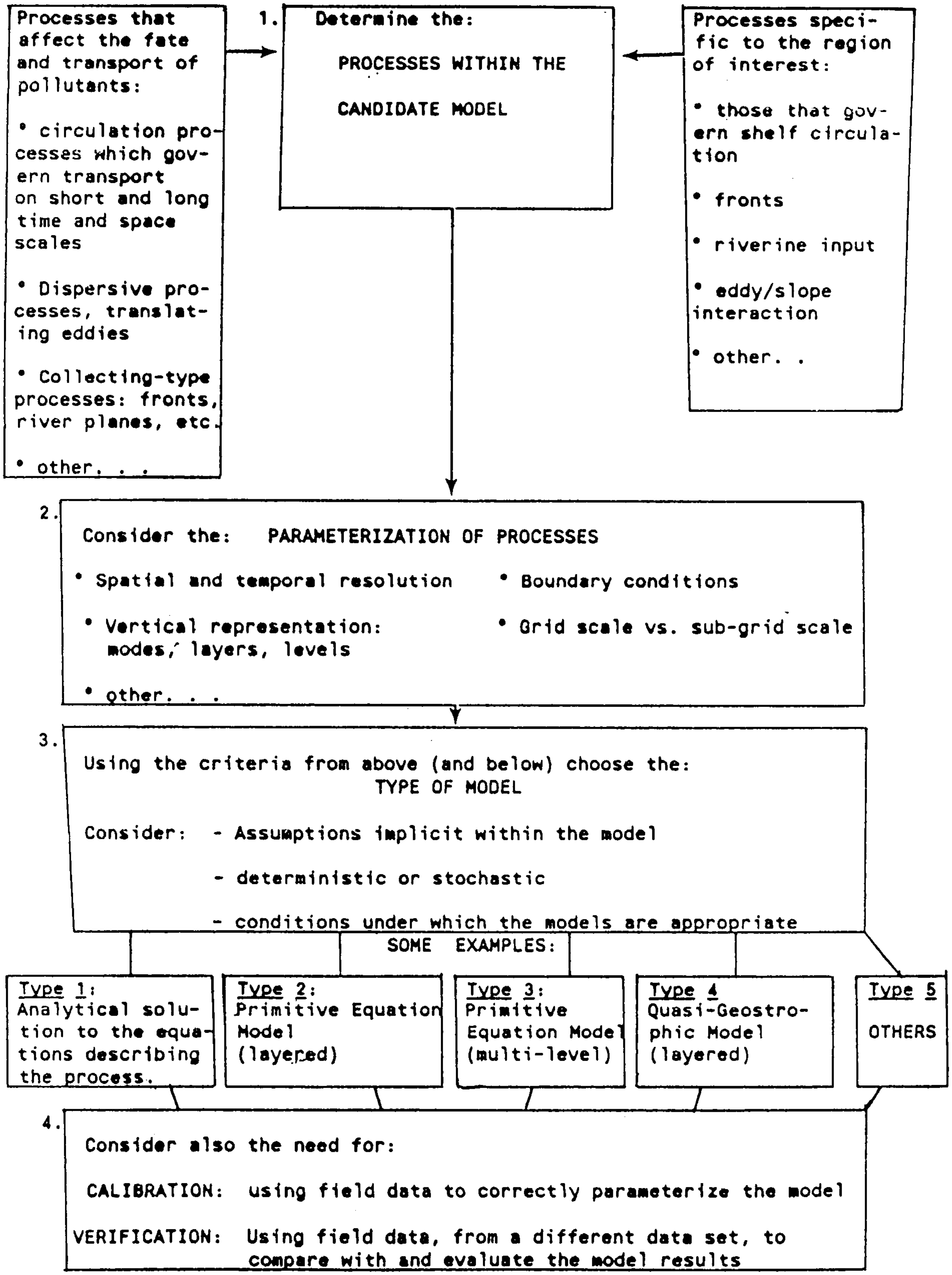

Figure 2. Decision tree used by Branch of Environmental Modeling to evaluate appropriateness of circulation models.

2.2 Invited Technical Presentations

2.2.1 OVERVIEW OF SHELF PROCESSES

Dr. Robert O. Reid
Texas A&M University
Department of Oceanography

This overview is intended to provide some background on the Louisiana-Texas shelf region and a reminder to the audience what the major processes are which control its dynamics; as such it is in the nature of a tutorial which requires no specific documentation in terms of references. It is an attempt to distill some well known facts and the insights of shelf dynamics into a small but coherent package.

The Louisiana-Texas continental shelf region is unique within the Gulf of Mexico in several respects; these include: its morphology, its proximity to a major source of fresh water, seasonal variation of its circulation, and possible modification thereof by encroachment of Gulf eddies. The occasional impact by severe tropical storms, while not unique to this region, is nevertheless emphasized by the shelf morphology; and while the disruption of the circulation has a short memory (perhaps weeks) for such events, the sediment redistribution may have a much longer memory (perhaps years). Shelf wave energy created by transient weather systems is effectively trapped in the stretch of shelf from Tampico on the southwest to the Mississippi Delta on the northeast where the shelf width approaches zero; yet off Galveston the shelf width is of the order of 200 km. The shelf width as used in the present context is the distance from shore to the sudden break in the bottom slope which generally occurs at a depth of about 180 meters.

The Louisiana-Texas shelf is subject to the influence of winds out of the southeast during most of the year, except during frontal outbreaks (northers) during the winter or the rare but dramatic hurricanes which can occur during the summer or early fall. Like most coastal regions in the Gulf of Mexico, it has a low energy wave climate (including tides), except during the severe tropical storm events. The shelf circulation is governed by the wind climatology, the influx of fresh water from the Mississippi and Atchafalaya Rivers and by possible influence of anticyclonic rings in the western Gulf which occasionally migrate northward and impinge on the continental slope off the Texas coast. Other papers at this symposium address the available data and inferred circulation regimes, including possible influence of rings on the shelf dynamics. My focus is confined to mechanisms or processes which control in varying degrees the shelf scale circulation and its temporal and spatial variability.

In focusing on the shelf scale circulation, and the slowly evolving changes thereof, one must remain aware of certain mechanisms which couple small scale, rapidly fluctuating phenomena with the quasi-steady regime in subtle ways. Examples are: <u>Reynolds stresses</u> wherein random turbulent motions, in the presence of mean current shear, produce a quasi-steady flux of momentum which provides an effective mechanism for balancing the driving forces; and <u>radiation stress</u> due to surface waves which provides the <u>driving</u> mechanism for quasi-steady littoral currents important in near-shore sediment dynamics. Of particular importance in shelf circulation is the vertical flux of horizontal momentum at the sea bed (bottom shear stress). Since it is known to be a quadratic function of the near bottom velocity, the existence of oscillatory signals due to waves and tides superimposed on quasi-steady currents can modify the quasi-steady part of the stress signal relative to that which would exist in the absence of the oscillatory currents. This requires that the proper parameterization of bed stress take this rectification effect into account via a knowledge of the variance of the oscillating part of the flow.

The forcing mechanisms important to shelf circulation in the Louisiana-Texas domain include: wind stress, buoyancy flux and mass flux (evaporation-precipitation) across the air-sea interface; influx of momentum/energy across the open seaward boundary; and influx of fresh water at the eastern lateral boundary. The quasi-steady circulation may represent a nearly quasi-geostrophic balance (modified by sea bed shear stress). However an understanding of how a given regime evolves and the means for predicting temporal changes in response to changing forcing is best addressed in terms of the following equation for the time rate of change of the depth-averaged potential vorticity (Q):

$$\frac{\partial Q}{\partial t} + A + R + S = C_s + B - C_b - C_l. \qquad (1)$$

Here A is the advection of Q by the current, R is the topographic restoring term due to flow across contours of f/h (f = Coriolis parameter, h = depth), S is a solenoidal term which is non-zero if density contours are not parallel to bathymetric contours, C_s is an Ekman pumping term associated with wind stress, B is a buoyancy pumping term caused by the supply of heat and mass at the sea surface, C_b is the Stommel type resisting bottom 'torque', and C_l is the Munk type resisting lateral 'torque' (due to lateral Reynolds stresses). The linear Munk type model for steady circulation in deep oceanic regimes is primarily a balance of R with C_s - C_l, the terms S, B and C_b playing minor roles.

For shelf circulation regimes S, B, C_b and A can play important roles because of the shallow but variable depth and the relatively large horizontal gradient of density which can exist in the presence of a significant fresh water source. Moreover the variable depth can be important in respect to the form of C_s. In particular C_s is proportional to

$$\mathrm{curl}_z\ (T_s/h)$$

where T_s is the wind stress. Even if T_s were uniform across the shelf, an effective Ekman pumping still occurs and is proportional to

$$(T_s \times \nabla h)_z.$$

The latter term is positive if the wind stress is directed with the shallow water to the right (e.g., easterly winds on the upper Louisiana-Texas shelf). Such a regime would tend to give cyclonic circulation (westward flow nearshore and eastward return flow in the deeper water offshore).

The role of fresh water supply on the evolution of a circulation regime enters via the solenoidal term S. It is proportional to

$$(\nabla h \times \nabla \rho)_z$$

where ρ is the vertically averaged density. The presence of fresh water supply at the eastward end of the Louisiana-Texas shelf can lead to a significant gradient of ρ from east to west. Since h increases offshore near the fresh water source, the effect is to produce negative S which in turn causes the development of positive (cyclonic) circulation, the contribution to the temporal change of Q being -S. The advection of ρ and Q produced by such circulation will modify the density distribution so as to keep the westward flowing fresh water on the near shore side and the denser saline water offshore. Thus the fresh water source can reinforce an easterly wind regime, but will be in opposition during a northwesterly regime (as can occur during the passage of a winter cold front over the shelf - and for which both C_s and the buoyancy driving are negative).

Superimposed on the quasi-steady circulation are: the superinertial motions due to surface waves and short internal waves, the near inertial motions due to tides and very long internal waves, and the subinertial motions associated with topographic shelf waves. The latter are the counterpart of Rossby waves in ocean basins in which the cross shelf component of flow produces vortex stretching (R term) which changes Q and causes the fluid to oscillate about a given f/h contour. While the phase propagation is always such that the shallow water is to the right, the energy can propagate either way, depending on the longshore wave length and the bathymetry. These trapped waves can be excited by changes in the wind forcing or by the encroachment of eddies into the continental slope region. It is perhaps the latter interaction phenomena which is least understood and deserves to be highlighted for serious further study.

2.2.2 GENERAL CIRCULATION PATTERNS/HISTORICAL DATA

Dr. Evans Waddell
Science Applications International Corporation

The Louisiana-Texas shelf region (Figure 3) varies in width between 30 km and 200 km with the widest regions offshore west Louisiana and east Texas. The coast and isobaths change orientation by approximately 90° in the west-central portion of the study area going from approximately east-west in Louisiana to almost north-south in west Texas. For the ocean forcing mechanisms, this change in coastal shelf and slope morphology can have a considerable impact on circulation patterns.

The inner-shelf is bordered by a series of economically and physically significant estuaries. Of first-order is the seasonally modulated estuarine discharge with the Mississippi and Atchafalaya Rivers being regionally dominant. The volume, timing, and location of this fresh water input to the shelf system substantially affect circulation on the inner half of the shelf. This influence extends along shore to the west well away from the source, resulting in a coastal boundary layer characterized during most of the year by lower densities.

As on many shelves, wind stress-related forcing is a major factor affecting circulation. The seasonal cycle of wind speed and direction relative to the local isobath orientation is believed to have a considerable influence on circulation patterns. As an example, winds directed to the NW will have an up-coast component in south Texas and a down-coast component in Louisiana. This could help drive a shelf-water convergence in the area of the bend in the isobaths. Tides in the study area are largely diurnal, and a relatively minor contribution to observed currents. Wind-induced water level fluctuations are often of greater amplitude than tides.

Limited measurements on the outer shelf and upper slope support the intuitive notion that circulation is the result of complex interactions between shelf processes and patterns in deeper water. The upper slope in the study area is directly affected by complex primary and secondary circulations patterns. Current time series suggests the presence of wavelike motion and remote forcing in the observed circulation.

Important processes affecting the slope include Loop Current eddies and related cyclones and frontal boundary features which drive regional circulation and shelf-slope exchange (flushing). As a result of an extensive MMS-funded study of eddies interacting with the slope, our identification and understanding of associated processes has been greatly expanded.

A variety of subsurface current measurements has been made in the study area (Figure 4). Of particular importance in Figure 5 are those at sites D, E, and H which are of sufficient length to allow detailed analyses of inner shelf circulation. In this figure, measurements may be grouped under a single letter identifier if they are in the same general area and/or made by the same group or sponsor. Note that measurements lasting a year or more are identified. Tables 1 and 2 provide greater detail concerning the ongoing observations during Year 5 of the MMS Physical Oceanography Program.

Relatively few regional hydrographic surveys have been made on this shelf. Several recent (< 5 years old) cruises have been made by NOAA, however these were directed towards fisheries and the synopticity desirable in physical studies was not always maintained. Several of the subsurface current measurement programs included hydrographic surveys but these were usually proximate to specific mooring arrays.

Between NDBC environmental buoys and C-MAN and coastal stations, meteorological conditions at the borders of the study area are reasonably well documented with the drawback that many of the coastal stations are fairly far inland (Figure 6). Conditions within the study area, especially the mid- to outer shelf, are not well covered. Water levels are measured at only two NOS tide stations within the study area. During several previous current measurement programs, water levels (bottom pressure) also were measured. As an example see sites E and H in Figure 5. Because of its intimate link to shelf circulation, water levels would be appropriate observations at the coast and at seaward positions.

High Resolution Picture Transmission data (HRPT, 1 km) thermal/visible imagery has been archived by NESDIS since 1985. This includes links via Wallops Island, MD and Gilmore Creek, AK. Prior to 1985, GAC data is archived. During its operational life approximately 1100 Coastal Zone Color Scanner images were made in the Gulf. Many (most?) of these will not provide useful historical data due to cloud cover, etc.

Since 1983 a series of MMS-funded, satellite-tracked ARGOS drifters has been used to document movement of Loop Current eddies and related deeper Gulf and slope circulation. The ARGOS drifters funded by other public and private sources have substantially expanded the MMS data base. These data provide important information concerning translation, size and dynamics during all phases of eddy movement. This becomes increasingly important during the warmer months when thermal fronts are marginally detectable, or undetectable using satellite thermal imagery.

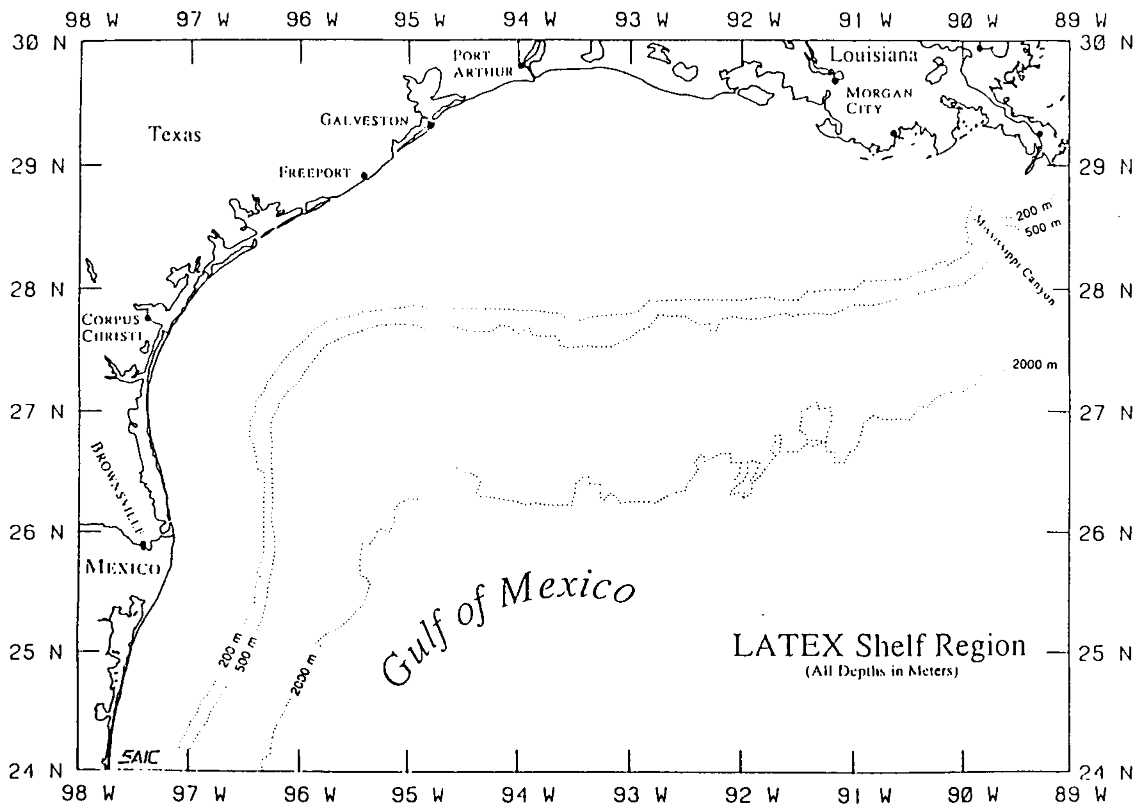

Figure 3. General study area with place names.

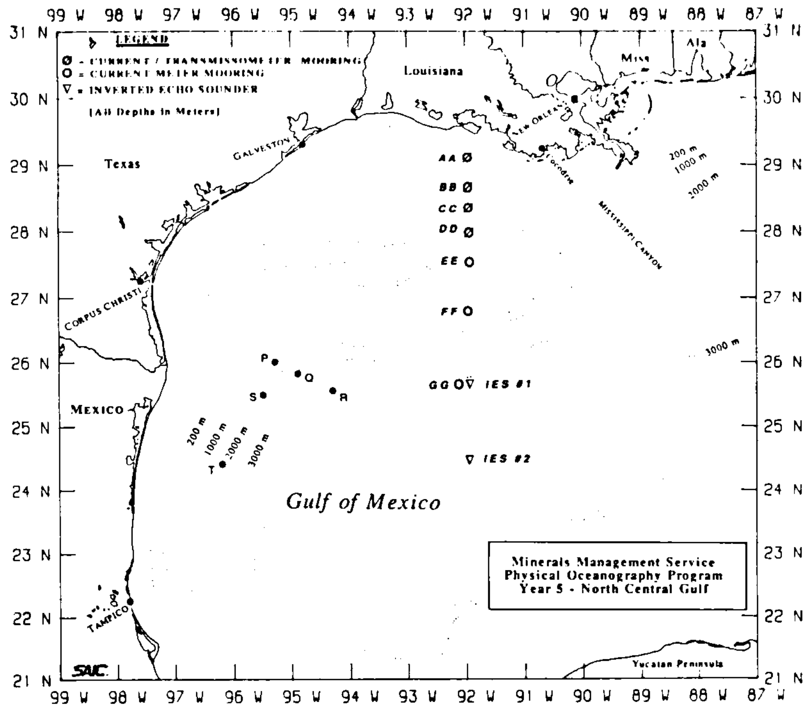

Figure 4. **Subsurface current measurement sites during Program Year 3 (P-T) and Year 5 (AA-GG).**

LATEX Shelf Region

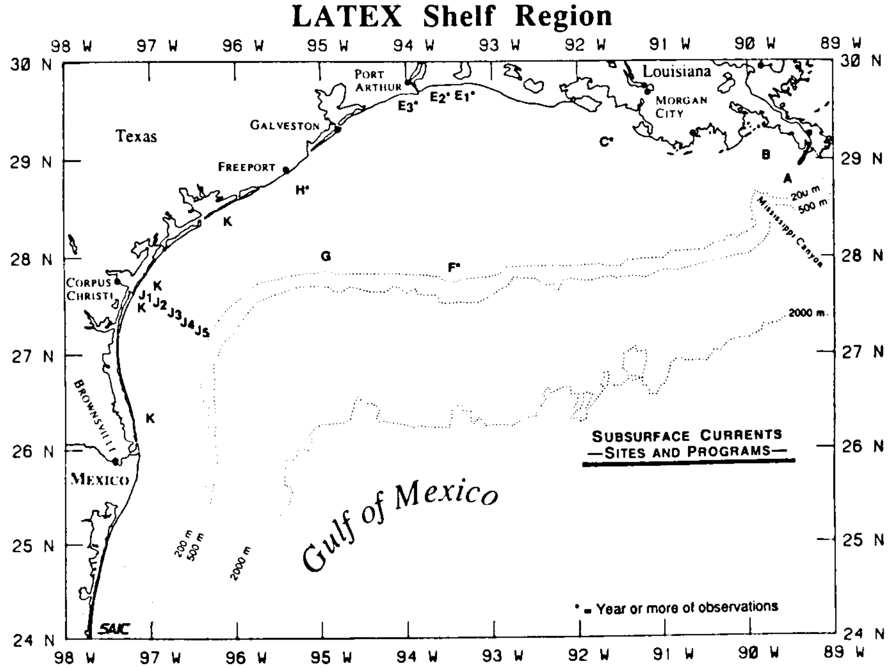

Figure 5. **Other relevant shelf moorings. Letters may indicate series of measurement at several sites. Subscripted letters are concurrent instrument arrays. An asterisk indicates measurements of a year or longer.**

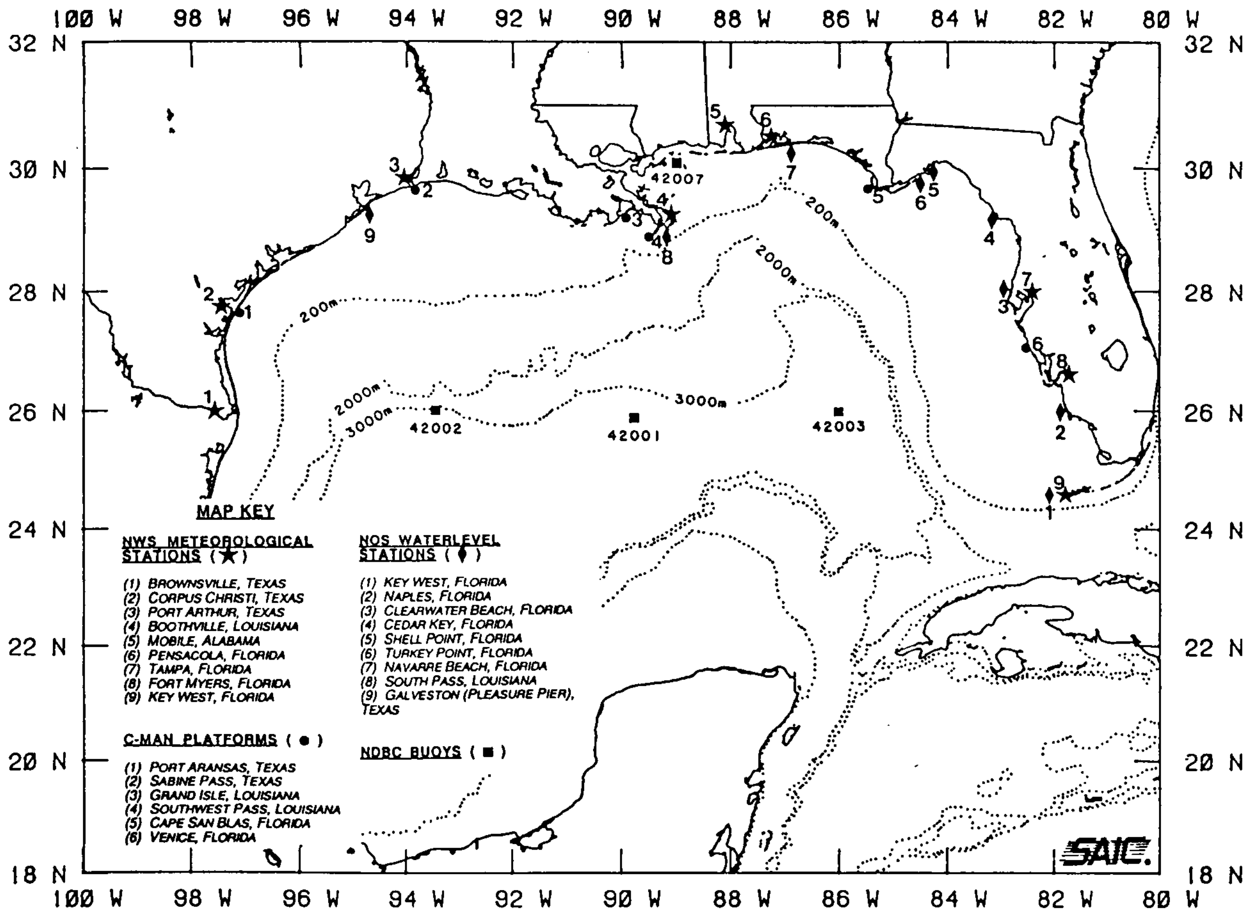

Figure 6. Meteorological and water level stations in the Gulf of Mexico.

Table 1. Mooring locations and corresponding depths for Year 5 of the MMS-sponsored Gulf of Mexico Physical Oceanography Program following the February 1988 rotation.

Mooring	**Loran C Time Delays**	Location Latitude	Location Longitude	Water Depth (m)	Top Depth (m)
AA	11189.5 27194.6 46871.0 64056.3	29°07.011'N	92°08.654'W	14	4.3
BB	11277.0 27097.2	28°40.57'N	92°05.92'W	40	8.8
CC	11344.2 26998.3	28°18.48'N	92°05.63'W	64	7.8
DD	11436.3 26945.8	27°52.68'N	91°59.40'W	184	10.5
EE	11502.0 26835.3 46561.2	27°28.026'N	91°59.961'W	825	97
FF	11608.7 26662.5 46420.1 64082.3	26°44.553'N	91°59.763'W	1750	97
GG	11736.6 26417.2 46213.2 64060.9	25°39.069'N	92°01.853'W	3000	97
IES 1*	11734.1 26412.7 46215.1 64061.1	25°39.4'N	92°02.4'W	3000	2998
IES 2*	11853.6 26241.0 46000.7 64024.9	24°29.57'N	92°00.95'W	3743	3741

***Sea Data inverted echo sounder**

Table 2. Contract specified mooring instrumentation levels for Year 5 of the MMS-sponsored Gulf of Mexico Physical Oceanography Program following the February 1988 mooring rotation.

Mooring	Water Depth (m)	Instrument	Instrument level (m)
AA	14	GO Mk 1 CM	7.5
		Sea Tech Transmissometer	9.5
		Aanderaa TR-2 Data Logger	9.5
BB	40	GO Mk 1 CM	12
		Sea Tech Transmissometer	14
		Aanderaa TR-2 Data Logger	14
		GO Mk 1 CM	18
		Sea Tech Transmissometer	20
		Aanderaa TR-1 Data Logger	20
CC	64	GO Mk 1 CM	11
		Sea Tech Transmissometer	13.5
		Aanderaa TR-2 Data Logger	13.5
		GO Mk 1 CM	28
		Sea Tech Transmissometer	32
		Aanderaa TR-2 Data Logger	32
DD	181	GO Mk 1 CM	13
		Sea Tech Transmissometer	15
		Aanderaa TR-1 Data Logger	15
		GO Mk 1 CM	100
		GO Mk 1 CM	150
EE	825	GO Mk 1 CM	100
		Aanderaa RCM 5	300
		Aanderaa RCM 5	725
FF	1750	GO Mk 1 CM	100
		Aanderaa RCM 5	300
		Aanderaa RCM 5	725
		Aanderaa RCM 5	1650
GG	3000	GO Mk 1 CM	100
		Aanderaa RCM 5	300
		Aanderaa RCM 5	725
		Aanderaa RCM 5	1650
		Aanderaa RCM 5	2500

2.2.3 INDUSTRY MEASUREMENTS: MOORED AND DRIFTING

Dr. George Z. Forristall
Shell Development Company

The oil industry makes oceanographic measurements both to support offshore operations and to provide criteria for the design of structures. The wave climate is usually of most interest for both types of problems, but there is also a long history of current measurements by many companies. Current meters have been installed on platforms mainly to get data during hurricanes for use in designing later platforms. From 1971-1977, the Ocean Current Measuring Program (OCMP) maintained three stations with electromagnetic current meters on the Texas-Louisiana shelf. The most notable result from that program was the measurement of 2 m/sec currents with little shear through 20 m water depth during tropical storm Delia. Later measurements in deeper water showed considerably more vertical structure. Platform-based measurements have continued with systems installed or planned on Exxon's Lena guyed tower, Chevron's MC133 platform, Shell's Bullwinkle platform, and Conoco's Joliet tension leg platform. The Lena system is interesting for its use of acoustic doppler meters which look outward from the tower to avoid interference effects from the structure.

As operations moved into deeper water at the edge of the shelf, it became more important to understand currents which were not dominated by the wind. From 1976-1980, operators maintained a significant number of current meter moorings near the shelf break in response to these needs. The flows observed were much more complicated and harder to explain than those in shallow water.

In recent years, there has been a shift from using instruments on fixed moorings to using boats and airplanes to take the instruments to the features of interest. Horizon Marine has used expendable current profilers (XCP's) to survey hurricane-generated currents from the National Hurricane Center's research aircraft in the Atlantic and Pacific. Plans have been made for surveys in the Gulf of Mexico, but there have not yet been any suitable storms. The eddy joint industry project (EJIP), described in this symposium by Cooper, has used shipborne acoustic doppler profilers, XCPs, and direct reading current meters to survey several eddies in the Gulf since 1983. Drifting buoys have also proved valuable for monitoring the Loop Current and its eddies, and more than 20 Argos buoys have been launched in the Gulf under industry sponsorship since 1984.

2.2.4 THE EDDY JOINT INDUSTRY PROJECT (EJIP)

Dr. Cortis Cooper
Conoco

EJIP was initiated in the spring of 1984 with the intent of coordinating the oil industry's research activity on Gulf of Mexico eddies. Participating members are: Amoco, Arco, Conoco, Exxon, Marathon, Mobil, Shell, and Sohio. To date EJIP has focused on gathering baseline measurements of eddy velocity and hydrographic data. Activities have included four detailed surveys of five eddies, as well as less extensive cooperative efforts with the Minerals Management Service (MMS).

Results from the first survey are described. The survey was done during a one week period in December 1983 using a shipboard acoustic doppler current profiler (ADCP), expendable current probes (XCP), expendable bathythermographs (XBT), and CTD. Two eddies were observed - an older one in the western Gulf adjacent to the west Texas shelf, and one just separated from the Loop Current. The western eddy was of order 200 km in diameter with peak currents of 1 m/s at the 100 m level. Water properties were uniform and characteristic of the high-salinity Caribbean subtropical underwater. The eastern eddy was of order 300 km in diameter with peak currents of near 2 m/s at the 100 m level. Water below 200 m is of Caribbean origin, while the surface waters show more variability, suggesting some inflow of Gulf of Mexico common water. The evolution of the eddies is also described based on the cruise measurements, satellite AVHRR, and other observations of opportunity. More details are given in Cooper, Forristall, and Joyce (1988, manuscript submitted to JGR Oceans).

2.2.5 SHELF PROCESSES RELATED TO OCEANIC EDDIES IMPINGING ON A CONTINENTAL SLOPE

Dr. James K. Lewis
Science Applications International Corporation

Introduction

Planetary-scale eddies can interact with shelf waters in a number of ways, many about which we know little. In this paper, we will present a brief review of some shelf processes related to eddies impinging or traveling along a shelf. The concepts presented here were developed from a consideration of Loop Current eddies in the Gulf of Mexico.

Shelf Processes
Entrainment of Shelf Waters

The entrainment process is one of the more simple forms of shelf processes related to eddies. In Figure 7, we show the beginning of an entrainment event as seen by drifters in the Gulf of Mexico. The two southern drifters were in Loop Current eddies. The two northern-most drifters were in shelf waters. As can be seen, the two shelf drifters were greatly affected by one of the Loop Current eddies, and this effect apparently was felt all the way to the inner reaches of the Texas shelf. Within two weeks, both shelf drifters had been incorporated into the flow field of the eddy (Figure 8). Hydrographic data indicate that this entrainment process increased the size of the eddy substantially, with little effect on its rotation rate. The entrainment appears to be extensive, yet the basic kinematics of the eddy did not appear to be significantly altered. And the data indicate entrainment only on the shoreward side of the eddy.

There are a number of questions related to the entrainment process for which we have no answers. For example, does the shelf interaction result in entrainment only on the shoreward side of eddies? Can we quantify how extensive a shelf entrainment event is? How can the eddy affect shelf waters that are almost 300 km away from its outer edge? What are the basic changes in the dynamics of an eddy during entrainment? Can we remotely monitor these changes for an indication of when an entrainment event has ceased?

Movement Along the Shelf

One of the most obvious effects of an eddy on shelf processes is its transfer of momentum to shelf waters. Gulf Stream or Loop Current eddies tend to have significant swirl speeds (angular momentum). As an eddy makes contact with a shelf region, it may begin to accelerate the shelf waters in the direction of the eddy flow field. We are not entirely sure that this occurs. It is possible that the flow field of the eddy is so close to zero at its outer edge that the lateral shear is too small to significantly accelerate the shelf waters. But we realize that entrainment of shelf waters can take place, so at least in that respect we must understand the movement of an eddy along shelf topography.

In Figure 9, we show the trajectory of a drifter in an anticyclonic Loop Current eddy. One will note that the center of the eddy moved up onto the 3000 m isobath at about 92°W. Considering the extensive vertical and lateral structure of these eddies (Hofmann and Worley 1986), it is difficult to imagine why the eddy would stay in this region of shallower water. After three rotations (approximately one month), the eddy made an abrupt southward adjustment, moving into deeper water within one revolution. The eddy then again moved onto the shelf slope, this time being the steeper Mexican shelf.

The case of this eddy's stalling on the 3000 m isobath is indeed worth investigating. Of the concerned physics, topographic and planetary beta would drive the eddy westward but non-linear accelerations would drive the eddy eastward (Smith and O'Brien 1983; Smith 1986). A balance between these effects could definitely be a plausible explanation for the stalling. If this can be verified, one might be able to establish a method by which one could predict the movement of an eddy so as to determine its effects on shelf processes.

Knowing the movement of the eddy along the shelf would allow one to predict times of possible shelf entrainment. The drifter data indicate that the eddy in Figure 9 began entraining shelf water after it stalled on the 3000 m isobath. But is the eddy losing mass to the shelf? Is there an exact exchange of water, with the result being an influx of eddy water onto the shelf? A simple argument would indicate an answer of "no" to these questions. Consider the conservation of mass and potential vorticity:

$$dH/dt + H\,D = Q$$

$$d(\zeta + f)/dt + D(\zeta + f) = 0$$

where H is the average depth, t is time, D is the horizontal convergence, Q is some source of mass (the entrainment process), ζ is the vertical component of vorticity, and f is the Coriolis parameter. Eliminating D between the two expressions gives

$$d[\ln(\zeta + f)/H]/dt = -Q/H.$$

Since Q is positive for entrainment, the above implies that $(\zeta + f)/H$ must decrease. This can be accomplished by moving southward, precisely what the eddy did after stalling on the 3000 m isobath. Thus, the abrupt southward adjustment would argue that the eddy had a net gain in mass and was not losing much water to the shelf.

Detrainment in an Eddy

There is a distinct form of detrainment for an ocean eddy which is interacting with a continental shelf. This comes in the form of a wake field generated by topographic interactions (Smith 1986). In essence, the eddy begins to shed energy in the form of trailing Rossby waves, and these form a wake of vortices. Unfortunately, we have little information as to how this loss of energy affects shelf processes.

Mass detrainment related to oceanic eddies can have a dramatic effect on shelf processes. An example of such a process was alluded to by Lewis and Kirwan (1985), but a more striking example is shown in Figures 10 through 12. In this case, a younger, more northerly eddy was stripping off mass from a smaller, older eddy along the Mexican coast. As a result, a tongue of warmer water was being whirled northward onto the Texas shelf. Thus, the result is an intrusion of water from the smaller eddy into shelf waters. But the intrusion is quite interesting in that it is well organized with the flow returning to the larger eddy. Subsequent data show that the jet disappears after some few weeks, and the flow field eventually consolidated around the larger eddy.

Such interactions must have significant implications for shelf processes. The mass contained in Gulf Stream and Loop Current eddies is substantial, so such tongues of water must be of considerable depth and velocities. Obviously, the short-term (order of several weeks) effect will be a displacement of shelf waters and the establishment of an intense jet-like flow regime. These types of effects can be quantified using drifter data. But what is the net effect on shelf processes? Is there any substantial exchange of mass, heat, or momentum during the duration of the jet? And how often could one expect such a process to occur?

Tropical Storms and Loop Current Rings
Frequency Distribution of Tropical Cyclones

We now consider a statistical analysis of tropical storms and hurricanes within the Gulf of Mexico over the period 1899-1978. Neumann and Pryslak (1981) produced charts of average storm frequency per unit area per 100 years. Their results were for three classes of storms; wind speeds of at least 34 kts (18 m/s), of at least 64 kts (33 m/s), and of at least 100 kts (52 m/s). The 34 kt storm data (Figure 13) show a distinct maximum in the frequency of occurrence in the Gulf. This maximum is over 70 storms per 100 years, and it is centered at about 26° North, 90° West. The magnitude of the maximum is significant, being at least 50% greater than other regional frequencies in the Gulf. The contour of 55 storms per year encloses the maximum and connects it to other areas of higher frequencies in the vicinity of Cuba. In addition, a secondary maximum of over 50 storms per 100 years is found in the western Gulf, centered at approximately 22° North, 94° West.

The frequency data for storms of at least 64 and 100 knts show trends similar to the above storm data. Position data show that most storms cross the Gulf from the southeast to the northwest (Neumann and Pryslak 1981). Thus, the maximums in the frequency data may represent one of two circumstances. The first is a central crossing point for storms in the Gulf of Mexico. In this instance, storms from all points would tend to converge on and pass through approximately 26° North, 90° West. This would imply that there exists a steering mechanism for many of the storms in the Gulf.

A second possibility is the intensification of tropical disturbances in the regions of the frequency maximums. If a weaker storm were temporarily energized while in the region south of the Mississippi Delta, it would be included in the frequency statistics of the stronger storms. Upon leaving the region, a loss of energy could result in the disturbance no longer being considered in the statistics of the more intense storms. Such an intensification process would lead to maxima in the frequency distributions.

Trajectory Data from the Loop Current and its Eddies

Since 1980, buoys have been placed in Loop Current rings in the Gulf of Mexico. The data (Figure 14) show that the rings are spawned between 25.5-26.0° North and 89-90° West. This is at the northern end of the Loop Current as it extends into the Gulf. Anticyclones may stay in this formation area for up to three months. The general movement of Loop Current rings is southwestward across the deepest portions of the Gulf of Mexico. However, a more westward track has been identified (Vukovich and Crissman 1986; Lewis and Kirwan 1987) which can take these rings along the slope of the Texas-Louisiana shelf. The rings eventually reach the Mexican shelf at about 22-24° North. The trajectory data show that warm core features can exist in this region of the Gulf quite a long period of time (order of 3 months and longer). In addition, older anticyclonic features in this region may be continually energized by newly arriving rings. The result is a semi-permanent warm core feature as has been detected by numerous hydrographic surveys (Merrell and Morrison 1981; Elliot 1982; Merrell and Vazquez 1983).

A Coincidence of Features?

A cursory examination of Figures 13 and 14 shows that the regions of maximum storm frequencies per 100 years closely correspond to that region in which Loop Current rings are spawned. Moreover, the region where rings persist off the Mexican coast coincides with secondary frequency maxima for the 34 and 64 kt storm data. The Loop Current and its eddies represent large, consolidated heat sources from which a storm can extract energy. These oceanographic features provide a surface mixed layer of the order of several hundred meters (Lewis and Kirwan 1987) as opposed to only 10's of meters for other portions of the Gulf of Mexico. Considering that tropical storms are heat conversion machines, it is not all that surprising that storm frequencies tend to be high over Gulf of Mexico regions with deep, mixed surface layers. However, we have never suspected that tropical storms might be significantly affected by the presence of Loop Current rings.

The coinciding of these atmospheric and oceanographic features raises a number of questions. First, is the net heat content of the water column a significant enough factor to bias the position and/or intensity of tropical storms? If so, what is the process? Do the spatial gradients of the net ocean heat content effectively steer storms by the differential intensification of areas within the storm? Or do rings just intensify storms which happen to pass over them?

There is another interesting process that should be mentioned, and pertains to the entrainment process. Entrainment was seen to occur for a ring associated with Hurricane Juan. Drifter and hydrographic data show that the ring had increased in size by about 60% prior to the formation of Juan (Lewis et al. 1988). The significance of such a process is that of consolidation of warm water masses. Because they are shallower, shelf waters typically become warmer than open ocean waters. However, this warm water is widely distributed, stretching from the Mississippi Delta to the Mexican coast. The entrainment process of a ring can consolidate these warm surface waters into one central area. In the situation of 1985, Hurricane Juan formed after the Loop Current ring entrained enough shelf water to increase its size by 60%. Is it possible that such a growth resulted in the appropriate amount of heat in one location to give the cyclogenesis process the boost needed to form Juan?

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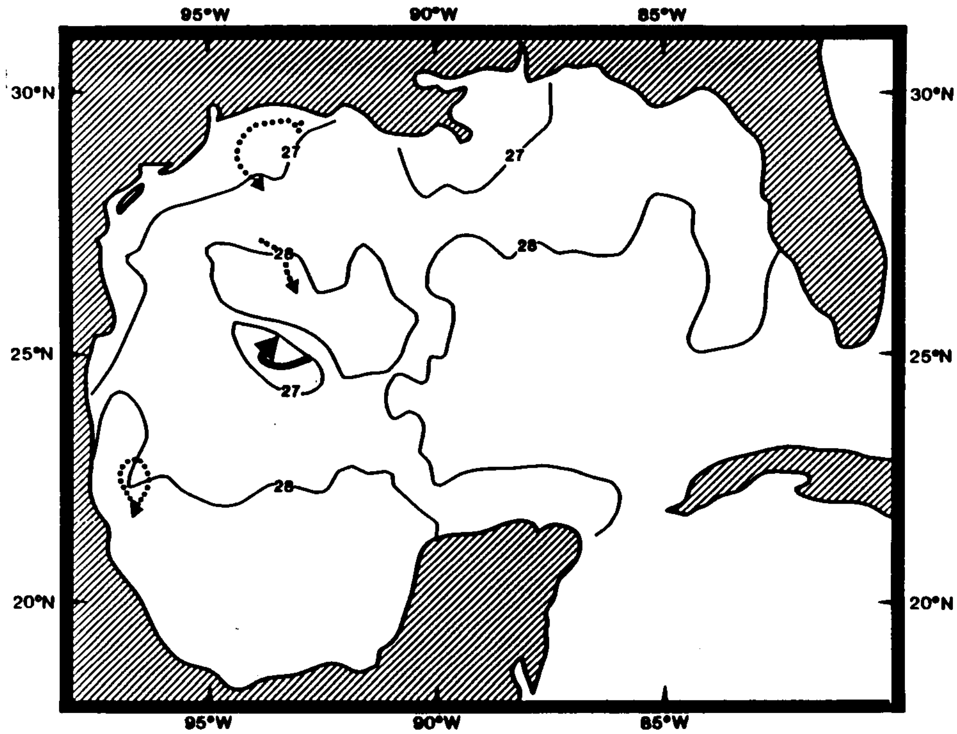

Figure 7. Sea surface temperature (°C) for the week of 29 October 1985. Corresponding trajectories of drifters are shown by arrows.

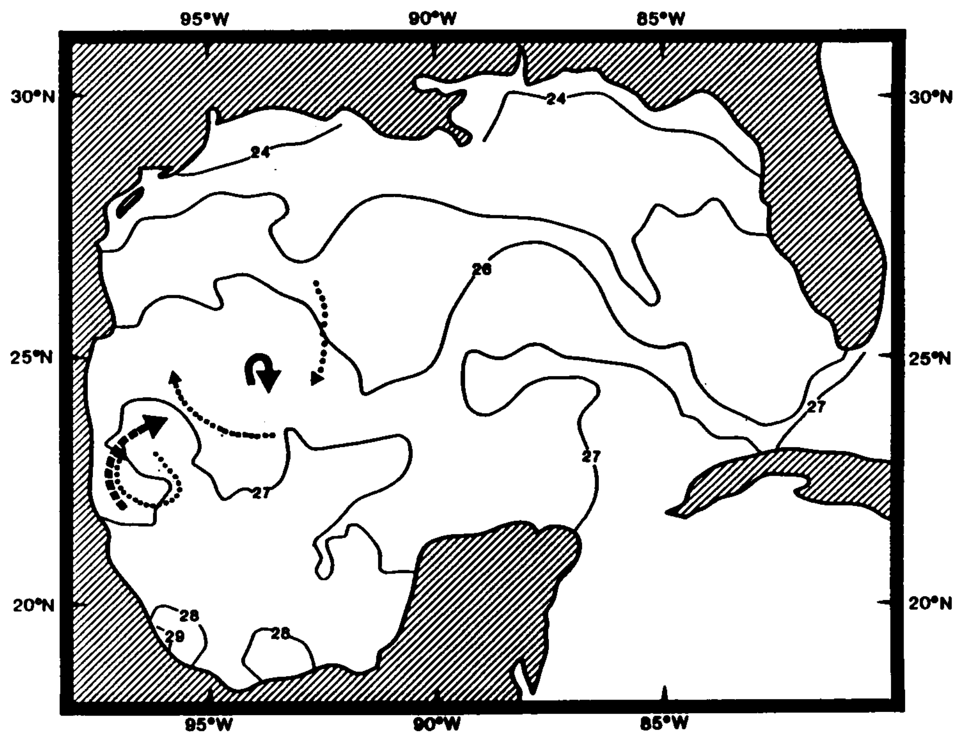

Figure 8. Sea surface temperature (°C) for the week of 19 November 1985. Corresponding trajectories of drifters are shown by arrows.

