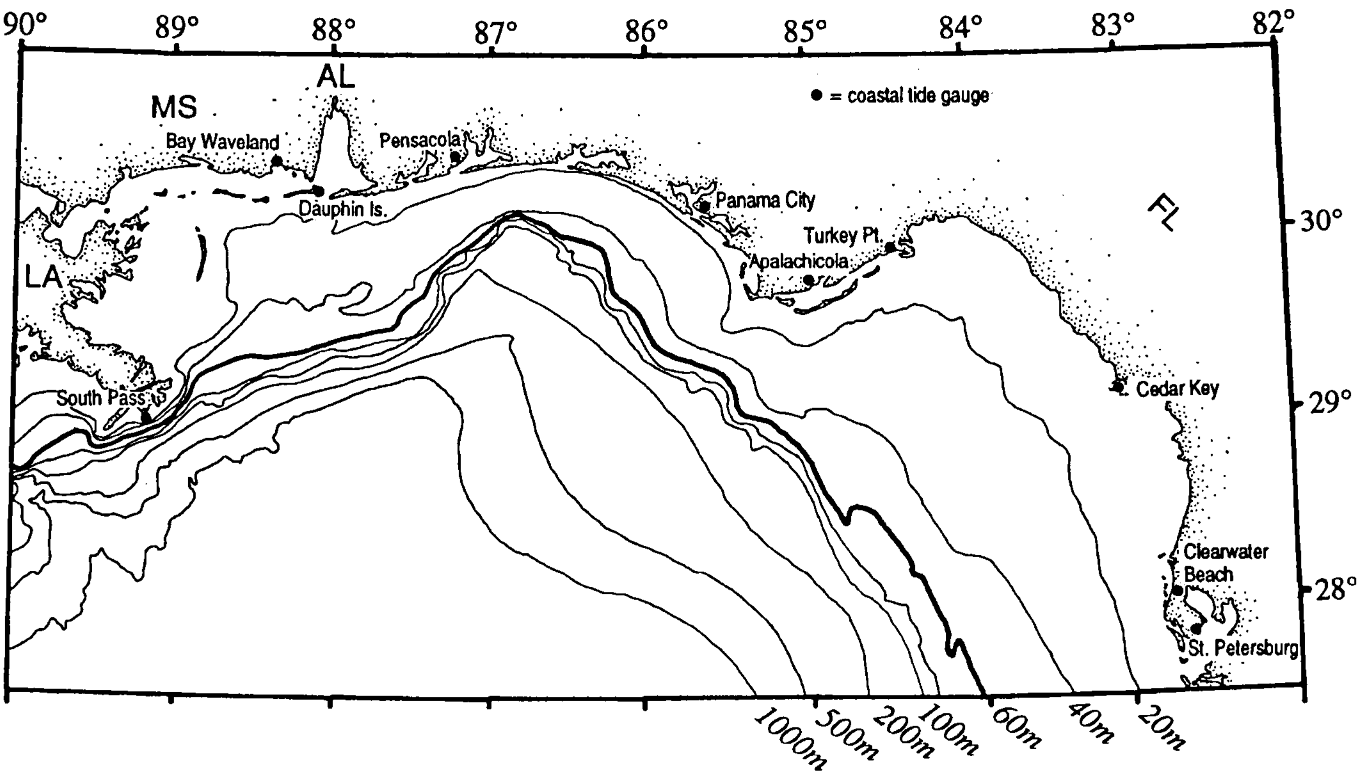
OCS Study
MMS 94-0044

Northeastern Gulf of Mexico Physical Oceanography Workshop

Proceedings of a Workshop Held in Tallahassee, Florida

April 5-7, 1994



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

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Editor

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EXECUTIVE SUMMARY

The Northeastern Gulf of Mexico, notwithstanding the richness of its shelf waters and its magnificent beaches, is arguably the least studied coastal region offshore the contiguous States. The region is presently being explored for oil and gas, prior to development. A new program of physical oceanographic studies, funded by the Minerals Management Service, may, subject to the availability of funds and programmatic approval, begin in FY 1996. The purpose of the Northeastern Gulf of Mexico Physical Oceanography Workshop, jointly funded by the Minerals Management Service and Florida State University, was twofold:

(1) Assess the state of knowledge of the circulation in the shelf and upper slope region of the northeastern Gulf of Mexico extending from the Mississippi Delta around, approximately, to Tampa Bay;

and

(2) Develop a strawman plan of possible experiments.

The workshop was divided into two parts. For the first one and one half days a series of invited speakers provided an overview of the physical oceanography and meteorology in the region and also discussed recent measurements, challenging problems, modeling and ongoing and planned measurements relevant to the study region. Following this background and an overview of some strawman plans formulated and provided to participants before the conference, the last half of the second day and the morning of the third day were spent formulating experimental plans.

The overview papers identified the main processes which operate on the shelf and upper slope. Nearshore buoyancy flow is more important in the west than east, because fresh water input by the Mississippi River and rivers flowing into Mobile Bay and to the west of it greatly exceeds that on the Florida part of the shelf. Dynamically we expect the buoyancy flow to be westward, but it seems that some of the Mississippi River water does influence the shelf in the Northeastern Gulf of Mexico (NEGOM) region of interest to the east. Although freshwater input to the Florida shelf is smaller, measurements near the Apalachicola River have shown that buoyancy effects are important shoreward of the 20 m isobath.

Tides in the Gulf of Mexico are modest. Shelf tidal currents in the NEGOM are strongest (~15 cm s^{-1}) on those sections of shelf which are wide because, in agreement with theory, semidiurnal tides are amplified across wide shelves. Diurnal tides are not amplified across the shelf and tidal sea levels at the coast are either diurnal or mixed depending on the amplification of the semidiurnal tide across the shelf.

Wind-driven currents and sea level fluctuations at "weather" time scales (periodicity of a few days to a few weeks) are strong in winter when the NEGOM shelf is influenced by a series of cold fronts from the north. The dynamics of the wind-driven, coastal sea level fluctuations is well understood but theoretical current predictions should be made and checked with the few available current meter measurements. Long term current measurements are sorely needed to assess the mean, interannual and seasonal flows which seem to be small but are not known over most of the shelf. Such flows are important because even if small they can still transport particles large distances. Particle displacements are important not only to the fate of pollutants but also for the transport of eggs and larvae of commercially important fish.

The Loop Current and eddies associated with it appear to influence mainly the outer continental shelf although in the region of the DeSoto Canyon, Loop Current water, probably trapped near the surface, has been observed to penetrate nearly to the coast. Satellite sea surface temperature patterns suggest eddy activity over the mid Mississippi-Alabama continental shelf at some times and unidirectional sheared flow at others.

Because of the unlikely availability of funds for a large comprehensive experiment like the western Gulf of Mexico LATEX experiment, the workshop focused on formulating plans for a series of smaller experiments. In order to stimulate thought before the workshop and discussion at the workshop, several strawman plans [see Appendix A] were formulated and provided to conferees before the workshop began. At the workshop three working groups in three breakout rooms considered plans for inner, mid and outershelf experiments. There was considerable discussion of the DeSoto Canyon because of the current drilling for natural gas in the region. The workshop included biologists, chemists and geologists and meteorologists and during discussions mutually beneficial collaborations became apparent. A summary of breakout room discussion is given in section 3.

1.0 INTRODUCTION

1.1 Background

The Northeastern Gulf of Mexico (NEGOM) has magnificent beaches and rich offshore waters supporting important commercial and recreational fishing industries. In spite of the beauty and value of these resources, the region is probably the least studied coastal ocean region offshore of the contiguous United States. Commercially important fish like the gag grouper are in danger of destruction yet we don't understand enough about the physical oceanography of the region to know how gag grouper eggs and larvae are transported from spawning grounds more than 100 km off the coast to the rich seagrass beds near the coast. This is just one of many coastal problems of great interest to the NEGOM States and its researchers.

The Minerals Management Service (MMS) also has an interest in the NEGOM, because it has responsibility for, among other things, assessing the impact of the oil and gas industry on the environment. The NEGOM is presently being explored for oil and gas, prior to development. It is therefore of considerable importance, both to the NEGOM states and the MMS that the basic physical oceanography of the region be understood. The MMS is considering a new program of physical oceanography studies in the NEGOM if funding is available.

In order to carry out such studies, we should assess what we now know of the physical oceanography of the region and, based on this, decide what the important problems are and make strawman plans. The NEGOM Physical Oceanography Workshop was convened to achieve these goals. The workshop was jointly funded by Florida State University and the MMS and took place on April 5-7 1994 in Tallahassee, Florida.

1.2 Workshop Structure

It is difficult for a group of about 135 researchers to formulate a coherent plan for a series of experiments over the limited time available during a workshop. It therefore seemed useful for a small group of physical oceanographers from the NEGOM States [M. Brown (MMS), A.J. Clarke (Florida State University), S. Dinnel (University of Southern Mississippi), W. Schroeder (University of Alabama), W. Sturges (Florida State University), G. Weatherly (Florida State University) and W. Wiseman (Louisiana State University)] to meet and formulate some strawman plans before the workshop. These plans would then be provided to workshop attendees before the workshop began so that attendees would be stimulated to think through their ideas before arriving in Tallahassee. The pre-workshop small group meeting took place in Tallahassee on November 1, 1993; strawman plans were discussed at this meeting, written later and then sent to each workshop participant 2 weeks before the conference. Appendix A contains these pre-conference strawman plans.

The workshop itself was divided into two parts. For the first one and one half days a series of invited speakers provided an overview of the physical oceanography and meteorology in the region and also discussed recent measurements, challenging problems, modeling and planned and ongoing measurements relevant to the study region. The schedule for the invited presentations is given in Appendix B and presentation summaries are given in section 2.

After overview and other relevant NEGOM oceanography had been presented on the first one and one half days of the workshop, W. Wiseman gave a brief overview of the pre-conference strawman plans and R. Defenbaugh (MMS) commented on MMS interests in the NEGOM. Breakout room discussion, chaired by L. Atkinson (outer shelf), K. Brink (mid shelf) and R. Garvine (inner shelf) then followed in three separate rooms. The breakout room discussion allowed ample opportunity for all conferees (see list of participants in Appendix C) to express their views and interact constructively. On the morning of the third day of the workshop, a plenary session allowed each breakout room chairman to present a summary of their group's discussions. There then followed final discussion in the breakout rooms and arrangements for a written report from each group. Breakout room summaries and experimental recommendations are presented in section 3.

2.0 INVITED PRESENTATIONS

2.0 INVITED PRESENTATIONS

The invited presentations were designed to summarize what is known about the physical oceanography of the NEGOM (see section 2.1) and provide other background for discussion of possible experiments. Recent measurements, challenging problems, relevant results from the Louisiana-Texas shelf experiment (LATEX) in the western GOM and modeling in the region were all discussed. Each speaker was required to provide a written summary of his presentation. These follow.

2.1 Overview of the Physical Oceanography and Meteorology on the West Florida, Alabama and Mississippi Shelves in the Study Region

2.1.1 OVERVIEW OF THE PHYSICAL OCEANOGRAPHY OF THE LOUISIANA-MISSISSIPPI-ALABAMA CONTINENTAL SHELF

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The Louisiana-Mississippi-Alabama continental shelf province is triangular in shape; bounded to the west by the Chandeleur Islands and Mississippi River delta and to the east by the western rim of the DeSoto Canyon off the Panhandle of Florida. It includes the region from the shoreline or barrier islands out to the shelf break around 100 m and is generally described as a gently sloping, flat plain punctuated by scattered clusters of topographic features, up to 18 m in relief, along the outer shelf. The shelf has a maximum width of approximately 125 km in the west and progressively narrows eastward to a width of 25 km at the head of DeSoto Canyon. A prominent characteristic of this shelf is the abrupt 90° change in the east-west orientation of the Mississippi-Alabama barrier island coastline to the north-south trend of the Chandeleur Islands and Mississippi River birdfoot delta coastline.

River runoff to this shelf is highly variable. The Mississippi River dominates the region with an average discharge of over 14,000 m^3s^{-1}. Although much of this runoff flows westward onto the west Louisiana shelf, it remains the largest source of freshwater to the Louisiana-Mississippi-Alabama shelf, followed in importance by the Alabama and Tombigbee Rivers. These rivers converge to form the Mobile River system flowing into Mobile Bay, Alabama. Average discharge into Mobile Bay is approximately 2,200 m^3s^{-1}. West of Mobile Bay to Chandeleur Sound, numerous rivers contribute an average discharge of just over 1,220 m^3s^{-1}, the largest coming from the Pascagoula and Pearl Rivers. To the east of Mobile Bay, runoff from the Florida Panhandle is considerably lower, averaging less than 800 m^3s^{-1}. Thus, most of the local runoff flows onto the shelf east of Mobile Bay.

High pressure over the Atlantic is the dominant factor controlling late spring and summer weather patterns. This semi-permanent subtropical anticyclone, referred to as the Atlantic (Bermuda) High, drives a persistent southerly flow of humid air. In addition, land-sea breeze systems are frequently observed along the coastlines. During the late fall through early spring, the Atlantic High retreats southward allowing the polar front to make numerous incursions into the region. On average, these cold waves of polar continental or Arctic air last for about three days.

Tides are diurnal in this portion of the northern Gulf of Mexico. The mean diurnal amplitude has been estimated to be 45-46 cm, while the tropic (maximum) and equatorial (minimum) amplitudes are estimated to be 60 and 0 cm, respectively.

Early studies of the surface flow patterns over the shelf region east of the Mississippi River delta were based on pilot charts (Leipper, 1970) and surface drifter and hydrographic data (Chew, 1955; Chew *et al.*, 1962; Drennan, 1963, 1968; Tolbert and Salsman, 1964). These studies suggest (1) the presence of a large semi-permanent cyclonic surface gyre and (2) in the area of DeSoto Canyon, a branching of the southeastern portion of the gyre into a northward-flowing component, which follows the western rim of the Canyon and is part of the gyre proper and, a southeastward-flowing component which moves along the west Florida Shelf break. Some investigators have speculated on the relationship between circulation on the shelf and the Loop Current (Chew *et al.*, 1962; Tolbert and Salsman, 1964). One of the more interesting considerations is the degree to which shelf waters, in particular nearshore coastal waters, are either mixed with or entrained by the Loop Current waters during periods of extreme northerly intrusion (north of 29°N).

Work in the 1970's and 80's began to improve our understanding of the variability of this shelf. For example, Chuang *et al.* (1982) and Schroeder *et al.* (1985) provide insight into the wind-driven component of the system, while Thompson and Leming (1978) addressed the role of density gradients imposed by seasonal fresh water runoff and Schroeder and Crozier (1974) documented the impact of an extreme flooding event from the Mississippi River. Additionally, Schroeder *et al.* (1987) describe examples of both wind-driven shelf circulation patterns and the direct entrainment of outer shelf water into the northern periphery of the Loop Current through a careful deductive analysis of the movement of buoys that broke free of moorings on the Alabama inner shelf.

Drennan (1968) suggested an eastward flow over the outer shelf which he associated with the Loop Current. Recent advances in our understanding of Loop Current intrusions make suspect the conclusion of a mean eastward flow. Dinnel (1988) analyzed all NODC hydrographic data from this shelf and identified a mean high in the dynamic topography (0/500 db) located at the shelf break near 88.25°W. Seasonal variability was present. The degree of influence of Loop Current intrusions and eddies on this data set is unclear. Long-term current meter measurements present a different picture. Molinari and Mayer (1982) and Kelly (1991) indicate mean eastward flows above 200 m over the outer shelf and slope, but these data sets are dominated by flow during Loop Current (or Loop Current eddy) interactions with the shelf/slope region. Wiseman and Dinnel (1988) observed oscillatory flow south of the Mississippi River delta for many months until the Loop Current penetrated to the vicinity of the delta when a strong eastward flow developed and persisted, in the mean, for over four months.

Over the inner shelf, the available current meter measurements suggest a mean westward flow south of the Mississippi-Alabama barrier islands (Dinnel, 1988). This flow is strongly responsive to wind-forcing and vertically coherent during the winter. During the stratified summer season, the vertical coherence is less significant. East of the Chandeleur Islands, the flow appears to be southward in the mean. The forcing for this flow is unclear, but may be related to unmeasured pressure gradients which develop in the corner region where the two island chains meet.

Few measurements exist over the mid shelf. Perhaps the most interesting observations are due to careful analyses of satellite sea surface temperature patterns by Vastano *et al.* (1991). They often observe a wealth of mesoscale activity in the derived surface flow field including features which resemble eddies, jets and squirts. At other times, though, the surface flow field appears to be a unidirectional sheared flow.

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2.1.2 OVERVIEW OF THE PHYSICAL OCEANOGRAPHY OF THE FLORIDA SHELF IN THE STUDY REGION

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Introduction

The region of interest consists of that part of the West Florida Shelf extending from about 27°N to the Florida-Alabama border. Flow on this shelf is due to the tides, the wind, fresh water input from coastal streams and springs and the deep sea Gulf of Mexico Loop Current. An interannual flow may also occur. I will consider each of these and sea level rise below.

The Tides

The diurnal tide in the Gulf of Mexico is dominated by the K_1 and O_1 constituents. Except near the two straits, both constituents are nearly uniform in amplitude and phase across the Gulf (see, *e.g.*, Figure 1). In the northeastern Gulf of Mexico shelf region of interest, the K_1 and O_1 tides have an amplitude of about 16 cm. Observations of shelf K_1 and O_1 tidal currents in the Northeastern Gulf of Mexico are sparse; on the very wide shelf seaward of Cedar Key (see Figure 3 for location of Cedar Key), Marmorino (1983a) estimated that the semi-major K_1 and O_1 tidal current ellipse axes were oriented approximately perpendicular to the shore and were as large as 7 cm s^{-1} and 4 cm s^{-1} respectively.

The main semidiurnal tide in the Gulf is the M_2. This tide is largely (65%) driven by direct tidal forcing on the Gulf (Reid and Whitaker, 1981). In contrast with the diurnal tide, this tide varies spatially and is strongly amplified across the wide West Florida Shelf (see Figure 2). Such semi-diurnal tidal amplification is typical across very wide non-polar continental shelves (Clarke & Battisti, 1981; for a detailed physical discussion see Clarke, 1991).

Figures 3 and 4 show M_2 observed tidal current ellipses and measurement location for the West Florida Shelf compared with those calculated using the analytical theory of Battisti and Clarke (1982a,b). Currents south of St. Petersburg (and therefore south of the region of interest) have been included to indicate likely tidal current behavior in the southern part of the region of interest. In the south the tidal current vectors rotate clockwise and have major and minor ellipse axes approximately perpendicular and parallel to the coast and in the ratio ω/f. This is typical of shelves in which friction and alongshore gradients play a minor dynamical role (see the dynamical discussion on page 97 of Clarke, 1991).

Further to the north on the wider part of the shelf the M_2 tidal current strengthens from about 10 cm s^{-1} to 15 cm s^{-1}. The single measurement shown in Figure 4 seems typical of the region -- Marmorino (1983a,b) deduced similar M_2 tidal currents (but with non-negligible semi-minor axis) from other moored current meter measurements in the region (see the locations M1, M2 and M5 in Figure 5). On the outer part of the shelf the M_2 current ellipse has similar orientation and shape (see the location M3 of Figure 5), but has its semi-major axis reduced to about 8 cm s^{-1} as the M_2 tide is less amplified in the deeper water near the shelf edge. As the shelf narrows to the north, we expect the shelf M_2 tide not to be amplified and this is consistent with the small 3 cm s^{-1} amplitude M_2 tidal current at location M4 in Figure 5. Finally, note that although diurnal and semi-diurnal tidal currents dominate the observed current field nearshore on the wide part of the shelf (Marmorino, 1983a,b), because such currents are of high frequency, maximum particle displacement due to the tides is only about 5 km.

The Wind-Driven Flow

The main wind forcing of the West Florida Shelf waters takes place in the winter as fronts from the north move over the shelf. The low-frequency (several day periodicity) coastal sea level fluctuations, which are highly correlated with the large-scale low-frequency wind, are therefore much larger in winter. The sea level fluctuations increase in amplitude northward along the straight part of the shelf from Key West to Shell Point (see Figures 6 & 7).

Why should the sea level amplitude increase northward? Since coastally trapped waves (CTWs) travel with the coast on their right in the northern hemisphere, the only way energy can enter the West Florida Shelf is from the narrow shelf off east Florida. Apparently only a small amount of energy rounds the Keys and enters the West Florida Shelf because the Key West sea level amplitude is small (see Figure 7). Suppose, for simplicity, that we put $\eta = 0$ at the Keys and consider a wind blowing northward along the coast as shown in Figure 8. At the coastline, where the depth integrated flow perpendicular to the coast is zero, the wind-driven onshore Ekman transport is balanced by an offshore geostrophic flow. This geostrophic flow has higher sea level on the right so sea level amplitude increases to the north. Similarly, sea level becomes increasingly negative (the sea level amplitude increases) northward when the wind is southward. A more precise explanation, taking into account time dependence and bottom friction can be given in terms of a sum of two mode 1 continental shelf waves; one corresponds to a forced, mode 1 wave traveling with the wind stress along an infinitely long straight coastline and the other to a free wave added to cause cancellation and $\eta = 0$ at the Keys (Mitchum and Clarke, 1986).

Theory indicates that wind-driven currents and sea levels are strongest near the coast where the blocking of the Ekman flow occurs [see, *e.g.*, the numerical West Florida Shelf results of Clarke and Van Gorder (1986)]. Low-frequency pressure observations (Marmorino, 1983a) across the shelf seaward of Cedar Key (see locations M1-M3 of Figure 5) are in agreement with the theory in that the pressure is highly coherent with the wind and decreases seaward. Marmorino found that the pressure field is barotropic and gives geostrophic flow in good agreement with the current observations. Barotropic low-frequency pressure and flow is to be expected theoretically (Clarke & Brink, 1985) since $N^2\alpha^2/f^2 << 1$ (N = buoyancy frequency, α = shelf slope, f = Coriolis parameter).

Current meter observations (see Figure 5 for a summary of those taken) consistently show that the low-frequency flow is wind driven on the inner and mid shelf and to a smaller extent on the outershelf where shelf edge processes associated with the Loop Current may be important (see below). The current meter observations also show the existence of a bottom boundary layer ~8 m thick which behaves qualitatively in the Ekman sense (Marmorino, 1983a).

In Florida's Big Bend (the section of coast containing Shell Point, Turkey Point and Apalachicola--see Figure 6), the isobaths curve strongly and the shelf width decreases by a factor of 3. Since the low-frequency ($\omega << f$) flow is barotropic, by the Taylor-Proudman Theorem we expect the flow to follow the isobaths approximately. Because of geostrophic balance pressure will then be approximately constant along the isobaths and when isobaths converge, the low-frequency current will strengthen. Measurements by Marmorino (1983a) confirm this; low-frequency currents approximately double from M3 to M4 in Figure 5. The circulation in the Big Bend region is of considerable importance to fisheries (see the article by C. Koenig in this volume) as eggs and larvae from spawning fish more than 100 km offshore are somehow carried to the coast.

Although we understand something of the fluctuating wind-driven flow on "weather" time scales, much less is known about seasonal and long-term mean flow because only at locations M5 and DD in Figure 5 are long term records available and these have not been fully analyzed and reported. We expect that the seasonal and mean flows are weak and, from dynamics, that they will approximately follow the isobaths; however, at this point we know neither the flow direction along the isobaths, nor the structure of the seasonal and long-term flow. On the outer shelf mean flows are probably associated with the loop current while nearshore are probably due to the wind or possibly buoyancy forcing from fresh water input. Note that even if the seasonal and mean flow is weak, it is important because it influences the long-term transport of suspended material along the coast.

As well as directly driving currents, the wind has a considerable influence on water temperature and stratification. In summer a thermocline exists over the shelf but in winter the wind mixes the water so that the isotherms are approximately vertical (see Figures 9 & 10). The temperature decreases shoreward presumably because the wind-induced evaporation extracts heat from a smaller depth of water.

Nearshore Buoyancy Flow

Although the major Florida rivers (see Figure 11) are puny compared to the Mississippi, they do seem to freshen significantly the nearshore region shallower than about 20 m (see Figures 12 & 13). A hydrographic section in Florida's Big Bend (see Figure 11) shows that in summer, a halocline, thermocline and pycnocline are all present; in winter these are usually mixed by the wind to give horizontal rather than vertical gradients (see Figures 12 & 13).

Where does the fresh water influencing the hydrographic section come from? Because of the Coriolis force, we expect entering fresh water to turn westward along the coast, so perhaps the lower salinity seen at the section is due to input from the Suwannee (see Figure 11). Or are wind-driven eastward currents bringing Apalachicola River water into the region? A related question is: How typical is this hydrographic structure of other nearshore sections along the northeastern Gulf of Mexico coast? And how important to the dynamics is mixing by the tidal currents? These questions are still to be answered. Jack Blanton (this volume, section 2.3.6) discusses the dynamics of nearshore buoyancy flows.

Loop Current Forcing of Shelf Waters

From shelf edge current meter and hydrographic measurements to the south of the region of interest, Niiler (1976) suggested that the Loop Current influences shelf flow near the shelf edge. This is consistent with Marmorino's (1983a) current measurements to the north. These show a marked increase in low-frequency current amplitude near the shelf edge. In addition, Huh *et al.* (1981) provided satellite and ground truth evidence of the intrusion of Loop Current water onto the shelf near the DeSoto canyon off Pensacola. It seems that the Loop Current probably influences outershelf flow over the length of Florida's shelf in the northeastern Gulf of Mexico region of interest. F. Kelly discusses this process in more detail later in this volume.

Sea Level Rise

Figure 14 shows that on both east and west coasts of Florida the sea level is rising. Because of the interdecadal variability, the trend can only be approximately estimated at about 2 mm/year. This is the same order as estimates of the global sea level rise (*e.g.*, Douglas, 1991). If, as it seems, the sea level rise is due to the global sea level rise, then sea level gradients are negligible and so, by geostrophy, is the flow.

Interdecadal Flow

The interdecadal variability in Figure 14 is related to a signal along the southern Atlantic coast of the United States (see the figures in Hicks and Crosby, 1974). This signal appears to be trapped on the shelf for it is distinct from the deep sea signal observed at Bermuda (see Figure 13.7 of Roemmich, 1990). If the signal is trapped on the shelf, then assuming that the sea level η becomes small near the shelf edge, an estimated average shelf alongshore flow $\bar{v}$ can be found from geostrophy as

$$\bar{v} = g\eta/Lf$$

where g, η, L and f refer, respectively, to the acceleration due to gravity, the coastal sea level, the shelf width and the Coriolis parameter. For interdecadal coastal sea level fluctuations of a few cm, $g = 10$ m s^{-2}, $L = 150$ km, $f = 7 \times 10^{-5}$ s^{-1}, $\bar{v}$ is a few cm s^{-1}. Although this flow is small, the frequency is so low that particle displacements associated with the flow will be of order 1000 km. Therefore this flow could be important to biological and other shelf processes that depend on the transport of material along the shelf.

Concluding Remarks

The West Florida Shelf is a commercially important resource--we must measure and understand it if we are to use it wisely. Although we have learned some things about the flow and how it is caused, there is still much to be discovered and understood.

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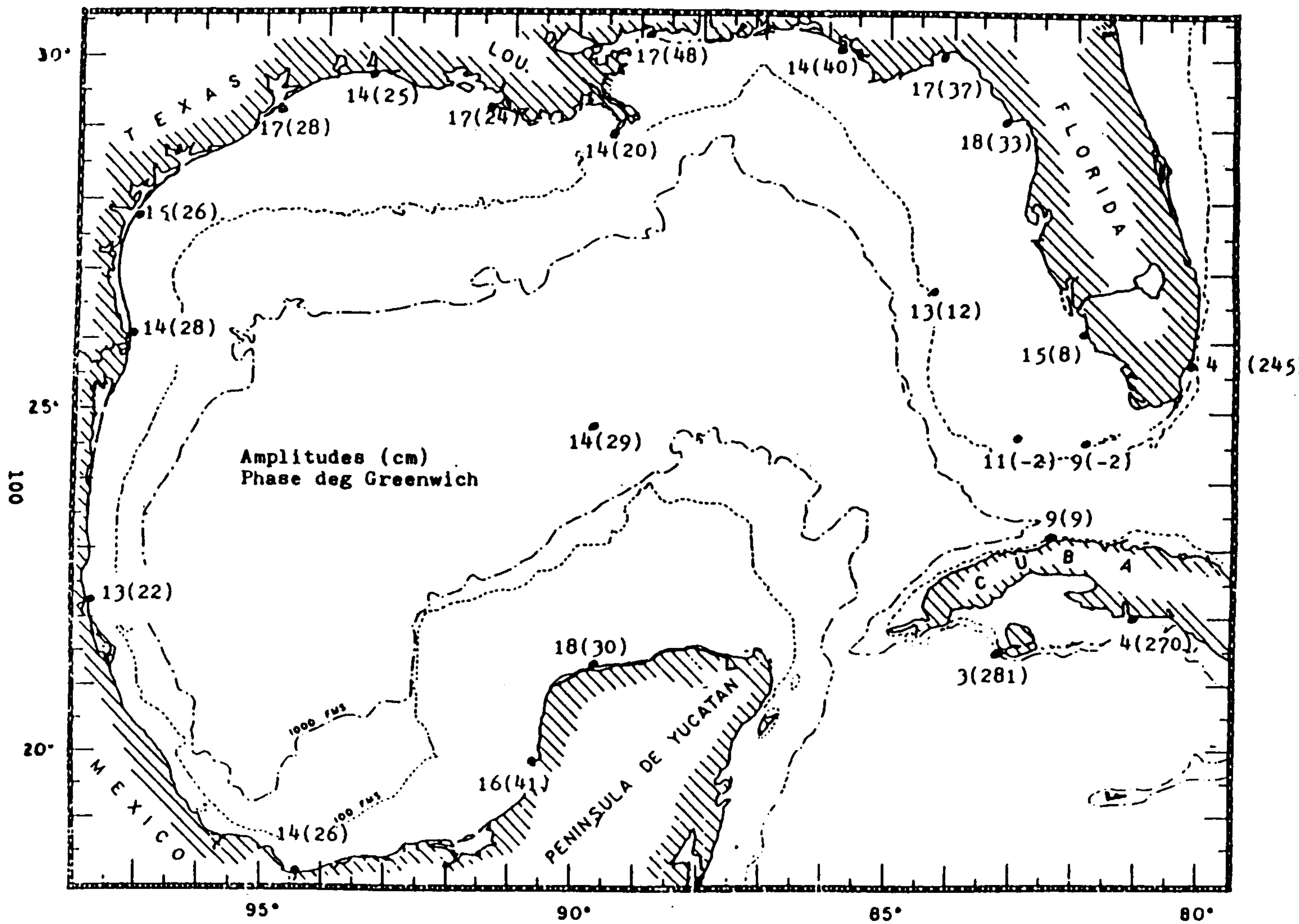


Figure 1. Observations of the K_1 tide in the Gulf of Mexico. Greenwich phase (in degrees) is given in parentheses. (After Reid, 1988).

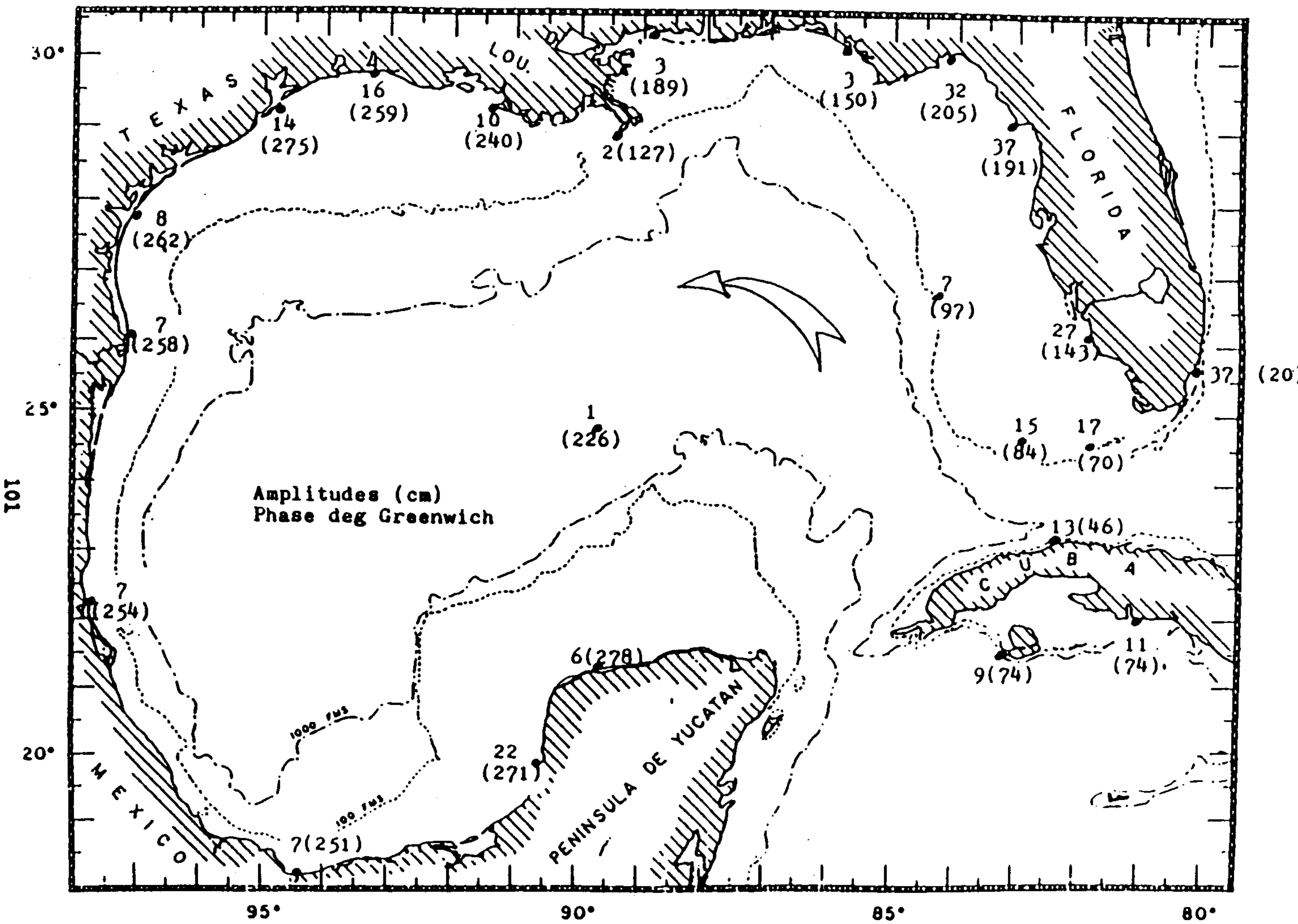
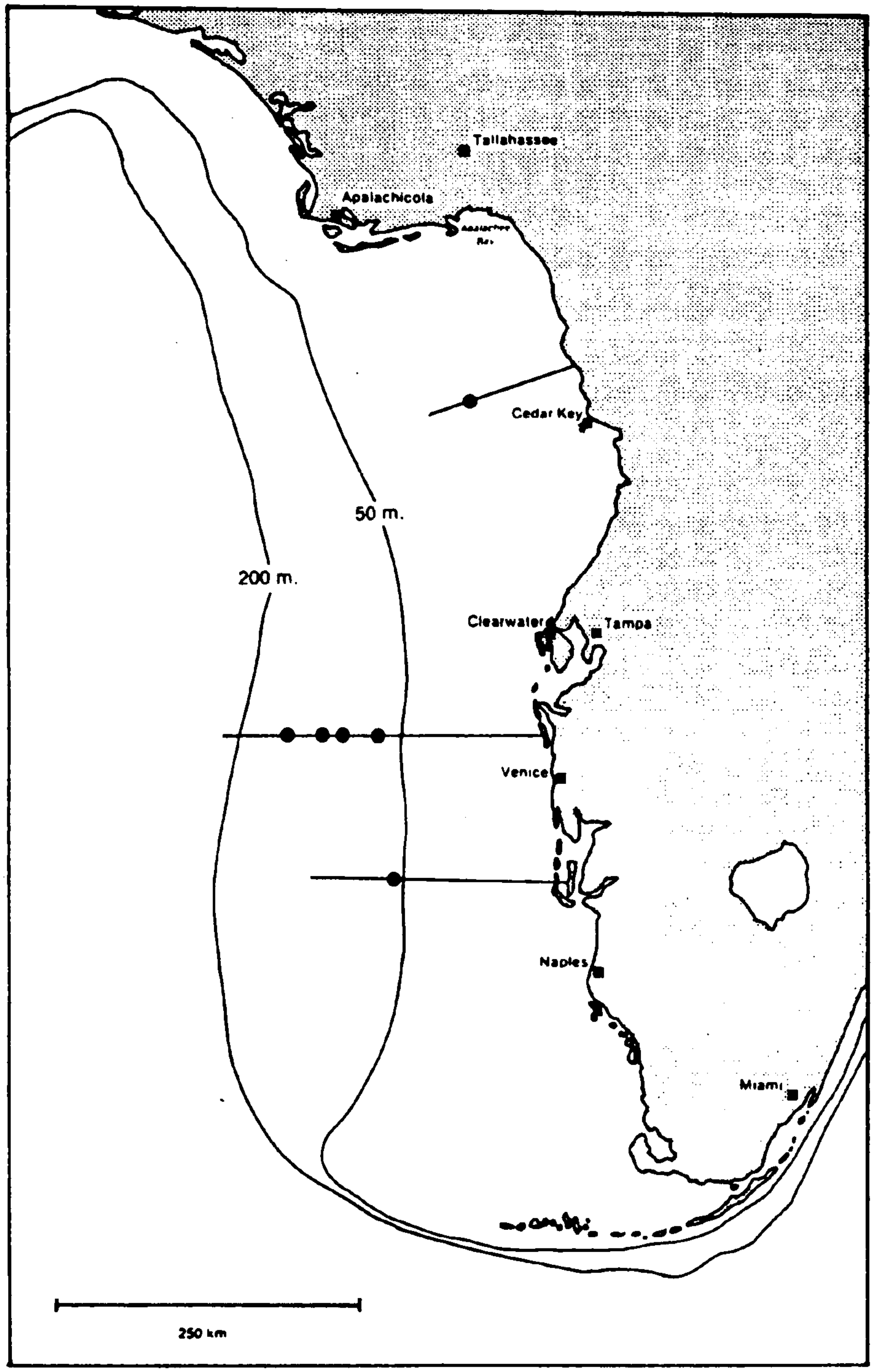


Figure 2. Observations of the M_2 tide in the Gulf of Mexico. Greenwich phase (in degrees) is given in parentheses. (After Reid, 1988).



WEST FLORIDA SHELF

Figure 3. Locations of some tidal current observations (solid dots) on the West Florida Shelf. (After Battisti & Clarke, 1982b).

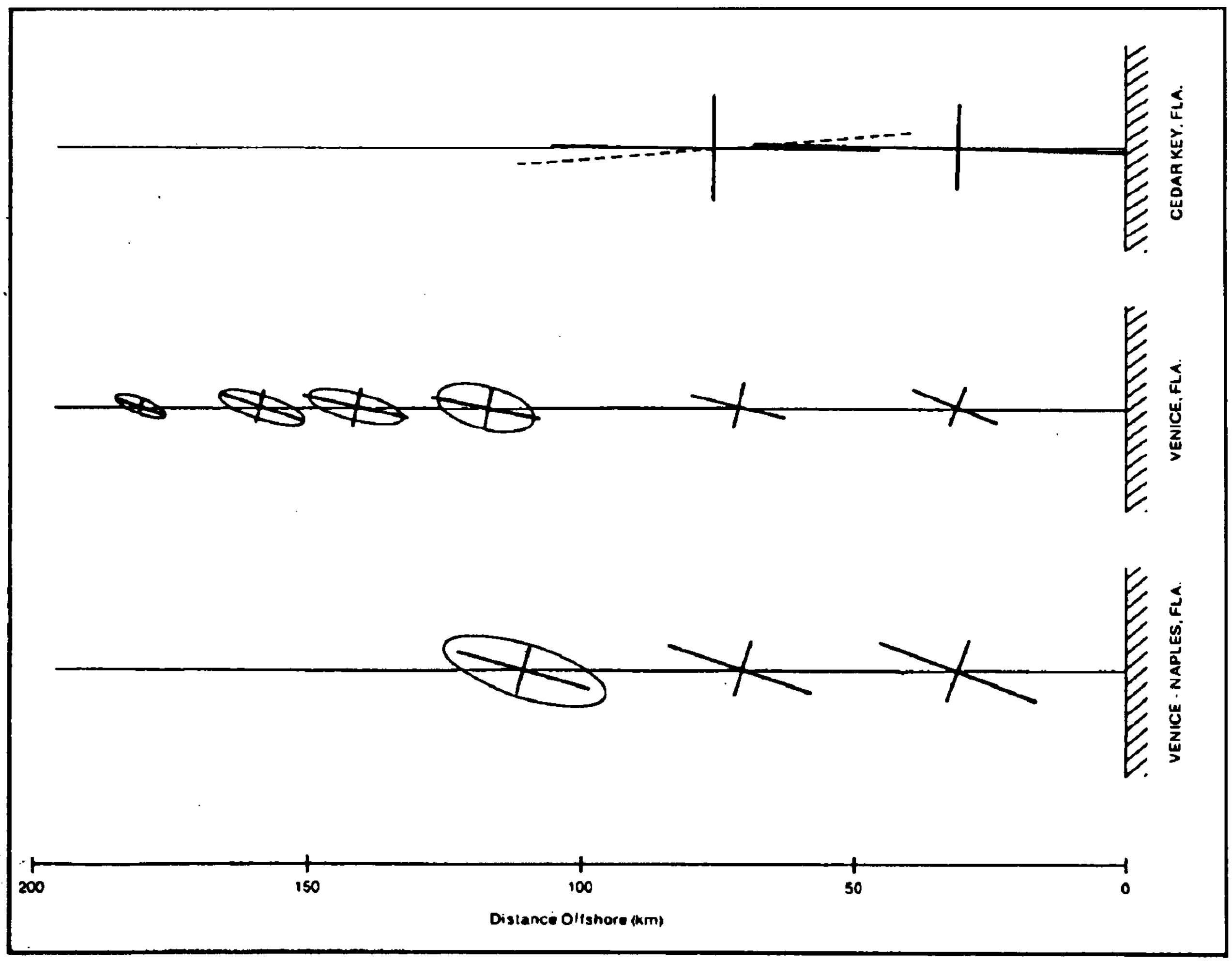


Figure 4. Observed tidal current ellipses and those calculated using the theory of Battisti and Clarke (1982a,b). The solid ellipse axes describe the calculated current ellipses and the ellipses themselves denote the observed tidal ellipses. Observation and theory are in perfect agreement when the axes fit exactly inside the ellipses. The oblique dashed line off Cedar Key is an observed current with zero semi-minor axis. Locations of the observed currents are given in Figure 3. (After Battisti and Clarke, 1982b).

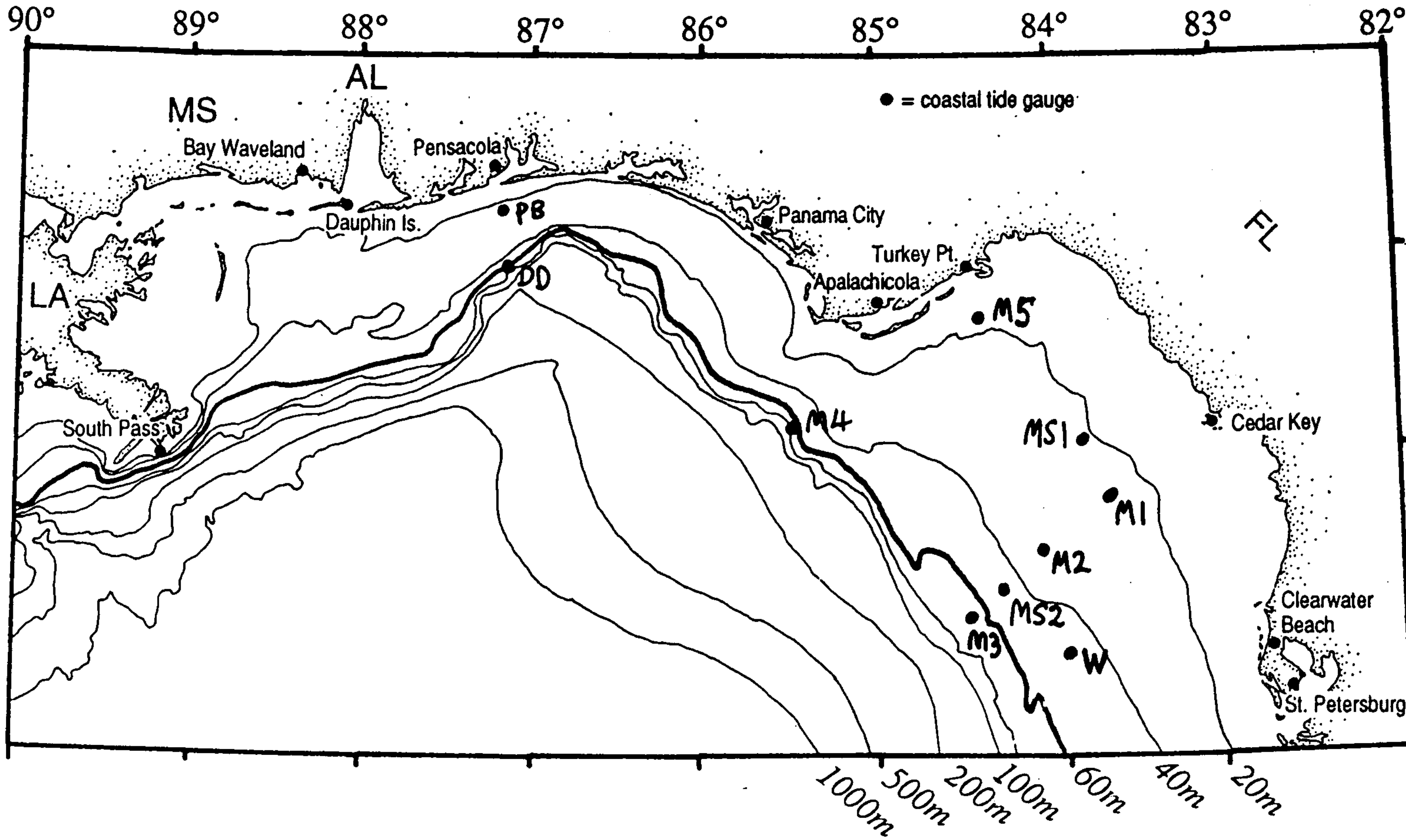


Figure 5. Summary of moored velocity measurements taken on the West Florida Shelf part of the region of interest. MS1-MS2 [26 Feb-20 Mar 1978 (23 days), Mitchum and Sturges, 1982]; M1-M4 [29 Nov 1981-8 Feb 1982 (71 days), Marmorino (1983a)]; M5 [15 Aug-15 Sep 1978 (31 days), Marmorino (1983b); Nov 1989-Apr 1990, Harkema *et al.,* 1991; Nov 1990-Apr 1991, Harkema *et al.,* 1992; Dec 1991-Apr 1992, Harkema *et al.,* 1993; Jul 1992-Oct 1992, Harkema *et al.,* 1994]; PB [Feb 1987-Jun 1987 and Oct 1987-Jan 1988, Pickett & Burns, 1988]; DD [more than 1 1/2 years of recent data, see Sturges (this volume)]; W [Weisberg, measurements in progress, personal communication].

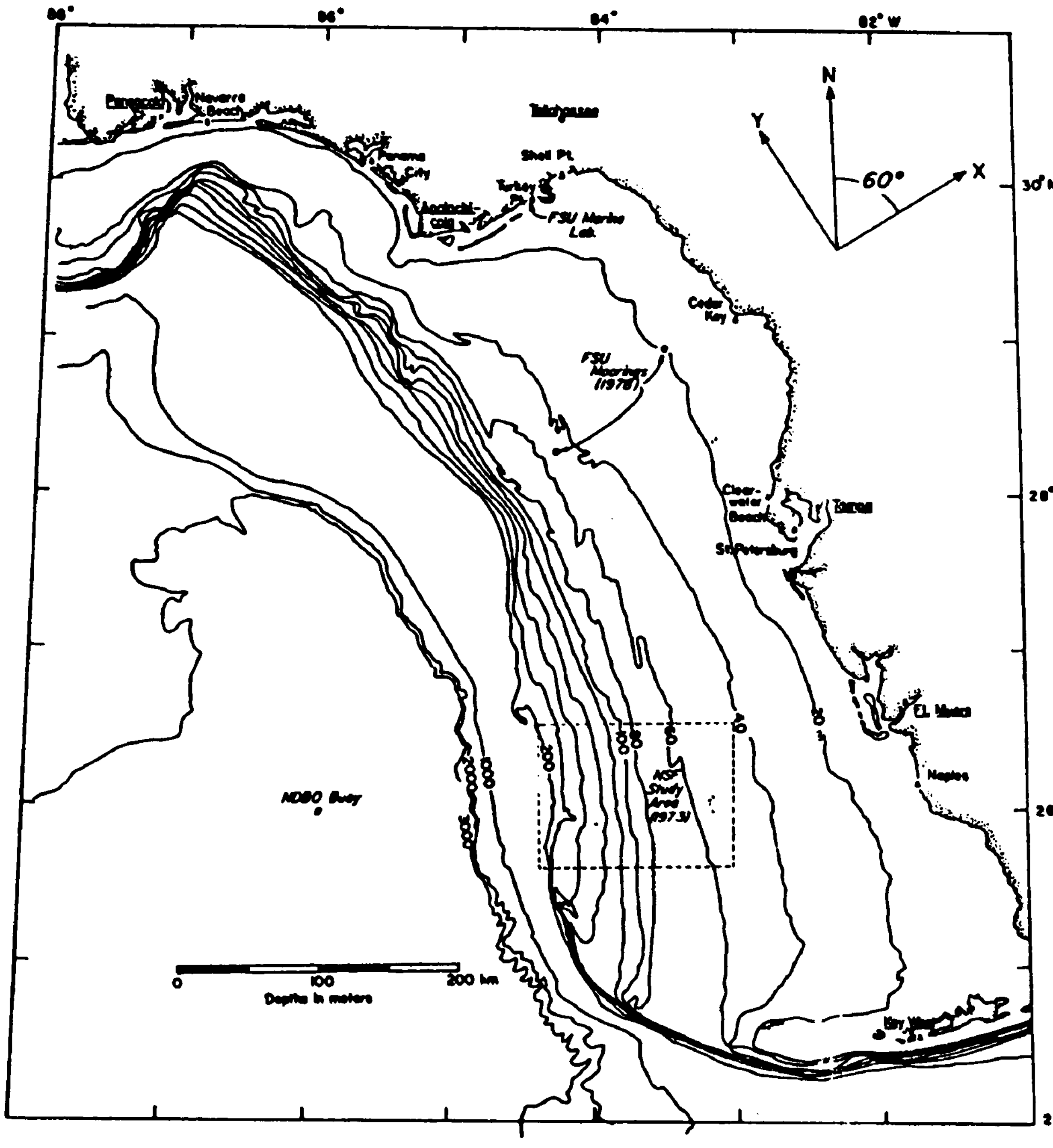


Figure 6. West Florida Shelf showing the coastal towns where coastal sea level measurements were made. (After Marmorino, 1982)

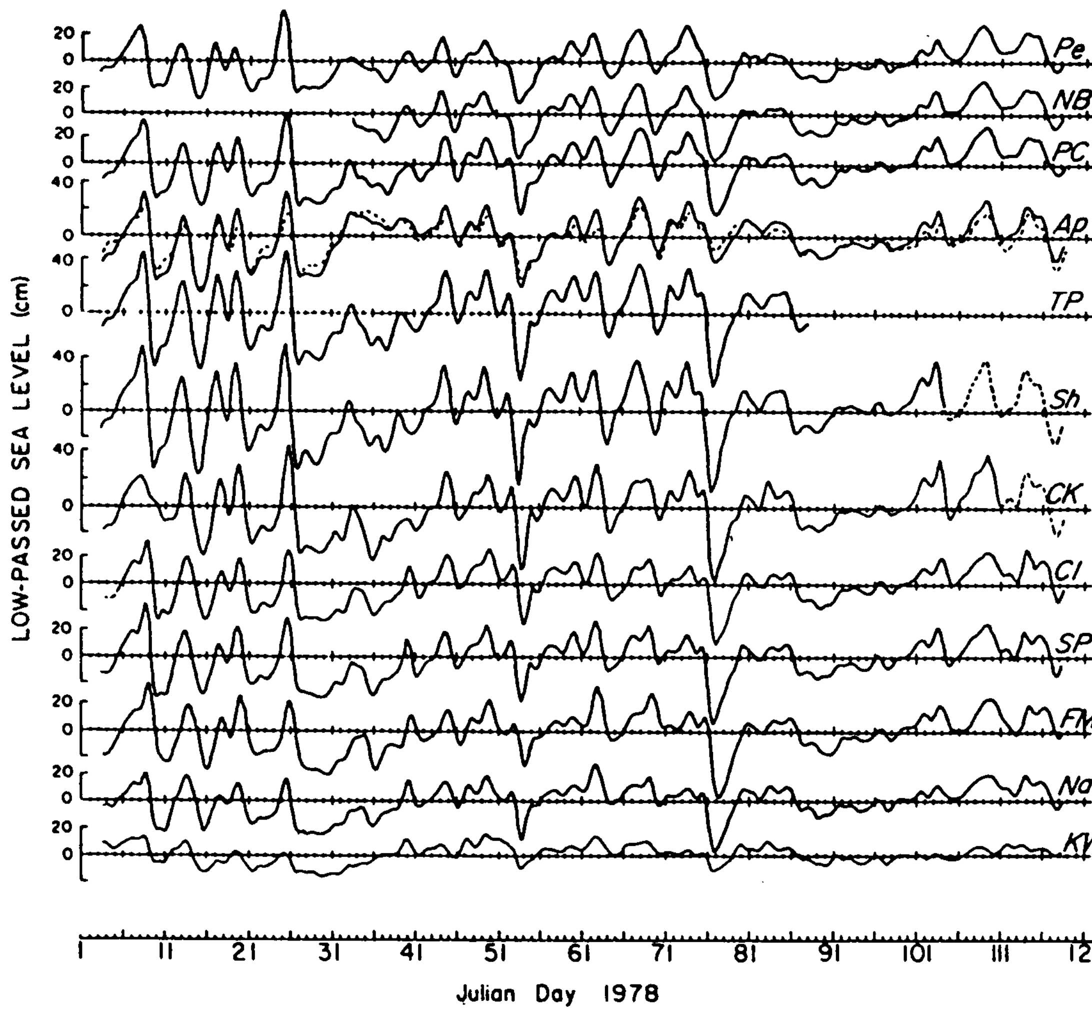


Figure 7. Low pass filtered West Florida Shelf sea levels. KW = Key West, Na = Naples, FM = Fort Myers, SP = St. Petersburg, Cl = Clearwater Beach, CK = Cedar Key, Sh = Shell Point, TP = Turkey Point, Ap = Apalachicola, PC = Panama City, NB = Navarre Beach and Pe = Pensacola. Station locations are shown in Fig. 6. (After Marmorino, 1982).

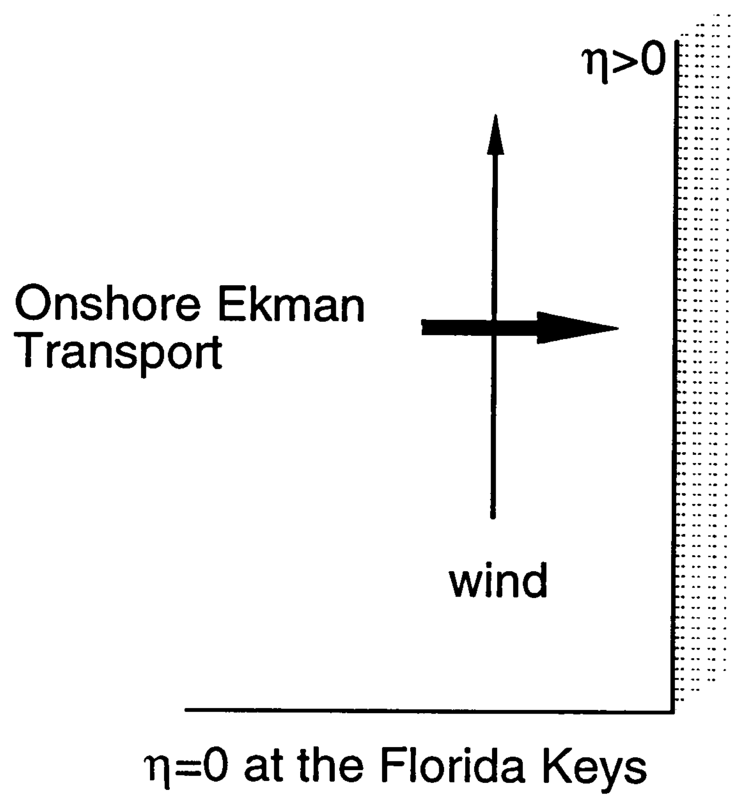


Figure 8. Idealized model explaining low-frequency sea level change along the West Florida Shelf (see text).

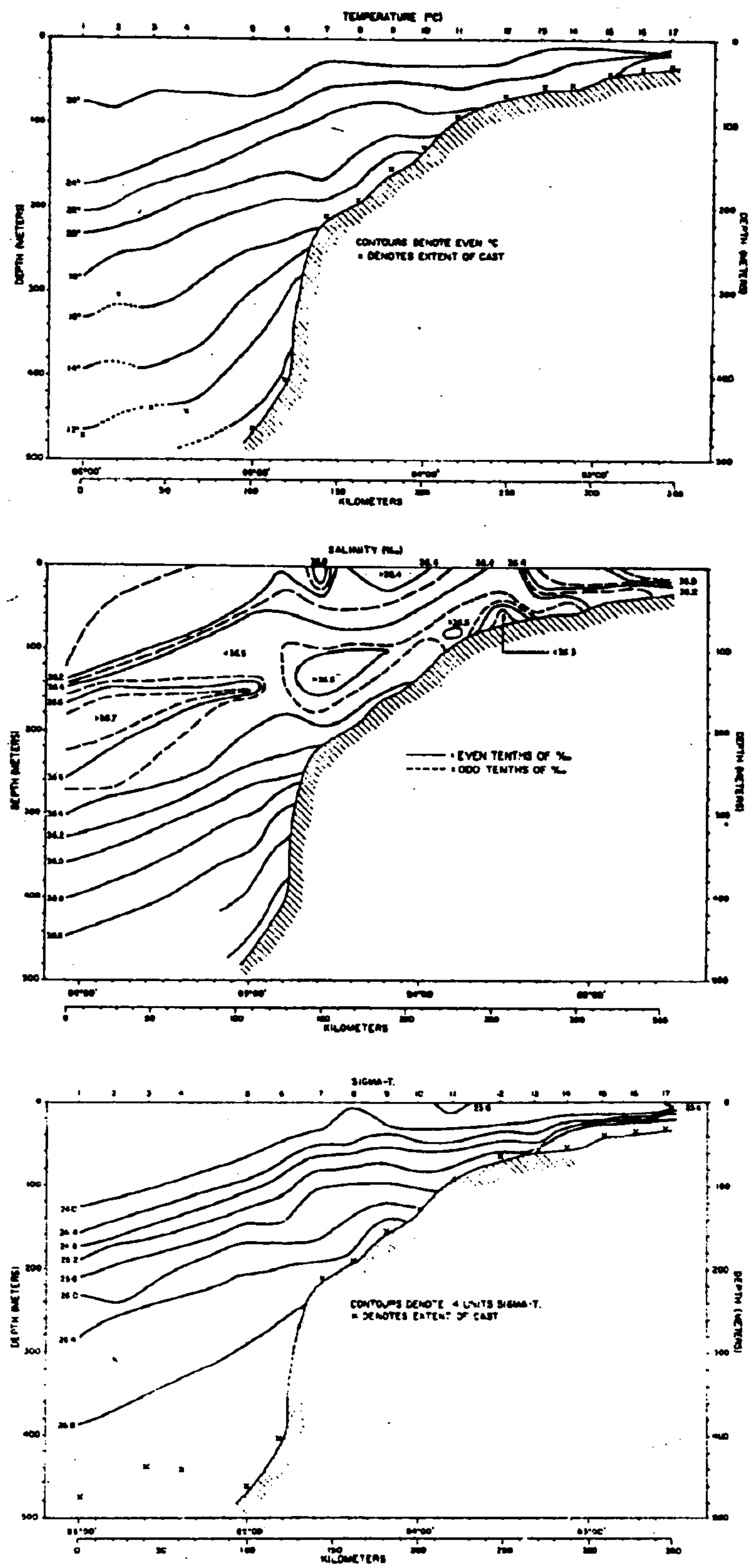


Figure 9. Summer (6 Jun 1972) conditions for a section across the West Florida Shelf at 26°N.