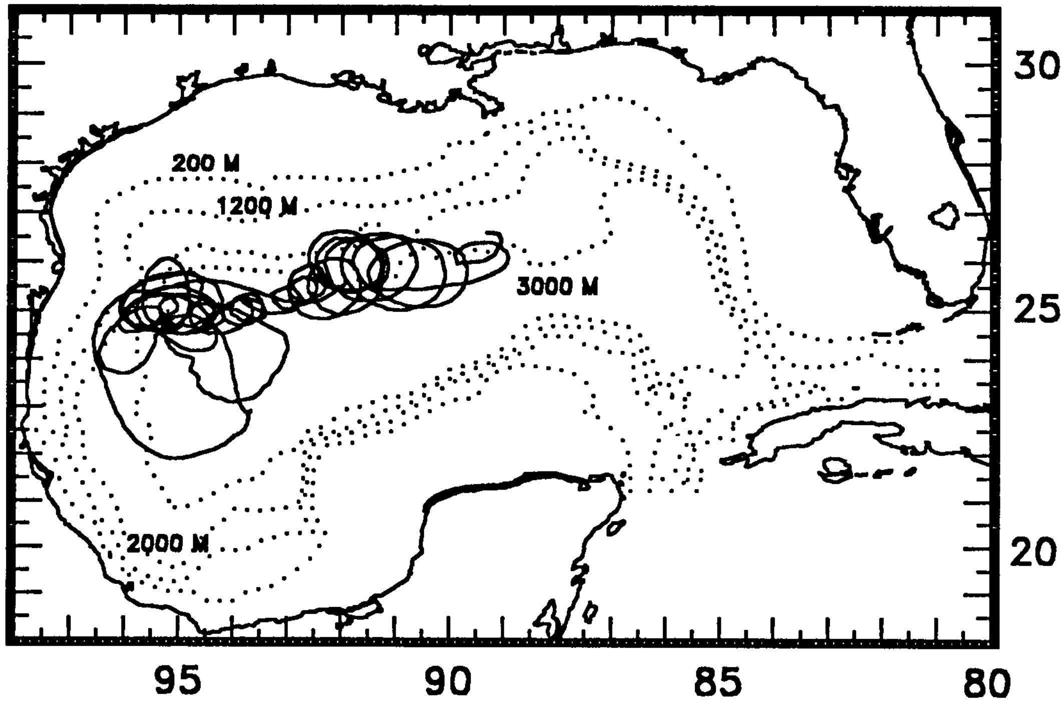

Figure 9. Trajectory for drifter 3378 in a Loop Current eddy. Depth contours are in meters.

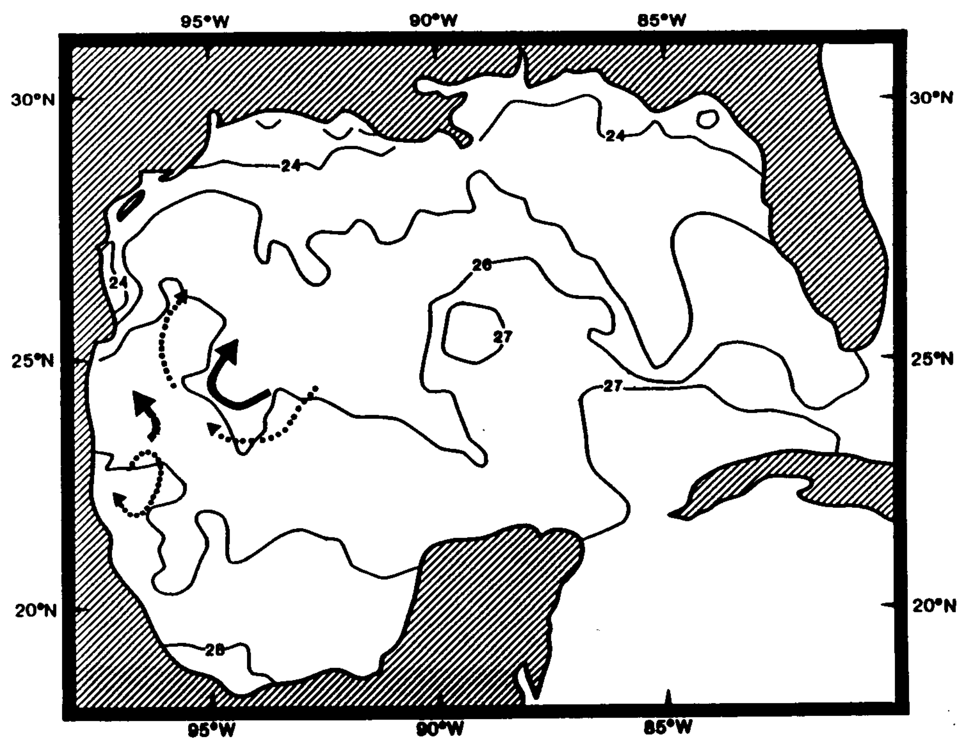

Figure 10. Sea surface temperature (°C) for the week of 26 November 1985. Corresponding trajectories of drifters are shown by arrows.

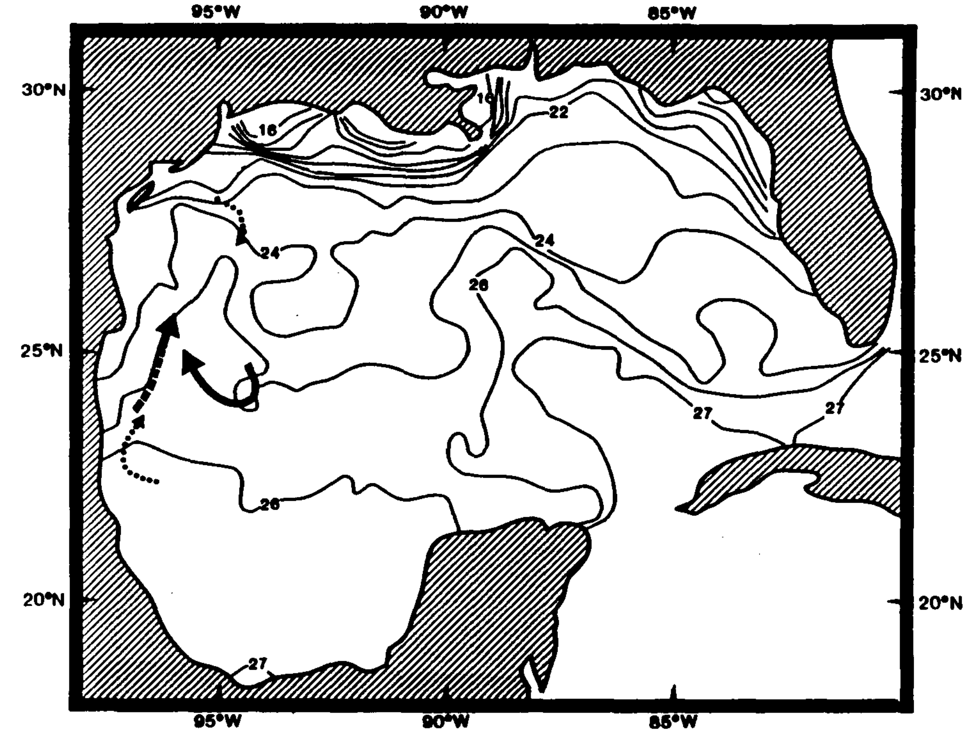

Figure 11. Sea surface temperature (°C) for the week of 17 December 1985. Corresponding trajectories of drifters are shown by arrows.

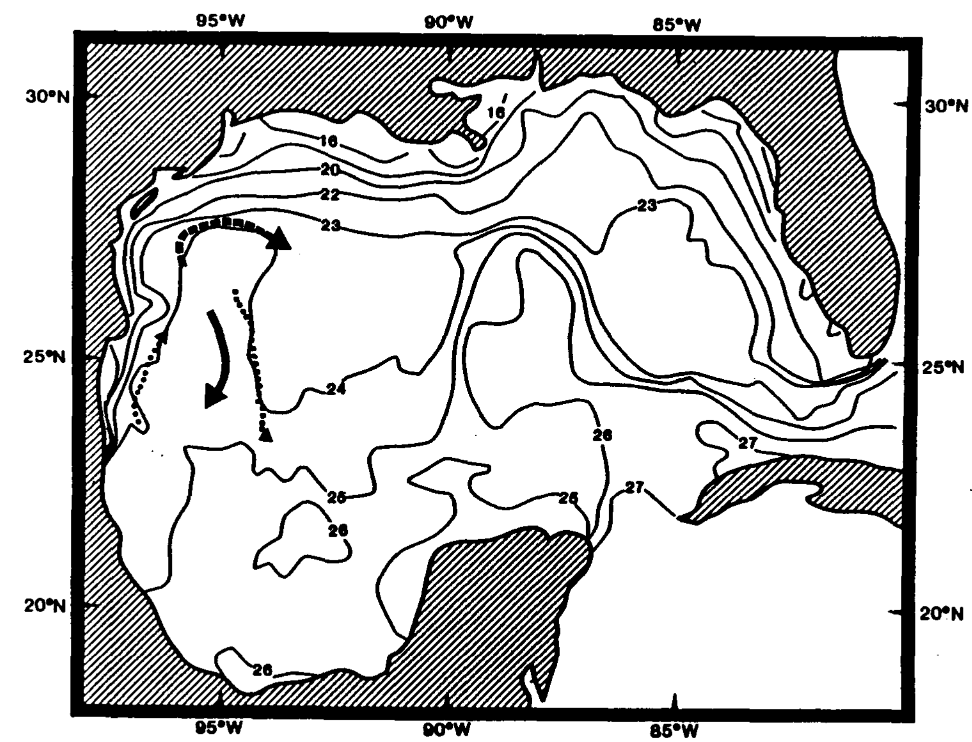

Figure 12. Sea surface temperature (°C) for the week of 28 December 1985. Corresponding trajectories of drifters are shown by arrows.

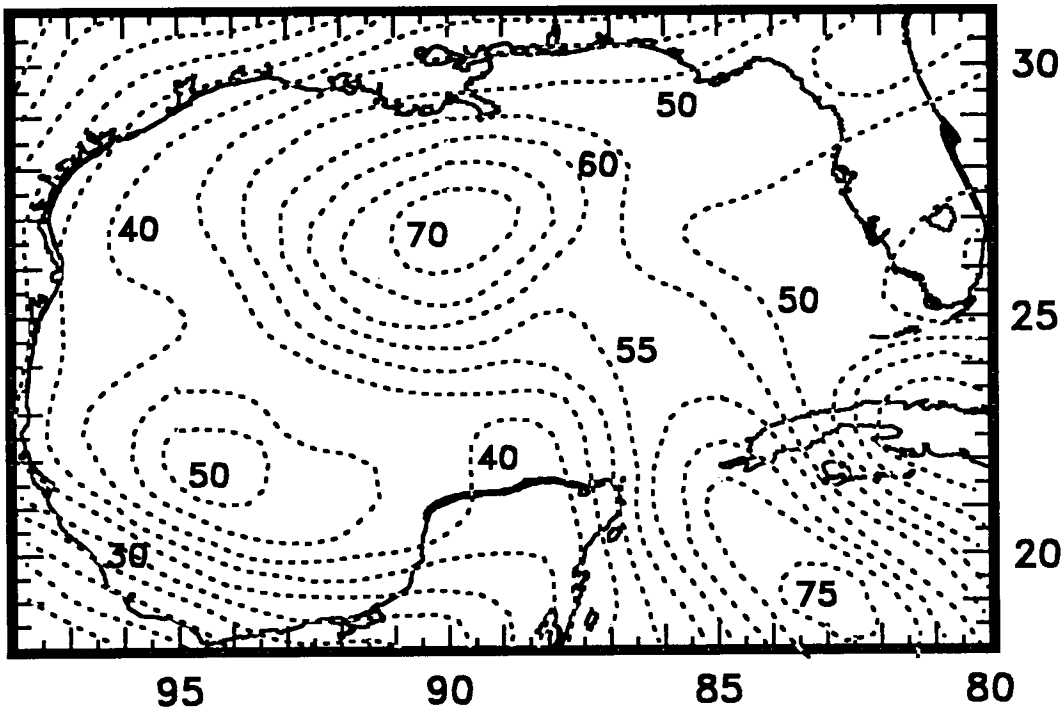

Figure 13. Frequency of tropical cyclones per 100 years with minimum wind speeds of 34 knots (18 m/s).

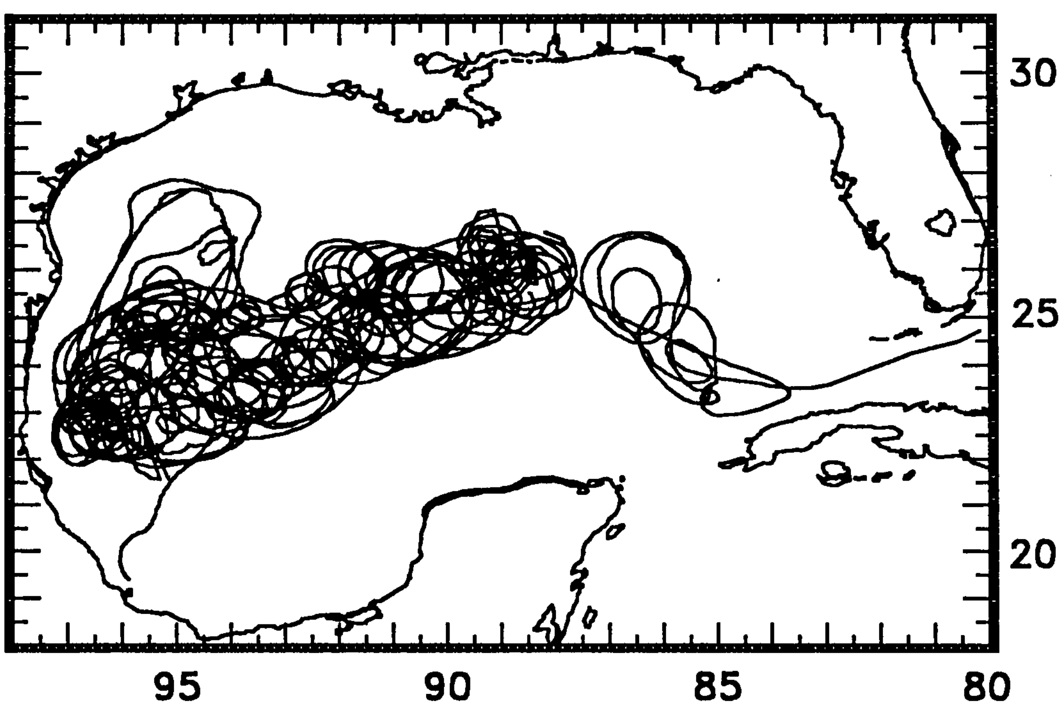

Figure 14. Drifter trajectories of Gulf of Mexico anticyclones.

2.2.6 INTERACTIONS BETWEEN EDDIES AND THE TEXAS-LOUISIANA OUTER CONTINENTAL SHELF AND SLOPE

Mr. Frank J. Kelly
Texas A&M University
Civil Engineering Division
and
Dr. David A. Brooks
Texas A&M University
Department of Oceanography

Large (diameters greater than 200 km), strong (swirl speeds greater than 50 cm s^{-1}) eddies, both anticyclonic and cyclonic, are frequently observed near the outer or deep part of the continental slope in the northwestern part of the Gulf of Mexico, but the degree to which they influence the circulation of the Texas-Louisiana Shelf and the continental slope out to a depth of about 500 m, the offshore extent addressed by this symposium, is poorly understood. Events of strong, persistent currents on the upper slope off Louisiana and Texas that suggest the influence of eddies have been reported by offshore industry operations and recorded by current meters. Usually, however, observations of eddies lack concurrent current meter and subsurface hydrographic observations on the shelf and slope, and vice versa, making it impossible to draw definitive conclusions. For example, Figure 15 shows a period of persistently eastward flow at the Flower Gardens during May 1980, when wind forcing at the time was weak and variable, the signature one might expect on the north side of an offshore anticyclonic eddy. Brooks and Legeckis (1982) and Brooks (1984) report that in April 1980 an anticyclone was centered near 25.5° N, 92° W, and its diameter was about 250 km. But if it moved due westward, its northern periphery would have extended only to the 500 m isobath, which is about 50 km south of the Flower Gardens, and so, a connection between the eddy and the currents in Figure 15 cannot be proved.

The anticyclonic eddies originate in the eastern Gulf where they separate from the Loop Current. Vukovich and Crissman (1986), in a study of 12 years of satellite infrared data, showed that, after separation, they follow three characteristic paths of westward migration across the western Gulf: a northern one, a mid-Gulf one, and a southwestern one. When an anticyclone follows the northern path its northern side brushes against the Louisiana-Texas slope, and the outer edge of its circulation frequently lies inshore of the 2000 m isobath. The MMS Gulf of Mexico Physical Oceanography Program observed an eddy that illustrates this case. Figure 16 shows the depth of the 8°C temperature surface, based on a mid-July 1985 XBT survey, in an anticyclone that had just separated from the Loop Current. (The depth of the 8°C temperature surface indicates the pattern of the geostrophic flow; deep regions correspond to regions of anticyclonic circulation, and shallow regions to cyclonic circulation.) The eddy's subsequent movement was tracked by satellite infrared imagery, ARGOS drifters and ship surveys. Figure 17 shows that by mid-November 1985 the eddy was interacting with both the western and northern slopes and that several small scale cyclonic and anticyclonic features were located around its periphery. During December 1985 and January 1986 (Figure 18), the eddy moved to a position against the western continental slope, and its shape became quite elliptical.

The Louisiana-Texas slope is broad, and the available evidence does not resolve the question of whether an anticyclone's circulation can penetrate inshore of the 500 m isobath and onto the shelf or, instead, influences the shallow regions indirectly through flows associated with filaments, dispersion products, entrainment around the periphery, cross-slope flow between the anticyclone and leading and trailing cyclones, or other secondary mechanisms. Just south of about 26°N, the Rio Grande slope narrows to about half the width of the Louisiana-Texas slope. Here, as Figure 18 and the results of Elliott (1982), Merrell and Vazquez (1983), and Brooks (1984) demonstrate, the perimeter of an anticyclone can press shoreward to the outer edge of the Mexican shelf, but it is not known if the circulation in the upper layer actually laps onto the shelf.

In the western Gulf of Mexico, cyclonic eddies are frequently observed in association with Loop Current anticyclones (Elliott 1979; Merrell and Morrison 1981; Brooks and Legeckis 1982; Merrell and Vazquez 1983; Brooks 1984). The formation of the cyclonic partner was observed for the first time during the Year 3 phase of the MMS Gulf of Mexico Physical Oceanography Program (SAIC 1988). Figures 17 and 18 show that between November 1985 and late January 1986, the small cyclonic feature on the northwest side of a Loop Current anticyclone greatly intensified as the anticyclone migrated onto the continental slope of the western margin. The cyclone's diameter increased to about 200 km and it lay entirely over the continental slope of southwest Texas between the 200- and 2000-m isobaths. The northeastward flow between the pair of vortices drew cool, low-salinity water off the Texas-Mexico continental shelf. Both this example and the studies cited above demonstrate that the vortex pair configuration drives a strong exchange between the western shelf and open Gulf waters. In Figures 17 and 18, one can also see a partially resolved cyclonic feature on the northeast side of the large anticyclone. Southward flow off the Louisiana-Texas shelf is suggested, but, since the slope is twice as wide as its western counterpart, the influence of this mechanism on the northern shelf may be much weaker.

To summarize, Loop Current eddies interact strongly with the base of the continental slope in the western Gulf of Mexico; they generate cyclonic eddies during topographic interaction; cyclonic eddies act in concert with Loop Current eddies to draw water on and off the shelf; other interactions between eddies and the continental shelf and upper slope are suggested by the existing data base but more information about the mechanisms through which eddies can influence the shelf and upper slope is needed.

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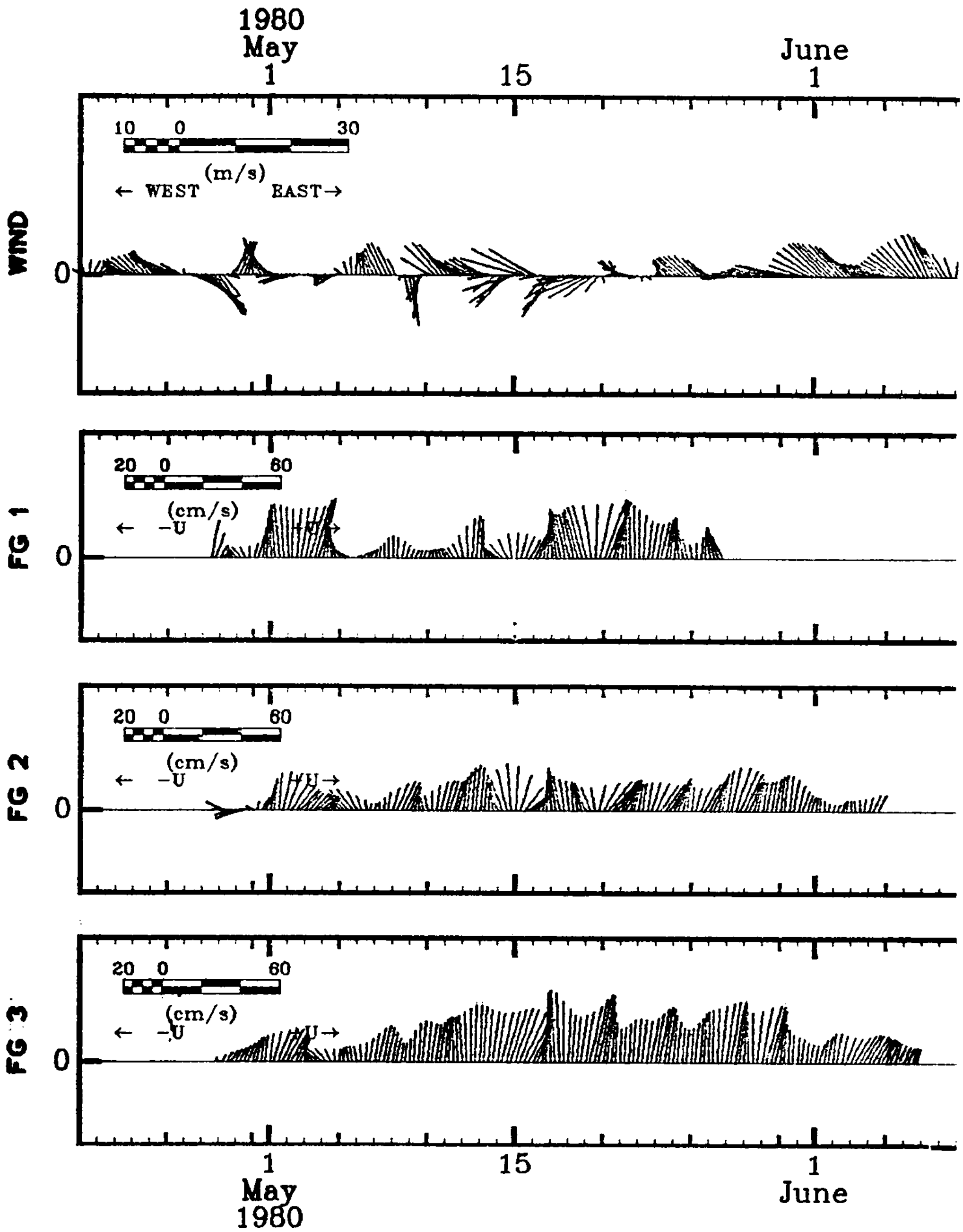

Figure 15. Comparative time-series plots of 40-hour low-passed stick vectors for wind from NDBC buoy 42008 (28° 47.07'N, 95° 18.71'W) and currents from Flower Garden sites 1, 2, and 3 (instrument depths, about 50 m; water depths about 100 m [Rezak et al. 1983]) for May 1980. Vertically up is toward the East for the current stick vectors and towards the North for the wind stick vectors.

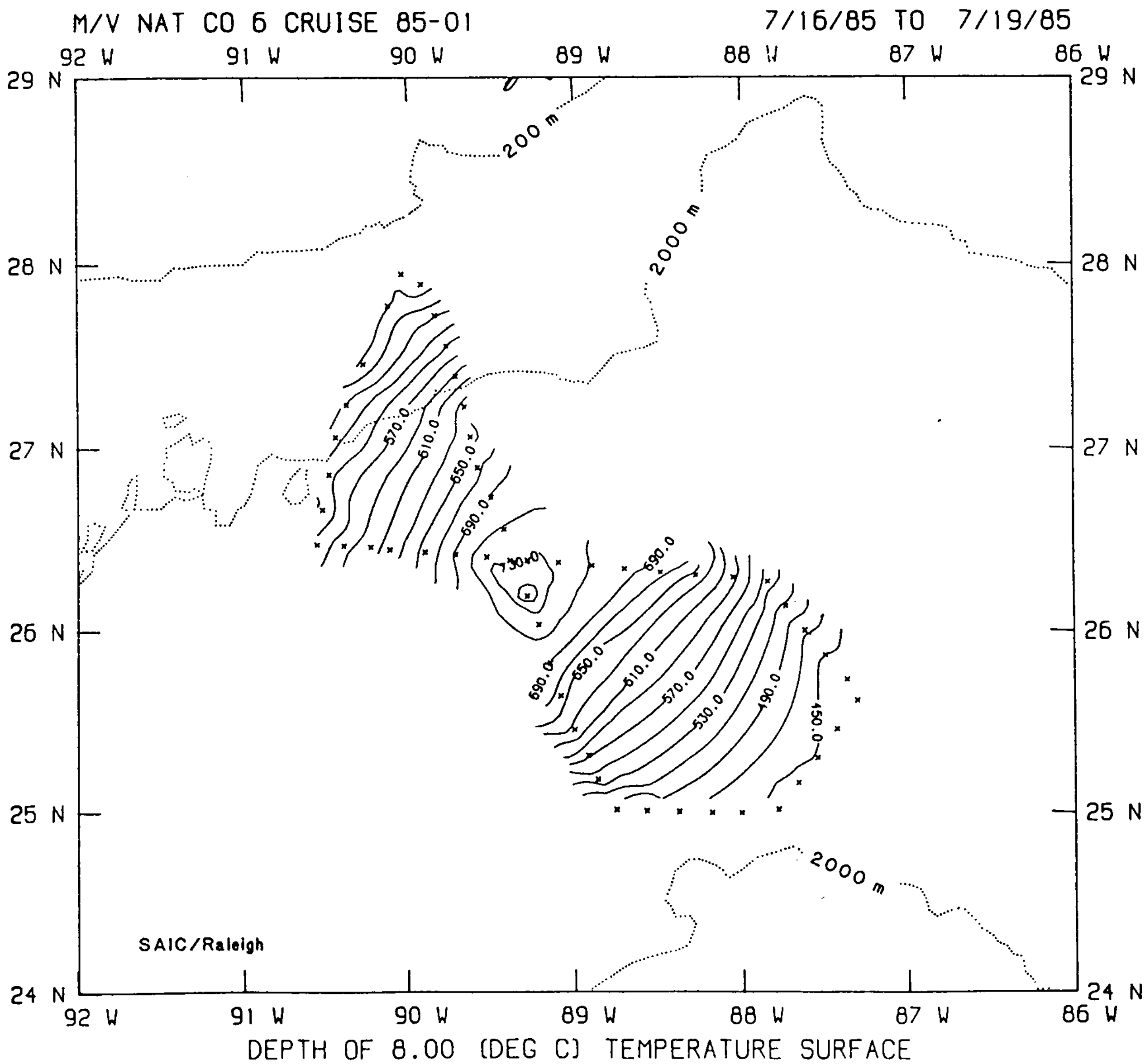

Figure 16. Depth of the 8 °C temperature surface from XBT data in mid-July 1985 in an anticyclonic, warm-core eddy shed by the Loop Current in late June 1985 (from SAIC 1988).

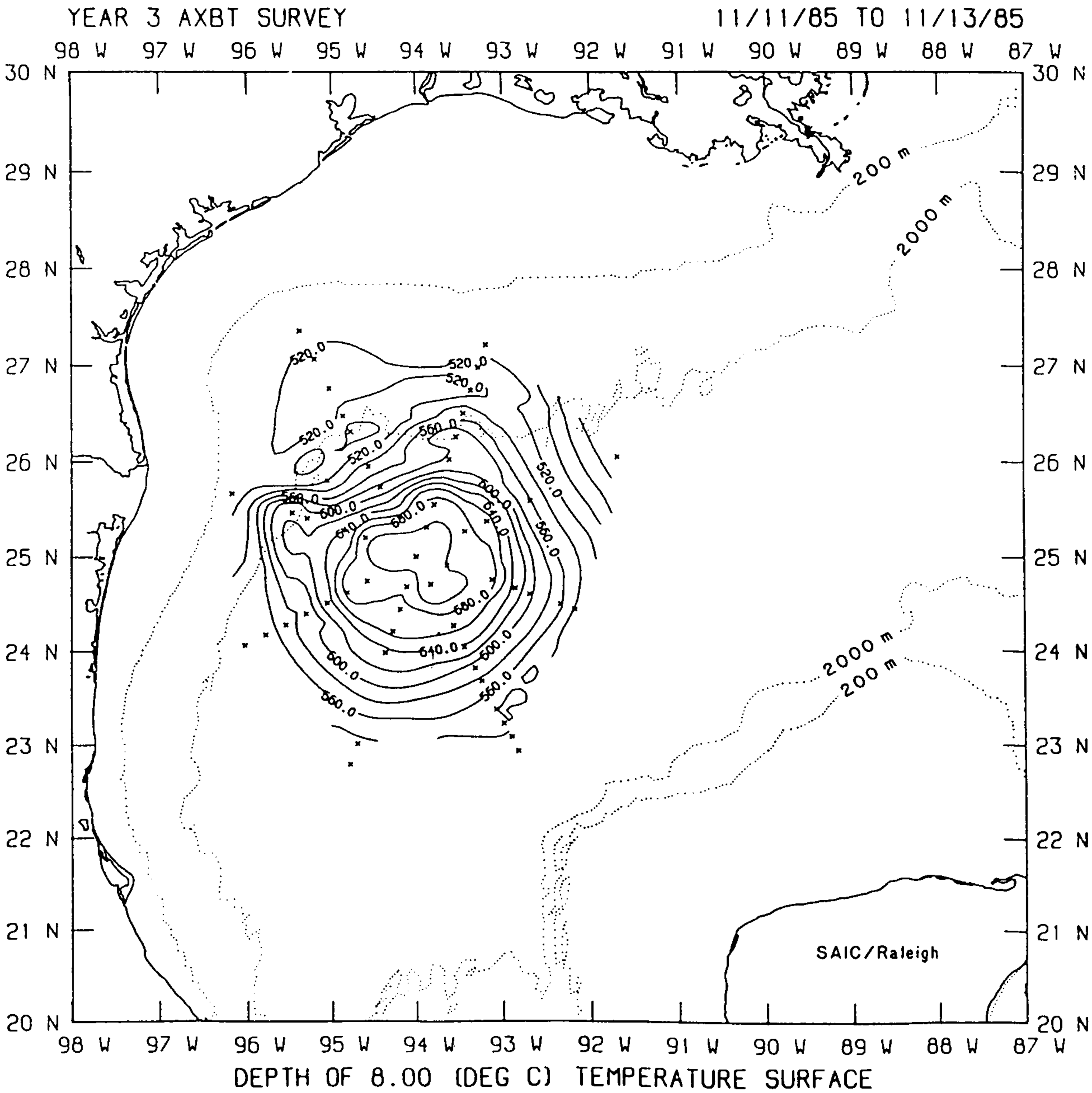

Figure 17. Depth of the 8°C temperature surface from AXBT data in mid-November 1985 in the same eddy as in Figure 16 (from SAIC 1988).

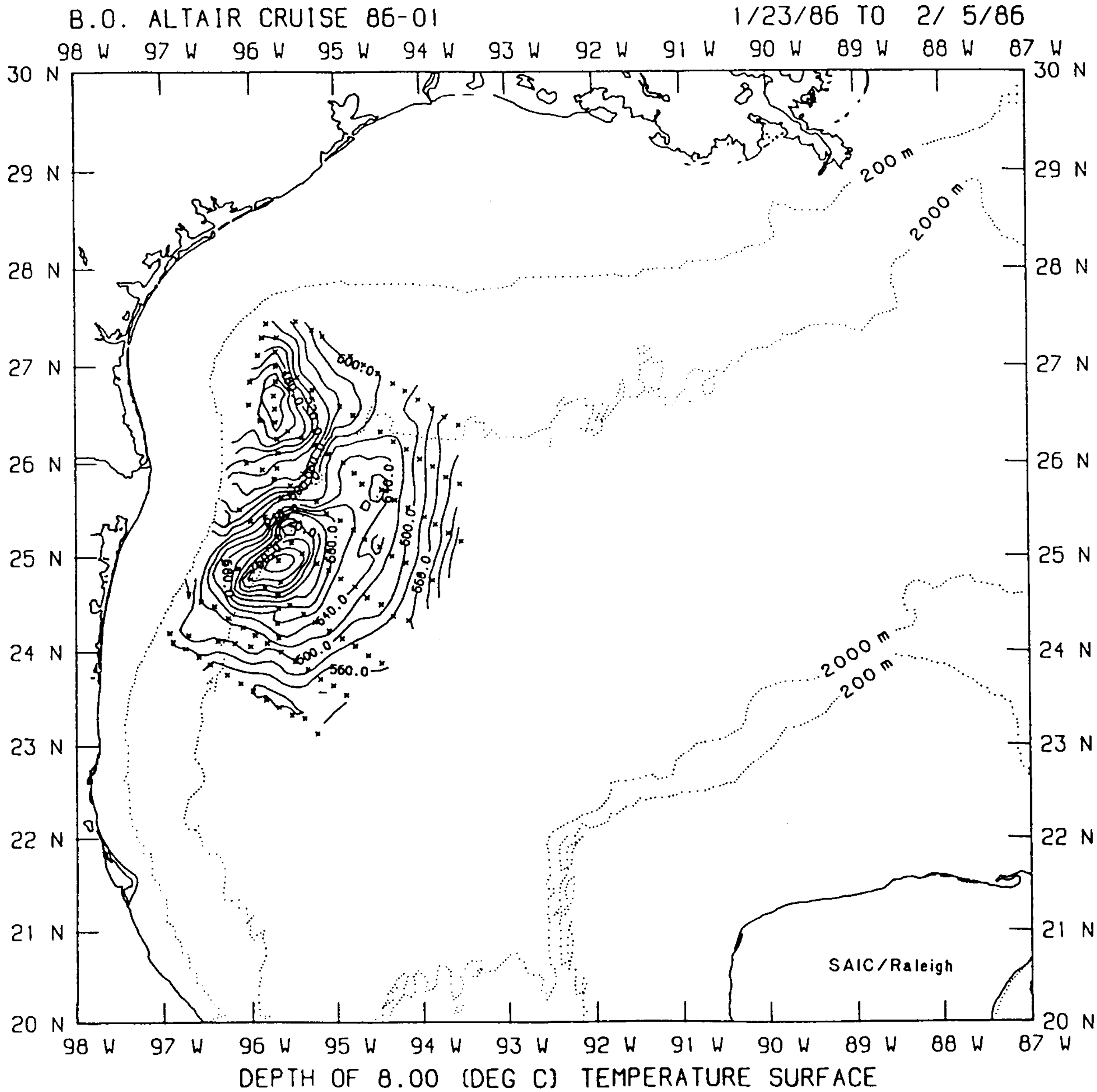

Figure 18. Depth of the 8°C temperature surface from XBT data in late January 1986 in the same eddy as in Figure 16 (from SAIC 1988).

2.2.7 PRIMARY PRODUCTION/UPWELLING

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Two 7-day cruises were conducted on the outer continental shelf off southwest Florida near 26° North latitude and 84° West longitude during April and September, 1982, to investigate the effects of upwelling along the Loop Current cyclonic front on phytoplankton productivity. During April, hydrographic and satellite measurements showed that we sampled a Loop Current frontal eddy as it propagated south near the shelfbreak. On the outer shelf, upwelling associated with the eddy raised the top of the nitracline to within 30 m of the surface. Chlorophyll a (Chl a) and productivity in the surface mixed-layer were relatively unaffected by the upwelling. However, the amount of Chl a in the subsurface maximum layer was inversely related to the depth of the top of the nitracline, and the depth-integrated rate of primary production was linearly related to the amount of Chl a in the subsurface layer. The Loop Current front was also near the shelfbreak in September. As during April, Chl a in the subsurface maximum layer was inversely related to the depth of the nitracline, and primary production was linearly related to the amount of Chl a in the subsurface layer. During September, a low salinity (35-36 ppt) surface layer of unknown origin was present on the outer shelf. The layer's maximum depth was 40 m and it had a cross-shelf dimension of 50 km. Coccolithophorids, primarily Emiliana huxleyi, and various species of diatoms dominated the subsurface Chl a maximum layer during both studies. The low salinity layer in September was dominated by the diatom Rhizosolenia alata. A comparison of results collected during these two cruises with those of previous studies of upwelling along the Gulf Stream front off the southeastern U.S. (Florida, Georgia, South Carolina) show that the effects on phytoplankton productivity and Chl a concentrations were more pronounced in the latter region. The probable reason is that upwelled nutrients reached closer to the surface, and thus enriched more of the euphotic zone in the southeast U.S. than was the case off southwest Florida.

2.2.8 INNER SHELF CIRCULATION: NORTHERN SHELF

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Civil Engineering Division

This brief presentation focuses on the effects of wind stress and freshwater influx from the Mississippi-Atchafalaya River System, which are the dominant factors controlling the long period motions and hydrographic characteristics, and much of the short period variability, of the Texas-Louisiana inner shelf. Numerous studies of currents along the Texas-Louisiana coast demonstrate the strong coherence between the alongshore components of wind stress and current (Smith 1978, 1979; Kelly et al. 1982; Crout et al. 1984; Lewis and Reid 1985; Cochrane and Kelly 1986) that results from the combination of wind stress, the earth's rotation and the presence of the coastal boundary (e.g., Csanady 1982). A visual example of the dynamics (Figure 19) comes from observations collected in 20 m of water about 20 km off Freeport, Texas (Figure 20) during the environmental monitoring studies for the brine disposal operations of the Department of Energy's Strategic Petroleum Reserve program (DOE/SPR). In Figure 19, the alongshore component of wind stress during the period 18-30 June 1980 is upcoast (toward Louisiana) and drives an offshore directed Ekman transport in the near surface layer, with a compensating onshore drift in the bottom layer. Water level at the coast (not shown) decreases, and the cross-shelf pressure gradient drives the alongshore component of current in the upcoast direction.

The DOE/SPR studies off Freeport, Texas and Cameron, Louisiana (Figure 20) produced the most statistically reliable evidence of this relation because of the length of the observations. Figure 21 shows the annual progressions of alongshore components of wind stress and current off Freeport, Texas in terms of monthly means based on hourly values of 3-hour low-passed data obtained between August 1978 and September 1984. Both components are positive (upcoast) in July, near zero in June and August, and negative (downcoast) during the rest of the year. By the criterion of standard error, the changes from May to June and from August to September are quite significant, and the values for July are significantly different from zero. The annual progressions off Cameron, Louisiana, from data collected between February 1981 and January 1985, are shown in Figure 22. Similar to the results for Freeport, the means for current are positive (upcoast) only in July, and those for stress are very nearly zero although not positive in July. The two sets of means are clearly correlated. Both the stress and current means are smaller off Cameron than off Freeport, in large part because of the change in the orientation of the coastline in relation to the mean direction of the winds and because of both the weaker response of current to alongshore wind in shallower waters (Chuang and Wiseman 1983) and an increase in bottom friction (Cochrane and Kelly 1986).

The downcoast currents dominating much of the coast except during June through August form the inner segment of a prevailing cyclonic gyre described by Cochrane and Kelly (1986) on the basis of several types of information. For example, sea-surface salinity distribution (Figure 23), viewed as a tracer, is consistent with the annual progression of currents described above. For the 1964 data shown in Figure 23, salinity values in the brackish band along the coast reach a minimum in May after the spring flood of the Mississippi-Atchafalaya River System that typically occurs in April. (The Mississippi-Atchafalaya mean discharge is an order of magnitude greater than the combined mean discharge of all the other rivers flowing to this shelf.) The band recedes upcoast in June and disappears by August, although brackish water remains along the coast from the delta to about 92 W and in a region extending seaward over the shelf. The absence of brackish water on the coast west of about 92.5° W results from the upcoast currents and from upwelling implied by the upcoast wind stress in July.

The upwelling current regime acting on the plentiful supply of brackish water in the coastal band produces a dramatically different distribution of the water masses than occurs during downwelling conditions. A typical example of the hydrography of the inner shelf during the downwelling regime is shown for 4 January 1983 by a transect extending 30 km off Freeport (Figure 24). The density field is determined primarily by the salinity field. The strongest part of the frontal zone lies between 10 and 20 km offshore, and the density interface has somewhat of an "S" shape. Contrast this with the conditions during 21-22 July 1983. Figures 25-27 show the observations along transects running offshore through the Bryan Mound, Big Hill and West Hackbery DOE/SPR brine disposal sites (Figure 20). Salinity again determines the density field. High salinity water extends shoreward along the bottom almost to the coast, while in the upper layers low salinity water extends seaward past the limits of the transects. The result is extremely strong vertical stratification. An environmentally important consequence is that vertical mixing in the bottom waters is suppressed and dissolved oxygen concentrations drop, becoming hypoxic, i.e., less than 2 mg/l, in some regions.

Although the available data support a prevailing annual progression of the currents and hydrography in the inner Texas-Louisiana shelf, it should be stressed that they also exhibit significant variability at all time scales from inter-annual to inertial (approximately diurnal for the latitudes of this shelf). Examples of variability at synoptic and inertial time scales can be seen in Figure 19. Some natural questions that arise given the strength of the stratification that the wind and freshwater influx create at times, and that are only beginning to be explored, concern the dynamics and associated variability of the strong frontal zones (both horizontal and vertical) and the effect of the frontal zones on biological, sediment and contaminant transport processes and nutrient distributions.

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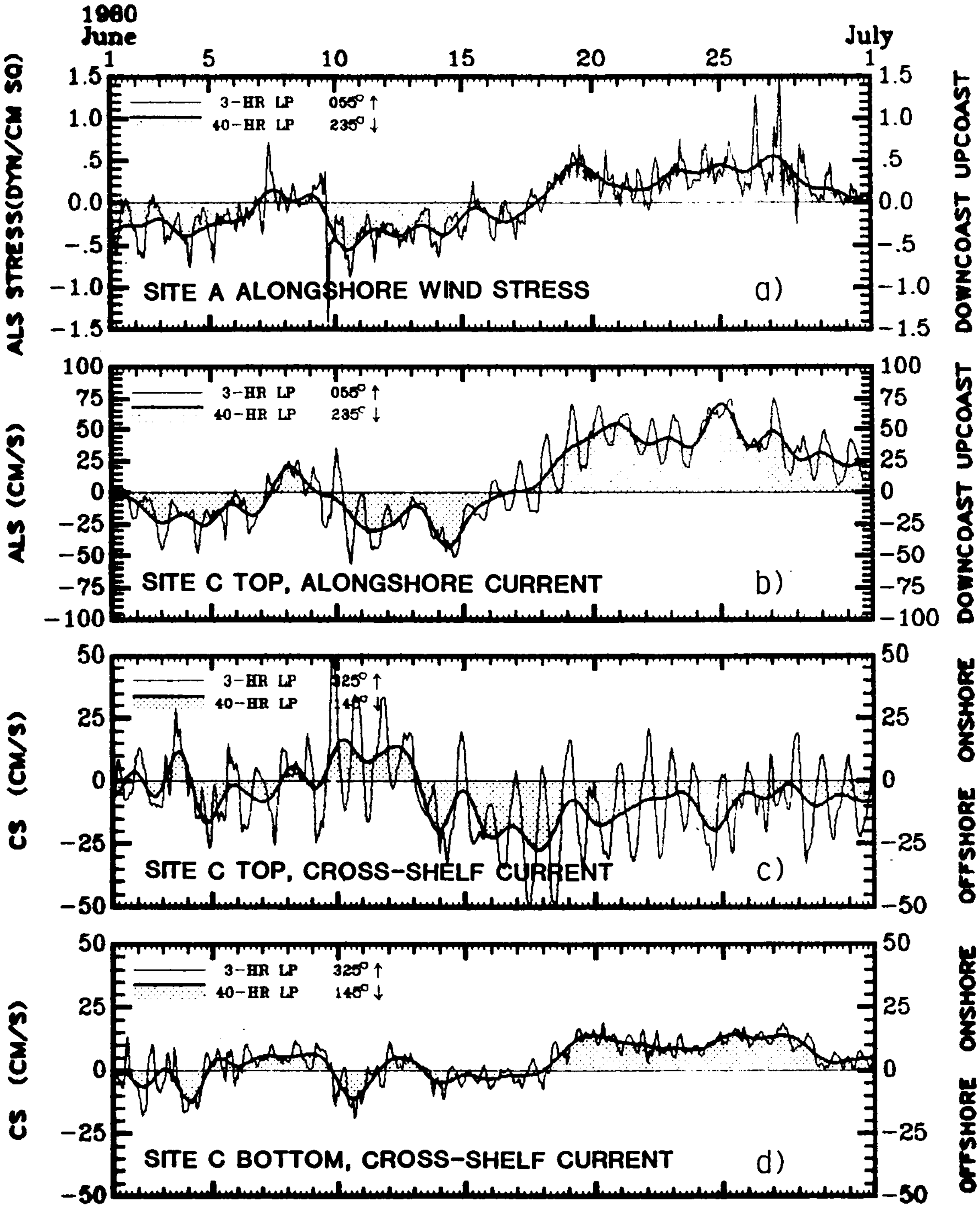

Figure 19. An example of the response of currents to the alongshore component of wind stress from data collected during July 1980 at the Bryan Mound site (Figure 20) where the water depth is approximately 22 m: a) alongshore (positive toward 55° true) component of wind stress, b) alongshore component of near-surface current (3.7 m below the surface), c) cross-shelf (positive toward 325° true) component of near-surface current, d) cross-shelf component of near-bottom current (1.8 m above the bottom). Light and heavy lines are 3-hour and 40-hour low-passed, respectively.