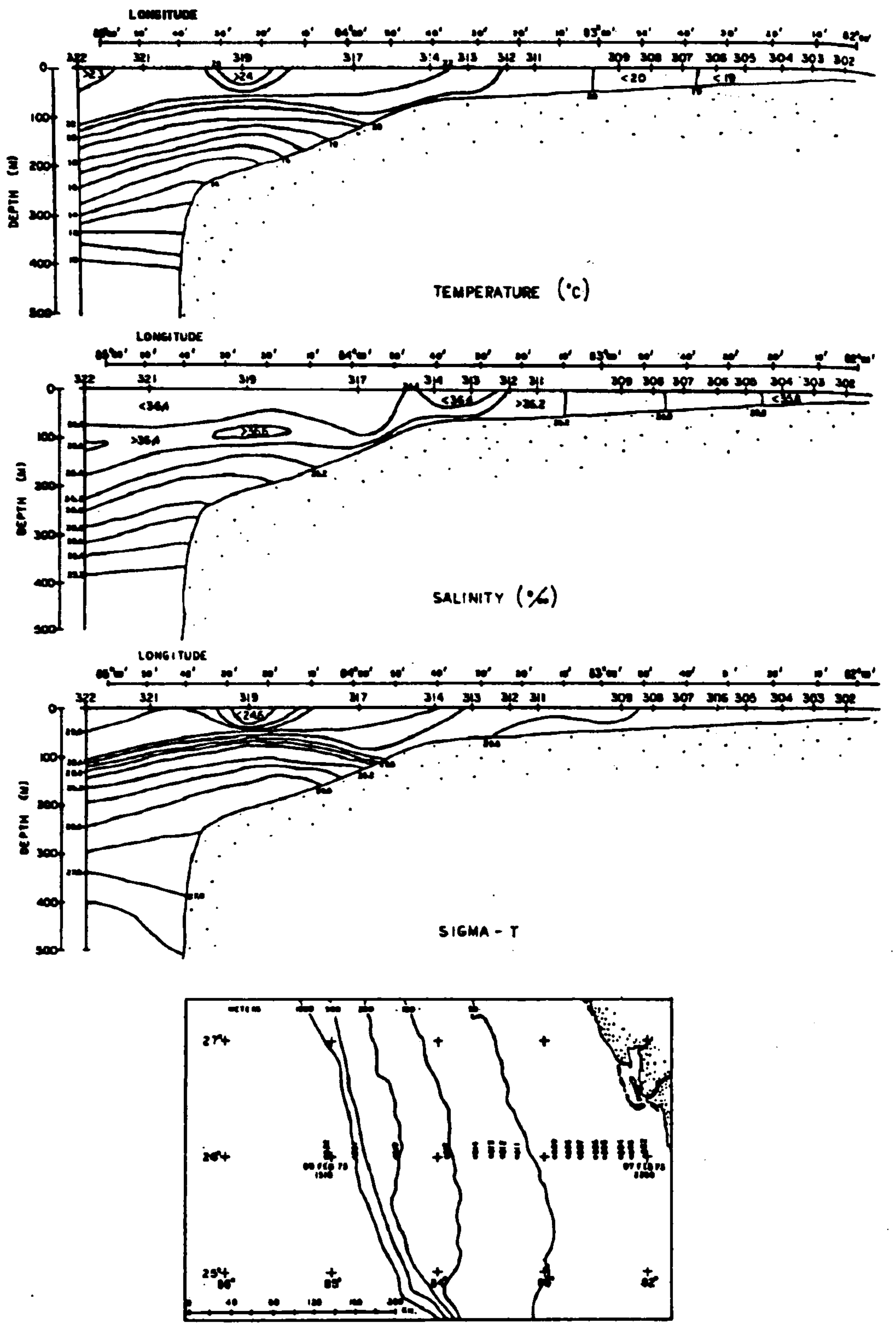


Figure 10. Winter (7-9 Feb 1973) conditions for a section across the West Florida Shelf at 26°N. The winter winds remove the summer stratification and cause temperature to decrease toward the coast (see text). (After Niiler, 1976).

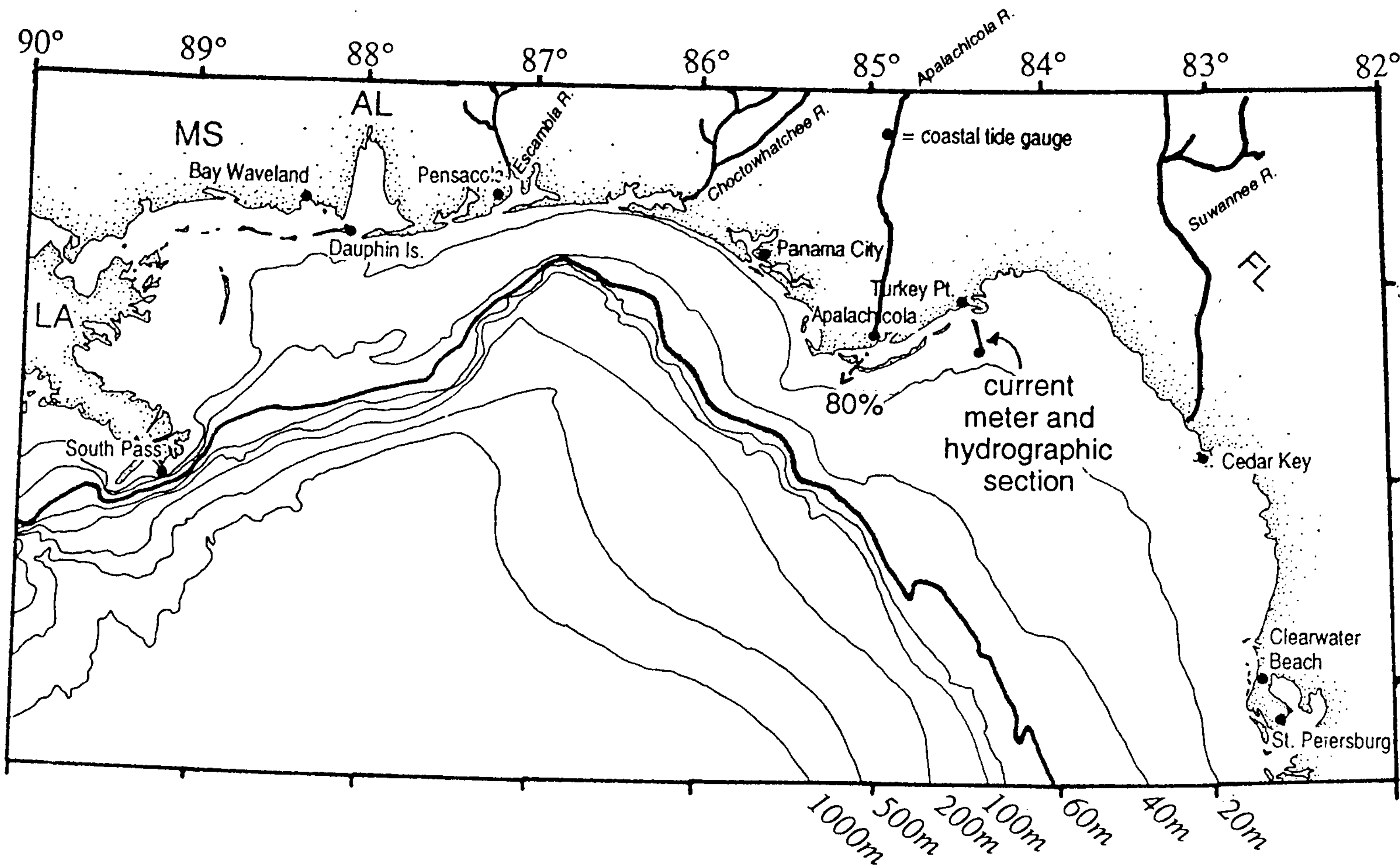


Figure 11. The major Florida rivers entering the Gulf in the region of study. Their measured average flows are: Apalachicola (701 m^3s^{-1}), Suwannee (301 m^3s^{-1}), Choctawhatchee (204 m^3s^{-1}) and Escambia (178 $m^3 s^{-1}$). These flows are tiny compared to the Mississippi (17,560 $m^3 s^{-1}$) but they have an influence on the coastal flow out to about the 20 m isobath (see text).

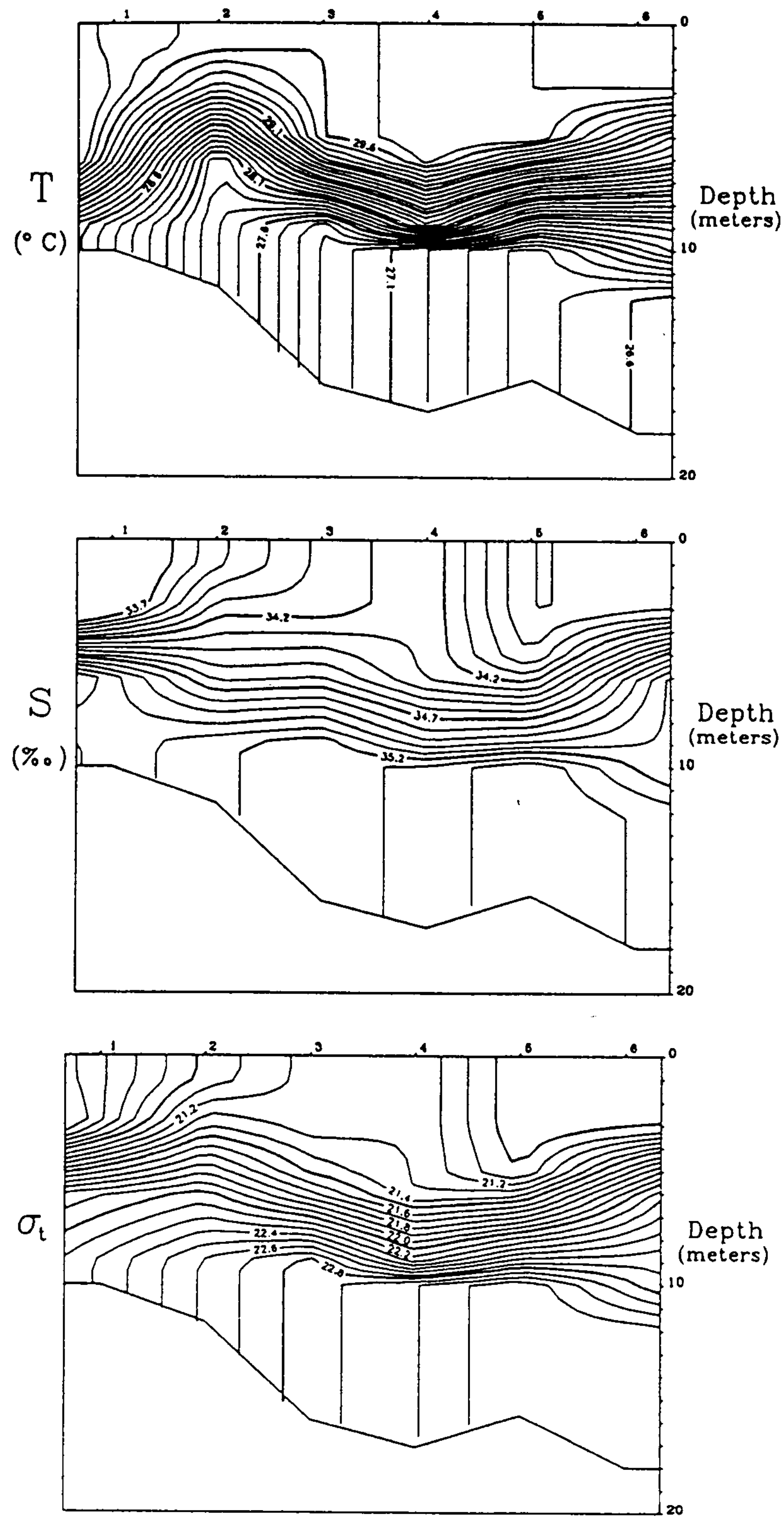


Figure 12. Hydrography along the section shown in Fig. 11. Summer (7 Jul 1992) (after Harkema *et al.,* 1994).

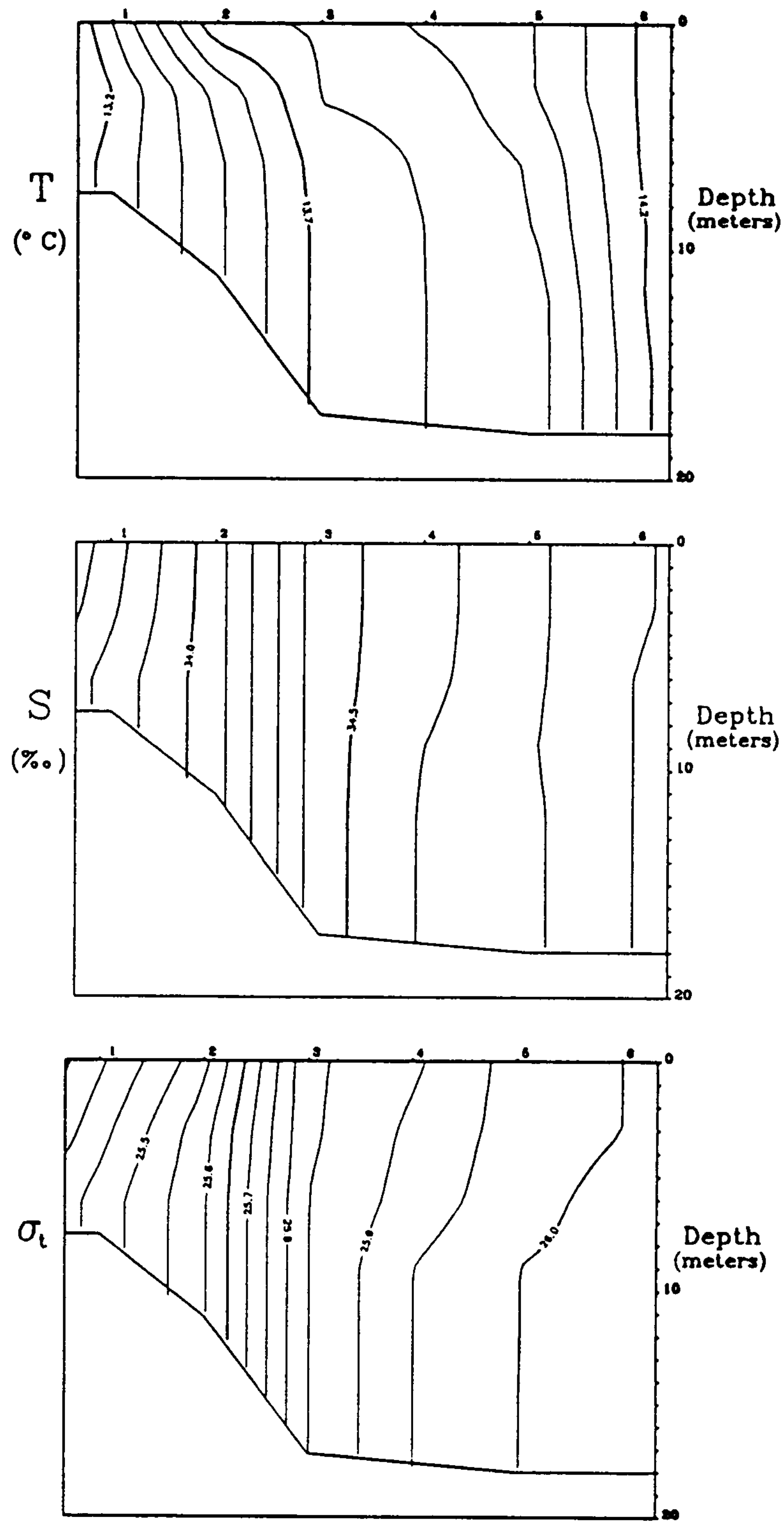


Figure 13. Hydrography along the section shown in Fig. 11. Winter (27 Jan 1992). (After Harkema *et al.*, 1993).

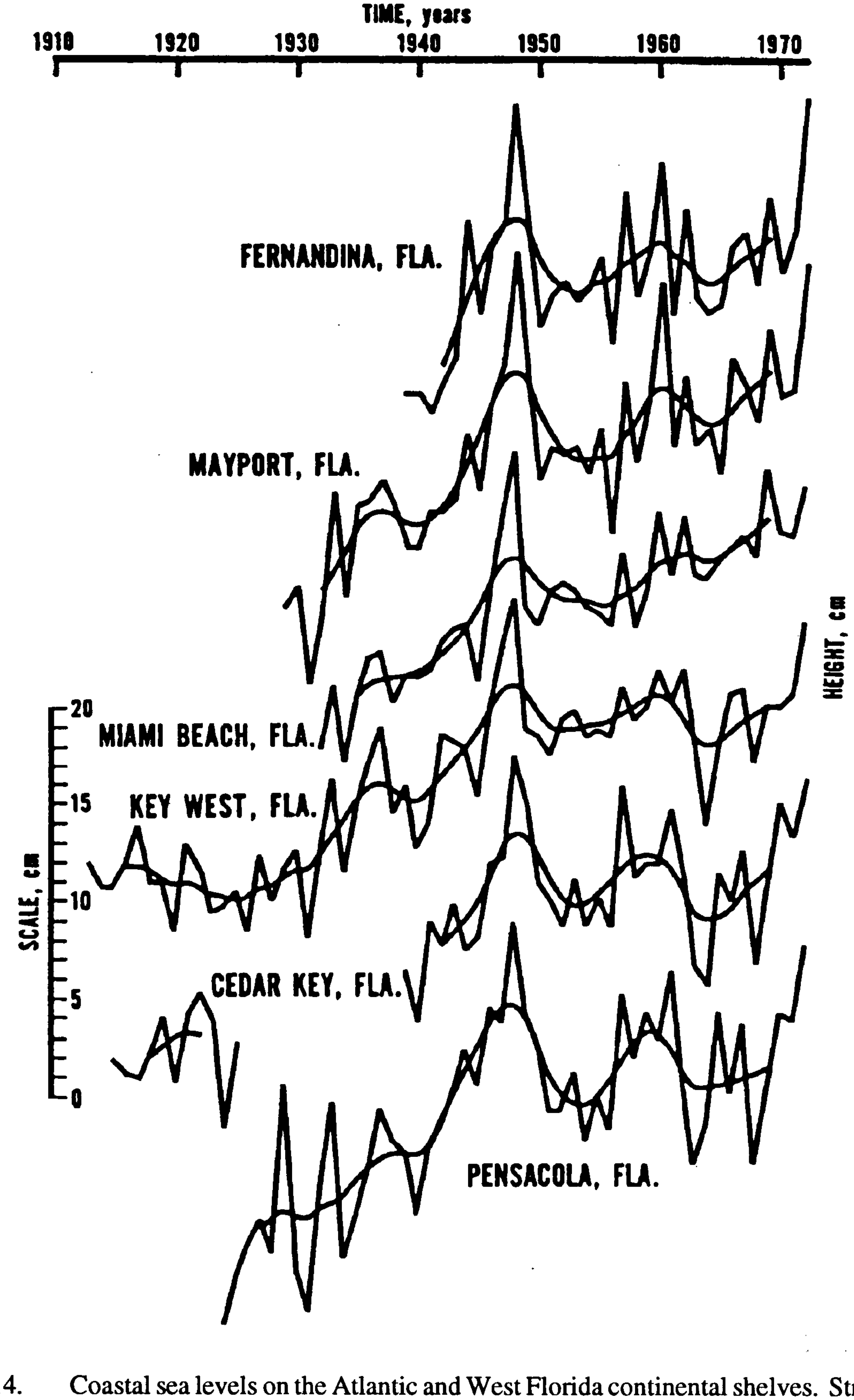


Figure 14. Coastal sea levels on the Atlantic and West Florida continental shelves. Straight-line segments connect annual mean sea levels. (After Hicks and Crosby, 1974).

2.1.3 OVERVIEW OF THE METEOROLOGY OF THE GULF OF MEXICO

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The Gulf of Mexico exhibits very interesting meteorological characteristics on a multitude of time and spatial scales, and air-sea interaction processes in the gulf are also quite varied. A brief survey of these processes will be presented in this paper.

Specification of the structure of the atmospheric boundary layer over the Gulf of Mexico is a very important meteorological problem affecting weather forecasts over the eastern United States. First, there are limited observations available from land stations over central America and Mexico to provide synoptic weather observations for conditions upstream from the Gulf of Mexico. There are also limited surface observations for *in situ* observations for the gulf region itself. Therefore, most understanding of the meteorological structure comes from limited research missions, remote sensing from environmental satellites, and extensive numerical modeling efforts.

Lack of surface data and upstream data hinder detailed reporting of the meteorological structure of the Gulf of Mexico, and also affects forecasting of the wind field over the Gulf of Mexico. Much of the modeling efforts which have made the transition to operations have been unsuccessful in obtaining the meteorological structure over the Gulf of Mexico, as indicated by largely inadequate attempts to predict the timing of "return flows" events for the Gulf of Mexico, which are so important for cool season severe weather forecasting for the central United States, and the difficulties associated with the major winter storm of mid-March 1993, to name a few. The other major data source, infrared satellite imagery from the geostationary and polar orbiting satellites, often suffers from inadequate signal quality during summer months, due to the ubiquity of warm surface water over the Gulf of Mexico during summer. Discussion of the most important meteorological data issues will be left to a later talk in this workshop by Prof. Kloesel.

It is clear that observations of the atmospheric boundary layer structure are essential for the documentation of air-sea interaction processes, and that formulations present relationships which depend on variations in atmospheric stability, and detailed observations of sea state parameters. Complete understanding of sensible and latent heat fluxes from the ocean surface into the atmosphere also requires knowledge of precipitation over land, as large discharges of fresh water into estuaries may pose complexities in the air-sea interaction process through salinity and temperature discontinuities (Huang 1993).

Variations of sensible and latent heat fluxes may vary on the order of 100 W/m^2 or more per day as synoptic and mesoscale meteorological features such as cyclones, fronts, and jet streams move across the Gulf of Mexico. Any understanding of the meteorology of the study region must take into account these transient features, at least to remove them from samples which require a larger scale understanding. During the winter, cyclones (low pressure systems) progress eastward across the Gulf Coast states, occasionally moving over the Gulf of Mexico in response to upper level steering currents. Cyclones may also originate in the Texas/western Gulf of Mexico region as the atmosphere responds to weak dynamical forcing and strong gradients in sensible heating when cold, dry air masses move out of the central United States into the western Gulf of Mexico. These features typically track across the northern Gulf of Mexico in a matter of days, moving ashore from Louisiana to Florida, and may become major winter storms affecting the entire eastern seaboard. These storms affect processes in the gulf directly by thoroughly mixing the upper ocean, addition of fresh water directly through precipitation and also by increasing fresh water discharges as storms move onshore. The typical cold front which emanates southward from the low pressure system may cause deep convection and intense thunderstorms deep into the Caribbean, as occurred during the March 1993 storm. Development of lines of thunderstorms called squall lines which extend north-south across the entire gulf are not uncommon with such intense winter season storms.

During the summer season, two quite diverse meteorological phenomena concern us, the tropical low pressure system and the land/seabreeze. Tropical waves are westward-propagating low level structures which occasionally spawn low pressure systems ranging from depressions to hurricanes, which may produce heavy precipitation, high winds, and swells and wind waves. Hurricanes in the Gulf of Mexico and the open waters of the Atlantic Ocean have been observed to substantially cool the upper mixed layer of the ocean through intense mixing, which seems to serve the purpose of forestalling further hurricane intensification in the same region by any subsequent storms, as substantial decreases in SST have been observed at buoys after hurricane passage.

The land breeze is a vertically confined thermal circulation which is the nocturnal counterpart to the sea breeze. The land breeze results from differential heating and typically involves weak to moderate offshore flow (1-5 m/s) at the low levels, onshore flow aloft (at altitudes of 1-3 km). Generally not an important consideration, the land breeze occasionally may aid in the generation of thunderstorms over the continental shelf, where the offshore flow becomes convergent in an area of particularly warm surface water. Such convection over the shelf is quite commonly observed in the early morning hours in Apalachee Bay, for example, as surface land temperatures cool to temperatures approaching 20°C, while sea surface temperatures may approach 30°C. The horizontal extent of the daytime sea breeze circulation for the shelf region of the Gulf of Mexico is generally not well understood. It may extend several tens of kilometers offshore, proving mesoscale diurnal structure (for an onshore wind component) to the wind field during synoptically quiescent periods.

The Southern Oscillation, associated with El Niño and El Viejo and the variability of the Inter Tropical Convergence (ITC) zone, also will provide longer term important geophysical input signals to any studies which examine meteorological and oceanographic structure of the Gulf of Mexico.

With such a diversity of scale of meteorological features affecting the Gulf of Mexico, it is clear that an examination of long time series of records over the Gulf of Mexico will exhibit multiple scales ranging from an important diurnal scale (which will become increasingly important as one approaches the coast on the shelf region), to a mesoscale/synoptic scale peak on the order of days which correspond to the transient features described above, to annual and interannual scales. [We are ignoring the forcing by atmospheric tides here.] The "Bermuda High" to some extent will modulate these synoptic and any larger scales, due to its semi-permanence as a feature of the global circulation of the atmosphere. This semi-permanent anticyclone (or high pressure system) is located to the east of the Gulf of Mexico throughout the year, and so provides generally southerly flow for the air above the gulf waters. The flow of the Loop Current in the gulf presents some interesting problems with respect to eddy shedding, which appears to occur on sub-annual time scales (Sturges, 1992), in spite of a dominant annual cycle in transport, wind forcing, and current reported by numerous investigators.

A summary of meteorological factors which may affect shelf studies over the study region include the following processes which must be taken into account:

- atmospheric tides
- atmospheric waves
- ENSO
- atmospheric cyclones and frontal incursions
- cold air outbreaks following frontal incursions
- tropical cyclones
- low level jets
- deep convection
- shallow convection
- secondary circulations (*e.g.,* land/sea breeze)
- surface layer wind
- boundary layer wind forcing
- response to irregular coastline and bottom topography

The presentation will illustrate examples of meteorological and climate data for the Gulf of Mexico study area and environs from a variety of sources, and a selected bibliography is included below.

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2.2 Recent Measurements/Challenging Problems in the Study Region

2.2.1 RELATIONSHIP OF PRIMARY PRODUCTION TO PHYSICAL OCEANOGRAPHY IN THE NORTHEASTERN GULF OF MEXICO

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Overview of Primary Production Studies in the Northeastern Gulf of Mexico

There is limited information about phytoplankton primary production in the Northeastern Gulf of Mexico (NE GOM). A few primary production measurements from this area were published prior to 1980 (El-Sayed, 1972; reviewed in Iverson and Hopkins, 1981). Subsequently, ocean color data from the Nimbus-7 Coastal Zone Color Scanner (CZCS) were used to infer characteristics of phytoplankton pigment distributions and their relationship to physical oceanographic processes (Yentsch, 1982, 1986; El-Sayed *et al.*, 1986). Further efforts have compared numerical models (Walsh *et al.*, 1989) with satellite observations (Muller-Karger *et al.*, 1991) in efforts to understand controlling mechanisms. Finally, there have been studies of primary production and phytoplankton growth rates that have focused on regional scale processes in the Mississippi River delta region (Lohrenz *et al.*, 1990, 1992; Redalje *et al.*, 1992; Fahnenstiel *et al.*, 1992) and Mobile Bay (Pennock *et al.*, in press).

In general, the satellite data provide evidence for coastal-offshore gradients in phytoplankton pigments, although direct observations are scarce. The mechanisms that maintain these gradients are not fully understood, nor are the temporal and spatial patterns well studied. Causative physical factors that have been identified include Loop Current- and wind-induced upwelling and continental run-off. A basin-scale coupled physical/biological model (Walsh *et al.*, 1989) simulated spatial patterns in chlorophyll in relation to Loop Current features offshore. However, the model was unable to reproduce the high chlorophyll observed by satellite on the West Florida shelf.

The objective of this commentary is to identify potential relationships between physical oceanographic processes and primary production distributions in the Northeast Gulf of Mexico, and to initiate dialogue that may lead to more fully developed strategies for future study. In the text that follows, the role of physical processes in influencing primary production at various scales is considered. Evidence for the importance of individual processes is discussed and possible research questions are suggested.

Key Variables

Variations in phytoplankton primary production can be attributed to 1) physiological responses of individual organisms to conditions of irradiance, nutrient availability and temperature, and 2) variations at the population level (species composition, biomass, growth rates and loss rates). For the purposes of this discussion, I propose the following list of key physical/chemical variables and the ecological variables pertinent to primary production that may be affected:

PHYSICAL/CHEMICAL VARIABLES
- nutrient supply and composition
- irradiance
- temperature
- salinity
- mixed layer depth
- stability/stratification
- horizontal and vertical advection/diffusion

ECOLOGICAL VARIABLES
- biomass (pigment, carbon)
- growth rates
- loss rates (grazing, sinking, advection)
- photosynthetic parameters
- species composition

Relevant Time and Space scales

Biological processes can vary over a wide range of temporal and spatial scales, making the task of characterizing all aspects of biological variability beyond the scope of any one method (Dickey, 1991; Bidigare *et al.,* 1992). In general, spatial and temporal scales are correlated. A necessary step in designing sampling strategy is to define the scales of interest. In the next section, I consider the dominant physical processes affecting key variables at different scales and the implications for primary production.

Physical Processes at Different Scales

LOCAL SCALE (1-10 km)
- waves
- Langmuir circulation
- small river/estuarine outflow

Included here as local scale processes are small scale physical processes (waves, Langmuir circulation) that can modulate the key variables at relatively high frequencies. The importance of these in affecting the overall magnitude of primary production in the NE GOM is questionable. Probably of more quantifiable significance is the behavior of land margin systems including coastal lagoons, estuaries, outflow regions of small rivers extending out onto the shelf. Such systems are likely to see higher frequency physical variability with abrupt spatial gradients. Localized effects of small river runoff (*e.g.,* Apalachicola) may be evident.

Key questions may include:

> What is the relative contribution of terrestrial inputs (continental runoff, atmospheric) to nutrients in the NE GOM?
>
> Do nutrient ratios vary with source terms, thus potentially influencing the type of nutrient limitation (cf. Myers and Iverson, 1981; Dortch and Whitledge, 1992; Ammerman, 1992)?

Does freshwater input to the NE GOM inner shelf significantly influence the water column structure, such that stratification/vertical structure may influence primary production?

MESOSCALE (10-300 km)

- tides
- upwelling
- meteorological events/air-sea interactions (storms, local and remote wind forcing)
- internal waves
- topographic effects
- Mississippi and Mobile Rivers/buoyancy circulation
- fronts
- Loop Current eddies, meanders, intrusions

Flow of water on, along and over the shelf will affect the key variables mentioned above, and thus influence primary production. Tidal mixing may generate fronts (Mann and Lazier, 1991) leading to locally enhanced primary production. Local and remote wind forcing could produce upwelling of nutrients onto the shelf. Storms may also influence water column structure, nutrient availability and distribution of water masses (*e.g.,* Iverson, 1977; Muller-Karger *et al.,* 1991). Internal waves can be important both offshore and as modified by coastal topography (Mann and Lazier, 1991). Flow from the Mississippi and Mobile Rivers can extend into the NE GOM. Enhancement of primary production by Mississippi River outflow has been demonstrated (Lohrenz *et al.,* 1990). In addition, eastward transport of plume waters has been shown (cf. Muller-Karger *et al.,* 1991; Walker *et al.,* 1994). Various types of fronts may occur on coastal margins. Fronts are often sites of high productivity because of the significant vertical and lateral transports and juxtaposition of chemically distinct water masses (Brink *et al.,* 1992). Finally, mesoscale eddies and meanders associated with the Loop Current have been studied on the West Florida shelf (Paluszkiewicz *et al.,* 1983). Various studies have used satellite evidence to infer augmentation of primary production related to Loop Current interactions (Yentsch, 1982; 1986; El-Sayed *et al.,* 1986). In other systems, boundary currents are known to impact biological processes. For example, nutrient transport and primary production in the mid and outer shelf zones of the South Atlantic Bight has been shown to be strongly affected by Gulf Stream intrusions (Menzel, 1993).

Key questions may include:

What is the effect of freshwater inputs from Mississippi/Mobile Rivers on physical structure, nutrients and primary production in the NE GOM?

What is the cycle of wind-induced upwelling and the effect on primary production in the NE GOM?

What are the magnitudes of tidally-induced cross-shelf flows, and the related transport of nutrients and biomass?

What is nature and frequency of fronts in the NE GOM and their relationship to primary production?

What is frequency and extent of internal waves, and their potential impact on primary production both offshore and as they impact the shelf?

What is the impact of storms on water column structure, cross-shelf and along-shelf flows and nutrient and primary production distributions in the NE GOM?

What is the magnitude and frequency of Loop Current-induced upwelling and downwelling, its contribution to nutrients on the shelf, and the impact on primary production?

How do topographic effects modify Loop Current interactions?

Do seasonal variations in shelf water properties influence the types of Loop Current interactions that occur, and their biological consequences?

SYNOPTIC SCALE (100-10,000 km)
seasonal wind forcing/mixed layer depth
Loop Current excursions

Currently, knowledge of seasonal variation in primary production is lacking for the NE GOM. Muller-Karger *et al.* (1991) provided evidence for an offshore seasonal signal in phytoplankton distributions from satellite ocean color data. This was attributed to seasonal wind forcing and variations in mixed layer depth. This seasonal pattern was simulated by a basin/scale coupled biological physical model. However, there have been few direct observations, and little is known about seasonal cycles of primary production on the NE GOM shelf. Superimposed on this seasonal variability are the north and south excursions of the Loop Current which vary interannually.

Key questions include:

Is there a consistent seasonal cycle in primary production in different regions of the NE GOM, and if so, what are the mechanisms that produce it?

How do Loop Current interactions modify these seasonal patterns?

Biological Sampling Strategies

One of the key problems in efforts to study physical-biological interactions is the need for greater spatial and temporal resolution of biological distributions and activities. Undersampling of potentially episodic processes can lead to significant underestimation of rates (Wiggert *et al.*, 1994). The solution to this problem for assessments of primary production is likely to come from the combined use of 1) instrumentation that can provide long term time series information on scales that complement physical measurements, and 2) bio-optical algorithms that allow prediction of photosynthetic rate processes from high resolution data.

Improved resolution of biological variables may be achieved using a variety of optical instrumentation that can deployed in various ways. In general, available instrumentation can provide information about the optical properties of particulate and dissolved materials as well as characteristics of the irradiance field. Types of optical sensors that may provide information useful for primary production measurements include the following:

- fluorometers (active, solar-stimulated, fast repetition rate, fiber optic, spectral fluorometers)

- transmissometers (spectral and single wavelength)

- spectral absorption meters

- irradiance sensors (photosynthetically active radiation, spectral downwelling/upwelling irradiance, reflectance)

- satellite/airborne sensors

Some of these sensors can be deployed on moorings or drifters as well as in shipboard profiling. Underway and tow-yo sampling may also be possible. In addition to the optical sensors mentioned above, there are a number of chemical sensors that are currently being developed and could provide information about nutrients, pCO_2 and other chemical properties.

Questions remain as to how to satisfy the minimum requirements for implementing bio-optical algorithms. Current technology limits the measurement of some parameters to direct observations using manual shipboard techniques (*e.g.*, photosynthetic parameters). The fast repetition rate fluorometer promises advances in that area (Kolber and Falkowski, 1993). In addition, autonomous instrumentation is available that allows periodic time series incubation measurements that could be used to "calibrate" bio-optical algorithms (Taylor and Doherty, 1990). Alternatively, it may be possible to characterize regions within a specified period of time on the basis of a limited set of direct observations (*e.g.*, Lohrenz *et al.*, 1994).

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2.2.2 U.S.G.S. COASTAL STUDIES IN THE NORTHEASTERN GULF OF MEXICO

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The U. S. Geological Survey's (USGS) Center for Coastal Geology and Regional Marine Studies is responsible for carrying out studies around the U. S. and the Great Lakes investigating critical issues related to: coastal erosion, coastal pollution, and wetlands change. Increasing population, coastal development, and possible sea-level rise will place increased stresses on the nation's coasts in the near future. Developing sound management in light of these coastal problems requires a thorough understanding of coastal settings and processes. To this end, the Coastal Center is currently involved in twelve major studies around the U. S., with eight in the Gulf of Mexico, including: erosion studies in west Louisiana/east Texas and west-central Florida; pollution studies in Alabama/Mississippi, south Florida (Florida Bay and the Keys), and Lake Pontchartrain; wetlands studies in Louisiana and Florida's Big Bend; and a study of the effects of Hurricane Andrew on coastal Louisiana. To assure the input of local expertise and knowledge into planning and carrying out the research, each of these studies is conducted in cooperation with appropriate federal, state or local agencies and universities.

Three of the major studies cited above are in the northeastern Gulf of Mexico and will be the focus of this summary, the Alabama/Mississippi pollution study, the Florida Big Bend wetlands study, and the west-central Florida erosion study. Each of these studies has components investigating the geologic framework and recent geologic history of the region, as well as studies of the important geologic and oceanographic processes in the area. This summary will highlight some of the fundamental coastal processes identified in these studies as relevant to the physical oceanography of the northeast Gulf of Mexico. These studies began at different times and are in varying degrees of completion. Field work for the Alabama/ Mississippi pollution study ran from 1990 to 1992 and data analysis is presently near completion. The Florida Big Bend wetlands study began in 1991 and will run until 1995. The west-central Florida erosion study is just underway and is scheduled for completion by 1997.

Alabama/Mississippi Pollution Study

The coasts of Alabama and Mississippi have diverse usage. The region supports a multi-million dollar commercial fishery, is a major recreational resource, and is home to a rapidly growing natural gas exploration and production program. The coastal areas of Mobile Bay, Mississippi Sound, and the inner shelf are being stressed by a variety of problems, including elevated concentrations of metals, sustained occurrences of low-oxygen water, and rapidly eroding coastlines. The objectives of the USGS study in this region were to determine coastal erosion rates and causes, recent sedimentologic history and geologic framework, and to determine the transport and deposition of pollutants adhered to fine-grained sediments. Cooperative efforts were established with the Geological Survey of Alabama, the University of Alabama, and the Mississippi Bureau of Geology.

The objective most relevant to this workshop entailed the study of the resuspension and transport of fine-grained sediment, and the dispersal of sediments onto the continental shelf. Accomplishing this objective involved deployment of a combination of moored instruments in Mobile Bay and on the inner shelf, collection of monthly CTD stations with water samples for chemical and biological analyses, and analysis of satellite data for the region. The moored data in Mobile Bay reveal numerous occasions of large surface waves associated with the passage of cold fronts. The large waves are correlated with the resuspension of bottom sediment, as detected by a decrease in light transmission from near-bottom and near-surface transmissometers. In addition, the waves, and associated surface mixing, are correlated with the breakdown of vertical salinity stratification, as observed in the overlap of near-surface and near-bottom salinity measurements. The vertical salinity gradient in Mobile Bay can be large (as high as 30 ppt/m) and highly variable, both spatially and temporally. This vertical stratification supports large shears, greatly influencing circulation and mixing in the estuary. Results from this study show vertical shears in both the tidal and sub-tidal currents, in the Bay and on the shelf.

Sediment dispersal on the Alabama/Mississippi shelf is dominated by buoyant plume processes. AVHRR satellite imagery of the Mobile Bay area processed for reflectance shows high river discharge events, producing buoyant plumes with enough fresh water and suspended sediment to cover over 2000 km^2 of the inner shelf. CTD profiles across the plume reveal a thin layer of fresh water along the surface less than 2 m thick, with salinity less than 10 ppt, extending 15-20 km offshore. Stratification at the base of the plume is large. The position of the Mobile Bay plume depends on river discharge, tides, and wind. AVHRR images from April 4 and 5, 1990 demonstrate the significant effects of both tidal pumping into and out of the Bay, and wind on the position of the plume. Calculations from the satellite imagery show that tidal height ranges from 11 to 22 cm cause from 43 to 76 km^2 of plume area on the shelf to be affected.

Images on these two days also show a rapid shift in the position of the plume caused by a shift in the wind. At a distance of 30 km from shore, the outer part of the plume moved approximately 30 km to the east after the wind shifted from northeasterly to westerly. A minimum speed of translation of the plume calculated from the change in position of the plume taken from the images and the time between images show the plume moved at 0.56 to 0.78 m/s, or 8 to 11% of the wind speed. The enhancement of the wind drift of the plume relative to the wind drift in a homogeneous surface layer (typically 3% of the wind speed), suggests a frictional de-coupling of the plume from the coastal water below. Predicted surface current speeds from a stratification-limited Ekman layer model show the surface trapping of wind-driven transport. For a layer having a thickness of 1.5-2 m, as was found for much of the plume, the predicted surface current drift is 6-8% of the wind speed, consistent with the observed drift of the plume.

Direct current-meter measurements taken in April, 1991 confirm that strong stratification at the base of and along a surface front of a buoyant plume can support large shears. In this case, a buoyant plume jet traveling west parallel to the coast converged with the ambient wind-driven surface current resulting from a southeasterly wind. Flow of wind-driven ambient water along the surface converged with the plume at a 45° angle, was downwelled, and apparently subducted beneath the plume. Wind-driven flow beneath the level of the plume continued under the plume and was undisturbed by the flow of the plume. Strong stratification at the pycnocline at the base of the plume and along the front inhibits mixing of ambient coastal water with plume water and limits the transfer of momentum between the water masses.

Florida Big Bend Wetlands Study

The northwest Florida coast has over 120,000 acres of nearly undisturbed coastal wetlands. Stressing the area is a rapid population growth of 250% since 1970. Also, the wetlands are directly exposed to the Gulf of Mexico, making them more susceptible to storm damage and saltwater intrusion. The objective of this USGS study is to describe the current state of the Big Bend wetlands and to determine the geologic characteristics and critical coastal processes that would cause erosion or decline of these wetlands. As part of this study, the USGS is cooperating with the University of South Florida, the Florida Geological Survey, the National Biological Survey, and the University of Florida.

Factors that control wetlands change include sediment supply, sealevel, and salinity. To monitor these factors a combination of techniques are employed: remote sensing to map wetlands change, and moored instrumentation to monitor water level, salinity, currents, and suspended sediment. It has been suggested from work in Louisiana wetlands that land loss rates are related to sea-level change rates. In the Florida Big Bend region remote sensing techniques are being used to map wetlands change. Wetlands change maps, produced from differences between 1986 and 1991 Landsat images in the Waccasassa Bay area, show several areas of wetlands loss. Although these areas are not immediately along the coast, inundation and salinity fluctuations are believed to be important factors in the observed changes.

A study of sea level around the Big Bend region and the rest of the Gulf of Mexico revealed several results that are potentially important for understanding wetlands loss. Time series of monthly mean sea level from Galveston, Pensacola, and Cedar Key show annual fluctuations of 20-40 cm. Sub-annual frequency fluctuations are also significant and vary up to 15 cm. Also, these multi-year fluctuations are highly correlated across the Gulf of Mexico. These fluctuations are likely climate controlled, but not well understood for the Gulf of Mexico. Long-term sea-level trends (calculated over 50 years) vary across the Gulf and are small in the Big Bend region. At Cedar Key the long-term sea-level rise rate is 0.12 cm/yr. Although this long-term rate is quite small, the shorter term fluctuations result in sea-level changing at 2 cm/yr over 5-year periods. These rates may be significant to the health of the wetlands in this region.

West-Central Florida Erosion Study

The state of Florida is highly dependent upon its coastline and coastal ocean for its economic and social well-being. Studies by the State's Division of Beaches and Shores have shown that the Florida coast is highly dynamic, changeable, and subject to erosion. Along portions of the west-central Florida coast, approximately 62% of the beaches are cited as "critical erosion areas." The barrier island-inlet system in west-central Florida is one of the most complex coastal barrier systems in the world. The combination of the fragile natural barrier-inlet environments with the pressures of high-density development and tourism demand a regional understanding of the underlying geologic controls and the physical and geological processes that are modifying this coast. The objective of this study is to understand the geologic history of the barrier island system and the processes that control the distribution and transport of sediment. Cooperators in this study include the University of South Florida, Eckerd College, the Florida Department of Environmental Protection, and the U. S. Army Corps of Engineers.

In addition to mapping sediment type and surface and sub-surface geologic features in this region, there is a strong component of processes studies. Processes effecting coastal erosion include waves, coastal currents, and catastrophic storms. In addition, the seasonal variation in sea level on the west Florida shelf may be an important factor effecting coastal erosion. This seasonal sea-level pattern results, in part, from the shelf-wide density distribution deriving from the circulation and air-sea interactions. Thus, the oceanographic goals of this study will be to describe the seasonal variations and geographic extent of circulation regimes on the shelf, add to the knowledge of how these currents respond to various forcings and to determine the interactions between the current regimes in relation to water property distributions, sediment, and coastal erosion.

To achieve these goals a combination of field experiments, modeling experiments, and remote sensing studies will be applied. Thus far, a pilot mooring at a mid-shelf location with a downward looking ADCP has been deployed. Preliminary analysis offers descriptions of seasonally varying mean currents, semi-diurnal tidal currents, inertial currents, and those due to synoptic weather forcing. The monthly mean currents appear to shift from a northwestward directed along isobath flow to a southeastward directed along isobath flow. Mean flow in both directions had an offshore component near the bottom.

Deployment of a large trans-shelf array of surface and sub-surface moorings between the near shore and the shelf slope is planned for the summer of 1994. In addition, numerical circulation models of the west Florida shelf for use in Eulerian and Lagrangian studies of both large-scale shelf circulation and smaller, regional scale problems are being developed.

2.2.3 COMPARISON OF CURRENT METER OBSERVATIONS SOUTH OF PENSACOLA WITH CALCULATIONS FROM THE CLARKE-VAN GORDER MODEL

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A series of moorings was maintained by Continental Shelf Associates, Inc. south of Pensacola at a depth of 55 m. The mooring site is just west of the right-angle bend in the topography near 87° W. The first ~3-mo mooring was installed in July 1992.

Inter-Ocean S-4s current meters were used, on two nearby moorings. On one, a 6' dia. met buoy was moored with a taut wire, rubber-band tensioning system; it had two instruments, at 3 and 5 m. The other mooring had sub-surface floats just above the upper instrument; instruments were at 13, 33 m; and ~1 m above bottom. The moorings were replaced at approximately 3-month intervals.

The observed currents show excursions as large as 60 cm/sec in both e-w and n-s components. The spectra show several standard features: there is a strong rise in power at periods longer than about 2-3 days (the so called wind-driven band), there is a large peak in the inertial band, and there is a steady fall-off to higher frequencies.

In the late summer, the effects of strong stratification and eddy motions become apparent. In August there is a strong, persistent flow to the northeast for 2 months. The peak speeds in the low-low-passed data are just less than ~ one knot. Toward the end of September, however, the surface flow is equally strong in the opposite direction. For much of September it appears that the flow is either very strongly sheared vertically or not coherent at all in the vertical.

In the late fall and winter the pattern appears much more in keeping with ideas of simpler, vertically coherent, wind-driven flow. The peak speeds are slightly less than 1 knot and the direction reverses often. The peak speeds in the full record, however, exceed 75 cm/sec. Figure 15 shows a progressive vector plot of the currents observed during one such mooring. The individual wind events are evident, as is a mean flow (during this mooring) to the north or northwest.

To show the inertial motion explicitly, the inertial currents have been filtered with a band-pass filter having a top at 22 - 26 hours. The speeds are greatest near the surface, as would be expected. The speeds in the inertial band at 3 m typically are over 10 cm/sec, and occasionally reach over 20 cm/sec.

To show the currents after the wind-driven components have been removed, a "low-low pass" filter suppresses motions at periods shorter than 2 weeks and passes periods longer than 4 weeks. It is obvious from looking at the plots that the mean value of the full record is dominated by a large single event, near the beginning of the record, that lasted several months.

We have made comparisons between the data at this mooring and calculations made with the Clarke-Van Gorder model. The wind input to the model includes wind stress at Key West, Tampa and Pensacola.

We have made our primary comparison with the data at 13 m. The general impression one gets is that the agreement during the fall and winter is fairly close, but the amplitude of the model-computed current is less than observed. We have lumped the uncertainty into a single gain factor. The shape of the amplitude structure in the offshore direction is known from the model, and the currents in the longshore direction have been matched at the mooring site to determine a gain factor of 2 at that location. At the coast, however, the amplitude of pressure predicted by the model needs no such adjustment. Figure 16 shows the comparison between the observed currents and model calculations for the longshore component.

We would like to know, of course, whether the lack of agreement between the model and the data is error or whether it is well correlated with forcing variables. The model computes the currents with a limited number of modes. It is believed that the local longshore wind can be used as a surrogate variable for these higher modes that are not computed. To this end, we compared the difference signal (Model minus observations) with the local longshore winds, and found high coherence in the wind-driven band. Figure 17 shows the coherence between these computed for two possible angles of "longshore wind."

One vexing problem with this region is that the bottom topography is so irregular. It is difficult to know how to choose the correct angle for the longshore direction reliably. Therefore, the wind angle (for local longshore wind) was varied to find the highest coherence with the difference signal. The angle that gave the highest coherence was an angle of 20° clockwise from East. This angle, on the map, appears to be roughly halfway between the angle of the coastline (zero depth) and the angle of the bottom topography just before the abrupt bend at the head of DeSoto Canyon.

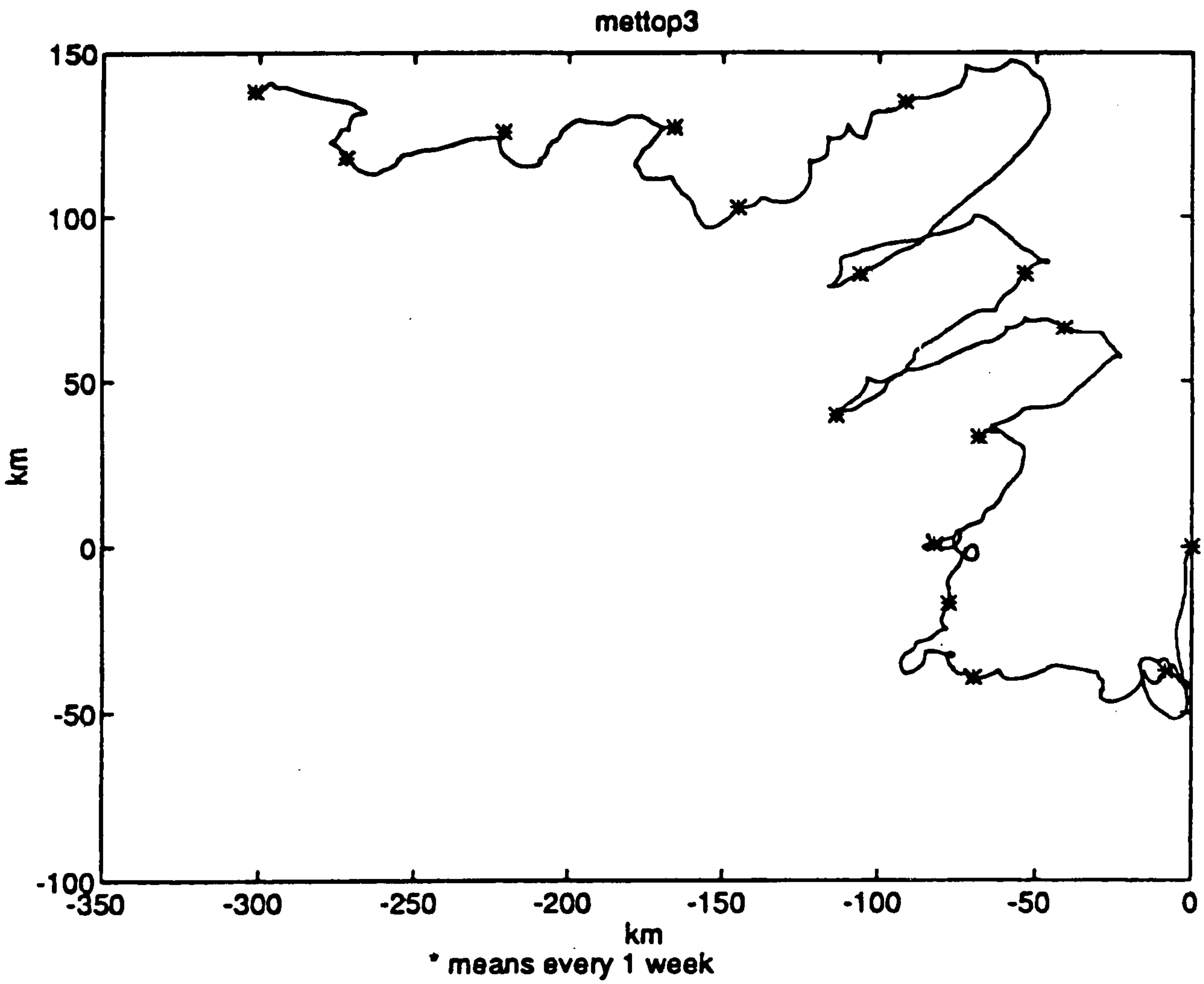

Figure 15. Progressive vector plot of the current observed. Diagram starts at 0,0; mooring begins October 26, 1992.

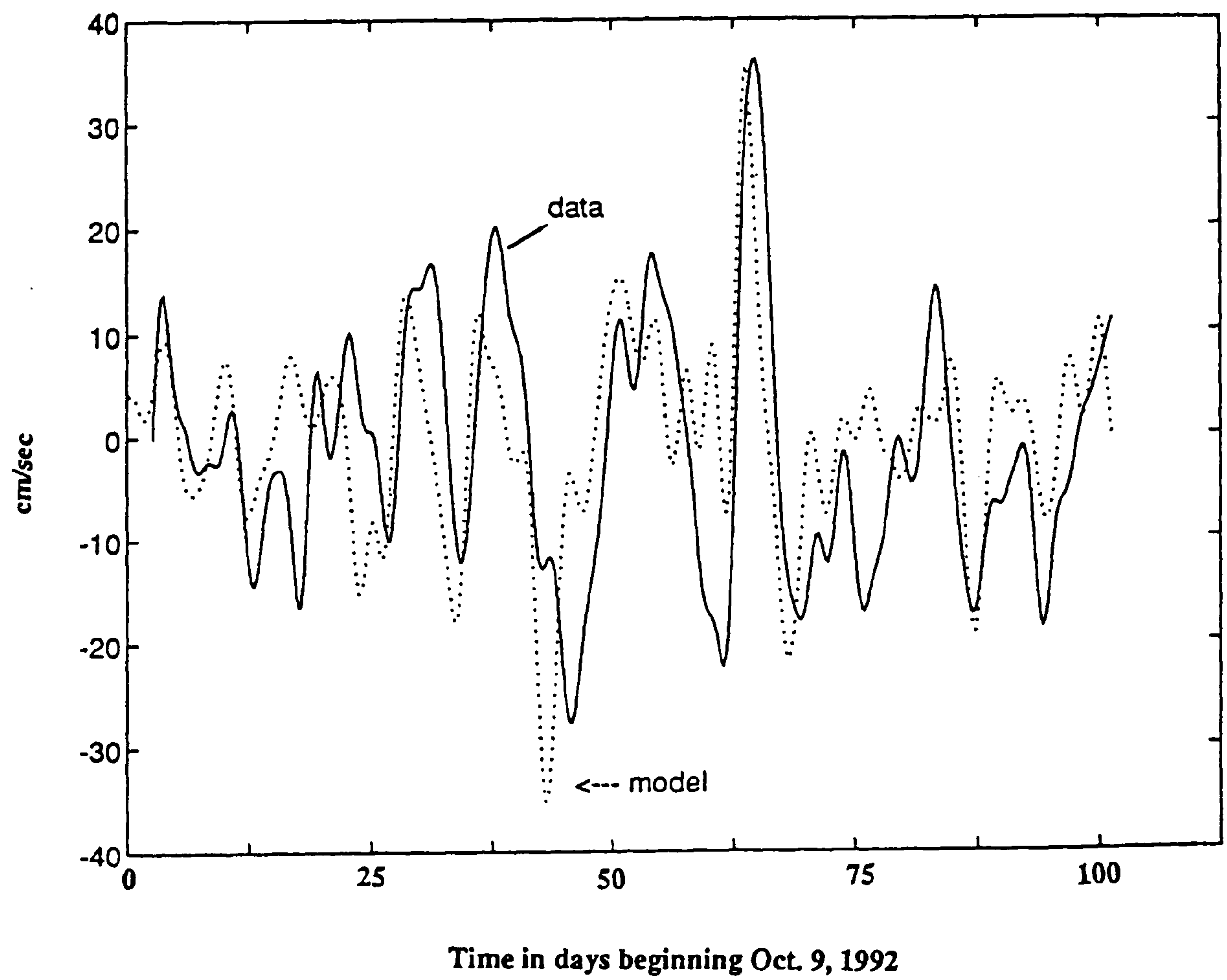

Figure 16. Comparison between the currents observed at the 13 m instrument and those computed from the model during the third mooring setting.

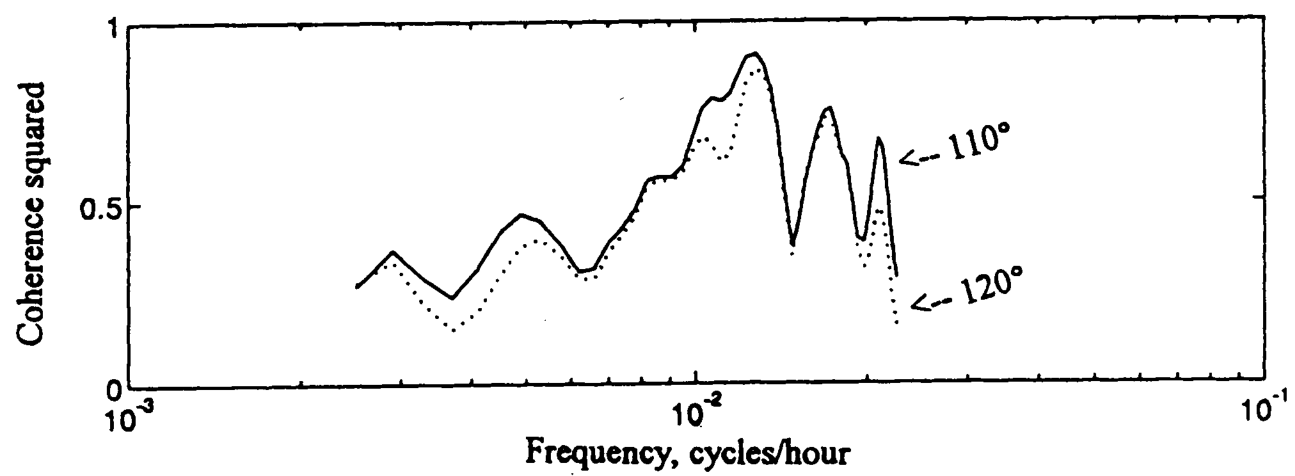

Figure 17. Cross spectra between two slightly different estimates of the longshore wind component (at Pensacola) and an error term in the offshore velocity component, computed for the second mooring. The error term is the difference between the observed offshore current at the upper instrument (3m) and that estimated by the model. The data records are from 10/9/92 to 10/22/93. The panel shows coherence squared.

2.2.4 SATELLITE RESULTS FROM THE NORTHEASTERN GULF OF MEXICO

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Introduction

For application to physical oceanography, satellite imagery with frequent repeat coverage of the eastern Gulf of Mexico is desired, with spatial resolution appropriate to the mixing scales of the coastal environment. This suggests pixel sizes of about 1 km for the outer shelf and perhaps 100 m for the inner shelf. These requirements have been met with visible and infrared imagery but not with passive microwave data (Njoku, 1980). On the other hand, satellite sensors typically used over land (*e.g.*, Landsat and Spot) have not been designed with adequate sensitivity to perform well over the ocean (see Goetz and Davis, 1991; Gordon, 1990). Except for bright (or hot), near-shore targets, then, most ocean requirements for satellite imagery have had to be met using Advanced Very High Resolution Radiometer (AVHRR) or Coastal Zone Color Scanner (CZCS) data, neither of which has adequate spatial resolution for the nearshore areas.

NOAA polar-orbiting satellites have carried infrared sensors for more than 20 years. The AVHRR is a thermal radiometer that has been carried by the TIROS-N satellite series since 1978. While the VAS sensors on the geostationary GOES satellite series and other specialized missions also have infrared capability, the relatively small pixel size (≈1 km nadir), high sensitivity, and operational status of the AVHRR has made it the primary oceanographic thermal radiometer. It provides sea-surface temperature (SST) data with rms errors of as little as +/- 0.5°C (McClain *et al.,* 1985), but warm, humid conditions such as for the summer Gulf of Mexico and cloud contamination can be a problem (see Abbott and Chelton, 1991 and references cited).

The CZCS was launched on the NASA Nimbus-7 satellite in late 1978 and continued to perform until mid 1986. The SeaWiFS sensor is a CZCS follow-on, planned for launch on the Sea Star satellite by Orbital Science later this autumn. With its increased sensitivity and additional spectral bands, it should provide data allowing quantification of chlorophyll *a* and colored dissolved organic matter (CDOM) absorption even in more turbid coastal environments. Atmospheric effects, as much as 90% of the signal at the sensor, are removed by evaluating the aerosol radiance in the infrared where water is typically "black." For highly turbid waters, however, even SeaWiFS data will have some application limitations (Gordon and Wang, 1994), and its pixel size (≈1.1 km) is too large to resolve many coastal ocean features.