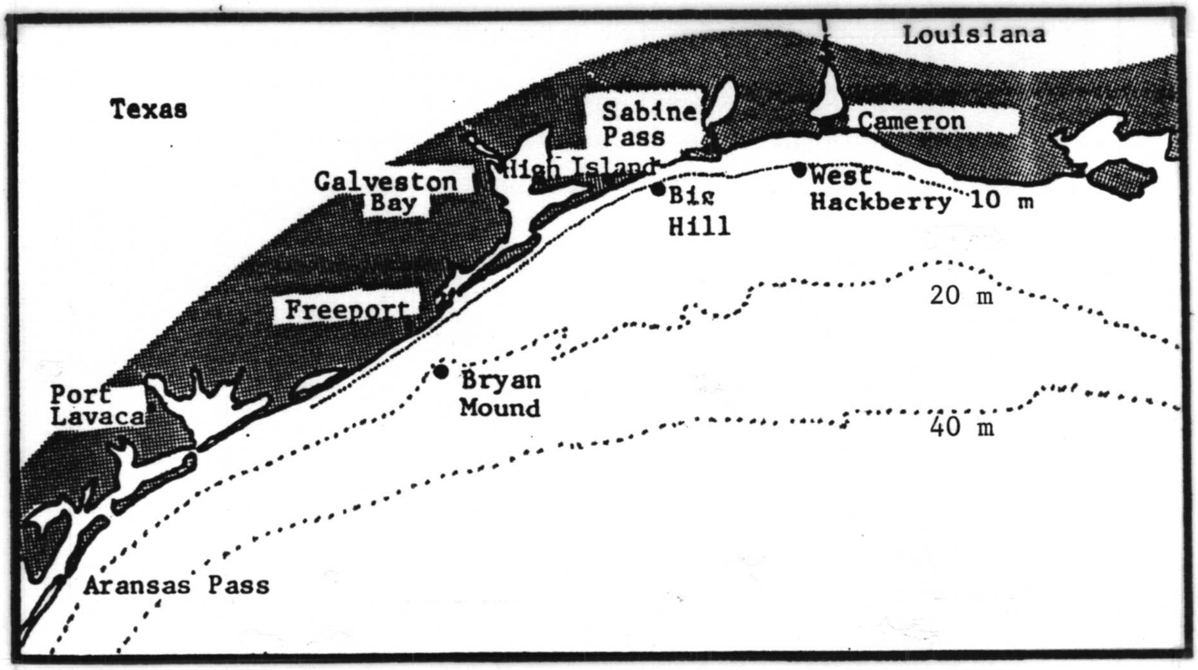

Figure 20. Locations of the Bryan Mound, Big Hill and West Hackberry offshore sites and coastal cities referenced in the text.

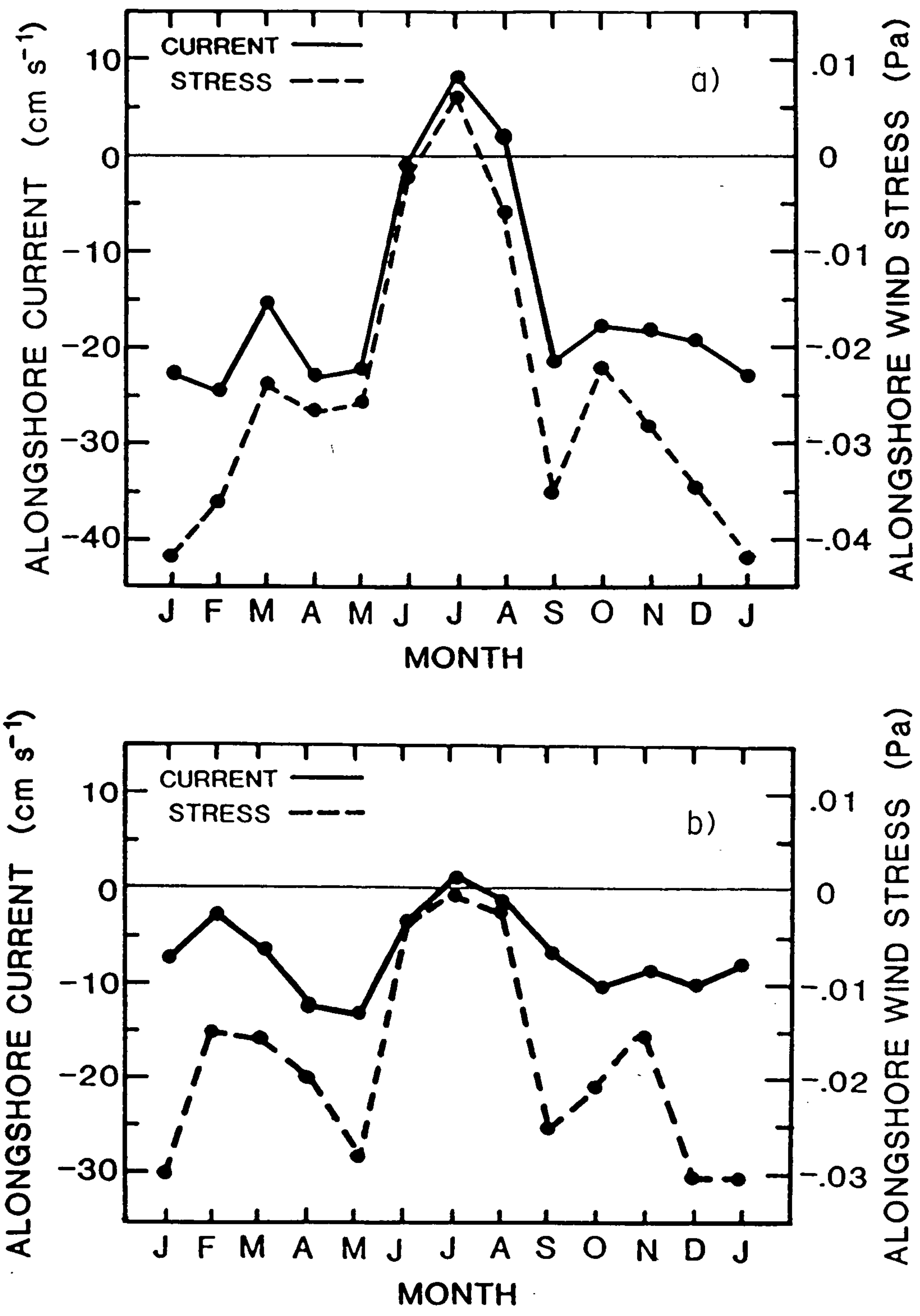

Figure 21. Monthly mean alongshore component of wind stress together with monthly mean alongshore component of surface current (3.7 m below sea surface): a) at the Bryan Mound site off Freeport, Texas, the positive alongshore direction is 55° true; b) at the West Hackberry site off Cameron, Louisiana, the positive alongshore direction is 86° true (from Cochrane and Kelly 1986).

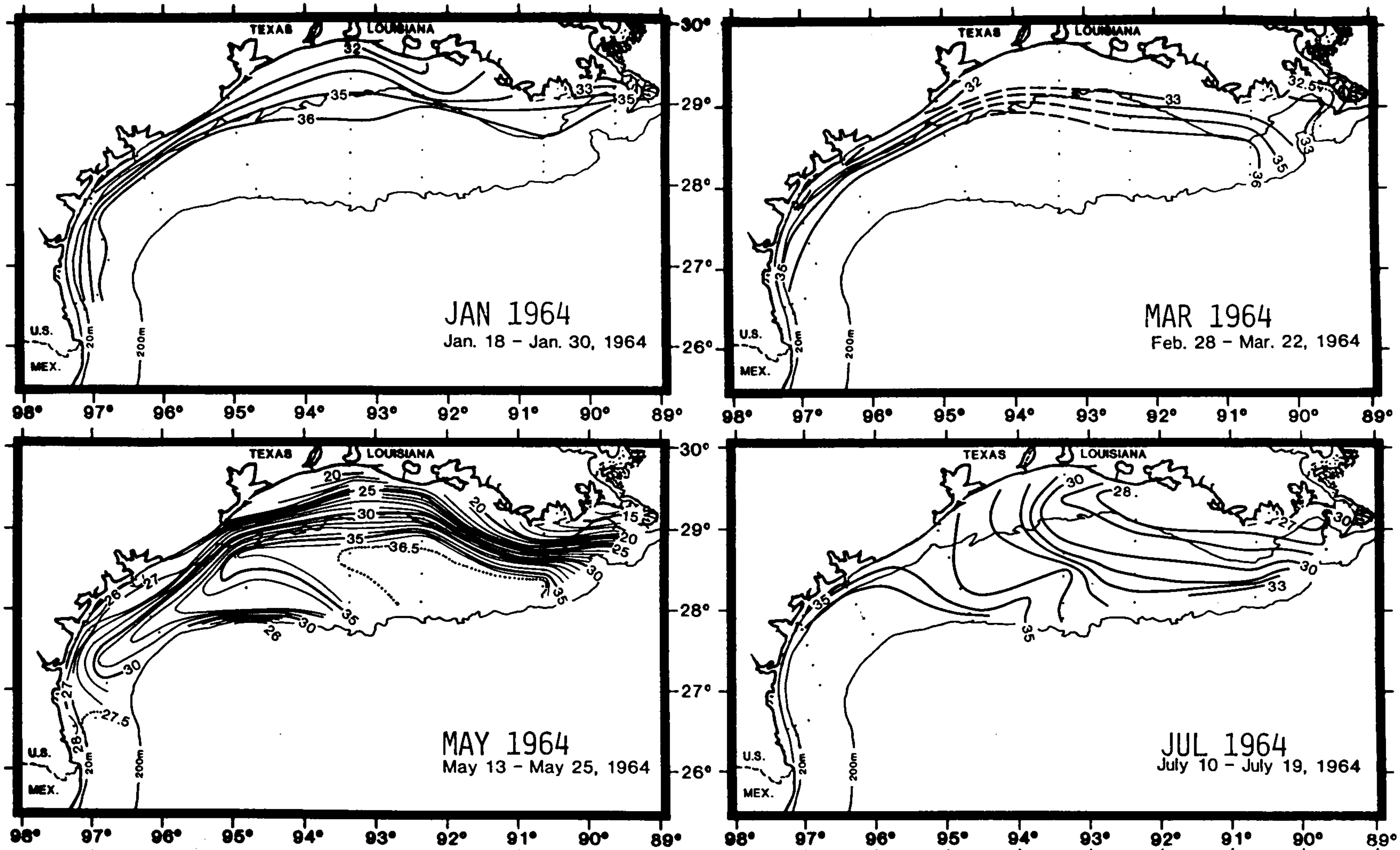

Figure 22. Sea-surface salinity (°/∞) for M/V Gus III cruises in January, March, May and July 1964 (from Kelly <u>et al</u>. 1980).

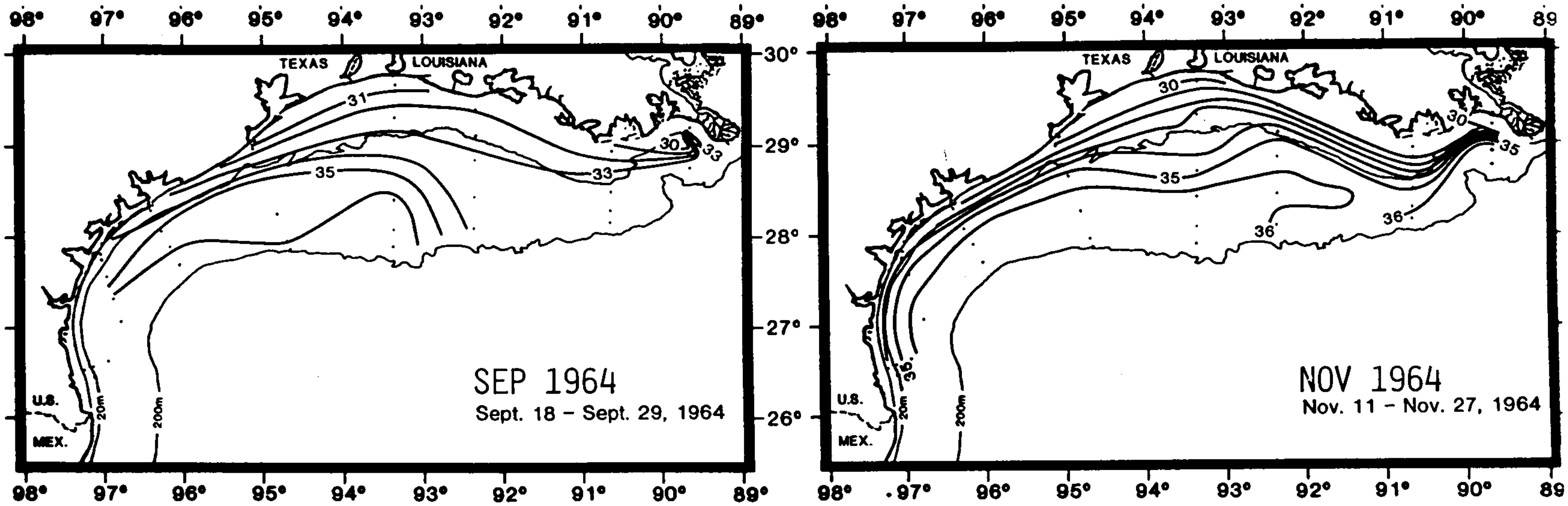

Figure 23. Sea-surface salinity for M/V Gus III cruises in September and November 1964.

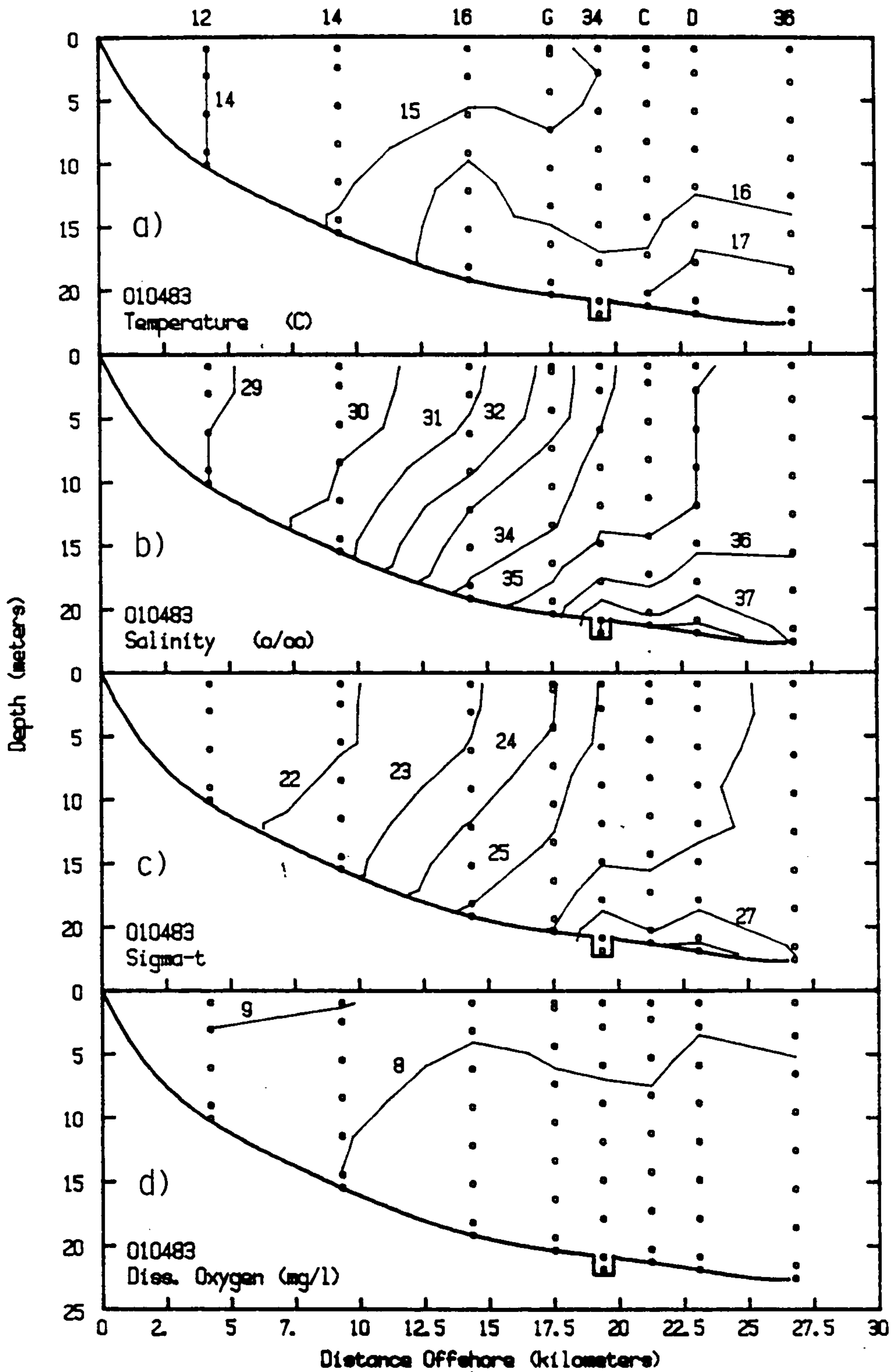

Figure 24. Hydrography for the cross-shelf transect offshore Freeport, Texas on January 4, 1983: a) temperature (°C), b) salinity (°/₀₀), c) sigma-t, dissolved oxygen (mg l^{-1}). (Note: the salinity values greater than about 36 °/₀₀ near the bottom in the vicinity of station 34 were caused by the DOE/SPR brine disposal operations)(from Kelly et al. 1984b).

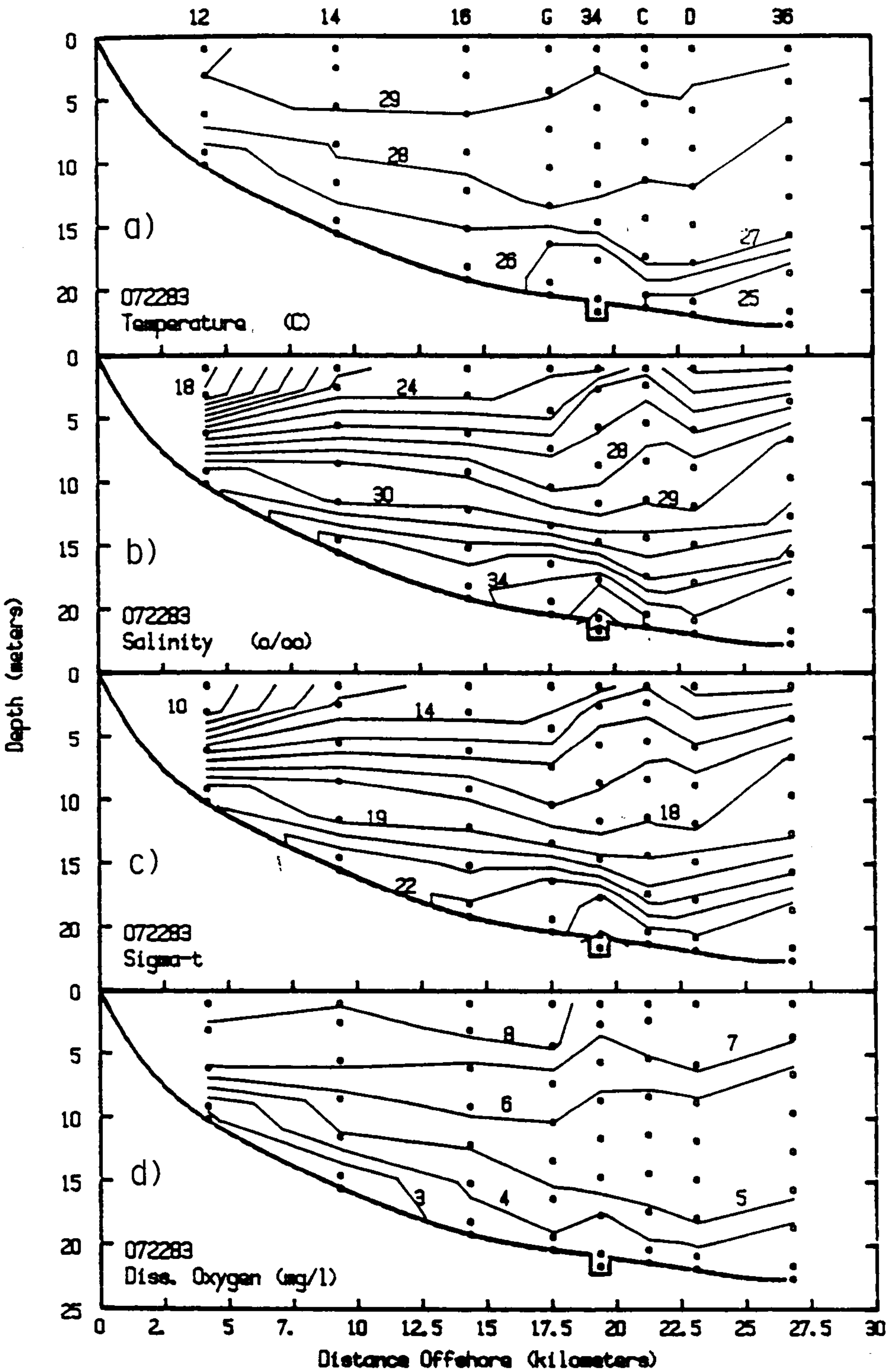

Figure 25. Hydrography for cross-shelf transect through the Bryan Mound site on July 22, 1983: a) temperature (°C), b) salinity (°/oo), c) sigma-t, dissolved oxygen (mg l^{-1}). (Note: the slightly higher salinity values near the bottom at station 34 were caused by the DOE/SPR brine disposal operations)(from Kelly <u>et al</u>. 1984b).

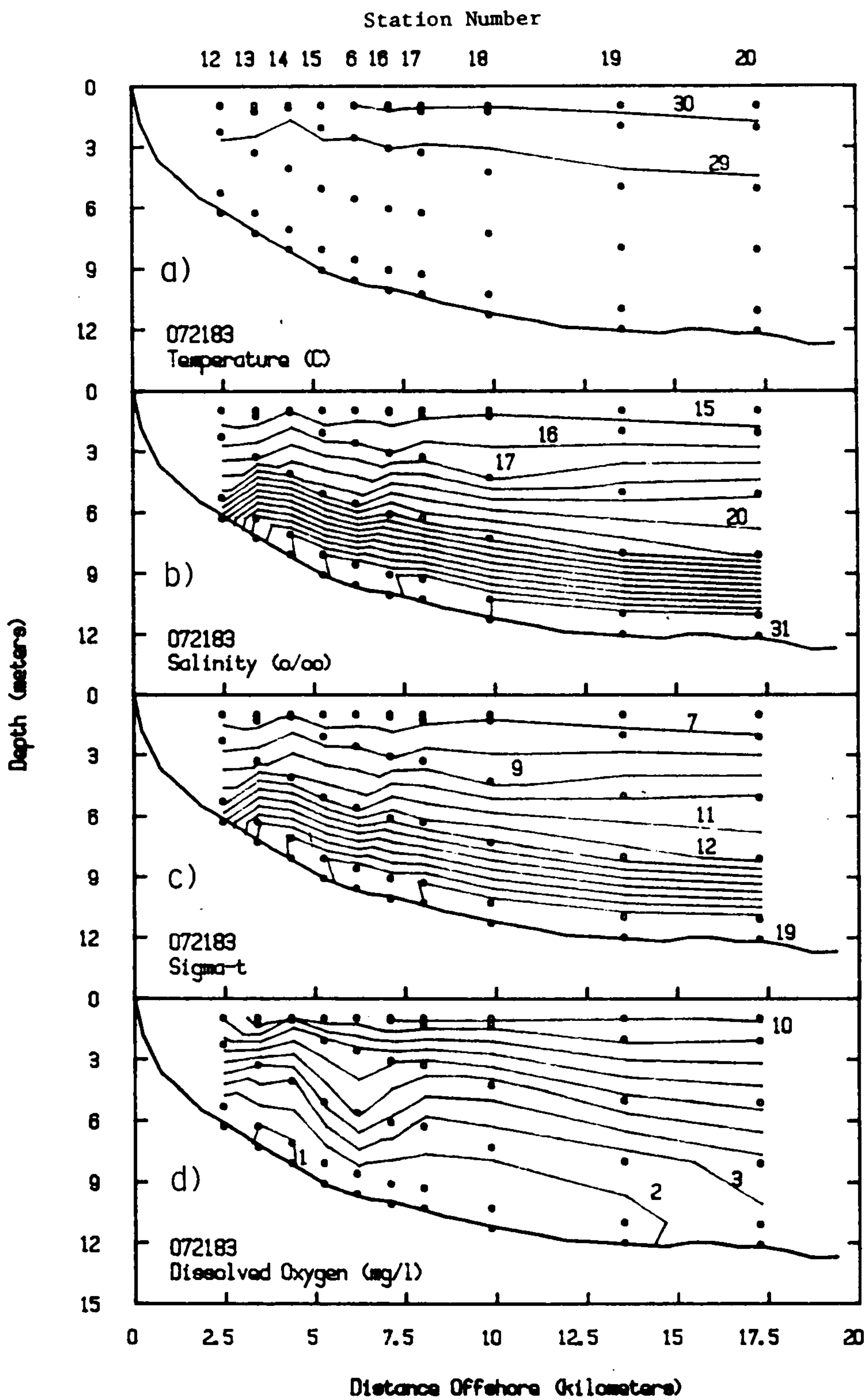

Figure 26. Hydrography for cross-shelf transect through the Big Hill site on July 21, 1983: a) temperature (°C), b) salinity (°/oo), c) sigma-t, dissolved oxygen (mg l^{-1})(from Kelly et al. 1984a).

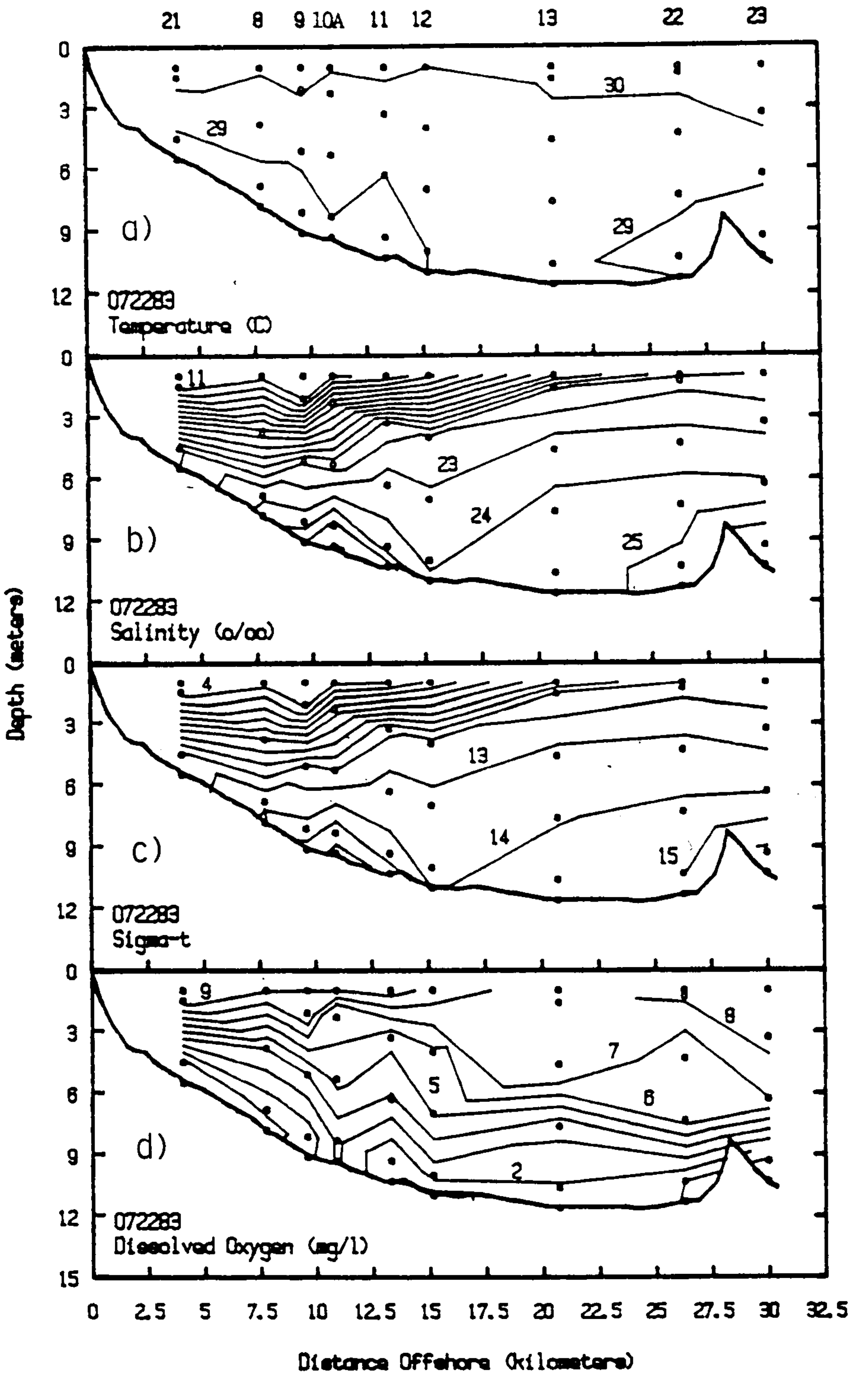

Figure 27. Hydrography for cross-shelf transect through the West Hackberry site on July 22, 1983: a) temperature (°C), b) salinity (°/oo), c) sigma-t, dissolved oxygen (mg l^{-1}). (Note: the slightly higher salinity values near the bottom at station A were caused by the DOE/SPR brine disposal operations)(from Kelly *et al*. 1984c).

2.2.9 INNER SHELF CIRCULATION OFF THE CENTRAL AND SOUTH TEXAS GULF COAST

Dr. Ned P. Smith
Harbor Branch Oceanographic Institution

The South Texas Gulf Coast has a radius of curvature of approximately 160 km; the local longshore orientation rotates through an arc of nearly 90° between Port Mansfield (26 degrees 34 minutes N) and Port O'Conner (28 degrees 20 minutes N). The continental shelf is relatively broad. Bathymetric cross-sections characteristically pass through a depth of 100 m approximately 85 km from the coast. Over the inner and middle continental shelf, a representative increase in depth with distance from shore is 1 m/km. The region is one of unusually strong winds, and windstress is a dominant force in shelf circulation. The National Weather Service lists the International Airport at Corpus Christi as the third windiest in the country, with a scalar mean wind speed of approximately 24 km/h.

The tidal component of the inner shelf circulation is a relatively small fraction of the total. Two field studies, in early 1973 (Smith 1975) and from late 1973 to early 1974 (Smith 1978), were conducted 11 km off Port Aransas in 18 m of water. Harmonic analyses (Dennis and Long 1971) of 29-day segments of current time series indicate that amplitudes of the principal tidal constituents are within the precision of the current meters used to make the measurements. K_1 and O_1 constituent amplitudes are approximately 1.1 cm/s for the longshore current components, and approximately 0.7 cm/s for the cross-shelf components. For many purposes, tidal oscillations may be assumed negligible.

Hydrographic data were collected approximately monthly from early 1976 through late 1977 along a transect extending seaward to the shelf break from Port Aransas. A time series of profiles from an inner shelf station at the 21 meter isobath reveals weak vertical stratification due to freshwater runoff effects from March into June both years. In midsummer months, vertical density stratification appears to be associated with ephemeral upwelling. From early fall through late winter, the water column is unstratified as a result of wind mixing and/or surface cooling. The same hydrographic data base indicates a significant seasonal cycle in water column expansion and contraction in a band extending 50-60 km offshore (Smith 1980a).

Climatological data from the International Airport at Corpus Christi show a distinct seasonal cycle in the variation of mean monthly resultant wind vectors. From late fall through early spring, the resultant wind vector is normal to the coastline in the vicinity of Port Mansfield; in midsummer months, the resultant wind vector is normal to the coast further north near Port O'Conner. At any time of year, there is considerable scatter about the monthly mean, but on average the longshore component of the windstress vector must vary seasonally as well. Variations in longshore windstress over time scales ranging from days to months explain many features of low-frequency current patterns which emerge from field studies conducted along the inner Texas shelf.

Current meter data over a 36-day study period in February-March, 1973 (Smith 1975), indicate a quasi-steady longshore flow to the south-southwest 11 km off

Port Aransas. Winds recorded during the same time period from a coastal weather station nearby indicated that the resultant windstress vector paralleled the local coastline to within a few degrees. Current data from the same location but recorded over a 32-day time period in June-July, 1974 (Smith 1978), indicate low-frequency reversals, however the resultant longshore displacement is negligible. Coastal winds recorded during this time period were nearly directly onshore. The resultant windstress vector was normal to the local coastline to within a few degrees. Available time series from nine field studies conducted over the Texas inner shelf suggest that low-frequency reversals may occur throughout the year, but the net longshore displacement is consistent with the seasonal variation in the mean monthly resultant vector. Drift bottle and bottom drifter studies conducted by the U.S. Geological Survey in Corpus Christi (Hunter et al. 1974; Hill et al. 1975; Hill and Garrison 1977) show similar seasonal patterns, with net transport into the southwesterly quadrant in winter months, and into the northeasterly quadrant in summer months.

Current meter data from study sites 6 and 34 km offshore at about 27 degrees 34 minutes North reveal distinct differences between inner and middle shelf circulation patterns (Smith 1980b). Specifically, energy density levels computed from cross-shelf components of the inner shelf time series are nearly half an order of magnitude lower than those computed using data from the outer station. The width of the coastal boundary layer cannot be determined with precision from the available data, however it is clear that the nearby coast constrains significantly cross-shelf deviations in the longshore flow.

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2.2.10

UTILITY OF REMOTE SENSING IN THE TEXAS-LOUISIANA SHELF/SLOPE REGION

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One of the most formidable and readily available tools to study the mesoscale and synoptic-scale oceanography on the Texas-Louisiana shelf/slope region is satellite remote sensing data, particularly, NOAA/AVHRR data. NOAA infrared imagery has revealed that some of the major forcing functions that influence the oceanography in that region are warm rings that separate from the Loop Current, cold rings that are believed to be spun-up by the interaction of warm rings with the slope topography, and by massive, shallow zones of warm water that are created by circulation systems associated with perturbations that form on the boundary of the Loop Current. The dynamics and thermodynamics of the interaction of these phenomena with the Texas-Louisiana shelf/slope region will affect the circulation and transport in that region. These interactions are not well understood and need to be studied in order to properly plan for the exploration and exploitation of the shelf region for gas and oil and for undersea mining.

In the future, a significant number of satellites will be in orbit that can provide data which can be used to study processes in the Texas-Louisiana shelf/slope region. Besides the standard infrared systems, NOAA/AVHRR and GOES VISSR, data from scatterometers (DMSP, EOS, ERS-1) will be available to estimate the sea-surface wind speed and the surface roughness, altimetry data (TOPEX, EOS, ERS-1, MOS) will be available to obtain the dynamic topography of the sea-surface, synthetic aperture radar data (EOS, ERS-1) will be available to obtain information on waves, microwave radiometer data (EOS, TOPEX, MOS, NOAA) will be available to provide all weather observations of the sea-surface temperature pattern, and ocean color data (MOS, NASA/SEA-WIFS) which will provide information on frontal locations in the warm season, as well as information that can be used to analyze processes that are involved in primary production. Most of these data will be available from the present through the 1990's. Extensive analyses of these data, together with the integration of these analyses with the analyses of in situ data can provide significant information on the processes that affect the Texas-Louisiana shelf/slope region.

2.2.11 VISUAL SATELLITE OBSERVATIONS OF FRONTS ON THE LOUISIANA-TEXAS SHELF

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The north central coast of the Gulf of Mexico is dominated by the presence of the continental scale Mississippi River. The fresh water discharge from this river, through its two major distributaries (Balize [birdfoot] and Atchafalaya Deltas), has been observed as far west as Port Aransas, Texas (Smith 1980). The sediment suspended in these waters is useful as a Lagrangian tracer for circulation of, at least, the surface mixed layer on the shelf. Visible satellite imagery, primarily Landsat, of the Louisiana shelf has been analyzed to provide synoptic information on the circulation in the vicinity of the river mouths. As is to be expected, the movement of the fresh, turbid discharge is strongly coupled with the wind.

The size and shape of the composite discharge plume from the Balize Delta is observed to be a function not only of the amount of fresh water discharge but also of the speed and direction of the wind. The plume enlarges with rising river stage, but the areal extent of the turbid water can be related to discharge only in a general way because of the concentration and dispersal effects produced by the wind. The plumes of suspended sediment are readily detected during favorable wind conditions at distances greater than 75 km seaward of the various river mouths.

The Landsat images which were analyzed tend to support the concept of a clockwise circulation on the Louisiana Bight, as suggested by Wiseman et al. (1975). Deviations from this pattern are associated with winds from other than the predominant southeasterly direction. Rapid variation in form can occur when the winds shift as a result of such events as the passage of winter cold fronts. Plume orientation shifts of 90° have been observed in images acquired one day apart.

The discharge from the Atchafalaya Delta is different in several ways from that of the Balize or "bird foot" Delta. Whereas the Balize discharges from an extended arm into relatively deep water near the shelf edge, the Atchafalaya discharges into a shallow open bay and then onto a wide continental shelf. Analysis of Landsat imagery has been able to relate the shape and orientation of this plume to synoptic weather conditions. Five synoptic weather type cases have been identified as representing most of the plume patterns. The first four cases represent a typical weather sequence associated with the movement of high pressure systems from the continent to the North Atlantic Ocean. The fifth case is a weather pattern that occurs primarily in the summer when a high pressure system centered over the Gulf of Mexico generates southwest and west winds along the coast. The wind intensity and direction and general plume geometry are given in the following table.

CASE	WIND	PLUME
1	NW-N moderate to strong	SSE offshore
2	NNE-ENE moderate	SSW-SW offshore
3	E light to moderate	W mostly alongshore
4	SE-S moderate	W some offshore can be wide
5	SW-W light to moderate	E-SE broad drift

The three cases for which the plume moves to the west (2, 3, 4) account for about 73% of the weather patterns. Within the general westward flow, these images and some aircraft data indicate that the most turbid waters often move in a band a few kilometers wide along the coast.

Because the Landsat revisit time is on the order of 10 days, the images analyzed so far can provide little information on the shorter term variability in the shelf circulation. The installation this summer at Louisiana State University (LSU) of a ground station to acquire and analyze AVHRR data will provide the opportunity to investigate these short term changes and to do so in near real-time.

Acknowledgements

Analysis of the Balize Delta images was in collaboration with J.M. Coleman and that of the Atchafalaya Delta was with R.H. Cunningham.

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2.2.12 HYDROGRAPHY OF THE LOUISIANA-TEXAS SHELF

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As is common on many other shelves, the hydrography of the Louisiana-Texas shelf is largely controlled by the shelf morphology, the local meteorology, and the freshwater inputs. The relative strengths and phasing of the latter two account for much of the spatial and temporal variability of the hydrography.

The Mississippi Delta effectively isolates the shelf from direct communication with the shelf waters east of the delta. The shelf is extremely shallow, the shelf break occurring at approximately 100 meters depth. Immediately west of the delta the shelf width is only a few tens of kilometers, but it rapidly widens west of the Mississippi Trough until it is approximately 200 km wide near the Louisiana-Texas border. It then narrows again towards the Mexican border. A mid-shelf break in slope near the Louisiana-Texas border is important to the formation of heavy shelf water during some winter seasons.

Summer meteorology is dominated by weak southerly or southeasterly breezes as the region falls under the influence of the Bermuda High. Occasional tropical storms and hurricanes cause significant mixing, but the more common mixing events are squall lines and convective thunderstorms. During winter, the Bermuda High weakens and moves to the northeast. Cold-air outbreaks dominate the regional meteorology. Spring and fall are transitional seasons.

Freshwater runoff to the shelf is dominated by the drainage from the Mississippi River system which enters the Gulf of Mexico through the Balize (birdfoot) Delta and through the Atchafalaya Delta. The former debouches directly onto the shelf while the latter empties into the shallow Atchafalaya Bay. Peak discharge normally occurs in late spring, but large runoff events are not uncommon in fall or even winter.

Discharge plumes from the Mississippi River rapidly separate from the bottom and spread due to buoyant expansion and vertical entrainment. Immediately west of the Mississippi Delta, a strong halocline forms which isolates the deeper waters from direct air-sea interaction. This halocline is often the site of strong internal inertial oscillations. Numerous weaker pycnoclines are also found in the region and represent locations of significant vertical shear. As one moves westward along the shelf outside the coastal boundary layer, the importance of thermal stratification increases.

The combined discharge from the Mississippi and Atchafalaya Deltas contributes to a well-developed coastal boundary layer. Some of this water appears to flow offshore along the southwestern Texas coast and then returns eastward along the outer shelf. The region of offshore flow moves eastward along the coast as the summer winds become dominant. During the summer a significant volume of freshwater is found over the mid and outer shelf where the shelf is widest. The effect of this water on the local density structure will necessarily be reflected in the geostrophic flows.

During particularly harsh winters, evaporative cooling of the shelf waters during cold-air outbreaks can result in the formation of anomalously heavy water at midshelf. This water then sinks and flows offshore, although some appears to remain and contribute to the cyclonic flow of the shelf waters.

Some indications of upwelling occur along the shelf. Temperature sections across the Texas shelf during the summer season, when the winds are favorable for upwelling, indicate a mass of anomalously dense water over the mid- and outer shelf. It is not clear how much of this is remnant and how much may be upwelled. Immediately west of the Mississippi Delta, the summertime intrusion of high salinity water onto the mid- and outer shelf has also been documented.

Fronts occur over the shelf on a variety of scales. Riverine fronts abound. The coastal boundary layer is separated from the inner shelf waters by an intense salinity front. All of these fronts are accompanied by turbidity fronts as well. Loop Current eddies are known to interact with the outer shelf waters generating chlorophyll and turbidity fronts over the outer shelf and slope. Somewhat surprisingly, no shelf break front is observed.

2.2.13 TEXAS-LOUISIANA SHELF SEDIMENT DYNAMICS AND ASSOCIATED POLLUTANT DISPERSAL PROCESSES

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Introduction

The New Orleans Office of the Minerals Management Service plans a large scale study of the physical processes on the Texas-Louisiana shelf. The dynamics of sediment transport and entrainment throughout the region is an important aspect of the problem. Sediment transport is driven by the general circulation with significant interactions. In fact, turbidity due to suspended sediment is a major water mass characteristic which affects its density and can be used through both satellite image analysis and direct in-situ measurements to identify and track some water masses. Furthermore, the fluid shear stresses developed through the combined action of waves and currents serves to entrain, suspend, and transport sediments while modifying nearshore and bottom currents through bottom friction. These processes are also important in controlling fluxes of particle-reactive pollutants, bottom-founded oil spill residues, and sunken marine plastic debris.

The purposes of this summary paper are to:

- Explain why sediment dynamics studies are a significant component of the proposed Texas-Louisiana shelf oceanography program;
- Demonstrate the connection between the dynamics of the bottom boundary layer processes which cause shelf sediment transport and the major components of shelf hydrography and circulation; and,
- Identify the main topics needing additional study.

Background

The sediment fluxes on the Texas-Louisiana shelf are broadly grouped as suspended, and bed loads. There are a variety of coastal and nearshore sources of the sediments. They are carried along and across the shelf by waves and currents in a system which combines slowly varying discharges and episodic transports. This means that a significant fraction of sediment transiting a shelf environment spends most of its time stored in temporary deposits. A major implication is that both chemical and discrete (i.e., debris) pollutants are frequently absorbed and buried for variable lengths of time. Consequently, the loading of the shelf waters with both chemical and physical pollutants cannot be properly understood without knowledge of the short-, and long-term exchanges with the bottom sediments.