Applications

Time sequences of both AVHRR and CZCS data have provided the means to develop surface velocity fields using a feature-tracking approach similar to the cloud winds derived from GOES data (*e.g.,* Vastano and Borders, 1984; Emrey *et al.,* 1986; Garcia and Robinson, 1989; and references cited). These approaches assume that SST and color patches behave in a conservative manner. While diffusion has been shown to be relatively unimportant on the time and space scales used in the velocity estimates (Wahl and Simpson, 1990), heat exchange with the atmosphere and primary production/ grazing are likely to affect the accuracy of velocity retrievals from the AVHRR and CZCS, respectively. Inversion of the SST field from a single AVHRR image has also been used to estimate geostrophic velocities (*e.g.*, Vastano and Reid, 1985; Vukovich, 1986; and Kelly, 1989), given temperature-salinity covariance functionalities or assumptions from the field data. Vukovich actually used the eastern Gulf of Mexico as his test location, with correlation r^2 values between measured and calculated velocity components of better than 0.92 for contemporaneous data.

Perhaps the most conservative tracer that can be quantified from space is CDOM absorption. Berger *et al.* (1984) and Carder *et al.* (1993) have found site- and season-dependent covariations of CDOM with salinity, with r^2 values of 95% or more. Carder *et al.* (1993) used such a relationship to transform a CDOM field derived from Airborne Visible-InfraRed Imaging Spectrometer (AVIRIS) data into a salinity field for the ebb tidal plume from Tampa Bay.

A similar CDOM plume is apparent in both Landsat Thematic Mapper (3-band composite color) and AVHRR (Band 1) data for the Suwannee River outflow (data courtesy of R. Stumpf). The plume is visible with these low-sensitivity sensors only because the water is so shallow (high bottom reflectance) and the CDOM concentration from the Suwannee is so large. The Suwannee originates in the Okefenokee Swamp and, in its lower reach, has a cypress-hardwood swamp in the floodplain. This drainage basin provides a substantial supply of tannins to the river especially during floods, giving the river water a distinctive brown appearance.

If salinity-CDOM relationships can be developed for the Suwannee and perhaps other rivers of northwest Florida, then it may be possible to use data from SeaWiFS to estimate salinity near their mouths and to trace their effluent. A sensor with higher spatial resolution than SeaWiFS and higher spectral resolution and gain than Thematic Mapper provide is really what is required in order to optimally perform such a task. Fortunately such a sensor could be available after 1996. A Small Spacecraft Technology Initiative (SSTI) by NASA has stimulated conceptual designs for at least two imaging spectrometers that could provide the spectral and spatial resolution and the signal-to-noise necessary for near-shore ocean applications. If one or both of these sensors are successful in the competition, then by mid-to-late 1996, an AVIRIS-like spacecraft sensor will be available for coastal studies.

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2.2.5 WEST FLORIDA SHELF CIRCULATION AND GROUPER RECRUITMENT

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Introduction

The broad shelf of the west coast of Florida is highly productive in terms of economically important reef fish. Nearly 95% of the groupers and over 50% of the snappers taken from the U. S. Gulf of Mexico are landed on the west coast of Florida. The mean annual commercial and recreational harvest (1986-1991) of major grouper and snapper species from the west coast of Florida amounts to over 15 million pounds of groupers and about 6.5 million pounds of snappers. The annual value of this production is in the tens of millions of dollars to the commercial fishing industry of west Florida and probably in the hundreds of millions of dollars when considering direct and indirect expenditures of the Florida recreational fishery (Bell *et al.,* 1982; Bell, 1993).

Many of our reef fish resources have either been overfished or are being threatened by overfishing. Many of the overfishing problems are directly related to a lack of understanding of the basic biology of the species involved (*e.g.,* Koenig *et al.,* in press). Therefore, it is imperative that we understand the basic biology of these valuable species, especially as it relates to reproductive success, in order to effectively manage our fisheries.

All of the groupers and snappers, and most other reef fish, have a pelagic larval stage. Upon spawning, eggs and larvae are shed directly into the water column and fertilization is external. Hatching occurs within several days and the larvae do not feed but rely on yolk reserves for the next few days. When the eyes and mouth are fully formed and the larva is capable of orientation and swimming, it actively pursues food, avoids pelagic predators, and modifies its drift in the ocean. Upon reaching the juvenile nursery habitat the larva settles to the bottom, metamorphoses, and takes on the benthic mode of existence that it will retain for the rest of its life. The duration of the pelagic phase is species specific, flexible to a certain extent, and is typically from 40 to 50 days for groupers and 20 to 30 days for snappers.

Groupers and snappers are highly fecund; annual egg production is usually in the millions per female spawner. Mortality of larvae is high and variable from year to year, which produces considerable variability in recruitment (the addition of new individuals to the population). Because adult population size is in large part dependent on pelagic-phase mortality, fishery scientists have been interested for many years in recruitment processes of exploited stocks and in the relationship between the size of the spawning stock and the size of the recruited stock. Only recently has this interest extended to reef species. Very little is known about the pelagic phase of any reef species. There are several reasons for this lack of information: (1) larval studies must be built on a firm foundation of knowledge of adult biology, and in many cases that foundation is lacking, (2) studies of larval fish ecology are challenging, due to the difficult working conditions at sea and around reefs, and expensive, and (3) many species are difficult to identify or distinguish from other closely related species.

Of the ten species of groupers and snappers that dominate the gulf fishery eight are associated with estuarine habitats, primarily seagrass beds, during their early juvenile phase. Early juveniles of most of these species are only found in certain estuarine habits and therefore are thought to depend on these habitats as critical to their early development. The question arises as to how these larvae arrive at their juvenile habitat destination. The opportunity exists with certain eastern gulf reef species to investigate oceanic transport mechanisms and the contribution of these mechanisms to recruitment variability. Such investigations require the collaborative effort of physical oceanographers and biologists as physics and biology are intimately tied in planktonic transport processes.

Gag grouper: Gag (*Mycteroperca microlepis*) is a dominant fishery species of the eastern Gulf of Mexico and annually contributes about 5 million pounds to the commercial and recreational fisheries of west Florida. Over 99% of gag fishery production in the gulf is from the west coast of Florida. In addition to its commercial importance, features of the gag life cycle provide unique opportunities for the study of planktonic processes and recruitment variability.

Gag spawn at depths greater than about 50 m and probably less than 120 m on the gulf and Atlantic coasts of Florida. Spawning aggregations begin to develop in the winter at specific sites which are concentrated along the 80 m isobath from south of Apalachicola to southwest of Tampa. This is probably the only significant spawning area in the U. S. Gulf of Mexico. Peak spawning occurs in February and March and aggregations dissipate by early May. Prior to hatching, fertilized eggs float at the surface for about 36 hours. Larvae settle in a discrete pulse in April and May after a period of 40 to 50 days in the pelagic environment. Early juveniles prefer shallow (< 2 m), high salinity (> 20 ppt) seagrass beds, and remain in that habitat until September or October at which time they migrate to offshore reefs. Juveniles attain maturity after several years and begin their annual migrations to offshore spawning grounds.

The seagrass habitat of the west coast of Florida is extensive comprising nearly 80% of the seagrass in the Gulf of Mexico. Significant juvenile seagrass habitat is probably restricted to the area between St. Andrews Bay and Ft. Myers with the dominant portion occurring in the Big Bend, which covers about 3,000 square km (about 30% of the gulf seagrass habitat). The extensive seagrass habits associated with Florida Bay have undergone serious ecological degradation in recent years and their value as juvenile gag nursery habitat is questionable.

We have studied the ecology of juvenile gag in seagrass habitats of the northeastern Gulf of Mexico. Mark and recapture methods have revealed that absolute abundance (number per unit area) of 500 juveniles per hectare are not uncommon and abundance may go as high as 1,000 per hectare (Koenig and Colin, in press). In addition, in the seagrass habitat survival is high, rates of movement are low, and small-scale spatial patterns are random. Such characteristics simplify the annual determination of juvenile abundance in seagrass habitats over the broad geographical area of the west coast of Florida. Our data suggest that the large scale distribution of juveniles is patchy, and this leads to high inter-annual variability on a local scale. Recruitment variability may be dampened somewhat on a large geographic scale.

The spawning characteristics of gag may provide an opportunity to make annual estimates of the size of the spawning stock. Churchill Grimes (director, NMFS, Panama City Laboratory) and I, on a recent cruise to the gag spawning grounds, investigated the feasibility of estimating spawning aggregation size and number and individual fish size using hydro-acoustic technology and underwater video. Although poor weather conditions and gear failure hampered our progress, the results are promising. Annual estimates of the absolute abundance of seagrass recruits in combination with direct estimates of the size of the spawning stock should be valuable in the quantitative evaluation of stock-recruitment relationships and the planktonic processes that modify that relationship.

Comparison with Other Species: Several other economically important species of reef fish provide opportunities for the comparison of planktonic transport processes. As noted above, gag recruit exclusively to the estuary, primarily seagrass. Scamp (*Mycteroperca henax*) spawns at the same times and places as gag but settlement never occurs in the estuarine habitat but always on offshore reefs (Koenig, 1993). The season and localities of spawning of red grouper (*Epinephelus morio*) also overlap with those of gag and scamp, but juveniles appear to settle inshore and offshore. We have recently described the larval development of all three species from laboratory-reared larvae (Koenig, 1993; Colin *et al.,* in press). Therefore it is now possible to distinguish the early larvae of all three species.

Physical Oceanography and Larval Transport: An understanding of the physical oceanography of the west Florida shelf is absolutely necessary to the understanding of the dynamics of recruitment processes. Unfortunately, few studies of fish larvae have addressed this requirement. This is due in part to the lack of cooperative effort between physical oceanographers and biologists. Thus, most studies of larval fish are either lacking in biological or physical data or both.

Considerable evidence indicates that reef fish larvae are not passive drifters in ocean currents but interact in a complex way with their environment (Leis, 1991). Fish larvae can potentially modify their drift by (1) controlling their vertical position in the water column, and (2) by active swimming. The modification of larval transport through vertical migrations have been amply documented in the literature, especially in association with tidal currents in estuaries, but also in offshore waters. Studies have shown that older fish larvae or pelagic juveniles of some species are capable of sustained directional swimming, and this may be an important mechanism of transport as the larva nears the juvenile nursery habitat.

The vertical position of fish larvae may be maintained by maintaining neutral buoyancy and by vertical swimming. The presence of a functional swimbladder in many fish larvae (including grouper) from a very early age implies that they are capable of a fine regulation of buoyancy. Before swimbladder formation, grouper larvae could avoid a downward drift by rapid vertical swimming.

If a larval fish is to directionally modify its drift, it must use some sensory/orientation capability to determine when such behavior is appropriate. Sensory capabilities of larvae may include phototaxis, geomagnetic orientation, olfaction, and hydrostatic pressure detection. Very little is known about the sensory capabilities of larval reef fish.

Evidence for the possibility of transport of grouper larvae from gulf spawning grounds to the Atlantic comes from the study of surface currents through drift bottle releases. Williams *et al.* (1977) released drift bottles monthly for two years at locations off Tampa. Of the drift bottles that had been released in the time and places of gag spawning and recovered within 65 days, which is the maximum recorded pelagic duration for gag larvae (Keener *et al.,* 1988), 61 were recovered. Seventy percent of these were recovered from the Atlantic (most off the east coast of Florida), 21% from the Florida Keys and 9% from the gulf. Although it is unlikely that gag larvae passively drift at the surface, these data do suggest the possibility of larval transport to the Atlantic from gulf spawning grounds.

Circulation patterns on the west Florida shelf have been little studied, but it is clear that a dominant structuring agent of the region is the Loop Current. Although intrusion of the Loop Current into the northeastern Gulf of Mexico varies inter- and intra-annually (Maul, 1977), it influences current patterns well onto the shelf (Sturges and Evans, 1983). Certain species of reef fish choose discrete areas along the shelf for spawning. For example, gag does not spawn shallower than about 50 m on both the west and east coasts of Florida (Gilmore and Jones, 1992; Koenig *et al.,* in press). Although we do not know whether those areas are exclusive for species other than gag, we do know that other species spawn in them. On the gulf coast we find scamp, red grouper, gray snapper, rock sea bass, and others spawning in the same area as gag; on the Atlantic coast scamp, gag, black sea bass, Warsaw groupers and others spawn in the same areas (Gilmore, personal communication). Similar observations were made in the Bahamas for other species of reef fish by Pat Colin (personal communication) while working on Nassau grouper spawning. Apparently, certain sites are used consistently by a number of reef fish species for spawning. What is unique about these locations is that a number of species spawn in them. It is often assumed that specific spawning sites, selected over evolutionary time, maximize reproductive success and enhance dispersal. If this is true, what specific transport mechanisms are involved in getting the larvae from the pelagic phase to settlement areas? Can larvae control the direction of their drift by swimming against currents and by vertical migration?

The analysis of reef fish recruitment questions in the eastern gulf using gag and other reef species may have broad application, not only to the management of the fisheries involved but also to recruitment processes in general. Only a coordinated interaction between physical oceanographers and biologists will bring about a clear resolution to these questions.

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2.2.6 FRESH WATER INPUT TO THE GULF OF MEXICO *VIA* SPRINGS AND SEEPS

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Introduction and Approach

Submarine springs and seeps deliver an unknown quantity of groundwater and recirculated seawater to the coastal ocean. This process has been demonstrated to be biologically important as a nutrient input in some local areas. Is the process important on a wider scale? Some information suggests that inputs of various chemicals *via* submarine discharge of groundwater may be globally significant. The problem is how to quantify this flow.

Our research is intended to develop an assessment method based on measurements of natural tracers, *i.e.*, components found at very high concentrations in groundwater relative to ocean water. To validate our technique, we are also making direct measurements of groundwater seepage and flow from submarine springs in the same area where we are collecting the tracer information. Our study area is a relatively small (~400 km^2) portion of the northeastern coastal Gulf of Mexico which is known to be influenced by submarine springs (Figure 18). Its location is convenient to our laboratory facilities and the area is characterized by relatively simple current flow. Current meter and hydrographic measurements have shown that the water column here has two distinct layers which are almost totally decoupled.

The tracers we are using, ^{222}Rn and CH_4, should be useful because: (i) they are conservative; (ii) their source term is high; (iii) production rates can be estimated; and (iv) they are relatively easy to measure, even at very low concentrations. Although methane is not strictly conservative, the rate of biogenic oxidation in our study area has been confirmed as being low. The source term for both tracers is very high with groundwater concentrations from coastal aquifers in the area approximately 4 orders of magnitude higher in concentration than ambient seawater.

Observations

Over the past two years we have made hundreds of direct flux determinations from offshore springs and seeps and analyzed many dozens of aquifer and seawater samples for radon, radium, methane, nutrients, and other components. Results from offshore waters typically show much higher concentrations of both radon and methane in the deeper layer, especially during the summer stratification. While the radon and methane profiles are normally very similar, they occasionally show differences in detail. We have observed that integrated amounts of excess (unsupported by ^{226}Ra) ^{222}Rn concentrations show a definite seasonal trend with higher concentrations occurring in the summer (Figure 19). This increase must be due, at least in part, to the decreased net current observed in the summer. This relationship was graphically illustrated in our data set from August, 1992. During this period there was one day (August 11, 1992) when the ^{222}Rn and CH_4 bottom water concentrations were highly correlated and reached values several fold greater than values measured either before or after. When the current meter results were examined for that same period, it became clear that the net flow at 1 meter above the bottom was at a minimum on the day preceding our measurements and remained at an extremely low level on Aug. 11*th* as well. When sampling resumed a few days later, the current vectors as well as the tracer concentrations were back to established patterns. Thus current advection clearly plays an important role in determining the measured concentrations of groundwater tracers in the water column.

In spite of the observed importance of current flow to tracer concentrations, there is a measurable groundwater signal in these data as well. The seasonal pattern referred to earlier is one indication of this signal. Another line of supporting evidence comes from our direct measurements of nearshore seepage made along a transect perpendicular to the coast out to about 500 m from shore. These data, collected with a standard seepage meters, show that seepage at this transect follows the expected pattern of being highest closest to shore and decreasing systematically offshore (Figure 20). Furthermore, results show very similar values and trends when measurements are made within hours to at least a few days of each other. However, on time scales of weeks or longer, we have observed substantial changes in seepage rates, with about a 5-fold change measured in the integrated flow over a period of a few months. When viewed over that type of time scale, it is clear that there are temporal changes in seepage which relate to local meteorological conditions and, most likely, to the hydrological head which drives the seepage flow (Figure 21). These nearshore seepage patterns show the same general pattern as the offshore temporal variation, suggesting that they are related to the same process. We feel that the changing hydrogeological conditions in the coastal aquifers are manifested in these seepage and offshore radon and methane patterns.

Estimation of the Magnitude of Flow

In order to estimate the magnitude of groundwater flow into the study area, we first estimate the "standing crop" or inventory of excess ^{222}Rn. This integration is performed by summing the excess radon over depth at each station where we have complete water column profiles. Estimates based on our profiles analyzed to date show that there is a range for individual stations from 7 to 87 x 10^3 dpm/m^2, with the highest values occurring in the summer (1992 average = 55.1 dpm/m^2 and 1993 average = 23.8 x 10^3 dpm/m^2).

In order to calculate the contributions from the diffusive benthic fluxes of radon that would be expected to originate from the bottom sediments, we ran a series of experiments on sediment samples collected from the same stations used for measurement of radon in the overlying water. Several tens of grams of wet sediment from several samples were loaded into flasks and covered with seawater with known ^{226}Ra concentrations. The flasks were then sealed, de-gassed, and stored for a period of approximately three weeks in order to allow the radon to equilibrate at which time the ^{222}Rn was measured by standard emanation techniques. We then used a form of the general diagenetic equation to estimate these diffusive fluxes:

$$\frac{dC}{dt} = k_z \frac{\partial^2 C}{\partial z^2} + w \frac{\partial C}{\partial z} + J_{Rn} - \lambda C \qquad (1)$$

where,

C = concentration of excess ^{222}Rn (dpm/m^3);

t = time (min);

K_z = vertical diffusion coefficient (m^2/min);

z = depth (m);

w = upwelling velocity (m/min);

J_{Rn} = diffusive flux of ^{222}Rn ($dpm/m^2 \cdot min$); and

λ = decay constant of ^{222}Rn (1.253×10^{-4} min^{-1}).

Assuming that the system is in steady state($dC/dt = 0$) and that the horizontal gradients are not important, it is possible to solve this equation under different assumptions for the upward advection of submarine groundwater discharge. We may then predict the amount of ^{222}Rn that will be produced by emanation from sediment grains into the pore waters of the sediment, followed by diffusion into the overlying water column. Since radon is also radioactive, this diffusive input will eventually be balanced by decay. The net standing crop or inventory (I) in units of $dpm \cdot m^{-2}$ is thus,

$$I = J_{Rn}\left(\frac{1}{\lambda_{222}}\right) \qquad (2)$$

where $1/\lambda$ = mean life of ^{222}Rn (5.54 days).

Using this approach, we calculate that the diffusive flux (no advection) of radon from the type of bottom sediments in this area supplies an inventory of $\sim 2.6 \times 10^3$ $dpm \cdot m^{-2}$ to the water column or only about 10% of the observed inventory. Diffusional flux from sediment, therefore, cannot account for the large standing crop of radon in the study area.

Using measured concentrations of ^{222}Rn from coastal wells in the area, and considering the estimates of diffusive input from the sediment equilibration experiments, we can adjust the groundwater flux term in equation (1) until we have balanced the radon inventories actually measured in the offshore waters. Assuming that the only significant contributors to this inventory are the diffusive flux of radon from the sediments and advection of radon due to groundwater flow, our calculations suggest a range in regional groundwater flow of 1,000 to 14,000 $m^3 \cdot min^{-1}$ into the study area during 1992-93. If evenly distributed throughout the region, this would be equivalent to an "average" seepage of about 1-12 $ml \cdot m^{-2} \cdot min^{-1}$. For perspective, this discharge is equivalent to the flow from about 1-20 Wakulla Springs, a very large (first-magnitude) spring near the study site. This is an impressive amount of flow that would be very obvious, even to the casual observer, had it been exposed above seawater. Further studies are now required to improve the model estimates so oceanic flow patterns can be considered as well in order to improve these estimates of groundwater flow into the coastal ocean.

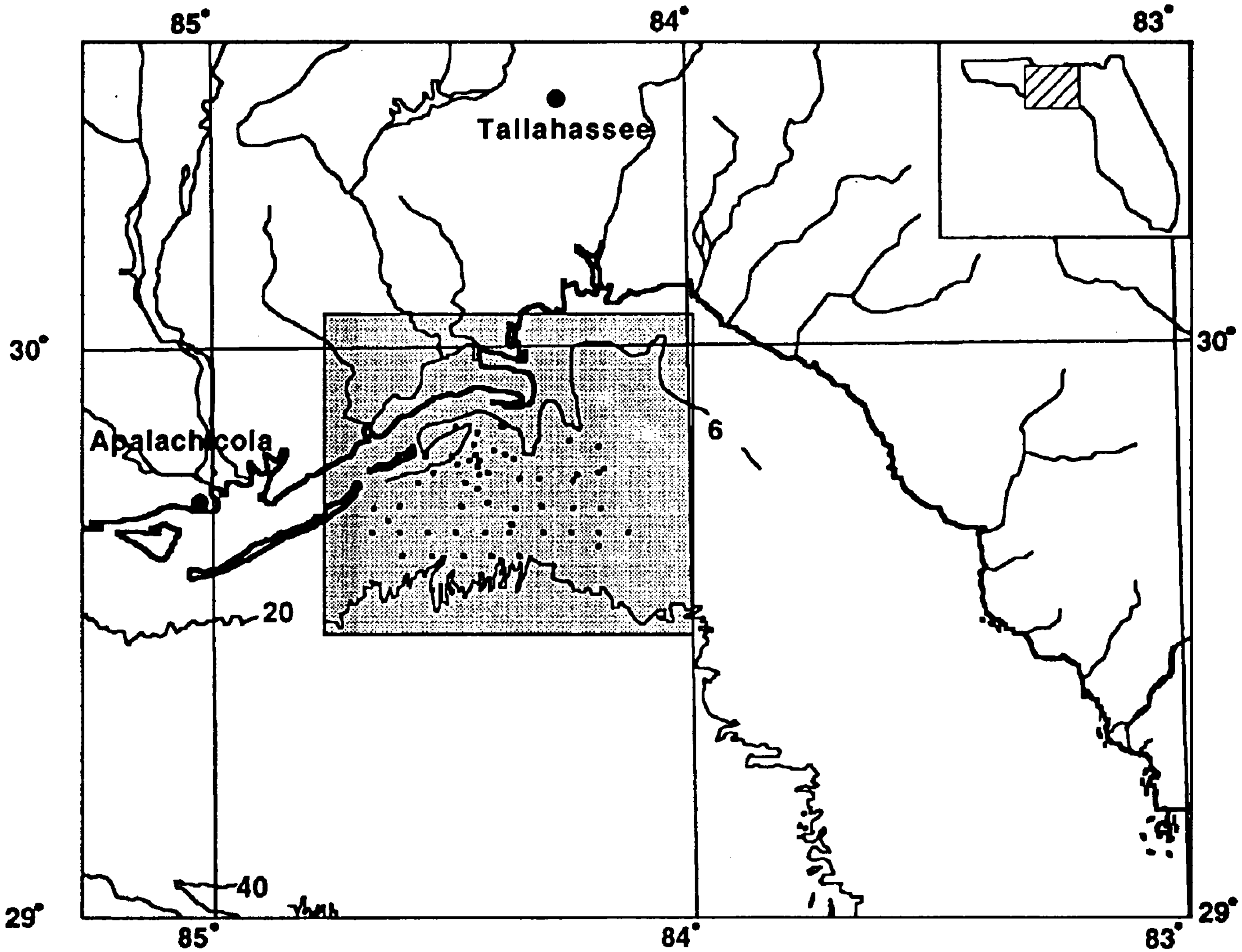

Figure 18. Map of the study region with the area of detailed interest shown in gray. The points shown represent the sample locations occupied during 1992.

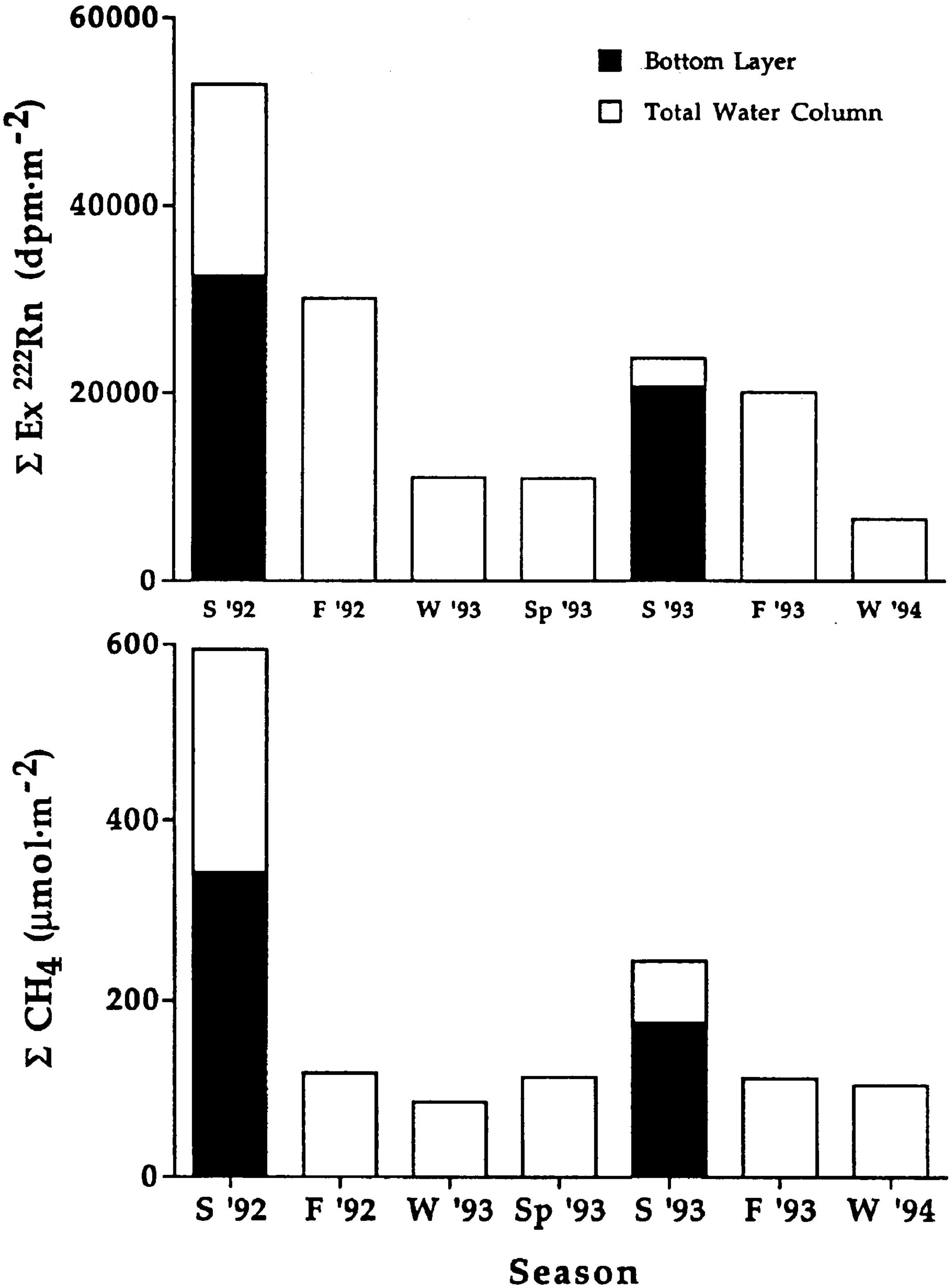

Figure 19. Average seasonal inventories of methane and excess radon measured in the study area during 1992-93.

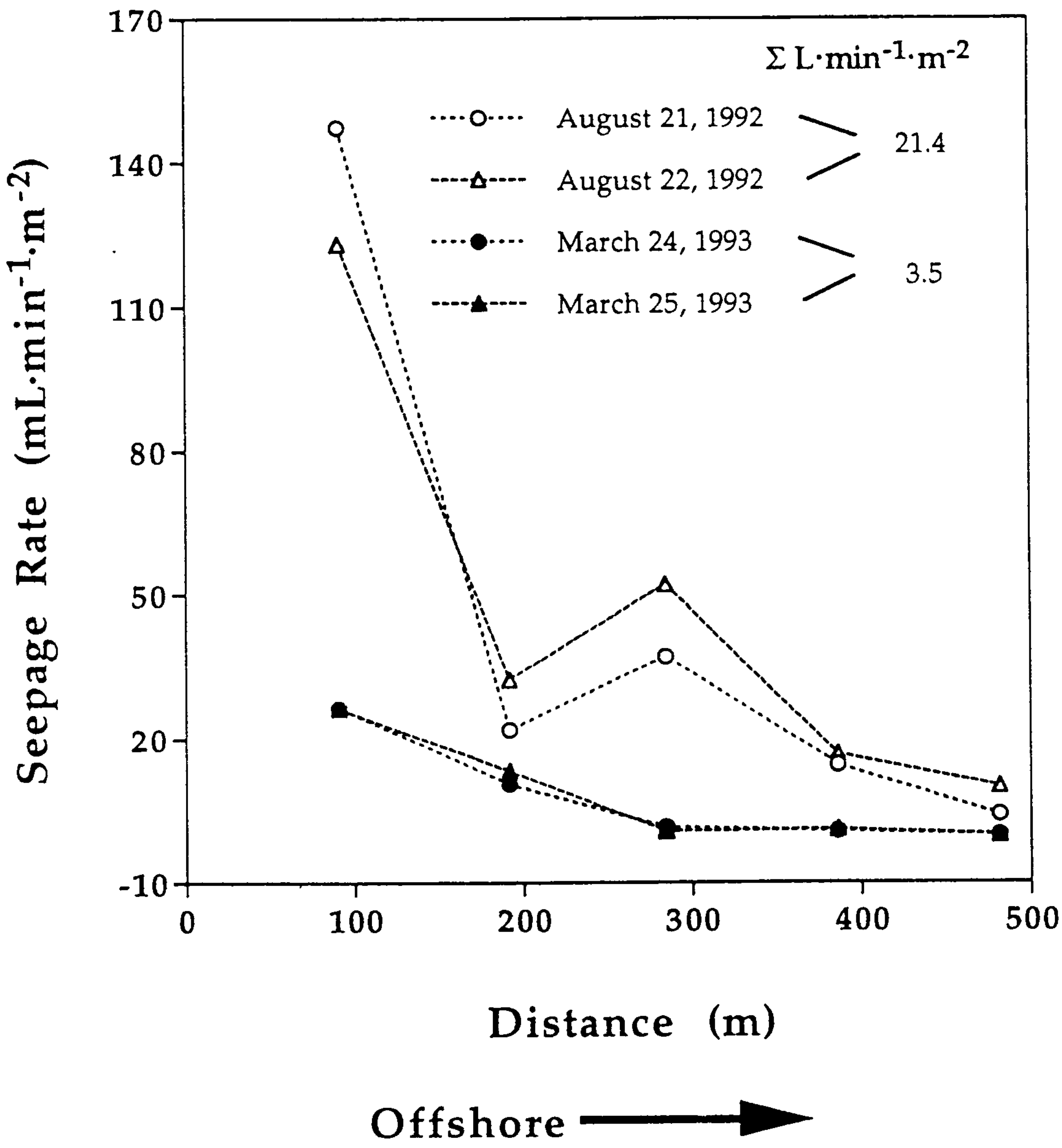

Figure 20. Seepage rate ($mL{\cdot}m^{-2}{\cdot}min^{-1}$) *versus* distance from shore at a transect perpendicular to shore near the FSU Marine Laboratory at Turkey Point. Two data sets are shown for measurements taken one day apart on August 21-22, 1992 and again on March 24-25, 1993. The integrated amount of seepage over the 500 m length of this transect is also shown for the two periods.

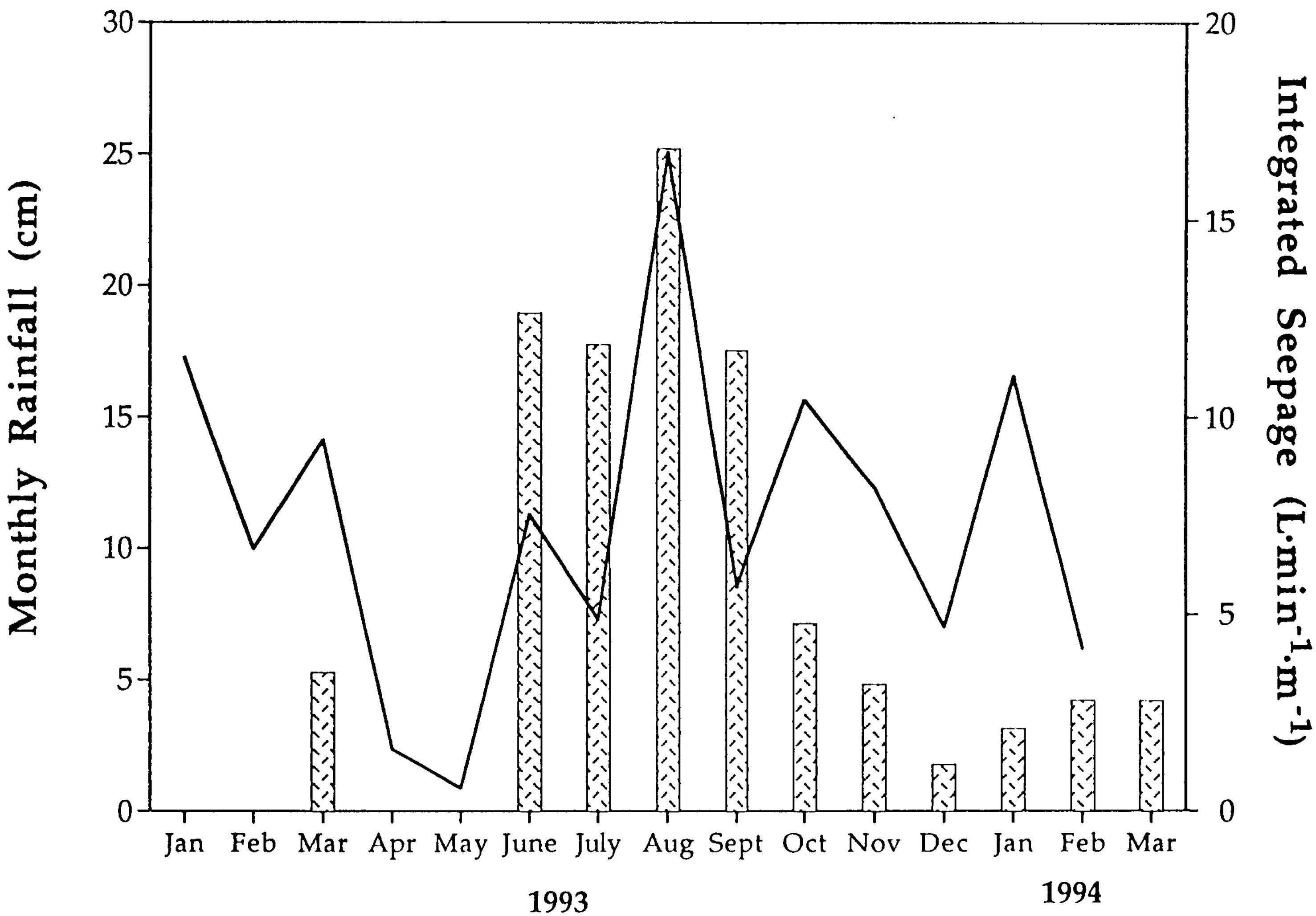

Figure 21. Comparison of the record for monthly rainfall (cm) measured at Apalachicola, Florida (solid line) to monthly averaged integrated seepage ($L \cdot min^{-1} \cdot m^{-1}$) measured at the Turkey Point transect (stippled bars).

2.2.7 SURFACE CURRENT AND LAGRANGIAN-DRIFT PROGRAM (SCULP)

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Abstract

In the period of 1 June 1993 - 30 March 1993, over 250 CODE drifters, drogued at 1 m depth, were deployed from three oil platforms and commercial aircraft at 15 stations on the Louisiana continental shelf. Principally, the drifters moved westward on the shelf, with the surface currents intensified near the coast. There was an accumulation of drifters on the continental margin, at about 75m depth, signifying existence of a surface convergence zone there. Significant exchange of drifters across the shelf and deep water boundary occurred on the south Texas and Mexican shelf in the western Gulf. Several large cyclonic eddies were also observed to draw surface water off the shelf south of the Louisiana-Texas border. The variance ellipse of supra tidal period surface currents is elongated principally along the isobaths and appears not to be related to the strength of the mean flow. Strong wind events occur both in summer and winter. In summer the coastal current system can accelerate to over 100 cm/sec in water depths of less than 20-m. In fall and winter, reversals of the entire surface current system on the shelf occurs with the reversal of synoptic winds from east to northwest. A computer movie of the drifter tracks shows several of these time dependent features. Drifter deployment will end in October, 1994 by which time about 400 drifters will have been deployed: the half life of which was observed to be 200 days. Analysis of this data, together with LATEX surface current meter data, will proceed well into 1995.

2.2.8 THE WEST FLORIDA SHELF AND FLORIDA MARINE RESOURCES STUDIED BY THE STATE RESEARCH LABORATORY

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For nearly 40 years the state marine research laboratory at St. Petersburg has been involved in studies on the biology of Florida's coastal waters including the West Florida Shelf (WFS). Originally begun in 1955 as the Florida State Board of Conservation laboratory to study red tides, a problem plaguing the area since the early 1930's, the laboratory grew to include studies of other organisms and their environment. As the Board of Conservation evolved into the Department of Natural Resources, so did the laboratory, becoming the Marine Research Laboratory including additional personnel, facilities, and field capabilities with the coastal research vessel *R/V Hernan Cortez.* In 1987, the Marine Research Laboratory became the Florida Marine Research Institute (FMRI), occupying a 3 building complex at the Bayboro peninsula with a fleet of small vessels and a new research vessel *R/V Hernan Cortez II*. The Institute shares the peninsula with the University of South Florida, Florida Institute of Oceanography and the U.S. Geological Survey. This year FMRI will inaugurate jointly with USF's Dept. of Marine Science, a satellite processing wing in the newly constructed research laboratory/ office complex.

Presently the main research efforts and programs at FMRI are:

Marine fisheries:	Critical Fisheries Monitoring Life-History Studies Stock Assessment
Marine Ecology:	Ecological Monitoring Marine Animal and Plant Health Studies
Protected Species:	Marine Mammal Studies Sea Turtle Studies
Marine Resource Enhancement:	Fish and Invertebrate Stock Enhancement Habitat Characterization and Enhancement
Coastal Production:	Trophic Dynamics and Coastal Hydrography of Marine Plankton Populations.
Coastal and Marine Resource Assessment:	Assessment and Geographic Information

Of the research efforts on the WFS, the Institute has participated in the following:

BLM or MMS sponsored research:	MAFLA - evaluation and advisement on benthic surveys on the WFS. South West Florida Shelf Ecosystem Study - evaluation and advisement on hydrography.
Federal (other):	SEAMAP (Dept. Commerce, NOAA/NMFS, Spring 1982 to present). Coastal Production (U.S. Fish and Wildlife, 1991 to present).
State:	Hourglass Cruises (Aug. 65-Nov. 67) Coastal Production (ongoing) Pelagic Fisheries Programs (ongoing) Red Tide Studies (ongoing)

A synopsis of these programs is:

Hourglass (Aug. 65 to Nov. 67)

Sample Type:	Benthic Trawls Drift Bottle Studies Ichthyoplankton
Coverage:	Tampa Bay to Ft. Meyers, on shore to 40 fathom isobath
Data Taken:	Temperature (air and sea surface) Salinity Turbidity Cloud Cover Sea State Wind Speed and Direction Wave Height
Data Availability:	Memoirs of the Hourglass Cruises, FMRI Publications Office and Library Archives.
Significant Findings:	Drift Bottle circulation, seasonal and can include transport around the peninsula to the east coast of Florida, Onslow Bay, North Carolina and Chesapeake Bay. Phytoplankton (diatoms and dinoflagellates) for the WFS in the study area. Species composition and seasonal variations.

Ichthyoplankton species composition and distribution in the study area. First to establish the importance of the WFS as breeding ground and early life history of many of Florida's marine fish species.

Planktonic Fish Series (Dec. 67 - Oct. 69)

Periodicity:	Monthly
Sample type:	Ichthyoplankton
Coverage:	Florida Shelf inside 100 m isobath.
Data Taken:	Temperature (sea surface) Salinity Ichthyoplankton
Data Availability:	FMRI Library Archives
Significant Findings:	Extended the ichthyoplankton observations from previous study to include the deeper waters where most or many of the adult fish species were found to spawn.

SEAMAP (Spring 1982 - present)

Periodicity:	Spring and Fall Cruises
Sample Type:	Ichthyoplankton
Coverage:	U.S. Gulf of Mexico in 1°grid; Florida samples, WFS from Lat. 29 - 25°N.
Data Taken:	Temperature (air and sea surface) Salinity Chlorophyll (extracted) Oxygen Turbidity Water Color Sea State Wind Speed/Direction Barometric Pressure Wave Height
Data Availability:	Ichthyoplankton Data - FMRI Environmental Data - Ken Savastano, NMFS Laboratory, Pascagoula, MS also SEAMAP reports available through NMFS.

Coastal Production (Spring 1990 to present)

Sampling Periodicity:	3-4 cruises per year (Mar.-Oct.)
Sampling Type:	Ichthyoplankton Phytoplankton Zooplankton
Process Measurements:	Primary Productivity Secondary Productivity Fish Conditioning (DNA/RNA ratios enzymes)
Physical Chemical Measurements:	CTD Casts for Temperature, salinity, Chl a, oxygen. Extracted Chlorophyll a and phaeo-pigments. Dissolved nutrients (Nitrate + nitrite; ammonium, phosphate and silicate)
Other:	Distribution of ichthyoplankton biomass relative to shelf features. Zooplankton distribution and abundance. Phytoplankton species composition, abundance and toxin content (for detection of *Gymnodinium breve*).
Data availability:	Ichthyoplankton samples presently being sorted and counted. Nutrients presently being analyzed and other data is in the process of reduction in preparation for grant reports.

In addition to the ongoing or past programs, since the late 1970's, FMRI has processed satellite imagery. This has been used to detect coastal blooms and presently in monitoring shoreline dynamics related to loss or restoration of habitat. Using the techniques for both color (CZCS) and infra red (AVHRR) imagery, coastal processes including bloom formation, Loop Current positioning and development of LC eddies have been monitored. These last are of particular interest to the Coastal Production program in helping to define the distribution of fish eggs and larvae. The dynamics of the hydrography, biological distributions and transport are supported by the observations via satellite imagery.

A new initiative includes a rapid response oil spill team which in 1993 was mobilized to identify and monitor the oil spill at the mouth of Tampa Bay and adjacent shelf area. This initiative included areal reconnaissance, location of spill using geographical positioning systems and plotting of the progression of the spill via computer generated maps. This activity will probably expand in the future to map various features on the WFS including oil spills and will be integral to biological studies to define the geographical distributions on the shelf of these phenomena.

2.2.9 COASTAL PRODUCTION PROGRAM AND DYNAMICS ON THE WEST FLORIDA SHELF

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Field studies conducted by the Florida Marine Research Institute (FMRI) as well as those of Houde *et al.* (1979) indicate that the West Florida Shelf (WFS) is a highly productive area where most adult marine fish species breed, release eggs and develop into larvae. This period in the early life history is critical and requires favorable conditions for larval fish populations to develop successfully into early stage juveniles which migrate from the shelf into coastal estuaries where further development and maturation occurs. The shelf, therefore, must provide the critical habitat for successful breeding, survival of eggs and larvae and early maturation. A tight linkage with an appropriate trophic structure is essential for the early survival of the fish and their eventual recruitment into estuaries. The dynamics governing the trophic structure on the West Florida Shelf (WFS) are key elements in sustaining the important fish stock.

There are several features to suggest that physical mechanisms are very important in making the WFS the critical breeding grounds. Historically, this area contains the most productive fishing zone, the "middle grounds", for the entire Gulf of Mexico region. Coastal Zone Color Scanner (CZCS) imagery for the years 1979 through 1985 repeatedly detected large chlorophyll concentrations within the upper meter for a region south of San Blas extending at mid to outer shelf until well below the Tampa Bay region (Figure 22). This area was estimated to have concentrations between 1 and 2µg/L of chlorophyll **a** where the normal pigment content was an order of magnitude less. These "chlorophyll plumes" overlay the middle grounds where over 90% of the annual catch of grouper from the Gulf of Mexico is harvested. In addition, this region is also known to be the site of eddies (Cochrane, 1972) produced by the incursion of the Loop Current which can dominate the circulation patterns in the eastern Gulf (Rezak *et al.*, 1985). The impact of these phenomena on the biology of the WFS is unknown although there is some suggestion that resuspension caused by Loop Current intrusions can stimulate dormant cysts of red tides species like *Gymnodinium breve* to form actively growing populations (Haddad and Carder, 1979).

In an effort to discern the variations on the WFS and how they may be related to larval fish survival, the FMRI Coastal Production Program was initiated. This program examines the dynamics of plankton on the WFS as related to the physical-chemical environment. It is oriented toward observing the species composition and abundance of the plankton components (ichthyoplankton, zooplankton and phytoplankton), their trophic dynamics through measurements of primary and secondary production, and the relation of these as well as physical-chemical factors on the condition of eggs and larvae. While the work of this program is still in progress, a few significant features have already emerged indicating the importance of some factors driving the dynamics of the shelf. A series of 60 to 70 stations were sampled during 3 to 4 annual cruises (1990-1993) to detect seasonal and spatial variation in plankton and the physical chemical environment (see Figure 22 for typical cruise). Besides the biological sampling for plankton made at each station, the water column was studied *via* CTD casts measuring temperature, salinity, chlorophyll fluorescence and later dissolved oxygen with depth. Discrete samples were also taken at various depths using a rosette sampler in conjunction with the CTD for measurements of extracted chlorophyll and nutrients (nitrate, nitrite, ammonia, phosphate and silicate). Although not routine, further specialized analyses were done for benthic chlorophyll, gelatinous zooplankton as well as surface reflectance for correction of satellite algorithms. The biological samples, *e.g.*, ichthyoplankton, phytoplankton and zooplankton are presently being analyzed while the process measurements are completed for the period from 1990 to 1994. The nutrient analyses for this same period are still underway and will be completed by the end of this year. Maps of fish species, and related processes supporting them will be a product of this study when completed.

The major findings to date indicate that the WFS is a much more dynamic region than previously suggested. During the spring (March) 1992 cruise, a large chlorophyll plume (Figure 23) was detected just south of Cape San Blas like the ones previously seen in the historical CZCS imagery. While the location of the plume confirms what was seen previously in the imagery, the surprise is that the maximum concentration approached 8 µg/L, which is over 4 times greater than that seen or predicted by the CZCS images. This finding is significant particularly since earlier views of the shelf were that it was mostly an oligotrophic region that was occasionally influenced by the Loop Current but mainly affected by riverine and anthropogenic sources in-shore. In terms of biomass and ultimate primary production, excluding periods of red tide blooms (Vargo *et al.* 1987), the north/central WFS has high values consistent with the highly productive fishery found there (Tomas, unpublished data). As a reproductive area, the chlorophyll concentrations during spring 1992 could certainly support secondary production to maintain large larval populations over a wide area. The plume was not found in subsequent cruises during April. This is not surprising considering that CZCS images indicated a plume was likely to develop anytime from February through May during the 1979-85 period. We know little about the timing of the blooms to be able to predict when we should find them.

Another important feature of the shelf was observed during the August of both 1992 and 1993. The 1993 year was marked by heavy rains in the region of the central and southern states during May thorough July. The extreme flooding experienced in the mid West that year was reflected in unusually high river discharge primarily from the Mississippi river as well as the 10 major northern Florida rivers. The discharge from the 10 Florida rivers, however, amounted to less than 10% of the Mississippi river discharge during these maximal flood periods. The August '93 cruise detected a large intrusion of low salinity water in the northeastern region of the WFS (Figure 24). Low salinity water (26‰) was introduced from the west into an area just south of the Florida panhandle and extended easterly and to the south towards the Florida Peninsula. A similar feature but with less drastic salinity values was observed in August 1992 when again the Mississippi had late summer floods. This was not observed in 1991 or earlier cruises. The eastward transport of Mississippi river water is atypical. Normally the river discharge travels west towards the Louisiana/Texas shelf. The eastward flow of river water in August 93 was confirmed by satellite imagery showing an eastward turbidity plume (Rick Stumph, USGS, unpublished data). The river waters were apparently stripped of nutrients prior to arriving on the WFS as observed in our nutrient analyses. However, substances like atrazine and resistant hydrocarbons were most likely transported unmodified. The biological impact of the Mississippi water on the WFS is presently being examined from analysis of the plankton samples. Certainly a major region of the shelf area was effected by this discharge. A low salinity lens over 20 meters deep covered nearly 60% of the shelf area by the end of September 93. This low salinity persisted until late October when a well mixed, homogenous water column was established.

During this same time (August, 1993) another feature of the WFS was discovered. Along with the intrusion of the low salinity water, a gradient in dissolved oxygen was seen (Tomas, 1994). This oxygen gradient, measured within the upper meter, varied from greater than 94% saturation (>4 ml/L) in the low salinity region and declined in a regular manner towards the south and the east with minimal values below 50% saturation (<2 ml/L) found at the southernmost region, the mouth of Florida Bay (Figure 25). This enigmatic decline cannot be explained simply as a function of oxygen solubility with salinity and temperature. The dynamics causing this notable oxygen gradient are presently unknown. The gradient on the WFS influences the biology since organisms are subjected to decreasing surface oxygen on the shelf and in Florida Bay. The latter region is a site of great dystrophy where massive seagrass dieoff, sponge mortality, and extensive phytoplankton blooms causing extreme turbidity and possible fish mortalities occur. The degree to which the physical-chemical processes of the shelf influence inshore environments like Florida Bay needs to be studied further.

Another aspect of the Coastal Production Program links the formation for toxic phytoplankton blooms on the shelf with distinct regions. Again during the August 1992 cruise, selected stations were tested using a sensitive Enzyme Linked Immuno Sorbent Assay (ELISA) technique for the presence of brevetoxin, the highly potent neurotoxin produced by the red tide organism *Gymnodinium breve*. Using the extremely sensitive antibody technique, populations of this species were detected on the shelf at two major loci (Tomas & Baden, 1993). These mid-shelf regions, one off Crystal River and another off of Sanibel Island represent incipient red tide blooms and are a feature of the WFS which has in the past caused great problems with fish kills, shellfish bed closings and irritation to humans at the shore areas. The blooms which originate 60 km offshore are postulated to be initiated by resuspension of dormant stages as well as stimulated by nutrients upwelled from deeper waters by Loop Current eddies. Some years, these blooms remain offshore and hardly impact coastal areas while in other times, dead fish as well as blooms themselves can be transported to inshore areas where they have sizable influence.

In summary, the WFS is a highly dynamic region where extensive biological activity is reflected in large phytoplankton blooms, breeding of marine fish species accompanied with high densities of eggs and larvae, and extremes in primary and secondary production. This is consistent with the rich shelf fisheries for which this region is historically known. Spatially, the northern sector appears to be most active. Regions south of Tampa Bay, (Lat. 27°30 N) are less rich and more oligotrophic in nature. Large chlorophyll plumes form extending from just south of Cape San Blas to below mid shelf Tampa Bay regions. These blooms, presumably fed by nutrients from rivers, can also be influenced by the Mississippi river which has been found to impinge on the shelf during more than one year . This shelfward movement of river water is dependent upon a deep penetration of the Loop Current accompanied by large flows and favorable westerly winds. Together these factors have allowed transport of Mississippi river water to the east onto the WFS. The influence of the river water regulating oxygen content of the surface shelf waters and larval survival is yet to be defined although processing of biological samples from our studies should help define the degree of influence. Continued and further studies in the north as well as the southern shelf regions are needed to fully quantify these perturbations and help explain the dynamics of this rich environment.

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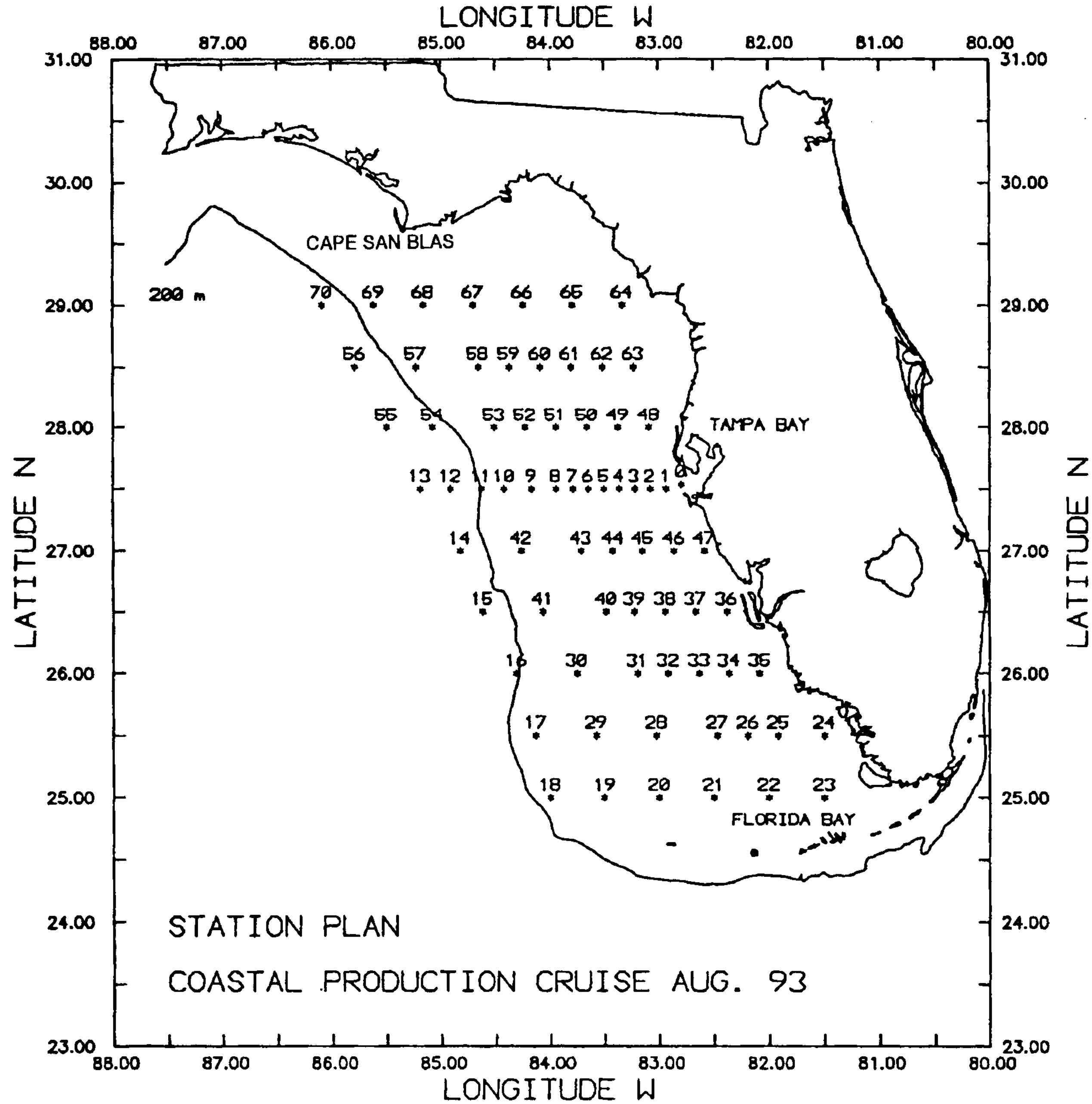

Figure 22. Typical areal coverage of the FMRI Coastal Production Cruises consisting of 70 stations. The order of the stations in this August 1993 cruise is not necessarily the order of other cruises.

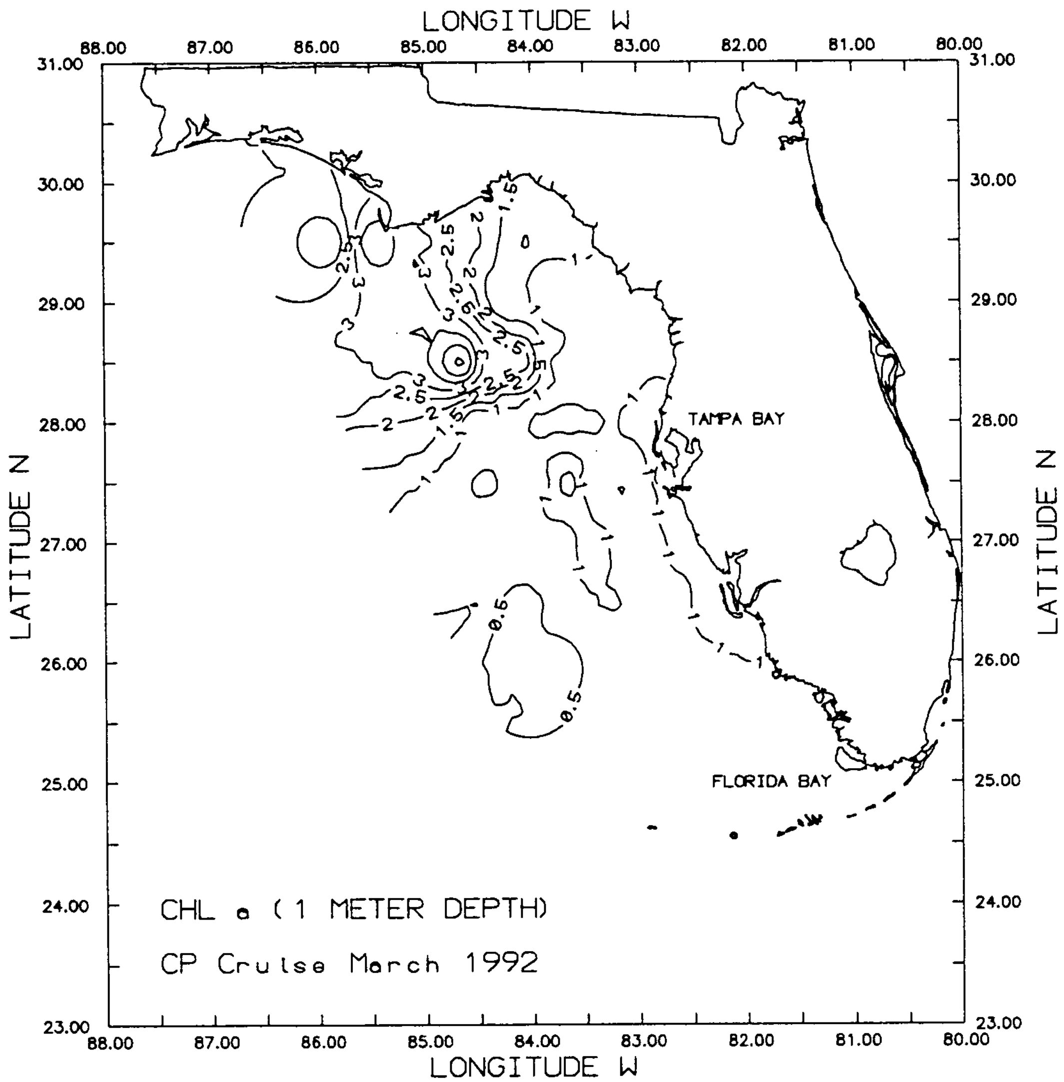

Figure 23. Heavy Chl **a** concentrations found at 1 meter depth south of Apalachicola and Cape San Blas during the March 1992 Coastal Production Cruise. Maximum subsurface values of 8 mg/m^3 were found within the upper 10 meters.

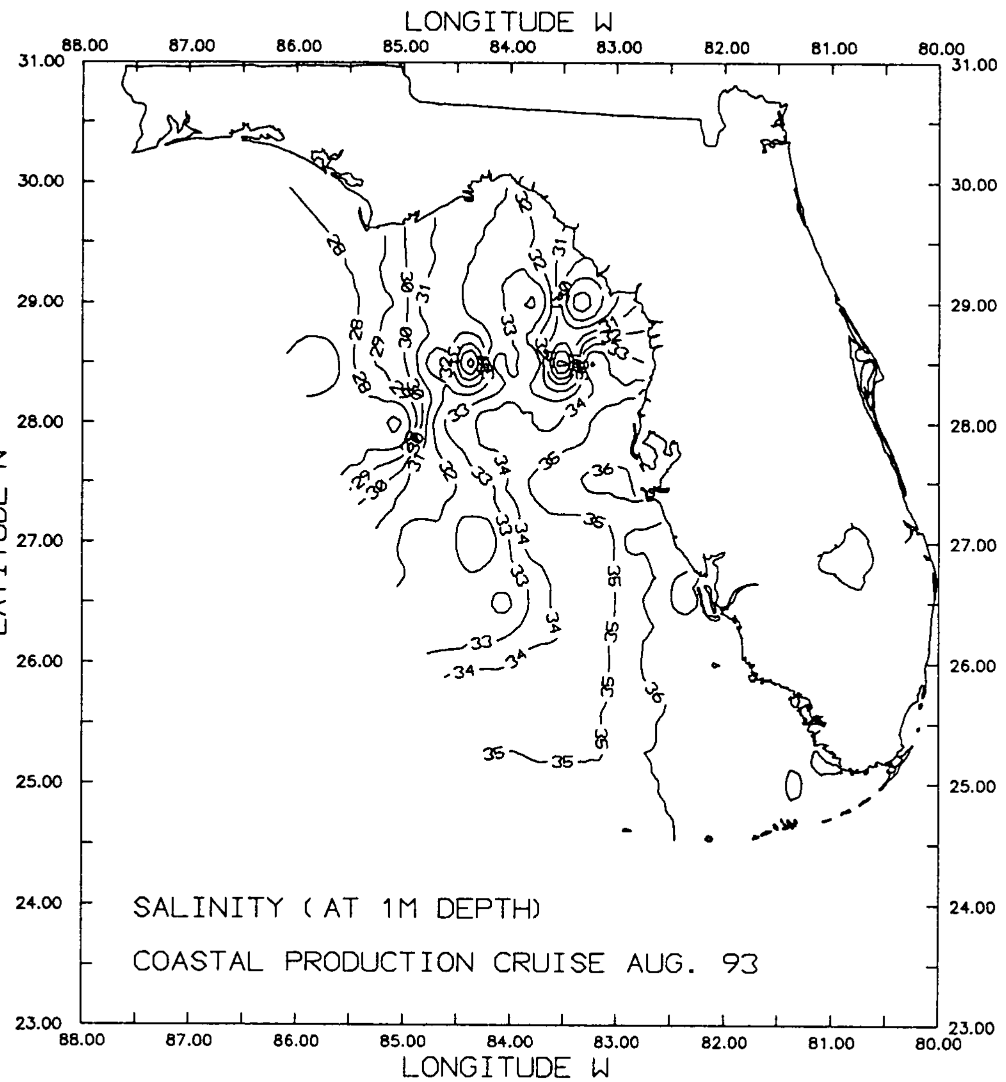

Figure 24. Low salinity lens within the upper meter observed during the August 1993 Coastal Production Cruise with values varying from 26 to 36 PSU.

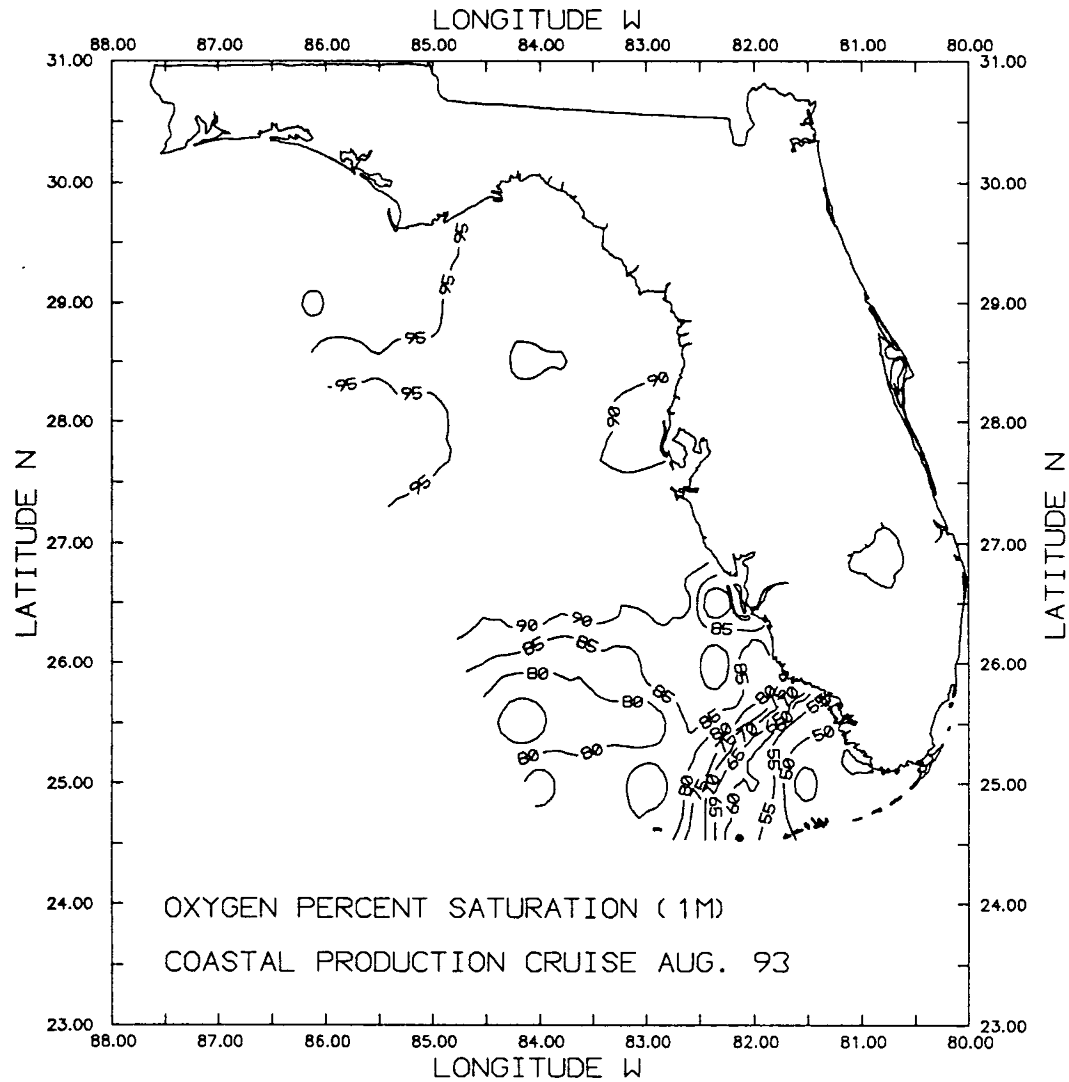

Figure 25. Gradient in percent saturation of dissolved oxygen in the upper meter for the entire West Florida Shelf observed during the August 1993 Coastal Production Cruise.

2.2.10 A CENSUS OF LOOP CURRENT RELATED INTRUSIONS ONTO THE MISSISSIPPI-ALABAMA CONTINENTAL SLOPE AND SHELF

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The Mississippi-Alabama Marine Ecosystem Study (MAMES) was conducted during 1988 and 1989 on the continental shelf and slope between the Mississippi Delta and DeSoto canyon. During this study, satellite images often showed plumes or filaments from the Loop Current pushing onto the shelf (Vastano *et al.,* 1991). The pathways were not restricted to the axis of DeSoto Canyon. A two-criteria index was defined in order to quantify the northern extreme of these features: (1) a continuous boundary reaching back to the Loop Current proper, and (2) a two centigrade degree difference or less with waters within the northern Loop Current boundary. This census (Figure 26) found warm intrusions north of 29.5°, *i.e.,* on the shelf, in December 1987, January, March and May 1988, and February, March and May 1989. Furthermore, Loop Current-related waters were persistently north of 29°, *i.e.,* near the continental slope, from mid-November 1987, to mid-January 1988, and from January to mid-March 1989. The extent of northward penetration of the Loop Current into the eastern Gulf was not a reliable indicator of the potential for intrusions onto the shelf because the filaments apparently can stretch over considerable distances. In some cases, filaments meandered hundreds of kilometers northward from the northern side of the main body of the Loop Current to reach the study area. The intrusion census using satellite images was hampered by intermittent cloud cover and the relatively isothermal sea surface conditions during July through September, which interrupted the continuity of observations.

The search for intrusive events was augmented by the results from four hydrographic surveys and the 40-hour, low-passed time series of temperature recorded at 150 m and 426 m at two current meter moorings on the 430-m isobath (Kelly, 1991). Every intrusion counted in the census by satellite corresponded to a temperature increase above the mean of one or more of the subsurface temperature series. The increase persisted for at least ten days and reached a peak deviation of at least one degree. Figure 27 shows the time series of the temperature records for 1989. The elevated temperature events that meet the criteria are marked. The temperature events were used to supplement the intrusion count when cloud-free satellite images were unavailable. The combination of satellite imagery, time series of sub-surface temperature and hydrographic surveys covered a total of 798 days. Intrusions were found during eleven periods of time, totaling 355 days, or forty-four percent of the time (Table 1).

The top panel in Figure 27 shows the adjusted sea level elevation at Dauphin Island, Alabama. (The "inverted barometer" effect was removed from the gage data.) For time scales longer than ten days, sea level elevation at the coast appears to be unrelated to the intrusions inferred from the subsurface temperature data on the continental slope.

Two of the hydrographic surveys were conducted during period when intrusions were clearly visible in the satellite thermal images. During the cruise of March 10-18, 1988, a plume of filament water, characterized by higher temperature, salinity, and dissolved oxygen values throughout the water column, pushed onto the western portion of the shelf and wrapped clockwise to the northeast (Figure 28). A southwestward return flow, with opposite water mass characteristics, was located east of the plume. The plume reached the innermost current meter site (29° 54' N; 87° 40.2' W; 30 m water depth), where bottom temperature rose abruptly by more than 2°C and salinity by about 1 PSU (Figure 28c). The hydrographic cruise conducted during February 1989 detected an intrusion of more limited horizontal and vertical extent on the shelf, compared to the one in 1988. However, a CTD profile over the slope (250 m) in the center of the plume clearly shows a salinity maximum greater than 36.7 PSU at about 125 m. A satellite IR image collected at the time of this cruise supports the presence of an intrusion (Figure 29a.)

The satellite images and the hydrographic surveys indicate the intrusions have spatial widths on the order of 30-45 km. (See Figure 29a,b.) The widths of the cooler, southward return flows are similar. During the two hydrographic surveys, the satellite images also showed warm filaments pushing up DeSoto Canyon, again with a spatial scale of 30-45 km.

We conclude that Loop Current related filaments frequently influenced the hydrography of the Mississippi-Alabama continental slope and shelf during the two-year MAMES study. The intrusions varied in vertical extent, but had a characteristic horizontal width over the shelf of 30-45 km. They appear to have displaced large amounts of shelf water. The data are insufficient to determine if the fate of the intrusions is to mix completely with the shelf waters or simply retreat.

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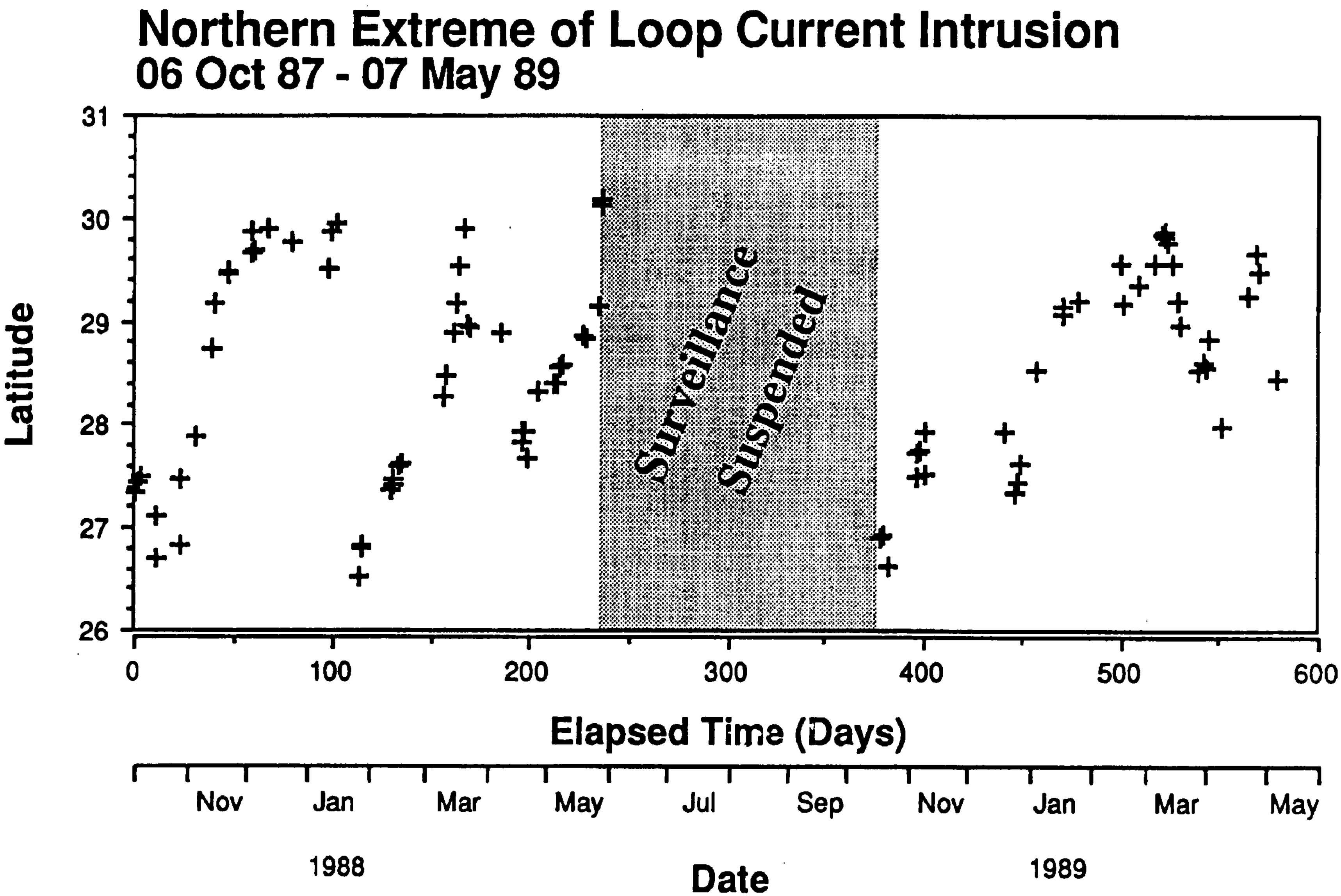

Figure 26. Loop Current intrusions into the northeastern Gulf of Mexico during the October-May intervals of 1987-88 and 1988-89.

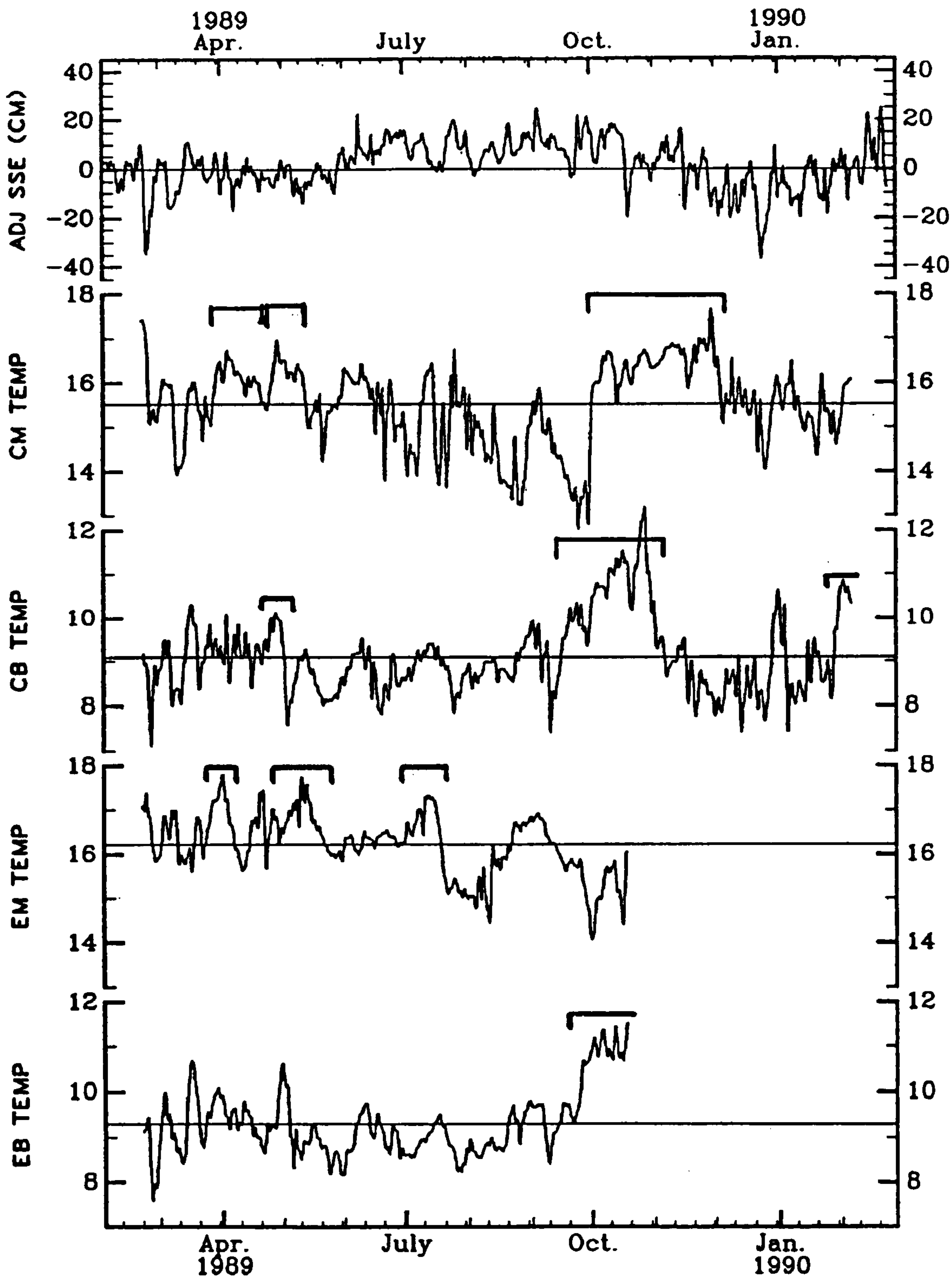

Figure 27. February 1989 to February 1990. 40-hour low passed time series of (a) adjusted sea level at Dauphin Island and temperature at (b) CM (mooring C, 150m), (c) CB (mooring C, 426 m) (d) EM (mooring E, 150m, (e) EB(mooring E, 426m) . The horizontal brackets indicate periods during which temperature changes are attributed to Loop Current related intrusions.

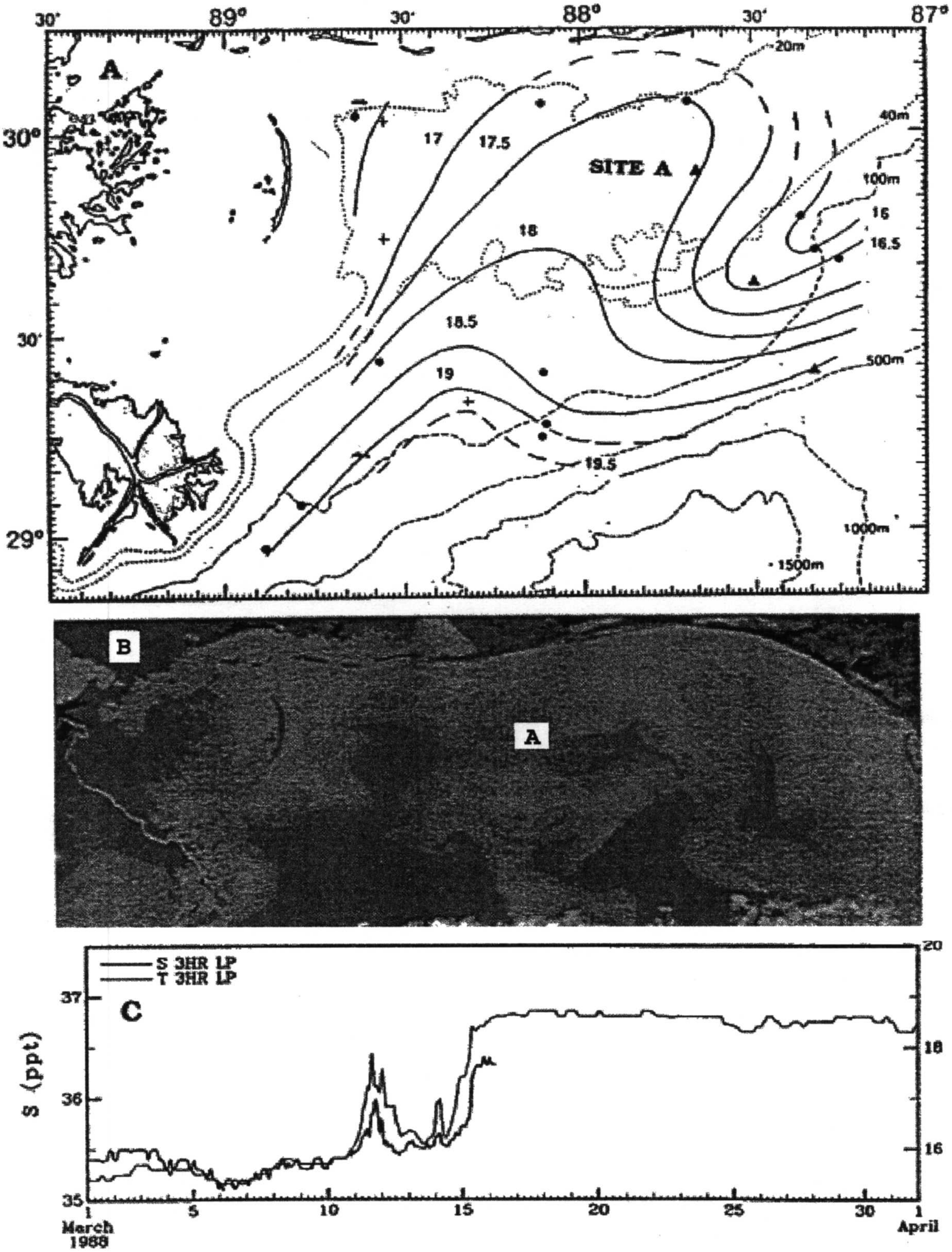

Figure 28. (a) Surface temperature field based on Cruise B2 (10-18 March 1988); (b) satellite IR image for 2110 hours GMT, 13 March 1988, darker regions correspond to warmer water; (c) temperature (light line) and salinity recorded by bottom current meter at Mooring A.

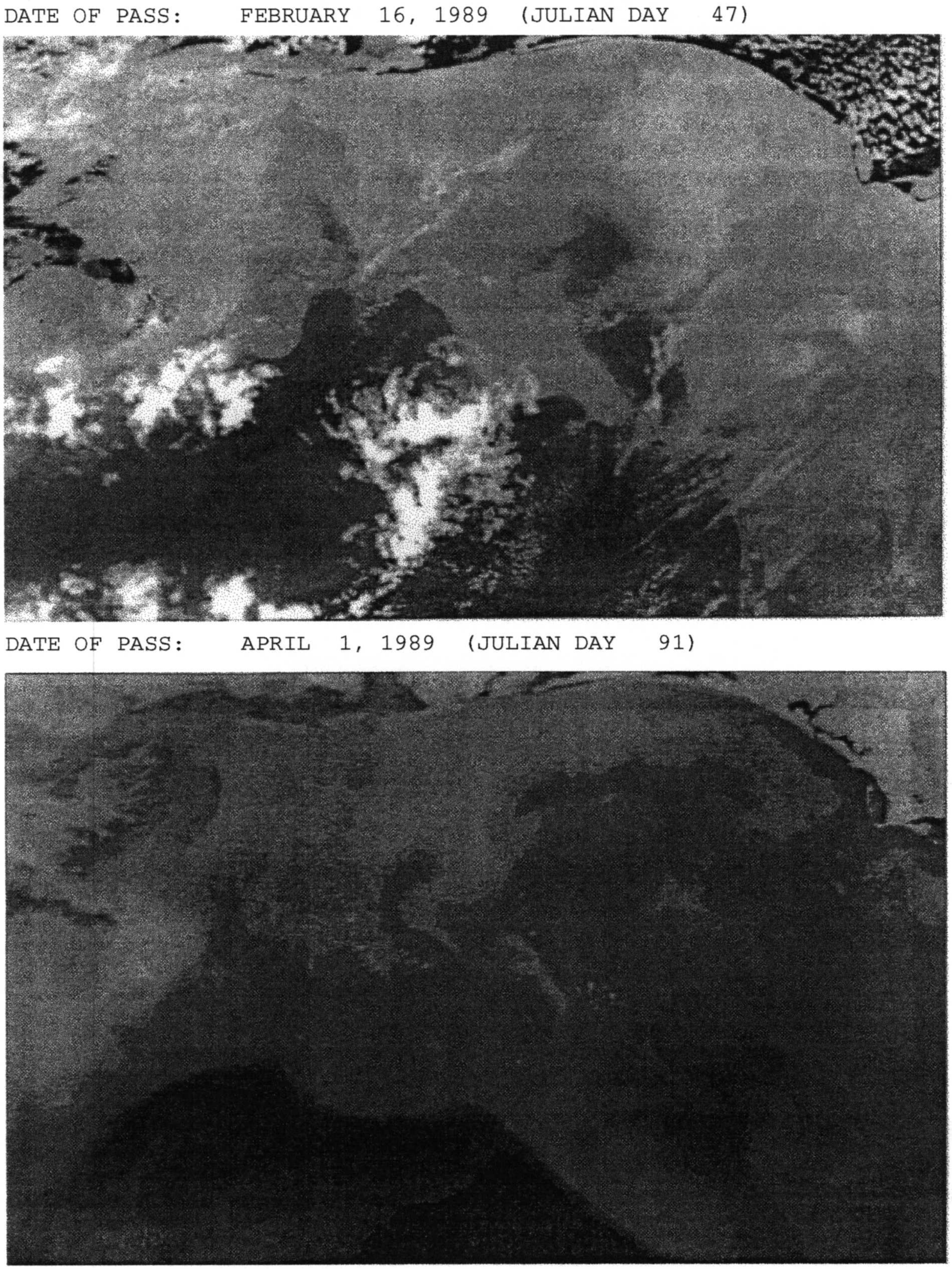

Figure 29. Satellite IR images taken on (a) 16 February 1989; (b) 1 April 1989. Warmer temperatures are darker.

Table 1. Periods during which warm intrusions were present and the data sets that indicate their presence.

	No. Days	S	H	CM	CB	EM	EB
Nov. 15, 1899 - Jan. 7, 1988	54	X					
Jan. 8-19, 1988	12	X		X			
Mar. 1-15, 1988	15	X	X		X		
May 1-22, 1988	22	X		X			
Oct. 18 - Dec. 13, 1988	57			X	X		
Dec. 28, 1988 - Jan 10, 1989	14	X		X			
Feb. 9-25, 1989	17	X	X			X	
Mar. 22 - May 20, 1989	60	X		X	X	X	
Jul. 1 - Jul. 18, 1989	18					X	
Sep. 18 - Dec. 1, 1989	75			X	X		X
Jan. 29 - Feb. 8+, 1990	11				X		

S = satellite AVHRR image
H = hydrographic cruise
CM = temperature recorded at 150 m at Mooring C
CB = temperature recorded at 426 m at Mooring C
EM = temperature recorded at 150 m at Mooring E
EB = temperature recorded at 426 m at Mooring E

2.3 Logistics and Ongoing/Planned Measurements of Relevance to the Study Region

2.3.1 MANAGEMENT AND LOGISTIC LESSONS LEARNED DURING LATEX

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We have now had over two years experience managing LATEX A, a large shelf oceanography program sponsored by the MMS. We have a combined experience of more than four decades of successfully carrying out research funded by the National Science Foundation, the Office of Naval Research, National Oceanic and Atmospheric Administration, and other sponsoring agencies. LATEX A is our first experience with the Minerals Management Service as a sponsor of research. These points are made because they undoubtedly affect our opinions regarding the manner in which research programs should be funded and managed. Some of our remarks may seem critical--and they are--but we offer them as positive criticisms. Please consider them as suggestions for improving future research programs funded by the MMS.

The research program in the Northeastern Gulf of Mexico should not be solicited/procured via a Request for Proposal (RFP). Science is not "bought by the yard". The winning proposal(s) should reflect the best possible science plan. Such a plan normally will be formulated by folks who intend to do the work, not by managers and consultants.

The Northeastern Gulf of Mexico program should be funded by grant or co-operative agreement, not by contract. Flexibility is much increased. We have learned that changes to contracts are slow--if possible--and may be decided on the basis of finances rather than scientific results.

There should be only one coordinator/manager of the program within the scientific community, and one coordinating manager within the funding agencies. This arrangement will assure the right hand knows what the left hand is doing--LATEX is a counter example.

Any new MMS program should provide contingency funds for flexibility. Such funding is necessary for needed, but unanticipated measurements or to observe interesting, pertinent phenomena, perhaps of relatively short duration. LATEX has been unable to add additional, needed measurements or carry out unplanned field programs because no contingency funds are available.

If modeling is foreseen as truly part of the program, support it in a manner to ensure close coordination between the modeling and observational components. To accomplish close coordination, sponsor coordination/management of field and modeling efforts should be done by the same person. Ideally, the research direction should be joint between field and model activities.

Any future programs should not have unneeded advisory groups, and the number of meetings should be limited to essential ones. Funds are better used on observations, interpretations and model development, not advisory groups. Too much of scientists' time during LATEX has been spent preparing for or attending unnecessary meetings.

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MMS should work toward obtaining multi-agency support and cooperation before the program is cast in stone. There were many opportunities missed in LATEX because other agencies were not closely involved in the program formulation. It is hard to sell a custom-built home except to the designers.

In future programs, MMS should work toward reduction of paperwork required by manager of scientific programs. A considerable fraction of LATEX personnel time is spent preparing reports (pre-cruise plans, post-cruise reports, monthly reports, annual reports, final report, GULF.MEX Bulletin Board postings, *etc.*).

If data sharing during the contract period is required, MMS should establish a data sharing and publication policy prior to award of the contract and funds should be budgeted for data sharing. There should be open data sharing between all of the program participants. This might be done by having preliminary data available for electronic transfer on demand to other participants. Agreements should require that data generators have options to contribute to and co-author manuscripts using their data. Sponsoring agency should not attempt to control distribution or publication of data. Sponsoring agency need not screen manuscripts submitted for publication in scientific journals.

We might define a "degree of difficulty" which grantees experience when sponsored by various federal sponsoring agencies. One criterion that could be used is the percentage of the project budget that is used in preparing products required by the sponsor but of no significant value to the scientific investigation. Another criterion might be the amount of effort that must be expended to obtain a grant from a funding agency. On the basis of the first criterion, we estimate the following:

NSF individual effort	< 01%
NSF programmatic effort	~ 06%
NOAA individual effort	< 01%
NOAA programmatic effort	~ 06%
ONR individual effort	~ 01%
ONR programmatic effort	< 05%
MMS programmatic effort	~ 13%

Program planners should be prepared to accomplish less science with MMS funding due to the increased bureaucratic workload associated with MMS projects. Alternately, MMS should consider reducing the bureaucratic burden on scientists to allow their funds to be expended more productively.

2.3.2 NEAR REAL-TIME REPORTING OF PHYSICAL OCEANOGRAPHIC DATA IN THE GULF OF MEXICO

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Oceanographers have traditionally made observations on research vessels, analyzed the data, published the results in journals and eventually submitted copies of the data to the National Oceanographic Data Center for archive and distribution. This mode of operation works well for research applications but is not responsive to operational requirements or management of ocean resources due to average delays of a decade or longer in data assembly and distribution (Figure 30). As a result monitoring of large ocean features and climatic changes is inhibited. Faster assembly, analysis and distribution of ocean data is required. An obvious way to do this is to report and process ocean data in near real-time; the same as weather data. The proposed MMS surveys in the northeastern Gulf of Mexico provide an opportunity to advance ocean data collection to near real-time reporting and analysis.

Near real-time reports of observations can help monitor the activities and data flow in an ocean survey program. If data are assembled months after their collection, many data can be lost due to instrument failures or improper calibrations without the chance to make appropriate corrections. But if data are reported in near real-time, maps can be drawn of current conditions and sampling plans modified to respond to changing conditions.

The data reported in near real-time from an ocean survey program do not have be the final, most calibrated or complete values so there is little danger that others will publish the data before the Principal Investigator has a chance to. Others would use the data mainly for large scale analyses and probably not for the same purpose as the PI's original problem. More important to the PI is that observations made by others in other areas are available to him in near real-time and thus can provide a larger scale context for his own observations.

Electronic Bulletin Boards

As most of you know, a lot of ocean data in the Gulf of Mexico region are exchanged on electronic mail using a simple mapping program, "OPCPLOT", developed by Dr. Murray Brown of the Minerals Management Service. OPCPLOT uses simple ASCII files that can be mapped on a PC, overlaid on other data, or sent over electronic bulletin boards such as OMNET GULF.MEX "kiosk". OPCPLOT data files include tracks of research and survey vessels, locations of observing stations and moored buoys, drifting buoy tracks, and locations of ocean features from satellite images. OPCPLOT is being implemented in other areas by the Intergovernmental Oceanographic Commission (IOC).

Near Real-Time Ocean Reports

Although exchange of oceanographic data on OMNET works well, electronic bulletin boards are expensive, have limited data storage capabilities and do not operate in near real-time. Real-time reporting of ocean data is necessary, together with weather data. Each month almost 100,000 surface marine weather observations are made and reported globally in real-time from ships of many nations, drifting and moored buoys, and coastal stations. The reports are relayed around the world on the Global Telecommunications System (GTS) of the World Meteorological Organization (WMO) to forecasting centers for marine weather forecasts and climate analyses.

A cooperative program of the IOC and WMO has been developed for global near real-time reporting of ocean observations. In this program, the Integrated Global Ocean Services System (IGOSS), physical oceanographic data are encoded in WMO message codes (Figure 31) and reported in real-time using GOES, ARGOS and INMARSAT satellites and other systems. Over 5000 IGOSS BATHY temperature profile reports are collected each month from XBTs on ships of opportunity, moored buoys and drifting buoys with thermistor tails.

Although the IGOSS reports are widely spaced and primarily from shipping lanes, the data provide near global coverage (Figure 32) and are used for low resolution, ocean-scale analyses. Many groups analyze the data, including the National Meteorological Center (NMC), Fleet Numerical Meteorological and Oceanographic Center (FNMOC) and Scripps Institution of Oceanography. Products include SST, depth of isotherms, and heat content of the surface layer (Figure 33).

There are insufficient IGOSS reports, however, for higher resolution analyses of smaller regions such as the Gulf of Mexico. While in some months there may be 50 to 100 BATHY reports in the Gulf, in other months there are only a few. The reports are primarily from NOAA research vessels with occasional reports from ships of opportunity.

Additional near real-time reports are required for routine monitoring of the Gulf. Additional ship of opportunity XBT sampling could be developed in the Gulf but a more cost effective program would be to make near real-time reports of available research vessel observations. BATHY reports from ships of opportunity cost roughly $100 each: $50 for the XBT probe and $50 for administrative costs. Reporting existing research vessel observations should cost much less.

Automated equipment for making near real-time reports of surface marine weather conditions and XBT profiles has been developed by the NOAA National Ocean Service. This equipment, the Shipboard Environmental data Acquisition System (SEAS), is based on inexpensive PC computers and is installed on over 100 merchant vessels and most NOAA research vessels. Although SEAS reports via GOES and INMARSAT, ships in the Gulf could use cellular telephone or report by OMNET or INTERNET when the ship returns to shore.

The WMO message formats are relatively simple and vessel operators can program their own equipment to make the reports. For example, a simple system to encode AXBT profiles in BATHY code was developed by SAIC scientists in the LATEX program. SAIC reported AXBT data taken during November 1993 (Figure 34) via OMNET to the NOAA Ocean Products Center (OPC) in Washington DC. OPC quality checked the BATHY messages, inserted them on the GTS, and passed them to the National Climatic Data Center (NODC) for archive. The reports were received at FNMOC in Monterey CA, entered into Navy ocean models and relayed back to users in the Gulf of Mexico region on the OMNET GULF.MEX bulletin board.

Underway Surface Reports

Near real-time TRACKOB reports of surface temperature, salinity and currents could be made by MMS survey vessels easily and inexpensively. Reports of vessel position could be used to track survey activities while reports of surface conditions would be used to map surface conditions and possibly modify the surveys in response to changing oceanographic conditions. The maps would also be useful for climate change studies, fisheries, navigation, and prediction of oil spill drifts and effect of currents on oil drilling rigs. Closely spaced observations of surface currents are needed to define the structure of frontal regions where current shears occur and may be hazardous for tanker lightering and other navigation operations.

Although many research vessels operate surface salinometers and SAIL data loggers, the data are often little used and seldom combined with observations from other vessels. If several vessels made TRACKOB reports of surface observations, monthly (or maybe weekly or even daily) maps of surface conditions would be possible. For example, maps of surface salinity could have been drawn last summer of the large, low salinity plume which flowed out of the Mississippi River and modified the circulation of the eastern Gulf. Although the plume was observed by several research vessels, detailed maps of its position and fluctuations were not possible due to lack of observations and delays in data assembly and processing.

Large numbers of near real-time reports of surface currents can be made inexpensively by ship drift calculations on ships with satellite navigation receivers. "Ship drift" is the difference between a ship's dead reckoning position and the actual position when a fix is made. Ship drift measurements were commonly made in the past with sextant sightings and manual calculations. The data were noisy and infrequent but in spite of the problems, ship drift reports are our major source of surface current information for the ocean and are the basis for the "Pilot Charts". Today navigation satellite receivers can make ship drift calculations automatically and routine mapping of surface currents would be possible if the data were reported in near real-time. Systems for ship drift calculations are being developed in Japan and the UK and could be used in the Gulf.

Data Processing and Distribution

Near real-time IGOSS reports are used in ocean analyses and products by NMC, FNMOC, NODC and other data centers. Users can obtain the data and products from several sources, including commercial weather data companies. Many of the products are distributed in printed form, such as the Oceanographic Monthly Summary from OPC, the Climate Diagnostics Bulletin from the NOAA Climate Analysis Center and the IGOSS Products Bulletin. Some of the data and products are distributed on CD-ROMs and can be plotted with the OPCPLOT program. As additional near real-time reports are made by oceanographers to the data centers, the resolution of their products will improve and they will be able to provide more valuable products and services in return.

Conclusion

The MMS surveys in the northeastern Gulf of Mexico provide an opportunity to advance beyond traditional, single ship surveys to multi-platform surveys with ships, buoys and satellites working in unison. Many of the data would be reported in near real-time to track the survey operation, monitor changing ocean conditions, and to verify and update coastal ocean models. The reports would be exchanged globally so that users in other areas could make larger scale analyses and provide a large scale context for the surveys.

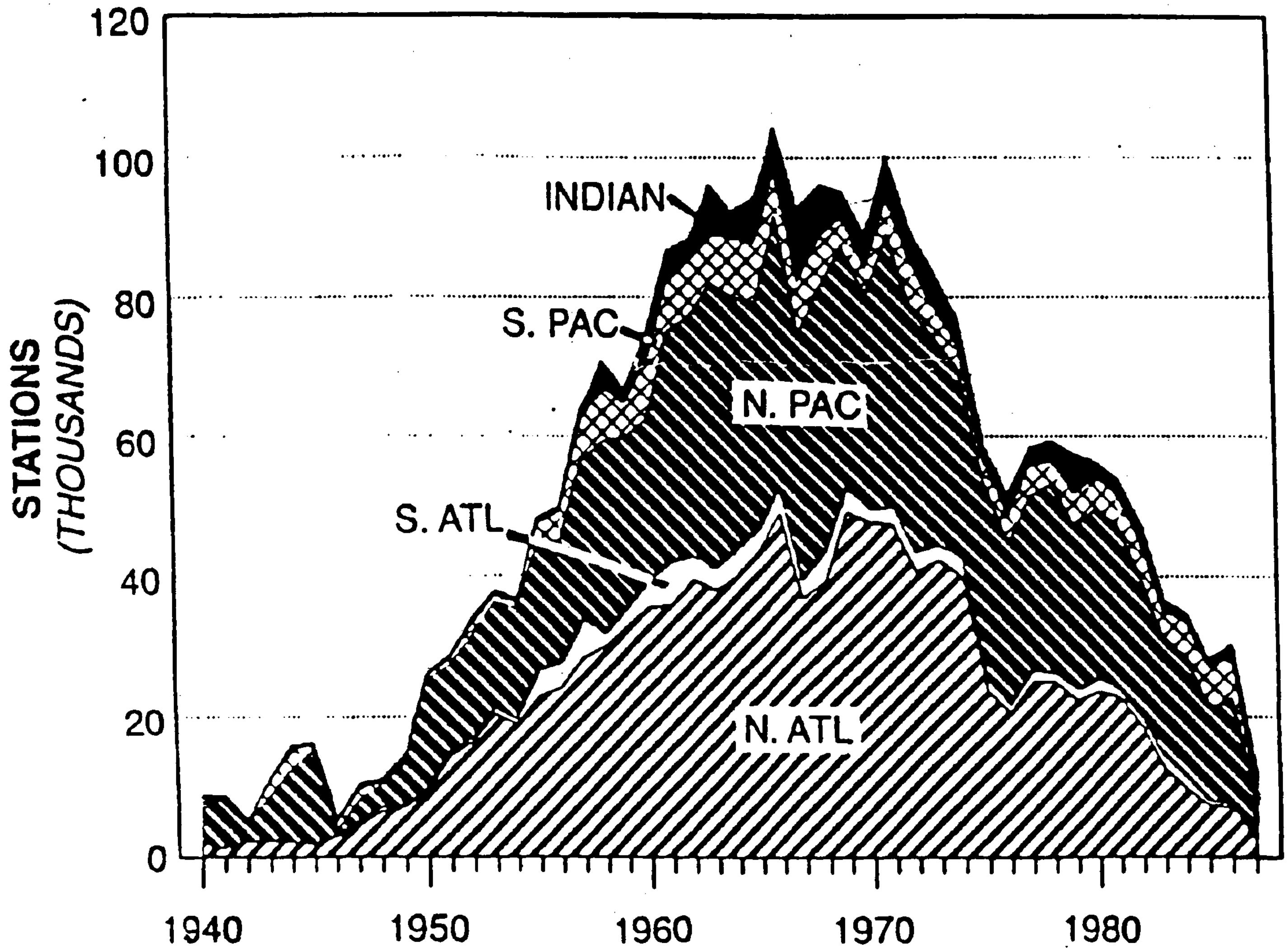

Figure 30. Distribution of ocean temperature profiles in NODC data files by ocean basin and year (1940-1987). It is assumed that: 1) the number of temperature profiles made globally by all ships generally increased during the period 1940-1987 and 2) the decreasing number of profiles in the NODC files during 1970-1987 reflects delays in data reporting and assembly. Thus it appears that there is a decade or longer lag in data availability.

Observation	Source	WMO Code
Surface marine weather	Ship, buoy	SHIP
Spectral wave data	buoy	WAVEOB
Drifting buoy data	buoy	DRIFTER
Temperature profile	XBT	BATHY
Subsurface temp/sal/curr	CTD, ADCP	TESAC
Surface temp/sal/curr	Salinometer, satnav	TRACKOB

Figure 31. IGOSS Message Formats

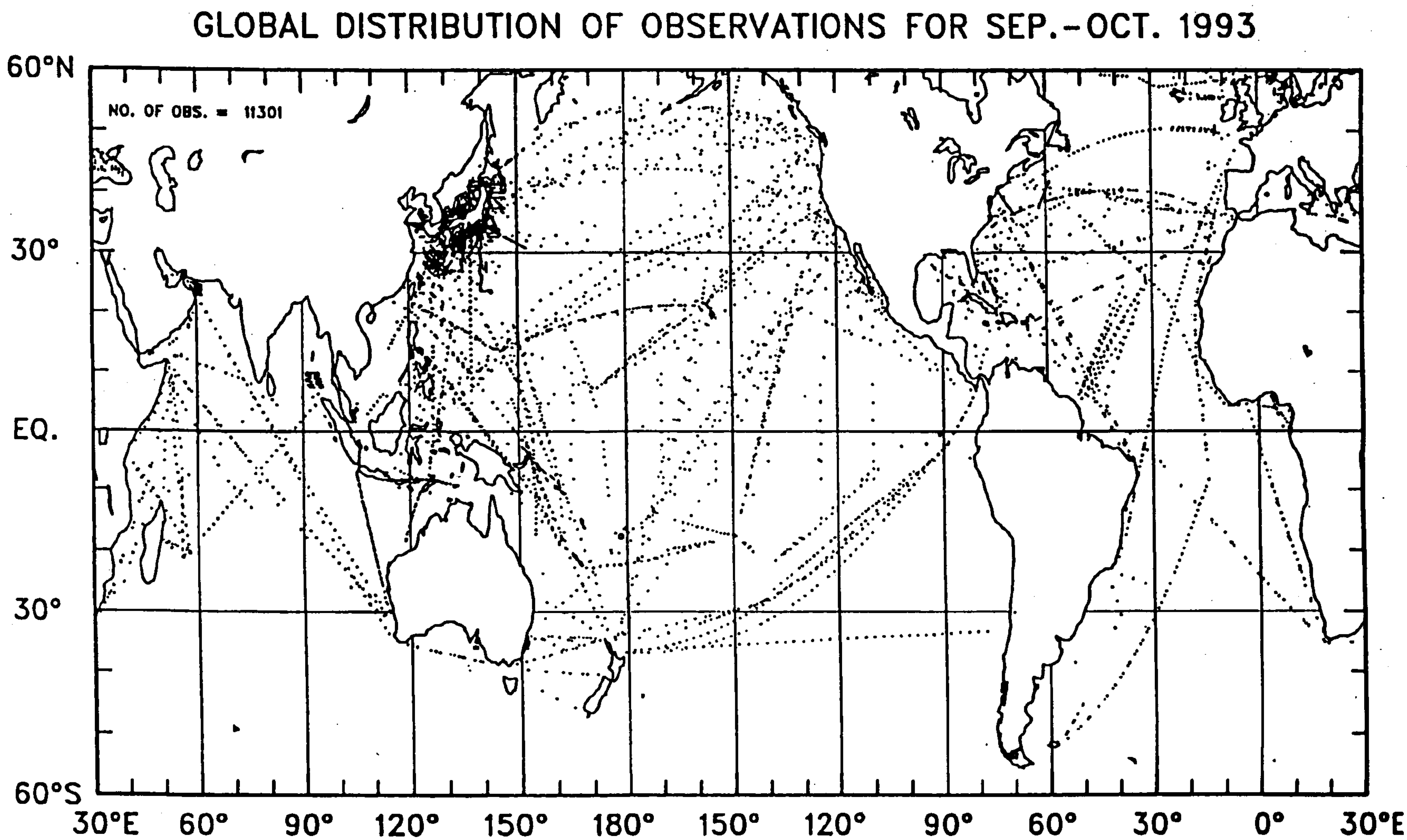

Figure 32. Global distribution of BATHY messages in IGOSS program. From W. White, Scripps Institution of Oceanography.

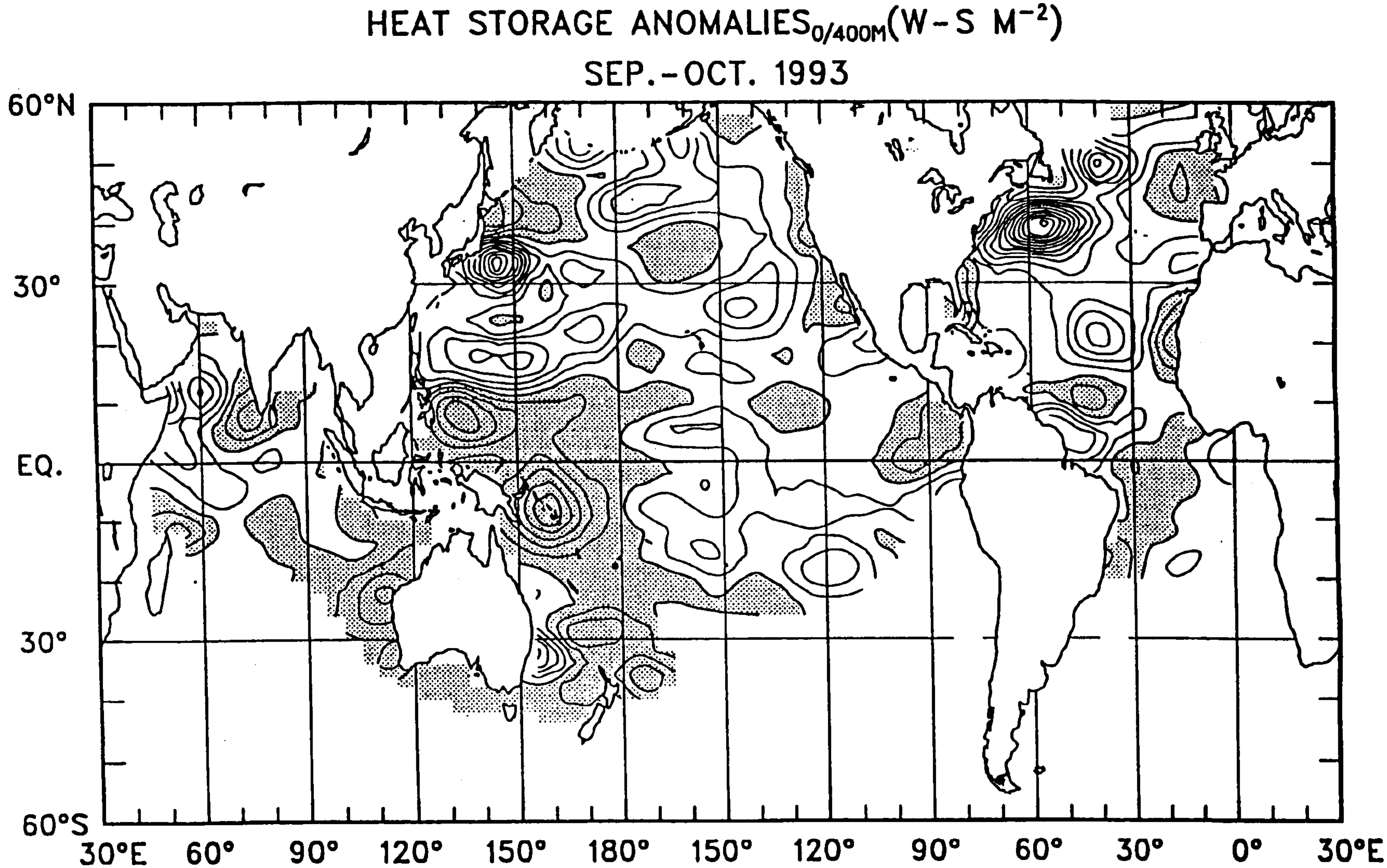

Figure 33. Sample map of heat content in the upper 400 m. From W. White, Scripps Institution of Oceanography. The analysis uses a grid with mesh lengths of 2 degrees of latitude and 5 degrees of longitude.

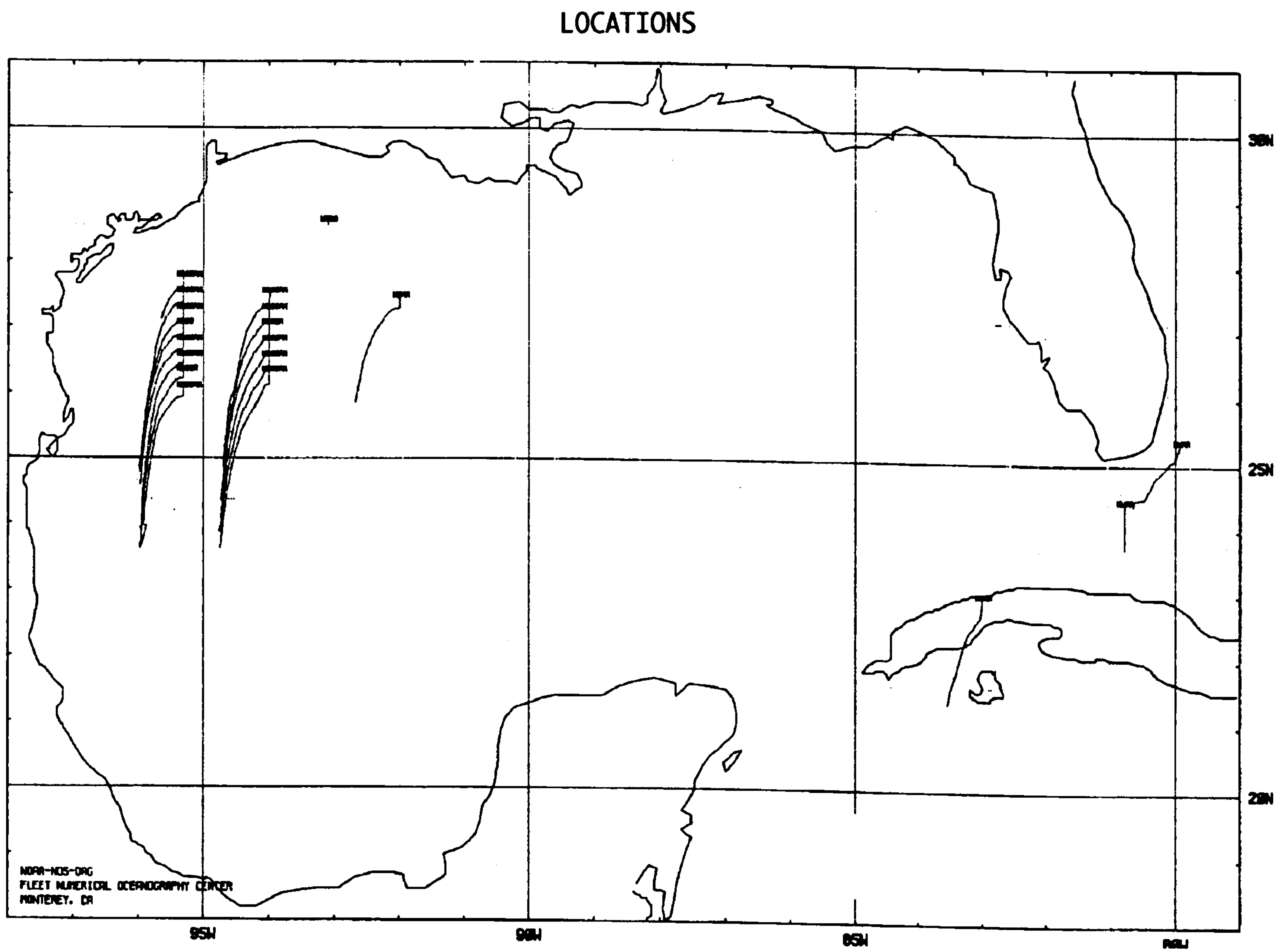

Figure 34. BATHY messages reported in the Gulf of Mexico in November 1993. Note the AXBT profiles in the northwestern Gulf reported by SAIC.

2.3.3 PRELIMINARY RESULTS OF LATEX RELEVANT TO THE PROPOSED STUDY

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Introduction

The Louisiana-Texas Shelf Physical Oceanography Program (LATEX) is a three-unit oceanographic data collection and analysis study in the northwestern Gulf of Mexico funded by the Minerals Management Service (MMS). The largest part, LATEX A, covers the middle and outer Texas-Louisiana continental shelf from the Mississippi River to the Rio Grande. It is supplemented by LATEX B, whose focus is on the coastal plume, and LATEX C, which provides information on the Gulf of Mexico eddies that impinge on the Texas-Louisiana continental slope. Physical oceanographic observations include: seasonal hydrographic surveys (CTD and ADCP), time sequences of current, temperature, and salinity at about 30 moorings over the shelf, satellite-tracked drifter observations, and meteorological data at eight moorings augmenting the NOAA coastal marine buoys and platforms.

My remarks about preliminary findings from this program are confined primarily to LATEX A. Moreover, I have selected only those points for discussion which seem to me most relevant to this workshop.

Hydrography and Circulation

Funding limitations, even in a large program, inevitably impose a compromise between spatial/temporal coverage and resolution. The strategy used in planning and execution of shelf hydrographic observations in the first field year of LATEX A (four surveys) favored good cross-shelf resolution over spatial coverage (Figure 35). As it turned out, the data indicate correlation scales (addressed later) that imply oversampling along the cross-shelf transects. This fact, plus the urging of our Science Advisory Panel (SAP), led to changing the original plan of overlapping shelf surveys (east, middle, and southwest in field years one, two, and three, respectively) to (fewer) full shelf surveys (Figure 36) for the remainder of the field measurements. Subsequent data on near surface currents from the LATEX A mooring array (Figure 37) confirms the wisdom of this change of plan. Figures 38 and 39 show current vectors from near surface meters (averaged over the cruise time span) for the first two cruises, superimposed on contours of sea surface geopotential anomaly relative to 70 decibars for the survey region of Figure 35.

One of the reasons for favoring full shelf surveys by the SAP was the potential impact of Loop Current Eddies (LCE), especially in the upper continental slope of the Texas bight region. Figure 40 shows evidence for such an eddy from drifter data, which is confirmed by the Eulerian current vectors near the shelf edge in Figures 38 and 39 for the same time span.

Subsequent full shelf hydrographic surveys in May, August, and November of 1993 are generally consistent with the Cochrane and Kelly (1986) seasonal cycle of salinity and quasi-geostrophic circulation. Figures 41 and 42 show near surface salinity patterns for LATEX A cruises 5 and 6, which are typical of spring and late summer. The differences that do exist provide evidence of interannual variation (and the possible impact of the episodic summer Mississippi flood of 1993).

It is of interest to note that in the first two years of the LATEX field measurement program three extreme events occurred: Hurricane Andrew in August 1992, the late winter "Storm of the Century" that evolved by cyclogenesis over the NW Gulf in March of 1993, and the Mississippi summer flood in August of 1993. Two of these events, plus the frequent frontal outbreaks over the Texas-Louisiana shelf in fall, winter, and spring, fully justify the investment in eight meteorological buoys to supplement other marine meteorological buoys and platforms of NOAA and industry (Figure 43). Brink *et al.* (1994) emphasize the need for good marine meteorological data for understanding the near shore circulation.

Wind Forcing and Circulation

Cochrane and Kelly (1986), as well as Lewis and Reid (1985), give evidence of the importance of wind stress forcing at seasonal and even weekly time scales, respectively, especially in the near coastal region. Figures 44 and 45 show the July 1992 monthly mean wind stress vectors (derived from the marine meteorological buoys and platforms) and the near surface monthly mean current vectors, respectively. The upcoast near shore flow is consistent with an upcoast component of wind stress as is typical of summer conditions. Figures 46 and 47 show contrasting plots for December 1992, indicating that winds having a downcoast component of wind stress drive the near coastal current down coast.

Note, however, that the currents at the shelf break in Figures 45 and 47 are probably controlled by the anticyclonic LCE and smaller scale cyclonic eddies that tend to be attracted to and persist along the Texas-Louisiana continental slope. The midshelf, in contrast, appears to represent a low kinetic energy region at subinertial time scales. This is confirmed by Dr. P. Niiler's drifter data from the SCULP program (personal communication).

Occurrences of reversals in the near shore current on weekly time scale associated with frontal passages dominate the 40 hour low pass current time sequences, particularly during the nonsummer months. They also are very evident in the nearshore drifter data. These reversals can occur over a period of a day or two even during times of a well developed coastal plume (as in spring). Moreover, the response through the shallow water column is equivalent barotropic (*i.e.,* unidirectional but not of uniform speed), in spite of the stratification. After discussions with P. Niiler (person communication), I am convinced that in the shallow coastal regime, the longshore wind drives the longshore current, which in turn causes the coastal salinity front to adjust its slope to maintain a near geostrophic balance. One could argue that this is the same thing as Ekman drift-induced upwelling or downwelling with an associated change in the near coast geostrophic flow. The important fact for the shelf domain is the ease and rapidity by which both the longshore current and the frontal slope can reverse. As W. Nowlin points out (personal communication), this simply could not happen in a major current system like the Gulf Stream since the potential energy associated with major oceanic frontal systems far exceeds the kinetic energy. However, for the coastal front on the shelf, the potential energy is many orders of magnitude smaller than its oceanic counterpart.

This raises another question concerning the coastal plume and associated boundary current. The mean discharge of the Mississippi River is of order 20,000 m^3s^{-1}. A reasonable estimate of the total transport in the coastal boundary current under well developed downcoast directed winds is of the order of 150,000 m^3s^{-1}, or about seven times that of the buoyant source. Clearly this requires an entrainment of water from offshore at the eastern end of the shelf, with compensating detrainment somewhere downcoast (perhaps as a "squirt" associated with a near coast convergence zone?).

Correlation Scales of Hydrography

Preliminary calculations have been made from LATEX A data of spatial scales of variability present in temperature, salinity, and geopotential anomaly distributions for the near surface water of the Texas-Louisiana shelf. Our objective was to determine whether the spatial station separation initially used on the LATEX hydrographic transects was unnecessarily fine, and what level of spatial variability was unresolved by the sampling scheme.

We began with calculations along cross shelf transects of individual cruises. The variability of a given property, like salinity for example, is clearly dependent on what form of mean or trend is removed. In our calculations a quadratic trend for each transect of each individual cruise was removed. Figure 48 shows a sample plot of near surface salinity (full line) on section 4 (about 94W) of the May 1992 cruise; the fitted quadratic trend is shown as the dashed line and the difference between the curves allows one to estimate the autocovariance of the salinity anomaly versus separation distance for section 4 of that cruise. In order to give a more robust estimate, all existing cruises (seven as of this report) can be combined for this same section. The resulting autocorrelation of near surface salinity versus separation for section 4 (after normalization by the salinity variance) is shown in Figure 49. Similar calculations for near surface temperature and geopotential anomaly (with removal of their quadratic trends) are shown in Figures 50 and 51, respectively.