Portions of the Texas-Louisiana shelf are undergoing long term sediment deposition. In addition to providing a sink for debris and pollutants, the resulting deposit provides a record of shelf conditions back in time. In these areas the major changes from the undeveloped prairie, through the growth of extensive midwestern agriculture, the channelizing of the Mississippi River, and ultimately the damming of rivers and tributaries has been recorded in marine sedimentary deposits. More recent changes, due to offshore petroleum activity, varying rates and types of pesticide and fertilizer application, varying agricultural practices, or with changes in the management of river discharges may also have left a signal. Analyzing this record can provide important insights into both physical processes of the Texas-Louisiana shelf and methods to appropriately manage its environmental, living, and mineral resources.

The factors which control the entrainment, transport and discharge of sediments on the Texas-Louisiana shelf are similar to most other shelf environments. Major factors include:

- Sediment sources and inputs;
- Antecedent deposits;
- Suspended loads;
- Bed loads;
- Event-scale (synoptic scale) transport processes;
- Fair weather processes; and
- Time-averaged transport processes.

There is a large amount of information regarding the distribution and major sources of sediments of the Texas-Louisiana shelf. This can be combined with available data on shelf currents and waves to provide an overview of the major sediment dynamics processes which can be used for planning future studies. Such an undertaking is beyond the scope of this summary. However, a review paper has been prepared and submitted to the journal Oceanography by the authors of this summary. Readers are encouraged to consult this related article as it provides the basis for many of the following research recommendations.

Research Recommendations

There is potential for considerable advancement in understanding the sediment dynamics of the Texas-Louisiana shelf at little cost by incorporating these studies into the physical oceanography program. Most of the important wave and current measurements will be utilized for several of the sub-programs (i.e., both shelf and sediment dynamics). Therefore the sediment dynamics aspect of the overall program will require only minor additions to the field measurements and will result in promoting much more intense analysis of the program data.

The primary research needs of a Texas-Louisiana shelf sediment dynamics study are:

- Conduct a Rapid Methods Study to devise the most adequate procedures for using current and wave data, characteristic of shelf circulation studies (e.g., mooring transects, hydrographic cruises, met./wave buoys, etc.), to evaluate sediment entrainment, transport, and deposition at the major relevant time-scales. This study will most likely produce different approaches to event-, seasonal-, annual-decadal- and long-term-time scale processes. The methods study will contain an assessment of the resolution and usefulness of the analyses techniques to shelf sediment dynamics questions of interest to MMS;

- Examine the forcing which creates the bottom nepheloid layer in the outer shelf environment;

- Examine the hypothesis that shelf waves are important in re-entraining suspended sediment in the inner shelf and shoreface environment and that this process significantly contributes to the persistance of the nearshore turbid zone. Also examine these effects on the stranding of bottom-founded oil spill residues and plastic debris. F. Kelly (personal communication, 1988) points out that shelf waves are poorly studied on the Texas shelf and that the proposed mooring transects would benefit from a high density of instruments in their inner sections to better resolve these processes;

- Evaluate the oceanographic mechanisms which control the exchange of sediments, bottom-founded oil spill residues, and sunken marine plastic debris between the shelf and the shorelines;

- Examine the short-, and long-term behavior of the bottom nepheloid layer in the outer shelf and create a predictive relationship between measured behavior of shelf-edge flow phenomena and the heights and concentrations of this turbid zone;

- Identify the major mechanisms which transport sediment from the shelf to the deep Gulf of Mexico;

- Determine characteristic patterns and rates of shelf sediment transport associated with wave and current conditions caused by different types (hurricanes, 'northers' etc.) and severities of storms;

- Determine the degree to which low nearshore salinities and high turbidity are linked; include possible cause and effect relationships;

- Determine the seasonal and average annual patterns of sediment transport over the entire Texas-Louisiana shelf. Identify the major processes responsible for this transport in varying sub-environments;

- Develop an annual-time scale representation of sediment dispersal on the Texas-Louisiana shelf from measured current records;

- Establish the seasonal flux of Mississippi-Atchafalaya system sediment over the Texas-Louisiana shelf. Identify the major transportation modes, the forcing, and the short- and long-term variabilities;

- Establish the relative volumetric contributions of sediment derived from the Mississippi-Atchafalaya system and sand stripped from the beach and shoreface by storms in the central Texas shelf;

- Evaluate the characteristic thicknesses of the sea floor mixed layer in different shelf environments distinguished by sediment types, water depths, and the adsorptive-release capacity of the sediment for particle reactive pollutants;

- Establish the volume of sediments and pollutants contributed by all rivers of the Texas-Louisiana shelf;

- Establish the changes in bottom sediment composition on event-, seasonal-, and annual-time scales at several key locations, for example: A) near S.W. Pass of the Mississippi River, B) off the growing Atchafalaya River delta, on the inner shelf near Matagorda Island (where sands and muds appear to alternate in time), D) on the outer shelf where D. McGrail suggested that the occurrence of a few centimeters of low-density clay may alternate with compact clay and silt and there may be substantial re-entrainment of this low-density sediment into the nepheloid layer;

- Develop a seasonal-, and long-term mass balance for the sediment volumes delivered to the Texas-Louisiana shelf by the Mississippi-Atchafalaya system. This is the dominant source of river sediments, nutrients, and pollutants.

Acknowledgements

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2.2.14 MARINE METEOROLOGY AND AIR-SEA INTERACTIONS IN THE NORTHWEST GULF OF MEXICO

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Coastal and marine meteorology in the northwestern Gulf of Mexico are reviewed in terms of atmospheric motion scales, which include synoptic scale (> 2000 km), exemplified by frontal overrunning; meso-α scale (200-2000 km), such as fronto- and cyclo-genesis; meso-β scale (20-200 km), such as low-level jet and sea breeze systems; and meso γ scale (2-20 km), which are important in the development of the internal boundary layer. In the field of air-sea interactions, discussion will be focused on momentum flux, particularly with respect to the "choice" of drag coefficient. Fluxes of latent and sensible heat are also important in the chilling of shelf water, which produces low sea surface temperatures (SST's) in the winter. It is demonstrated that the air temperature over shelf water is nearly the same as that over nearby land masses from January to May, causing the preferential location of fronto- and cyclo-genesis to shift from the coastline in the fall to larger SST gradients at the edge of the shelf break in winter. Therefore, regions of wind-stress curl will shift accordingly. This "newly found mechanism" may be an important agent in oceanographic processes operative in across-shelf exchange.

Oil company contributions are indispensible as sources of existing meteorological data in the offshore region. The Coastal Studies Institute of Louisiana State University has archived hourly observations from Conoco rigs (including air temperature, wind speed and direction, water level, atmospheric pressure, and wave height and period) from 1981 to the present and observations from Mobil rigs (including air temperature, wind speed and direction and atmospheric pressure) from 1978 to 1984. These rigs are located mainly on the Louisiana and the upper Texas shelf. However for evaporation and latent heat studies, humidity measurements are also needed. It is recommended that the NOAA Buoy Office deploy newly developed 3 m coastal buoys (at least one on the Louisiana-upper Texas shelf and one on the lower Texas shelf) to measure humidity (recent sensor technology has shown that this is possible). In addition, for fronto- and cyclo-genesis analysis and prediction, an upper-air rawinsonding station should be set up in the winter season. The Coastal Studies Institute has this upper-air sounding capability. Experimental design to encompass meso-α, β, and γ scales to investigate atmospheric forcing on Louisiana-Texas shelf water will be discussed.

2.2.15 COLD FRONT PASSAGES AND THE RESPONSE OF COASTAL WATERS AND SEDIMENTS: MISSISSIPPI DELTA REGION, USA

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(Ed. Note: This paper was presented by S.-A. Hsu)

Winter storms (cold fronts, extratropical cyclones) are the common high-energy weather systems in latitudes above 25o. Tropical cyclones (hurricane/typhoons) are largely confined to the 5-45° latitude belt. The Mississippi River Delta region lies between 29 and 30 latitude, the overlap zone affected by both kinds of storms. The hypothesis articulated here is that winter storms, occurring some 20-30 times each winter, are the dominant process active in the geomorphic evolution of the Mississippi River Delta coast. Except where temporarily overwhelmed by sediment discharge, the coastal geomorphology has a hydraulic geometry created by movement of sediment and water within the inner shelf and fluvial/tidal channels, forced predominantly by cold front passages. This hydraulic geometry is disrupted locally by the occasional hurricanes (occurring between 7 and 17 yrs apart) and deposits by major floods. A winter's cold front sequence will reshape the coast to a predictable pattern following these events, with only major inlets, overwash lobes, and alluvial delta lobes remaining. Cold front passages operate in Louisiana on the three kinds of deltaic coasts: (1) seaward prograding, (2) landward transgressing, and (3) transitional. The evolution of these coastal types under the influence of cold front passages is currently under investigation.

Synoptic (remote sensing) studies of this coastal region are being conducted with data from NOAA, Landsat, GOES, SPOT (10 & 20 m), and aircraft cameras/scanner. The coarse-resolution weather satellite data have been useful in following the advance of individual cold fronts, their transit speeds, angles of approach to the coast, as well as the progressive cooling of shelf waters and advective processes they drive. It has been possible to detect estuarine discharges, shallow-water frontogenesis, and movement of mudstreams through the inner shelf. At a finer resolution for examining changes in coastal geomorphology, a series of aircraft overflights are being conducted over selected areas with the Calibrated Airborne Multispectral Scanner (CAMS, 6 and 30 m resolution) and aerial photography. Models of cold front types, oceanic responses, and coastal sedimentological responses are being developed and tested.

A new NOAA satellite earth station is being installed in the Geoscience Complex of Louisiana State University (LSU) in June 1988. This system will track the NOAA satellites and provide local investigators with real time access to the High Resolution Picture Transmission data (HRPT, the 1.1 km AVHRR, TOVS, and System Argos data). The location and receiver sensitivity allows coverage of all of the Gulf of Mexico, the western part of the Caribbean, and large portions of both east and west coasts of the U.S. The facility includes a 1.2 m tracking antenna, data receiving and storage equipment, and a Hewlett Packard 9000-825SRX superwork station which will provide near-real-time interactive processing, access, and display of data. Data will be routinely captured and archived using new state-of-the-art data storage system with costs of $7.00/2.2 Gigabytes of data. This system is truly transportable, compact, and ruggedized allowing investigators to support research with real-time data out of state/country.

2.2.16 FISHERIES AND SHELF INTERACTIONS IN THE NORTHWEST GULF OF MEXICO

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Experience with both commercial and recreational fisheries operating on the Louisiana-Texas continental shelf indicate that daily variations in catch result from the use of static fishing techniques by fishermen in areas where the physical and biological conditions vary daily. Simply stated, fish seek and reside in ocean areas, known as "preferred habitats," where the hydrographic conditions allow for their optimal physiological functioning for extended time periods. Within a preferred habitat, the distribution and catchability (availability and vulnerability) of fish are a function of the location and concentration of their forage at ocean frontal boundaries. The major factors affecting the distribution of commercially valuable fish (pelagic and demersal) on the continental shelf in the northwest Gulf of Mexico are the: location, orientation, and stability of ocean fronts; current speed and direction; mixed layer depth; mean, median, and mode water temperatures from the bottom of the thermocline to the surface; and water color and transparency.

The ability to diagnose and forecast the distribution and concentration of biological productivity in the Gulf of Mexico is important for accessing the potential impact of drilling and transportation activities on the Louisiana-Texas shelf. Sampling on the appropriate time and space scales for conducting fisheries oceanographic analyses requires synoptic observations of fish and hydrographic conditions. In situ measurements from ships, buoys, and other platforms provide discrete samples of ocean conditions. However, repeated synoptic scale monitoring of small (1 km) to meso-scale (>100 km) size oceanographic features by geostationary and polar orbiting satellites are needed. Sampling from airborne sensors from airplanes also provide needed coverage. Satellites, followed by airplanes, buoys, and ships provide the most economical source of oceanographic data on a cost per byte basis.

There have only been a few comprehensive fisheries oceanographic studies in the Gulf of Mexico in which the collection of fisheries and hydrographic data was conducted in a synoptic manner (Kemmerer et al. 1974; Kemmerer 1980; Roffer et al. 1981, 1987; Maul et al. 1984). Overall, these studies attempted to develop fisheries forecasting models and the results are the foundation of the currently used ROFFS fisheries forecasting models. As a commercial service, ROFFS provides fisheries oceanographic analyses to clients throughout the Gulf of Mexico and U.S. east coast, seven days a week, 18 hours a day. Our success rate for forecasting productive fishing areas is significantly higher than results derived using other forecasting techniques which rely on climatology or random chance.

A cohesive, multidisciplinary research effort is needed to extend our knowledge of the major physical and biological components of the Louisiana-Texas shelf ecosystem. Along with past research, new research results should serve as a foundation for the development of predictive models. New research should be directed to answer such questions as: How deep are the cyclonic and anticyclonic circulation features which are routinely observed in satellite imagery?; What is the longevity of these features?; What are the spatial and temporal characteristics of ocean frontal zones that are related to variations in ocean productivity?; What are the time/space characteristics of interactions between bottom topography and circulation in terms of accumulating or dispersing particles (oil, eggs, larvae, plankton, fish)?; Are there certain areas or pathways where eddies travel?; Are there dimensional aspects of eddies and other large scale ocean features which can be used to index rotational, horizontal and vertical circulation velocities, as well as, to index the longevity of these features?; Can these indices be used for developing predictive circulation models?; What are the temporal and spatial responses of episodic wind events?; and Can one predict the location, strength, and longevity of phytoplankton blooms and accumulations of fish?

The proposed Minerals Management Service (MMS) research initiative is expected to facilitate interaction between oceanographers in private industry, government service and academia. As a private company, ROFFS is interested in mutually beneficial exchanges of data and technology. Our personnel interact daily with commercial fishermen who operate in the Texas-Louisiana shelf region. Upon request, our clients have deployed buoys, XBT probes and have taken scientists offshore during 5-20 day fishing trips. As part of the MMS research program, we are interested in developing a dependable and inexpensive system for the deployment and recovery of oceanographic equipment using commercial fishermen. As a routine service to our clients, ROFFS provides sea surface temperature and ocean frontal analyses in near real-time (1.5 hour delay) using various advanced, radio and telephone facsimile equipment systems which do not require expensive satellite communication links. We also can provide multispectral data derived from aircraft in real-time. We are interested in a cooperative, real-time data exchange program which would allow us to validate our data products, while sharing our data. ROFFS continues to develop portable, low cost work stations which are designed for real-time reception and manipulation of satellite infrared data on commercial fishing and research vessels. We are interested in a cooperative effort to refine these systems.

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2.2.17

HYPOXIA ON THE CONTINENTAL SHELF OF THE NORTHWESTERN GULF OF MEXICO

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Oxygen-depleted bottom waters are found worldwide, with the incidence and extent of such areas in coastal waters increasing due to eutrophication. The implications of widespread hypoxia to living resources, particularly those of commercial importance are of significance. On the inner continental shelf of the northwestern Gulf of Mexico, hypoxia, and often anoxia, is widespread and seasonally regular. The largest, most severe, and most persistent zone of hypoxia in United States coastal waters is found in the northern Gulf of Mexico on the continental shelf off Louisiana.

Since the early 1970s, areas of oxygen-depleted bottom, or near-bottom, waters have been documented off the Alabama, Mississippi, Louisiana and Texas coasts (Rabalais et al. 1985; Renaud 1985). A review of the historical data for the northwestern Gulf would indicate that hypoxic areas might be patchy and ephemeral, and that two of the most affected areas were the Mississippi River Delta Bight and the inner shelf west of the Atchafalaya River off Cameron, Louisiana. These conclusions are a reflection of the types of data available and the study-specific locations. Our studies show the hypoxic areas off Louisiana to be extensive, covering an area of bottom as large as 8,000 to 9,500 km^2, and continuous but with shifting location. The zones occur primarily from May through September, at depths of 15 to 30 m.

In 1985 a program to assess the distribution, causes and effects of oxygen depletion on the continental shelf of the northern Gulf of Mexico was begun sponsored through the Louisiana Sea Grant Program by NOAA's National Ocean Service, the Louisiana Universities Marine Consortium, and Louisiana State University. Under this program, shelf waters west of the Mississippi River Delta were systematically surveyed for the first time starting in June, 1985. An intensive field effort was mounted during 1986, beginning in early spring when hypoxic conditions started to develop. The survey extended through their breakup in the fall. A survey of shelf waters in 1987 completed the assessment phase of our studies. The major findings are summarized as follows:

In mid-summer of 1985, 1986, and 1987 critically depressed dissolved oxygen concentrations below 2 mg/l occurred over very large (ca. 8,000 to 9,500 km^2) areas of the shelf (Figure 28) from the Mississippi River Delta onto the upper Texas coast (Rabalais et al. 1986a; Rabalais 1987). In 1985 the low oxygen zone was most intense and extensive in the Mississippi River Delta Bight and westward to Marsh Island. The band narrowed to the Texas border and was confined to 9 to 12 m water depth. The configuration of the area of hypoxia in 1986 differed from that in 1985 with a larger area being found off southwestern Louisiana and the area off southeastern Louisiana being smaller. The configuration in 1987 was similar to that of 1986, with the area off southwestern Louisiana extending farther to the west and the area in the Mississippi River Delta Bight being smaller and shaped differently. In the three semi-synoptic surveys, hypoxic bottom waters were found in 5 to 60 m water depth, from 5 to 60 km offshore, and extended up to 20 m above the bottom.

In mid-summer, the Louisiana inner shelf was dominated by the presence of a coastal boundary layer which contained the runoff of the Mississippi and Atchafalaya Rivers as well as local drainage. The Mississippi and Atchafalaya River plumes were evident in the surface salinity distributions mapped during the shelf-wide cruises. The locations of the plumes differed, however, as well as the extent of less saline surface waters across the shelf.

The bottom salinity field was characterized by the intersection of the bottom with the front separating the low salinity coastal waters from mid-shelf waters. The core of the minimum oxygen concentration bottom waters appeared to lie immediately offshore of the intersection of the pycnocline with the bottom and displaced from the occurrence of the maximum surface-to-bottom density differences. There were indications of a nearshore convergence along the upper Texas and southwestern Louisiana coastlines, the location of which affected the salinity front and possibly the breakdown of the physical structure that maintained hypoxic waters. The characteristics of the hypoxic water masses appear to be complex and linked to offshore stratification phenomena and the three-dimensional circulation patterns associated with the nearshore frontal zone.

Stations in 5 to 30 m water depth situated along a transect off Terrebonne and Timbalier Bays were sampled intensively from June, 1985 through 1986 (Rabalais et al. 1986b). Strong pycnoclines and oxyclines and low oxygen conditions were persistent through the middle of August, 1985 after which the water column was mixed by waves from a series of tropical depressions and hurricanes. Areas of oxygen deficient bottom waters began to develop as early as mid-April through late-May in 1986 but did not become persistent until mid-June. The summer of 1986 was an inactive hurricane season, and stratified waters and low oxygen conditions persisted through mid-October. The zones were persistent, continuous, and intense from mid-June through mid-August.

The flow within the coastal boundary layer and the adjacent nearshore waters responds strongly to the local wind stress. A wind blowing from the west will cause an offshore Ekman flux of surface water and a compensatory onshore flow of bottom water. Similarly, a wind blowing from the east will cause an onshore surface flow and an offshore bottom flow. Our preliminary analysis of wind data and cross shelf hydrographic data has shown this to be the case along the transects occupied off Terrebonne/Timbalier Bays (Figure 29). For example, the winds on 6/14/85 and the two previous days favored downwelling. This would tend to pile water up against the coast and raise the inshore pycnoclines to a more vertical state, as observed on 6/14/85. From 20 to 25 July, winds favored upwelling and the data from 7/24/85 clearly indicated upwelling. Thus it appears that much of the onshore-offshore temporal variability can be attributed to wind-induced cross-shelf advection. It is likely, however, that our sampling scheme was not sufficiently rapid to resolve all the variability present.

Hydrographic measurements accompanying the hypoxia surveys indicate that oxygen deficient bottom waters are maintained by intense and persistent density stratification resulting from large coastal freshwater inputs and relatively calm meteorological conditions during the summer months. Significant oxygen consumption rates may occur in the water column, benthos, or both, and re-aeration rates are not sufficient to maintain adequate oxygen levels. The principal source of organic matter in the bottom waters of the northern Gulf of Mexico is probably from phytoplankton production in surface waters. Whether this production originates in situ, from the coastal boundary layer, from the Mississippi and Atchafalaya River plumes, or a combination of these is unknown. The level of organic material reaching the bottom waters is high (Turner et al. 1987). In addition, the respiration rate in these waters appears to be proportional to phytoplankton pigment concentration (Turner and Allen 1982), and we have found very high levels of decomposition products (phaeopigments, dissolved nitrogen, silicate, and phosphorus) in hypoxic bottom waters.

The source of the respired organic material in bottom waters is not clear. Examination of surface chlorophyll levels and bottom water oxygen conditions does not provide any correlative information. In 1985, during the shelf-wide cruise in July and at the time series stations off Terrebonne/Timbalier Bays, the highest surface chlorophyll concentrations (>5 g/l) were found inshore of or along the inner margin of the zone of oxygen-depleted bottom waters. Sampling along the transect did not begin, however, until mid-June, at which time a significant input of organic material to the bottom may have already occurred. A pattern of surface chlorophyll concentrations and oxygen deficient bottom waters is even less clear in 1986. During the shelf-wide cruise, surface waters lower in salinity and higher in chlorophyll were present across the shelf instead of limited to the nearshore areas, but these patterns were still not reflected in the configuration of the zones of hypoxia. Similarly, the surface waters of the transect off Terrebonne/Timbalier Bays were consistently lower in salinities and higher in chlorophyll across the shelf through the spring and summer, a condition not seen in 1985. Also, high levels of chlorophyll in bottom waters in March through April indicate that sampling frequency was inadequate to properly assess any in situ surface production that may have occurred at this station that later accumulated in the bottom waters.

The model (Figure 30) we have developed for the hypoxia in the northwestern Gulf of Mexico incorporates physical and biological components. Obviously the discharges of the Mississippi and Atchafalaya Rivers, thermohaline stratification of the water column in the warmer months of the year, wind driven forcing mechanisms, and inner continental shelf circulation patterns all play important roles in creating the physical structure of the water column which creates conditions conducive to the development and maintenance of oxygen deficient bottom waters. The water column chemistry, especially nutrient concentrations, the quantity and source of organic material introduced below the pycnocline, and oxygen consumption rates in the water column and in the benthos are all integral processes in the formation of hypoxic waters.

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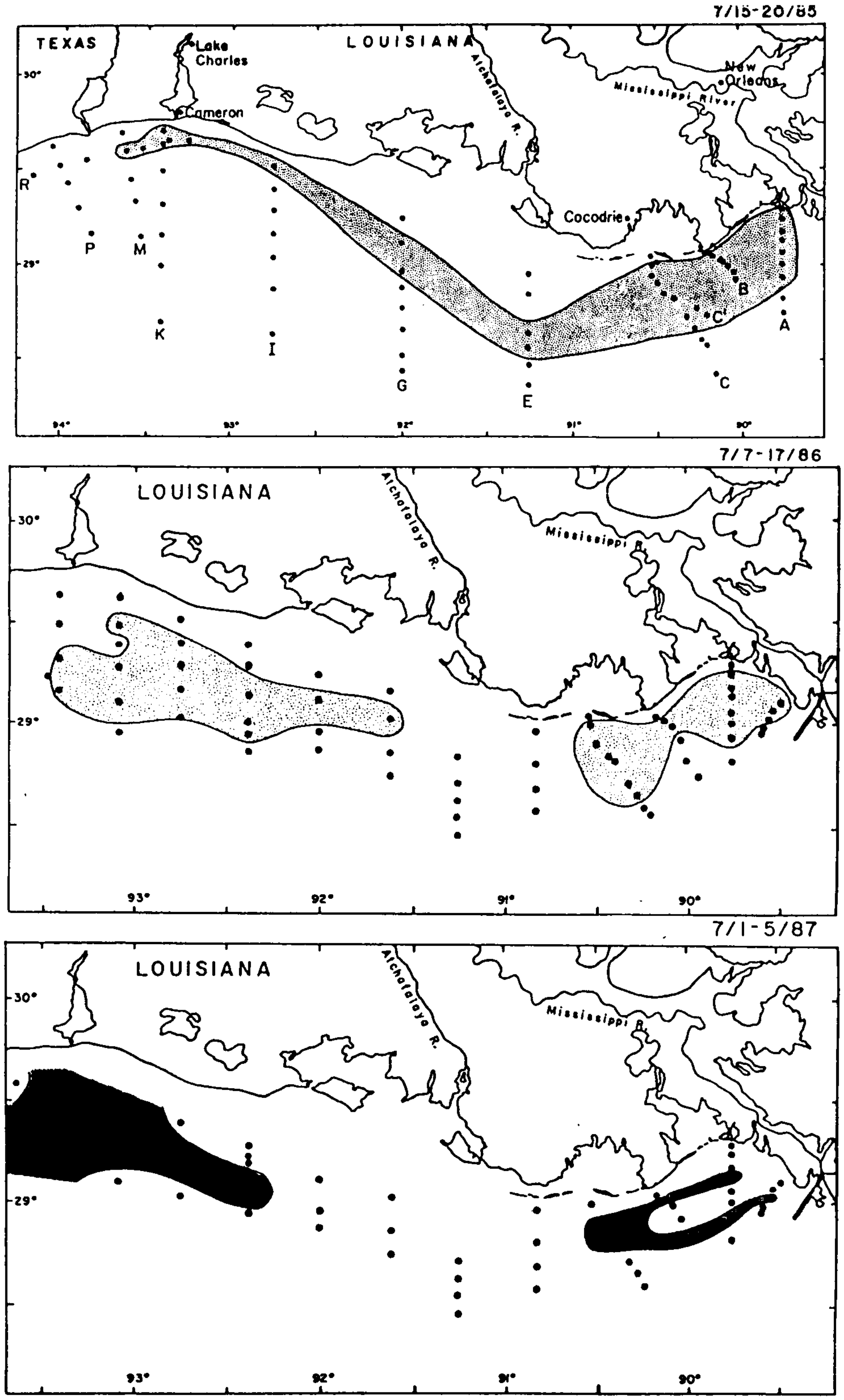

Figure 28. Areas of the Louisiana shelf where hypoxic bottom waters were found in 1985, 1986 and 1987. Note difference in map size for 1985 as compared to 1986 and 1987.

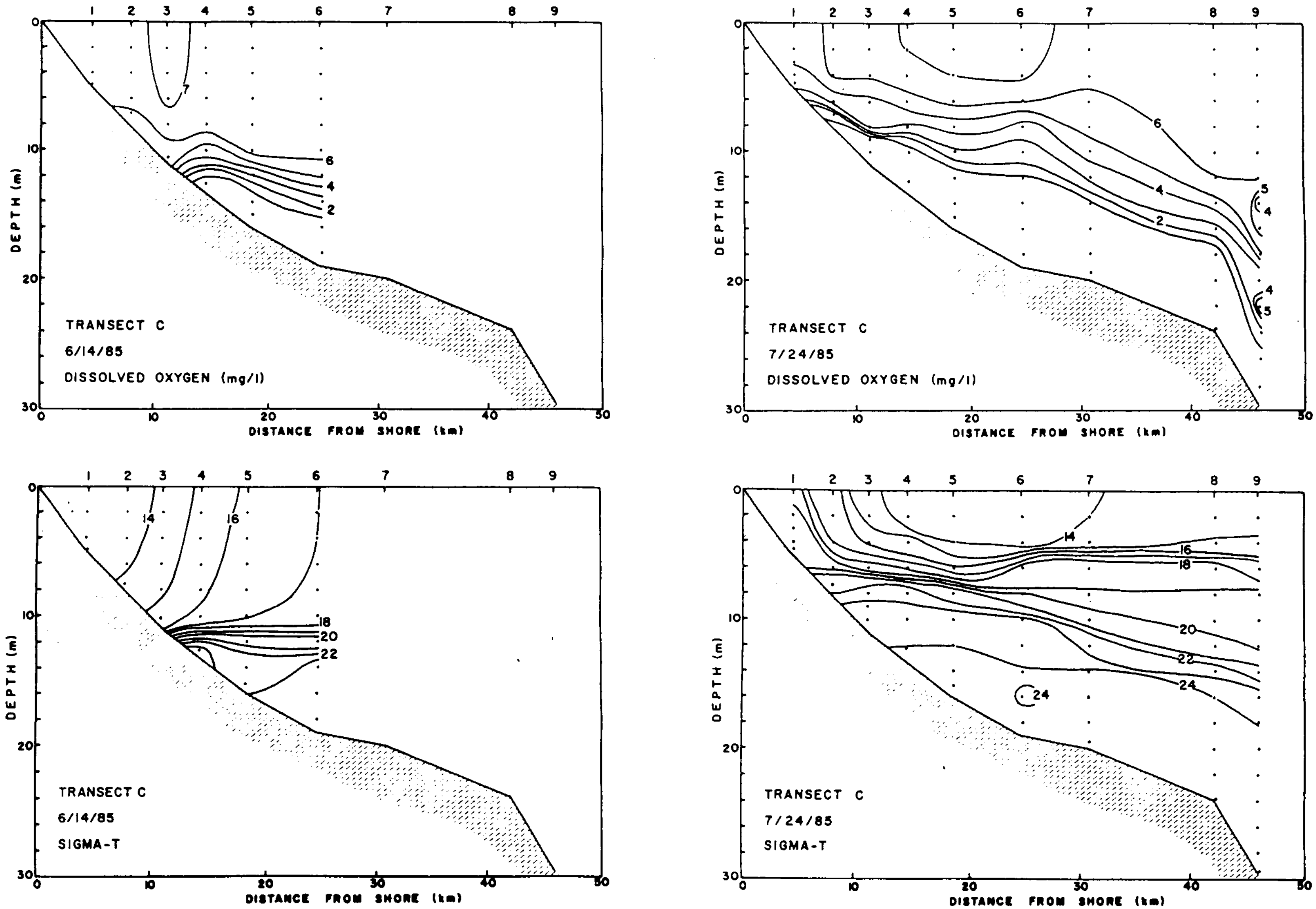

Figure 29. Sigma-t and dissolved oxygen contours for Transect C.

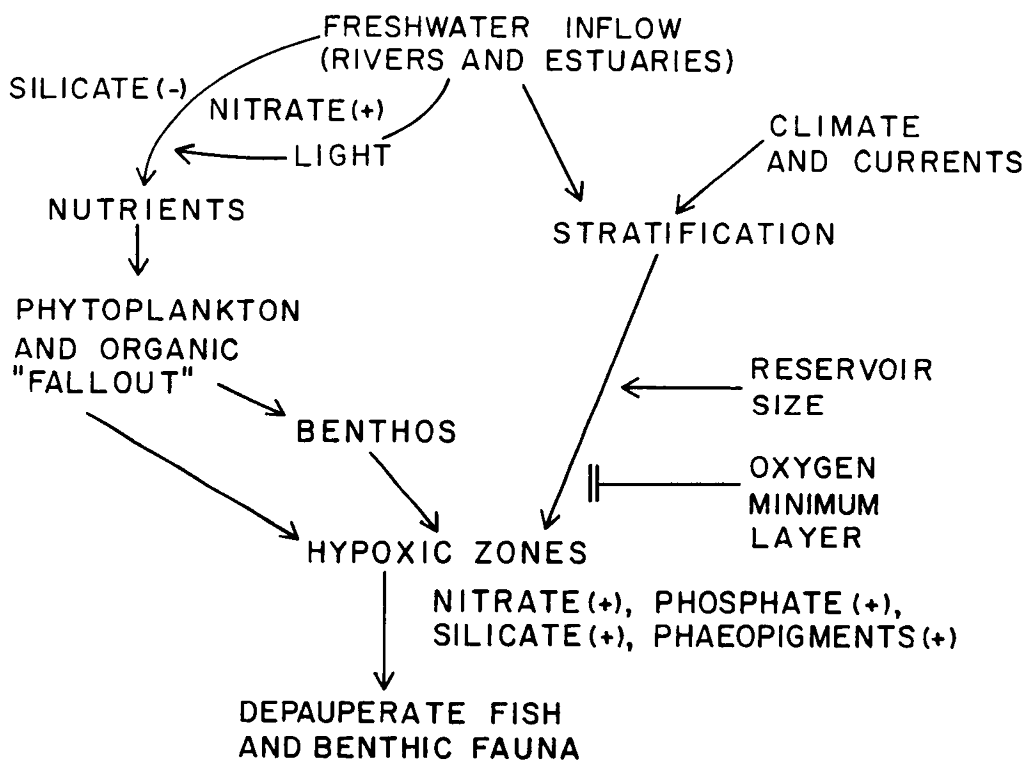

Figure 30. **Interrelationships of hydrographic, chemical, and biological aspects of bottom water hypoxia. Changes in water quality parameters indicated by "+" (higher) and "-" (lower). The oxygen minimum layer does not contribute to hypoxic water masses.**

2.2.18 PETROLEUM INDUSTRY USES/NEEDS

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The petroleum industry needs meteorological and oceanographical data for the design, transportation, installation and operation of exploration and production platforms and facilities on the Louisiana-Texas shelf/slope of the Gulf of Mexico. The petroleum industry currently operates and maintains over 3,000 platforms and facilities in the Gulf of Mexico. Since 1978 the industry has drilled over 1050 wells in water depths greater than 183 m (600 ft). Fixed, compliant and floating production platforms are being planned, appropriate for the entire range of water depths of the Louisiana-Texas shelf/slope.

Extreme Environmental Data

Extreme meteorological and oceanographical data are required for the design and analysis of exploration and production, fixed and floating platforms. Wind, wave and current data are required for calibrating hindcast models and for both deterministic and probabilistic designs of platforms and facilities. Principal applications for the environmental data from the Louisiana-Texas shelf/slope include:

- o Design and analysis of fixed, compliant and floating platforms and facilities;
- o Design and analysis of subsea systems; and
- o Design and analysis of shore connected facilities.

Normal Environmental Data

Normal meteorological and oceanographical data are required for the transportation, installation and operation of exploration and production platforms and facilities on the Louisiana-Texas shelf/slope of the Gulf of Mexico. Wind, wave and current data are required for operational considerations. Principal applications for the environmental data from the Louisiana-Texas shelf/slope (see Table 3) are:

- o Transportation/towing and installation considerations for platforms;
- o Platform design considerations related to boat landing and crane locations;
- o Helicopter and aircraft ground predictions;
- o Crew and supply boat down-time prediction and boat to platform transfer considerations;
- o Geophysical survey and core hole drilling down-time prediction and scheduling;

- Motion prediction for floating drilling vessels, construction barges, work-over vessels and drilling risers;
- Waiting time prediction for self-elevating platforms to move on and move off location;
- Diver effectiveness prediction;
- Oil spill movement and dispersion prediction; and
- Overall economic evaluation; production system concept selection; planning safe, efficient operations; and environmental impact evaluation.

Summary and Conclusions

The Gulf of Mexico is a market with proven deepwater discoveries and available deep water acreage. Major petroleum operators and independents believe the Gulf of Mexico contains profitable prospects across the entire range of water depths. Exploration and production of the prospects will require a range of platforms from fixed to floating. Extreme and normal environmental data will be required for design, transportation, installation and operation of these exploration and production platforms and facilities.

Table 3. Environmental data needs: normal considerations.

Principal Applications	Storm Systems	Wind Conditions Velocity		Wave Conditions Height/Period/ Direction		Current Conditions Velocity		Astronomical and Storms Tides
		Freq of Occur	Duration	Freq of Occur	Duration	Freq of Occur	Duration	
Fixed Platform Design Consider-ations Related to Towing and Install-ation, Boat Land-ing and Crane Operations.	X			X	X	X	X	X
Helicopter and Air-craft Grounding Predictions (Drilling, Construction, Maintenance, and Schedul-ing).	X	X	X					
Crew and Supply Boat Down-Time Prediction, Boat to Platform Transfer (Drilling, Construction, Maintenance and Scheduling).	X	X		X	X	X	X	

Table 3 (cont'd). Environmental data needs: normal considerations.

Geophysical Survey and Core Hole Drilling Down-Time Prediction and Scheduling.	X			X	X				
Motion Prediction for Floating, Drilling Vessels, Construction Barges, Work over Vessels (Vessel and Barge Selection, Drilling Risers, Construction, Maintenance, and Scheduling).	X	X	X	X	X	X	X		
Movement Prediction for Waste Spills (Oil Spills, Chemical Spills, and Toxic and Non-toxic Wastes).	X	X	X	X	X	X	X		X

Table 3 (cont'd). Environmental data needs: normal considerations.

Waiting Time for Prediction for Self-Elevating Platform Moving on/ Moving off Location (Self Elev. Platform Selection, Drilling Scheduling).	X			X	X	X	X		
Underwater Television Useability Prediction (Drilling, Construction, Maintenance, Scheduling, and Subsea Drilling and Completion System Design).						X	X		
Overall Economic Evaluation, Production System Concept Selection, Planning Safe, Efficient Operations and Environmental Impact Evaluation.		X	X	X	X	X	X		X

2.2.19

HURRICANE-DRIVEN CURRENTS ON THE OUTER CONTINENTAL SHELF AND SLOPE

Dr. Cortis Cooper
Conoco

A numerical model is developed to simulate currents generated by hurricanes on the outer continental shelf and slope. Emphasis is on the mixed-layer response within a few hours of storm passage; however some attention is given to the lower layer and shelf wave responses. The model is based on a layered, explicit, finite difference formulation using the nonlinear primitive equations including conservation of heat. The problem of topography intersecting the model layer is resolved by introducing artificial steps of order 100 m where the layer intersects the slope. Model comparisons are presented for two Gulf of Mexico hurricanes using a 0.2° grid. The model reproduces better than 80% of the observed velocity variance with correlation coefficients of order 0.8 for the mixed layer. Discrepancies in the comparisons are traced to unresolved local topography. Further model simulations reveal: 1) substantial shelf waves were generated with phase speeds of 4 to 10 m/s; 2) the response is primarily baroclinic even in water as shallow as 200 m; and 3) deviations from a straight line path can significantly alter the response.

Numerical experiments were also performed in a simple basin with a straight shelf. The sensitivity of the response to changes in storm parameters, direction of storm approach, and topography is quantified. Response is measured in terms of the mixed-layer velocity and depth at sites along the storm track. Results reveal the most important factors are (in decreasing order): wind speed, storm translation speed, direction of storm approach, asymmetry in the wind field, entrainment parameterization, and advection at slower storm translation speeds. Response is largely insensitive (less than 10%) to: radius of maximum wind, shelf and slope configuration, bottom friction, atmospheric pressure gradients, and further reductions in the model grid size. For a storm approaching cross-shelf, the response is primarily baroclinic (greater than 90%) and only weakly dependent (less than 10%) on the water depth at the site. Further details on the effort are given in Cooper and Thompson (1988a, b; in press JGR Oceans).

2.2.20 TIDE/STORM SURGE MODELING

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Tides in the Gulf of Mexico

While not dramatic in amplitude, the tides in the Gulf of Mexico are rather unusual because of the totally different character of the diurnal versus the semidiurnal tides. The three principal constituents are the K1, O1, and M2; Figures 31 and 32 show amplitudes and phases for the K1 and M2 tides at coastal, island and benthic gauge locations (the O1 tide is very similar to the K1). Note in particular the benthic station in the central Gulf and one at the shelf break on the west Florida shelf.

Except for minor variations, the diurnal K1 (and O1) tide has nearly uniform amplitude (about 15 cm) and nearly uniform phase over the whole Gulf (except close to the straits). It is basically a volumetric Helmholtz mode driven by in-phase volume transport at the two straits (Grace 1932; Platzman 1972; Reid and Whitaker 1981).

In contrast, the semidiurnal M2 tidal regime represents a well defined amphidromic system with counterclockwise phase propagation having negligible amplitude in the deep central Gulf and maximum amplitudes along the coast, particularly along west Florida where the shelf width is very large. The shelf morphology is clearly important in producing sharp contrasts in amplitude and phase, as occur between the west Florida shelf and Mississippi Sound. The model study by Reid and Whitaker (1981) showed that the M2 tide in the Gulf is driven primarily by the direct tidal forces in contrast to the diurnal tide (only 35 percent of the energy of the M2 tide in the Gulf comes from the Atlantic Ocean or Caribbean Sea).

An analysis of tidal currents on the Florida shelf by Koblinsky (1979) shows that the tidal ellipses have clockwise rotation for both the diurnal and semidiurnal tides. Figure 33 shows ellipses for the M2 tide. Largest currents occur near shore.

Non-tidal Water Level Variations

Figure 34 shows a time series of water level at Galveston for the period 1 August to 30 September 1961; this has been smoothed via a 40-hour low pass filter to remove the tidal signal. The major event during this two month sample is the occurrence of Hurricane Carla which entered the Gulf on September 7. Another two month filtered sample at Galveston for the period 1 July to 31 August 1980 during which Hurricane Allen occurred (and made land fall near Port Isabel some 400 km southwest of Galveston) is shown in Figure 35.

Aside from the clear hurricane-induced signal, both samples show about the same variance of long period background. Similar records for Port Isabel and Grand Isle, Louisiana show coherent background variations, which for common time windows are nearly in phase. It is unclear whether the origin of the background is due to local forcing over the Louisiana-Texas shelf or is due to some basin scale vorticity mode. The range of variation is comparable to the tide. Deployment of bottom mounted, self-recording pressure gauges at the shelf edge could help shed some light on such questions.

The hurricane surge signals evident in Figures 34 and 35 present a real challenge to even the most comprehensive storm surge model in the following respect: the data for both hurricanes show clear evidence of an initial slow rise in water level at Galveston even before the hurricane center has entered the Gulf of Mexico! Clearly a limited domain surge model which models only the Louisiana-Texas shelf cannot be adequate without knowledge of the response of the Gulf of Mexico as a whole to the proximity of a hurricane within the Caribbean Sea or the Atlantic Ocean.

Modeling of Barotropic Tides and Surges

Both tides and storm surges are commonly modeled in terms of an appropriate numerical implementation of the depth-integrated primitive equations of motion and continuity, which if expressed in a spherical coordinate system with allowance for Coriolis acceleration, are the Laplace tidal equations or LTE (for details see Hendershott 1977, 1981).

In respect to numerical implementation, both finite difference and finite element models have been employed for spatial representation; and both explicit and semi-implicit time stepping codes exist, of which the alternating-direction-implicit (ADI) method is advantageous in terms of economy but is less accurate than explicit codes. Adequacy of boundary conditions, forcing, resolution and parameterization of damping are far more important than the subtle differences among various numerical methodologies. It is on these topics which the remainder of this paper focuses.

The governing equations (LTE) for tides and storm surges are the same except in terms of forcing. Direct forcing for surges is provided by wind stress and the gradient of atmospheric pressure. Direct forcing for tides is provided by the gradient of the net astronomical tide potential, modified by changes in the earth's gravitational field by earth tides and the variation of water level (self-attraction effect) and by sea bed loading. The effect of elastic distortion of the earth by the tide-producing forces is to produce a time varying anomaly of gravity equal to 31 per cent of the tide force and in opposition to it, so that the effective tide force is only 69 per cent of the astronomically-induced force (Hendershott 1977; Schwiderski 1980). For limited domain models such as a bay with an open boundary, one must specify either the (time variable) water level, the volume transport or some combination (tidal impedance matching, Hendershott 1981).

The primary differences between the forcing for tides and storm surges are:

- Tidal forcing is at discrete frequencies and of planetary scale (spherical harmonic modes);

- Storm forcing has a continuum frequency and wave number spectrum with dominant spatial scales generally less than 100 km for extra-tropical cyclones and less than 200 km for hurricanes.

Sensitivity of Tide Models

There has been a renewal of interest in global tide models motivated by the need to have accurate tide elevation information at any point in the ocean to allow the removal of tide signal from satellite-derived altimetric data. Observational information exists only at coastal stations, including islands and a few benthic pressure gauges scattered around the world ocean.

The ideal global tide model ought to be able to predict the tide at any point in the ocean solely in terms of the astronomically-induced tidal forces (with due account for earth tide, etc.). This was the dream of Laplace, the realization of which still remains an elusive goal even in an era of super computers; however we have come a long way. Figure 36 is a reproduction of co-phase (full lines) and amplitude contours (dashed lines in units of cm) for the M2 world tides based only on the tide-producing forces (Accad and Pekeris 1978). The major features of the amphidromic systems and the sense of rotations of the tidal phase is in accord with empirical data. The primary discrepancy is the lack of quantitative agreement with the coastal water level amplitudes.