Parametric fits of such correlation data can be carried out (*e.g.*, Denman and Freeland, 1985) to yield at least two scales -- a zero crossing scale and an asymptotic decay scale at large separation. We have chosen to summarize here only our estimates of the zero crossing scale, which is readily determined from plots such as Figures 49-51. A summary of these (in kilometers) for near surface salinity, temperature, and geopotential anomaly based on all cruises available for cross-shelf sections 2, 4, and 7 is given in Table 2. Section 2 is along 92W, section 4 is approximately along 94W, and section 7 is in the Texas bight region running cross-shelf from Baffin Bay. The scales for all three properties are 20 12 km for sections 2 and 4 but significantly smaller for section 7 (which is much shorter in length than the other two sections). The results indicate that 5 km spacing of CTD measurements represents oversampling and that 10 to 15 km is probably adequate.

Acoustic Doppler Current Profiler Data

The coastal plume surveys of LATEX B employ high frequency ADCP which seem to yield results that are coherent from one crossing to the next along the coastal current. In contrast, the ADCP surveys of the middle and outer shelf in LATEX A are disappointing. This is not because of instrumentation or navigation problems but is due to the presence of a very significant near inertial period signal in the current. The current meter data from the fixed moorings allow one to examine this signal, and it is found to be excited by frontal passages and most pronounced in the mid- to outer shelf with little if any signal in the near coastal zone. The amplitude of the near inertial current signal can be as large as the low frequency quasi-geostrophic signal on the outer shelf. Separation of the unwanted high frequency signal from the ADCP records is a very challenging (perhaps unsolvable) problem. It is an important thing to be aware of in planning similar kinds of measurements in the NE Gulf and Florida shelf.

Acknowledgments

Dr. Changsheng Chen, Mr. Yongxiang Li, and Dr. Worth D. Nowlin, Jr. contributed significantly to the preliminary results, and interpretation thereof, discussed herein.

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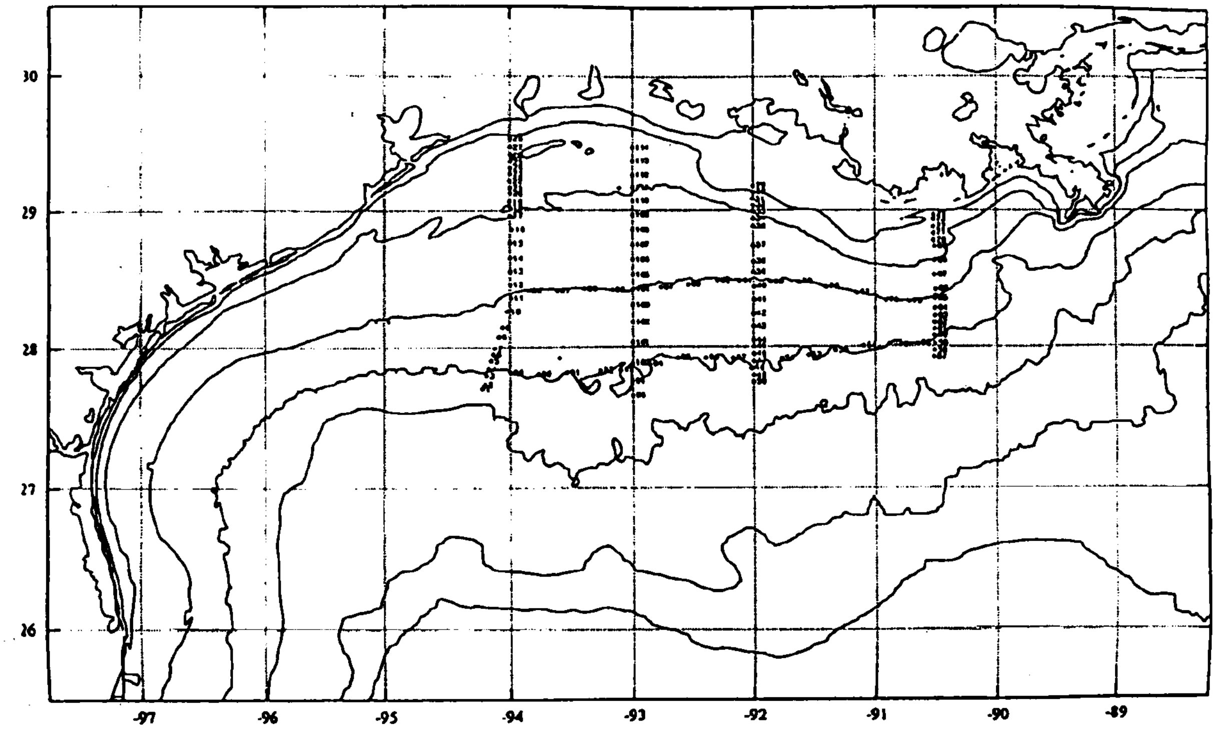

Figure 35. Cruise track for LATEX hydrographic survey H01CGY9205 (92A) in May, 1992.

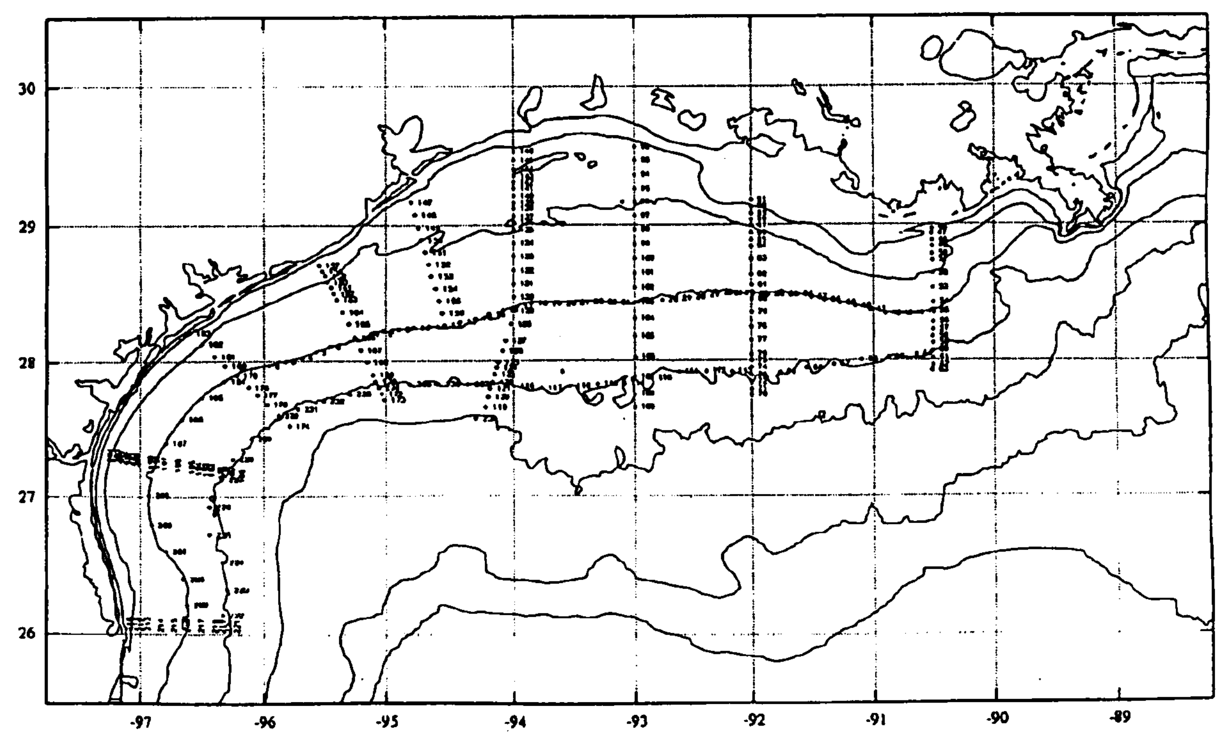

Figure 36. Cruise track for LATEX hydrographic survey H07CPW9314 (93G) in November, 1993.

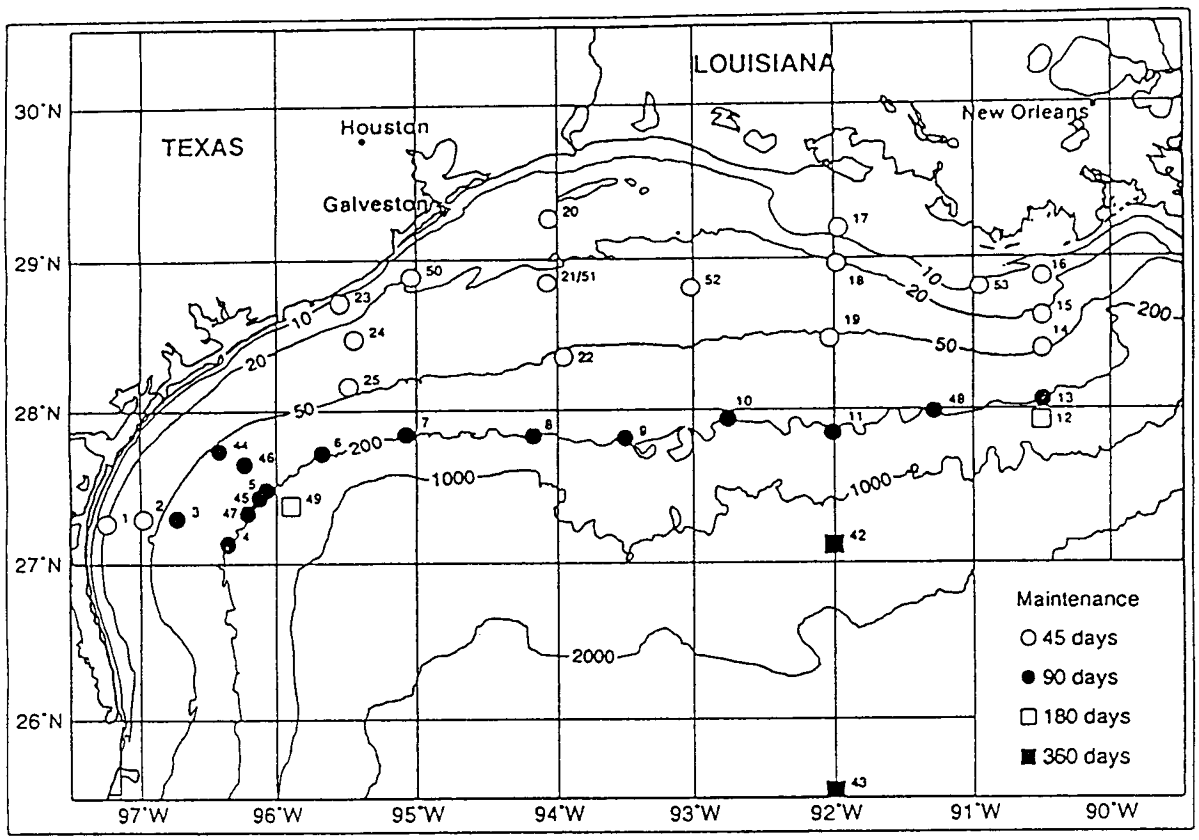

Figure 37. Initial moored array locations, LATEX A.

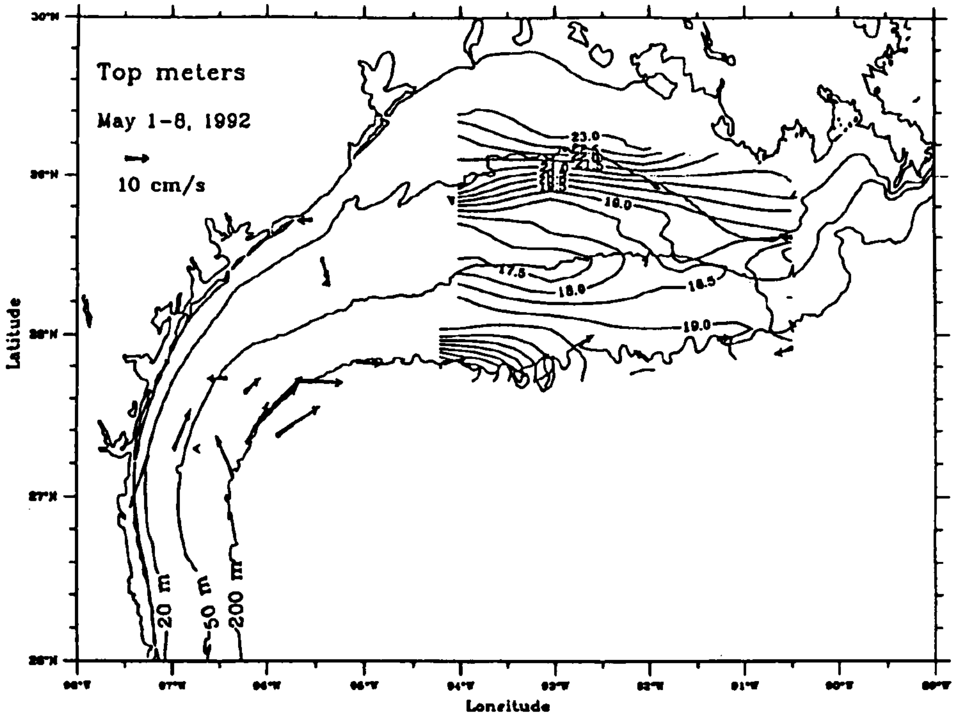

Figure 38. Currents from top meters averaged over the duration of cruise 92A (May 1-8, 1992) superimposed on geopotential anomaly (dyn cm) of the sea surface relative to 70 decibars.

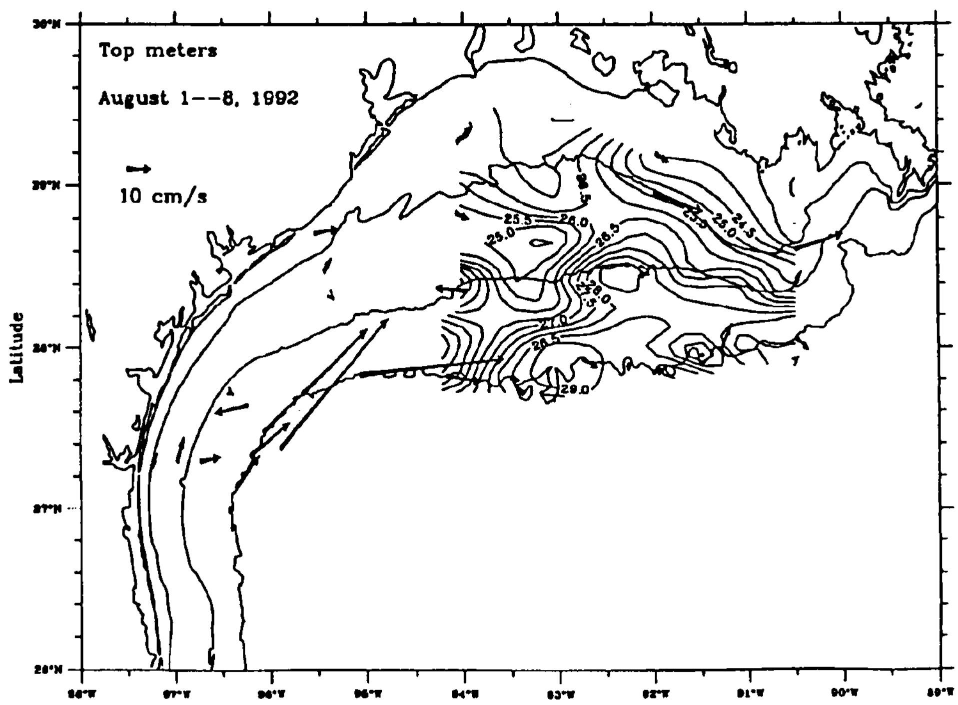

Figure 39. Currents from top meters averaged over the duration of cruise H02CGY9208 (92B) (August 1-8, 1992) superimposed on geopotential anomaly (dyn cm) of the sea surface relative to 70 decibars.

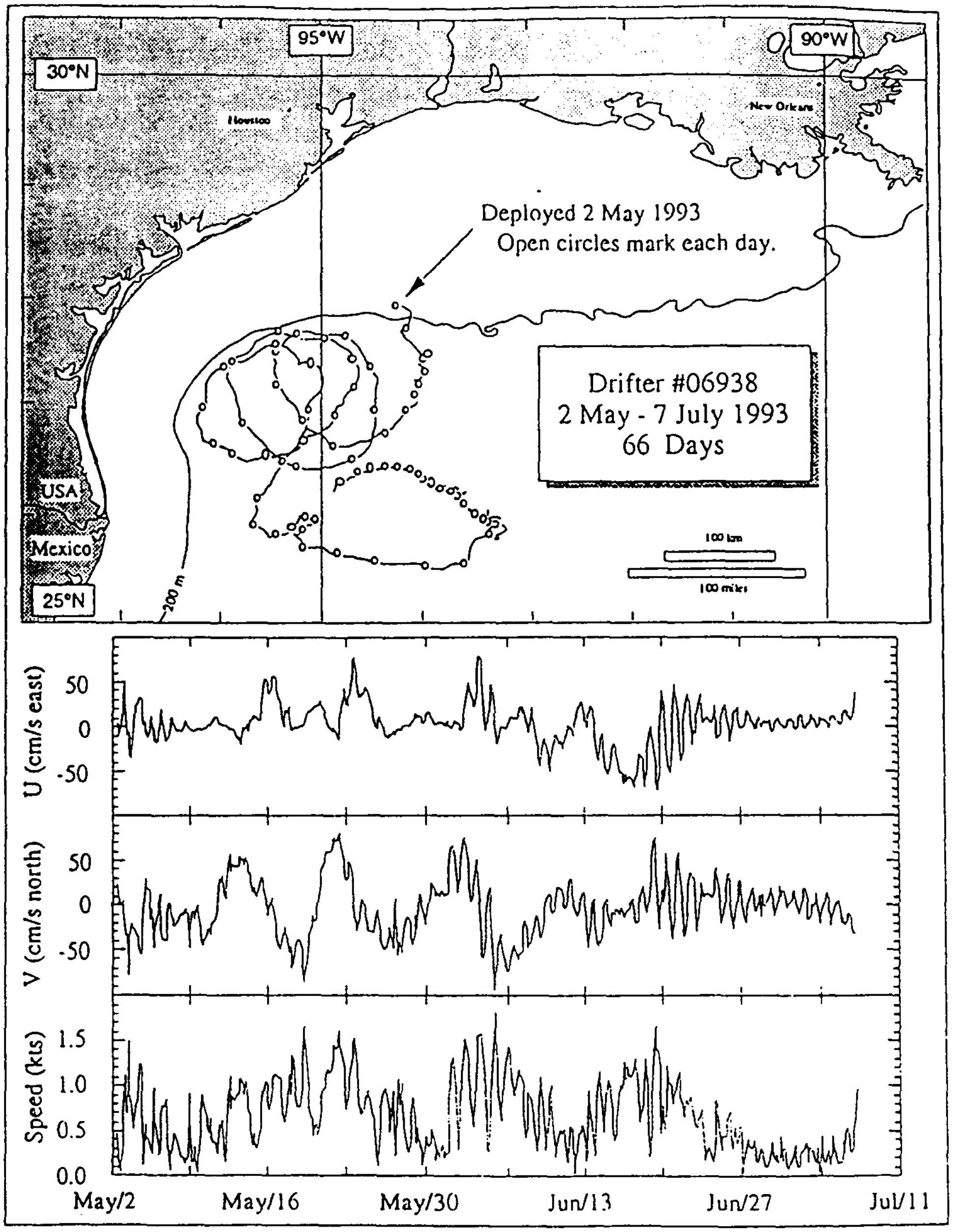

Figure 40. LATEX A drifter 06938 trajectory, speed, and velocity, 2 May - 7 July, 1993.

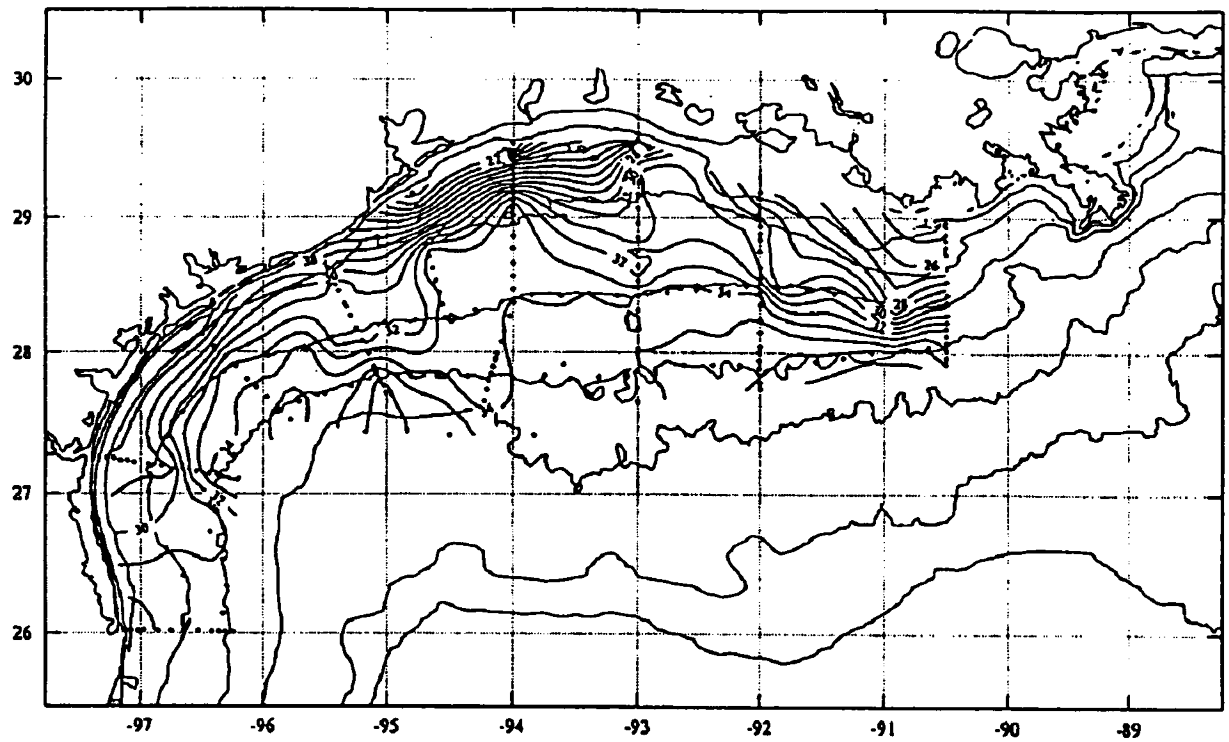

Figure 41. Salinity at z = -3m for LATEX cruise H05CPW9306 (93E), April - May 1993.

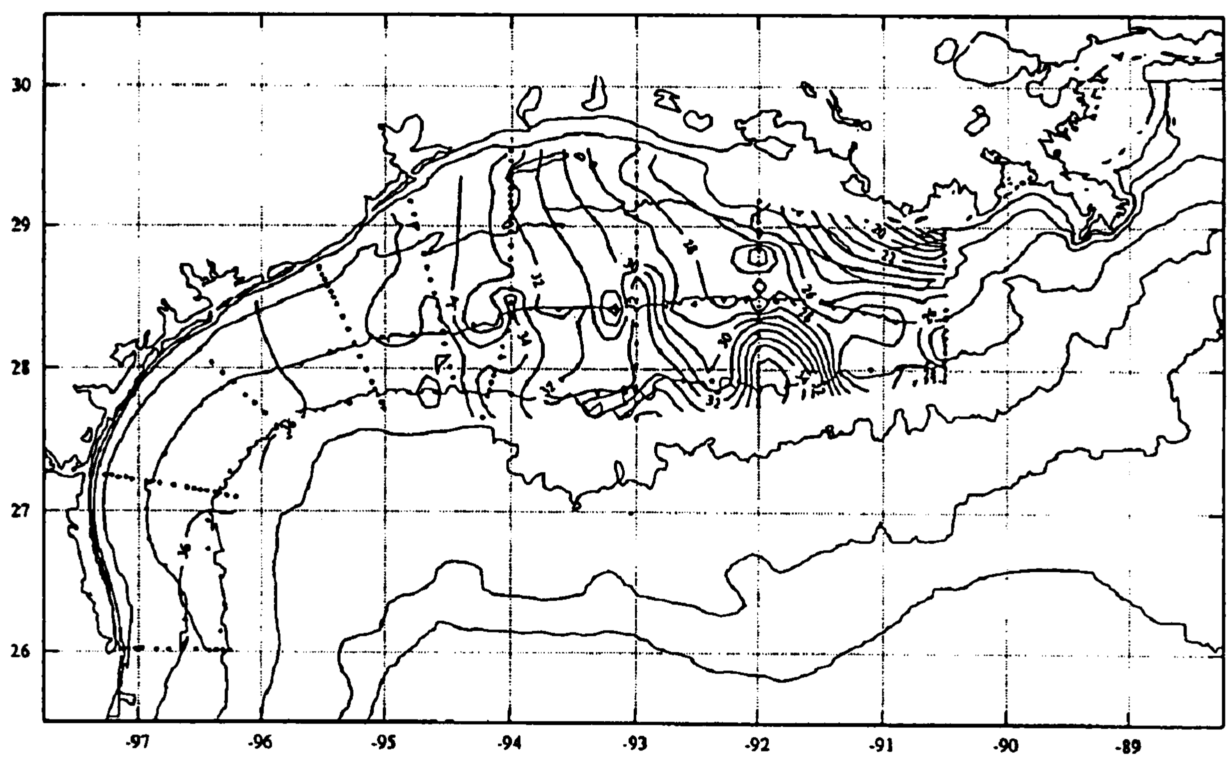

Figure 42. Salinity at z = -3m for LATEX cruise H06CPW9311 (93F), July - August 1993.

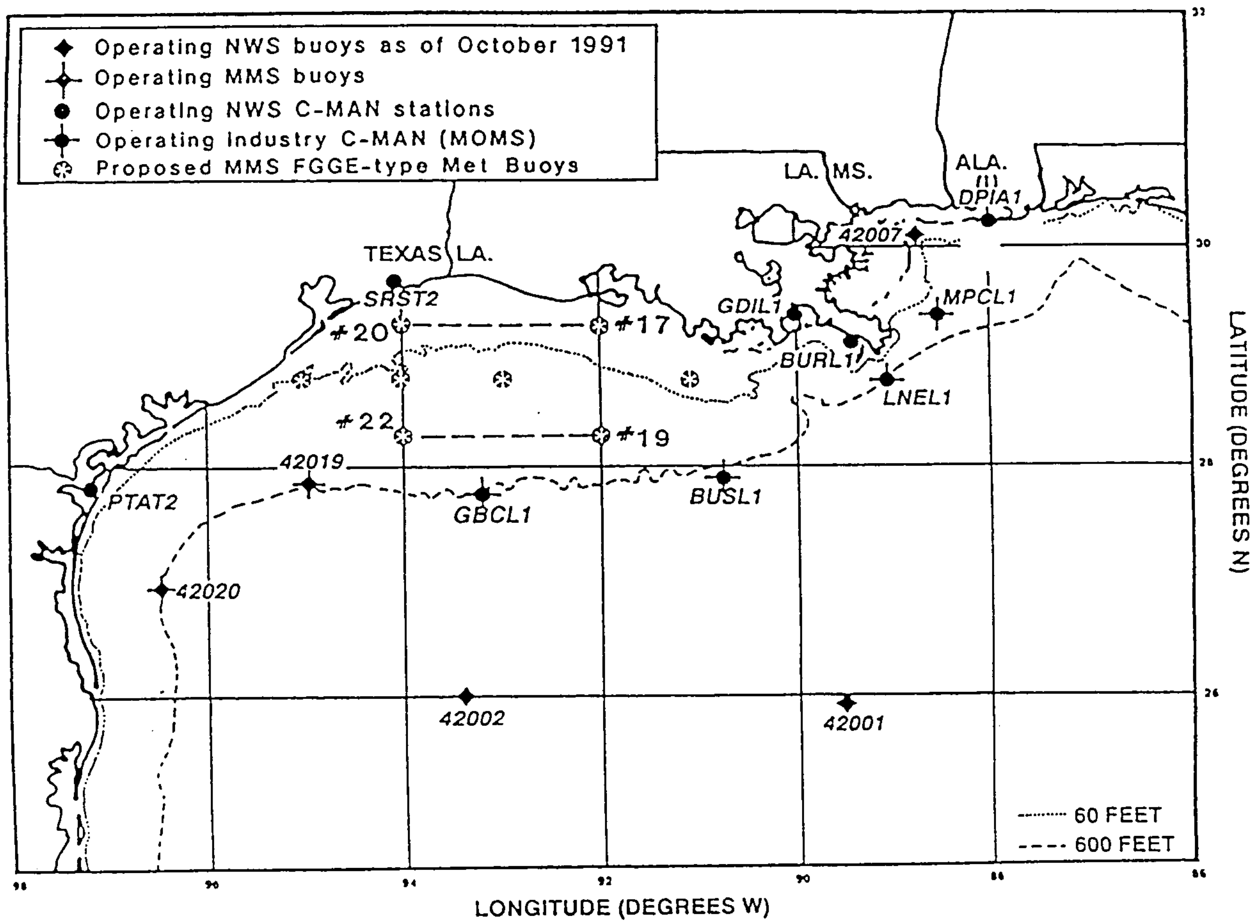

Figure 43. Locations of eight FGGE-type LATEX meteorological buoys on the mid shelf that supplement the NOAA/NWS coastal marine buoys and stations.

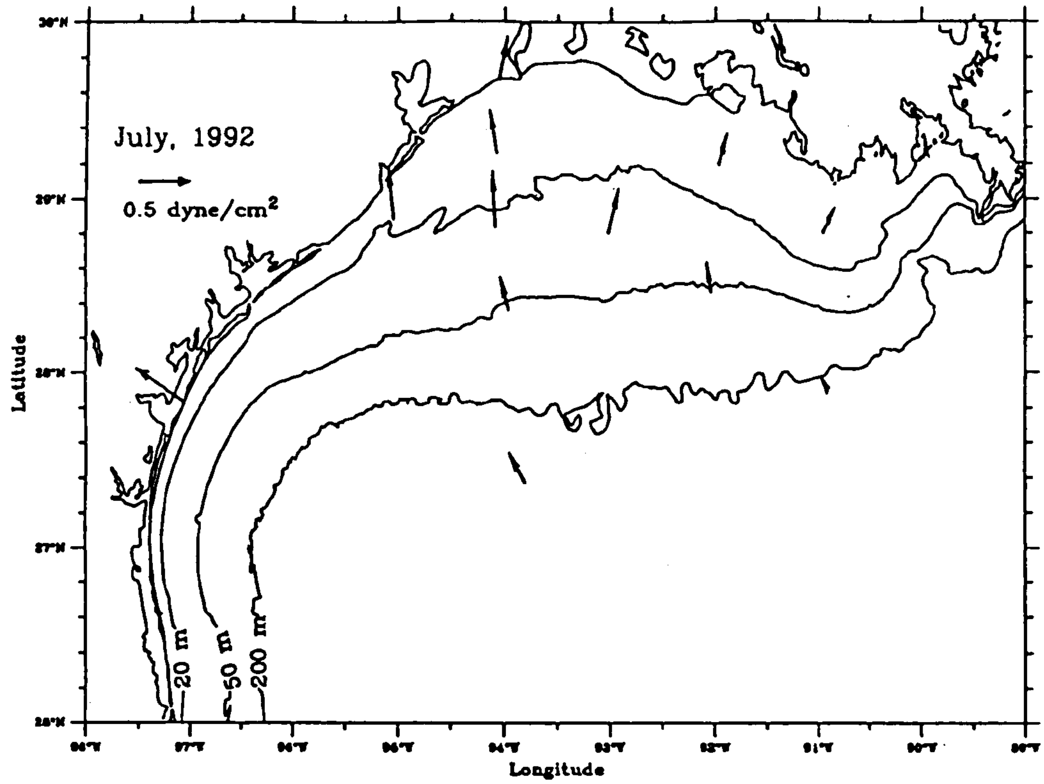

Figure 44. Monthly averaged surface wind stresses for July, 1992.

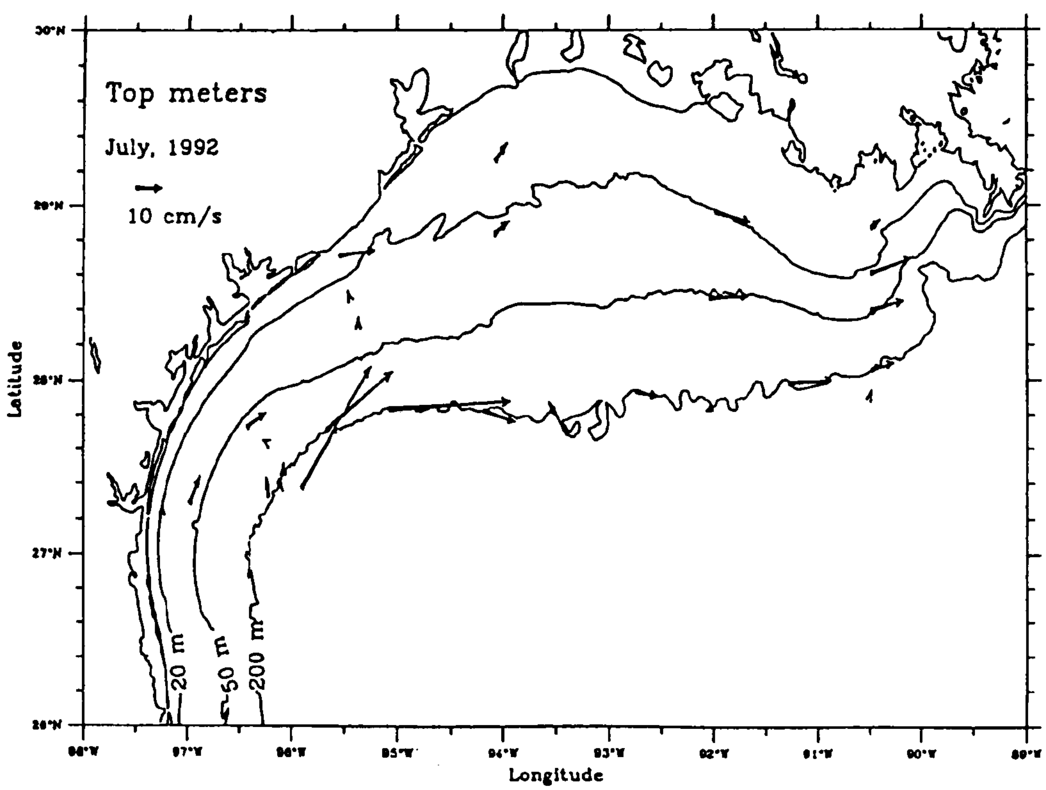

Figure 45. Monthly averaged currents at the top meters for July, 1992.

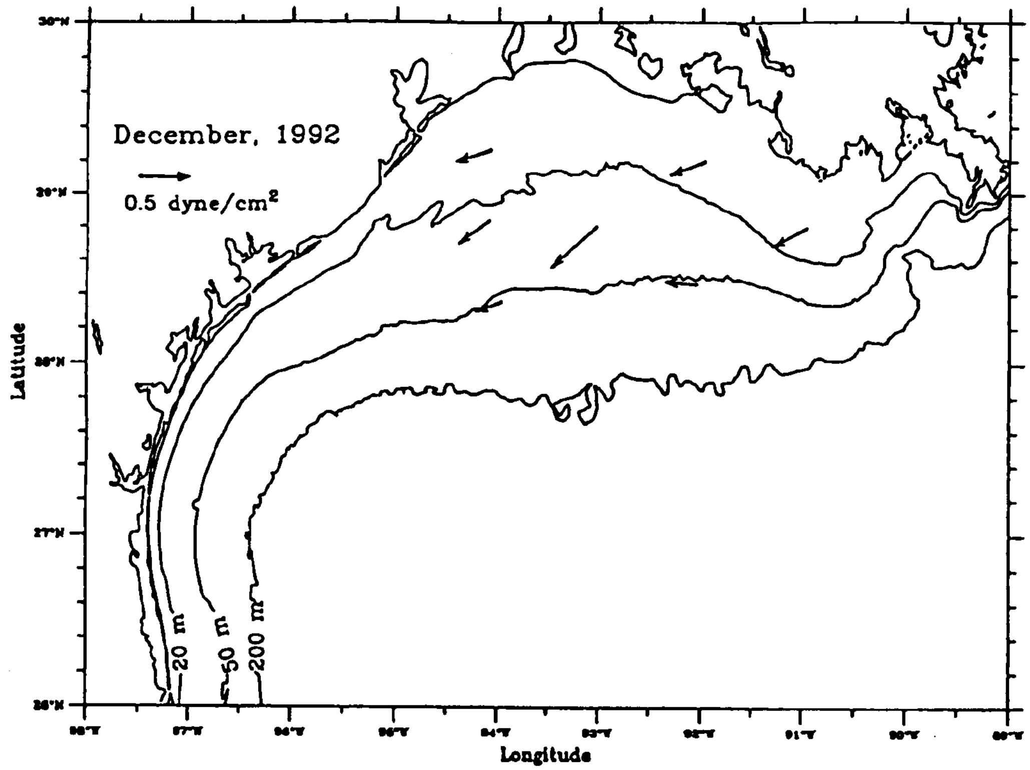

Figure 46. Monthly averaged surface wind stresses for December, 1992.

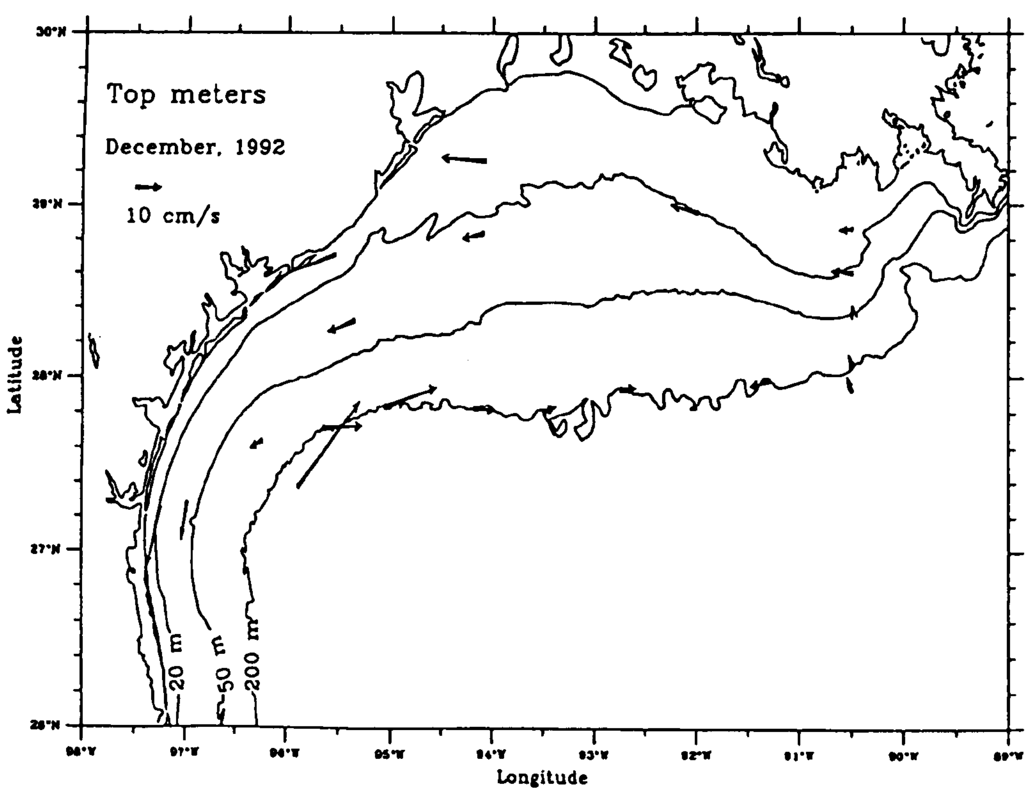

Figure 47. Monthly averaged currents at top meters for December, 1992.

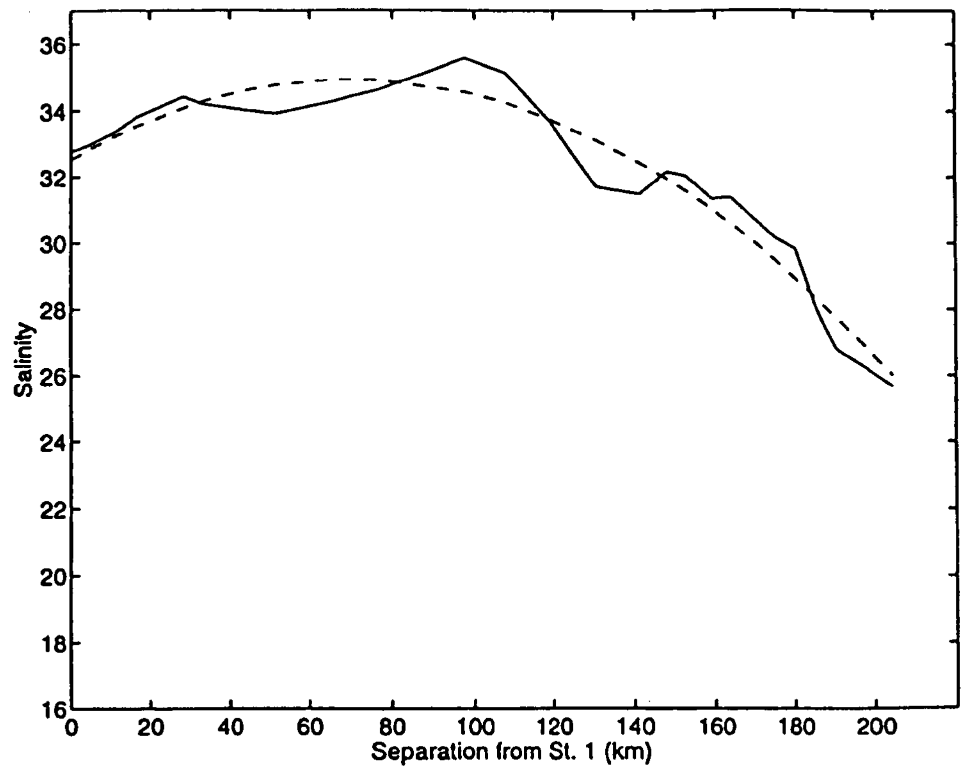

Figure 48. Salinity at z = -3m along section 4 of LATEX cruise 92A; dashed line is the fitted quadratic trend.

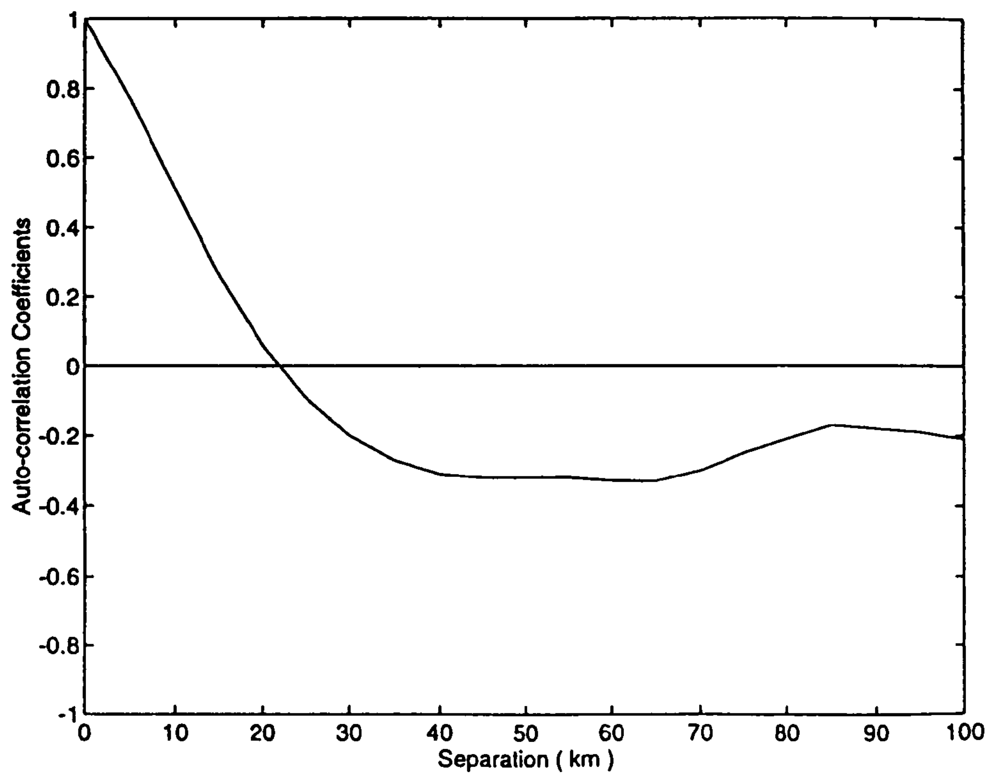

Figure 49. Autocorrelation of near surface salinity for section 4 based on seven LATEX cruises.

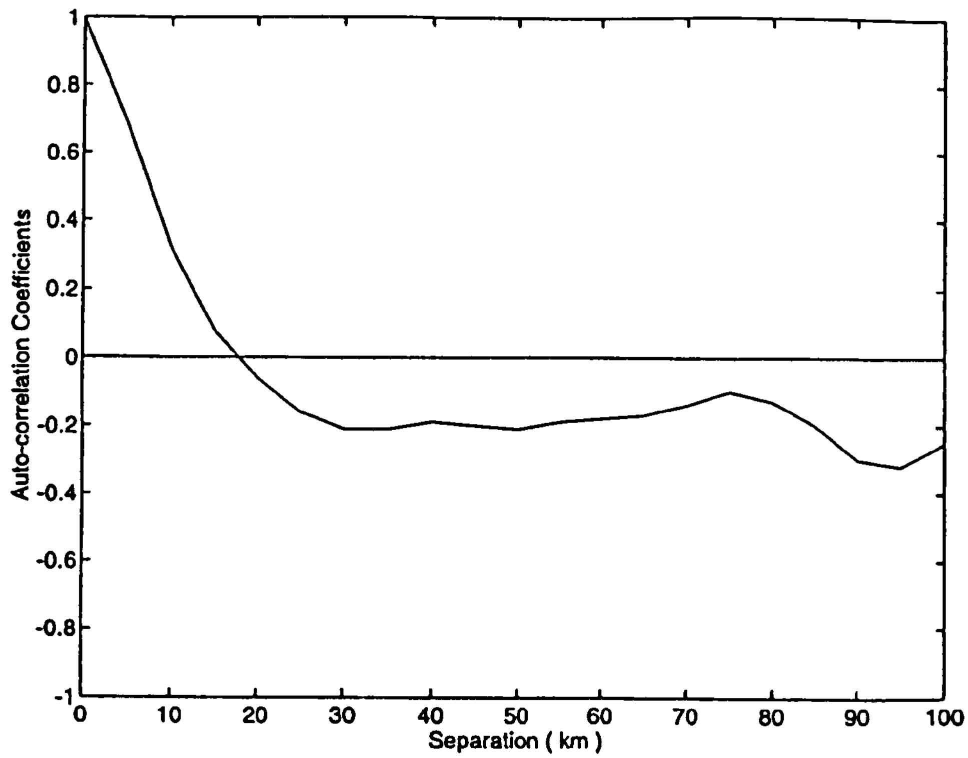

Figure 50. Autocorrelation of near surface temperature for section 4 based on seven LATEX cruises.

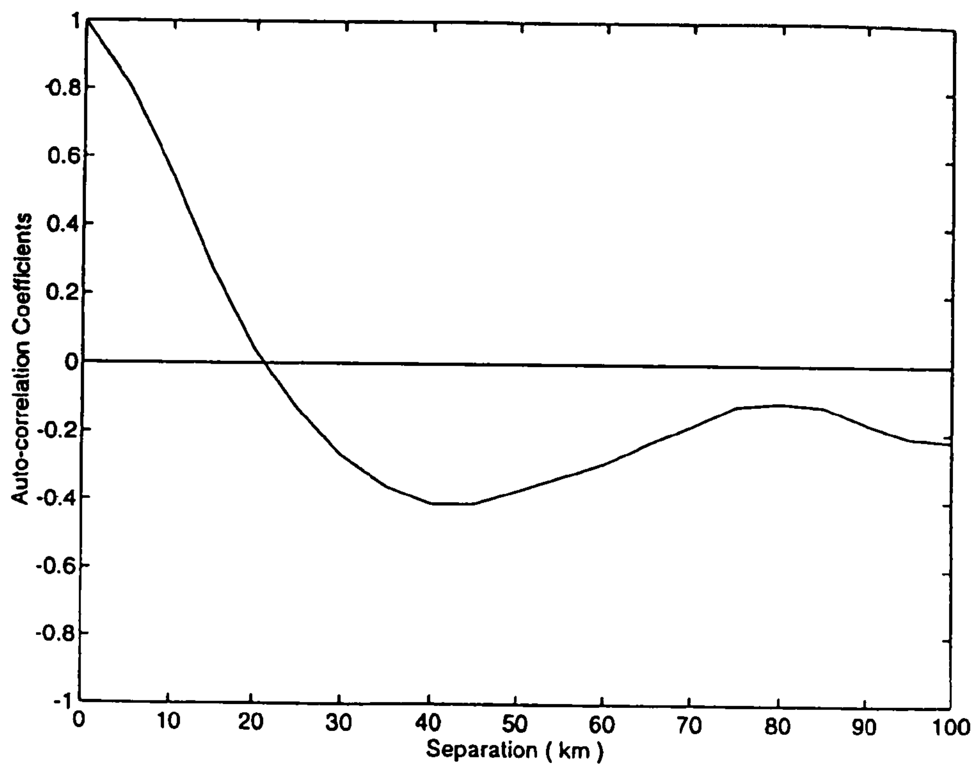

Figure 51. Autocorrelation of geopotential anomaly at the sea surface relative to 70db for section 4 based on seven LATEX cruises.

Table 2. Estimates of correlation scales* (km) of hydrography over the Texas-Louisiana shelf.

Transect	2	4	7
Salinity	18	22	14
Temperature	17	18	9
Geopotential relative to 70db	20	22	14
Number of cruises	7	7	3

* The correlation scale shown is the separation at which the autocorrelation of the variability of a given property is zero. The variability is that remaining after removal of a quadratic trend along a given transect and survey.

2.3.4 SURFACE CURRENT MEASUREMENTS USING A SHORE-BASED HF DOPPLER RADAR

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Background

The surface circulation of the world's oceans plays an important role in the transport of heat and momentum between the continental margin and the deep ocean and air-sea exchange processes, which contribute to the earth's climate system. With increasing interest in the coastal ocean there is also a requirement to acquire high-quality surface current data for long-term monitoring of the surface circulation to study its effect on a broad spectrum of societal and environmental issues such as coastal pollution, oil spills, beach erosion and sediment transport.

One of the more promising techniques that has evolved over the past three decades is the Doppler radar technique which is sure to revolutionize the field of coastal oceanography and provide a new methodology to measure surface currents in "real time" over a large domain. Furthermore, active probing of the ocean surface with radio waves is non-intrusive and shows much sensitivity to small-scale dynamics in ocean processes.

The HF Doppler radar technique is based on the premise that radar pulses are backscattered from the moving ocean surface by resonant surface waves or "Bragg waves." The wavelength, λ_B, of these Bragg waves is given by

$$\lambda_B = \frac{\lambda_r}{2\sin\theta_I},$$

where λ_r is the radar wavelength and θ_I is the incidence angle. For the HF radar system, $\theta_I = 90°$, so λ_B for this case is equal to one-half the radar wavelength. The Bragg scattering effect results in two discrete peaks in the Doppler spectrum. In the absence of a surface current, the position of these spectral peaks is symmetric and their frequency, f_B is given by

$$f_B = \frac{2C_0}{\lambda_r} \quad \text{no current}$$

where $C_0 = \sqrt{(g/k_B)}$ is the linear phase speed of the surface Bragg wave.

If there is an underlying surface current, the Bragg peaks in the Doppler spectrum are displaced from f_B by an amount

$$\Delta f = \frac{2V_r}{\lambda_r} \quad \text{with current}$$

where V_r is the radial component of surface current along the look-direction of the radar.

To determine both components of the two-dimensional current fields (magnitude and direction), two radar stations are required, and their baseline separation determines the domain of the mapped region.

Field deployment during HIRES Experiment in June 1993

The High-Resolution Remote Sensing Experiment (HIRES), an accelerated research initiative jointly funded by the Office of Naval Research and the Naval Research Laboratory, conducted a preliminary experiment in September 1991 and a full-scale experiment in June 1993 off the Outer Banks of Cape Hatteras.

The scientific objective of HIRES is to improve the understanding of the physics responsible for submesoscale features, ranging from 100 m to 1 km in length, which are detected in microwave radar images. In order to achieve this goal, simultaneous observations of ocean features with imaging radars, infra-red sensors and *in-situ* measurements from ships and buoys were needed. A critical component to the experimental success was to measure the surface current field over a wide area and with sufficient spatial and temporal resolution.

To achieve this later requirement, the Radar Ocean Sensing Laboratory of the University of Miami deployed a dual-frequency ocean surface current radar (OSCR) which utilizes HF (25.4 MHz) and VHF (49.9 MHz) radio frequency to map surface current patterns over a large area in coastal waters. The shore-based radar system consists of two units (Master and Slave) which are deployed several kilometers apart. Each unit makes independent measurements of current speed along radials emanating from its phased-array antenna system. The data are then combined via UHF or telephone communication to produce accurate vector currents (speed and direction) and display them in near real time. The measurements can be made simultaneously at up to 700 grid points either at 1 km (HF mode) or 250 m (VHF mode) resolution. The measurement interval for one vector current map is repeated every 20 minutes. Figure 52 shows a surface vector current map on 23 June 1993 which displays an eddy in the OSCR domain. The current flow in the southeastern portion of the domain is the Gulf Stream.

On 20 June 1993 a special data set was collected over the continental shelf region off the coast off Cape Hatteras, NC. A dedicated flight of the NASA DC-8 imaged the ocean surface for about six hours alternately with an L-band interferometric synthetic aperture radar (INSAR) and a tri-frequency (P-, L-, and C-band) synthetic aperture radar (SAR). Concurrent with the airborne SAR observations was an overflight by the ERS-1 (C-band) SAR at 11:47 LT and the measured surface current vectors from the RSMAS HF Doppler radar system covering a 1000 km^2 region at a resolution of about ~1.2 km. Additional measurements were obtained in the area of interest from two research vessels, the *USNS Bartlett* and *UNOLS Columbus Iselin* and two directional wave buoys.

The NASA DC-8 flight pattern consisted of four legs oriented towards east, west, south and north. This flight pattern was once flown with the tri-frequency SAR and then repeated with the interferometric SAR. The experimental objective of this flight was to obtain simultaneous measurements of polarmetric and interferometric backscatter within the domain covered by the HF Doppler radar and near the directional wave buoys.

On flight leg II, aircraft heading 90°, the SAR imaged in both modes a distinct and prevalent surface feature oriented in an east-west direction and somewhat northeast of buoy D-WEST. The undulating shape of the surface feature separated two flow regimes which converged along this irregular boundary. The length of the surface feature was approximately 25 km and the width was less than 100 m. A secondary feature, similar in shape and displaced about 5 km south, was also imaged by both SAR modes. This somewhat weaker feature, about 5 km in length, was intersected at two locations by the USNS *Bartlett* which collected extensive measurements of the flow and water properties near this feature.

Data Processing

Initial research efforts in HIRES-II have focused on time series at buoys **D-West**, **D-East**, **MMS-B1** and **MMS-B2** over 27 day experimental period and on the evaluation of the interferometric SAR measurements on June 20, 1993. Data from OSCR is now routinely processed to extract all tidal components using a harmonic analysis. In addition, with appropriate filters the mean, near-inertial and internal wave flow characteristics can be determined from data. Vertical shears have been estimated for each component and ensemble averaged surface and subsurface currents calculated to estimate complex correlation coefficients.

Summary

Our results show qualitatively and quantitatively good agreement between OSCR-derived surface current vectors and the location of fronts imaged by synthetic aperture radar (SAR). Furthermore, OSCR appears to be sensitive to small changes in flow characteristics and capable of locating fronts and eddies. Comparisons between surface and subsurface currents show mean differences of about 1-4 cm s^{-1}. Low-passed mean flows are highly correlated ($r = 0.95$) and intrude onto shelf at intervals of 4-7 days. This is consistent with previously found results along the inner shelf and shelf break off Cape Hatteras. Near-inertial oscillations have periods shifted 10-20% above and below the Coriolis frequency. Residual flows, ranging from 5-10 cm s^{-1}, may be due to other effects such as surface waves, Stokes drift and Ekman forcing.

Acknowledgment

Portions of this research were supported by the Office of Naval Research and the Minerals Management Service.

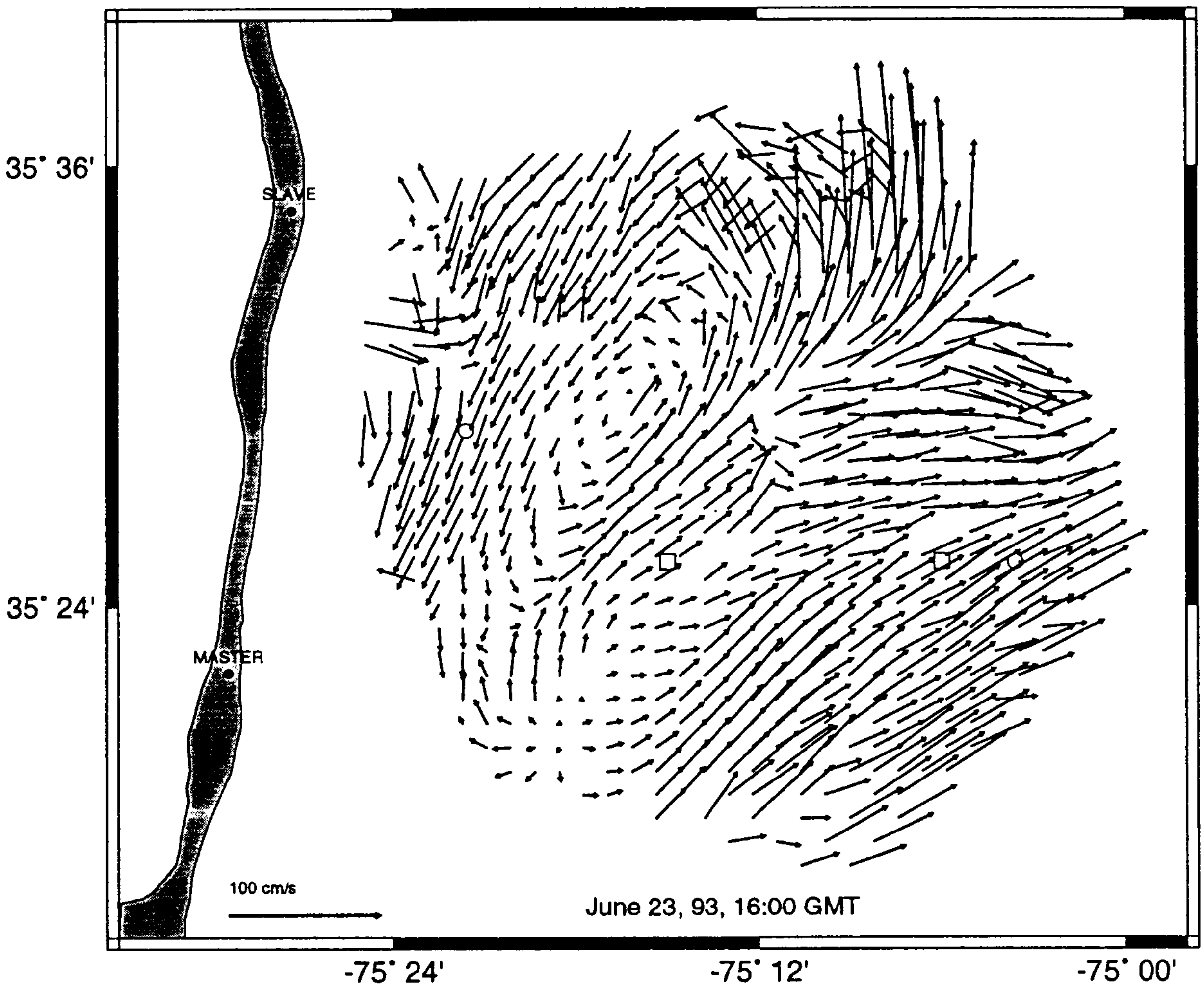

Figure 52. Map of surface vector currents off the coast of Cape Hatteras observed with an HF Doppler radar during the HIRES experiment. The flow pattern shows a distinct eddy over the shelf and in the southeastern portion the edge of the Gulf Stream.

2.3.5 SURFACE AND UPPER-ATMOSPHERIC METEOROLOGICAL MEASUREMENTS OVER THE NORTHEAST GULF OF MEXICO (NEGOM)

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Understanding the physical processes characteristic of coastal land and shelf regions such as the Northeast Gulf of Mexico (NEGOM) are vital in attempting to establish identifiable links between marine, terrestrial, and atmospheric systems. Furthermore, exchanges across these systems are fundamental to the understanding of the global significance of these regions in determining hundreds of factors from sustainable management of coastal resources to global climate change. Therefore, any attempt to study the physical oceanographic characteristics of the NEGOM region must be accompanied by a carefully constructed means of acquiring meteorological data in order to address the complex interactions between these synergistic systems. This abstract briefly outlines the types of meteorological data available to coastal shelf researchers investigating the NEGOM region, as well as additional proposed sources which could be used to augment the current data in this region. Table 3 briefly outlines the types of data currently available over the NEGOM region

Figure 53 illustrates the locations of National Weather Service observing, Automated Surface Observing System (ASOS), and Weather Service Radar - 88D (WSR-88D) sites. The radar sites are denoted as 'dishes' on this figure. Although the actual headers are not legible in this reduced figure, the intent of the figure is to provide a general feel for the density of observation sites. Figure 54 shows the locations for NDBC moored buoys and operating C-MAN stations. Note that in the near coastal regions (both onshore and offshore) from Panama City, FL (PFN) extending around the Big Bend and southward down the Florida Peninsula to near Brooksville, FL (BKV), there are virtually no surface observation sites. Therefore, in support of any coastal research endeavor in the NEGOM, it is imperative that data acquisition systems be placed in this region. The network of upper air stations is even less dense in this region, and very few aircraft observations are available since most of the airspace over the NEGOM is restricted. At this time, only data collected remotely or computed in predictive meteorological models are available to describe the near-surface characteristics over the NEGOM region.

However, these model products are improving in resolution both temporally and spatially. It is expected that by early 1995, the 30 km version of the Eta mesoscale model being developed at the National Meteorological Center will be operational. Currently, the Eta model now supplying surface data for the NEGOM region is supplying data at 80-km resolution in the horizontal with 38 vertical levels. Figures 55 and 56 display the current Eta model grid and levels. In addition to the model products and data available via remote means (more details will be presented at the workshop), there are several proposed data acquisition sites which may be available for the field study. These sites could be implemented prior to the field activity in the NEGOM region, or implemented as part of any field activity. In progress are discussions with the US Air Force on instrumenting at least one navigational beacon tower in the NEGOM region. Other activities ongoing at FSU Meteorology (cooperative activities with the Southern Region of the National Weather Service) could result in additional instrumented towers both onshore and off. These include the possibility of instrumenting platforms and towers in support of sea breeze studies. The NDBC also has plans to place a drifting buoy in the Gulf of Mexico although the exact details are not available at this time.

Table 3. Primary Data Types Currently Available (on-line or archive)

Surface Observations:

National Weather Service Direct Observations
Department of Defense Direct Observations
Automated Surface Observing System
Coastal-Marine Automated Network
National Data Buoy Center moored buoys
Ship-bourne Observations

Upper-Atmospheric Observations:

National Weather Service Radiosonde
Department of Defense Radiosonde
Aircraft observations
Air National Guard Aircraft Dropsonde

Remote:

Satellite observations from polar orbiting and geostationary satellites
Weather Service Radar - 57
Weather Service Radar - 88D
Department of Defense Weather Service Radar - 88D

Model output:

Nested Grid Model -
Eta Model

Possible additional sources (199?):

NGM Navigation towers (offshore)
Drilling Platforms (offshore)
Radio towers (onshore)
Drifters (buoy)

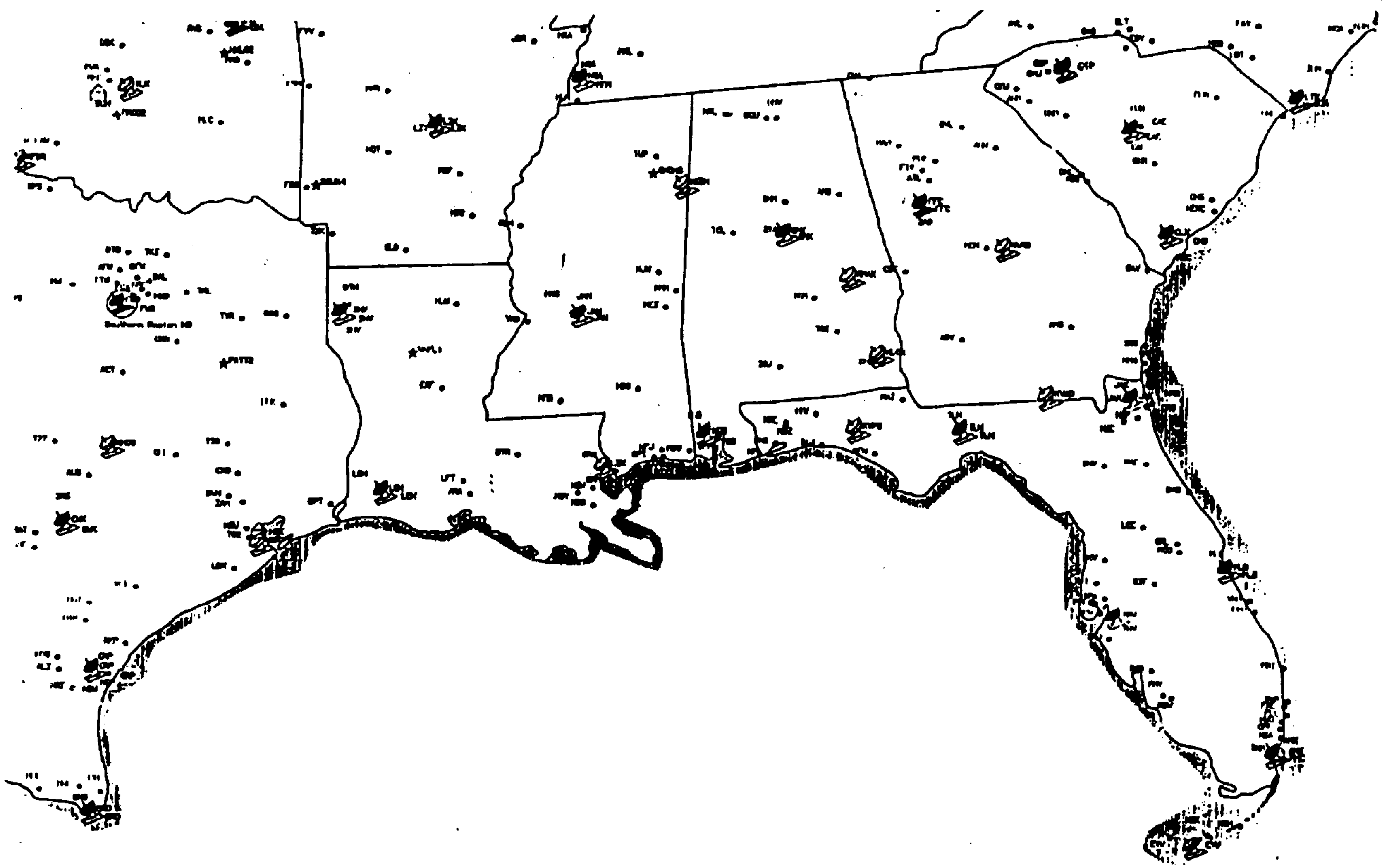

Figure 53. NWS forecast office (dark 'dish'), ASOS (dot), and WSR-88D (dark and light 'dish') sites.

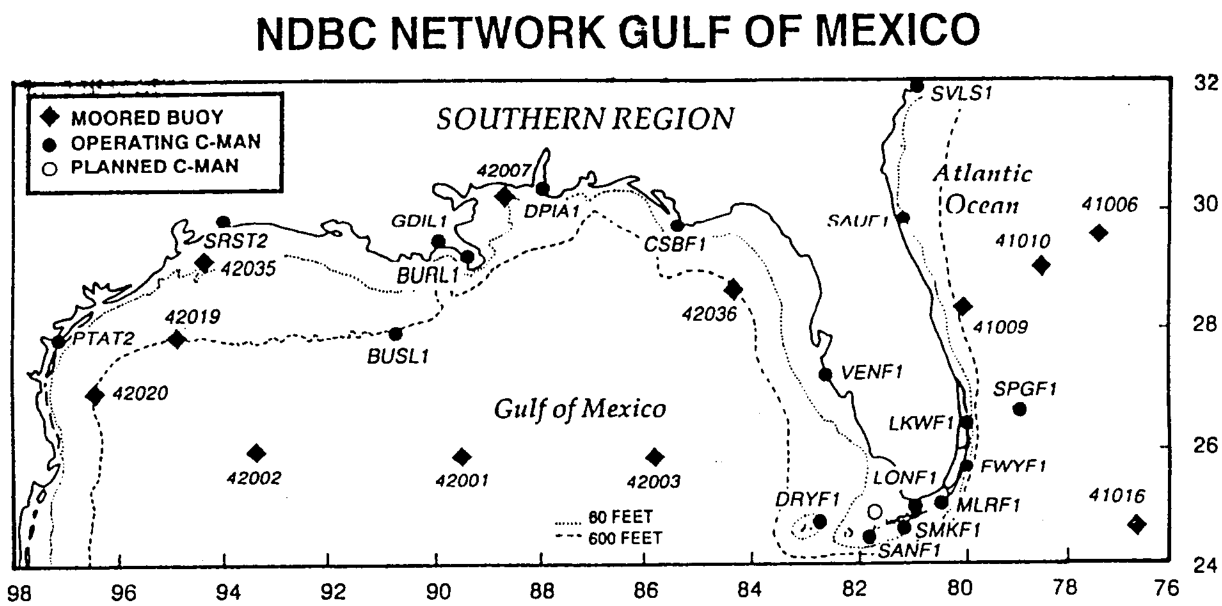

Figure 54. NDBC moored buoy and C-MAN sites

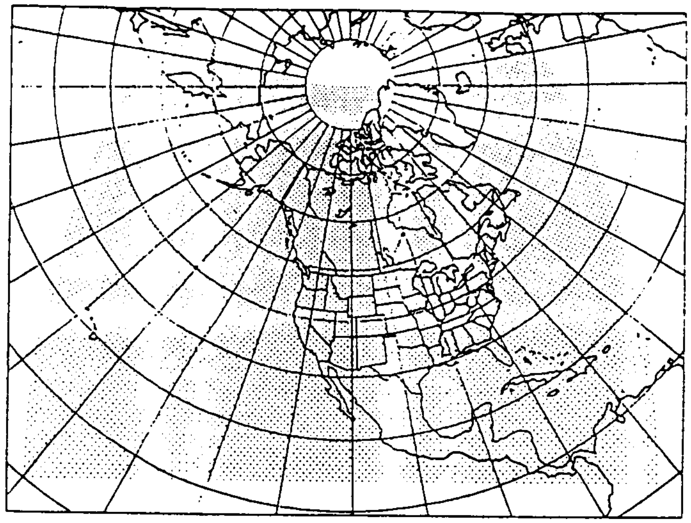

Figure 55. Eta 80-km version grid

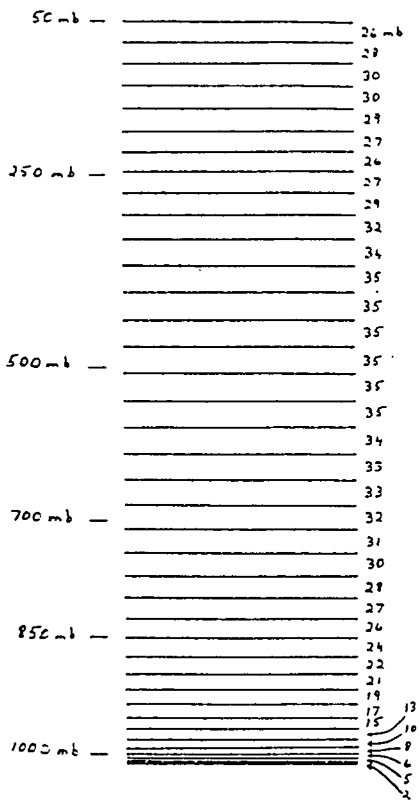

Figure 56. Eta 80-km vertical levels

2.3.6

US SOUTHEAST CONTINENTAL SHELF INNER SHELF PROCESSES RELEVANT TO THE NORTHEASTERN GULF OF MEXICO INNER SHELF

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Introduction

This talk focuses on oceanographic processes occurring on the southeastern US continental shelf (SAB) that are perhaps unique to shallow inner-shelf environments. There are other important processes that occur shelf-wide. Intrusions from the Gulf Stream can significantly affect large areas of the shelf environment, particularly areas in proximity to the shelf break. Winter storms (cold air outbreaks) dramatically impact shelf water through sea to air heat losses causing convection and producing temporary fronts. These topics have been studied in the SAB but are beyond the scope of this article.

The inner shelf central region of the southeastern US continental shelf (SAB) has a multi-inlet coast line connecting low-lying coastal marshes to the ocean (Figure 57). Several rivers, five of them each discharging freshwater at rates exceeding 100 m^3/s, form plumes of low-salinity (low-density) water at the coast. Subsequent tidal and wind mixing blends the plumes into a band of low salinity that extends along the coast over a distance greater than 400 km. While we customarily define the inner shelf to be at depths between 0 - 20 m, the seaward extent of the low-density band defines, in a dynamic sense, the inner shelf. The extent varies temporally and spatially.

The depressed density of the low-salinity water causes it to override ambient shelf water of higher density to form a coastal frontal zone (CFZ) that usually extends 20 - 30 km offshore (Figure 58). The resulting offshore pressure gradient turns water to the right within a baroclinic Rossby radius of about 5 km (Blanton, 1981). In the absence of wind, a weak baroclinic coastal current flows southward within the CFZ at a speed less than 5 cm s^{-1} (Blanton *et al.,* 1989).

Vertical and horizontal mixing is particularly enhanced in shallow water typical of inner shelf environments. The gravitational cross-shelf circulation component is theoretically greater than the alongshelf component for coastal environments where the vertical diffusion of momentum is comparable to the effect of the Coriolis acceleration (Garrett and Loder, 1981). Frictional forces clearly dominate the inner shelf environment of the SAB resulting in a high Ekman number environment.

The inner-shelf bight of the northeastern Gulf of Mexico has many similarities to the southeastern US shelf. This part of the Gulf has two medium-size rivers (Apalachicola and Suwannee) that account for combined annual discharge rates of about 1000 m^3/s. Numerous springs account for an additional 200 m^3/s, a source that may be underestimated. The distance to the 20-m isobath varies from about 20 km off Apalachicola to more than 60 km off Cedar Key. This is within the range found in the SAB. The primary difference is in the strength of tidal currents, where semidiurnal tidal currents 1 meter above bottom appear to be about 50 to 100 percent greater in the SAB than those found in the northeastern Gulf.

Buoyancy Inputs and Mixing

The dynamic significance of the low salinity band formed by estuarine discharges is that it provides the main buoyancy source for the CFZ. Vertical density gradients exhibit a high degree of spatial and temporal variation due to (1) vertical mixing provided by friction of tidal currents at the sea bed, (2) surface friction provided by wind stress and (3) the source strength of freshwater discharge and its spatial distribution.

While buoyancy inputs due to solar radiation can be important in many coastal regions, significantly more power is required to mix the freshwater-induced buoyancy along the South Carolina and Georgia coast (Blanton and Atkinson, 1983). Approximately 10^{-4} to 10^{-3} W m^{-2} is required to mix observed ranges of total river discharges varying between 1000 m^3 s^{-1} in autumn to 8000 m^3 s^{-1} in spring.

Semi-diurnal tidal currents provide the most consistent mixing agent. They typically account for about 90 percent of the cross-shelf current variance and less than 60 percent of the alongshelf variance (Pietrafesa *et al.*, 1985). Maximum surface tidal currents can reach 35 - 45 cm s^{-1}, while those near bottom decrease to 10 - 20 cm s^{-1} (Blanton *et al.*, 1994). Neap and spring tidal amplitudes significantly modulate tidal current strength.

Blanton and Atkinson (1983) estimated that tidal power dissipation at the bottom ranges from 0.3 to 2 x 10^{-4} W m^{-2} off the Georgia coast. This is sufficient to vertically mix buoyancy due to heat additions but is too weak to vertically mix the buoyancy normally provided by freshwater discharge. However, wind-induced surface stress can provide a significant increment of power over that of tidal currents. Mixing power due to strong wind events can range between 1 and 3 x 10^{-3} W m^{-2} (Atkinson and Blanton, 1986), or an order of magnitude greater than that provided by tidal power.

Response of Coastal Frontal Zones to Wind

The pressure gradient caused by low-density water at the coast drives a cross-shelf gravitational estuarine-like circulation that is offshore in surface layers and onshore near bottom. The strength of the gravitational component is proportional to the horizontal density gradient, which in turn is proportional to the magnitude of riverine discharge. Model studies (Werner *et al.*, 1993) have shown that the strength of this cross-shelf flow component is less than 10 cm/s.

Alongshelf wind stress produces an Ekman-induced cross-shelf flow that is combined with the gravitational circulation component. Upwelling favorable offshore Ekman transport spreads the front seaward, and there is an offshore component of flow above and within a strong pycnocline (Figure 59). Currents are onshore below the pycnocline. Thus, upwelling reinforces the estuarine circulation component, and the cross-shelf flow structure resembles the along-axis flow of a partially mixed estuary.

Onshore Ekman transport during downwelling-favorable wind (southward stress) advects the frontal zone shoreward and steepens the front. In contrast to the upwelling-favorable case, the downwelling-induced cross-shelf flow opposes the gravitational component (Figure 59).

Estuarine/Ocean Coupling

Estuaries can provide an important coupling mechanism between the inner shelf and inland marine waters. When an estuary extends its gravitational circulation regime onto the shelf, an undercurrent of shelf water can flow into the estuary through any deep channels connecting it to the ocean. In addition, freshwater discharges can provide a buoyancy driven coastal current along the inner shelf (Garvine, 1991).

Theoretical studies (Chao, 1987) predict that river plumes respond differently to upwelling- and downwelling-favorable wind stress. Upwelling forces the plume to spread seaward against the natural tendency to spread to the right looking downstream. Downwelling winds cause the plume to narrow and extend downwind along the coast, within which a strong coastal jet develops.

Current meters were moored along the 8-m and 15-m isobath (Blanton and Amft, 1987) extending from just north of the Savannah River mouth southward for 15 km (Figure 60). Subtidal alongshelf currents at the southernmost site were significantly correlated with alongshelf wind stress (coherence squared = 0.81). Currents just north of the river mouth were correlated with wind stress but were noticeably smaller than at the other two sites. The currents just south of the river mouth were poorly correlated with wind stress (coherence squared = 0.29), but subtidal currents often had a jet-like character during downwelling-favorable wind stress.

While estuarine/ocean coupling has not been adequately addressed in the SAB, there is preliminary evidence that a strong coastal current flows southward in the immediate vicinity of the Savannah River. The above current meter data coupled with recent tracer studies using tritium suggest that the jet-like current is directly coupled to the Savannah River.

Relevance to the NE Gulf of Mexico

The shoreline orientation in the northeast Gulf changes by almost 90° within a 50-km distance centered on the 84° W meridian. Within this region, the alongshore component of a given wind field changes significantly. As a result, the response of coastal fronts to wind stress here may be quite complex where strong pressure gradients may result from the set-up and set-down of sea level in the bight.

Inner shelf studies in the northeast Gulf of Mexico will provide an interesting comparison to some of the findings in the SAB where the mixing power of the tides is greater. Measurements of the coastal frontal zone off St. Theresa (Harkema *et al.*, 1994) show significant temporal changes in the horizontal and vertical density structure. Determining how these changes correlate with buoyancy supply, tidal currents and wind-generated currents may prove to be particularly challenging.

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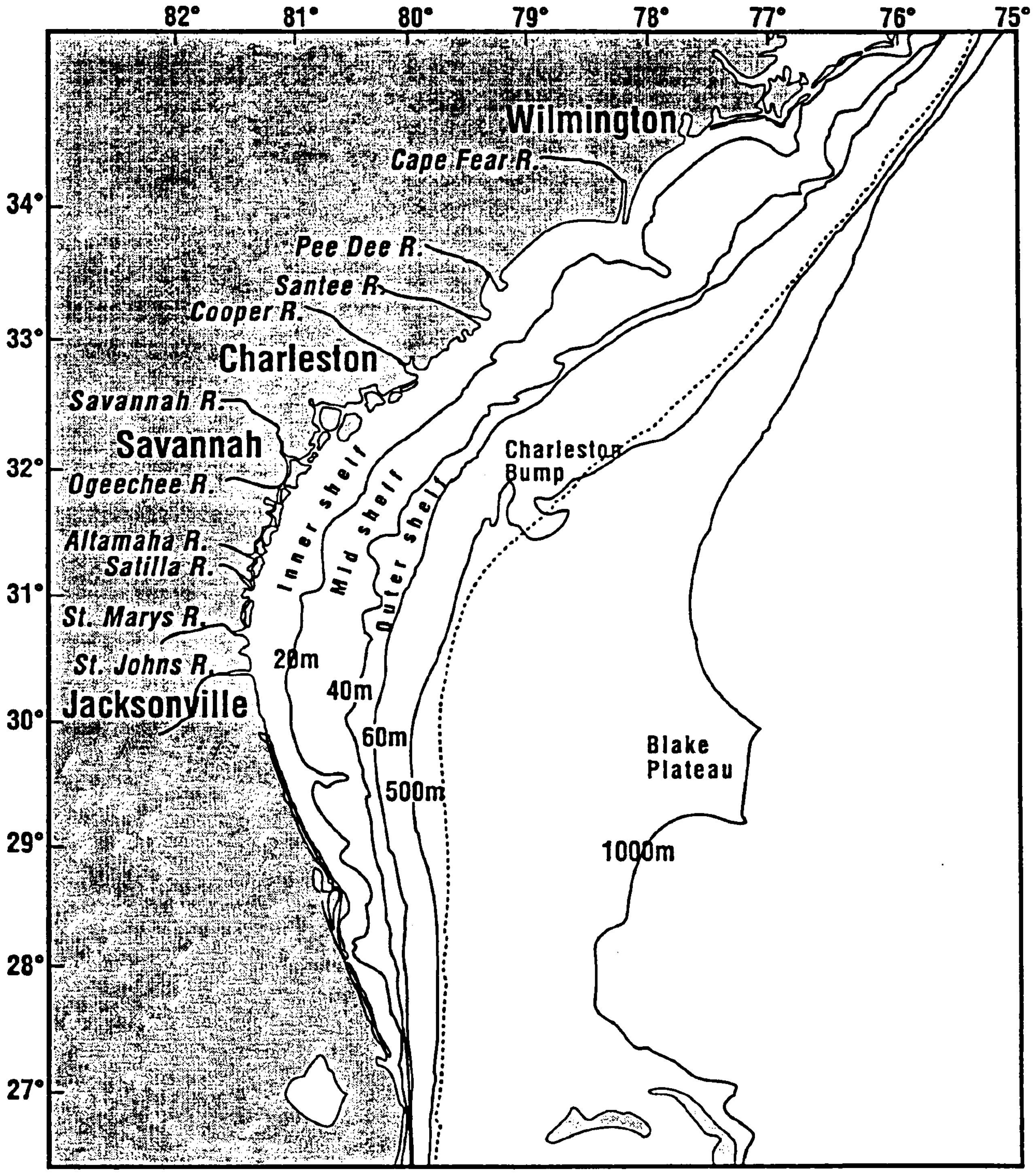
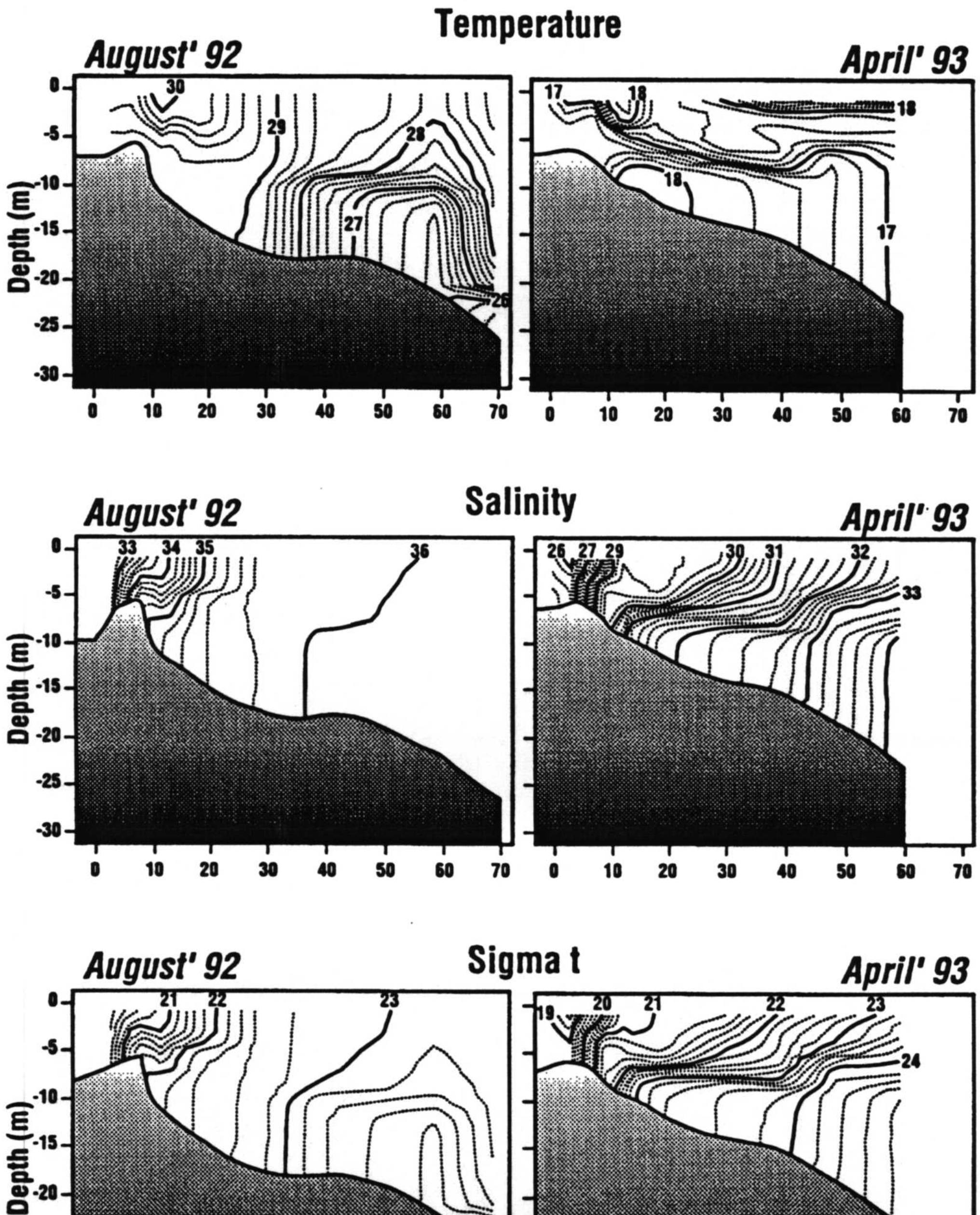


Figure 57. Map of the southeastern U.S. continental shelf. The inner shelf domain is defined as bottom depths less than 20 m.

Hydrography - CTD Surveys



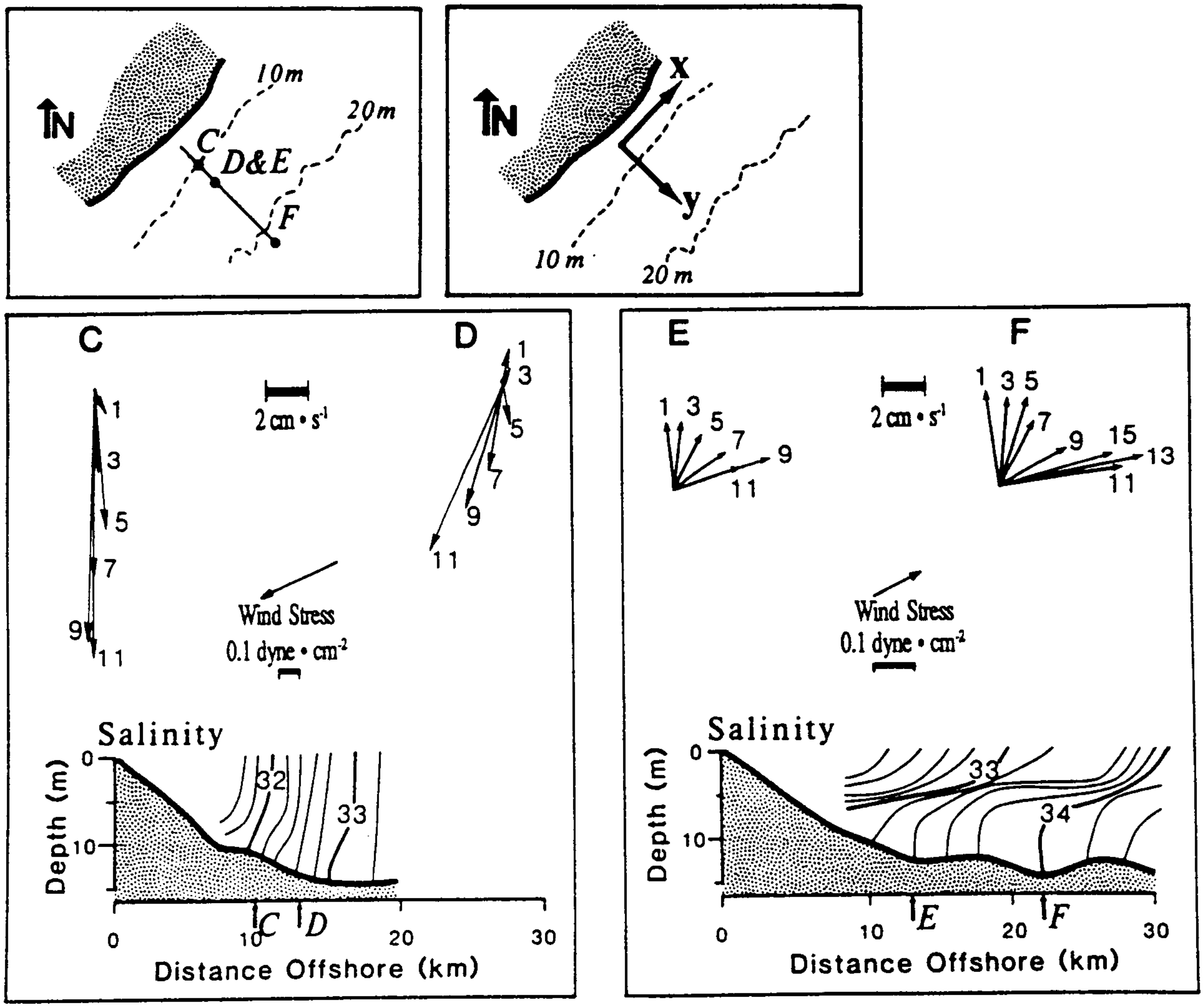


Figure 59. Mean currents averaged over four tidal cycles in two opposing wind regimes. (Left) downwelling, 7-9 November 1979. (Right) upwelling, 2-4 April 1981. Vertical sections are off Wassaw Island, GA, and show the salinity distribution at the beginning of each observation period. Numbers adjacent to the vectors denote distance in meters above bottom.

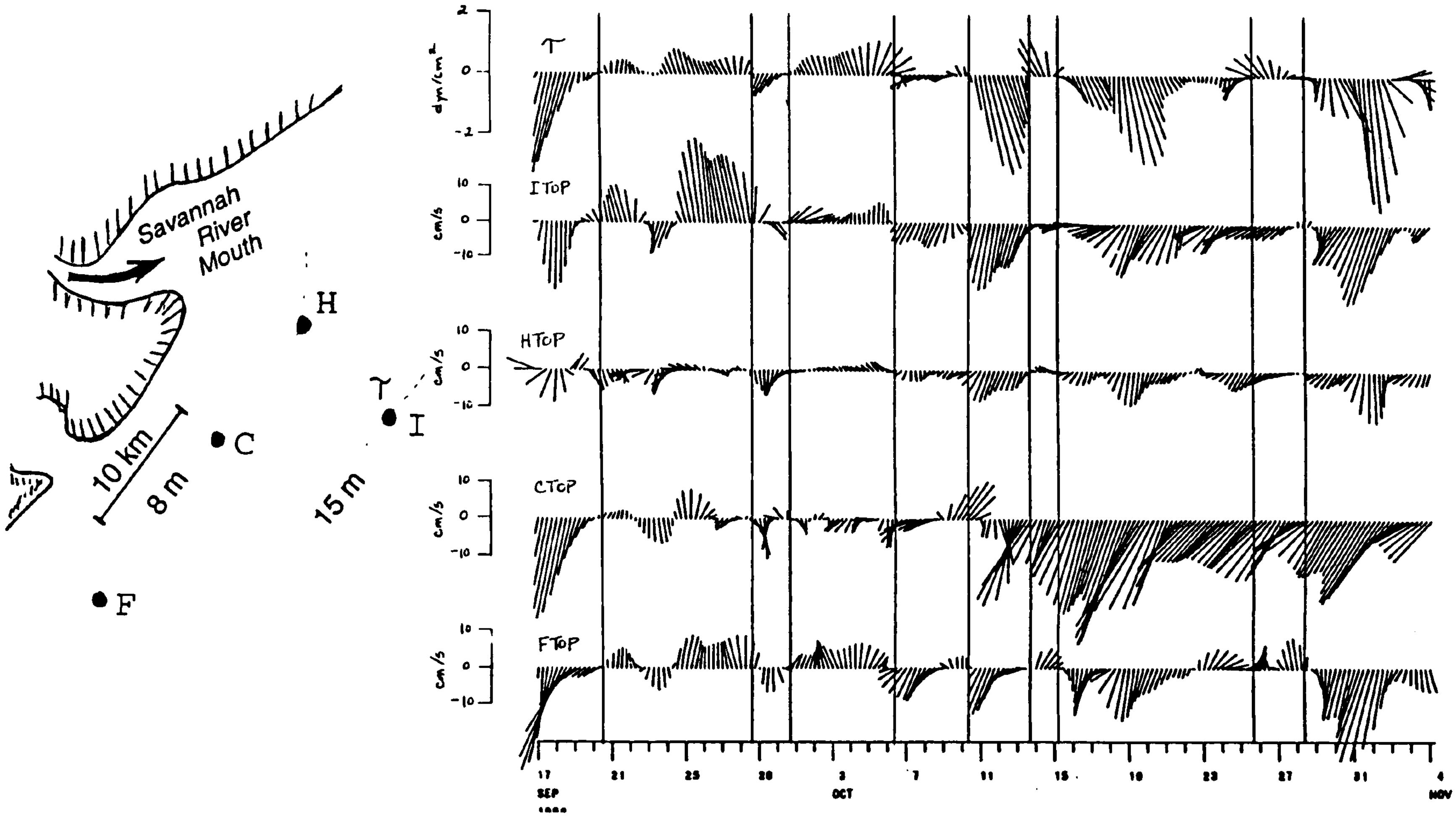


Figure 60. Simultaneous current measurements along the 8-m and 15-m isobaths near the mouth of the Savannah River. "Top" meters were located about half-way between surface and bottom. All vector components have been 40HLP filtered and the coordinate system rotated -45 degrees from north. Note the strong jet-like current at Station "C" that appears on 12 October 1986 compared to the weak currents at Station "H". Wind measurements were made at Station "I".

2.4 Modeling of the Region

2.4.1 NEEDS OF MMS/OIL SPILL RISK ANALYSIS

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Needs of MMS

Summary: The chance of oil spills contacting sensitive marine and coastal resources is a major environmental threat. Thus, controversy over the various risks and benefits of offshore oil development indicates a need for an objective, quantitative estimate of the oil-spill risk associated with a particular lease or development proposal.

MMS position: The MMS addresses the threat of oil spills contacting sensitive marine and coastal resources as a major environmental concern.

Oil Spill Risk Analysis

Background: The DOI has developed the Oil-Spill Risk Analysis (OSRA) model to help estimate the environmental risks of developing oil resources in Outer Continental Shelf (OCS) lease areas. The model uses data on ocean currents and winds, along with historic oil-spill occurrence data, to estimate the likelihood of a large oil spill occurring and contacting environmental resources as a result of an OCS development proposal.

Current status: The MMS conducts an OSRA for pre-lease and post-lease environmental decision making documents. An OSRA estimates the following:

The chance of spills occurring, estimated by using oil-spill statistics for OCS platform and pipeline spills, and for worldwide tanker spills.

The probability of oil contacting environmental resources, using analyses of oil-spill trajectories calculated from wind and ocean current data.

The combined risk of oils spills from production and transportation from pipelines and/or tankers, using resource estimates and the trajectory analyses.

The OSRA model is continuously being evaluated and upgraded by MMS through:

Improvement of ocean surface currents, based on simulations produced by dynamic ocean and meteorological models and compilations of oceanographic observations.

Use of state-of-the-art flow visualization and particle tracking techniques to perform quality control of the ocean model products.

Improvement of wind fields based on meteorological data and atmospheric model results.

Identification of oil-following drifting buoys as an important research and development initiative and sponsorship of intensive Lagrangian drifter- release experiments to provide model verification data.

Maintenance of an extensive data base of oceanographic and meteorological observations and model products. Close working relationships exist with NOAA/HAZMAT (oil-spill response group) and the U.S. Coast Guard to provide information to them for spill/accident response and risk assessment.

Analyses of Oil Spill Contingency Plans

Prior to the approval of exploration plans or development and production plans for OCS oil and gas leases, operators are required to prepare oil spill contingency plans (OSCP). These plans set forth the procedures to notify all concerned government agencies, to curtail the spill and to clean up any oil that has escaped. Plans are reviewed by the U.S. Coast Guard under a cooperative agreement with MMS. The operator may not begin operations until the OSCP has been approved by MMS.

The enactment of the Oil Pollution Act of 1990 (OPA '90) supplemented by Executive Order 12777 expanded MMS jurisdiction to include OSCP's for all offshore facilities, except those associated with deepwater ports, including those located in State waters. As mandated by OPA '90, the Coast Guard is evaluating tanker routing alternatives to reduce oil-spill risk. The MMS is assisting in these efforts through application of its oil-spill risk model.

2.4.2 RESULTS FOR THE NEGOM USING THE DYNALYSIS MODEL

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This effort was conducted by the Deterministic Modeling Group, which is one component of the Minerals Management Service's Coastal Ocean Modeling (COM) Program. The members of the Deterministic Modeling Group are Richard Patchen, Lie-Yauw Oey, and George Mellor. The scientific goal of the deterministic modeling group is the implementation of a deterministic eddy-resolving circulation model which will predict realistic, statistically representative hydrodynamics for the Gulf of Mexico, with particular emphasis on the shelf circulation on the Louisiana-Texas (LATEX) shelves. These model predictions will be subject to a rigorous skill assessment with contemporary hydrodynamic observations to evaluate the model performance in simulating basin and shelf dynamics and the interaction of the basin large-scale circulation with local shelf processes.

Although the emphasis of the research for the COM program is the LATEX shelves, the model developed encompasses the entire Gulf of Mexico, including the Northeastern Gulf of Mexico (NEGOM). A family of models has been implemented for the Gulf of Mexico, initially with a $0.2^o \times 0.2^o$ (18-22 km) rectangular grid, with a transport distribution based on available historical information; climatological river inflow at the three major rivers systems entering the LATEX region; and climatological winds and heat flux. Recently, the model resolution has been refined on an orthogonal curvilinear grid, with finest resolution in the LATEX shelf and evenly distributed in the Loop Current separation region. A Dynalysis digital bathymetry for the Gulf of Mexico on a 0.01^o grid (DDBG1) was constructed by use of objective analysis to synthesize the NAVOCEANO DBDB5 data (a global 5' by 5' digital bathymetry); the National Ocean Services's (NOS) hydrographic data (consisting of NOS soundings for U.S. coastal waters); and a digitized bathymetry for the entire Gulf of Mexico prepared by Texas A & M. To resolve the surface layer, the model was configured with 15 levels in the vertical and the transport distribution is based on the MMS sponsored, 1990-1991 Straits of Florida Physical Oceanography Field Study. To provide surface and lateral boundary conditions the data are: 12-hourly wind stress available on a $9/8^o$ Grid; daily river flow at 20 rivers along the U.S. coastline of the Gulf of Mexico; 6-hourly atmospheric pressure; and monthly climatology (T and S) at open-ocean lateral boundaries. The model grid, including the transports specified and locations of the rivers; the DDBG1 bathymetry; and the model's horizontal resolution are shown in Figures 61-63, respectively.

The objectives of this presentation were to provide information at this planning meeting to aid in the design of the observational program for the NEGOM using the model results to-date. The model results can be used to provide guidance in planning locations of fixed moorings in the NEGOM; locations of transects in the NEGOM; and possible locations to monitor remote forcing, *i.e.*, oceanographic events occurring south and/or west of NEGOM.

The morphology of the Loop Current can have a considerable impact on the circulation in the NEGOM. To illustrate its effect Figures 64-66 depict the modeled process of the Loop current extending northward to the NEGOM, then shedding an eddy over a 40 day period. These figures depict the five-day (the period for the average is given in the upper left corner of each figure) averaged near-surface velocity and temperature. The process begins with the Loop Current extending northward to 28°N, then after 20 days a Loop current eddy is being formed by the pinching off of the Loop Current at 25°N, and finally 20 days later a Loop current eddy has been formed with the Loop current retreating to 25°N, thus having a minimal effect on the circulation in the NEGOM.

The Mississippi river plume primarily is to the west; however, during atypical oceanographic conditions, a plume can be deflected to the east and have a direct impact on the circulation in the NEGOM. On April 27, 1987, during a period of high river flow and winds from the northwest, the modeled river plume is to the east. This eastward modeled plume is shown in Figure 67. This figure depicts the five day average of the synoptic winds, and the modeled sea surface elevation, near-surface currents and salinity.

As the MMS's COM program evolves, the family of deterministic models will expanded. Plans for 1994-1995 include further enhancements in model resolution, *e.g.* the resolution for the entire Gulf of Mexico will be halved, thus a resolution of roughly 5 km in the NEGOM; and model enhancements will be implemented. All model data will be objectively and rigorously compared to historical observations, especially those collected by the MMS's LATEX measurement program. In summary, both presently available deterministic model results, and those to be made in the near future will be available while plans for the NEGOM observational program are being established.

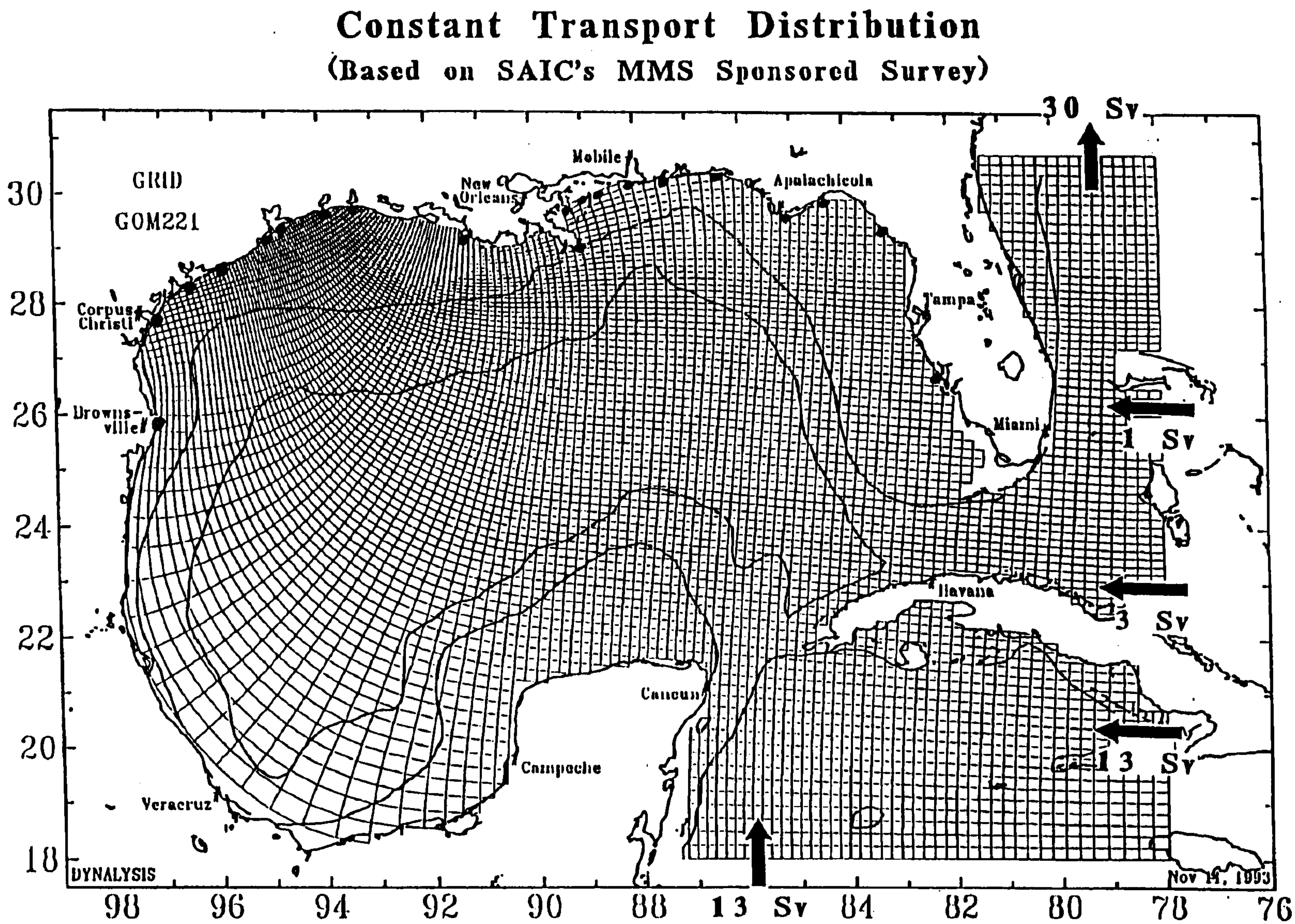

Figure 61. The Dynalysis Gulf of Mexico orthogonal curvilinear grid, the transport distribution imposed, and the location of the 20 rivers along the coast of the U.S. where daily inflow is specified.

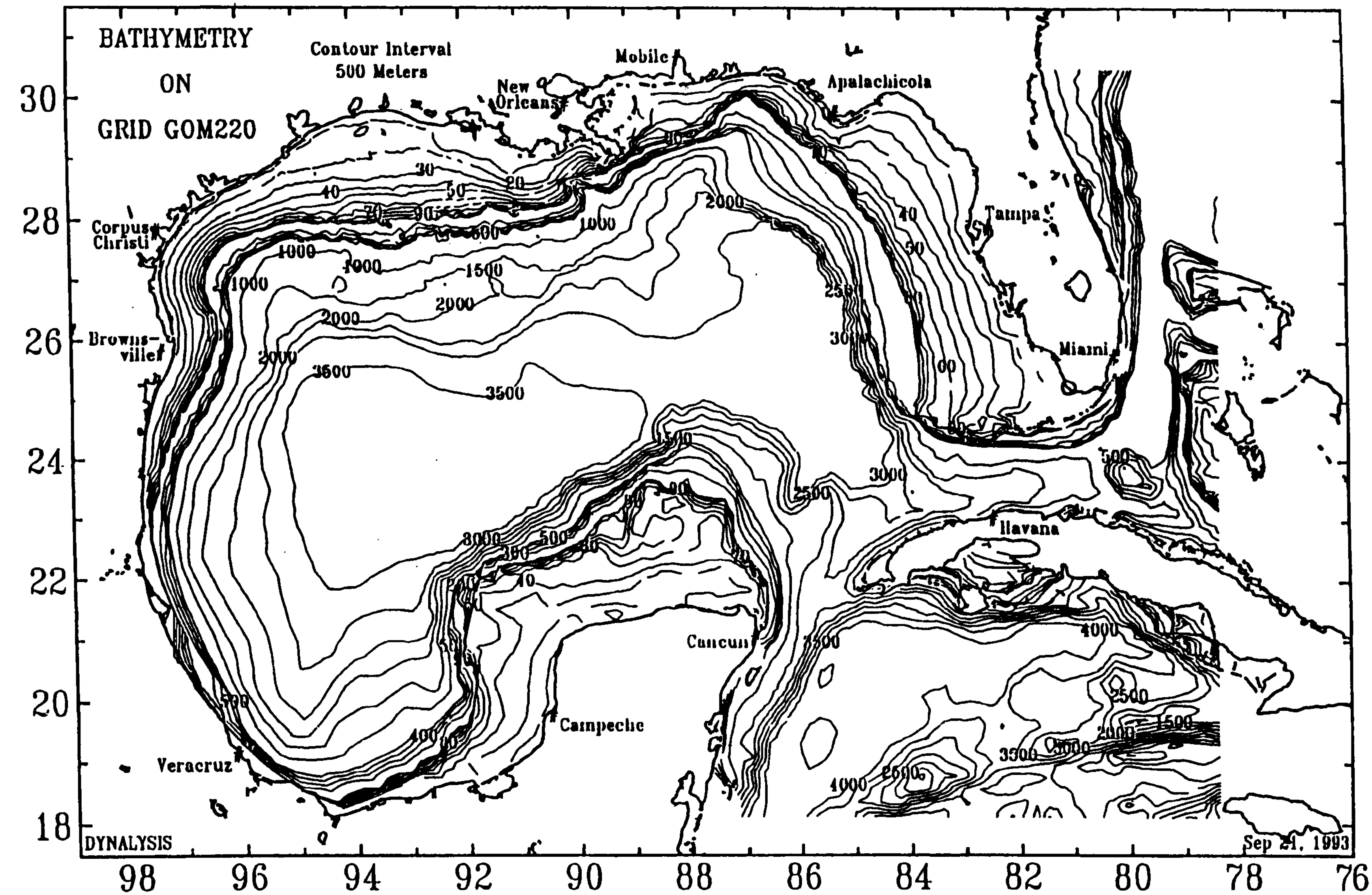

Figure 62. The Dynalysis digital bathymetry for the Gulf of Mexico on a 0.01° grid (DDBG1).

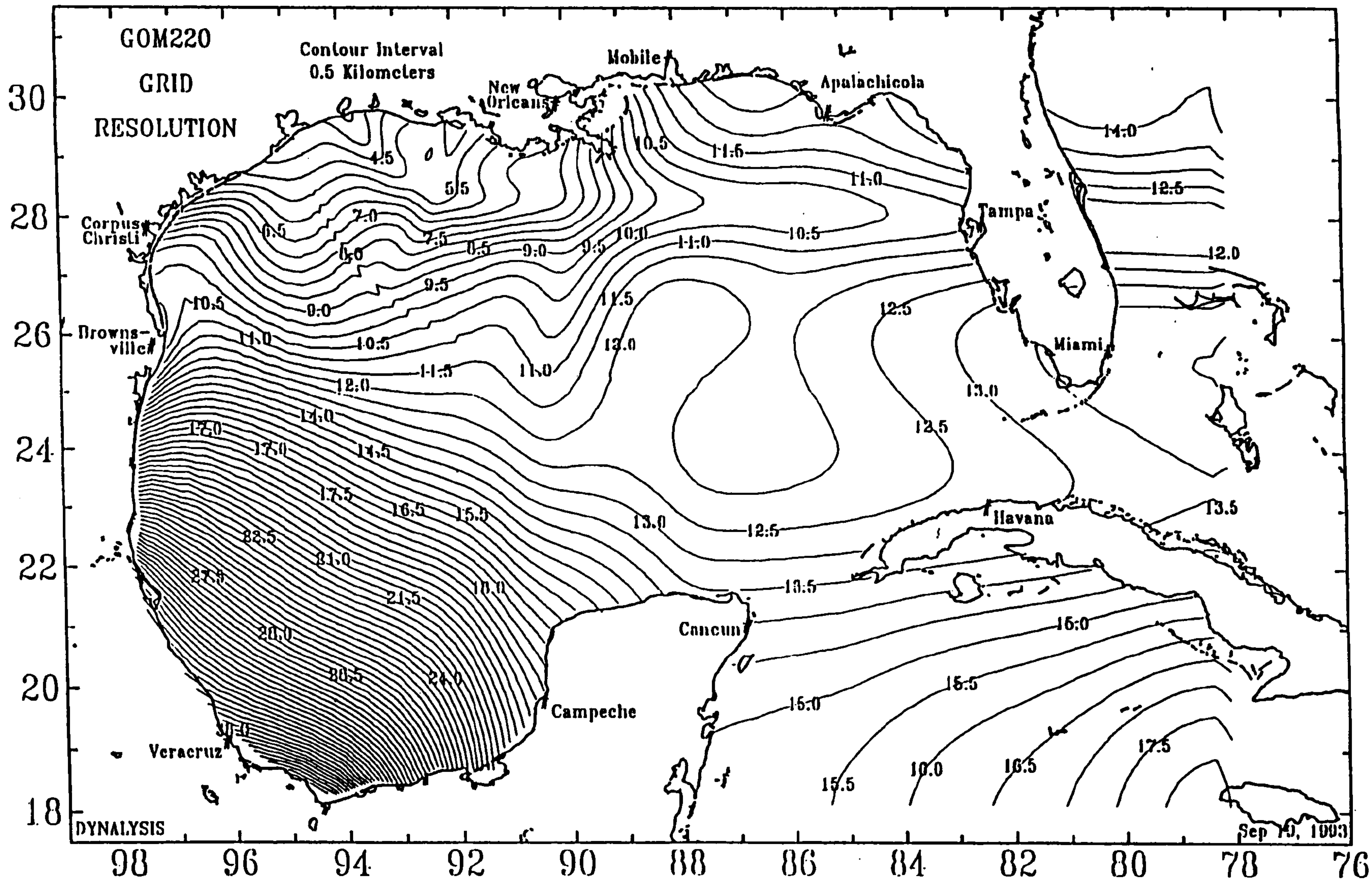

Figure 63. The horizontal model resolution, in km, for the Dynalysis Gulf of Mexico grid, shown in Figure 61.

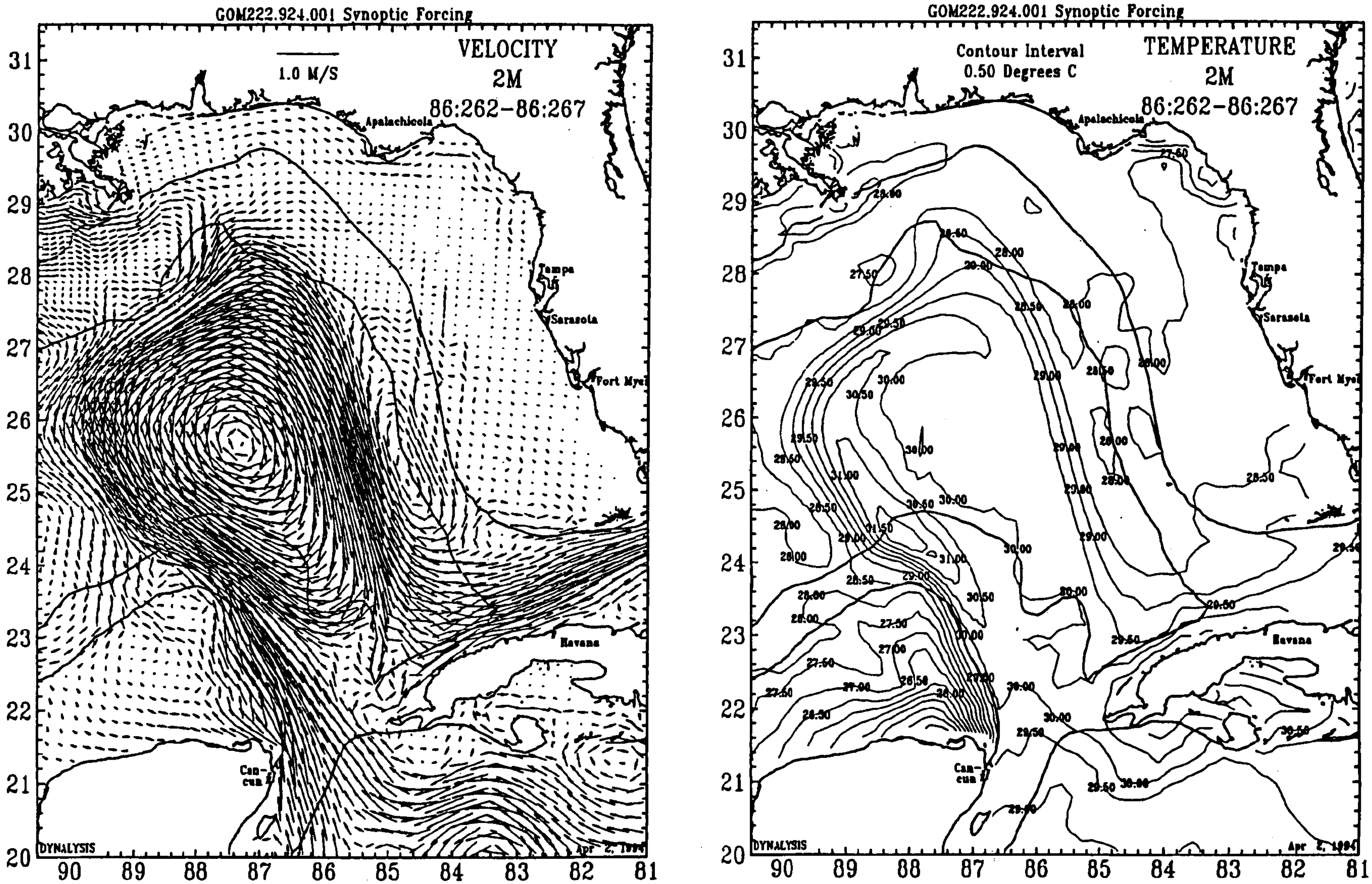

Figure 64. The modeled process of the Loop current extending northward to the NEGOM, then shedding an eddy 40 days later.

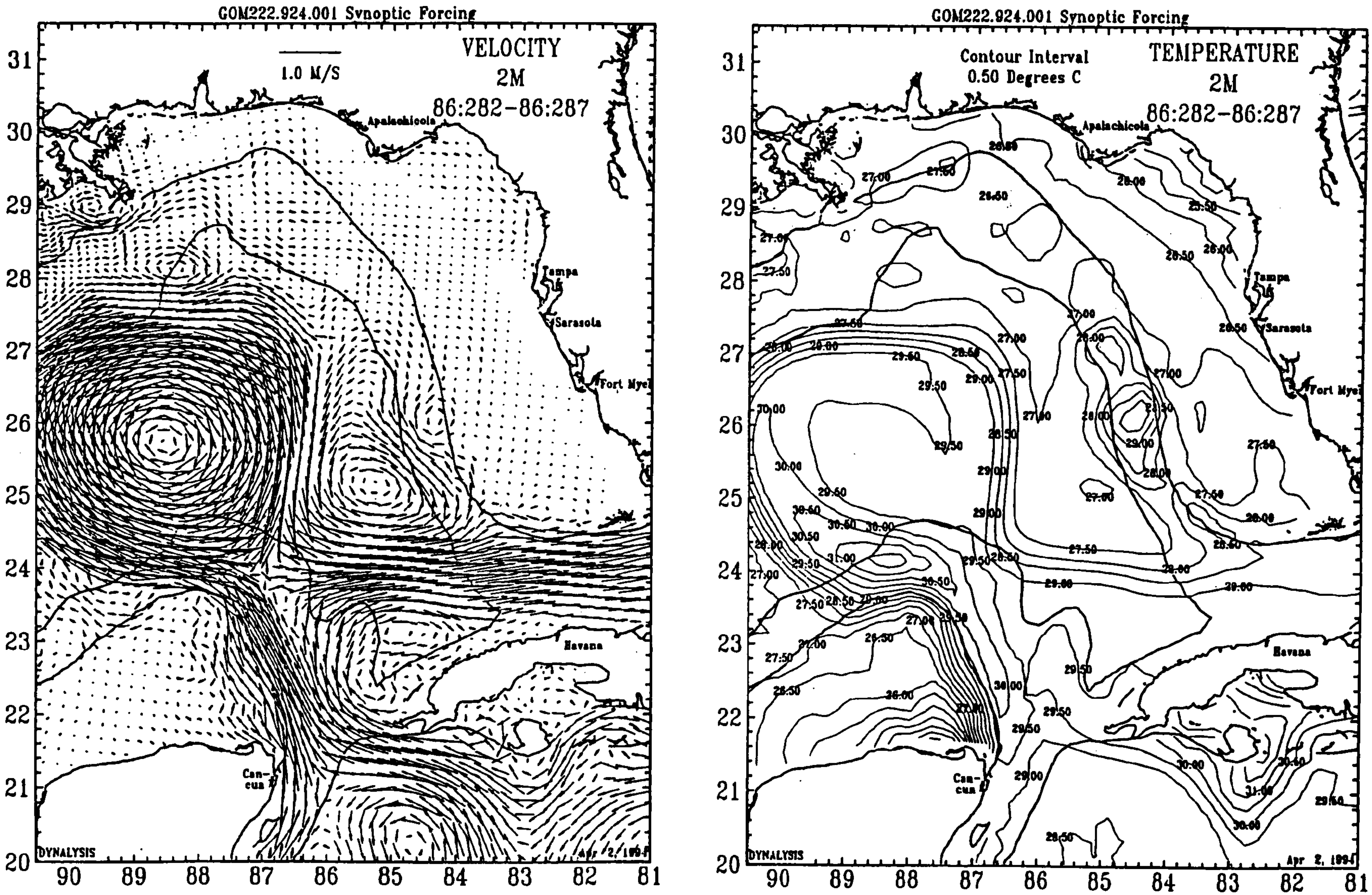

Figure 65. Continuation of the formation of a Loop current eddy. The fields shown are for 20 days after those shown in Figure 64.