The Accad and Pekeris model is one which employs the physically meaningful condition of impermeable coastlines and predicts the water level at shore. From a purely mathematical standpoint, on the other hand, one can solve the LTE with the boundary condition that the water level is prescribed at the coast. Hereafter I refer to this kind of boundary value problem as diagnostic, since it relies on observations and represents an objective interpolational model to map the interior. The global model of Schwiderski (1980) is of this type; it has a resolution of 1 degree x 1 degree for the world ocean and has been used to map all the major tidal constituents. However, Hendershott (1981) has serious reservations about the accuracy of such diagnostic models, particularly for those basin domains of the ocean where the period of an admissible normal mode of oscillation matches that of the forcing period. Indeed the Gulf of Mexico (GOM) is an example where the gravest rotational mode has a period close to that of the M2 tide (Reid and Whitaker 1981) and it is for this reason that this mode can be driven directly by the astronomical tidal forcing within the Gulf. The GOM predictive model of Reid and Whitaker (1981) yields an error variance of only 10 percent for the M2 tide based on a comparison with the observations at the twenty stations in the Gulf shown in Figure 32. This compares favorably with a 5 percent error variance in the prediction of the O1 and K1 tides in the Gulf.

In order to reduce the error variance of tide models to say the one percent level, the procedure of Platzman (1984) offers the best hope. In this method the tidal response for a basin is represented by an appropriate superposition of normal mode basis functions in latitude and longitude, the latter being determined numerically with the physically realistic condition of zero flow across coastal boundaries. The fitting procedure should involve a convolution with the tidal forcing in the interior and a projection onto the observed tides at observational stations.

The accuracy of such a procedure depends on that of the normal modes. Moreover the accuracy of the normal modes is <u>critically</u> dependent on the resolution over the continental shelf regions of a basin. For example the normal mode analysis for the Gulf of Mexico by Platzman (1972) using a resolution of 60′ x 60′ gave for the gravest rotational mode a period of about 7 hours, while the Reid and Whitaker (1981) model with 15′ x 15′ resolution gives a period close to 12 hours for the same mode. Table 4 compares the periods of the volumetric Helmholtz mode, as well as the gravest rotational mode, for the two models. Thus the proper resolution of shelf topography can be critical for tidal studies just as it is for storm surge studies.

In future studies the use of finite element models which would allow very good resolution over continental shelves and less resolution in the interior could be used to advantage.

Finally in tuning tide models with respect to damping effect by bottom stress, the sensitivity is dependent upon whether any of the basin modes are nearly resonant to the forcing period. This is the case for the M2 tide in the Gulf of Mexico.

Sensitivity of Storm Surge Models

There are two aspects of storm surge modeling which should be stressed in this final section:

- Adequacy of the storm data;
- Adequacy of spatial domain (or the limitations of limited domain models).

Of these, the first is the most critical. Even in a hindcast mode of modeling of the storm surge produced by a hurricane of record, where the path is known and the maximum data are available, the accurate representation of the fields of wind stress and barometric pressure leave much to be desired. One must resort to parametric models of a hurricane to fit to the available data. Such storm models are usually limited to four or five parameters and give a reasonable rendition of the storm in the most intense part but not in the outskirts. Hurricanes Carla in 1961 and Allen in 1980 are events for which a maximum amount of storm data are available. A model study by Bunpapong <u>et al</u>. (1985) addressed the surge hindcast for these two events using a Gulf domain surge model with a parametric storm model which allows increased degrees of freedom in terms of radial and azimuthal distribution of wind stress and inflow angle. Figure 37 compares the computed and observed hydrographs for the Carla event at Galveston, both referred to a common mean monthly level. Note that the observed signal contains the tide while the computed does not. Both would agree quite well if smoothed with the 40-hour low pass filter as in Figure 34. Figures 38 and 39 show similar comparisons at Galveston and Port Isabel for Hurricane Allen. These represent probably the best one can do; the primary limitation being the adequacy of storm data rather than the surge model.

Limited area renditions of these same events when one employs a model domain limited to the Texas shelf fall far short from the agreement achieved with the

Gulf domain model. The reason for this is that large scale basin modes are excited even in the early stages which help explain the slow initial rise well before the hurricane center reaches the continental shelf.

The particular surge model employed by Bunpapong et al. (1985) was actually a two-layer model which allowed the development of strong upper layer circulation in the wake of the hurricanes. Examples of this are shown in Figures 40 and 41 for Carla and Allen respectively. The wake of alternating flow strongest on the right of the storm track is characteristic of that found in studies by other modelers. These examples also serve to emphasize the magnitude of possible effects on existing eddies which hurricanes can have. As a final comment, the modeling of currents by purely barotropic or even two-layer models is far from adequate. While such models give reasonable rendition of tide and surge elevations and volume transport, they are not adequate for vertical structure of currents (which impacts on the adequacy of bottom stress parameterization). The alternative to the expensive 10 to 20 level 3-D models is to employ a modest number of coupled vertical modes, which oceanic modelers like Haidvogel et al. (1985) are investigating.

Summary

- The K1 and O1 tides in the Gulf are primarily a volumetric Helmholtz mode driven by in-phase pumping through the straits. The GOM model reproduced these tides with an error variance of 5 percent.
- The M2 tide in the Gulf is primarily the gravest rotational (shelf) mode which is nearly resonant with and driven by the direct tide forces in the Gulf. The GOM model reproduces this tide with an error variance of 10 percent.
- Resolution of shelf regions is critical for accurate tide and normal mode basin models, just as is true of storm surge models.
- Bottom stress can be important for nearly resonant modes (e.g., M2 tide in the Gulf), but otherwise plays a secondary role in tidal and storm surge models.
- Diagnostic tide models, while attractive, can yield erroneous results for basins in near resonance with tidal forcing. The fitting of accurate normal mode basis functions to tidal observations is the preferred alternative.
- The critical factor in hurricane surge modeling is the adequacy of storm field data and the parameterization thereof.
- Limited area surge models in the Gulf cannot adequately simulate the slow initial rise in water level which precedes the arrival of a hurricane near the shelf. Basin models are the obvious alternative.

- o Multimode models accounting for density stratification are required if one wishes to adequately predict vertical structure of currents related to tides and surges, as well as low frequency circulations.

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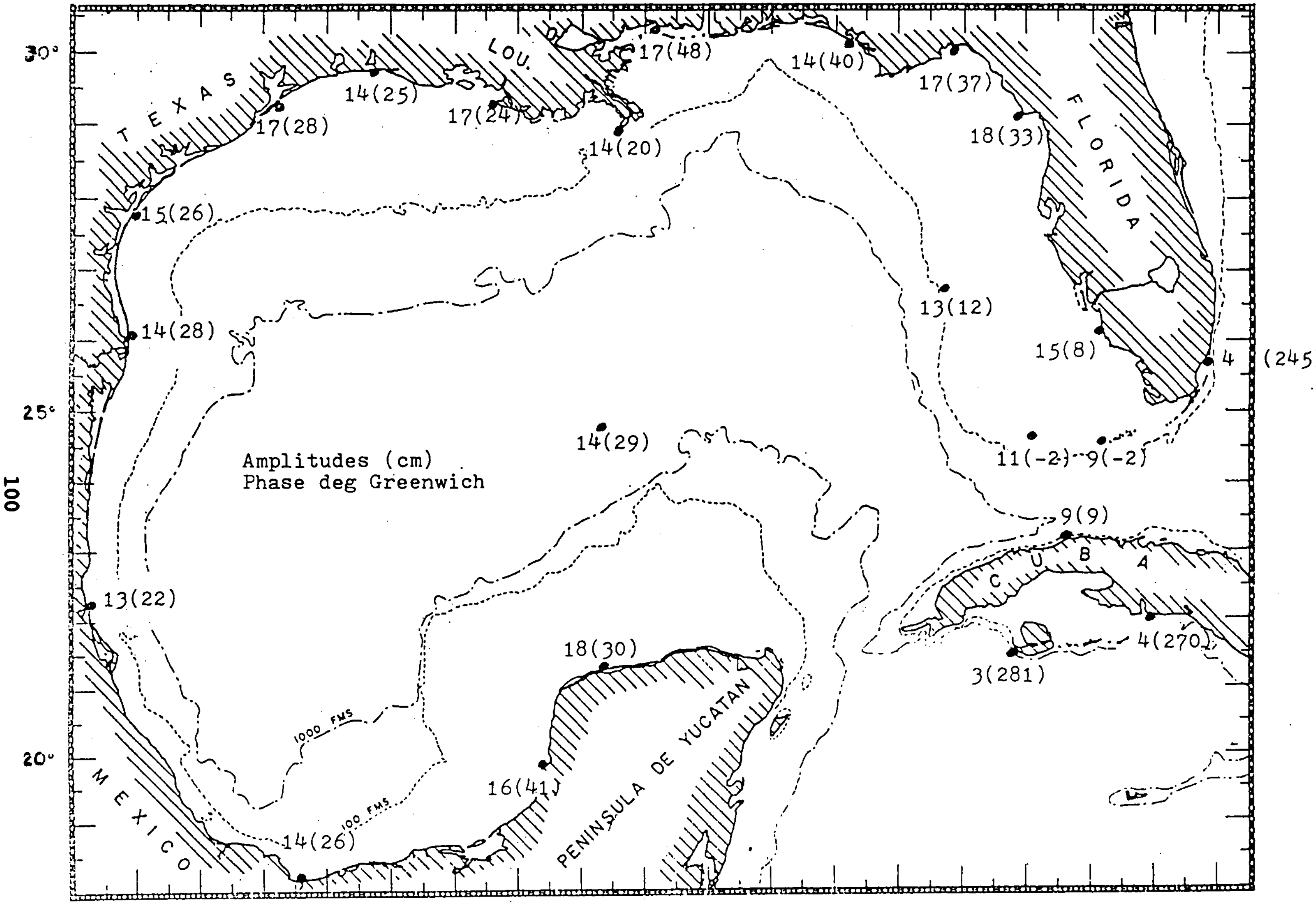

Figure 31. K1 tide.

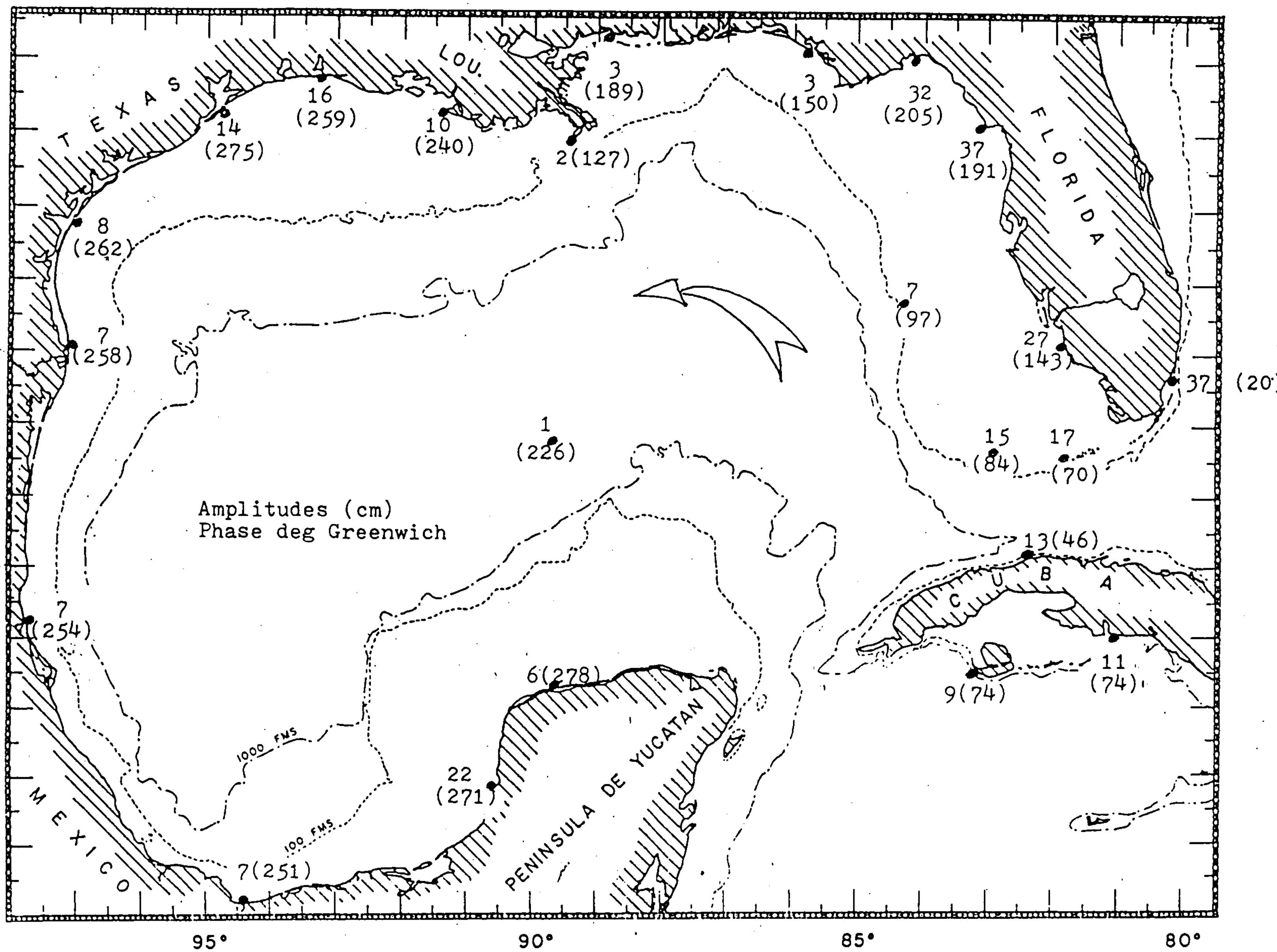

Figure 32. M2 tide.

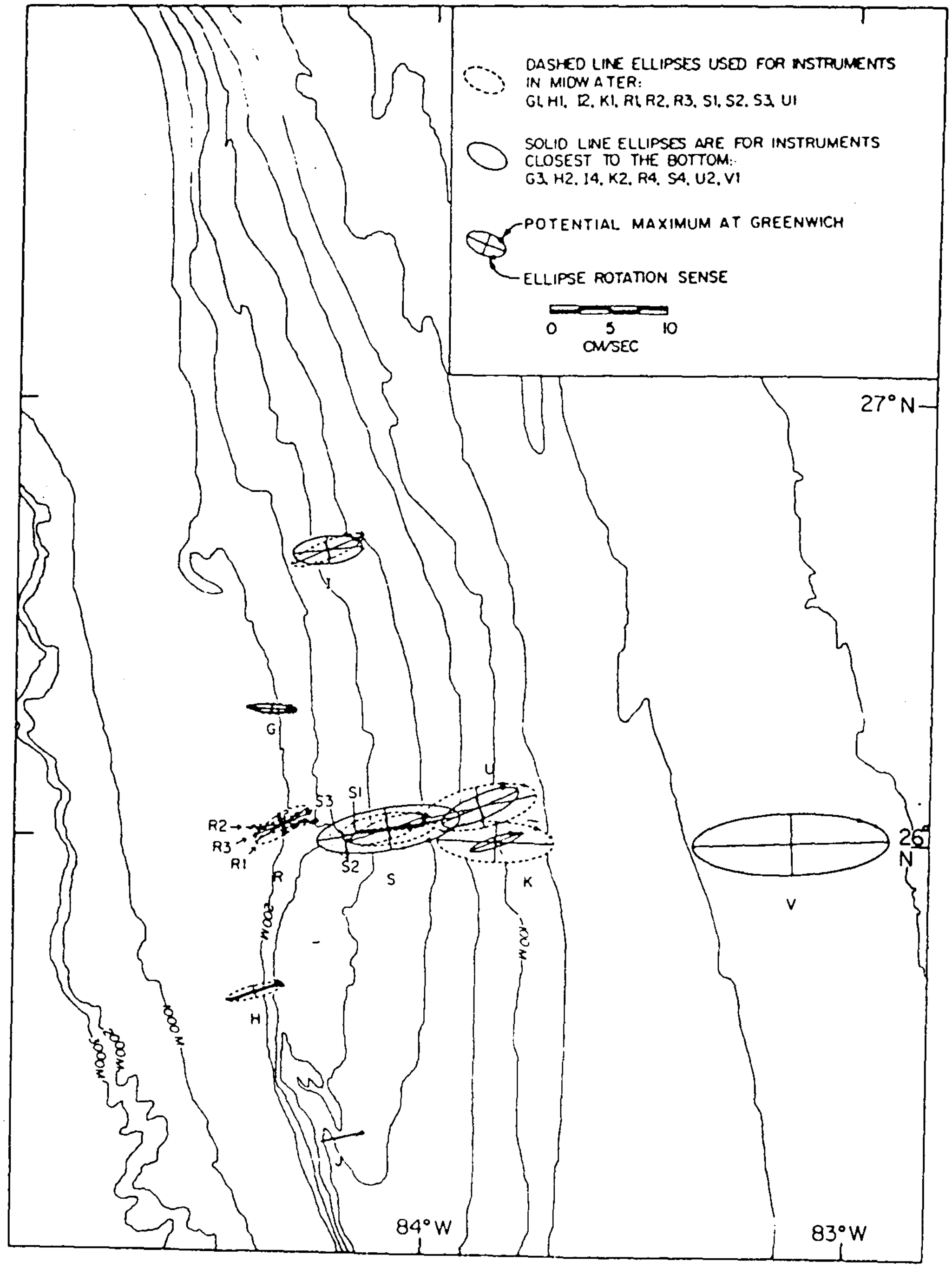

Figure 33. M2 tidal ellipses for west Florida shelf (from Koblinsky 1979).

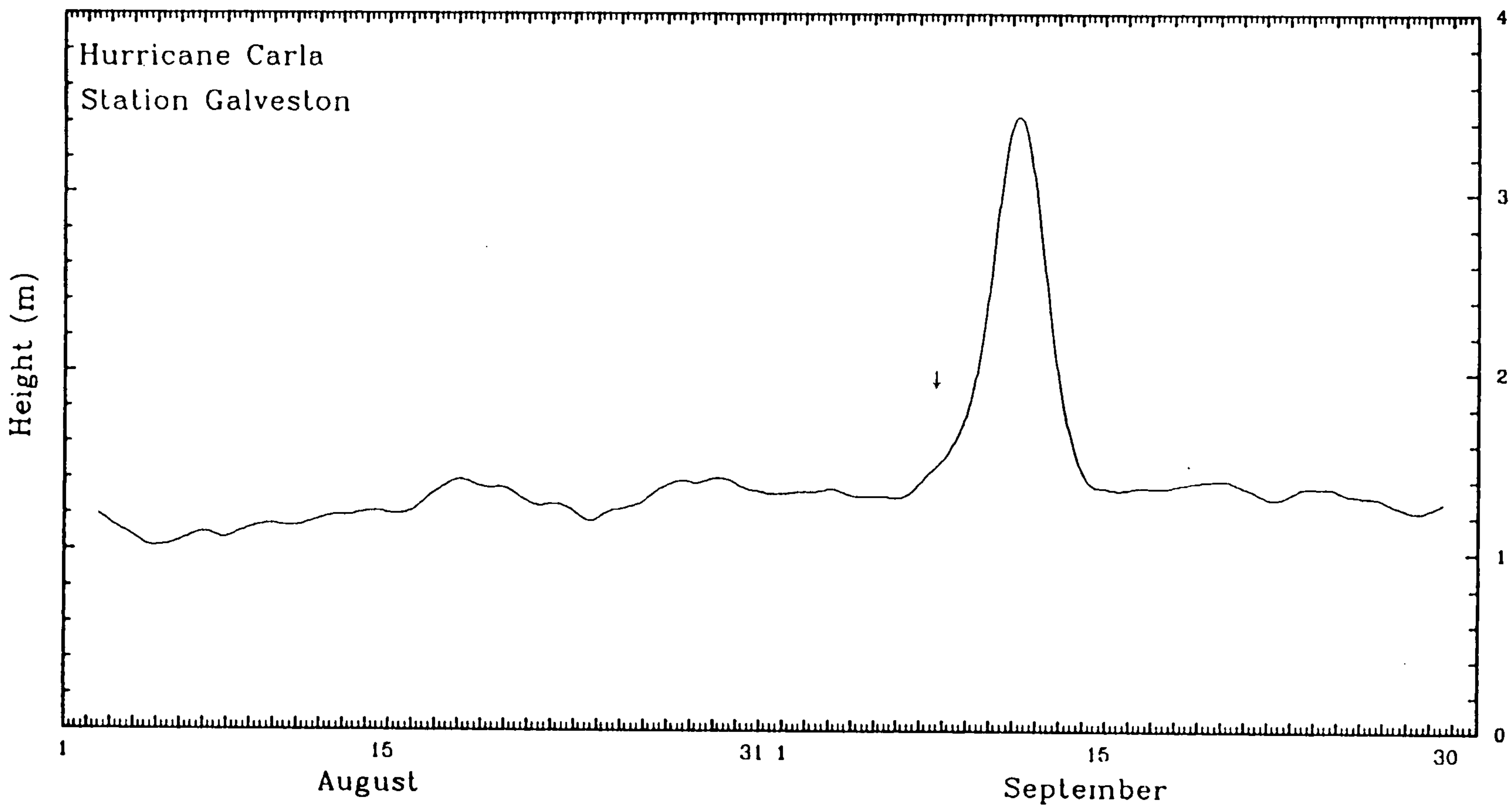

Figure 34. Observed water levels at Galveston during Hurricane Carla, 1961. The arrow indicates the time at which Carla entered the Gulf through Yucatan Strait. The datum is gauge mean low water. Record smoothed via 40-hour low pas filter.

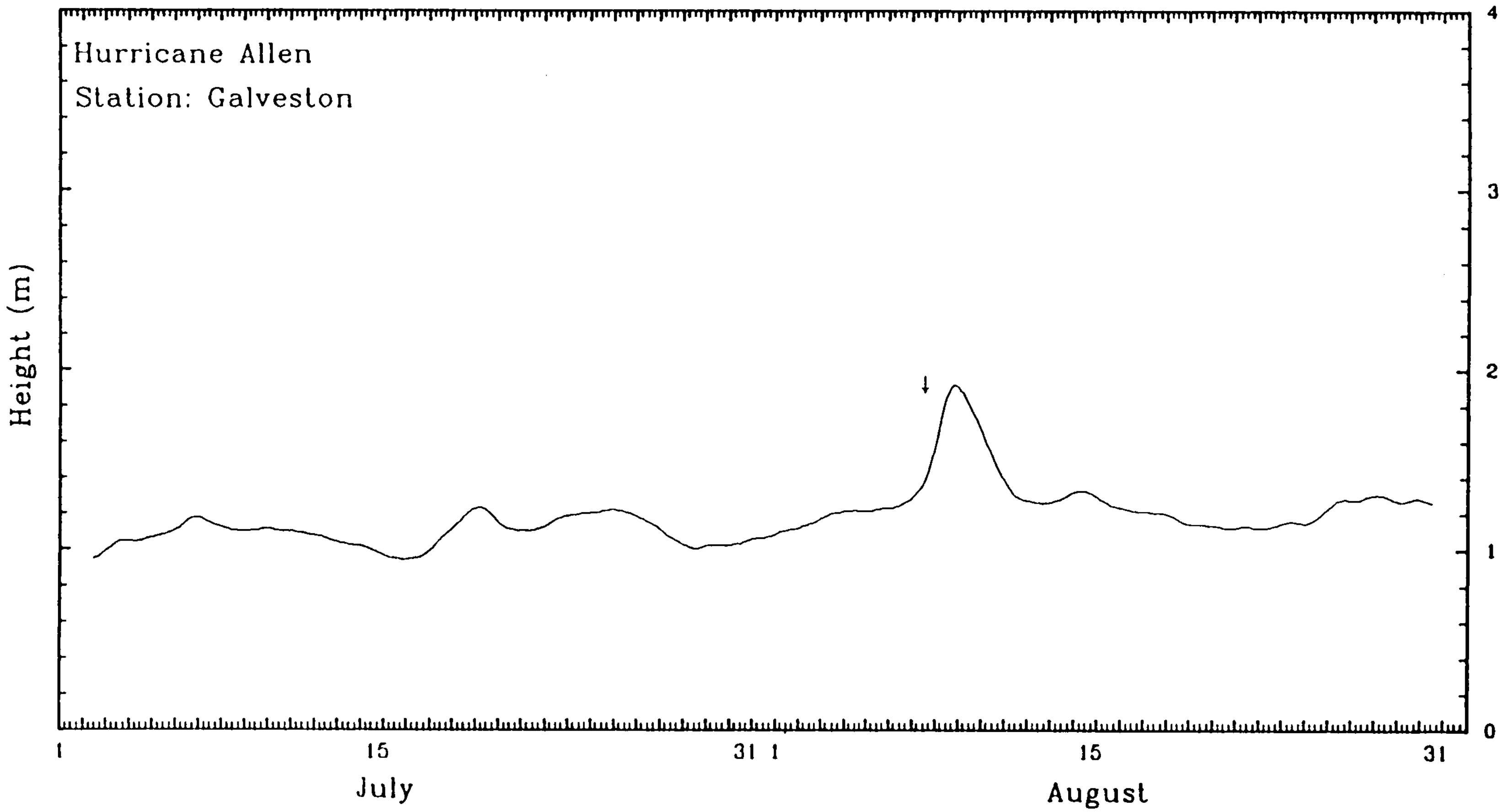

Figure 35. Observed water levels at Galveston during Hurricane Allen, 1980. The arrow indicates the time at which Allen entered the Gulf through Yucatan Strait. The datum is gauge mean low water. Record smoothed via 40-hour low pass filter.

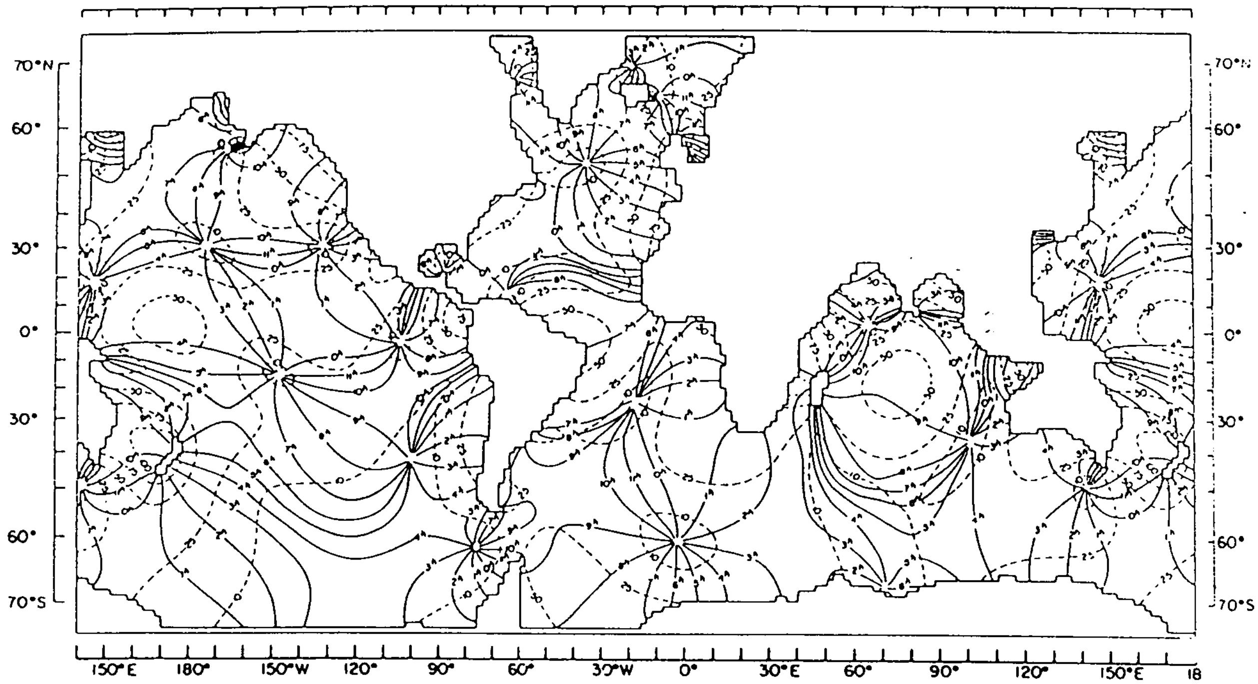

Figure 36. Calculated global M2 tide solely from tide-generating forces, including Earth tide, loading and self-attraction (from Accad and Pekeris 1978).

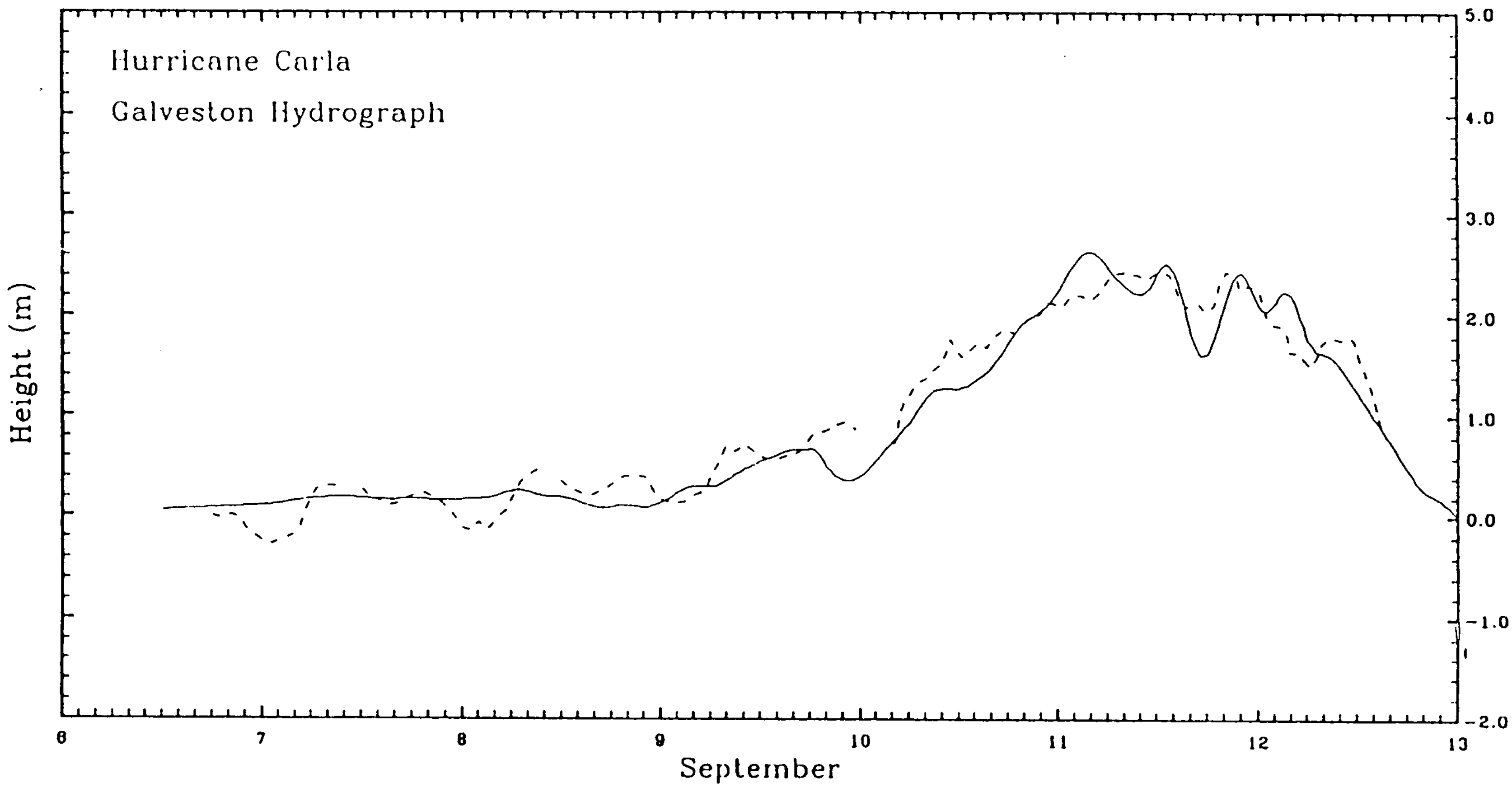

Figure 37. Computed (solid) and observed (dashed) hydrographs at Galveston during Hurricane Carla, 6-13 September 1961. The datum is mean sea level.

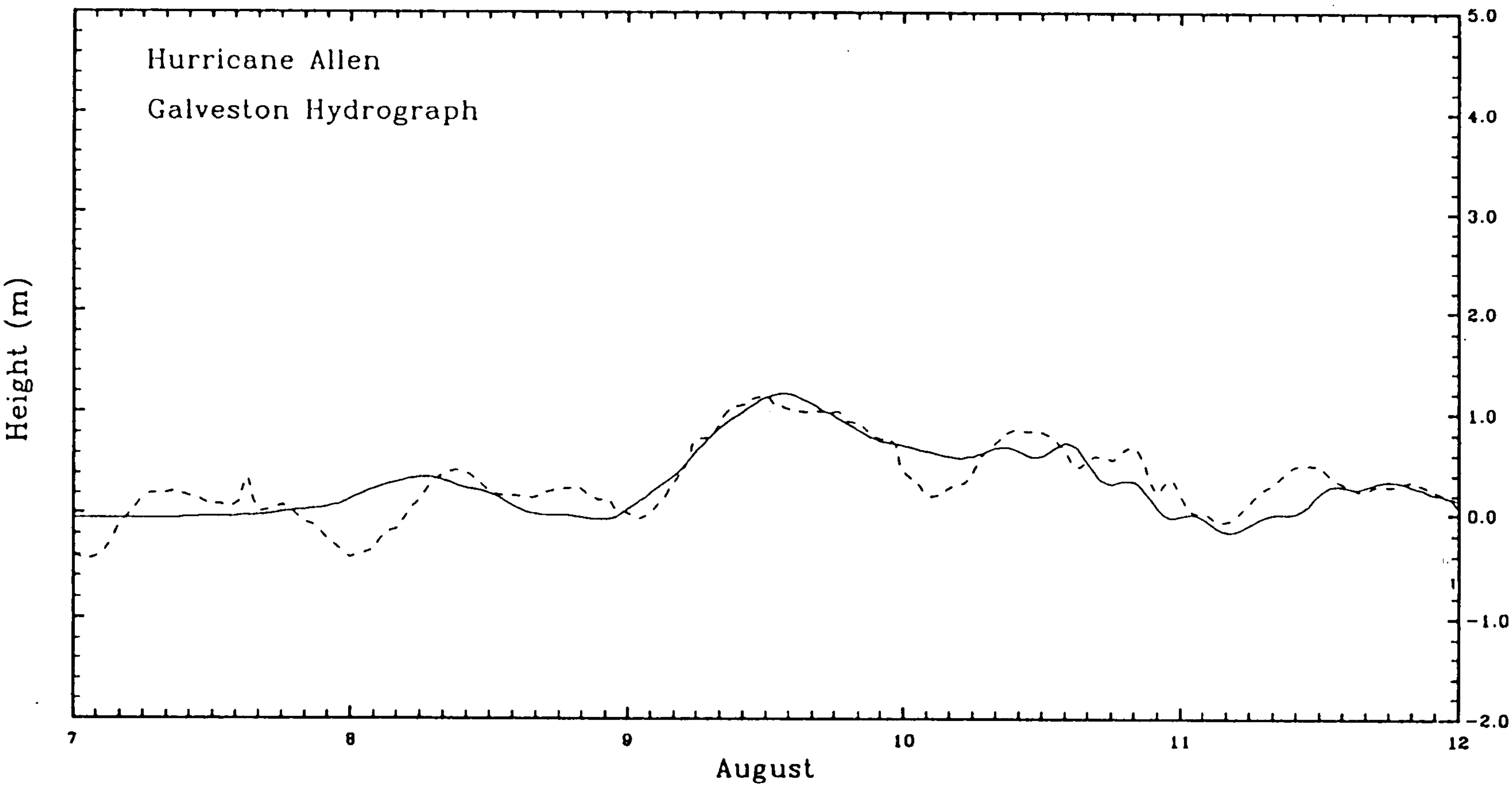

Figure 38. Computed (solid) and observed (dashed) hydrographs at Galveston during Hurricane Allen, 7-12 August 1980. The datum is mean sea level.

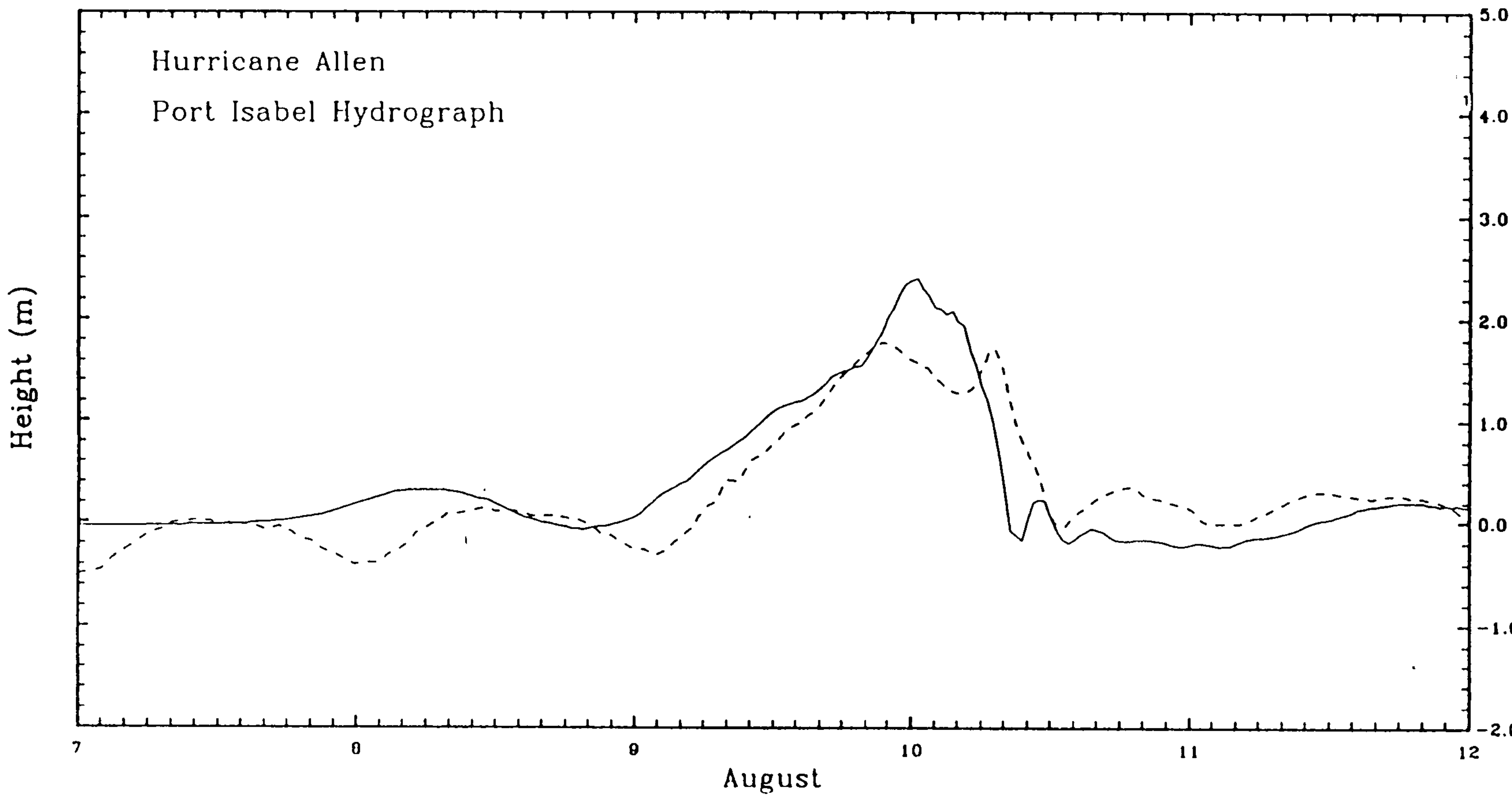

Figure 39. Computed (solid) and observed (dashed) hydrographs at Port Isabel during Hurricane Allen, 7-12 August 1980. The datum is mean sea level.

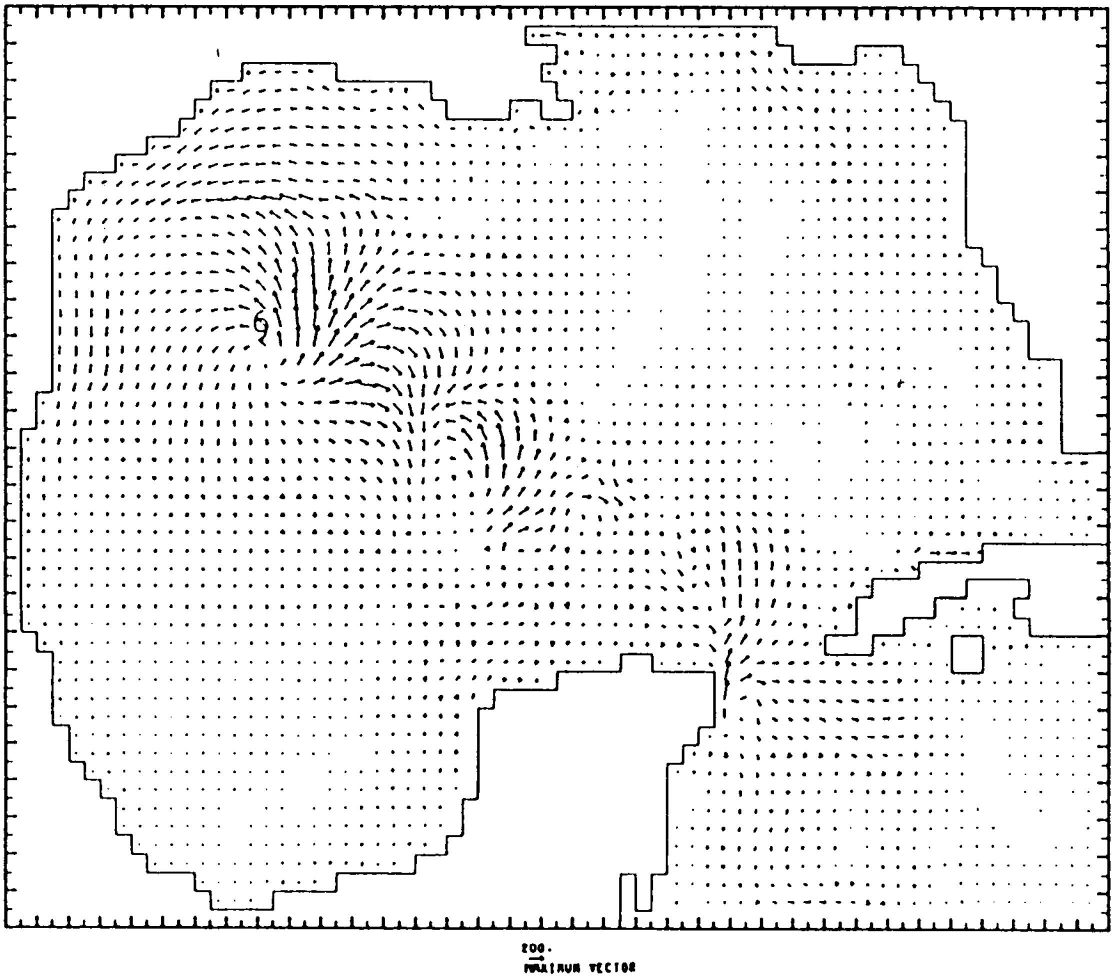

Figure 40. Computed surface current field (cm/s) for Hurricane Carla at 1200 GMT, 10 September 1961.

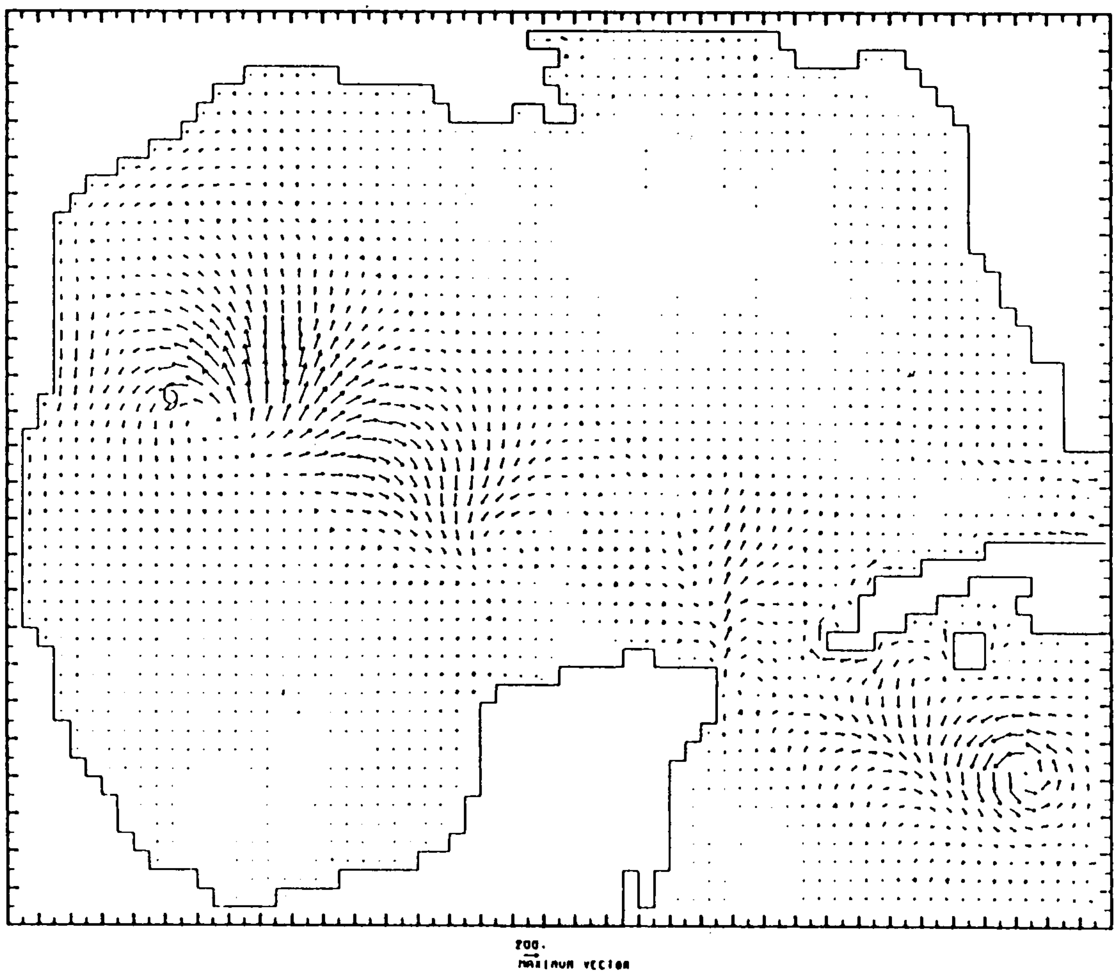

Figure 41. Computed surface current field for Hurricane Allen at 1200 GMT, 9 August 1980.