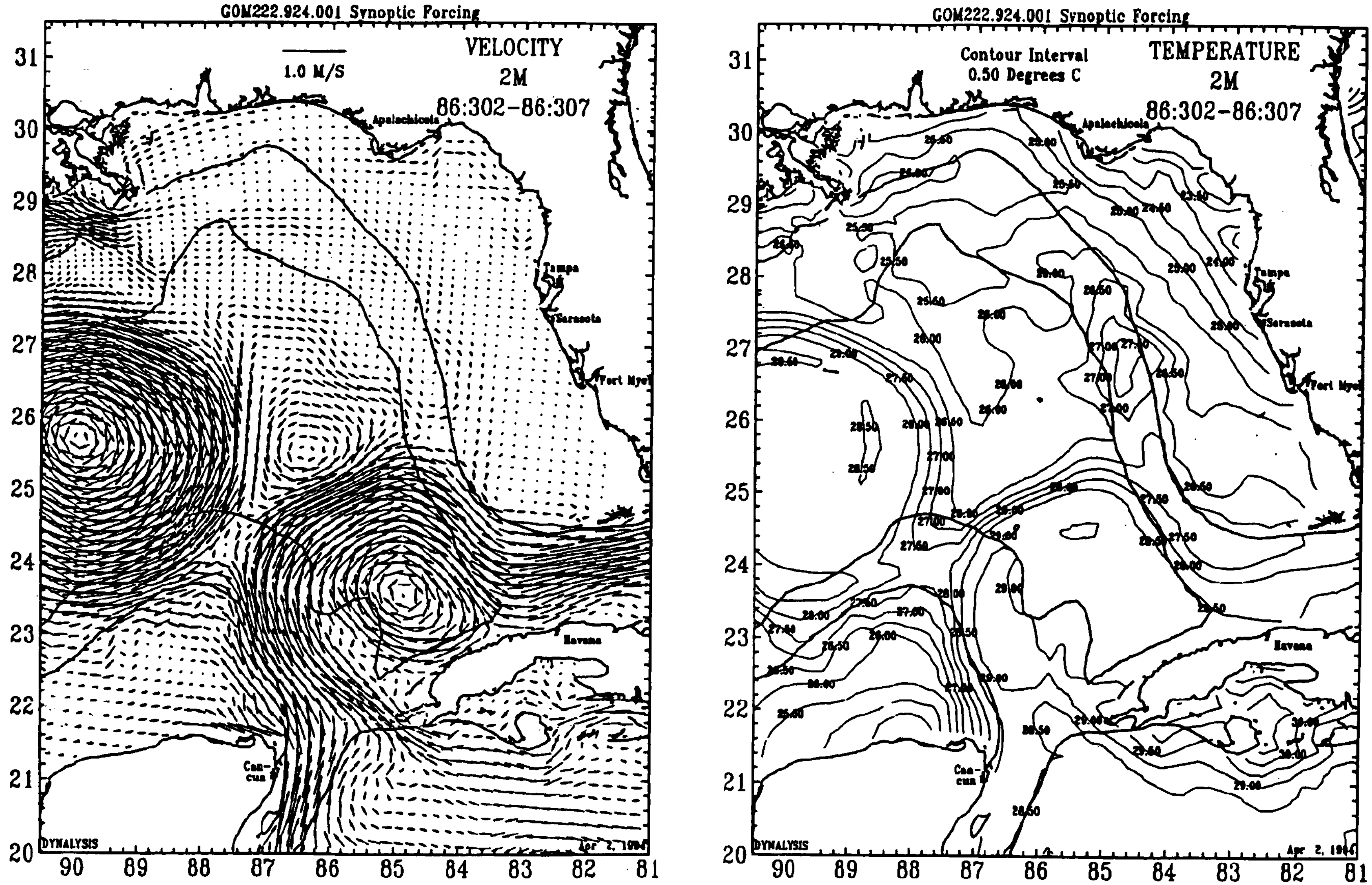

Figure 66. Continuation of the formation and shedding of a Loop current eddy.

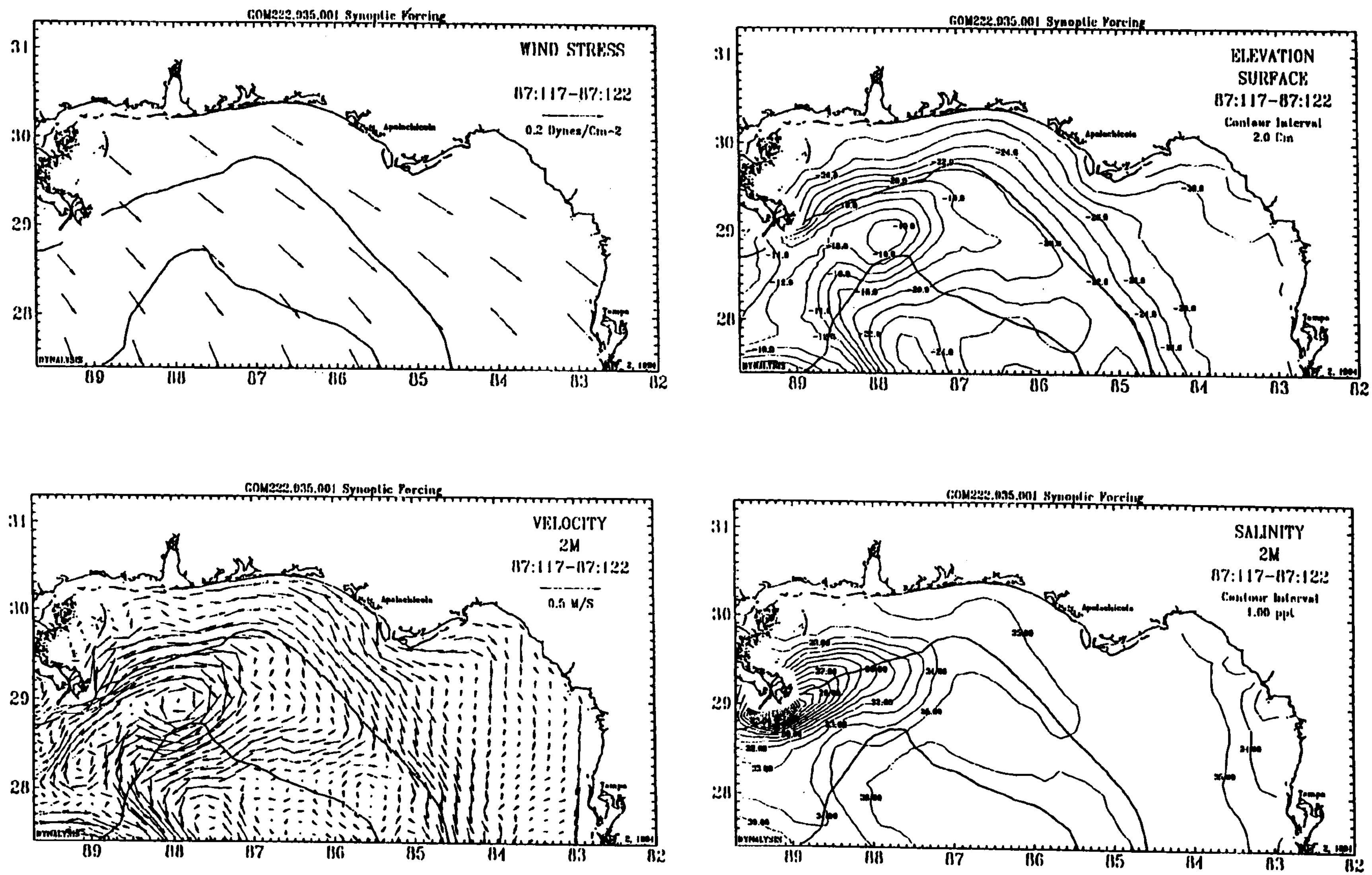

Figure 67. The Mississippi plume extending to the east to the NEGOM.

2.4.3 EFFECTS OF THE LOOP CURRENT AND LOOP CURRENT EDDIES ON WEST-FLORIDA SHELF CIRCULATION -- A 3-D MODEL STUDY

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Abstract

Results from a three-dimensional model are used to infer that the west-Florida shelf circulation may be due to forcing by the Loop Current expansion and eddy shedding south of the Mississippi Delta and DeSoto Canyon.

Introduction

Loop Current (LC) frontal meanders along the west-Florida slope have been observed (Niiler, 1976; Paluszkiewicz *et al.,* 1983). The meanders can result in intrusions onto the shelf, facilitate local exchange of water masses, and generate shelf currents. Another clear forcing signal of large-scale origin is associated with LC expansion and eddy intrusions observed south of the Mississippi River delta, as well as east of it in the DeSoto Canyon on the Mississippi-Alabama shelf (Vukovich *et al.,* 1979; Huh *et al.,* 1981; Wiseman and Dinnel, 1988). We describe here model results which suggest that the forcing south of the delta and in the DeSoto Canyon can affect the water mass and currents of the west Florida shelf.

The Model

A nested-grid calculation of the LC including the west Florida shelf and slope (Figure 68; Nest C: 6.7km'6.7km' 21 sigma-levels) had been conducted, initialized from one of the 10 years' coarse-grid (6.7km'6.7km' 21 sigma-levels) simulations presented in Oey and Zhang (1993). Discharges from the Mississippi, Atchafalaya and other smaller rivers are included. Effects of the LC and LCE's (outside the nest) are obtained from the coarse-grid solution imposed as forcing at the nests' open boundaries. Details of the nested-grid model are in Oey and Chen (1992a,b).

Results

Figure 69 gives typical LCE shedding results from the coarse-grid calculation. Note that the model tends to produce a LC which 'bends' more westward than what is typically observed (*e.g.,* Elliott, 1982). Figure 70 compares the modeled temperature (top left panel) and SST contours from satellite data (from Paluszkiewicz *et al.,* 1983). This shows typical LC frontal meanders in the model, with similar shapes as those observed. However, the model meanders are away from the shelf, as seen also from the potential vorticity (PV) plot. Thus the modeled meanders do not appear to interact with the shelf, at least not as intensely as one might infer from the observations. However, the temperature contours, as well as velocity vector plot, clearly indicate the appearance of energetic shelf currents (Figure 71). The alongshelf current magnitudes are about 0.2 m s^{-1}, fairly uniform vertically over the 30 to 50 m isobaths, as shown in the vertical cross-shelf section plot in Figure 72. The figure also shows that the current separates waters of LC origin to the west, and cooler coastal waters in the east.

Figure 73 gives PV maps at different phases of LC northward expansion and subsequent LCE shedding. These show that expansion and shedding 'feeds' LC's PV to region south of the Mississippi delta. Along-slope currents (Figure 74) are produced which advect the PV along the DeSoto Canyon and eastward into the west Florida shelf. The intense cross-shelf gradients of PV coincide with strong tilt in the section temperature contours in Figure 72.

Acknowledgment

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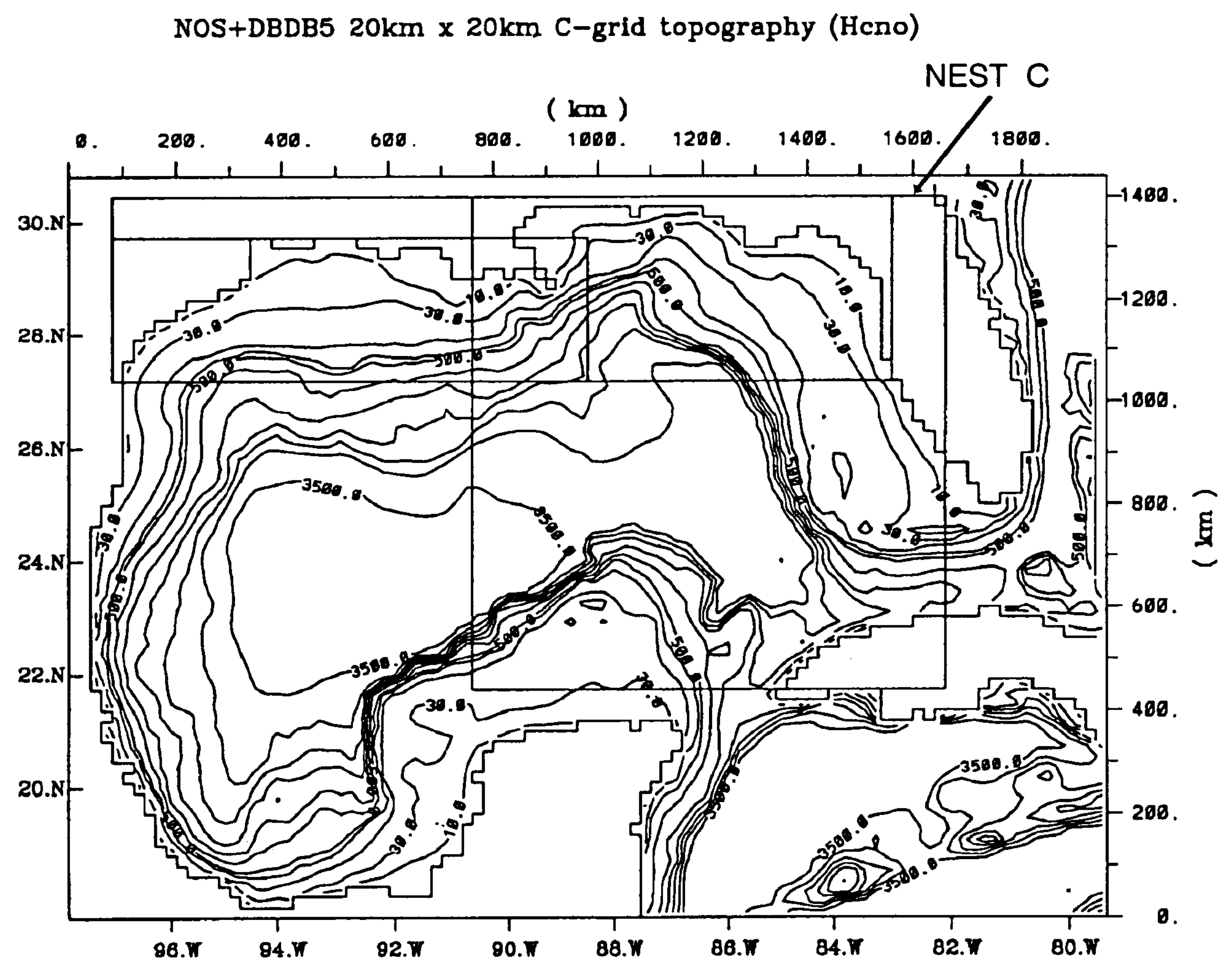


Figure 68. The Gulf of Mexico and nested model domains with topography.

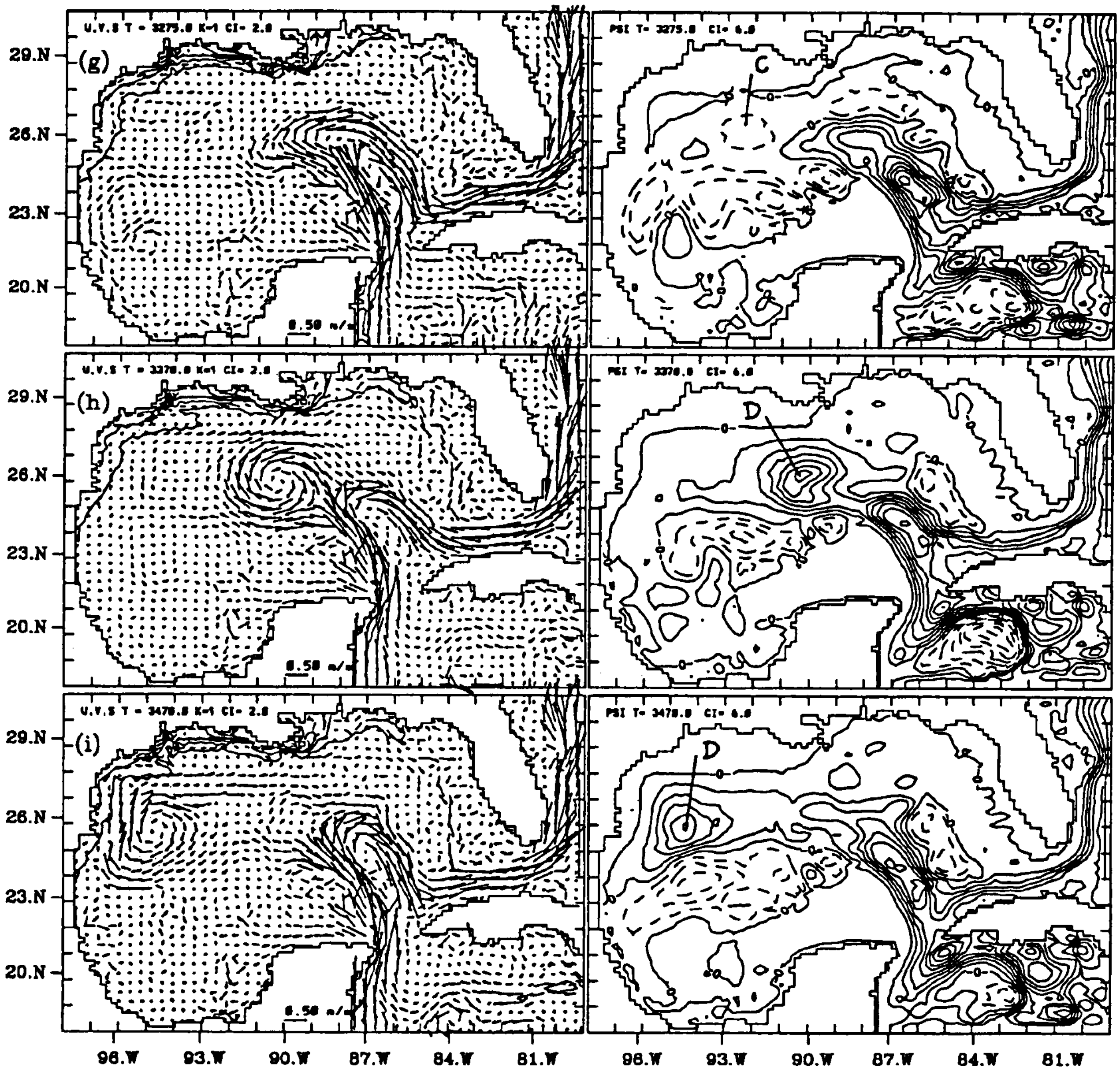
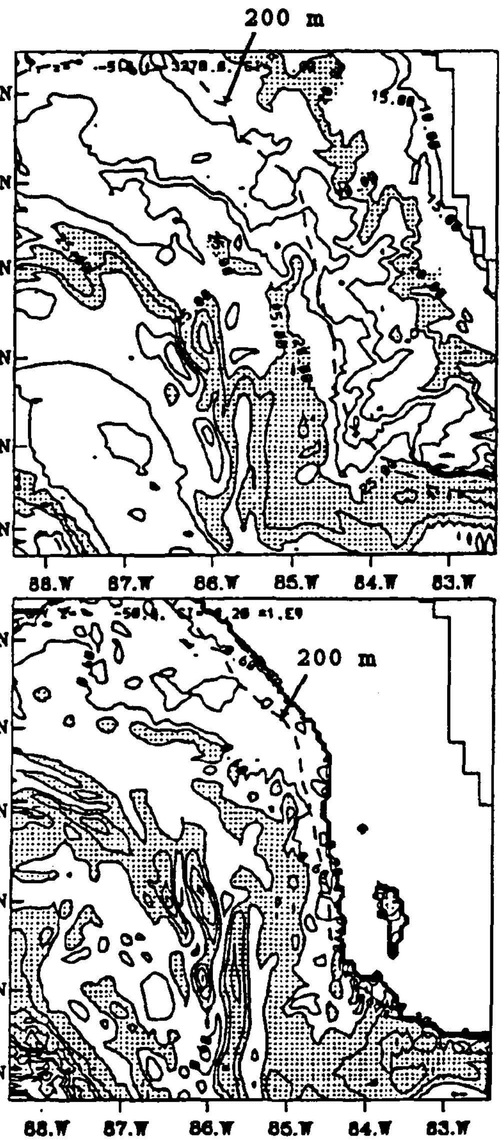
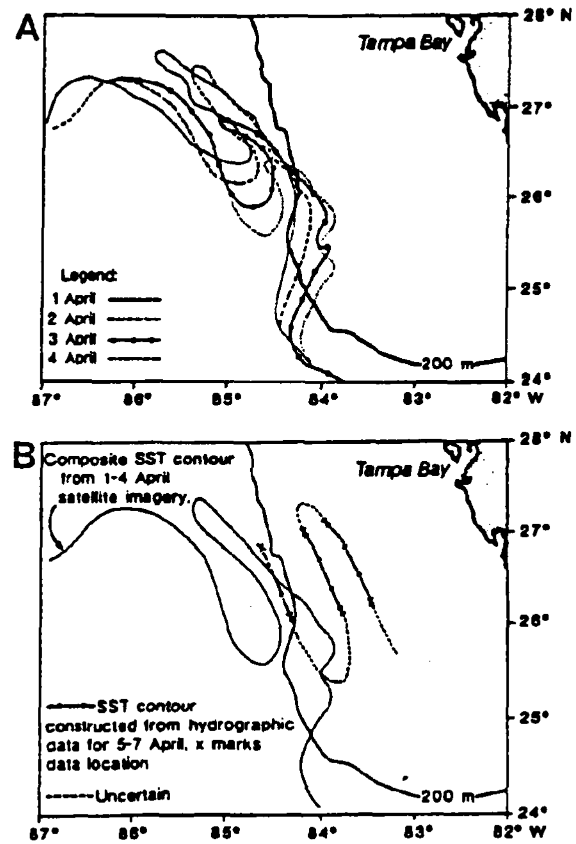


Figure 69. Typical LC and LCE's from coarse grid.





(*a*) A time series of SST contours (~24°C) for April 1–4 derived from AVHRR data which define the Loop Current/shelf water front and the Loop Current filament. The length of the filament may be longer than appears in this figure and on the imagery which is limited by coverage and cloud cover at the northern extent of the filament; (*b*) the projected position of the frontal eddy on April 5–7 based on hydrographic data and the last position from the satellite data.

Figure 70. Left panels: modeled temperature (z=-5 m) and potential vorticity (z=-50m); right panels: satellite data from Paluszkiewicz *et al.* (1983), showing LC frontal meanders.

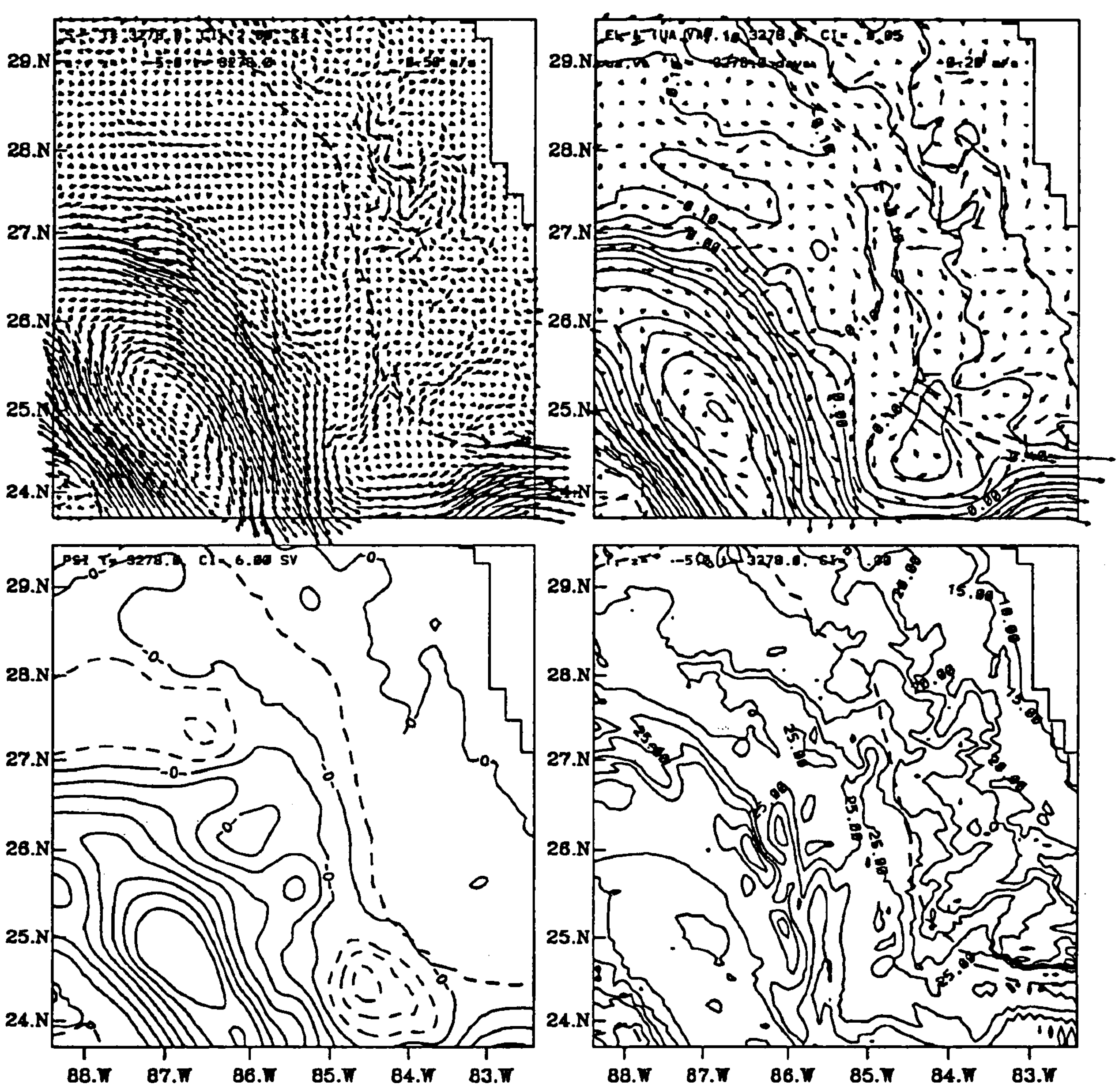


Figure 71. Clockwise from top left: modeled current vectors at z=-5m, surface elevation and depth-averaged velocity vectors, temperature at z=-5m, and stream function.

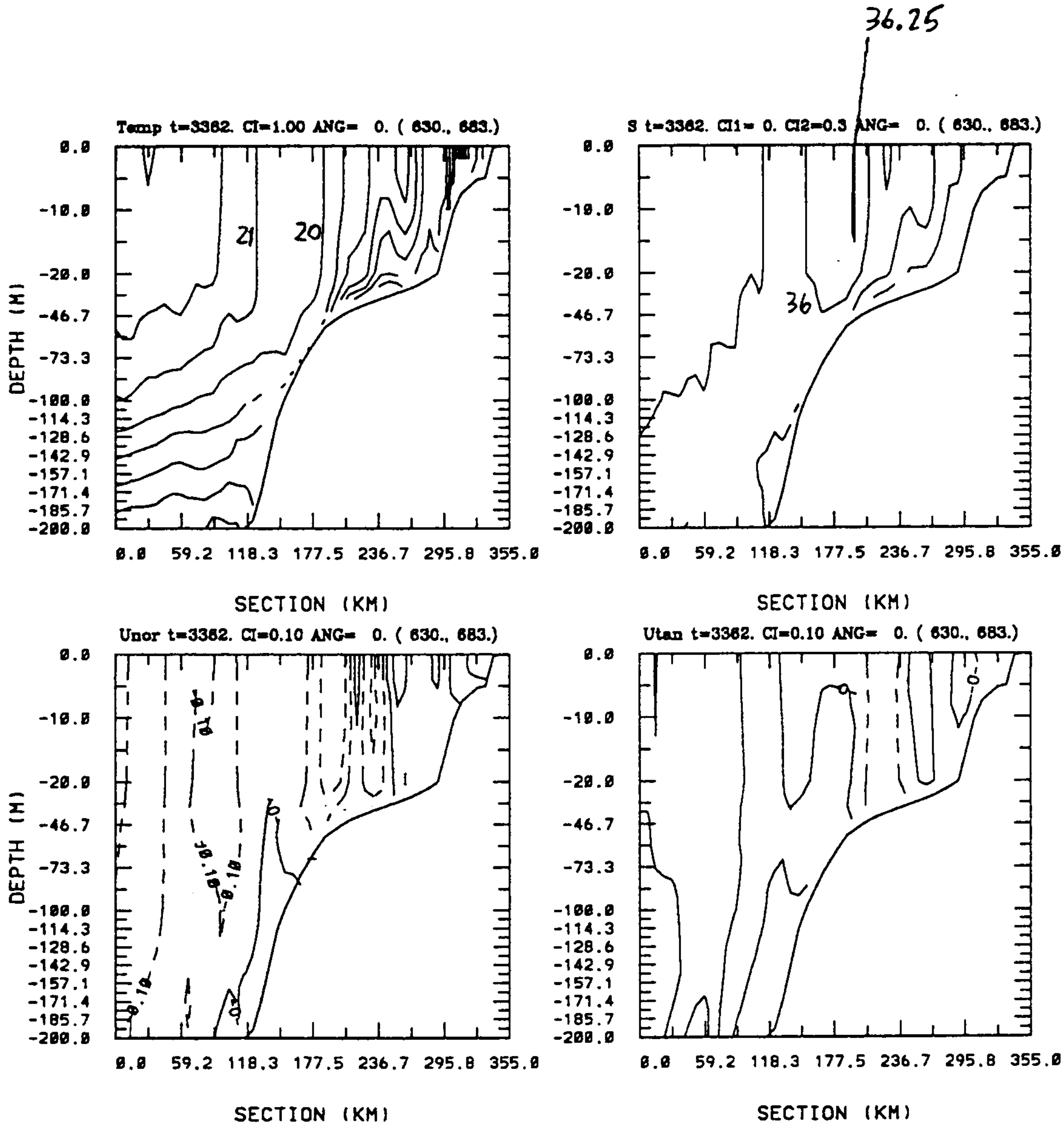


Figure 72.Vertical section plots along 28ºN, clockwise from top left: temperature, salinity, alongshelf velocity (negative southward), and cross-shelf velocity (positive onshore).

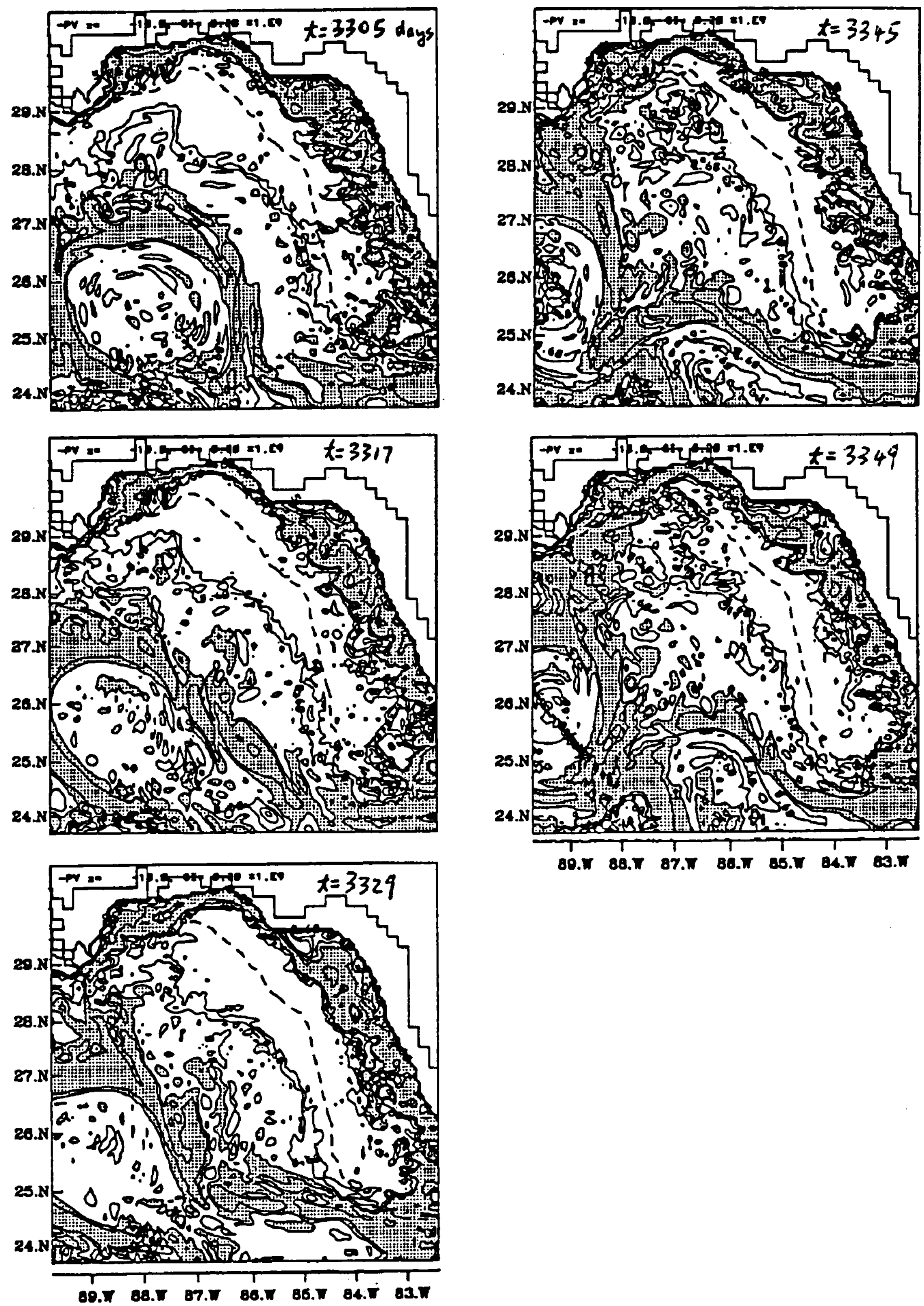


Figure 73. Potential vorticity maps at different phases of LC northward expansion and subsequent LCE shedding.

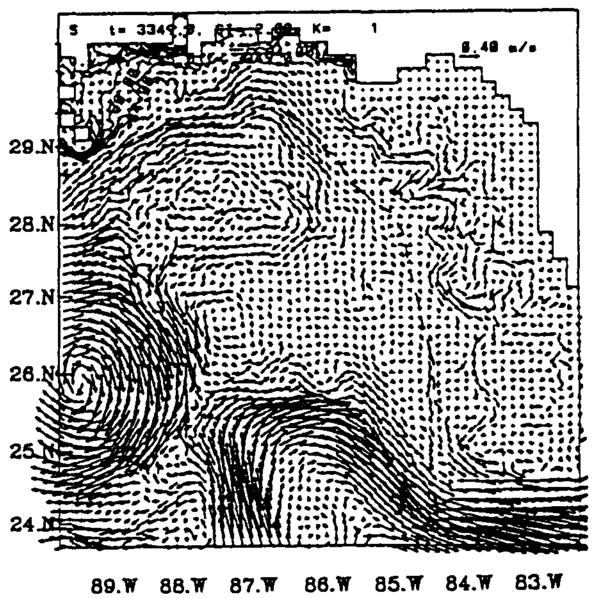


Figure 74. Velocity vectors at z=-5m corresponding to t=3349 of Figure 73.

2.4.4 REGIONAL MODELING IN THE NORTHEASTERN GULF OF MEXICO

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Introduction

The Office of Naval Research (ONR) is sponsoring a number of shallow water modeling studies as a result of a new emphasis on coastal oceanography. Some work concentrates on the application of regional numerical models. Such models provide a means of producing forecasts at relatively high resolution using personal computers. A calibrated regional model with appropriate open boundary conditions and turbulent closure schemes can provide tremendous insights into various physical processes, specific events, and controlling dynamics. Most primitive equation models have now been adapted to include accurate turbulent closure methods for both the vertical and horizontal directions. The most pressing problem is the specification of conditions at the open boundaries. Additional problems can arise when the domain of a model must include very deep water (order of thousands of meters) as well as the shallow water along the coastline. Studies sponsored by ONR are addressing these and other problems, and one of the test sites for regional modeling is the northeastern Gulf of Mexico.

Shallow water regions with medium-to-wide continental shelves are typically influenced by buoyancy forces, tides, local wind forcing, and shelf waves propagating from outside the area. The northeastern Gulf of Mexico (NEGOM) has an additional major influence, that of the Loop Current and associated eddies. With such a complicated mix, it is often difficult to separate competing influences, no less develop a regional model with appropriate boundary conditions to simulate such processes. But a regional model may be able to define contributions of one or more process so that observations over the shelf can be more readily interpreted. For example, one may wish to determine the mean flow based on a shelf-wide survey using an acoustic Doppler profiler. A model of the shelf could be used to estimate the tidally-induced currents as a function of space and time as the Doppler profiler data were being collected. These currents could then be subtracted from the profiler data in order to consider the non-tidal flow.

Our present research program deals with a variety of issues, all with increasing orders of complexity. In this paper, we discuss aspects dealing with model formulations, simulating tidal surface heights and currents, and specifying boundary conditions for more complicated regimes. Included are some preliminary results of tidal modeling for the a region in the NEGOM.

Model Formulations

The most persistent flow regime over most shelf regions is that induced by tides. Thus, tidal simulations are a logical choice to begin the testing and calibration of a regional model. But we must consider the forcing of the model at the open boundaries and the associated tidally-induced currents. The boundary forcing can come from tidal observations or from larger scale tide models. Since tidal observations are difficult to come by, we usually rely on coarse-grid tidal models that cover areas which include that of the regional model. The Schwiderski global tide model (Schwiderski, 1981, 1983) is often used to provide tidal boundary forcing. The global model has a 1°x1° resolution, so it often cannot resolve coastal regions. As a result, we commonly move the open boundaries of our regional models into relatively deep water (1000's of meters) where we would expect such a coarse-grid model to be more accurate.

Although observations of the surface height variations are easier to obtain, any internal tide energetics would be missing from such information. However, the signature of the internal tide is almost exclusively the result of barotropic tidal energy impinging upon the continental slope and shelf break in stratified water. Thus, if the majority of the open boundaries of a model are in deep water beyond the shelf slope, then the use of a surface height boundary condition could still provide appropriate predictions of both the barotropic and baroclinic components of the tide.

Coordinate Systems

One of the principal hydrodynamic models used by Navy researchers was developed by Blumberg and Mellor (1987). The model is a primitive equation model with turbulent closure and uses a sigma-coordinate scheme in the vertical. A sigma-coordinate model can use actual bathymetry but has a variety of difficulties in going from deeper water to shallow water (Haney, 1991). In order to eliminate problems with sigma-coordinates over steep topography, we have developed a version of the Blumberg-Mellor model which uses a step-wise approximation of bathymetry (a so-called z-level model). The z-level model eliminates any potential problems associated with sigma-coordinates while being more efficient operationally since there are less computational cells as the water becomes shallower.

The primary disadvantage of a z-level coordinate system in the vertical is the step-wise representation of the bathymetry. This can often lead to less than accurate predictions of the propagation of long waves. The model provides a simple means of overcoming this problem by the use of a dual mode calculation scheme. For each time step, water velocity is calculated using the momentum equations in a vertically averaged mode using actually bathymetry. These velocities are saved in a two-dimensional array. The model is then be executed for the same time step in an n-level mode to calculate the three-dimensional field of currents using the step-wise approximation to the bathymetry. Before moving on to the continuity equation to calculate the surface height anomalies, the transports calculated in the n-level mode are adjusted (barotropically) to match the transports calculated in the vertically average mode. Since the latter mode uses actual bathymetry, this adjustment allows long waves to propagate at the appropriate speed so as to provide reliable predictions.

Other Enhancements

This version of the Blumberg-Mellor model solves the momentum equations using an adaptation of the semi-implicit scheme of Casulli and Cheng (1992). The surface height is solved implicitly, eliminating the linear stability criteria for the external mode. Thus, the model time step is limited only by the stability criteria of the internal modes, and we commonly use a time step of 10-15 minutes. This further enhances model efficiency and eliminates the "mode splitting" found in the original Blumberg-Mellor model.

A final enhancement of the model will be the drying and wetting of grid cells. This is a common feature of vertically- integrated models, but far less common in models that must consider that various levels must be eliminated or added from the computational grid with time. The benefit of this enhancement is in allowing the modeler to specify relatively thin top levels (order of 1 m or less) if required by coastal processes occurring in the region.

Boundary Forcing for Tides

Much of our work has focused on open boundary conditions formulated for the surface height. We investigated the more commonly used open boundary conditions for tidal forcing for vertically averaged, constant density models and have found the formulation of Reid and Bodine (1968) to be the most effective:

$$U = \pm (\eta - \eta_F) (g/D)^{1/2}$$

where U is the velocity, η is the first interior surface height in the model, η_F is the specified tidal height with time, D is the water depth, g is the acceleration due to gravity, and the expression is positive for open boundaries in the positive x and y directions but negative in the negative x and y directions. The expression allows for the specification of U by using a tidal height (from a source such as a global tide model) and the surface height of the interior of the grid cell (determined from the model itself).

The Reid and Bodine (R&B) formulation assumes two linear, progressive waves at the open boundary. The first is the tidal wave entering the model domain (the η_F component of the expression) and the second is the wave reflected from the interior of the model domain (the η component in the expression). Thus, any reflected wave energy reaching the boundary is allowed to pass through. Moreover, depending on the relative amplitudes and phases of the waves, the R&B formulation can result in a progressive wave, a standing wave, or anything between.

The R&B formulation effectively accounts for the barotropic mode, but we must still deal with the internal modes. For simplicity, we first consider only the internal modes associated with the baroclinic tides (*i.e.,* there are no buoyancy forces as a result of horizontal variations of the density field, and the mean surface height anomaly at each boundary grid cell is zero).

Simulations with a Single Density Profile

The Sommerfeld (1949) radiation condition appears to be a good candidate for handling the freely propagating internal modes at the boundary:

$$\partial\xi/\partial t + C\, \partial\xi/\partial n = 0$$

where t is time, n is the coordinate perpendicular to the open boundary, and C is the propagation speed. In this case, the boundary condition applied to each level within the model allows for the specification of the vertical structure of the current at the boundary. However, the total transport is always matched to that determined for the dominate, barotropic mode.

Chapman (1985) reviews of number formulations of the Sommerfeld condition. Following Orlanski (1976), we tested formulations which used values of U near the boundary to calculate C. We also tested the modified Orlanski condition (Camerlengo and O'Brien, 1980) which effectively sets $C = \Delta x/\Delta t$ at the grid cell boundary.

Model simulations with realistic vertical density variations indicate that baroclinic tides travel at a speed of ~1 m/s. For regional models with Δx = ~10^3 m, Δt = ~10 s, the C for the modified Orlanski condition would be too large at 100 m/s. For models with Δx = ~10^3 m, Δt = ~10^3 s (which is possible with the semi-implicit solution scheme), the C for the modified Orlanski condition would be more reasonable at about 1 m/s.

The test simulations in which C was calculated based on values of U near the boundary produced reasonable internal wave structure. Surprisingly, simulations which just used the U determined by the Reid and Bodine formulation (*i.e.,* no specification of vertical structure at the boundary) also produced reasonable internal wave patterns.

Handling Buoyancy Fluxes

One of the more difficult boundary value problems is that in which a spatially varying density field is involved. We may choose to use a climatological temperature-salinity (T-S) in a regional model by running the model in a diagnostic mode. By keeping the T-S constant in time, we can establish the U's and η's at the open boundaries. This allows us to consider, for example, tidal forcing as well as the density driven field using a boundary condition of the form

$$U = U_D(x,y,z) + \pm (\eta(x,y,t) - \eta_D(x,y) - \eta_F(x,y,t) (g/D)^{1/2}$$

where U_D is the density-induced current and η_D is the density- induced surface height. Unfortunately, a diagnostic simulation and the above expression does not allow for any internal modes propagating within the model domain.

Future research plans will concentrate on dealing with time-varying density-driven fluctuations at the open boundary. Along these lines, the z-level model is being applied to the Gulf of Mexico basin at a 1/8°x1/8° resolution. The model will be used to produce boundary forcing parameters for the regional model of the NEGOM. Our approach will be to assure that energy, heat, and mass fluxes across the grid cells of the regional model boundaries are consistent with those of the Gulf-wide model. At the same time, our boundary conditions must allow for external and internal modes reflected from the interior domain of the regional model to pass through the boundary.

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2.4.5 A WIND-DRIVEN SHELF FLOW MODEL (AS APPLIED TO THE WEST FLORIDA SHELF)

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The Model

On many shelves, including the West Florida Shelf, much of the flow is driven by low-frequency (frequencies $\omega << |f|$) wind. At such frequencies, by the Taylor-Proudman Theorem, flow tends to follow the isobaths. This physics suggests that analysis may be simplified by choosing an orthogonal set of coordinates (n,s,z) parallel and perpendicular to the isobaths and vertically upward from the ocean surface (see Figure 75). For such a coordinate system, water depth h is a function of n alone. We insist on a "well-defined" coordinate system -- one in which, in the shelf and slope region of interest, each point in the horizontal plane has only one (n,s) coordinate pair. In practice this means that features with closed contours (*e.g.,* seamounts) cannot be modeled nor can bay-like features with radius of curvature smaller than the shelf width.

The model ocean is stratified (buoyancy frequency N(z)), linear, driven by a large-scale wind-stress and is retarded by bottom stress. The boundary conditions are essentially the same as those in Clarke and Brink (1985): a rigid lid condition at the free surface, a bottom boundary condition involving Ekman pumping out of a thin bottom boundary layer on the sloping bottom, no depth integrated flow perpendicular to the model coast (20 m isobath) and a seaward boundary condition allowing for appropriate decay into the constant depth deep sea (see Appendix B of Lopez & Clarke, 1989).

After writing the field equation and boundary conditions in general form in terms of the pressure p, we make use of the approximation that the flow nearly follows the isobaths. This enables us to deduce that the pressure gradient along the isobaths is much smaller than that across the isobaths. On this basis the governing equations can be considerably simplified and the following solution obtained (see Clarke *et al.,* 1995, for details):

$$p = \sum_{j=1}^{\infty} F_j(n,s,z)\, \phi_j(s,t) \tag{1}$$

where the $F_j(n,s,z)$ are generalized coastally-trapped wave (CTW) eigen functions for each alongshore location s and the amplitude functions $\phi_j(s,t)$ satisfy the coupled set of equations

$$-\frac{1}{c_j}\frac{\partial \phi_j}{\partial t} + \frac{\partial \phi_j}{\partial s} + \sum_{i=1}^{\infty} a_{ij}\,\phi_i = b_j\,\tau^s \qquad j = 1,2,... \tag{2}$$

In (2) t refers to time, b_j to the forcing coefficient for the j^{th} CTW mode, $\tau^s(s,t)$ to the local alongshore component of the wind-stress, c_j to the j^{th} CTW eigen value and a_{ij} to coefficients which couple the CTW modes together. These coupling coefficients are zero if there is no bottom friction or alongshore variation in bottom topography.

The CTW eigen functions and eigen values can be found for each coastal section by some small modifications to existing CTW programs for the straight coast case. The coupled set of equations (2) for the amplitude functions ϕ_j can be efficiently solved by the same method as that used for the straight-coast case (Clarke & Van Gorder, 1986).

The model can be interpreted physically as follows. When there is no wind forcing, no bottom friction and the isobaths are straight and parallel, (2) simplifies to

$$-\frac{1}{c_j}\frac{\partial \phi_j}{\partial t} + \frac{\partial \phi_j}{\partial s} = 0 \tag{3}$$

which has a solution

$$\phi_j = \Phi\,(s + c_j t) \tag{4}$$

where Φ is any amplitude function. This solution represents a long CTW traveling along the coast in the negative s direction at speed c_j. When the alongshore component of the wind stress is included, the term $b_j\tau^s$ is added to the right-hand-side of (3) and the equation describes CTWs forced by the alongshore component of the wind. The full equation (2) thus describes CTWs forced by the wind and scattered by bottom friction and bottom topography. In the full equation the CTW speed c_j depends on alongshore location s, the speed tending to increase for wider shelves and for shelves with 'bay-like' curvature and to decrease for shelves with 'cape-like' curvature.

Testing the Model with West Florida Shelf Sea Levels

The model boundary is at the 20 m isobath but we need to provide model results at the actual coast where the sea level observations were taken. To do this we estimate the sea level difference between the model and actual coasts by integrating the cross-shelf sea level gradient between these limits. The cross-shelf sea level gradient is obtained by linear interpolation of the known cross-shelf sea level gradient at the model coast and an estimated one at the actual coast. The latter is found from

$$f\,\bar{v} = g\left[\frac{1}{h_1}\frac{\partial \eta}{\partial n}\right] \tag{5}$$

with the depth averaged alongshore flow $\bar{v}$ determined from a coastal balance between wind stress and linearized bottom stress. In (5) f is the Coriolis parameter, g the acceleration due to gravity, η the sea level and h_1 the distance scale factor for the n coordinate (a small distance in the direction of increasing n is $h_1\delta n$).

Figure 76 shows the wind and sea level stations along the West Florida Shelf coastline and Figure 77 shows the results. Observation and theory would be in perfect agreement if the correlation coefficient q and regression coefficient m were both 1. The agreement is quite good.

All correlations are significant at the 95% level and in the worst case the model still explains 76% of the variance. The regression coefficients are all near 1. At the three stations furthest north the model underestimates the observed sea level slightly.

Closing Remarks

Much of the flow on the West Florida Shelf is driven by the wind. Low-frequency wind-driven shelf flow can be estimated using a forced CTW model which takes into account the alongshore shelf variations. Tests of the model show that it can successfully hind-cast coastal sea level. It also has provided insight into how the strongly curved isobaths in Florida's Big Bend affect the low-frequency currents and has helped in the design of a strawman experimental plan for the region. Should such an experiment take place, the model could be used to help understand the observations.

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Lopez, M., and A. J . Clarke, 1989. The wind-driven shelf and slope water flow in terms of a local and a remote response. *J. Phys. Oceanogr.*, 19:1091-1101.

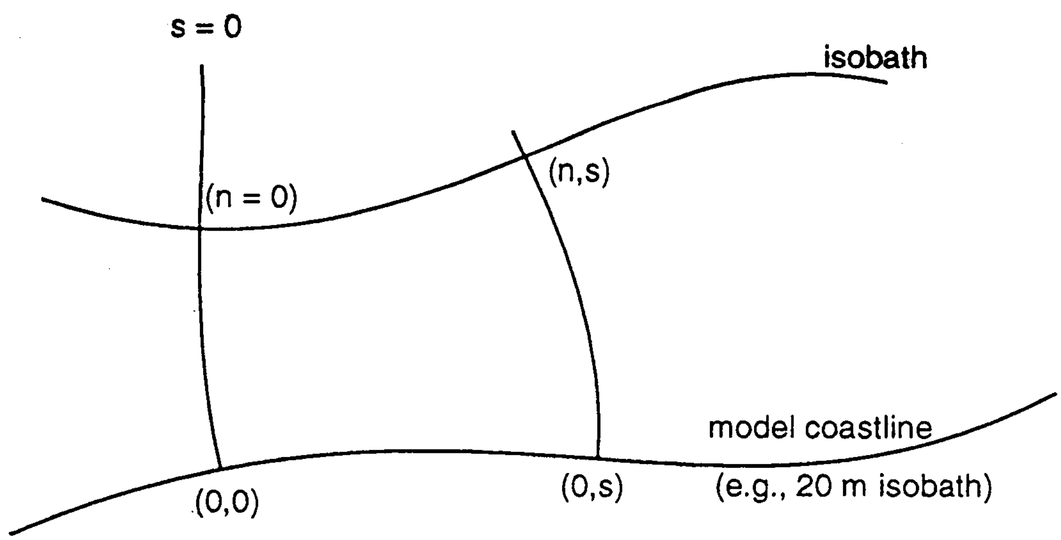

Figure 75. The (n,s,z) coordinate system in the horizontal plane z = 0. The n = constant lines coincide with the isobaths so the depth h is a function of n alone. The model coastline is an isobath (*e.g.*, 20 m) and the coordinate s is the distance along the curved model coastline from the origin. The value of n for each isobath is the distance of that isobath seaward from the model coast along the curved orthogonal line s = 0.

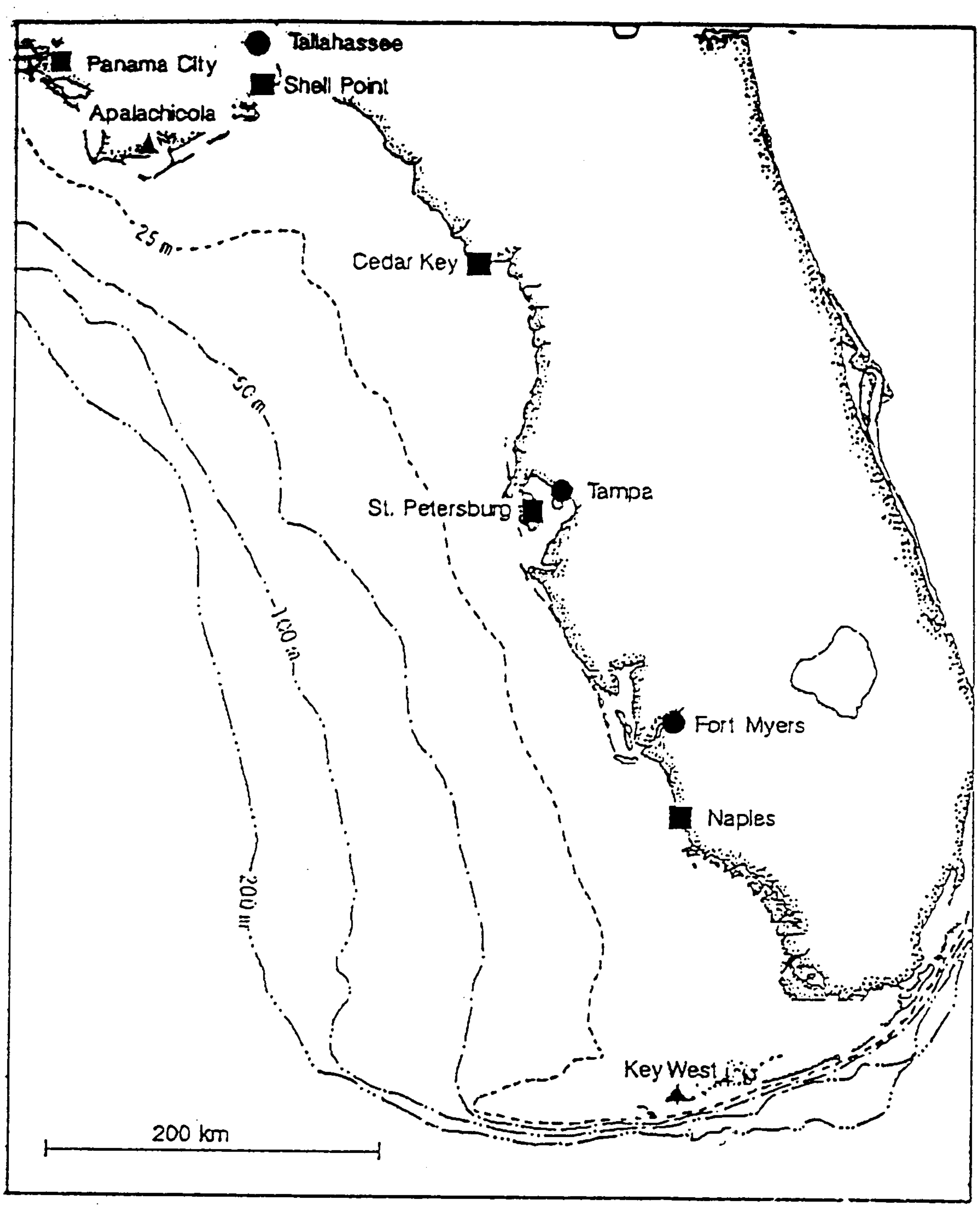

Figure 76. The topography and the location of the data stations of the West Florida Shelf. The squares represent tide gauges, the closed circles meteorological stations and the triangles tide gauges and meteorological stations.

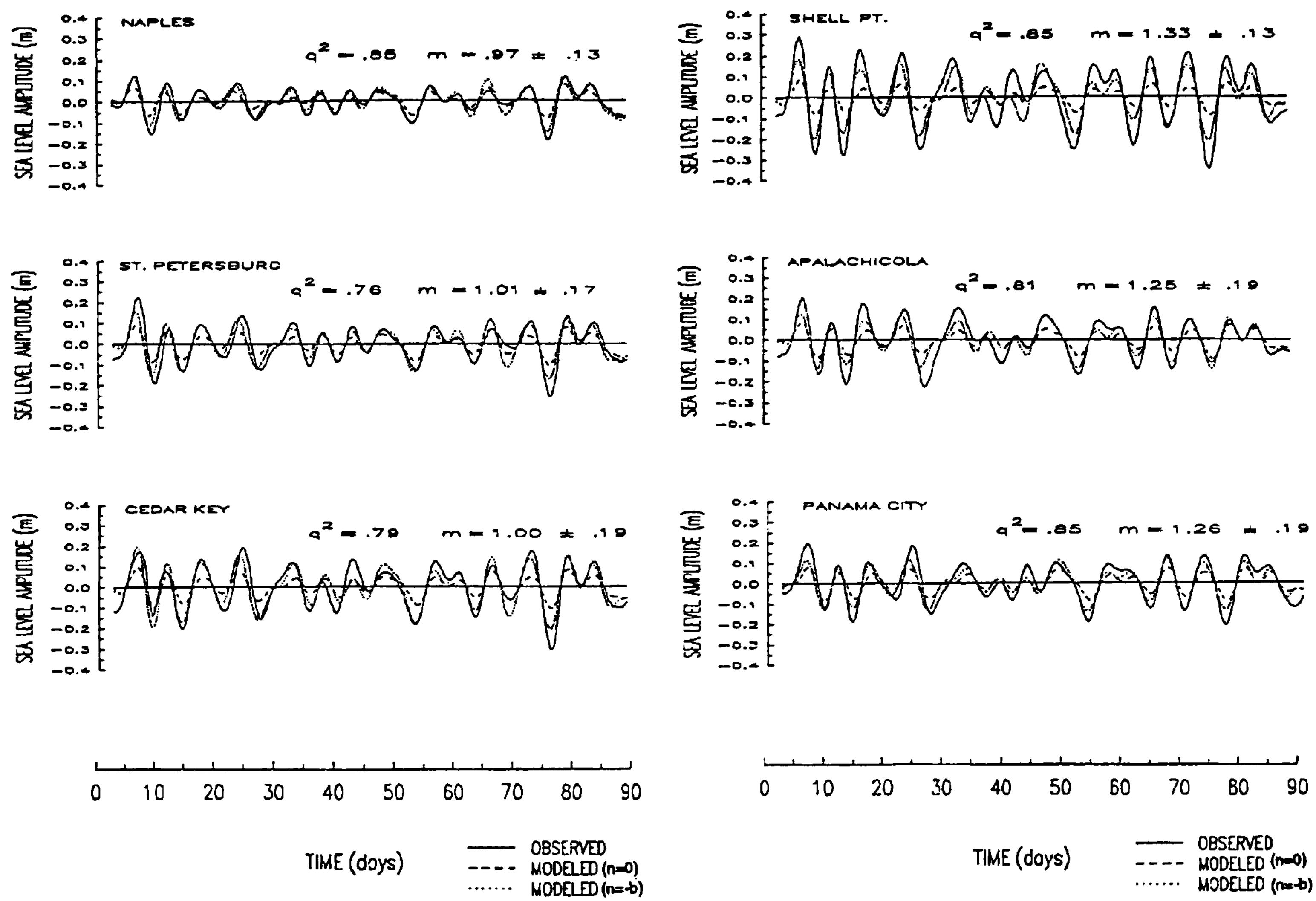

Figure 77. Comparison of observed coastal sea level (solid line) and calculated sea level at both the model boundary n = 0 (dashed line) and the coastal boundary n = -b (dotted line). Calculated values are the sum of thirteen modes. Day 0 corresponds to 1 January 1978. q^2 is the square of the correlation coefficient and m is the regression coefficient with its 95% confidence interval shown. m greater than 1 means that the theory is underestimating the measured sea level amplitude.

3.0 WORKING GROUP SUMMARIES

3.0 WORKING GROUP SUMMARIES

The second part of the workshop began after lunch on the second day. In a plenary session, W. Wiseman briefly summarized the pre-workshop strawman plans and then R. Defenbaugh (MMS) commented on MMS interests in the NEGOM. He noted that drilling for natural gas is occurring in the Destin Dome near the DeSoto Canyon, but that working groups need not focus on this region -- all of the shelf and upper slope from the Mississippi Delta around to Tampa should be discussed.

Each working group was required to summarize their discussion of possible experiments. These working group summaries follow.

3.1 Inner Shelf Working Group

3.1 REPORT OF THE INNER-SHELF WORKING GROUP

Richard W. Garvine, Chair
Inner Shelf Working Group,
with assistance by William Schroeder,
William Wiseman, and Glen Wheless

The Regime

As a working definition for the inner shelf regime the group selected that part of the Northeastern Gulf of Mexico (NEGOM) region inshore of the 40m isobath (see Figure 78). This regime possesses several physical characteristics that distinguish it from other, more commonly studied, parts of the U.S. continental shelf. It has strong shoreline and isobath curvature on a variety of scales. On the largest scale the isobaths turn persistently left in the direction of coastally trapped wave propagation with a radius of curvature of about 500 km. But at intermediate scales the isobath turning is not monotonic. The coast protrudes near Apalachicola, while at the western reach of the regime the Mississippi River delta imposes an abrupt 90° turn to the south and forms an embayment that includes Mississippi Sound. The regime has numerous sites where river discharge enters from the coast that are strongly concentrated to the west in both numbers and volume flux (see the thick arrows in Figure 78). This pattern divides the inner shelf regime into two zones, an eastern zone where buoyancy forcing is weak or absent, and a western zone where it is strong. Finally, the buoyancy sources potentially impose multiple alongshelf scales to the hydrographic and current fields: a local plume scale near each riverine source of about 10 km, an interplume spacing scale of about 50 km, and a scale relative to the intermixing of these buoyant waters of perhaps 100 km.