Table 4. Important natural periods for Gulf of Mexico (GOM) tides.

	Period (hrs)
Platzman 1972 model 60'x60' resolution	
(1) Volumetric Helmholtz mode	21.2
(2) Gravest rotational mode*	6.7
Reid/Whitaker 1981 model 15'x15' resolution	
(1) Volumetric Helmholtz mode	28.5
(2) Gravest rotational mode*	12.2

* Counterclockwise rotation of phase.

(1) Differences for this mode are due to different conditions employed at the straits.

(2) Differences for this mode are due to the very significant difference in resolution.

2.2.21 THE PRINCETON/DYNALYSIS OCEAN MODEL

Dr. George Mellor
Princeton University

This is a brief description of a numerical ocean model created by Alan Blumberg and me around 1977. Subsequent contributions were made by Leo Oey, Jim Herring, Lakshmi Kantha and Boris Galperin.

The principal attributes of the model are as follows:

- It contains an imbedded second moment turbulence closure sub-model to provide vertical mixing coefficients;
- It is a sigma coordinate model in that the vertical coordinate is scaled on the water column depth;
- The model has a free surface and a split time step. The external mode portion of the model is two-dimensional and uses a short time step based on the CFL condition and the external wave speed. The internal mode is three-dimensional and uses a long time step based on the CFL condition and the internal wave speed.

The turbulence closure sub-model is one that I introduced and then was significantly advanced in collaboration with Tetsuji Yamada. It is often cited in the literature as the Mellor-Yamada turbulence closure model (but, it should be noted that the model is based on turbulence modelling hypotheses by Rotta and Kolmogorov). The Level 2.5 model is used and includes prognostic equations for the turbulence energy and macroscale.

By and large, the turbulence model seems to do a fair job of simulating mixed layer dynamics although there have been indications that calculated mixed layer depths are a bit too shallow. This could be due to an inadequacy in the model or due to the fact that important processes are missing in the various simulations. For example, the turbulence model is often run in a one-dimensional mode which removes the influence of eddies and small or large scale Ekman pumping due to wind stress curl. Even in three-dimensional simulations, available wind forcing may be spatially smoothed and temporally smoothed. It is known that the latter process will reduce mixed layer thicknesses. Further study is required to quantify these effects.

The sigma coordinate system is probably a necessary attribute in dealing with significant topographical variability such as that encountered in estuaries or over continental shelf breaks and slopes. Together with the turbulence sub-model, the model produces realistic bottom boundary layers which are important in shallow water.

The free surface makes the model useful in estuaries and in coastal ocean studies where tidal effects are important.

Generally a standard rectangular grid is used but, as illustrated in Figure 42, an orthogonal curvilinear grid has been adapted to the western part of the North

Atlantic. This model is still under development. It presently has 12 vertical σ-levels and a 45 x 121 horizontal grid. The average grid size is about 20 km. Figure 43 shows the stream function and surface elevation from one of our exploratory runs.

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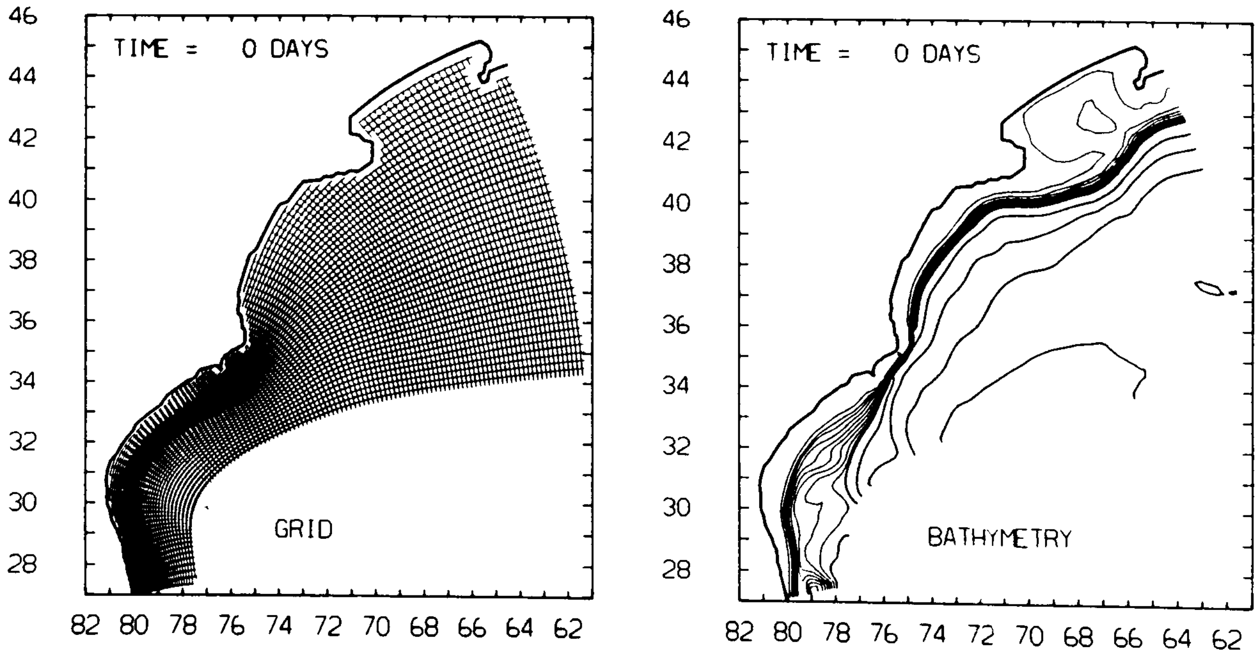

Figure 42. **An orthogonal, curvilinear grid applied to the western part of the North Atlantic. The left panel is the grid whereas the right panel is the bathemetry (light lines are 100 m isobaths, boundary lines are 1000 m isobaths).**

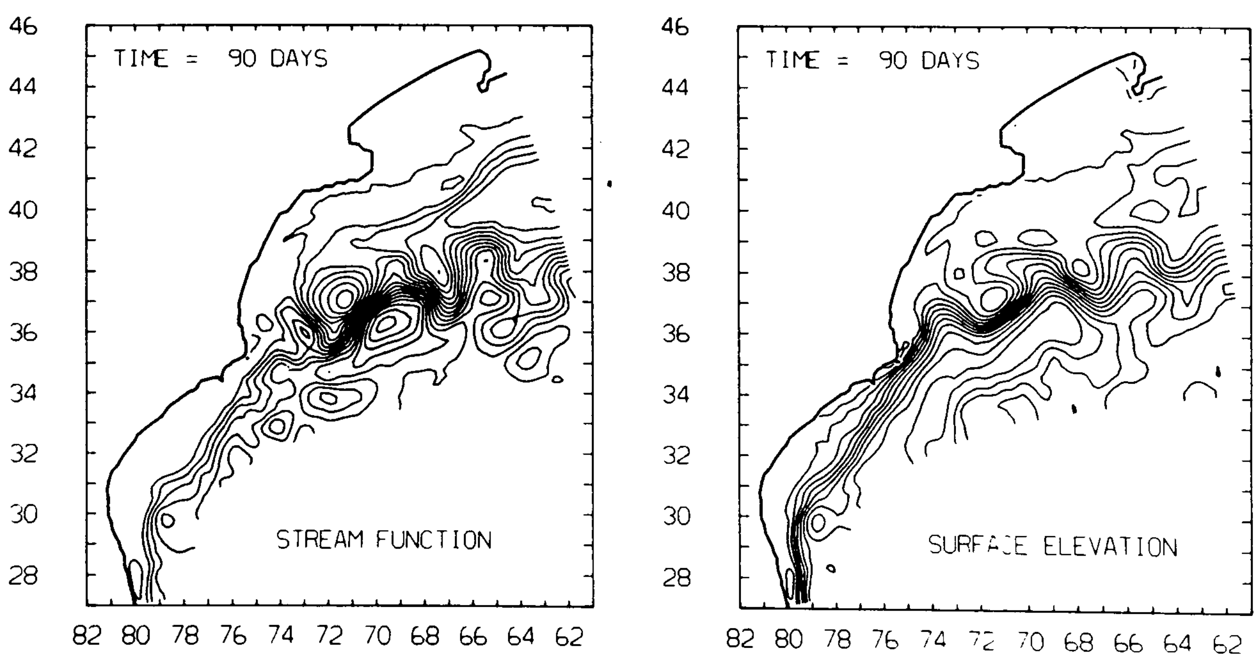

Figure 43. **A result from an exploratory run of the model, 90 days after initialization with temperature and salinity climatologies.**

2.2.22 GULF OF MEXICO CIRCULATION MODELING STUDY

Dr. Alan J. Wallcraft
JAYCOR

Introduction

The Gulf of Mexico Circulation Modeling Study was started by MMS in October 1983 as an "extremely modest effort building on existing/ongoing modeling efforts in the Gulf of Mexico." The initial requirement was for an existing circulation model with capabilities approaching those required and the ability to deliver an "early simulation run." At the end of the four year program the requirement was for a circulation model of the entire Gulf with horizontal resolution approaching 10 km, and vertical resolution (initially less important) approaching:

- o mixed layer: 1 - 10 m;
- o thermocline: 10 m;
- o deep layer: 100 m.

with realistic bottom topography, coastline, and wind forcing, which must exhibit Loop Current eddy shedding, and other known regional circulation features.

The Existing NORDA/JAYCOR Model (October 1983)

This was a two layer, nonlinear, hydrodynamic, free surface, semi-implicit, primitive equation ocean circulation model on a beta plane, with realistic coastline, and full scale bottom topography confined to the lower layer. The horizontal grid resolution was 0.2° (20 by 22 km), with an upper layer rest depth of 200 m. The model can be driven by inflow through the Yucatan Strait compensated by outflow through the Florida Strait, and/or by winds.

Problems with the Existing (1983) Model

- o Only 0.2° horizontal grid resolution - need 0.1°;
- o Model is hydrodynamic - thermohaline circulation particularly important during fall and winter, and over shelf areas;
- o Crude representation of the vertical density profile - need mixed-layer physics;
- o Model has full scale bottom topography (which is essential for a good simulation), but the layer interface(s) must not intersect the bottom. Shallowest topography in model is at 500 m.

Model Development Plan

Year 1

Use existing 2-layer 0.2° Gulf of Mexico model. Find "best" representation of coastline and bottom topography. Initially use seasonal wind forcing and constant inflow, later simulations will use winds based on 12 hourly Fleet Numerical Oceanographic Center (FNOC) surface pressure analysis and time varying inflow.

Year 2

Use 2-layer model, but on a 0.1° grid, and with lower eddy viscosity. Expect richer flow field, including wind induced flow instabilities. Some experiments will use 1-layer (reduced gravity) model, but all delivered simulations will have 2-layers.

Year 3

Develop 3-layer model with bulk thermodynamics. Densities in the upper two layers will be allowed to change locally with time, under control of the equation of state and temperature equation added to model. Initially 0.2° simulations, later 0.1° grid will be used.

Expect to see thermohaline circulation and improved representation of permanent thermocline. Three layers also better resolve "hydrodynamic" circulation, and thinner upper layer increases accuracy of surface velocities.

Year 4

Complete 0.1° 3-layer simulations. Then couple circulation model results to a mixed layer model (TOPS). TOPS is the Navy's operational mixed layer forecast model. Simplest version of TOPS is one dimensional, with 15+ fixed vertical levels covering upper 500 m. It can accept geostrophic currents from any suitable source. The 3-layer model is suitable but the 2-layer (hydrodynamic) is not.

This final coupled model will give detailed vertical density profiles, and greatly improve the simulation accuracy in shelf regions.

Progress

Years 1 and 2

All tasks in years one and two are complete and final reports have been accepted by MMS (Wallcraft 1985, 1986). It was clear by the end of the second year that the model simulated deep water features, such as the Loop Current and its associated eddies, remarkably well, but it had problems simulating flow in continental shelf regions.

Year 3

The lack of realism over the continental shelf is to be expected since the bottom topography is confined to the lowest layer, i.e. in the model the shallowest topography is 500 m deep. This model deficiency, and its probable consequences, were clearly stated from the beginning of the project. However it was also apparent that it was not possible to simulate most shelf regions in the Gulf without also simulating the very strong near shelf currents associated with the Loop Current. Five years ago, the only known models that might be capable of simulating both deep and shallow circulation were those with many levels in the vertical. However such models are on the order of 100 times more expensive to run than layer models, and were therefore excluded on the basis of cost. Since that time there has been some success with isopycnic ocean models that effectively allow layers to intersect the bottom topography (Bleck et al. 1983). An additional task was therefore added in the third contract year to attempt to develop a version of the layered ocean model that will allow layer interfaces to effectively intersect the bottom topography. This would allow the minimum bottom depth to be raised from 500 m to about 20 m. Layer intersection is not generally found in layered ocean models, and so its successful implementation was less certain than other phases of the program.

Two dimensional (x-z) versions of a two layer hydrodynamic model that allow layers to intersect the bottom were demonstrated on sections across the Gulf of Mexico on a 0.2° grid, but the extension of this model to three dimensions was not completed within the funding and time limits allowed.

Year 4

In light of the situation at the end of year 3, the work on developing a model that allows layer interfaces to intersect the bottom was abandoned. Instead the modified year 4 tasks concentrate on obtaining the best possible currents over the shelf regions within the framework of the existing layered models, and then interfacing with TOPS.

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2.2.23 WAVE INFORMATION STUDY

Dr. Jon M. Hubertz
U.S. Army Corps of Engineers
Coastal Engineering Research Center

The Wave Information Study (WIS) was authorized in 1976 by the Office of the Chief of Engineers, U.S. Army Corps of Engineers. It was initiated to address the need for wave information along the coastlines of the United States. At that time, sufficient statistics on wave parameters were not available for use in designing engineering projects along the coastlines. It was not uncommon for estimates of design wave parameters to differ by 100 per cent. Since the design of a project at the coast is almost always dependent on a knowledge of wave conditions, an overly conservative estimate of design wave height, for example, could translate into millions of dollars for an over designed structure. The task of the study was to produce an accurate wave climatology along U.S. coasts.

Wave gaging along the coasts was not considered economical to accomplish the task and such measurements would need to be made for years before statistical estimates of wave parameters could be of use. Numerical simulation was chosen as the approach to produce a wave climatology. Computer models were capable of generating and propagating ocean surface waves given a time history of wind velocities on a numerical grid. Wave model results compared satisfactorily with available measurements showing the approach was feasible.

Historical meteorological data were needed to reproduce wave conditions in the past, for example the previous twenty year period 1956-1975. Use of past meteorological data to produce wave conditions is termed a wave hindcast as opposed to a forecast which estimates future conditions from predicted meteorology. Gathering past meteorological data and synthesizing it to produce a time series of past wind fields, for example over the Gulf of Mexico, is the major task in producing a wave hindcast.

For the Gulf of Mexico, wind fields were deduced from the distribution of surface atmospheric pressures. Particular attention was paid to situations with closed isobars. Hurricanes were not included in the general climatology, but were hindcast in a separate study. A geostrophic wind field was estimated first from the pressure fields and modified when necessary by gradient, isallobaric and thermal wind components. Next these winds were transformed to surface winds using a planetary boundary layer model. Finally, surface observations of wind speed from ships were blended in to produce a surface wind field every three hours for twenty years for input to the wave model. More details on the objective specification of surface wind from historical data is given by Resio et al. (1982).

The wave model used in the Gulf of Mexico hindcast is a shallow water discrete directional spectral model. It is described in more detail by Hughes and Jensen (1986) and Jensen, Vincent and Able (1987), with the theoretical foundation given by Resio (1987). It is an arbitrary depth model which includes refraction, shoaling, wave-wave interactions and surf zone breaking. The model reflects the latest thinking on the role of wave energy transfer through the spectrum and equilibrium shape of the spectrum in different water depths. Verification of the model is presented by Jensen et al. (1987) and Resio (1988).

A twenty year (1956-75) wind and wave hindcast has been completed for the Atlantic, Pacific and Gulf of Mexico coastlines. Locations in the Gulf of Mexico where wave information is available are shown in Figure 44. A thirty year hindcast (1956-1985) is presently under way for the Great Lakes. Numerous reports (a list of which is available from the author) document the methodology and results of these studies. A time series of wave parameters at all coastal sites is stored on a data base along with precalculated statistical summaries. Access to the data base is restricted to Corps of Engineer personnel, however requests by others for information from the data base will be honored for the costs incurred in retrieving and storing the information on the desired media. Some of the data are available from the National Climatic Data Center and reports are available from the National Technical Information Service. Some examples of the data summaries available at each location are: percent occurrence tables for wave height and period by direction and for all directions, wind and wave roses, mean and maximum wave height by month and year, 20 year statistics such as mean wave height and period, maximum height and associated period, direction, date, and most frequent direction.

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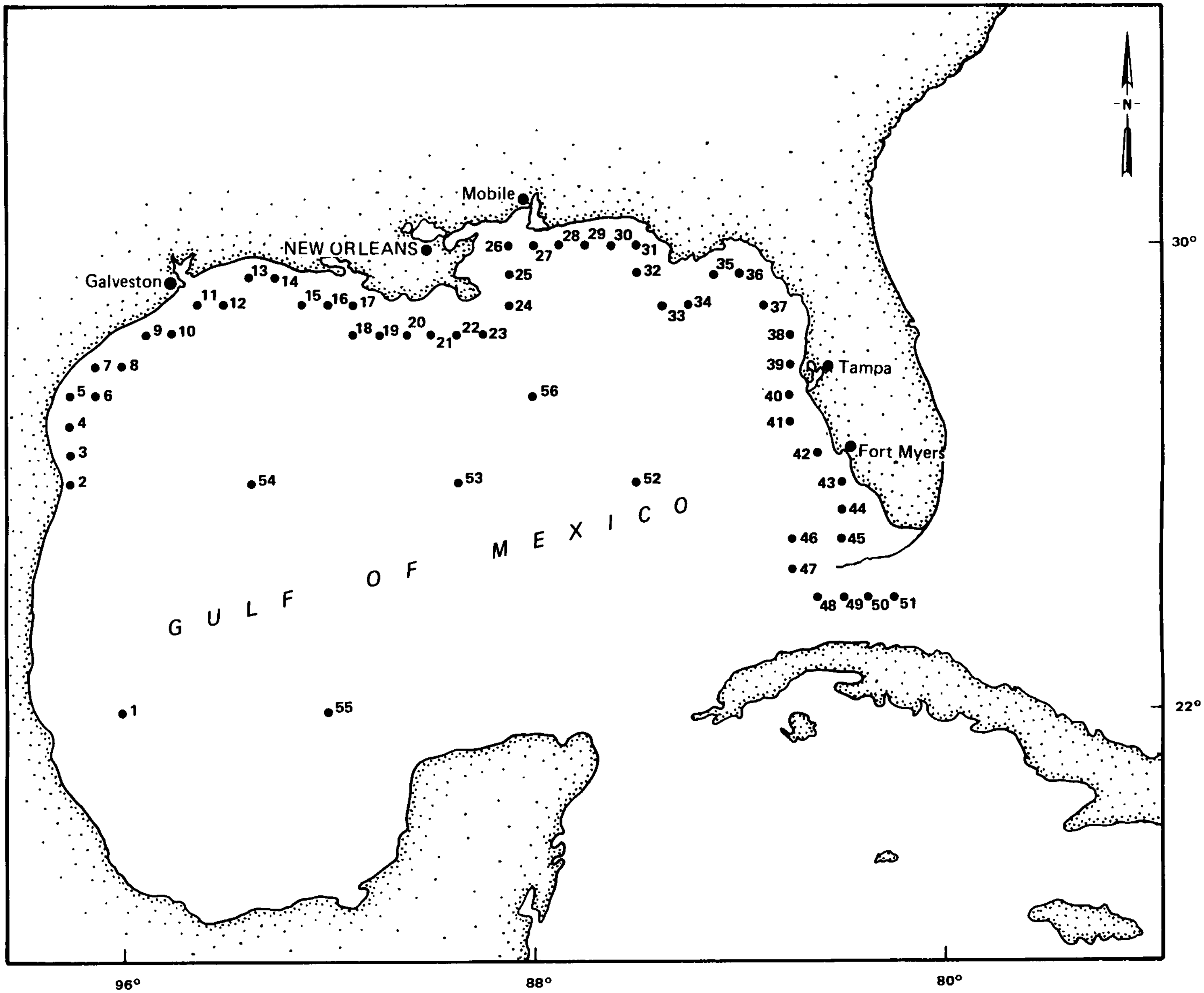

Figure 44. Gulf of Mexico locations for which WIS wave data have been archived for 1956 through 1975.

2.2.24 SHELF CIRCULATION MODELING

Dr. Donald T. Resio
Offshore and Coastal Technologies, Inc.

In recent years much research has been focused on developing accurate numerical models for the prediction of 3-D current structure and storm response. There are three primary aspects involved in the practical application of such models:

1. Understanding of forcing mechanisms and hydrodynamics;

2. Accurate, efficient modeling techniques; and

3. Appropriate information synthesis techniques.

Via recent experiments and theoretical analyses we have begun to get a very good concept of aspect 1. Since there are many competitive modeling groups actively working on improved modeling techniques, important recent advances relative to aspect 2 have been made; however, computer requirements and stability problems with some 3-D models can be significant. Unfortunately, even though there has been considerable work on synthesizing measured data and incorporating these data into data bases, aspect 3 is usually only a small part of a numerical study.

At Offshore and Coastal Technologies, Inc. (OCTI) we have concentrated on aspects 2 and 3 in application-oriented studies. Using a $K-\varepsilon$ turbulence closure model coupled with a depth-integrated model we have been able to achieve results which agree well with observed currents at sites in approximately 20 meters depth located about 5-10 miles off of Pensacola, Florida. Using a direct mapping of steady-state winds to currents we obtained estimated current roses for these sites at multiple levels. As a simple approach to estimating the magnitude of currents under extreme forcing, we modeled via the same technique two hurricanes which affected these sites.

During recent studies, it became apparent that bottom friction is a critical factor in determining the current magnitudes, directions, and profile. Three studies (Scott and Csanady 1976; Forristall et al. 1977; Smith 1978) have recently indicated that anomalous values of bottom stress appear to exist during storms in coastal areas (i.e., the bottom stress is much larger than the surface wind stress). As part of a research effort at the Bedford Institute of Oceanography, we have been examining wave-current interactions. One part of this study has produced preliminary results which suggest that waves actually decrease the effective drag although they increase the apparent roughness, z_o. If this is indeed the case, it would help explain certain problems in adopting such bottom drags into numerical models.

As a final part of our ongoing effect, OCTI has been involved in the development of statistical techniques for the synthesis of data in spatial fields (2-D and 3-D). Results in these developments show that such techniques offer good alternatives to the use of conventional site-by-site analyses or linear multivariate techniques.

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2.2.25 OBSERVATIONS OF MESOSCALE CYCLONIC CIRCULATION FEATURES IN THE NORTHWEST GULF OF MEXICO

Dr. Douglas C. Biggs
Texas A&M University
Department of Oceanography

In April and November 1987, training and research cruises aboard Texas A&M University's R/V GYRE carried out hydrographic survey work in the NW Gulf of Mexico between 28° N and 26° N. On cruises 87G-04 (11-17 April) and 87G-11 (17-24 November), we alternated CTD and XBT stations every 20 n miles along 93° 15' W, 94° 00' W, 94° 45' W, 95° 30' W, and 96° 15' W. In both spring and fall, we observed a cyclone some 100-200 km in diameter over the continental slope, which was centered between 26° N and 27° N. Data collected by our Technical Support Services Group offer a detailed look at the vertical T/S and nutrient chemistry signatures of these features, which for example shows these cyclonic circulations had nitrate in excess of 10 ug-at/liter at 100 m. Because such high nitrate concentrations just underlying the mixed layer should support high levels of planktonic "new" production, there is interest in characterizing planktonic standing stocks, production, and biogeochemical fluxes out of surface waters within these features.

A 10-day A&M Training & Research cruise will return to this region of the NW Gulf in November 1988 for further study of cyclonic circulation features, and additional cruises are projected for 1989. The 1987 hydrographic data have been archived in a 360 page Technical Report (88-01-T) which is available for the cost of xeroxing plus postage from the Department of Oceanography, TAMU (ATT: D. Biggs).

2.3 Invited Government/Industry Presentations

2.3.1 SEA-WIFS AND OTHER NASA REMOTE SENSING CAPABILITIES

Dr. James A. Yoder
NASA Headquarters
Oceanic Processes Branch

NASA is planning 3 major oceanographic satellite missions for the early 1990s. TOPEX is a high-precision radar altimeter planned for launch in 1992. NSCAT is a scatterometer to measure sea surface wind stress. NSCAT was designed for the Navy's NROSS satellite, now cancelled, but may fly on the Japanese ADEOS satellite planned for late 1993. To replace the Coastal Zone Color Scanner (CZCS), NASA and the Earth Observation Satellite Company (EOSAT) are planning a new satellite ocean color instrument (Sea Wide Field Sensor or Sea-WiFS) to be launched on the Landsat-6 satellite in 1991.

Sea-WiFS will have the same 5 visible/near-infrared channels as CZCS, as well as an additional channel centered at 860 nm. Data from the extra channel will be used to increase the accuracy of atmospheric correction in comparison to what is possible with CZCS. Because of the extra channel and other improvements, Sea-WiFS will yield better results than CZCS for both coastal and oceanic waters. Sea-WiFS will also have 3 thermal infrared channels for determining sea surface temperature.

Sea-WiFS will record 40 minutes of data per orbit, which is essentially all the daytime data. Of the 40 minutes of data per orbit, 10 will be recorded at full resolution (1 km^2) and the remainder will be recorded at reduced resolution (ca. 16 km^2). A fixed location on the sea surface will be covered every 1-2 days. In addition to the tape-recorded data, full resolution data will be continuously broadcast using the High Resolution Picture Transmission (HRPT) format. The latter data stream is primarily designed for commercial and operational users who must license a de-coder to be able to interpret the HRPT downlink. Research users will have access to the global data (from the tape recorders) through the NASA Sea-WIFS project to be located at Goddard. The project is planning to process and distribute Sea-WIFS data within days-weeks from the time the data are collected. An Announcement of Opportunity to fund Sea-WIFS research projects is expected from NASA prior to launch.

2.3.2 SOME OCEANOGRAPHIC RESULTS IN THE GULF OF MEXICO

Captain Alberto M. Vazquez
Secretaria de Marina, Mexico

The Gulf of Mexico is a reservoir of water cooler than the Caribbean Sea and Equatorial Atlantic Ocean at the end of winter; the subsequent increase of its temperature is in great part due to anticyclonic eddies.

Introduction

The international cooperation in meteorology and oceanography in 1979, denominated FGGE (First Global GARP Experiment), was divided into two Special Observation Periods (SOP I and SOP II). Mexican Oceanographic Ship H-02 (DM-20) from Secretaria de Marina obtained and contributed observations in the Atlantic Equatorial Ocean offshore of Brazil in both periods.

Transect from Brazil to Mexico

Seventeen stations and 34 XBTs were done on the transect between Brazil and Mexico by the Oceanographic Ship H-02 during March 1979 (Figure 45). The cruise track ran approximately 200 nm offshore of South America, and then passed through the middle of the Caribbean Sea and finally the middle of the Gulf of Mexico.

The transect was divided into three parts, corresponding to the Atlantic Equatorial Ocean, Caribbean Sea, and the Gulf of Mexico, respectively. The temperature structure between the sea surface and 400 m depth is shown in Figure 46. The undulating line represents the boundary of the mixed layer and the thermocline with an average depth of 100 m. In the Atlantic Ocean and Caribbean Sea its temperature value was above 26°C, while in the Loop Current region of the Gulf of Mexico isotherms of 24°C and 26°C reached the sea surface. The boundary between the mixed layer and the thermocline in the Gulf of Mexico was 23.2°C.

The Equatorial Current, reaching more than 400 m depth, between stations 103 and 104, seems to be part of the anticyclonic eddy of the Amazon (Cochrane *et al*. 1979). East of the Lesser Antilles, between stations 106 and 107, the Equatorial Current had northward direction. Structure east of the Caribbean Sea reflects light currents to station 111 near Jamaica which shows the entrance of water from the Windward Passage. The anticyclonic eddy south of Cuba (Molinari 1976) is noted between stations 112 and 113.

The strong structure of station 114 to 115 indicates that the Loop Current was at its maximum extension into the Gulf of Mexico, which corresponds with the great upwelling off the continental shelf of Yucatan, a configuration for the summer and winter suggested by VNIRO (1967).

The surface boundary layer of the Gulf of Mexico was 4°C cooler than in the Equatorial Atlantic Ocean and the Caribbean Sea. Near the middle of the Mexican Anticyclonic Eddy (Vazquez 1975) the 20° isotherm reached depths usually found for this isotherm in the Caribbean Sea. The Mexican Anticyclonic Eddy showed a deeper and wider structure than that found in 1971 (Vazquez 1975).

Cooperation between U.S.A. and Mexico

In April 1978, separate cruises were taken in the western Gulf of Mexico, by the R/V Gyre from Texas A&M University and the R/V H-02 from the Mexican Navy. In a period of less than 30 days, the movement and displacement of cyclonic and anticyclonic eddies were observed. An intensive eastward moving jet with a transport of more than 29×10^6 m^3 and a speed near 2 knots was reported between them (Merrell and Morrison 1981; Merrell and Vazquez 1983).

From the beginning of 1985 to late 1986, Kelly, Vazquez and Brooks (1987), studied the circulation pattern and displacement of an anticyclonic eddy over the western Gulf of Mexico, its subsequent deformation and the creation of new cyclonic eddies.

This kind of collaboration can lead to a better understanding of oceanic phenomena in regions of joint interest. Recent efforts are utilizing personnel and ships from different disciplines of oceanography from both countries to understand variations and consequences of eddies over the western Gulf of Mexico.

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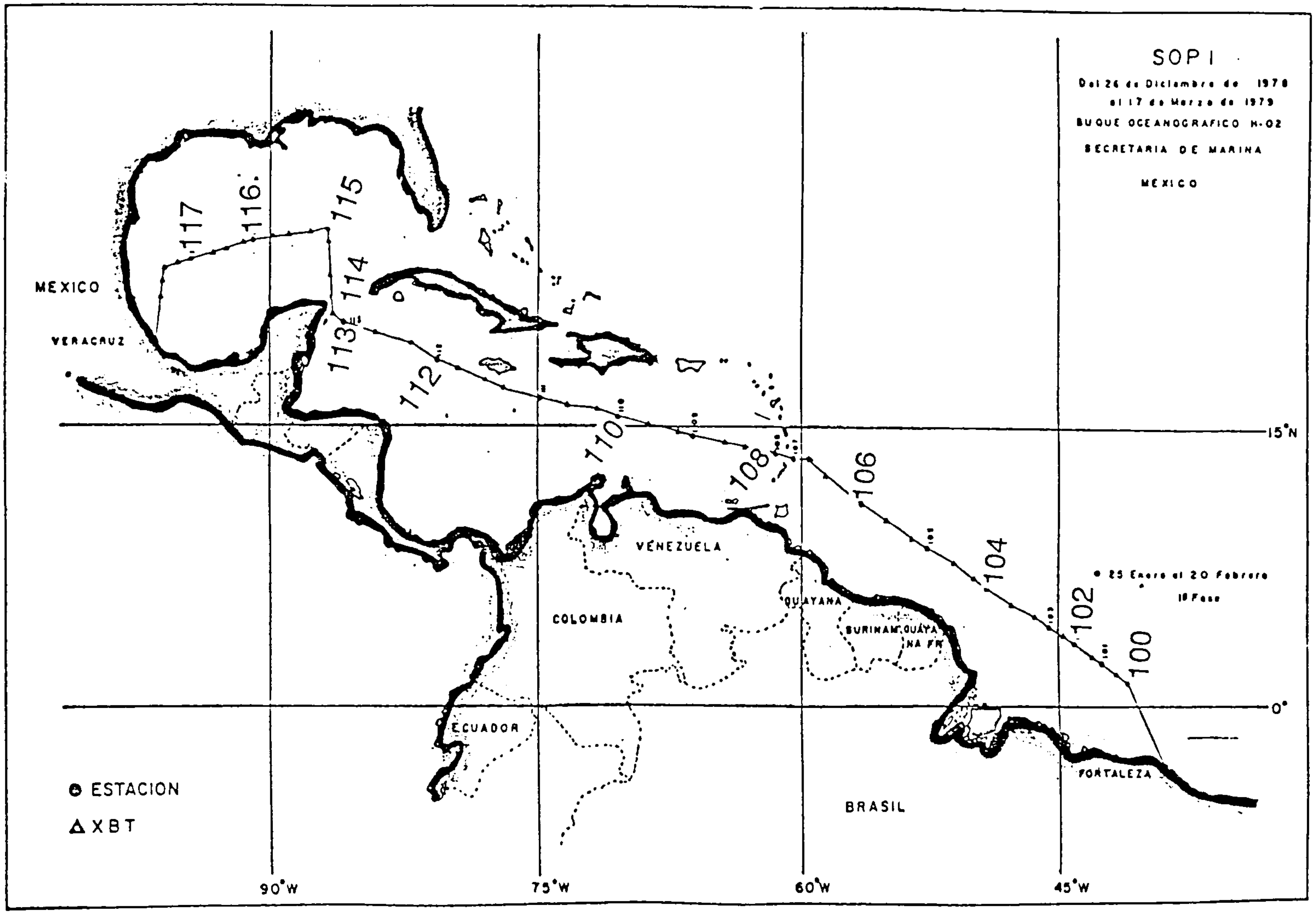

Figure 45. Dead reckoning in SOP I, March 1979.

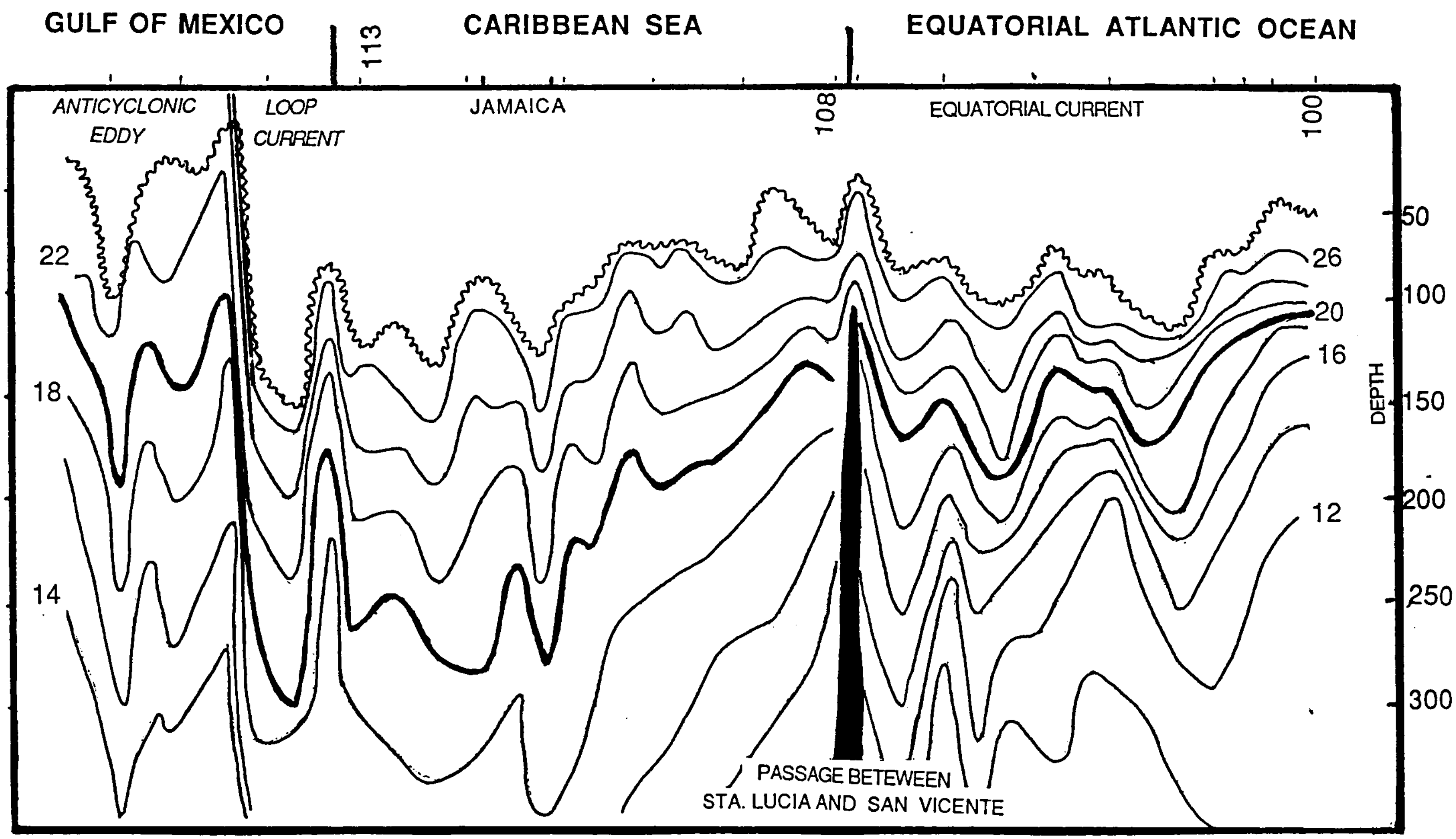

Figure 46. **Thermal structure in the transect between Brazil and Mexico SOP I, March 1979.**

2.3.3 THE SOUTHEAST AREA MONITORING AND ASSESSMENT PROGRAM

Mr. Tom Van Devender
Gulf States Marine Fisheries Commission

The Southeast Area Monitoring and Assessment Program (SEAMAP) is a state/federal/university program for the collection, management and dissemination of fishery-independent data (information collected without direct reliance on statistics reported by commercial or recreational fishermen) in southeastern United States waters. The program presently consists of two operational components, SEAMAP-Gulf of Mexico, which began in 1981, and SEAMAP-South Atlantic, implemented in 1983. A third component, SEAMAP-Caribbean, is in the planning phase. A major SEAMAP objective is to provide the large, standardized data base needed by management agencies, industry and scientists to wisely manage and develop fishery resources for the least possible cost.

The SEAMAP-Gulf Program began in March 1981 when the National Marine Fisheries Service (NMFS), Southeast Fisheries Center (SEFC), presented a SEAMAP Strategic Plan (January 1981) to the Gulf States Marine Fisheries Commission (GSMFC). This strategic plan outlined the proposed program organization (goals, objectives, procedures, resource requirements, etc.); within the existing framework of the GSMFC, a SEAMAP Subcommittee was then formed. The Subcommittee consists of one representative from each state fishery management agency [Florida Department of Natural Resources (FDNR); Alabama Department of Conservation and Natural Resources (ADCNR); Mississippi Department of Wildlife Conservation (MDWC), represented by the Gulf Coast Research Laboratory (GCRL); Louisiana Department of Wildlife and Fisheries (LDWF) and Texas Parks and Wildlife Department (TPWD)], one from NMFS Southeast Fisheries Center and a non-voting member representing the Gulf of Mexico Fishery Management Council. The Subcommittee organized and successfully coordinated three assessment activities in 1982: an April-May plankton survey, a June-July shrimp and bottomfish survey, and environmental sampling, in conjunction with the two surveys; four assessment activities in 1983: an April-May plankton survey, a June-July shrimp and bottomfish survey, a December plankton survey and environmental sampling in conjunction with these three surveys; and five assessment activities in 1984: an April-May plankton survey, a June-July shrimp and bottomfish survey, an August plankton survey for mackerel, a December plankton survey and environmental sampling in conjunction with these four surveys.

Surveys in 1985 continued the same types of survey activities conducted in 1982, 1983 and 1984 but with several exceptions. The offshore plankton survey conducted during April-May of 1982, 1983 and 1984 was cancelled due to other NMFS commitments. A coordinated July-August squid/butterfish survey was established to collect data on the abundance and distribution of several squid species and butterfish across the northern Gulf of Mexico. The September assessment conducted in 1984 at the request of the Gulf of Mexico Fishery Management Council (GMFMC) for king mackerel eggs and larvae was not requested by the GMFMC in 1985. Finally a shrimp/groundfish survey was added to the SEAMAP survey activities between September and December to assess the abundance and distribution of the fall shrimp and groundfish stocks across the northern Gulf of Mexico. Survey activities in 1986 included an April-May plankton survey, spring squid/butterfish survey, June-July shrimp and bottomfish survey, a

September plankton survey, a fall shrimp and groundfish survey and environmental sampling in conjunction with each. With the goal of a long-term data base, Gulf activities in 1987, with the exception of the spring squid/butterfish survey, were identical in scope. Overall survey objectives have been to assess the distribution and abundance of ichthyoplankton and trawl-caught organisms and document environmental factors that might affect their distribution and abundance.

A major purpose of SEAMAP is to provide resource survey data to state and federal management agencies and universities participating in SEAMAP activities.

It is the policy of the SEAMAP Subcommittee that all verified non-confidential SEAMAP data, collected specimens and samples shall be available to all SEAMAP participants, other fishery researchers and management organizations approved by the Subcommittee.

Data and specimen requests from SEAMAP participants, cooperators and others will normally be handled on a first-come, first-serve and time-available basis. Because of personnel and funding limitations, however, certain priorities must be assigned to the data and specimen requests. These priorities are reviewed by the SEAMAP Subcommittee.

Data requests and inquiries, as well as requests for plankton samples, can be made by contacting the SEAMAP Coordinator, Gulf States Marine Fisheries Commission, P.O. Box 726, Ocean Springs, MS 39564; 601/875-5912.

2.3.4 REGIONAL OCEANOGRAPHICAL STUDIES OF THE GULF OF MEXICO PRESENT AND FUTURE PLANS

Dr. Victor M.V. Vidal
Instituto de Investigaciones Electricas

The Grupo de Estudios Oceanograficos (Oceanographical Studies Group) of the Instituto de Investigaciones Electricas (IIE) is conducting the project REGIONAL OCEANOGRAPHICAL STUDIES OF THE GULF OF MEXICO.

The project integrates intensive oceanographical measurements (CTD, XBT, hydrochemistry) in the Gulf of Mexico (GOM) with data processing, analysis and interpretation of hydrographic data collected aboard R/V Justo Sierra. Since January 1984 we have conducted six oceanographical cruises, each with an average duration of 35 days. Hydrographic measurements are carried out with state-of-the-art equipment (Neil Brown CTD) calibrated to highest oceanographical scientific standards (pre-cruise, on-cruise and post-cruise calibration). Hydrographic data is processed on board ship using state-of-the-art hardware (Micro VAX II cluster with advanced graphics [VAX workstation] capability) and software. Final analysis of hydrographic data includes: cruise reports, data reports, data analysis reports, publication of scientific findings and editing of an oceanographical atlas of the GOM. The project's objectives are outlined below.

A. Hydrography of the Gulf of Mexico.

- o Spatial distribution of principal hydrographical parameters (temperature, salinity, dissolved oxygen, micronutrients, chlorophyll);

- o Spatial distribution of principal water masses (shallow and deep).

B. General circulation of the Gulf of Mexico.

- o Interaction of regional circulation and coastal circulation
  - Water mass exchange between oceanic and coastal waters
  - Transport mechanisms

- o Influence of general circulation on accidental releases of contaminants (radionuclide and petroleum by-products).

C. Influence of Loop Current rings on the general circulation within the Gulf of Mexico.

- o Loop Current ring hydrography

- o Kinematic properties of Loop Current rings

- o Cyclonic-anticyclonic ring interactions

- o Collision of Loop Current ring against western boundary of the Gulf of Mexico

D. Dispersal of contaminants within the far field of coastal sites of the Gulf of Mexico.

- o Calculations of differential kinematic properties from Lagrangian observations.

E. Editing of Oceanographical Atlas of the Gulf of Mexico.

- o From hydrographic data collected in Argos oceanographical cruises aboard R/V Justo Sierra.

F. Publications of results.

2.3.5 GULF OF MEXICO METEOROLOGICAL/OCEANOGRAPHIC MONITORING SYSTEM (MOMS)

Dr. James H. Allender
Chevron Oil Field Research Company

The objective is to develop a Gulf-wide meteorological and oceanographic monitoring system (MOMS) in the Gulf of Mexico through an industry-sponsored project, in cooperation with the National Weather Service (NWS) and the National Data Buoy Center (NDBC).

The benefits of the MOMS project are:

- To provide near-real time data to aid in hurricane evacuation;
- To collect and provide access to Gulf-wide weather data and forecast products for better day-to-day operations planning;
- To build a data base for improved platform design criteria.

NWS strongly believes that the data collected would result in better forecasts and marine warnings by filling a marine data void that exists at the present time.

The parameters to be measured include: wind speed and direction statistics, barometric pressure and air and sea temperatures, current speed and direction, directional wave spectra and derived parameters, such as significant wave height and period, and dominant wave direction. All of these parameters except current are transmitted hourly via the GOES satellite to NDBC for quality control and data archival. (Current data is proprietary but requests for release would be considered, case by case, by the project steering committee.) If the wave height exceeds a preset threshold, time histories of surface elevation and water particle velocity are also saved on board the platform for subsequent analysis.

A prototype measurement station has been installed on Chevron's Main Pass 133C platform east of the Mississippi River Delta (Figure 47). It consists of a Coastal Marine Automated Network (C-MAN) station, a Sea Data directional wave and current processor, and various interfaces for local display and connection with other data collection systems.

The complete station can operate for at least three days from battery power alone, in the event of an extended power failure, such as during a hurricane.

Participants are being sought to fund at least five measurement stations in the Gulf (Figure 47). Participants would either enter the project with a measurement station of their own, or enter with cash which would go toward a station similar to the prototype. NDBC would provide quality control (except for wave directional parameters and current) and data archival.

NWS (Southern Region, Fort Worth) would extend existing software, developed for their Marine Reporting Program (MAREP), to provide a centralized access to all hourly data from measurement stations and buoys. Participants would dial NWS and receive, via computer, the available data and forecasts.

Software would be developed per specification of the project participants for data manipulation and presentation, such as maps showing Gulf-wide wave or wind measurements for a given time, or trend plots for a selected variable.

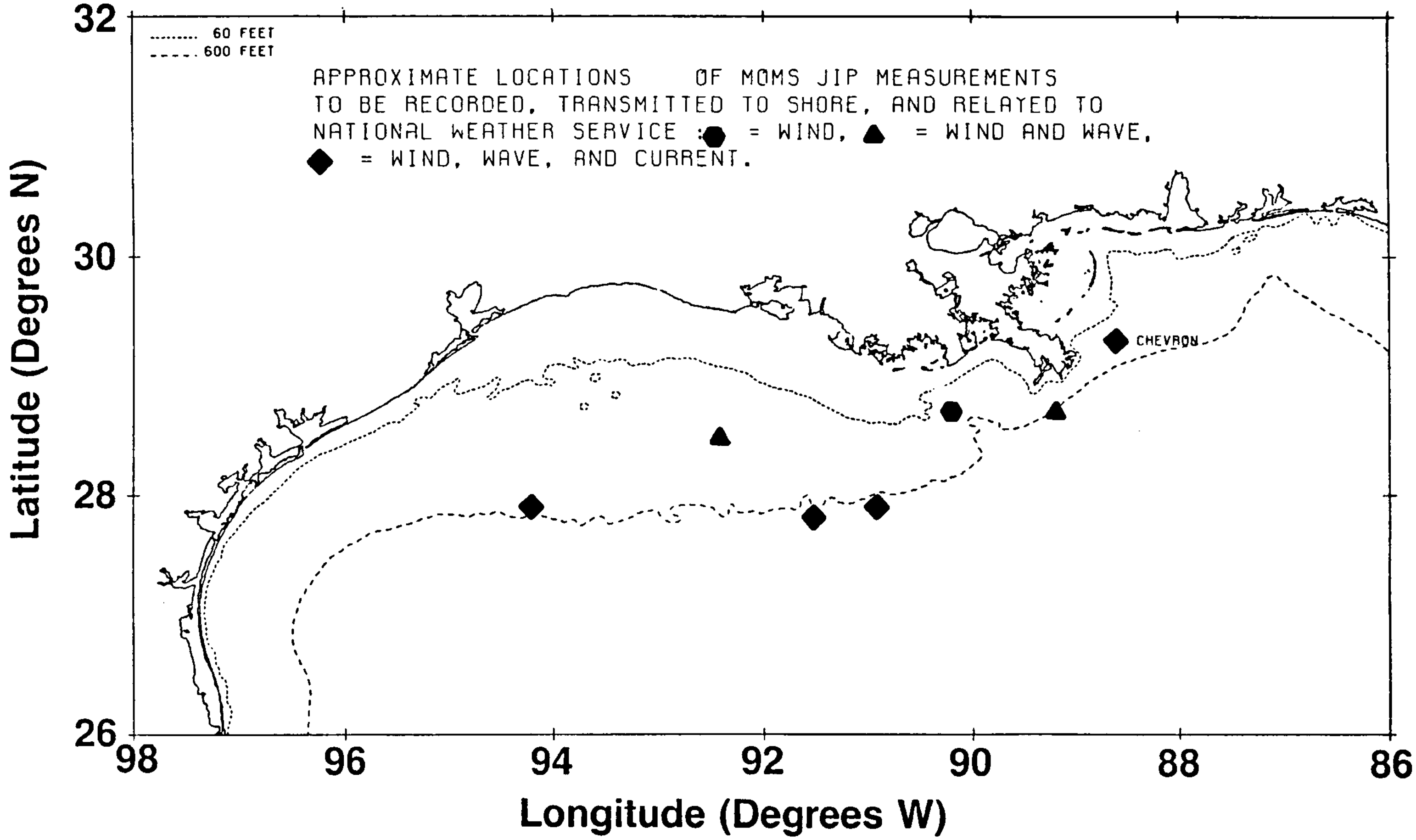

Figure 47. Approximate locations of MOMS joint industry project measurements to be recorded, transmitted to shore, and relayed to the National Weather Service.

2.3.6 NMFS OPERATIONS OF INTEREST TO PHYSICAL OCEANOGRAPHERS IN THE GULF OF MEXICO

Dr. Scott Nichols
National Marine Fisheries Service

The National Marine Fisheries Service (NMFS) conducts research cruises from its Mississippi Laboratories in Pascagoula and Bay St. Louis. Two NOAA vessels based in Pascagoula, the OREGON II and the CHAPMAN, are dedicated to fisheries research in the southeast US. Activities are directed at stock assessment monitoring in support of fisheries management, and at development of fisheries for underutilized species.

Surveys are conducted using a wide array of fishing gear, including trawls, longlines, traps, gillnets, video, acoustics, and plankton gear. Approximately 1000 stations are occupied each year. Measurement of several environmental variables are taken at every station. Salinity, temperature, oxygen (all with depth), surface chlorophyll, and meteorological observations are routinely taken. Sampling strategies in time and space vary among projects, but usually are based on stratified random designs in space. Cruises are conducted throughout the year, but by necessity each cruise is usually directed at a particular set of species, lasts 3-5 weeks, and attempts to sample throughout the spatial ranges of the stocks being considered. Some special projects are directed at smaller spatial scales. Historically, many of these have been mark/recapture projects. More recently, efforts have focused on relationships between fish eggs and larvae with river plumes and oceanic fronts.

Several problems important to NMFS have a physical oceanography component. Many deal with instantaneous observation, e.g., locating fronts or plumes, and including such features in sampling designs. Interpretations of catch per effort measurements are also enhanced with information about the physical environment, and knowledge of the organisms' responses to it. Remote sensing can play a major role here, and considerable expertise has been developed at our Bay St. Louis facility. Another major family of problems requires integrating observations over extended time periods (often using indirect or proxy variables) to characterize year to year variations in the physical environment important to fluctuations in year class strengths of fish populations. Estimations of passive transports of eggs and larvae, which affect both establishment of year class strength and the presence or absence of multiple stocks of the same species within the Gulf, are also of particular interest to NMFS.

Since 1982, NMFS has joined with the several state fisheries agencies, and universities, in the South East Area Monitoring and Assessment Program (SEAMAP). The several agencies may have quite different missions or applications, but often have similar sampling needs. SEAMAP coordinates fisheries sampling Gulf-wide. SEAMAP is also a vehicle for data management. The SEAMAP data manager at the NMFS Bay St. Louis facility is the point of contact for requests for data.

2.3.7 **THE GULF OF MEXICO GULF INITIATIVE PROGRAM**

Mr. Russell E. Putt
Environmental Protection Agency

The Gulf of Mexico serves as a vastly important resource to the United States: five sates share more than 1,600 miles of Gulf coastline containing 207 estuaries, half of the nations' coastal wetlands, and four of the nations' top five fishery ports by weight. The Gulf provides 97 percent of our offshore natural gas production, while approximately 45 percent of the nations' export/import tonnage pass through its ports. Over two-thirds of the contiguous United States drains into the Gulf of Mexico. During the past few decades the Gulf has begun to show signs of deteriorating environmental quality. Serious conflicts are emerging among the users of the Gulf, its coastal environments, and its resources.

In response, the U.S. Environmental Protection Agency (EPA), Region IV, has proposed a Gulf-wide strategy termed "The Gulf Initiative" to identify Gulf-wide problems, set goals and research needs, while developing a strategy in response to those problems. During an initial Gulf Initiative workshop held in Gulf Shores, Alabama on August 4, 5, and 6, 1986, fifty-nine persons, representing a broad spectrum of organizations concerned with marine pollution, identified critical issues and activities causing problems in the Gulf, made recommendations for a program management structure and provided a strong consensus that such a program was needed.

With authorization and financial support from EPA Headquarters, EPA Regions IV and VI have begun to establish a program to reach the goals of the initiative. The Gulf of Mexico Program is an interagency, inter-disciplinary effort to develop and implement a comprehensive strategy for managing and protecting the resources of the Gulf. The program will utilize management models and experience gained from previous regional efforts such as the Great Lakes and Chesapeake Bay programs.

The institutional structure of the program will provide a mechanism for addressing complex problems in the Gulf of Mexico that will cross state, Federal, and international boundaries, provide better coordination among Federal, State, and local programs affecting the Gulf which will in turn increase the effectiveness and efficiency of the long-term effort to manage and protect the resources of the Gulf. A regional perspective to address research needs for the Gulf will result in improved information and methods for supporting effective management decisions, and provide a forum for affected user groups, public and private educational institutions, and the general public to participate in the "solution" process.

For further information, please contact:

U.S. Environmental Protection Agency
Gulf of Mexico Program Office
National Space Technology Laboratories
NSTL, MS 39529
(610) 688-3726 FTS 494-3726

U.S. Environmental Protection Agency
Region VI
1445 Ross Avenue, Suite 1200
Dallas, Texas 75202
(214) 655-7145 FTS 255-7145

U.S. Environmental Protection Agency
Region IV
345 Courtland Street, NE
Atlanta, Georgia 30365
(404) 347-2125 FTS 257-2126

2.3.8 A SATELLITE FOR MEASURING GLOBAL CURRENTS

Dr. Robert H. Stewart
California Institute of Technology
Jet Propulsion Laboratory

The U.S. National Aeronautics and Space Administration and the French Centre National d'Etudes Spatiales, in support of global oceanographic studies and the large scale oceanographic experiments of the World Climate Research Program, have begun a program for measuring currents and tides from space. The program is based on the Topex/Poseidon satellite mission that includes altimeters for measuring the height of the satellite above the sea surface; a precision orbit determination system for referring the altimetric measurements to geodetic coordinates; a data-analysis and distribution system for processing the satellite data, verifying their accuracy, and making them available to the scientific community; and a Principal Investigator program for scientific studies based on the satellite observations. Instruments which will be aboard the TOPEX/Poseidon satellite are listed in Table 5.

The satellite system will be able to measure sea level globally with an accuracy of ±14 cm and a precision of ±2.0 cm along a fixed global grid every 10 days for three years (Figure 48). These measurements can be used to calculate the time-varying and permanent surface geostrophic currents at the sea surface, oceanic tides, and ocean wave height.

Launch of the satellite is planned for 1991 so that data from the mission will coincide with global measurements of the ocean made by other large programs. These include: (a) the global measurements of surface winds that will be made by a NASA scatterometer on the proposed Japanese Advanced Earth Observation ADEOS satellite and by a scatterometer on the European Space Agency's Remote Sensing Satellite (ERS-1); (b) and two large-scale oceanographic experiments of the World Climate Research Program, the World Ocean Circulation Experiment and the Tropical Ocean Global Atmosphere program which will measure other important variables on and below the sea surface. By combining the satellite, surface, and subsurface measurements with new computer models of the circulation of the ocean it will be possible to determine, for the first time, the general circulation of the ocean and its interannual variability. The results of these studies will lead to a much improved understanding of the role of the ocean in the climate system and improved predictions of weather patterns a season or two in advance.

More information about these programs and satellite altimetry can be found in the following papers and reports:

Cheney, R.E., J.G. Marsh and B.D. Beckley. 1983. Global mesoscale variability from collinear tracks of Seasat altimeter data. J. Geophys. Res. 88(C7):4343-4354.

Freilich, M.H. 1985. Science opportunities using the NASA scatterometer on N-ROSS. NASA Jet Propulsion Laboratory Publication, Pasadena, 84-57. 36 p.

Fu, L.L. 1983. Recent progress in the application of satellite altimetry to observing the mesoscale variability and general circulation of the ocean. Rev. Geophys. Space Phys. 21(8):1657-1666.

Joint Oceanographic Institutions. 1984. Oceanography from space: A research strategy for the decade 1985-1995, Part 1, Executive Summary. Washington, D.C. Joint Oceanographic Institutions Incorporated Report. 20 p.

Joint Oceanographic Institutions. 1985. Oceanography from space: A research strategy for the decade 1985-1995, Part 2, Proposed measurements and missions. Washington, D.C. Joint Oceanographic Institutions Incorporated Report. 32 p.

NASA. 1981. Satellite altimetric measurements: Report of the Topex Science Working Group. Jet Propulsion Laboratory Report 400-111, Pasadena. 78 p.

NASA. 1986. Earth system science: Overview. NASA Report, Washington. 48 p.

Stewart, R.H. 1985. Methods of satellite oceanography. Chapters 12 and 14. University of California Press, Berkeley. 360 p.

Stewart, R.H., L.L. Fu and M. Lefebvre. 1983. Science opportunities from the Topex/Poseidon mission. Jet Propulsion Laboratory Publication 86-18, Pasadena. 58 p.

Tai, C.K. and C. Wunsch. 1984. An estimate of global absolute dynamic topography. J. Phys. Oceanogr. 14. pp. 457-463.

Woods, J.D. 1985. The world ocean circulation experiment. Nature 314(6011). pp. 501-511.

World Meteorological Organization. 1984. Scientific plan for the world climate research program. World Meteorological Organization, Geneva. WCRP Publication Series No. 2. 95 p.

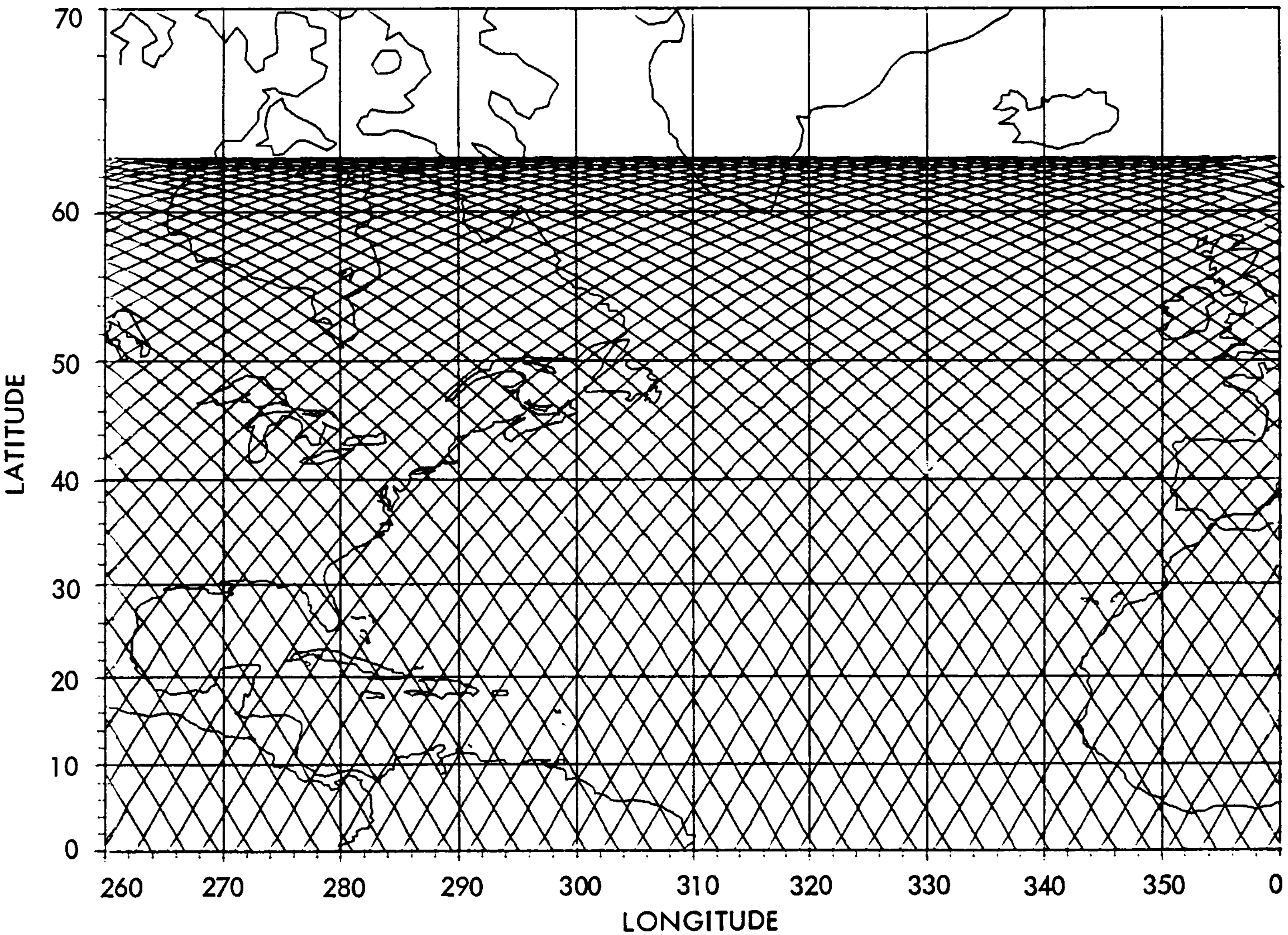

Figure 48. Proposed grid of subsatellite track in the North Atlantic that would be traced out by the TOPEX/Poseidon altimeters in a ten-day repeating orbit.

Table 5. TOPEX/Poseidon instruments.

Altimeters

System	Frequency	Power	(Averaging Time)
Topex	13.6 GHz	20 W	2.4 cm* (3s)
	5.3 GHz	20 W	3.1 cm (3s)
Poseidon	13.65 GHz	2 W	10 cm** (1s)

Microwave Radiometer

Frequency	Field of View (Half Power Beamwidth)	Noise Equivalent T (K)	Averaging Time
18.0 GHz	42 km (1.81°)	0.11	1s
21.0 GHz	35 km (1.49°)	0.11	1s
37.0 GHz	21 km (0.92°)	0.15	1s

Tracking Systems

System	Frequency (MHz)	Ground Stations	Ephemeris Accuracy (cm)
Laser	Light	15	13
	400		
Doris†	401.2	30—40	10—20
	2036		
GPS†	1227.6	6—8	<10
	1575.4		

*After correction for ionospheric delay, $H_{1/3} = 2$ m, wave skewness = 0.1.
**Without correction for ionospheric delay.
†Experimental systems not yet tested or flown in space.

2.3.9 DATA ARCHIVING AND MANAGEMENT ACTIVITIES AT THE NATIONAL OCEANOGRAPHIC DATA CENTER (NODC)

Mr. John C. Sylvester
National Oceanographic Data Center

A briefing on NODC operations and data holdings is presented.

An overview of general data archiving and management requirements is presented and discussed (Figure 49). Archiving and management needs relating to the Minerals Management Service (MMS) objective of making preliminary environmental data available to the community in a timely fashion (e.g., preliminary current meter data within 90 days of recovery) are emphasized.

These particular requirements are:

- Rapid communication (electronic mail);
- Data existence information (data tracking and single contact point at contractor and NODC);
- Data availability information (data status information);
- Data security (data backup);
- Data exchange mechanisms (format/medium compatibility);
- Data currency (rapid ingest by NODC to an archive of originator tapes/diskettes);
- Data quality control (minimum standards for preliminary data to be determined);
- Data documentation (minimum documentation needs for preliminary data to be determined);
- Products (only NODC product will be copies of originator's preliminary data provided to requestors);
- Data adequacy/timeliness (timely availability of preliminary results).

Requirement
<u>Rapid Communication</u> Electronic mail
<u>Data Existence Information</u> Data tracking Single contact point Data catalog Data referral
<u>Data Availability Information</u> Data status information
<u>Data Security</u> Data backup Long-term databases
<u>Data Exchange Mechanisms</u> Format/medium compatability Networking
<u>Data Currency</u> Rapid archive ingest
<u>Data Subsetting Capabilities</u> Multiple criteria
<u>Data Quality Control</u> Standard policies/procedures Data integrity Questionable data flags Duplicate data
<u>Data Documentation</u> Standard policies/procedures Full documentation Documentation-data linkage <u>Products</u> Standard products Modelling/gridded datasets QC climatology products
<u>Data Adequacy/Timeliness</u> Continuous time/space resolution Timely availability
<u>Responsiveness to User</u>

Figure 49. Overview of general data archiving and management requirements, NODC Operations.

2.3.10 U.S. COAST GUARD RESEARCH AND DEVELOPMENT CENTER

Dr. David F. Paskausky
U.S. Coast Guard Research and Development Center

To improve the probability of detection of the target in search and rescue (SAR), the U.S. Coast Guard Research and Development Center (USCG R&DC) is conducting research to determine sweep widths for search platforms and sensors such as Night Vision Goggles, forward looking infra red (FLIR), and new radars (including side and forward looking and synthetic aperture radars). Research in measurement of currents in real time to hindcast and nowcast target movement includes development of Loran-C position transmitting buoys, satellite image analysis to initialize a current field in a search area and a search planning test bed utilizing desktop computers to analyze and transmit this information to the rescue command center. This SAR planning system is to be included as an ocean module in a ports and waterways management information system (PAWMIS). PAWMIS utilizes a microcomputer-based automated information system which will provide information required for emergency response, port security, vessel traffic management, aids to navigation management and permit review by means of computer-generated site specific charts, databases and video response-planning images. The modules of PAWMIS are designed for use by Marine Safety Officers, Captains of the Port, Operations Centers and others. It will permit access to mainframe data bases as necessary.

2.3.11 QUALITY ASSURANCE OF NOAA TIDE AND CURRENT PREDICTIONS FOR GALVESTON BAY - HOUSTON SHIP CHANNEL

Dr. Henry Frey
National Oceanic and Atmospheric Administration
Office of Oceanography and Marine Assessment

The Office of Oceanography and Marine Assessment (OMA) of NOAA's National Ocean Service (NOS) plans to make current, water level, temperature and salinity measurements in the Galveston Bay - Houston Ship Channel region in late summer, 1988, using new technology measurement systems. This will be the beginning of a quality assurance (QA) project for Gulf of Mexico ports and harbors. The QA project will provide cost-effective field checks of NOAA tide and current table predictions. If significant errors are found, plans will be made for additional measurements and for circulation models on which new predictions will be based.

Recent information from Galveston - Texas City Pilots, the Houston Pilots, the Port of Houston Authority, the U.S. Coast Guard and NOAA's National Marine Fisheries Service indicates that NOAA's predictions are significantly in error.

The last major survey was conducted in 1936, with addition of a small number of secondary stations in 1962. Major dredging operations have taken place in this area since that time. The strong influence of weather on currents and water levels suggests the need for the installation of a real-time current and water level measurement system to enhance the safety of ship operations.

OMA plans to deploy a self-contained, bottom-mounted remote acoustic doppler sensing (RADS) system at the entrance to Galveston Bay. It will be located at the present reference station for tidal current predictions for a period of one month. A second RADS will be deployed at a location in the Bay for 15 days, and at a location in the Houston Ship Channel for 15 days. The RADS provides 10-minute averages of water current speed and direction from the bottom to within 2 meters of the surface, at one meter intervals. Water level measurements will be acquired at Pier 21, and at Galveston Flagship Pier. Wind speed and direction will be obtained from the meteorological mast on Flagship Pier. Temperature and salinity measurements will be made from a small boat. The data will be used to determine the accuracy of present NOAA tide and current tables and predictions, and a report on the findings will be issued.

Ship support for the deployment/retrieval of the RADS will be provided by Coast Guard Group Galveston.

For further information, please call Dr. Robert G. Williams, NOS, at 301-443-8510, or write to him at:

NOAA/National Ocean Service (N/OMA13)
6001 Executive Boulevard
Rockville, MD 20852

2.3.12 **NOAA's Ocean Programs for the 1990s**

Mr. James S. Lynch
National Oceanic & Atmospheric Administration
National Ocean Service
Office of Ocean Services

(Ed. Note: This paper was not presented at the Symposium but is included for completeness.)

NOAA's basic mission is to apply scientific understanding to oceanic and atmospheric data in order to provide environmental information and prediction services to the public. Scientific knowledge and the scientific process (observation - analysis - description - prediction) are the common threads that tie NOAA together.

NOAA's new Administrator, Dr. William E. Evans, envisions the agency's third decade as "revitalizing the scientific content of NOAA's operational programs." In the coming decade, NOAA will be in the forefront to address the degradation of the nation's coastal areas, depletion of living marine resources, loss of life due to weather or flood hazards, and the effects of oceanic and atmospheric global change processes on the entire planet.

At least four scientific challenges are planned to recapture the spirit of the scientific revitalization:

- Climate & Global Change: a systematic effort to understand the processes of oceanic and atmospheric change so that scientific predictions can be developed;
- Marine Ecosystem Analysis: a multidisciplinary effort to understand and predict the behavior of marine ecosystems as a basis for responsible stewardship of marine life and resources;
- Coastal Ocean Prediction: an integrated approach to understand physical, chemical, geological, and biological processes occurring in the most intensely used portion of the nation's marine environment; and
- Hydrometeorological Prediction: the application of new technologies for observation and analysis to convert the severe weather flood warning programs to a process of scientific prediction, in contrast to the limited detection capability now in use.

Observations and Data Management

NOAA's ability to meet these challenges requires a new approach to observe ocean processes, introducing a Lagrangian (rather than an Eulerian) methodology. An inventory of available observing platforms/systems operated by federal, state, and local governments is being established and will be maintained. This inventory will be an invaluable tool for designing an optimum ocean observing network that will support operational and research programs.

A variety of ocean-based observations is envisioned, and NOAA is making a concerted effort to make ocean data available to all users in a timely manner. Subsurface thermal profilers will become standard sensors aboard NOAA's moored buoys in the coastal ocean. In addition, acoustic doppler current profilers will be widely implemented, both ship mounted and sea-floor mounted. As new technology becomes available, such as optical sensors for observing ocean turbidity, NOAA plans its prompt implementation for operational use.

Furthermore, NOAA is actively involved in establishing requirements for space-based ocean sensing systems for possible inclusion in future space missions (polar orbiting satellites and/or NASA and international polar platforms). NOAA is also actively pursuing real-time access to planned domestic and foreign satellite data (NASA SeaWiFS, ERS-1, and JERS-1 data).

An end-to-end data management program is under development within NOAA. This program will ensure that: NOAA and interagency requirements for ocean data and products are periodically addressed and reviewed; the design, development, deployment, and maintenance of NOAA's ocean observing platforms meet stated objectives/requirements; data from ocean platforms are distributed in a timely manner and in an appropriate format; quality control information from operational processing centers, platform managers, and archive facilities are exchanged to maintain optimum platform performance and data useability; and data are archived and can be retrieved in a timely manner.

Data Analysis, Assimilation, Prediction

To address the four programs within the scientific revitalization effort, NOAA is committed to modernize its ability to assimilate and synthesize data to produce analyses, predictions, and assessments. At field offices, for example, this commitment entails the introduction of interactive workstations and super-PCs, as well as the communications infrastructure required to support a network of these systems.

The Interactive Marine Analysis & Forecast System (IMAFS) is being designed to store, process, and display conventional ocean observations, gridded fields, digital satellite data, and climatologies. IMAFS will permit the overlay of multiple data and product sets, the computational capacity to merge data sets and produce new fields, and the interactive capability to redefine or reanalyze products. IMAFS will provide a unique and powerful capability to NOAA and other Federal agencies involved in ocean climate, fisheries productivity, environmental quality, and coastal hazards programs.

The IMAFS system is being designed to support a variety of super-PCs (such as McIntosh, 386 machines, etc.). These systems will be able to download data/products from a host IMAFS, generate new regional/local products, and upload the new products to the host IMAFS. The PC systems will provide an interactive analysis capability at federal, state, and local government offices which have smaller data storage and processing requirements than offices with IMAFS.

The communications capabilities are being designed to provide a wide-area network which will distribute data and products from appropriate central databases to the IMAFS workstations. In time, the wide-area network will be augmented by

satellite broadcast of data and national scale products via NOAAPORT. Asynchronous ports at the IMAFS sites will provide establishment of local-area networks for two-way communications with other federal, state, and local government offices using super-PC systems.
These capabilities will:

- o Increase the availability and enhance the utility of real-time and archived data, analyses, products, and model output by users (NOAA, federal, state, and local) for specific ocean applications;

- o Provide the ability to incorporate and combine a wide variety of data and product types, including the capability to merge various data/products to generate new products to meet specific ocean applications; and

- o Introduce a two-way communications capability to exchange data/product sets generated at national processing centers, national archive centers, regional IMAFS facilities, and local PC workstations.

Centers of Excellence

These capabilities, introduced into the ocean applications arena, will inevitably lead to several NOAA Centers of Excellence. The Centers will focus on ocean processes affecting the entire nation, not just a specific region. These ocean-related National Centers will incorporate many of NOAA's disciplines, such as physical/chemical oceanographers, numerical modelers, marine biologists, marine meteorologists, ocean climatologists, computer system programmer/analysts, and database managers.

NOAA presently maintains a number of National Centers. The National Meteorological Center, Climate Analysis Center, National Hurricane Center, and National Severe Storms Forecast Center are operated by NOAA's National Weather Service, and principally have weather-related missions. Two existing ocean facilities include: the National Tsunami Warning Center - providing national/international warning and advisory services for tsunamis generated by oceanic seismic disturbances; and the Ocean Products Center - providing real-time analyses and numerical modeling support for marine weather and physical oceanographic users.

A new facility is envisioned which will develop ocean information and products (from a variety of ocean data sources) that focus on biological, chemical, and physical oceanographic applications related to fisheries productivity, habitat and coastal zone management, offshore dumpling and pollution, and ocean climate processes. The Center will address real-time and delayed real-time capabilities in support of these programs, including:

- o Timely quality control of chemical, biological, and physical oceanographic data;

- o Develop and operate numerical analysis and modeling capabilities;

- Develop and provide high-priority ocean information and products;
- Provide interpretative services to support federal, state, and local government operations; and
- Operate and maintain a communications system to support the IMAFS network.

Closing Remarks

NOAA's planned activities for the 1990s are a bold and exciting venture. The nation requires an ability to proactively analyze and predict ocean processes so that appropriate measures can be taken to mitigate natural and/or man-made hazards, to make optimum use of the nation's abundant natural and living marine resources, and to enhance aquaculture and fisheries productivity through protection of marine ecosystems and habitat. NOAA is prepared to address these issues.

3.0 WORKING GROUP RECOMMENDATIONS

3.0 WORKING GROUP RECOMMENDATIONS

On the third day of the symposium (May 26), following the technical and government/industry presentations, the participants divided into three working groups. These groups, and the chairman of each were:

- Inner shelf and Mississippi River plume processes
  Dr. Gabriel T. Csanady
  Old Dominion University
  Norfolk, VA

- Outer shelf and upper slope processes
  Dr. George Z. Forristall
  Shell Development Company
  Houston, TX

- Modeling and model/observation comparisons
  Dr. Dong-Ping Wang
  State University of New York
  Stony Brook, NY

The working group topics were chosen to address the three most important aspects of a program design to meet the needs of the MMS. Two groups discussed physical processes and methods to adequately measure and study the processes. The third group discussed problems associated with modeling the pertinent physical processes.

Approximately one-third of the participants joined each group. The groups met for two hours, then reconvened in plenary session. Each group chairman presented a synopsis of his group's discussions. The following three subsections summarize the recommendations of the working groups, and were prepared by the group chairmen, as indicated.

3.1 LOUISIANA-TEXAS SHELF STUDY: RECOMMENDATIONS FOR A RESEARCH PROGRAM

Dr. Gabriel T. Csanady
Old Dominion University

Introduction

The present set of recommendations arose from discussions of the "inner shelf" group at the Galveston meeting on May 26, 1988. While the focus of the discussions was the inner shelf, they necessarily encompassed inner shelf-outer shelf exchange and the continuity of circulations between the inner shelf and deeper water. Also, the recommendations were refined and coordinated with those of the other two groups in the plenary sessions, with the result that much of what follows presumably overlaps with the reports of those other groups. As far as possible, the recommendations are organized into a sequence of separate "tasks", to be carried out possibly by different contractors, but constituting in the aggregate a coherent research program satisfying the objectives summarized in a brief strawman document handed out at the meeting, within realistic limits on resources.

Objectives

These are repeated here for convenience. Although not explicitly discussed in detail, they were favorably commented upon and implicitly endorsed by the different groups.

- Identify key dynamical processes governing circulation, transport and cross-shelf mixing on the Louisiana-Texas shelf;
- Upgrade existing empirical evidence on the same processes, fill in gaps in the evidence, synthesize the evidence into a scheme of circulation, and quantify transports and mixing rates;
- Develop a hierarchy of models of small to large scale processes and circulation features, from coastal plumes and fronts to shelf-edge eddy exchange, and large-scale shelf-circulation, on event to seasonal scales.

Synthesis of Information: (See Tasks 1 and 2, below). These two tasks are considered second in priority (following Tasks 3 through 9).

The Nearshore "Plume Extension": Various bits of evidence suggest that nearshore waters are distinct from offshore ones, and that there is in fact a quasi-continuous "plume extension" extending from the Mississippi River as far as Brownsville. Freshening caused by the Mississippi discharge is presumably the principal reason for the existence of this plume extension, but its distinctness may also be supported by differential heating and cooling of shallow waters. In any case, the front separating this plume extension from mid-shelf waters is a _prima facie_ barrier to cross-shelf mixing, and the along-front geostrophic current a fast lane to the southwest shelf. The density contrast characterizing this front well west of the Atchafalaya River is much larger than seen on east coast shelves, making the front an interesting object of scientific study, as well as an important one. The properties of this front and frontal current should be investigated by the best techniques available, and the mass-continuity (or otherwise) of the plume extension along the entire Texas shelf should be explored. The next four tasks relate to these recommendations (see Tasks 3, 4, 5, and 6, below) and are considered to be of primary priority (with Tasks 7, 8, and 9).

Inner Shelf: The Louisiana-Texas shelf is much wider than the nearshore plume extension, and an important part of its circulation is accommodated on what may still be described as the "inner" shelf. The main determinants of circulation on the inner shelf are expected to be the wind stress field, and the pressure field, which arises in response to the wind field, but which may be significantly influenced also by the nearshore plume extension. Previous observation has suggested the existence of a cyclonic gyre between about Galveston and the Mississippi Delta: although the return leg of this gyre occupies mostly the outer shelf, the dynamics of the gyre is an important problem also of interest in connection with the inner shelf. The next three tasks relate to inner shelf dynamics (see Tasks 7, 8, and 9, below) and are considered to be of primary priority (with Tasks 3 through 6).

Special Studies: In addition to the "core" program outlined above, important information could be economically obtained by sponsoring small scale studies which require for their interpretation the background information gained in the large scale study. These include the Mississippi plume study, the sediment transport study and the surf zone study (see Tasks 10, 11, and 12, below). These three tasks are considered to be third priority.

Methods

Task 1. Prepare synthesis of existing knowledge of shelf circulation and mixing.

An important immediate need is to synthesize existing evidence on circulation and mixing processes on the Louisiana-Texas shelf, including shelf-deepwater eddy interactions. As the results of such a synthesis become available, they should be used to improve and refine the plans for field work. The synthesis should aim at a coherent picture of shelf circulation and quantitative characterization of mixing processes, and should not be simply a catalogue of available information. It should be based primarily on information published in the literature, but it should also make use of other analyzed and interpreted data, if of good quality.

Task 2. Organize publication of synthesized results derived from MMS-supported studies into a "Gulf of Mexico" volume.

The initial synthesis should be followed by a continuing effort to upgrade it with the aid of the information flowing in from the MMS supported studies both in the deep Gulf and on the Louisiana-Texas shelf. The end product to be aimed at is an authoritative series of review articles on various aspects of Gulf and shelf dynamics, collected in one or two dedicated volumes, similar to the American Geophysical Union (AGU) volume on the South Atlantic Bight. This work should be coordinated by an editor of appropriate standing and experience.

Task 3. Maintain high resolution cross-front moored array at 94° W.

One dense moored array should be deployed and maintained for at least one full year at ca. 94° W, with at least three upward looking acoustic doppler current meters covering the frontal current, to yield vertical resolution of the order of 2 m. Thermistor-conductivity chains should support the current meters, with similar resolution. The conductivity cells should be rugged low-tech instruments, adequate to detect the high salinity signal, but resistant to fouling and other problems, as far as possible. The cross-front array should form the continuation of a cross-shelf array deployed further offshore (see below).

Task 4. Maintain shallow moorings on other transects.

To investigate mass continuity of the plume extension, the two western arrays, at 28° and 26° N (see below), should be instrumented with standard current meters, thermistors and conductivity cells well into shallow water.

Task 5. Monitor hydrography of the nearshore plume extension over the entire extent of the study region.

Frequent hydrographic sections should be taken of the nearshore zone, along the arrays as well as between them, at 100 km alongshore spacing or shorter, over the entire extent of the study region. Dissolved oxygen determinations should be part of this task.

Task 6. Carry out drifter studies to determine convergent and divergent regions of nearshore frontal current.

The continuity of alongshore flow should also be checked by a program of drifter releases at several alongshore locations from the Mississippi River to Brownsville. At least one group of drifters should be released once in each of the four seasons. The drifters should be followed as long as possible in order to gain information on the continuity of circulation from inner to outer shelf, in particular on the presumed cyclonic gyre between Galveston and the Mississippi Delta (see below).

Task 7. Maintain cross-shelf moored array of current meters with temperature and conductivity sensors at 92° W, 94° W, 28° N, and 26° N.

These transects continue the three nearshore arrays mentioned before, and connect to shelf-edge moorings proposed by the outer shelf group. Also, they extend the operation of the 92° W array into the next study period. Good quality conventional instrumentation is acceptable throughout. Meters (moorings) are to be deployed at depths of 15, 40, 60, and 180 m water depths (several meters on each mooring).

Task 8. Maintain an array of bottom pressure recorders at the seaward and shoreward edge of each of the four mooring lines.

Standard instruments should be used, surface (atmospheric) pressure to be also recorded.

Task 9. Maintain meteorological instrument packages in the same locations as bottom pressure recorders.

Over-water winds, air-sea temperature differences, and wave data are needed. Conventional instrumentation is acceptable.

Task 10. Conduct a detailed survey of the Mississippi-Atchafalaya plume's near field.

A several months' long investigation is required of the behavior of this complex region under different wind conditions. Mostly event-scale hydrography is envisaged, guided by satellite information. Frontal zones should be explored in adequate detail, the observations to include Lagrangian tracer studies.

Task 11. Conduct sediment transport studies, by deploying transmissometers on nearshore current meter moorings, and using towed transmissometers in conjunction with the Mississippi plume study.

Conventional instrumentation should be used.

Task 12. Conduct surf zone study, to establish intensity of longshore currents under varying wind and wave conditions, at 94° W.

A one month long study using electromagnetic current meters is envisaged.

The various tasks described above are schematically indicated on Figure 50.

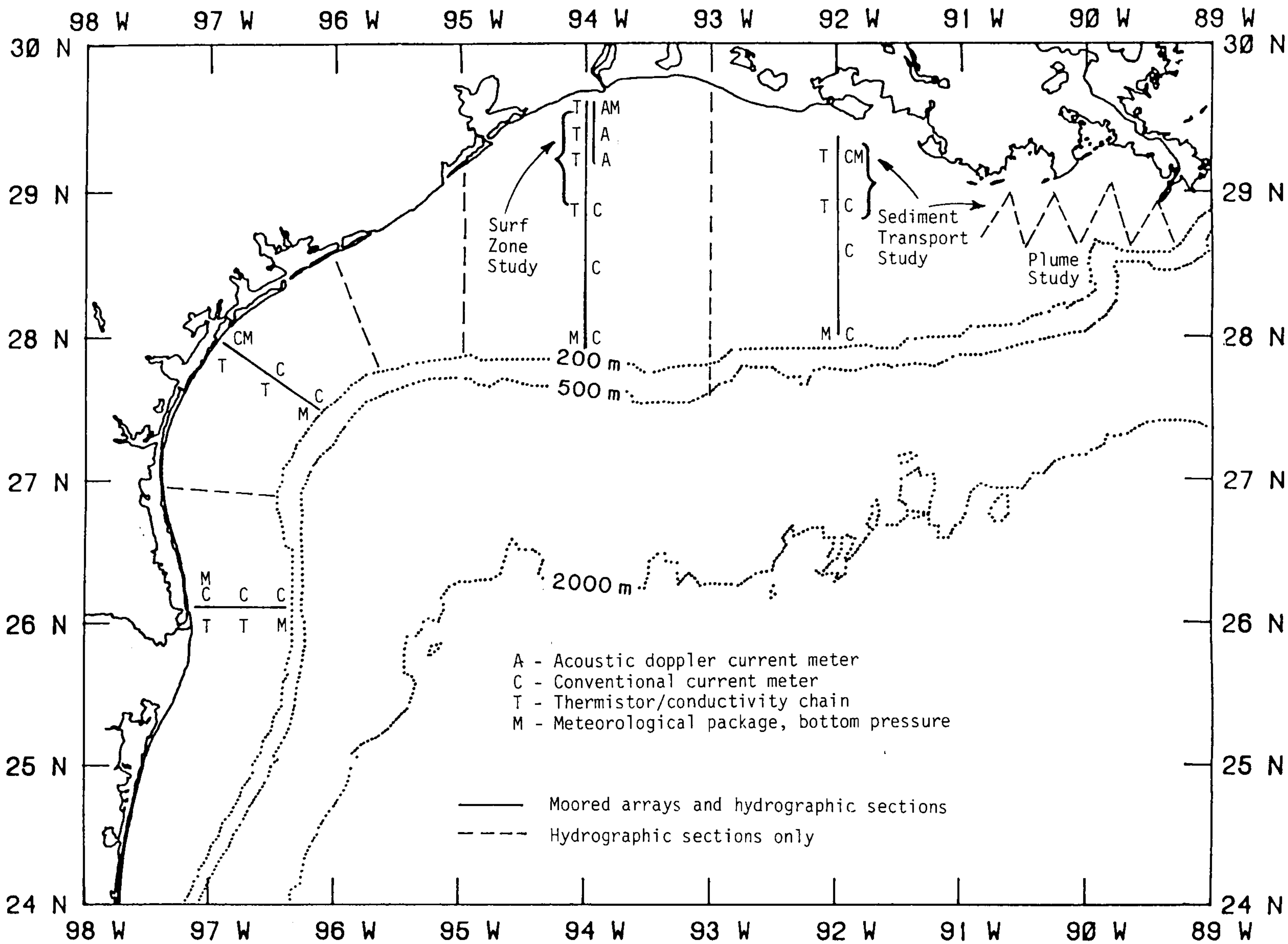

Figure 50. Measurements recommended by the inner shelf processes working group.

3.2 OUTER SHELF/SLOPE WORKSHOP

Dr. George Z. Forristall
Shell Development Company

Introduction

The workshop on the outer shelf and slope began by preparing a list of important open questions. It then considered the processes which must be understood to answer the questions and formulated a list of experiments and instrument deployments.

Questions/Objectives

Many of the questions involve the effects of the Loop Current and Loop Current eddies (LCEs) impinging on the slope. Despite the advances in our knowledge of LCEs in the open Gulf over the last few years, many specific questions about their evolution remain unanswered. What is the detailed mechanism of their formation? Fresh eddies often re-attach to the Loop Current. Why do they do this and when is the separation final? LCEs have also been observed in close proximity to one another. How do they interact? Forecasts of LCE motion across the Gulf are important both for engineering operations and experiment planning. What parameters govern the motion? All LCEs are not the same. What is their variability and climatology? The hydrography and motion of LCEs are better known than their kinematics. What is the three dimensional structure of currents in eddies and what is its variability? The interaction mechanisms between a hurricane and an eddy could be important. What are they?

All of these questions about LCEs deserve further study for eddies in the open Gulf. When the eddies near the slope, and bathymetry becomes important, much less is known and the questions become much harder. The response is also likely to be considerably different along the Louisiana slope which trends east-west along the path of the eddies than along the lower Texas coast which trends north-south and intercepts their path.

Small cyclones, probably barotropic, have been observed near LCEs. What are the processes that form and intensify them?

There are many questions which do not involve the Loop Current. What are the effects of wind forcing? What is the effect of storms on the slope? How much of the steady circulation does the seasonally averaged wind stress drive? What is the kinetic energy balance across the slope? How much energy input is due to the wind, compared to LCEs or other oceanic forcing? Much of the variance in typical current meter records made on the slope is not clearly related to either the wind or LCEs. What causes these unexplained currents? What are the dissipation mechanisms for LCEs? What is the rate of dissipation of tidal and wind driven currents due to bottom friction?

Satellite images show many squirts and jets along the slope. How deep are these features? Are they the surface manifestation of important exchange processes across the slope? Eddies and front lines are often seen on the shelf. What is under them? What are the processes that exchange mass and momentum across the slope and the outer shelf?

The topography along some portions of the slope is quite rough. What are the effects of this topography? What mechanisms govern the downslope motion of the bottom turbid layer?

Many of these questions could be asked in terms of the fundamental questions which seem to arise in any regional study. What is the hydrography of the slope and outer shelf? What are the time and space scales? And what is the momentum balance?

The fundamental processes which must be investigated in order to understand the circulation include:

- The effect and interaction of LCEs with the slope and shelf circulation;
- Wind induced exchanges;
- Buoyancy driven flow, including the effects of river plumes as well as cooling from the atmosphere and evaporation;
- Oceanic forcing other than from LCEs;
- The role of squirts and jets;
- Transports in the bottom boundary layer.

Finally, it is not clear that these processes will explain all the variance in the current meter records. If not, the most important question may be what processes must be added to the list.

Methods

Task 1. Current meter moorings will undoubtedly be an important part of any experiment which studies the questions and processes listed above. The existing line along 92° W should certainly be continued in order to improve the climatological data base.

Task 2. The trend of the slope changes from E-W along the Louisiana slope to N-S along the lower Texas slope. Most LCEs seem to dissipate along the lower Texas and upper Mexican shelf. Thus another line should trend E-W along about 26° N.

Task 3. An intermediate line could help to connect these different regimes. Somewhere between 94° W and 96° W could be selected depending on how representative the shoreward topography is.

Task 4. An expanded set of sea level measurements near the shore will complement the current meter data.

Task 5. Hydrographic surveys of the entire slope and outer shelf are needed.

Task 6. A review of existing measurements will help determine how detailed and how often these surveys should be, as well as which properties they should measure.

Task 7. Lagrangian measurements using drifting buoys have proved very valuable in studying circulation patterns in the deep Gulf. Each LCE should continue to be seeded with at least one buoy.

Task 8. Thermistor strings under the buoys would be very useful if they could be made to work reliably.

Task 9. Buoys have occasionally been entrained in cyclones at the edges of LCEs, but seem to spin out quickly. The deep thermal structure of these features indicates that they might best be studied with drogues at greater than 200 meters depth.

Task 10. Buoys drogued at shallower depths will give a valuable picture of the circulation above the slope and shelf. This would seem to be the best way of measuring the circulation in the jets and squirts observed above the shelf in satellite images. The MMS is, of course, most interested in the transport of pollutants, and drifter data is directly applicable to this problem. In the past, there has been some reluctance to rely on Lagrangian measurements in physical oceanographic studies, probably because methods for the analysis of the data were not well developed, but there has recently been great progress in this area.

Task 11. Images generated from infrared scanners on satellites have provided the most regular synoptic views of surface features in the Gulf in recent years. Unfortunately, these images are of limited value in the summer months since the surface waters of the Gulf heat to nearly an isothermal condition. In the next few years a number of new satellite instruments promises to give new opportunities for observation along with new challenges in data interpretation.

Task 12. The MOS color scanner which will be flown on a Japanese satellite will give the first images of ocean color since the demise of the Coastal Zone Color Scanner. There is the possibility that front lines in the deep Gulf could be seen in the summer, and the certainty that many coastal features will appear. The challenge is to relate these color changes to thermal and kinematic features.

Task 13. The scatterometer on the ERS will give a good measure of surface wind speed. This data should prove valuable in filling the gaps between in situ sensors.

Task 14. If a synthetic aperture radar (SAR) is flown, it will give information on surface waves, internal waves and current shears. Experience with the SAR on SEASAT demonstrated that much work remains to be done in separating these effects which produce such strong radar signals.

Task 15. Geosat is now giving sea surface topography with a resolution of about 5 cm. Two more radar altimeters with even higher resolution may be flown in the next few years. These data can be used to directly calculate surface currents, at least in deep water. Cruise tracks and current meter locations should be chosen to maximize the usefulness of these data.

Task 16. All of the instruments used on satellites can also be flown on aircraft. Remote sensing from aircraft has the advantage that the survey lines can be at exactly the time and place required by the experiment. (I would like to suggest that the ideal platform for physical oceanographic studies is probably a blimp. It would offer a marvelous combination of good endurance, stability, and speed combined with the ability to loiter. - GZF)

Task 17. Over the last several years, Ship of Opportunity (SOOP) XBT lines have given a very effective method of sampling the hydrography of the deep Gulf. Unfortunately, the schedules of the shipping lines have changed, and no SOOP lines are presently in operation. In view of the efficiency of the method, we believe that high priority should be placed on finding new operators willing to carry the instruments. For a reasonable additional capital cost, it should also be possible to equip these ships with Acoustic Doppler Current Profilers (ADCP) in order to get direct current measurements.

Task 18. Some hydrographic cruises should be budgeted as surveys in response to events seen by remote sensing instruments. The survey ships can be fitted with ADCPs as well as using XBTs and expendable current profilers (XCPs). Even faster surveys can be made using AXBTs and AXCPs deployed from aircraft.

3.3 REPORT OF WORKING GROUP ON MODELS

Dr. Dong-Ping Wang
State University of New York

Introduction/Objectives

Physical processes over continental shelves have diverse spatial and temporal scales. Eddies that impinge on shelf edges have horizontal scales of several hundred kilometers, vertical scales of several hundred meters, and time scales of several months. In contrast, plumes that exit from the Mississippi Delta have horizontal scales of kilometers, vertical scales of meters, and time scales of hours to days. To simulate these processes would require models of different spatial and temporal resolutions.

Methods

The working group recommends that a Gulf of Mexico Model System should be an evolving hierarchy of models consisting of the following components:

Task 1. Basin scale, eddy-resolving model for Loop Current and eddies

Development of a basin scale model is an ongoing project sponsored by MMS. The numerical model is based on the NORDA/JAYCOR two-layer, eddy-resolving, Gulf of Mexico circulation model.

Task 2. Basin and sub-basin scale models for shelf-edge eddy exchange

Models for shelf-edge eddy exchange processes should be fully three-dimensional. A sigma coordinate system or an isopycnal coordinate system might be useful alternatives to a level coordinate system. The model domain should include a sub-basin with open boundaries sufficiently removed from the influence of eddies, or, it might include the entire Gulf basin to circumvent the open boundary problem. The initial eddy field could be derived from a nested basin-scale eddy-resolving model, or obtained from objectively assimilated eddy observations. The model study is to simulate the interaction between eddies and the continental slope.

Task 3. Shelf circulation models

Models for the shelf circulation should be three-dimensional, and should include nearsurface mixed-layer dynamics. The bottom boundary layer of wave-current-sediment interaction might also need consideration. The model domain should include the Louisiana-Texas shelf and possibly extend to the western Florida shelf. The offshore boundary should extend well beyond the shelf break. The initial temperature and salinity field could be the climatology. The atmospheric forcing should include realistic wind stress fields over the water and the empirically derived heat flux. It is particularly important to characterize the explosive cyclogenesis which usually develops near the shelf break. The model study is to simulate the wind driven circulation on event to seasonal time scales.

Task 4. Coastal Plume/Front Models

Models for coastal plume/front simulation should be three-dimensional, and should have high horizontal and vertical resolutions. The model domain should include regions directly affected by the Mississippi plume (Louisiana-Texas inner shelf). The initial condition is probably inconsequential since the plume adjustment is rapid. The forcing should include runoff from major rivers, and the nearshore wind stress. The model study is to simulate the plume/front circulation of the near and far fields.

Task 5. To achieve full benefit of the modeling hierarchy would require nesting of models of different designs. For example, models for shelf-edge eddy exchange might have to be nested in a basin scale eddy-resolving model for consistency in the background eddy field. These two models however will have vast differences in model parameters, model resolution, and coordinate systems.

Task 6. Careful examination of the physical and numerical issues associated with model interfacing is recommended. An intermediate step towards a total model integration is to generate surface flow fields for the Oil Spill Risk Analysis (OSRA).

Task 7. Data assimilation and interpolation methods should be exploited to derive a dynamically consistent flow field from observations and the hierarchy of models.

Task 8. Several models that might be useful for the Gulf of Mexico model system already exist, and have demonstrated considerable skill in ocean simulation. They should be carefully evaluated and adapted to the Louisiana-Texas shelf.

Task 9. The available flow and hydrography data over the Louisiana-Texas shelf should be synthesized to yield seasonal flow patterns for preliminary model evaluation.

Task 10. It is recommended that procedures be established for an independent assessment of model performance.

Task 11. The Louisiana-Texas shelf circulation study will provide rich data sets for model validation. It is recommended that field data should be made readily available to the modeling community. For example, the statistics of surface flows (from drifter trajectories) and surface front positions (from satellite images) could be computed and continuously updated through the field experiment. The surface statistics could be used for model verification, data assimilation, and the OSRA model.

Task 12. Feedback from the model analysis to the experimental design should be encouraged.

Summary Recommendations

The Gulf of Mexico model system should be an evolving hierarchy of models consisting of (1) a basin scale model for the Loop Current and eddies, (2) basin or sub-basin scale models for shelf-edge eddy exchange, (3) shelf circulation models, and (4) coastal plume/front models.

Investigations of nesting and coupling of models are recommended, including (1) nesting of circulation models of different model designs, and (2) coupling of model outputs and observations to the Oil Spill Risk Analysis (OSRA) model.

Critical examination of model physics, model validation, and model sensitivity is recommended. The model study should be coordinated with the Louisiana-Texas shelf circulation experiment.

4.0 RECOMMENDED PROGRAM DESIGN

4.0 RECOMMENDED PROGRAM DESIGN

4.1 General

Each workshop chairman presented his group's discussions and recommendations in plenary session. The discussions which followed formed the basis of a program design which can be used by the MMS to identify key dynamic processes on the shelf, collect and synthesize the data to develop an understanding of shelf circulation, and develop a shelf circulation model (or hierarchy of models). From these discussions and the written summaries from the working group chairmen, a coordinated field measurement and modeling program plan has been developed.

The recommended program consists of a data synthesis effort, field measurements, and a modeling program. In summarizing the recommended field program, it has proven convenient to organize it into a "core" program (to achieve the basic goals of the MMS), and a group of special studies. The core program has been subdivided further by type of measurement: moored instrumentation, hydrographic surveys, and Lagrangian measurements. Each of these conceivably could be conducted as a separate program, perhaps by different contractors.

Section 3.0 presented the recommendations of the working groups, primarily based on processes associated with different water depths. It is the intent of this section to integrate the recommendations of Section 3.0 into a coherent total program to measure and model the pertinent parameters from the surf zone, to beyond the shelf break, and even into deeper water where necessary to monitor Loop Current eddies. More detailed discussions and justifications for the components of the recommended program can be found in the working groups' summaries in Section 3.0.

4.2 Information Synthesis

4.2.1 Synthesis of existing knowledge of shelf circulation and mixing

A synthesis of existing data on circulation and mixing processes on the Louisiana-Texas shelf, including eddy/shelf interaction is needed. It should be a quantitative characterization of shelf processes which presents a coherent picture of the shelf circulation. It is emphasized that this should be a synthesis of published information (as well as any other analyzed data which can be obtained) and not merely a catalog of available information. Where possible, the data should be presented in a format suitable for model testing. The synthesis should be started as soon as possible so that results from it can be used to improve plans for the field program. (Task 1 - inner shelf group).

4.2.2 Publication of synthesized results of MMS-supported studies in a "Gulf of Mexico Volume"

It is recommended that the MMS refine the synthesis of Subsection 4.2.1 and upgrade it with the results of other MMS programs, to publish a series of review articles on Gulf of Mexico physical processes. The work should be coordinated by an experienced editor of appropriate standing to produce one or two peer-reviewed, authoritative volumes on the Gulf of Mexico. (Task 2 - inner shelf group).

4.3 Field Program

The recommended field measurement program consists of across-shelf measurements (core program) to investigate the nearshore plume extension of the Mississippi River, inner shelf processes, and outer shelf/upper slope processes and interactions. In addition, special studies of the Mississippi River/Atchafalaya River near field plume, regional sediment transport, and near-shore currents are recommended. These special studies could provide important additional information for a small incremental cost when conducted concurrently with the core program.

The field measurement program is shown schematically in Figures 51 and 52. Instrumentation and deployment sites associated with both the core program and the special studies are shown.

4.3.1 Core program

The core program consists of four across-shelf current meter/thermistor/conductivity mooring transects, eight across-shelf hydrographic transects (four of which coincide with the mooring transects), and an along-shelf hydrographic survey.

4.3.1.1 Moored instrumentation

Four mooring transects, extending from water depths of 15 m to 1000 m are recommended (see Figure 51). For reference, these transects are referred to herein as the 92° W, 94° W, 28° N, and 26° N transects. Vertical instrumentation arrays should be deployed at water depths of 15 m, 40 m, 60 m, 180 m, 500 m, and 1000 m. The 40 m mooring is omitted from the 28° N and 26° N transects since the shelf is so narrow along the south Texas coast. Instrumentation recommended for each array is shown in Table 6. Good quality conventional instrumentation is recommended throughout the program to collect data of sufficient quality, while maintaining high reliability. Rugged, low-tech conductivity sensors, adequate to sense the wide variation in the salinity signal but resistant to fouling, are recommended as a means of increasing reliability.

The 92° W transect recommendation is designed to extend (in time) the moorings presently deployed there by the MMS. It would be beneficial to obtain a long time-series of measurements across the shelf to improve the climatological data base. The recommended instruments and deployment depths are identical with those presently deployed along this transect. Some additional instrumentation has been added for the purposes of this program.

The 94° W transect is instrumented with three upward looking, bottom-mounted acoustic doppler current meters to study details of the frontal current. Vertical resolution on the order of 2 m is desired. These meters should be deployed such that one is at the average position of the front/bottom interface, one is at the average position of the front/surface interface, and one is mid-way between the other two meters.

The instrumentation shown in Figure 51 and Table 6 will provide the information for the outer shelf/inner slope processes studies, the nearshore plume extension study, and the inner shelf processes study (see Section 3.1, by G.T. Csanady), with the exception of the drifter studies (Task 6 - inner shelf group), which are covered in subsection 4.3.1.3.

4.3.1.2 Hydrographic surveys

Hydrographic surveys are recommended at seasonal intervals throughout the field study period. The surveys should include transects across the shelf spaced at approximately 100 km intervals, and a transect along the shelf break. These are shown schematically in Figure 52.

The across-shelf hydrographic transects are vital to all process-oriented studies and to the modeling effort. They will contribute to the nearshore plume extension study, the inner shelf processes studies, and the outer shelf/upper slope processes studies. Dissolved oxygen determinations should be included at all hydrographic stations in water depths of less than 150 m to define hypoxic conditions along the coastline. Four of the transects coincide with the mooring transects shown in Figure 51. The transects should extend from as near shore as practical out to the 1000 m isobath.

A hydrographic survey approximately along the shelf break is recommended to more accurately resolve spatial scales of the processes impinging on the shelf from offshore. It is recommended that the survey be conducted as rapidly as possible along the 500 m isobath, between the 92° W and 26° N transects. Thus a reasonably quasi-synoptic set of measurements could be obtained. The along-shelf transect could be conducted either prior to, or after the across-shelf transects, but should not be conducted while steaming from one across-shelf transect to the next, in order to increase the synopticity of the along-shelf measurements.

4.3.1.3 Lagrangian studies

Two Lagrangian studies were recommended for the core program by the working groups:

- o Continuity of alongshore flow (Task 6, inner shelf group);
- o Drifter studies of Loop Current eddies (Task 7, outer shelf group).

The outer shelf group recommended deploying drifters in all Loop Current eddies which form during the measurement program. Eddies are strong features which have significant effects on the dynamics of shelf circulation. It is important to know not only the positions of such eddies, but also their kinematic characteristics. Drifting buoys with thermistor strings, drogued at 200 m or greater, would provide eddy position (especially important during warm months when satellite infrared data do not show eddies), velocity, and thermal structure. The outer shelf group also recommended drifting buoys drogued at shallower depths be deployed above the shelf and slope to measure circulation in the squirts and jets observed there in satellite imagery.

The inner shelf group recommended that drifter studies be conducted "to determine convergent and divergent regions of (the) nearshore frontal current". At least three drifter deployment areas would be required to determine the circulation patterns associated with the convergence/divergence: (1) area offshore Atchafalaya Bay (approximately along 91.5° W), (2) area half-way between Atchafalaya Bay and Galveston (approximately along 93° W), and (3) same distance west of Galveston (approximately along 96° W). The buoys' positions should be monitored continuously as long as possible to provide a synoptic picture of the surface circulation and its evolution over time.

4.3.2 Special studies

The inner shelf working group recommended three special studies to investigate certain processes of importance in the nearshore zone. These are a Mississippi River plume study, a sediment transport study, and a surf zone study. If conducted separately from the core program, each of these studies would still require much of the current and hydrographic data which will be collected by the core program. Therefore significant additional information on important processes could be obtained economically by conducting these special studies concurrently with the core program.

4.3.2.1 Mississippi River/Atchafalaya River plume near field study

A survey, several months in duration, is required of the combined plume from the Mississippi and Atchafalaya rivers. It was shown in the invited presentations that this is a complex region whose behavior is highly dependent on wind conditions.

The survey should be conducted under various wind conditions and should be guided by satellite observations. It should consist of hydrographic measurements in, and across the plume, with sufficient detail in the frontal zones to define the three-dimensional structure of these highly complex features. A possible hydrographic survey pattern is shown schematically in Figure 52. Lagrangian drifters should be deployed and tracked as part of the study.

4.3.2.2 Sediment transport studies

This study should be conducted to determine the extent and concentrations of sediment in the rivers' plume. The results could be used to ground-truth Landsat images, and perhaps other types of satellite imagery as well. Conventional transmissometers should be deployed on nearshore current meter moorings along the 92° W transect (Figure 51). A towed transmissometer, towed in a zig-zag pattern across the plume (in conjunction with the river plume study) is recommended (see Figure 52). Conventional instrumentation should be used.

4.3.2.3 Surf zone study

A surf zone study is needed "to establish (the) intensity of longshore currents under varying wind and wave conditions" (Task 12 - inner shelf group). It is recommended that electromagnetic current meters be deployed at the inner end of the 94° W transect, in the surf zone, for a period of one month (Figure 51).

4.4 Modeling Program

A hierarchy of models should be developed for the Gulf of Mexico. Physical processes ranging in scale from basin-wide to the Mississippi River near-field plume will require nesting of models of varying designs. The existing Gulf of Mexico basin-scale circulation model, which is capable of resolving the Loop Current and eddies, should be matched to a shelf-edge eddy exchange model, which in turn would provide the offshore boundary conditions for a shelf circulation model. The shelf circulation model would encompass the broad mid-to outer-shelf and would model the wind-driven circulation on the shelf. A coastal plume/front model should be suitably matched to the inner side of the shelf circulation model to simulate the extension of the river plumes, which effectively separates shelf circulation from the shore along the Louisiana-Texas shelf.

The shelf circulation model should treat surface and bottom mixed layers realistically, be driven by realistic winds, taking into account especially the explosive cyclogenesis near the shelfbreak, and should allow for surface heating and cooling. Interaction with typical offshore eddies should be analyzed for different time scales from frontal or tropical storm wind-events to the long-term seasonal mean circulation.

The inner shelf front model should contain all the important physical factors, including allowance for mass transfer via small-scale eddy shedding, aiming mainly for a realistic prediction of along-front transport (with an eye on risk analysis). Effects of changing river runoff and wind stress should be analyzed.

The shelf-edge eddy model should account for the effect of the steep continental slope on eddy dynamics, and should yield a realistic pressure field on the outer shelf, to be used in the shelf circulation model simulations.

4.5 Supporting Data

In addition to the specific programs recommended above, several other recommendations were made by the symposium participants. These are discussed briefly in the following subsections.

4.5.1 Satellite Imagery

Satellite imagery could prove to be of great benefit by supplementing, and aiding in the interpretation of the _in situ_ measurements. Remotely sensed images also could be used to monitor certain events (e.g. plume front) and plan event-oriented measurements. Several specific applications suggested during the symposium (and summarized by the outer shelf group) include:

- o Infrared scanners - These provide useful information for the Gulf of Mexico from about October through May. They can be useful in tracking eddies, and identifying thermal fronts.

- o Color scanners - Color scanners are useful for many of the same applications as infrared scanners, with the additional benefit of providing useful information year round. There are no color scanners in operation now, however one may be launched aboard the

Landsat-6 satellite in 1991. If this takes place in time to be useful, the MMS should incorporate data from it into this program. The relationship between color images and thermal and kinematic features would need to be defined however.

- Scatterometer on ERS - Surface wind speeds over the study area could be generated, particularly for special studies.

- Synthetic aperture radar - Information on surface waves, internal waves, and current shears could be generated and used to interpret some of the in situ data.

- Geosat altimeter data - Sea surface topography generated from Geosat data could prove useful when used in conjunction with the outermost current meter data and the trajectories of eddy-tracking buoys.

- Landsat - Landsat imagery has proven useful in identifying coastal currents and eddies, based on different sediment concentrations in the water masses. Landsat could be beneficial to the plume study and some of the other nearshore studies.

4.5.2 Ship of Opportunity hydrographic lines

The MMS has used ships of opportunity to economically deploy expendable bathythermographs (XBTs) in the past. It is recommended that the Service place high priority on finding ship operators willing to deploy XBTs (and possibly obtain thermal or acoustic doppler data) during the duration of this program.

4.5.3 Meteorological data

Meteorological data will be essential for many of the process studies recommended by the symposium participants. It was recommended by the inner shelf group that meteorological sensors and wave height sensors be installed at both ends of the four moored instrumentation transects (see Figure 51). In addition, it is recommended that data from appropriate shore stations be obtained and integrated with the other meteorological data.

Several oil companies are planning a joint program (Gulf of Mexico Meteorological/Oceanographic Monitoring System [MOMS]). Meteorological sensors, current meters, and wave height and direction sensors will be mounted adjacent to oil production platforms. (See paper by J. H. Allender.) All data except currents will be transmitted over the GOES satellite system and will be available in the public domain. The current data may be available on special request from the oil companies. MOMS data, where appropriately located, should be obtained and integrated with other data.

4.5.4 Data management and archiving

Large oceanographic programs frequently suffer from a lack of proper data management. This program undoubtedly will involve a large number of principal investigators (PIs) studying different, but interrelated processes who will need much of the same data. An efficient data management and dissemination program will be essential. The program must be capable of processing the raw data, producing plots, tables, correlations, etc., in a timely manner for all the PIs to obtain the data they need.

It also was recommended by the participants that the MMS include a requirement and funding for the PIs to submit all data to a central data bank such as the National Oceanographic Data Center. Data management and archiving might be handled most efficiently by one or two organizations, rather than individually by each PI.

4.5.5 Data interpretation

The data resulting from the field program should be analyzed and interpreted to answer questions such as those raised in the working group reports (Section 3.0). The analyses should be conducted to address the processes which influence shelf circulation and should be presented in a form which the modelers can use to calibrate and verify their models.

4.5.6 Event studies

It was recommended that some funding be set aside for event studies. Candidate events include eddies (particularly one which interacts with the shelf), river plumes, fronts, a hurricane wake, etc. Hydrographic measurements (XBT's, conductivity/temperature/depth) and current measurements (acoustic doppler current profilers, expendable current profilers) from either ships or airplanes, should be made.

4.5.7 Agency/industry studies

Four other measurement programs which may be conducted concurrently with the MMS Louisiana-Texas shelf program were identified during the symposium. These are:

- The Meteorological/Oceanographic Monitoring System to be conducted by a consortium of oil companies (see Section 2.3.5);
- Tide, current, and hydrographic measurements in Galveston Bay to be conducted by NOAA (see Section 2.3.11);
- Hydrographic measurements made by Texas A&M University during training cruises (see Section 2.2.25);
- Ongoing wave and meteorological measurements made by the National Data Buoy Center.

The locations of these measurement programs are shown in Figure 53. It was recommended that data from these programs be procured and analyzed with data from the MMS program. Locations of National Weather Service meteorological stations, C-MAN platforms, and NOS water level stations which will be active during the MMS programs are shown in Figure 6. These data also should be acquired and integrated into the MMS program, as appropriate.

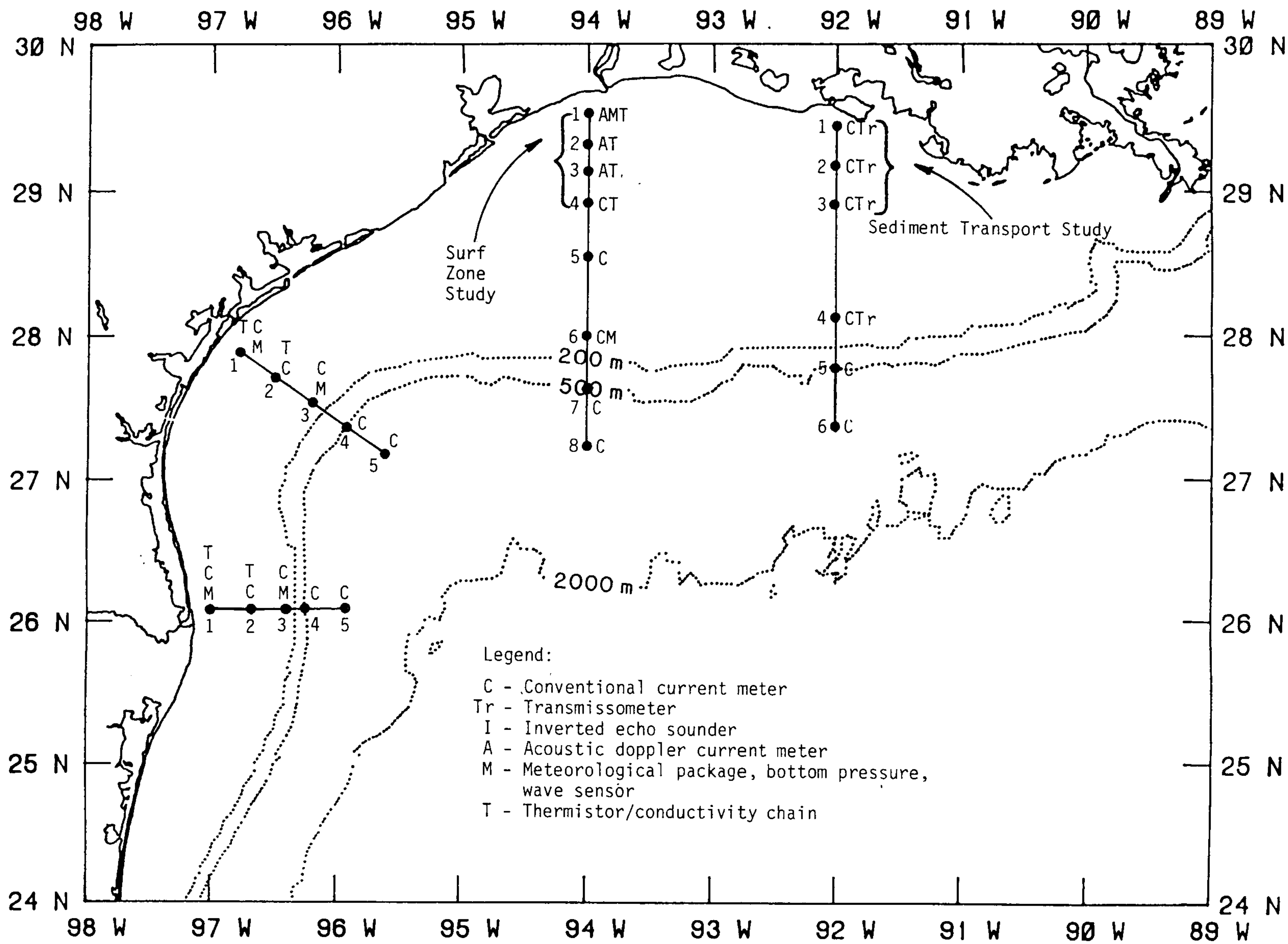

Figure 51. Moored array transects and instrumentation.

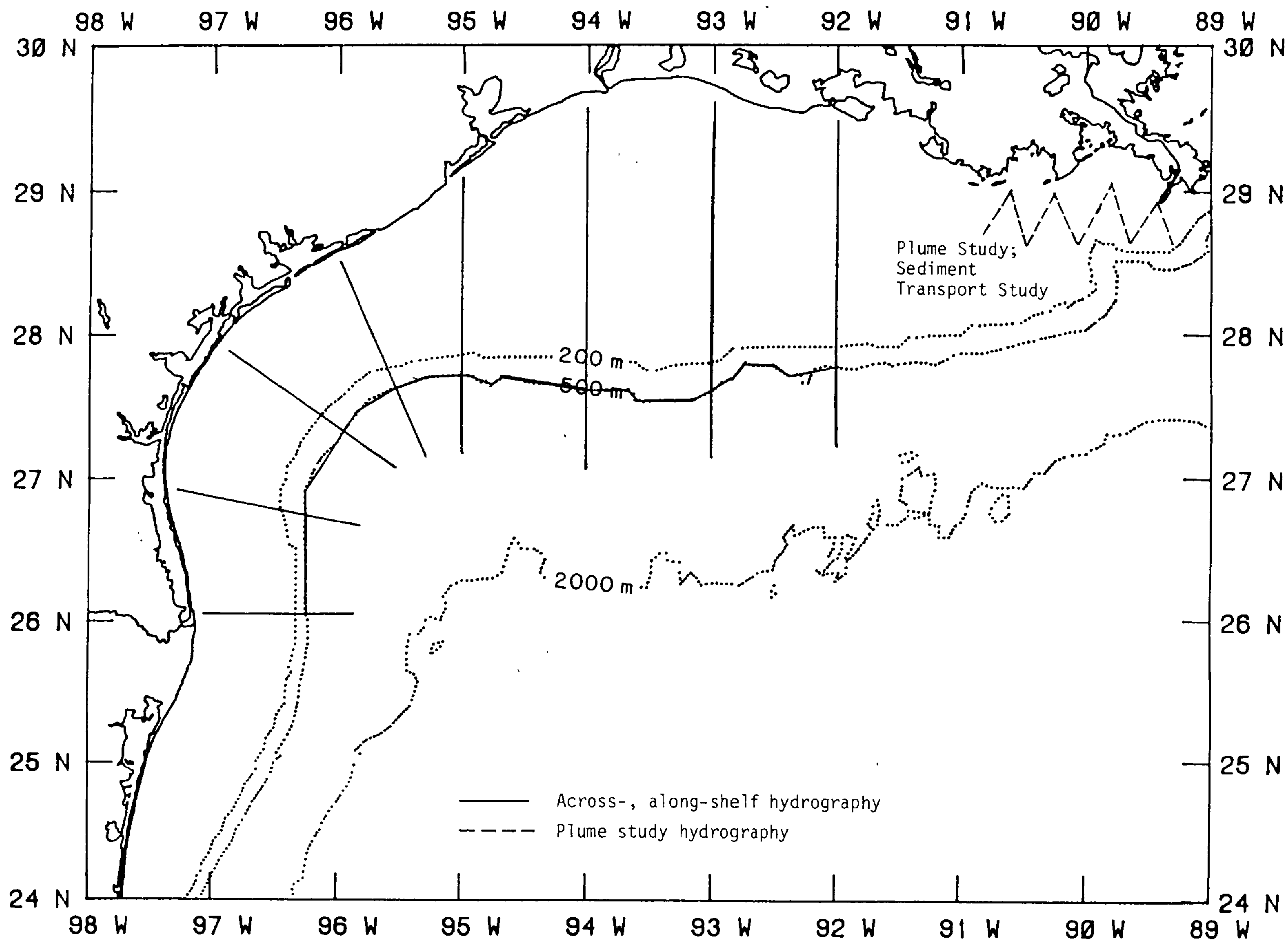

Figure 52. Hydrographic survey lines.

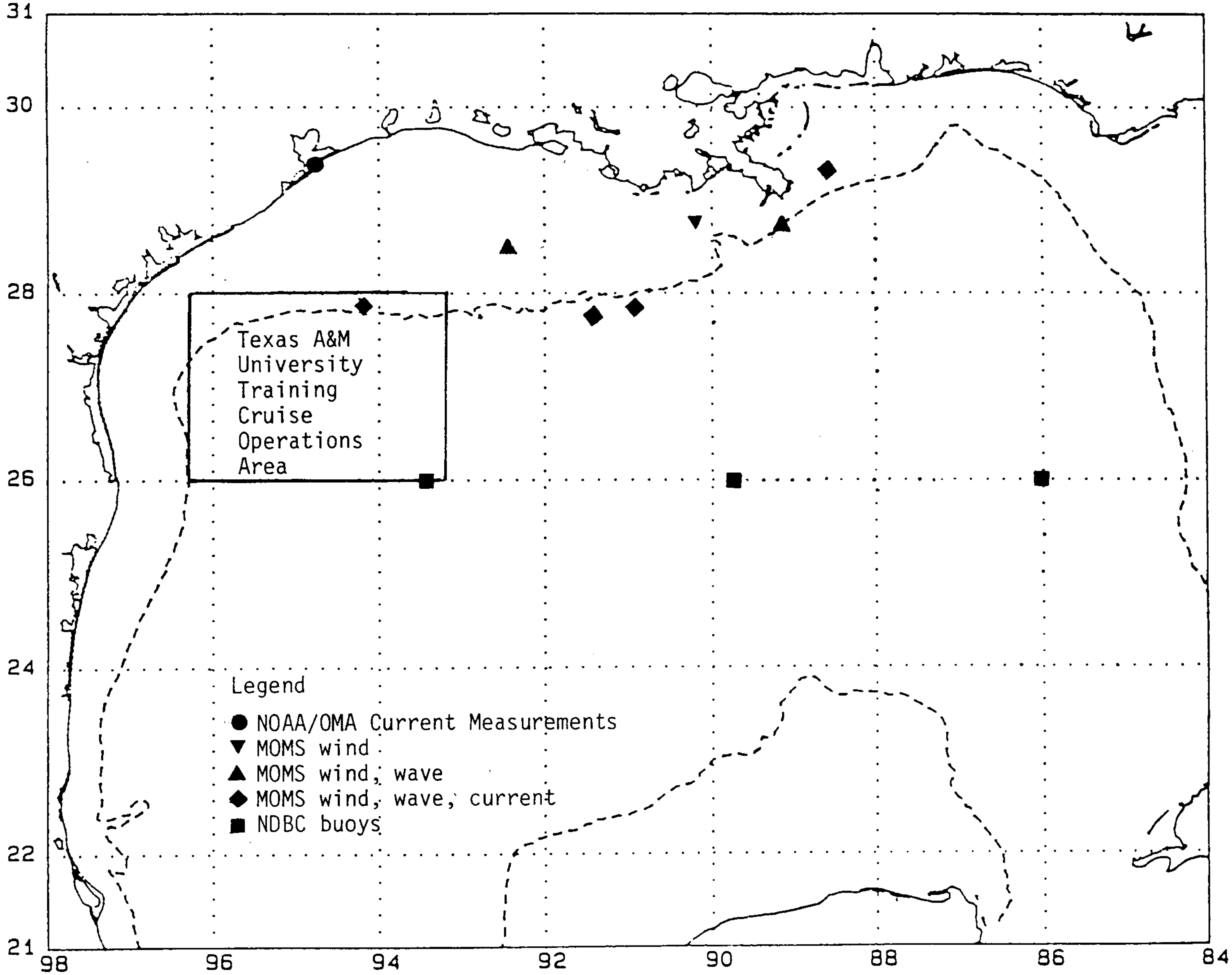

Figure 53. Agency/industry measurement sites which may be occupied during time period of the MMS physical oceanography program.

Table 6. Moored instrumentation.

92° W Transect

Array No.	Water Depth (m)	Instrumentation/Water Depth (m)
1	15	CM/7.5*, 12 Transmissometer/9.5* Pressure/Bottom Meteorology/Surface Waves/Surface
2	40	CM/12*, 18*, 37 Transmissometer/14*, 20*
3	64	CM/11*, 28*, 37, 57 Transmissometer/13.5*, 32*
4	181	CM/13*, 37, 57, 100*, 150*, 177 Transmissometer/15* Pressure/Bottom Meteorology/Surface Waves/Surface
5	500	CM/12, 37, 57, 177, 300, 400, 497
6	1000	CM/12, 37, 57, 177, 300, 400, 497, 997

Note: * - Instrument presently deployed by MMS
CM - Conventional current meter

Table 6 (cont'd). Moored instrumentation.

94° W Transect

Array No.	Water Depth (m)	Instrumentation/Water Depth (m)
1	TBD	ADCP/Bottom Pressure/Bottom Meteorology/Surface Waves/Surface Thermistors & Conductivity/ 2 m spacing: surface - bottom
2	TBD	ADCP/Bottom Thermistors & Conductivity/ 2 m spacing: surface - bottom
3	TBD	ADCP/Bottom Thermistors & Conductivity/ 2 m spacing: surface - bottom
4	40	CM/12, 37 Thermistors & Conductivity/ 2 m spacing: surface - bottom
5	60	CM/12, 37, 57
6	180	CM/12, 37, 57, 177 Pressure/Bottom Meteorology/Surface Waves/Surface
7	500	CM/12, 37, 57, 177, 300, 400, 497
8	1000	CM/12, 37, 57, 177, 300, 400, 497, 997

Note: TBD - To be determined, based on plume position
ADCP - Acoustic doppler current profiler
CM - Conventional current meter

Table 6 (cont'd). Moored instrumentation.

28° N and 26° N Transects

Array No.	Water Depth (m)	Instrumentation/Water Depth (m)
1	15	Thermistors & conductivity/ 2 m spacing: surface - bottom Pressure/Bottom Meteorology/Surface Waves/Surface CM/12
2	60	Thermistors & Conductivity/ 2 m spacing: surface - bottom CM/12, 37, 57
3	180	CM/12, 37, 57, 177 Pressure/Bottom Meteorology/Surface Waves/Surface
4	500	CM/12, 37, 57, 177, 300, 400, 497
5	1000	CM/12, 37, 57, 177, 300, 400, 497, 997

Note: CM - Conventional current meter

APPENDIX A

Agenda

"AS-CONDUCTED AGENDA"

U.S. Minerals Management Service

SYMPOSIUM ON THE PHYSICAL OCEANOGRAPHY OF THE LOUISIANA-TEXAS SHELF

Tuesday May 24, 1988
Galveston, Texas

1:00	Introduction and announcements	Dr. Thomas Mitchell University of Southern Mississippi Center for Marine Science Dr. Murray Brown Gulf of Mexico Region Minerals Management Service
1:10	Welcome to Galveston	Dr. James McCloy, Vice President for Academic Affairs Texas A&M University at Galveston
1:15	Why the Minerals Management Service conducts physical oceanographic studies	Mr. Ken Adams Gulf of Mexico Region Minerals Management Service
1:20	How the MMS Branch of Environmental Modeling will use the results of Gulf physical studies	Mr. Bob Labelle Branch of Environmental Modeling Minerals Management Service
1:40	Overview of shelf processes	Prof. Robert Reid Department of Oceanography Texas A&M University
2:00	General shelf circulation patterns/data sets available	Dr. Evans Waddell Science Applications International Corporation
2:20	Industry measurements: Moored and drifting	Dr. George Forristall Shell Development Co.
2:40	Eddy joint industry program	Dr. Cortis Cooper Conoco, Inc.
3:00	Break	**

3:15	Eddy circulation	Dr. James Lewis Science Applications International Corporation
3:35	Eddy/shelf interaction	Mr. Frank Kelly Civil Engineering Dept. Texas A&M University
3:55	Primary production/upwelling	Dr. James Yoder National Aeronautics and Space Administration
4:15	National Aeronautics and Space Administration: SEA-WIFS and other NASA remote sensing capabilities	Dr. James Yoder
4:30	Inner shelf circulation: Northern shelf	Mr. Frank Kelly
4:50	Inner shelf circulation: Southern shelf	Dr. Ned Smith Harbor Branch Oceanographic Institute

DINNER

7:30	Remote sensing: Frontal occurrence, future capabilities	Dr. Fred Vukovich Research Triangle Institute
7:50	Visual satellite observations of fronts on the LA/TX shelf	Dr. Lawrence Rouse Coastal Studies Institute Louisiana State University
8:10	Influence of Mississippi River plume on shelf hydrography	Dr. William Wiseman Coastal Studies Institute Louisiana State University
8:30	Shelf sediment dynamics	Dr. Alan Niedoroda Environmental Science and Engineering, Inc.

****************** Wednesday May 25, 1988 *****************************

8:00	Introduction	Dr. Thomas Mitchell
8:10	Marine meteorology and air-sea interactions in the NW Gulf of Mexico	Dr. Shih-Ang Hsu Coastal Studies Institute Louisiana State University
8:30	Ocean response to meteorological input	Dr. Shih-Ang Hsu, for Dr. Oscar Huh Coastal Studies Institute Louisiana State University
8:50	Fisheries and shelf interaction in the NW Gulf of Mexico	Dr. Mitchell Roffer ROFFS
9:25	Hypoxia	Dr. Nancy Nash Rabalais Louisiana Universities Marine Consortium
9:50	Oil industry uses/needs	Dr. Jerry Machemehl Civil Engineering Dept. Texas A&M University
10:15	Break **	
10:40	Hurricane modeling	Dr. Cortis Cooper
11:05	Tide/storm surge modeling	Prof. Robert Reid
11:40	Dynalysis circulation model	Dr. George Mellor Princeton University
12:05	Mexican Government programs, Future plans	Captain Alberto Vazquez Secretaria de Marina Mexico

LUNCH

1:30	National Marine Fisheries Service SEAMAP Program	Mr. Tom Van Devender Gulf States Marine Fisheries Commission
2:05	NORDA circulation model	Dr. Alan Wallcraft Jaycor, Inc.
2:35	U.S. Army Corps of Engineers wave hindcast	Dr. Jon Hubertz U.S. Army Corps of Engineers Waterways Experiment Station

3:00	Shelf circulation modeling	Dr. Donald Resio Offshore and Coastal Technologies, Inc.
3:25	Mexican Government programs, Future plans	Dr. Victor Vidal Instituto de Investigaciones Electricas
3:45	Break	**
4:00	Oil Industry Meteorological and Oceanographic Monitoring System	Dr. James Allender Chevron Oil Field Research Company
4:15	Studies of Mesoscale Cyclones in the Northwest Gulf of Mexico	Dr. Douglas Biggs Department of Oceanography Texas A&M University
4:25	National Marine Fisheries Service Operations in the Gulf of Mexico	Dr. Scott Nichols National Marine Fisheries Service
4:45	Environmental Protection Agency Gulf Initiative	Mr. Russell Putt Environmental Protection Agency
5:05	National Aeronautics and Space Administration: TOPEX	Dr. Robert Stewart Jet Propulsion Laboratory
5:30	National Oceanic and Atmospheric Administration: Data Archiving Activities	Mr. John Sylvester NOAA-NESDIS
5:50	U. S. Coast Guard Nowcasting surface currents for Search and rescue	Dr. David Paskausky U.S. Coast Guard Research and Development Center
6:10	National Oceanic and Atmospheric Administration: NOAA's Coastal Ocean Circulation Program	Dr. Henry Frey NOAA Office of Oceanography and Marine Assessment

******************* Thursday May 26, 1988 *************************

8:30	Introduction, instructions	Dr. Thomas Mitchell, Dr. Murray Brown Dr. Gabriel Csanady
9:00	Workshop session	
	* Inner shelf and Mississippi River Plume processes	Dr. Gabriel Csanady Department of Oceanography Old Dominion University
		Dr. Robert Guza Center for Coastal Studies Scripps Institution of Oceanography
	* Outer shelf and upper slope processes	Dr. George Forristall
	* Modeling and model/ observation comparisons	Dr. Dong-Ping Wang Marine Science Research Center State University of New York
11:00	Plenary: Workshop reports	Dr. Gabriel Csanady, Dr. George Forristall, Dr. Dong-Ping Wang

LUNCH

1:15	Plenary: Experiment design recommendations to accomplish MMS goals	All attendees
4:00	Closing remarks	Dr. Murray Brown

APPENDIX B

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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. The includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, 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 assure that their development is in the best interest of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. Administration.