Scientific Issues

We identified a number of issues and list them here under their respective forcing agents.

Buoyancy-driven currents are likely to be prominent in the western zone. We discussed four questions regarding them.

1) Does the westward gradient in buoyancy input (Figure 78) organize a large scale inner shelf response, or does its concentration have only local impact?

2) We expect that in the western zone interplume mixing will produce a coastal current with associated density front analogous to that which Blanton has found in the South Atlantic Bight. Does the coastal density front serve as a barrier to onshore movement of surface contaminants such as oil? Would the same barrier prevent surface materials released near shore from passing offshore to the mid-shelf?

3) The major part of the buoyant discharge of the Mississippi River in its delta moves westward, but an estimated 30% moves eastward into the NEGOM region. Does this eastward flow reach the inner shelf to add more buoyancy forcing, or is it confined to the mid- and outer shelf?

4) Is the alongshore flow of buoyant water from Apalachicola Bay persistently eastward ("upcoast") as some have suggested? If so, why?

Wind-driven currents must be present, as in other inner shelf regimes. Is the current response strongly affected by the isobath curvature remarked above? In particular is the alongshore current response to wind forcing asymmetric in the western zone because of alongshore pressure gradients set up against the Mississippi delta barrier to the west?

Tidal currents are notable for their weakness in the Gulf of Mexico, but their properties may need to be well studied because of coupling with coastal life cycles of biota. The spawning of several coastal species has been linked in time to tidal current phase. Because the tidal regime appears to shift alongshelf from semi-diurnal dominance in the eastern zone to diurnal dominance in the western zone, is there a consequent impact on spawning behavior?

Observational Difficulties

The group recognized four particular difficulties.

1) The isobath curvature and frequency of buoyant sources impose quite short alongshelf spatial scales for both hydrographic and current fields. These will require higher resolution than is generally needed elsewhere.

2) The inner shelf here is reported by several scientists to be an especially hostile regime for installing moored instruments, particularly shoreward of the 20 m isobath where trawling for shrimp is frequent.

3) Frequent cloudiness prevents collection of remotely sensed imagery for time series purposes.

4) Anecdotal evidence points to very weak currents at very low frequencies. If this proves to be correct, estimation of climatological mean currents may prove to be unreliable.

Elements of an Observational Program

Given the expected hazards to moored arrays, we recommend focusing effort on shipboard observations and Lagrangian methods.

Shipboard observations

These should be at about bimonthly intervals for a few years. Use of multiple, but smaller, vessels was judged better to obtain adequate coverage and spatial resolution at acceptable cost. To enhance coverage of the regime, each vessel could concentrate on continuous underway sampling and minimize stopping for traditional oceanographic station work. Such method would include use of a pumping system for recording temperature, salinity, fluorescence, and nutrients, use of an ADCP unit (probably 1200 KHz for these depths) in bottom-tracking mode, and use of a tow-yo" CTD or "Aqua Shuttle" for sampling at depth. Where stations were occupied, water bottles could be collected to add biological sampling and geochemical assessments, such as for Atrazine to identify riverine sources.

Lagrangian methods have obvious advantages in this regime. They are directly relevant to risk assessment for oil spills. A majority might be set out as expendable drifters reporting only position through System Argos. But a minority might also be deployed that contained sensors, such as for conductivity, temperature, and light transmission. These would probably require recovery for repeated use to make them economically sound choices because of high unit costs.

A modest array of moored instruments would still be an important component. These could include both ADCP units and traditional current meters with conductivity and temperature sensors for time series purposes at strategically chosen sites. In addition, a more extensive alongshore array of thermistors and/or bottom pressure gauges could help provide alongshore resolution at moderate cost. These might be placed along the 20 m isobath.

Elements of a Modeling Program

The objective is to ascertain general circulation of the NEGOM inner shelf region and its response to forcing from tides, wind, buoyancy forcing, and episodic interaction with events from deep water areas (Loop current, eddies). One could use a combination of models, both "simple" process type models and more complex 3D hydrodynamic models (SPEM or Princeton model variants). Particle tracking capability is a necessity. Process modeling would be used to examine the effects of tides and tidal currents. Wind effects should include shore scale (sea breeze), medium scale and long scale (seasonal) with a subcomponent to study cyclogenesis effects. The buoyancy forcing component should examine "point" and "line" source freshwater effects in idealized settings.

Simulation modeling is needed to examine all forcing in concert with realistic bathymetry and coastlines. This component should use a model with 3D capability and sufficiently "realistic" mixing schemes.

Major questions of interest are:

- What effect does freshwater input to the inner shelf have on pollutant transport or on larval transport from or to the inner shelf?

- What are the effects of coastal trapped wave energy on the shallow, wide shelf off central Florida?

- Why do freshwater plumes appear to be non-rotationally effected at times? Is shelf geomorphology somehow central to the plume behavior? Are they parameterized best in terms of Kelvin number?

- How does inner shelf water react to interaction with Loop current eddies? Is there a way to describe the effects of entrainment/detrainment of inner shelf water?

- On what scales must mesoscale features be resolved to adequately describe circulation effects?

- What are the maximum velocities found on the inner shelf?

- Using a fine resolution model ($\Delta x,y < 1$ km), ascertain mixing processes along the coastal front due to buoyancy inputs.

- What are the vorticity dynamics in the Big Bend area (low energy) vs. the area from Panama City to Mobile Bay (high energy)?

- What are the effects of a submarine canyon on the shelf circulation, *e.g.*, DeSoto Canyon?

- What are the effects of the alongshelf gradient of freshwater input and associated pressure gradients?

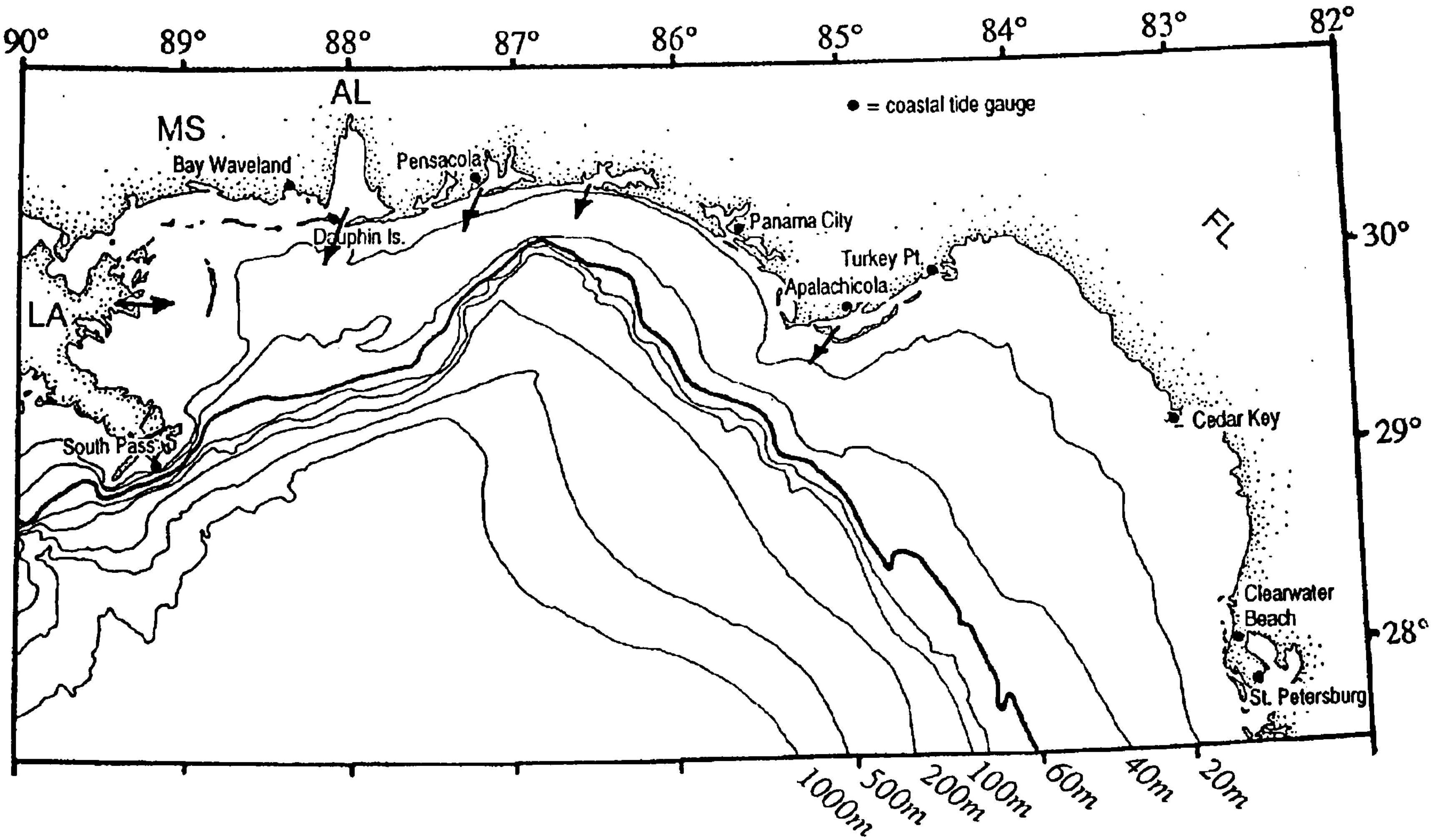

Figure 78. The inner shelf study area lies inshore of the 40 m isobath. Major river outflows (apart from the Mississippi) are noted by the thick arrows.

3.2 Mid-Shelf Working Group

3.2 REPORT OF THE MID-SHELF WORKING GROUP

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Background

The group defined the "mid-shelf" to include water of depths roughly 20-60 m. This definition is meant to exclude phenomena occurring over the slope and in deep water, although their potential effects are part of the mandate. Processes likely to be important include wind-driving and the intrusion of loop-current waters onto the shelf.

The philosophy of the group called for defining a sequence of useful, scientifically important, measurements that could be carried out logically either in sequence or in parallel. This thinking follows from the perception that MMS does not have a large annual budget for measurements in this region. It was recognized that it would be desirable to conduct a large-scale, coherent field program that includes many of the elements below, but it was acknowledged that this would require a good deal of effort to define the major scientific questions that proposal-driven funding agencies would require.

The findings of this working group are necessarily incomplete, and should be viewed only in the context of the other two working groups charged with considering other regions of the shelf.

Lagrangian Measurements

A strong case was made for repeated aerial deployments of near-surface drifters on two regular grids (Figure 79). The two grids are designed to encompass the west Florida shelf and the region offshore of Dauphin Island. We expect that, as the drifters move about, they will provide information about currents over most of the Northeastern Gulf of Mexico shelf. The grids, of course, can be modified as time goes on to adjust to what is learned about the shelf circulation. About 10 deployments over one Fall-Winter period are envisioned as a preliminary effort. Ideally, the drifter deployments should be supplemented by current meter moorings (perhaps two: one in each deployment area) to assess the similarity of surface to deeper currents. A more ambitious, comprehensive effort may be warranted at a future time.

There is much that can be learned from these deployments.

- Maximal currents can be estimated over much of the shelf, including the inner part of the shelf.

- The drifter information can be used directly for estimating oil spill trajectories.

- Residence times of water over the shelf can be estimated, and preferred locations of particle accretion or divergence can be located.

- The drifter studies can be coordinated with biological efforts in order to understand the planktonic-stage transport of commercially important species.

- Arrays of drifter information can be used to estimate space-time scales of flow over the shelf: important information for designing further field studies.

- Drifter velocities can be used for model evaluation, both in an Eulerian sense ("what is the velocity at this time and place?"), and in a stochastic Lagrangian sense ("how well can the model predict where an average drifter will go?").

Eulerian Measurements

Several types of fixed-location measurements were proposed.

Meteorology Measurements

It is always valuable to have direct meteorological (especially wind stress) measurements over the continental shelf, since the wind is often a primary driving agency here. Wind measurements (as well as those relevant for estimating surface heat fluxes and waves) can be used to drive models as well as to interpret the observations themselves. The situation is especially interesting in the coastal ocean because it is generally characterized by a non-equilibrium sea state, meaning that traditional bulk relations between wind velocity and wind stress may not be valid. Since it is the wind stress that is of most interest, it makes sense to measure it directly, if possible. Fortunately, this technology is now available and tested through the recent ONR Surface Wave Dynamics Experiment (SWADE). It would be valuable to place one such buoy in each of the drifter deployment areas (Figure 79), as well as one north of the head of DeSoto Canyon (for reasons described below).

Surface Currents

Based on presentations in the plenary session, it appears that the head of the DeSoto Canyon (southeast of Pensacola) may be a preferred site for Loop Current eddies to extrude water onto the shelf. For dynamical reasons, it seems likely that such intrusions would take place primarily in the upper part (upper 10 m?) of the water column. It is thus desirable to have maps of surface currents in this area on a continuous basis. The Ocean Surface Currents Radar (OSCR) system provides a nearly ideal tool for this purpose. It could be deployed south and east of Pensacola, with a 30 km separation between units, allowing coverage of surface currents out to about 45 km offshore (well offshore of the head of the canyon). Complete maps of the surface currents could be had at about 1 km (or better) resolution at intervals of about 20 minutes for periods of up to about two months. A meteorological buoy should be deployed in the coverage area to help in interpreting the measurements. The OSCR coverage should be supplemented with a moored current meter array to assess the representativeness of surface currents for the rest of the water column.

The advantage of this system is that it provides the well-resolved and continuous surface current measurements that would be needed to interpret the flow as a Loop Current eddy approaches the shelf edge. No other economical system is likely to provide such a measurement. The measurements should be made in coordination with any outer-shelf eddy impingement study. In addition, an OSCR study will require access to remote-sensing measurements to aid interpretation.

In-Situ Currents

A program is already underway to make long-term measurements of subsurface currents west of St. Petersburg using Doppler-acoustic instruments (R. Weisberg, see also Figure 79). This effort could be supplemented by making current measurements farther toward the northwest. Specifically, two ideas came forward.

1) In coordination with a potential study of eddy intrusion onto the slope near DeSoto Canyon, a line of Doppler acoustic current meters could be run along the 60 m isobath with alongshore resolution of about 10 km. The goal would be to quantify cross-shelf transports associated with the eddies. The good depth coverage of the ADCP systems could be used to test the hypothesis that the eddy-related flow occurs mainly in the upper ocean. Conventional current meters, mounted densely on the mooring, could also be used to address the same question.

2) Experience elsewhere and all existing dynamical models suggest that the Loop Current eddies should not act to drive measurable currents in the interior of the water column over the shelf. A cross-shelf line of three moorings could be run across the narrowest part of the shelf north of DeSoto Canyon to test this idea in the NEGOM setting. This moored array would also be useful for estimating exchanges between the eastern and western parts of the NEGOM shelf.

Hydrographic Measurements

Two scientific motivations came up for making detailed hydrographic measurements in the region. First, Fanning *et al.* (1982) found that nutrient concentrations below the seasonal thermocline over the shelf west of Cape San Blas tend to be substantially higher than in the region to the east. The reason for this dramatic difference is not known, but one conjecture is that it is related to sediment resuspension. A second interesting question arises in the context of ground water outfalls. Repeated ship-board surveys of nutrient and radiochemical concentrations, as well as of more traditional hydrographical variables could help to resolve these interesting scientific issues.

Numerical Models

Numerical modeling capabilities are improving dramatically with time. Recent results, such as those shown by Oey at the meeting, appear to be well-resolved and show a number of features that are of definite interest, such as the shedding of small-scale eddies by the Loop Current. It thus seems reasonable, in planning any field study, to exploit existing numerical model results, as well as existing observations, in planning a field program. Future model runs could be improved to include and evaluate the contributions of forcing agencies such as tides and realistically varying winds, that have not always been included to date. All numerical model studies of this sort must be tied closely to observations: both for model inputs and for the required model evaluation.

A Coastal Ocean Prediction Study

As the U.S. Navy continues to develop predictive ocean models for the shelf and slope region, it may become desirable to carry out a dedicated, major field study for testing models in real time, as well as in retrospect. One possible place for such a study could be in the waters offshore of Panama City, Florida. This location would include a number of challenging aspects including offshore eddies, wind driving, and buoyancy forcing due to nearby river outfalls. Such a study would likely encompass a cross-shelf line of current meter moorings somewhere between Panama City and Apalachicola, as well as an alongshore line of moorings offshore of the 100m isobath and west of the cross-shelf line. In addition, moored meteorological and current measurements within the prescribed volume would also be needed for model verification. Supporting hydrographic and pressure measurements would also be desirable. It goes without saying that advances in models, especially in the area of data assimilation, would also be desirable before this study takes place. The project is mentioned here as one of interest to the academic community, but that would likely be funded primarily through channels outside of MMS. The potential for MMS cooperation, however, is considerable.

Reference

Fanning, K. A., K. L. Carder and P. R. Betzer, 1982. Sediment resuspension by coastal waters: a potential mechanism for nutrient re-cycling on the ocean's margins. *Deep-Sea Res.*, 29:953-965.

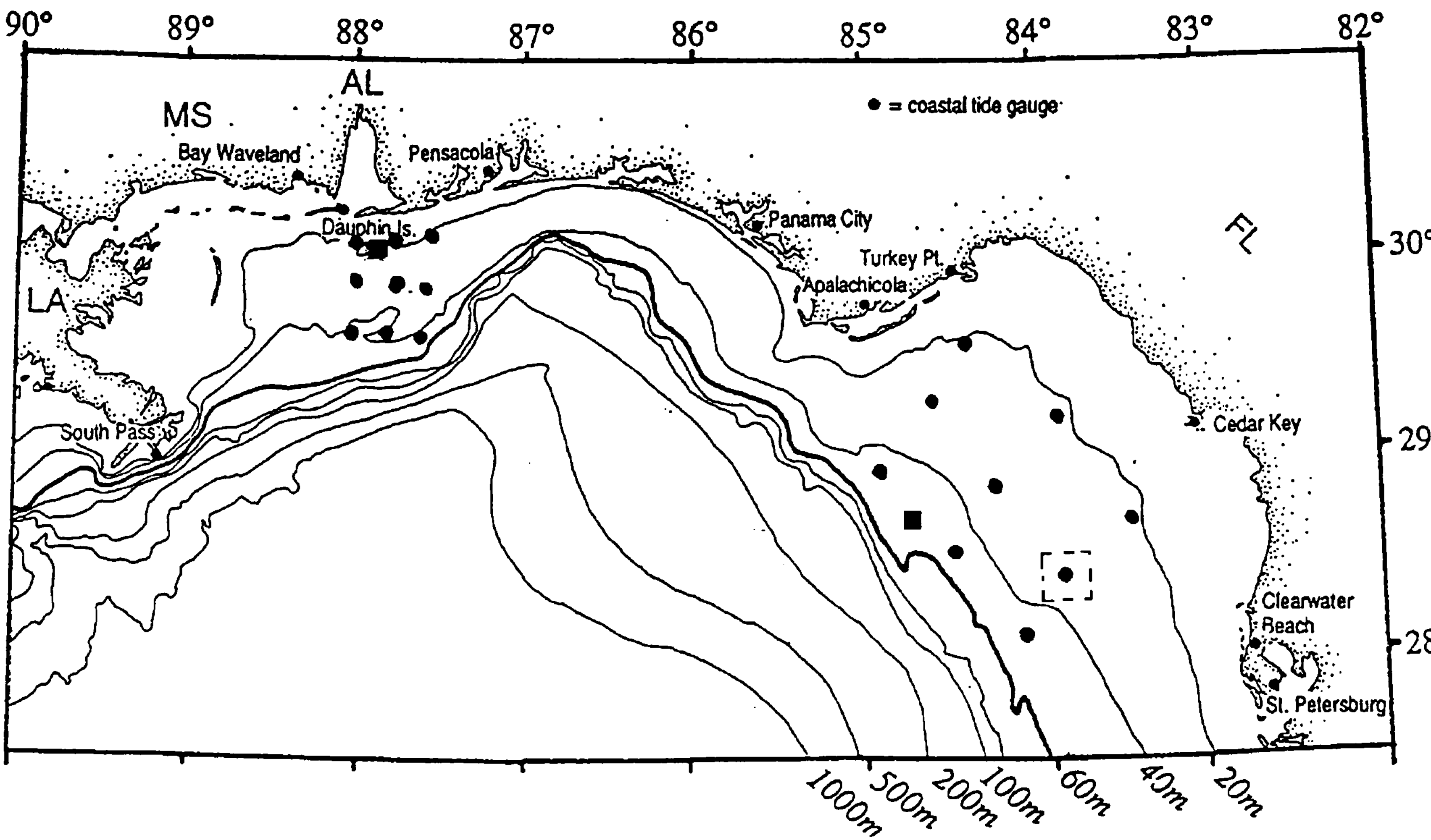

Figure 79. The NEGOM region, showing potential drifter deployment locations (dots), meteorological buoy placements (solid boxes) and the approximate site of currently underway long-term current and wind observations (dotted box).

3.3 Outer-Shelf Working Group

3.3 REPORT OF THE OUTER-SHELF WORKING GROUP

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Physical Processes

Issues to be addressed by a slope measurement program are centered on how eddy circulations on the continental slope, between the Mississippi Delta and the DeSoto Canyon, entrain and detrain shelf waters as well as move Loop Current derived waters onto the shelf. Previous data from the Alabama-Mississippi shelf and slope suggest that Loop Current derived water may be exchanged with the shelf up to 40 to 50% of the time. Large Loop Current (LC) anticyclones have been observed to generate strong currents on the upper slope and outer-shelf east of the delta. However, smaller anticyclones and cyclones of order 50 km in diameter are suspected to be prevalent over the slope when a LC anticyclone is not present. These smaller eddies also generate cross-isobath exchanges. Their origin may be related to LC instabilities (frontal eddies and cold-domes) but these eddies also may be separate entities that move in from the deeper basin. The LC periodic northward excursions are likely to have important consequences for slope circulations, besides the direct effects of LC anticyclones that are in the process of being shed. Model results suggest that the NEGOM slope is particularly active in terms of secondary eddies with cyclones being generated and persisting in the DeSoto canyon region.

Secondary eddies and LC anticyclones over the slope are often persistent, though direct measurements are scarce, and characteristic time scales may be of order weeks to months. Such persistence can lead to long-lasting, large-scale shelf exchanges. The dynamics of the modification of eddy circulations by steep slope topography as eddies move northwards from the deep basin has not been comprehensively studied in the GOM. The NEGOM slope has a great deal to recommend it for these kinds of studies due to its limited longslope extent and the richness of the eddy fields. It is also the region in which models are likely to have the most difficulties simulating these processes and thus data to verify model dynamics is especially important over steep slopes.

Elements of Field Program

To address both the eddy field and its consequences for the shelf, three approaches are proposed: 1) A moored array over the middle slope to properly capture the vertical and horizontal structures of the eddies as they evolve, 2) Hydrographic/biological sampling cruises, and 3) Rapid response aircraft and/or ship-based surveys, guided by remote sensing, to examine shelf-slope exchange events. Drifters are proposed to provide crucial surface information for the studies. Satellite imagery provides large scale areal and spatial coverage. The next section will outline experimental plans for these measurements and third section will discuss trade-offs between these three different approaches.

Moorings

The major purpose of the mooring program is to further understand the dynamics of eddies over the NEGOM slope, including the effects of interaction with steep topography. The suggested array of current and temperature time series data will provide crucial information for verifying numerical models for the region and for processes that models seem, at present, to have the greatest difficulties in generating reasonable calculated flows. Extensive time series data from a closely spaced slope array to study these eddy processes are not available from any previous studies of the Gulf to the authors' knowledge. The moored array program, sketched below, is not designed to study shelf/slope exchange directly even though the slope eddies are probably the major agents for such exchanges. The advantages of studying eddies over the NEGOM slope are that it is an area of relatively limited extent and seems likely to have intense eddy activity because of the vicinity of the LC. The slope is also fairly uniform between the delta and the DeSoto Canyon when compared to the complex topography further west.

Figure 80 shows the nominal position of a total of 6 to 8 ADCP moorings centered on the 500 m isobath along the middle slope. Deeper and shallower moorings are placed on the 1300 m and 250 m isobaths, respectively. The spacing is designed to resolve along-slope and across-slope length scales of order 50 to 100 km, the expected diameters of smaller secondary eddies, independent of or derived from the LC. These scales should be confirmed by examination of model outputs. If smaller scales predominate then the along-slope spacing could be reduced, resulting in more limited spatial coverage. The 250 m moorings are designed to resolve eddy activity towards the head of the DeSoto Canyon, a place where LC derived water has been observed to move towards the coast. This array easily resolves the northern edges of LC anticyclones (diameters 200-300 km) that have been observed to impact the upper slope east of the delta.

Each mooring would consist of an upward looking 150 kHz ADCP mounted in a syntactic foam float at a nominal depth of 300 m. Such an instrument would measure the velocity profile at 4 to 8 m intervals (bins) to about 30 m from the surface. Temperature is measured at the instrument depth of 300 m. If new instruments are contemplated, the RD continental shelf broad band ADCPs should be used. These ADCPs should be supplemented by conventional current meters (GOs or Aanderaas) at 500 m, 750 m and 1200 m on the three deep moorings and at 100 m from the bottom on the 500 m depth moorings.

Deep velocity structure is an important part of eddy topographic interactions (*e.g.*, the generation of TRWs) but the vertical scales should be large (100-500 m) and thus a small number of current meters should adequately resolve the velocity structure below 300 m.

An ADCP mooring outlined above will have similar costs to a conventional subsurface mooring instrumented with current meters to within 50 m of the surface. The advantages are that an ADCP generates detailed velocity profiles in the upper layers, thus resolving shears on scales which are not possible with conventional current meters. Also the top of the mooring is well below the strong currents expected from LC anticyclones and is unlikely to be interfered with by fishing activities. At 300 m depth, fouling should be minimal. Similar designs have been successfully used under the Gulf Stream off Cape Hatteras. The disadvantage over a conventional mooring is that no upper layer temperature information is collected and thus shallow warm intrusions derived from the LC cannot be detected by their temperature signal. However, the 300 m ADCP temperature measurements should adequately map the eddy field because 300 m is approximately the neutral level of the 12C surface and both warm and cold eddies will cause anomalies at this depth.

To better map the upper level temperature structure, 7 temperature moorings are suggested to be positioned as in Figure 80. Low cost temperature sensors or thermistor chains could be used to extend the temperature profiles from 300 m to 50-100 m below the surface (25 m nominal spacing). These moorings could be co-located with the ADCP moorings so that the temperature profile could be directly related to the velocity profile or placed between the ADCP moorings so that thermal wind relationships could be examined as well as increasing the effective resolution of the temperature field. Such a temperature array would be able to detect LC or eddy derived exchanges with the upper slope that extend to at least the 100 m level. These moorings would be subject to draw down by strong LC related upper-layer currents and thus pressure sensors are needed at the top of the mooring so that the temperature profiles can be corrected for depth changes.

Both sets of moorings would be rotated and serviced at 6 month intervals and the experiment should last at least 2 years with 3 years preferable so that the consequences of 3 to 5 LC northward incursions towards the NEGOM slope are experienced. The six month rotation cruises could be used to perform seasonal hydrographic/chemical/biological surveys of slope region area bounded by the 60 m isobath and the two lines extending from Cape San Blas and the Mississippi River delta as indicated in Figure 80. These surveys would provide detailed maps of the upper water column and would supplement the hydrographic/biological and rapid response surveys discussed below.

Hydrographic/Biological Sampling Cruises

Objective: To determine the relative importance of shelf circulation and offshore (Loop Current related) circulation features in contributing to variability in biological distributions and processes south of Mobile Bay.

Rationale: Various physical processes may contribute to biological variability in the NEGOM region south of Mobile Bay. These processes may be roughly divided into shelf circulation processes (*e.g.*, wind-driven circulation, tidal mixing, buoyancy flow) and offshore effects (dominated by loop current-related circulation). Seasonal conditions and topographic effects may modify the above physical processes and their biological consequences. Physical processes will affect key physical/chemical variables including nutrient supply and composition, irradiance, temperature, salinity, mixed layer depth, stability/stratification, horizontal and vertical advection/diffusion. These variables may in turn influence ecological variables including biomass, loss rates (grazing, sinking, advection), and species composition. Such effects could be manifest over a range of trophic levels.

Field Sampling Program: Relating biological distributions and activities to the physical regime would ideally be accomplished using high-resolution sampling techniques. For example, time-series observations using moored optical sensors (fluorescence, beam transmission, irradiance, spectral absorption) could provide information about phytoplankton pigment concentrations, irradiance and absorption. Such information could subsequently be used in bio-optical models to estimate primary production. A proposed location for the mooring might be an area where Loop Current-related interactions would be expected (*e.g.,* head of De Soto Canyon). Satellite/airborne ocean color observations could also be used to support bio-optical algorithms for estimating primary production over the entire NEGOM region.

Some types of biological sampling require ship operations (*e.g.*, photosynthetic parameters for bio-optical models, microbial processes, characterization of abundances at higher trophic levels). In addition, regular ship operations will be required to service and calibrate optical moorings. At a minimum, such shipboard surveys would cover seasonal cycles in meterological conditions as well as provide a representative characterization of river discharge levels (Mississippi, Mobile). Thus, a concerted hydrographic/biological sampling strategy is proposed. This could consist of a repeated station or series of stations along an onshore-offshore transect that encompasses the mooring location. In addition, an adaptive component is recommended to allow for flexibility in sampling so that dominant physical features in the vicinity can be investigated. An effective sampling approach might involve two ships. A fast ship would be used for physical measurements as well as biological/bio-optical measurements that can be made rapidly. The fast ship could collect information with sensors of the same type as on the mooring using profiling, underway and/or tow-yo modes of operation. A second, slower ship would conduct the more time-intensive biological sampling. The contemporaneous physical observations will provide context for interpretation of the biological observations, and thereby account for any aliasing of episodic features.

Rapid Response Hydrographic Surveys

Ideally, such hydrographic/biological surveys would be complemented by a fast response component which would be fielded when remote sensing or other real time data pointed to the onset of Loop Current interactions with the continental margin. Such rapid response surveys might be conducted by aircraft, vessel(s), or a combination of the two.

Aircraft: Aircraft offer a range of useful capabilities, which could support quick response missions to survey Loop Current intrusions. Summary details of aircraft type, equipment type, and the generic characteristics of air deployable expendable probes and drifters are given in Appendix 3.3 A. Typical missions might involve deployment of twenty-four A/3 size AXBTs or sixteen A size devices of mixed type along multiple transects that might extend up to several hundred miles along and offshore. Additional aircraft survey capabilities include IR radiometry (below cloud bases), drifter deployment, radar mapping, photo/videography, and marine fauna observations.

A typical feature definition survey might involve two or three flights, or as many as a half dozen or a dozen flights. A generic mission profile (Appendix 3.3 B) has been offered by Aero-Marine Surveys, Inc., based on their experience gained on aerial surveys flown in support of the LATEX.Eddy program in the NW Gulf of Mexico. Most of the survey plans appropriate to a quick response scenario could be accomplished with a week or less advance notice, given adequate planning/preparation and prestocked stores at a forward air base.

Vessel(s): XBTs and XCPs could also be dropped and/or drifters deployed from a vessel(s) which might be chartered in the NEGOM field area. For example, there are quite literally dozens of offshore supply vessels available for charter in the Mississippi-Alabama-NE Florida area, so there should be few logistic problems in contracting one or more for event-oriented missions on short (1-2 days in advance) notice. Especially during periods when large numbers of these vessels are unscheduled, prices of such a charter(s) should be very cost effective. Appendix 3.3 C gives some examples. Even if these vessels do not have hydrographic winch capability, experience from other MMS-sponsored programs has shown that a "portable" general purpose winch and hydraulic pack can be offloaded from a trailer and tack-welded aboard to support net tow or trawl work, or water sampling with CTD/rosette, in just a few hours pre-cruise. Moreover, because vessels in the 100-150 foot size range generally have a 30 ft x 70 ft or larger footprint of open space on the main deck aft, they could readily be outfitted with one or more temperature-controlled vans which might be outfitted with laboratory analytical equipment (*i.e.*, salinometry, autoanalyzer for nutrients, dissolved oxygen titration rig, plus data loggers) and/or for biogeochemical sampling and experimentation.

The advantages of using a vessel(s) to supplement/extend a rapid response survey carried out by aircraft include: 1) water samples can be retrieved for biogeochemical analysis as well as for experiments at sea; 2) underway currents can be profiled if the vessel is outfitted with ADCP and GPS navigation capability, 3) underway high-resolution mapping of salinity as well as temperature can be accomplished, if the vessel can pump water through a thermosalinograph, and 4) hours-to-days of process-oriented time series work can be conducted quite cost effectively, if a remote sensing or aircraft survey vectored the vessel directly to one or more regions of highest eddy-margin interaction. Especially if several different kinds of underway measurements are desired concurrently or if extended laboratory manipulation is of interest, it would be desirable to charter vessels that might be available on short notice from Gulf Coast institutions of the University National Oceanographic Laboratory System (UNOLS). Appendix 3.3 D lists UNOLS vessels and other research boats available along the northern and eastern Gulf of Mexico.

Drifters

One effective method of mapping surface circulation of eddies and exchanges with the shelf are through the use of Lagrangian satellite tracked drifters. The shelf components of the experimental plan (see chapter) call for the deployment of large numbers of drifters in the mid-shelf regions off Pensacola and Cedar Key. A large number of these drifters are expected to seed the slope region and reveal eddy circulations present on the slope. This has been the experience of the SCULP program which has deployed of order 400 drifters on the LATEX shelf. Some of these drifters could also be entrained from the slope region into the LC or LC anticyclones. To supplement this "fallout" from a shelf drifter program, it is suggested that regular deployments of drifters at about weekly intervals be made from deep water moored production platforms that are present just east of the delta (*e.g.*, Cognac). These drifters should be entrained into slope eddies and provide statistics on surface eddy circulation and slope exchanges with the shelf and the LC. The regular releases from a fixed point would provide more direct statistics of slope eddies than the more random incursions from shelf drifters.

Satellite Monitoring

Satellite monitoring data are important for the execution of event-based surveys as well as for the interpretation of subsurface current data from moorings and surface Lagrangian drifter tracks. Two forms of satellite data are readily available and have proved useful in past studies.

1) AVHRR. This is available 2-3 times per day and gives detailed high-resolution (~1 km) images of the sea-surface temperature field. Its disadvantages are obscuration of the SST field by clouds and lack of discernable temperature contrasts in the summer months. AVHRR data ARE therefore useful between November and May and will generate about 7/8 useful images per month during winter and spring. Cloud cover is quite frequent in the NEGOM. This type of data has been extensively used to investigate Loop Current behavior over many years. SeaWifs color scanner data are expected to be available by 1995 and will provide similar coverage as AVHRR except that the LC should be able to be monitored during the summer months. This is because of the contrast between chlorophyll poor surface waters of the LC and the surrounding slope and shelf waters. Cloud cover is still a problem as is the high water vapor content of the atmosphere during summer months.

2) Altimetry. Satellite altimetry data has been shown to be able to track sea-surface height anomalies caused by LC eddies and some of the smaller secondary cyclones and anticyclones. Because of the time to assemble a spatial picture from many overpasses of multiple satellites (presently ERS-1 and TOPEX/POSEIDON), it is best suited to features that evolve on time scales of weeks to months such as the LC and LC eddy propagation into the western Gulf. Recent research (Leben-presentation at Ocean Sciences Meeting, Feb 1994) has shown that satellite altimeters can resolve sea-surface height anomalies over continental shelves as well as in the deep basin. However, they still have difficulty in resolving signals over steep continental slopes. Altimetry has the advantage that the LC can be tracked through the summer season.

Trade-offs

Three approaches have been outlined above; a moored instrument program deployed for 2 to 3 years, a series of hydrographic/biological cruises, and rapid-response surveys of shelf-slope exchange events. All three types complement each other in that knowledge of time and space evolution of the eddy field on the slope are likely to be major forcing functions for shelf-slope exchange, and detailed snapshots of the hydrographic structure help resolve upper layer spatial gradients to much higher degree than possible with moored instrumentation. All three types of studies will benefit from maps generated by imagery, which place the experiments in a larger scale context, and drifters, which give a lagrangian view of surface circulation and show where shelf-slope surface exchanges may preferentially occur.

The disadvantages of a moored array are its fixed positions and limited horizontal resolution such that small scale features may be difficult to resolve (*e.g.*, meandering filaments of LC derived water). The disadvantages of rapid surveys are their limited time resolution and aliasing. However, regular hydrographic/biological surveys would provide a baseline for comparison and thereby allow ranking of importance of forcing mechanisms. If upper layer circulation could be mapped at two weekly intervals, say, with AXBTs and AXCPs, the evolution of an exchange event could be followed. However, this degree of effort could only be sustained for several months and this overall time scale is short compared with the dominant eddy time scales (2 months) and Loop Current eddy shedding cycle (6-20 months). Drifters, by themselves, provide no information on subsurface fields.

If funding is limited, compromises on the number and kind of surveys may be necessary. Reducing the number of moorings limits the areal extent of the array for the same along-shelf and cross-shelf resolutions and thus makes it less effective in resolving the movements of the eddies. It could be argued that the upper layer temperature moorings are less important since it has been indicated that the 300 m temperature field measured by the ADCPs could adequately map thermocline depth and dynamic height using the 12C surface as a surrogate. The temperature moorings would also miss upper layer events that occur between moorings or do not extend down to the level of the upper most sensor (~ 50-100 m). Limiting the number of hydrographic/biological sampling cruises and/or the number of rapid response surveys by increasing their spacing in time produces the usual aliasing problems, and unless drifter data is available to identify and track features between surveys, getting an adequate interpretation of the evolution of the mapped fields can be difficult, if not impossible.

The experimental designs presented here are preliminary suggestions for a study of slope circulation and exchange events in the NEGOM. Refinements in the design and instrumentation would be needed before a final study plan is generated.

Appendix 3.3 A: RESOURCES FOR RAPID RESPONSE AERIAL SURVEYS
by T. L. Flynn, President, Aero-Marine Surveys, Inc.,
New London, CT 06320

Aircraft: Twin-engine (AZTEC F or equivalent), long-range/high-endurance, 1800 lbs useful load, short/medium field capable, IFR equipped with radar and loran/GPS, belly hatch, launch tube.

Equipment: Multi-channel sonobuoy receiver/data logger (4 channel ARR-75 or equivalent).

Optional: Airborne radiation thermometer (ART/PRT), side looking airborne radar/synthetic aperture radar (SLAR/SAR) and/or medium format aerial cameras (Hasselblad MK70 or 500 EL or equivalent).

Stores: AXBT: AN/SSQ-36 (305 meters), AN/SSQ-36 (760 meters) A or A/3 size. AXCP: Sippican air-deployable XCP (1500 meters) A size only. AXCTD: No final specifications at this time; projected availability late 1994.

Drifters: Various air-deployable drifters are available from several vendors. The most appropriate to a rapid response survey are A size (*e.g.,* Met Ocean: drogued Argos) or near A size as they can be launched in the geographic sequence with other types of expendables. Larger drifters are usually deployed out of sequence or on a dedicated flight as either belly hatches or cargo doors must be opened, which is potentially hazardous and requires that all equipment and personnel be secured during the time that doors and hatches are open.

Note: It is current practice to inventory one survey's worth of stores at the forward air base. This is required by the high weight and higher value of the stores, which drive up shipping/handling costs if stores are not shipped till needed. Suitable secure, air-conditioned storage should be identified and obtained in connection with any aerial survey effort.

Appendix 3.3 B: AERO-MARINE HYDROGRAPHIC SURVEY: SOME BASIC ELEMENTS OF AN INTERACTIVE AIR-SHIP SURVEY

by T. L. Flynn, President, Aero-Marine Surveys, Inc., New London, CT 06320

1. **Pre-plan mission:** Assume 6 hours at a net speed of 120 knots for a total trackline length of 720 nautical miles. This assumes airspeeds of up to 150 knots to accommodate adverse winds and necessary maneuvers and includes 2 hours additional fuel pad for typical operational contingencies. Drop positions have a minimum spacing determined by channel availability (1-4 typically), ground speed (100-150 knots typically), flight altitude, and the transmission characteristics of the expendable probes employed. A shallow AXBT (305 m) such as SSQ-36 requires 5 minutes from initiation of RF quieting to termination of probe drop. A deep AXBT (760 m) requires ten minutes per drop. A flight employing shallow AXBTs utilizing 4 channels and a ground speed of 120 knots could therefore use a minimum drop spacing of 2.5 nautical miles or approximately 5 km. The short air time and low ground speed would not assess altitude penalties. By contrast, a flight employing deep AXBTs utilizing only 2 channels would require a minimum drop spacing of 10 nautical miles and would face altitude penalties (1000'a.s.l.) which increase with sea state. AXCP planning criteria are very similar to those for deep AXBTs. Typical loads may include as many as 25 A/3 size AXBTs or 16 A size devices.

2. **Pre-stock stores:** Quantities for highest comsumption scenario should be available at forward air base.

3. **Issue warning order:** As soon as a feature is identified or a suspicion raised, the aerial survey team should be alerted. A dedicated aircraft can respond within 24 hours. An aircraft that is unavailable due to maintenance or conflicting contract obligations can take considerably longer to respond. It is strongly advised that selective availability windows be negotiated, that provide levels of response commensurate with the likelihood of mobilization.

4. **Mobilize survey aircraft:** Once coordinating arrangements are finalized for the hydrographic cruise, the aircraft should be mobilized to arrive on scene approximately 48 - 96 hours before the hydrographic survey vessel. All equipment maintenance and calibration should be accomplished prior to arrival.

5. **Conduct recon flight:** The initial flight could employ up to 25 AXBTs to occupy a 50 nm x 50 nm block to obtain an initial position on the feature. Other sensors could also be utilized to map the feature, such as: ART/PRT, SLAR/SAR, and/or photography or video. The results should be quickly scanned for steering information to allow the hydrographic vessel to plan its cruise track and the effort to conduct a detailed mapping of the feature.

6. **Conduct detailed survey:** The second flight should concentrate a high density pattern in the feature proper consisting of a combination of AXBTs and AXCPs (and/or AXCTDs). Using the planning criteria above, design/execute detailed coverage of the feature. At this stage, an exchange of data must be effected to provide tactical support to the surface unit. At the same time, there must be a handoff from the aircraft commander (or aerial survey PI) to the vessel commander (or the hydrographic PI), with the aerial survey team now assuming a subordinate role for the hydrographic cruise.

7. **Support hydrographic cruise:** Work up all data and transmit it to ship. Prepare to deploy drifters and conduct operations in support of hydrographic cruise. Perform ground checks and maintenance on aircraft and equipment.

8. **Deploy drifters:** As mentioned above, drifters significantly larger than A size should be launched on dedicated flights. Lay days often provide the opportunity to conduct drifter deployments as well as drops of hardware to the ship.

9. **Conduct replicate surveys:** Depending on the nature of the feature and the results of the ship based hydrographic work, it is often desirable to conduct either replicate or revised aerial surveys in direct support of the hydrographic cruise. Since the biggest expense factor in aerial surveys is often mobilization, additional tasking usually involves significantly reduced costs per unit effort. Additional tasking under these conditions may enhance efficiency by allowing the shipboard capabilities to be focused on those tasks or stations, which can best be accomplished on the surface.

10. **Release aircraft:** After satisfying data transfer requirements and ensuring that no contingencies are foreseen, which might require additional aircraft support, release aircraft to avoid further expense to project. If contingent needs are uncertain, it is often possible to have aircraft placed on reduced availability or on standby.

11. **Conduct AAR:** Final data should be obtained after quality assurance and final formatting have been accomplished. As soon as possible an AAR should be conducted allowing PIs to critique the conduct of the response effort. This will also permit all participants to evaluate the quality of initial planning and preparation. A brief "lessons learned" synopsis should then be published for use in accompanying necessary revisions in planning/preparation. If possible a time or date for next earliest response could be estimated.

Appendix 3.3 C: EXAMPLES OF VESSELS AVAILABLE FOR CHARTER FROM OFFSHORE CONTRACTORS IN THE GREATER PENSACOLA, FL, AREA (information provided by Dr. Ann Bull, MMS)

All vessels USCG inspected and approved; charter costs include crew for 24 hour operation but there is an add-on surcharge for bunk (linens provided) and food (3 hot meals) of $35-50 per person per day. Vessels have different transit speeds and operational limits, ranging from 7-10 days for crewboats to 14-42 days for supply vessels, and they can provide 30-40 kw power (crewboats) to 50-60 kw power (supply boats) for scientific equipment. Prices quoted are for example only and represent low-end prices for period November thru April-May.

Category 1: Crewboats (sleep crew plus 3-4 persons; operational limit 4-6 foot seas)

Length	Open Deck	Speed	Charter Cost/Day
100-125 ft	56-60 x 20	20-24 knots	$2000-$2500

Category 2: Utility Vessels (sleep crew plus 12-16 persons; op limit = 6-8 foot seas)

Length	Open Deck	Speed	Charter Cost/Day
110-135 ft	60-80 x 26	8-10 knots	$3000

Category 3: Supply Vessels (sleep crew plus 14-16 persons; op limit = 8-10 foot seas)

Length	Open Deck	Speed	Charter Cost/Day
150-220 ft	100-150 x 40	10-12 knots	$3000-$4000

Commercial Contractors in the Greater Pensacola Area include:

1) **Tidewater Marine, Inc.**
Approx Number of Vessels:
22 in Category 1
12 in Category 2
62 in Category 3;
Contact Mr. Alvin Arcement (504) 384-4711
Tidewater Bases are in Pascagoula MS, Mobile AL, Theodore AL, Panama City FL

2) **John E. Graham and Sons**
Approx Number of Vessels:
40 in Category 1
140 in Category 2
7 in Category 3;
Contact Billy Maples (205) 824-4136
Graham Bases are in Bayou La Batre AL and Panama City FL

3) **Southern Transport Service**
Approx Number of Vessels:
20 in Category 1
60 in Category 2
10 in Category 3;
Contact Chuck Youngdale (904) 784-0927
Southern Transport Bases are in Mobile AL and Panama City FL

4) **Marine Transport, Inc.**
Approx Number of Vessels:
18 in Category 1
23 in Category 2
14 in Category 3;
Contact Grover Davis (904) 768-1459
Marine Transport Bases are in Mobile AL and Panama City FL

Note: Ship fitters, electricians, *etc.*, are available at contractor bases and are regularly used by the vessel companies. Not all of the commercial contractors have had experience with oceanographic cruises, but most of them would presumably be attentive to rapid-response needs.

Appendix 3.3 D: RESEARCH VESSELS BASED IN NORTHERN AND EASTERN GULF OF MEXICO

Institution	**Vessel**	**Length (ft)**	**Phone**
University of Texas Marine Science Institute Port Aransas, TX	R/V Longhorn	105	512-749-6760
Texas A&M University Galveston, TX	R/V Gyre	182	409-740-4469
	J.W. Powell	155	409-690-0095
	D.W. McGrail	82	409-740-5000
LA Universities Marine Consortium Cocodrie, LA	R/V Pelican	103	504-851-2800
	Acadiana	56	504-851-2800
Gulf Coast Research Lab Ocean Springs, MS	Gulf Researcher	65	601-875-2244
Gulf Marine Lab? Biloxi, MS	Tommy Munro	98?	???
Marine Environmental Sciences Consortium Dauphin Island, AL	Verrill	65	205-861-2141
Florida Inst. Oceanography St. Petersburg, FL	Suncoaster	110	813-893-9100
	Bellows	65	813-893-9100
Florida State University Marine Laboratory Turkey Point, FL	R/V Seminole	48	904-697-4095

Note: R/V designates UNOLS affiliation

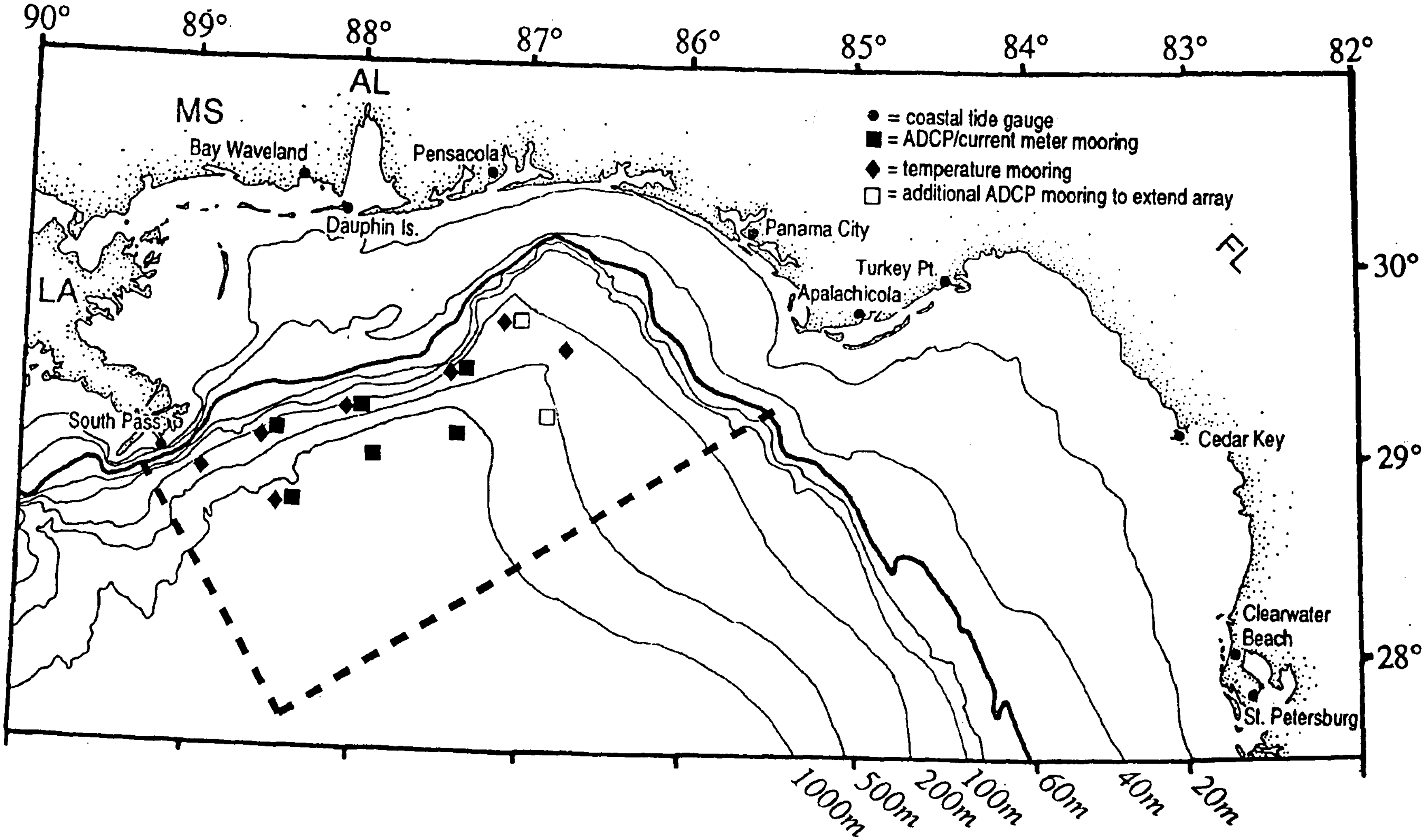

Figure 80. Preliminary experimental design for a NEGOM slope process study. Moored array positions are marked and the heavy dashed line is the seaward boundary for the rapid response and hydrographic surveys.

APPENDICES

APPENDIX A. Pre-Conference Strawman Plans

A Strawman Plan for the Northeastern Gulf of Mexico Physical Oceanography Workshop, April 5-7, 1994, Tallahassee, Florida

Operational Remote Sensing in Support of Field Measurements

by
Murray Brown
Minerals Management Service

The current paradigm for physical oceanographic field measurements programs is the provision of services (through subcontract or separate laboratory group) to obtain, process, analyze and share remote sensing images, principally AVHRR sea surface temperature (SST). Typical products include:

a. SST gridded fields (for contour chart production)

b. Cartoons of front locations (digital and hard copy)

c. "Transects" of SST along selected tracks (such as survey lines and/or mooring locations)

d. Gridded fields and/or front location charts of suspended sediments (from AVHRR visible channel)

Newer products, based on other satellite sensors include:

a. Altimeter-sensed anomalies of sea surface height from specified geoid(s)

b. SAR, SLAR, and/or scatterometer images

All of the above (which is not a complete list of all sensors available) have been used extensively in various coastal ocean programs in an after-the-fact mode, primarily to make sense of the field measurements. Increasingly, measurement program mangers have required the ready availability of near-real time remote sensing data to aid in planning field surveys, in deployment of moorings and/or buoys, and in managing (or setting up) "ship-of-opportunity" arrangements. In current Gulf of Mexico programs the close cooperation between Federal, State, and offshore industry marine research has fostered a community awareness of the value of operational remote sensing. This stems partly from over a decade of Loop Current eddy monitoring, but is also a product of recent projects (*e.g.,* NECOP, LATEX, GOSAP) that focused on features/processes observable wholly or principally from satellites.

The success of physical oceanographic experiments in the NEGOM area will also require remote sensing support, but recent developments in the availability of operational data products from Federal programs will reduce both the price tag and the personnel requirements:

a. NOAA's "Coast Watch Program" provides regional centers of AVHRR image processing, resulting in fully processed images (in a non-standard NOAA format, however) available to non-commercial researchers or commercial researchers working on Federal contracts. The "CCOAST" public domain software (and documentation for the CCOAST format) is also provided to further process and enhance these images. The image files for the NEGOM area are accessed at the National Marine Fisheries Lab in Bay St. Louis, *via* INTERNET. NEGOM researchers would be expected to become fully conversant with the Coast Watch system, and be high baud rate participants in the INTERNET.

b. NOAA's traditional "Ocean Feature Analysis" (the "OFA", or the "Jennifer Clark charts"), produced by the Ocean Product Center (OPC), have been a staple of operational oceanography for over a decade. In mid-1994, however, a digital version of the OFA will be available through INTERNET and/or a dedicated digital bulletin board on OMNET (probably SE.US.COAST). NEGOM researchers would be expected to use this product together with the CCOAST files.

c. A developmental product from NOAA's OPC recently previewed for the South Atlantic bight, is a surface current vector chart based on the motions of hydrographic features visible in remote sensing images. This product is expected to be extended to other coastal regions, and to become digital. NEGOM researchers would be expected to interface with this product, and to develop means for synthesizing vector information originating here with those results (*e.g.*, buoy trajectories, telemetered surface current vectors).

Although not easy to evaluate at present, the future availability of Sea-WIFS color scanner data will provide a whole host of new data products of great value to coastal work (where optical properties experience their greatest variability). NEGOM researchers would be expected to participate in NASA-organized data and product distribution programs, and to use these products both as identifiers of water masses and as keys to physical and biological coastal processes.

Finally, it is possible that the resolution and/or scene limits of available Federal operational remote sensing products might not be optimal for NEGOM research needs. If this might be the case, limited funding for the "in-house" obtaining, processing, analyzing and sharing (within the NEGOM research group) of remote sensing images may be provided.

Coastal Hydrography and Optics of the Big Bend Seagrass Area

by
Murray Brown
Minerals Management Service

The northeastern "corner" of the Gulf of Mexico contains the Nation's second largest seagrass beds (after Florida Bay). The area is marked by a very wide continental shelf and very low wave or current energy, with sandy to sandy to silty sediments. The Apalachicola River and numerous smaller rivers enter the region, providing fresh water rich in organic humus compounds (yellow substance). Because grassbeds throughout the region have been charted out to the 20-m isobath, indicating relatively great clarity compared to the rest of the Gulf coast, and because lateral transport processes (from adjacent areas) are known to be small, it is believed that the Big Bend area represents the coastal ocean archetype for extremely low vertical mixing processes.

Water clarity in the Big Bend area is probably due to a delicate balance between inputs from rivers, occasional storms, and planktonic primary production from (principally) recycled nutrients, and the following sinks: particle settling and/or particle agglomeration, flocculation of macromolecular humus substances into new particles, biological scavenging in the water column, and photo-induced "bleaching" of humus. Evidence that there are "good years and bad years" for seagrass growth and the extent of the beds, taken together with the absence of evidence for gross nutrient budget perturbations, indicates that the balance can swing toward a significantly reduced submarine light field integrated over time. To date, no one has measured the downwelling light field (or any of its commercially vended surrogates) sufficiently to say what the normal or abnormal annual cycle of photons available for primary production might be, nor have sufficient physical parameters been gathered (at appropriate time and space scales) to relate the vertical structure of optical properties to vertical mixing.

The field measurements program necessary to determine the relation between the hydrography and optics of the Big Bend area to the presence and continued (albeit variable) maintenance of the seagrass beds would closely parallel (and might find some coordination with) the Coastal Mixing and Optics Accelerated Research Initiative observational program (partially quoted below) announced by the Office of Naval Research:

"Turbulence parameters (*e.g.* dissipation rates of kinetic energy and temperature variance, and indirect or direct estimates of turbulent fluxes) through the water column;

"Inherence and apparent optical properties (*e.g.* spectral absorption, attenuation, scattering, upwelling and downwelling irradiance, [and upwelling radiance];

"Vertical structure of temperature, salinity, density, and particulate matter;

"Vertical distribution of various particle sizes, from small optically important particles to large, amorphous mineral and detrital aggregates, that act as important sources and sinks for smaller particles;

"Vertical distributions [and spectral fluorescence and absorption properties of [yellow substance];

"Velocity structure in the surface layer, pycnocline, and bottom boundary layer;

"Surface fluxes (wind velocity, air and sea temperature, humidity, and long and short wave radiation;

"Topographic and bathymetric features of the shelf which can interact with flows and affect pycnocline optical properties and turbulence."

Finally, the regional nutrient balance should be studied through seasonal (or more frequent) hydrographic surveys.

A Strawman Plan for the Northeastern Gulf of Mexico Physical Oceanography Workshop, April 5-7, 1994, Tallahassee, Florida

Flow on Florida's Big Bend Shelf

by
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In Florida's Big Bend region coastline direction changes by nearly 90° over a distance less than the shelf width. What does the shelf circulation in Florida's Big Bend look like? How are currents distorted by the strong alongshore changes in bottom topography? Such circulation is important not only for the determination of the fate of pollutants, but also for the recruitment of commercially important fish like the gag grouper and gray snapper.

Previous limited measurements and theory suggest that the currents in the region are largely due to the tides, wind forcing and fresh water flow near the coast. Based on this, I attach a strawman experimental plan (see Figure 81). Some comments on it follow.

(1) Low frequency currents tend to follow the isobaths and, because of geostrophy, pressure should be approximately constant along the isobaths. Hence it is appropriate to structure an observational array along and perpendicular to the isobaths.

(2) Since pressure should be approximately constant along isobaths, cross shelf pressure gradients should increase as isobaths converge. By geostrophy, currents should therefore strengthen. This effect should be clearly apparent along the 20 m isobath from B2 to C2 to D2 and along the 40 m isobath from B3 to C3 to D3.

(3) Line B will extend right across the shelf and should show the influence of the Loop Current at the outer mooring and how this influence decreases and wind driven variability increases as one moves shoreward. The pressure gauges at B1, B2 and C2 will test the theoretical prediction that the strong change in sea level amplitude between Shell Point and Apalachicola occurs over the nearshore frictional region shallower than 20m. The nearshore current meter, wind, pressure and sea level measurements can also be used to check the shallow water momentum balance. The nearshore current measurements at A1 and B1 will also tell us something of the nearshore buoyancy driven flow which we know occurs (Harkema *et al.*, 1994). Because trawlers will destroy nearshore moorings, and because of the need to determine velocity profile to estimate bottom stress in the frictional nearshore region, measurements at A1 and B1 should be done by ADCPs.

(4) Hydrography will be measured when current-meters are rotated and/or removed. Ideally, moorings should be out for a whole year to measure seasonal variability. Most moorings will have a meter as near as practical to the surface to estimate the near surface flow (which is of primary importance to the transport of surface pollutants and fertilized eggs) and a mooring at mid-depth. If enough instruments were available, a near bottom meter could be added to measure flow in the bottom boundary layers.

(5) Surface drifters should be released to check that flow scales are resolved by the array and to assess the Lagrangian flow. From a biological point of view, drifter release would be of prime importance in February and March when gag grouper spawning is at its height and June-August when gray snapper spawn.

(6) Wind measurements could be made at K-tower, a centrally sited navigation tower (see Figure 81). Winds are also available at the NDBC buoy and CMAN station marked on the map, as well as the coastal towns Apalachicola, Turkey Point and Cedar Key.

(7) A wind-driven flow model already exists to calculate and understand the wind-driven flow (Clarke *et al.,* 1995). This model gives good results for coastal sea level at Shell Point and Apalachicola. A model is also available for calculating and understanding the tidal flows whose structure should be resolved by the array.

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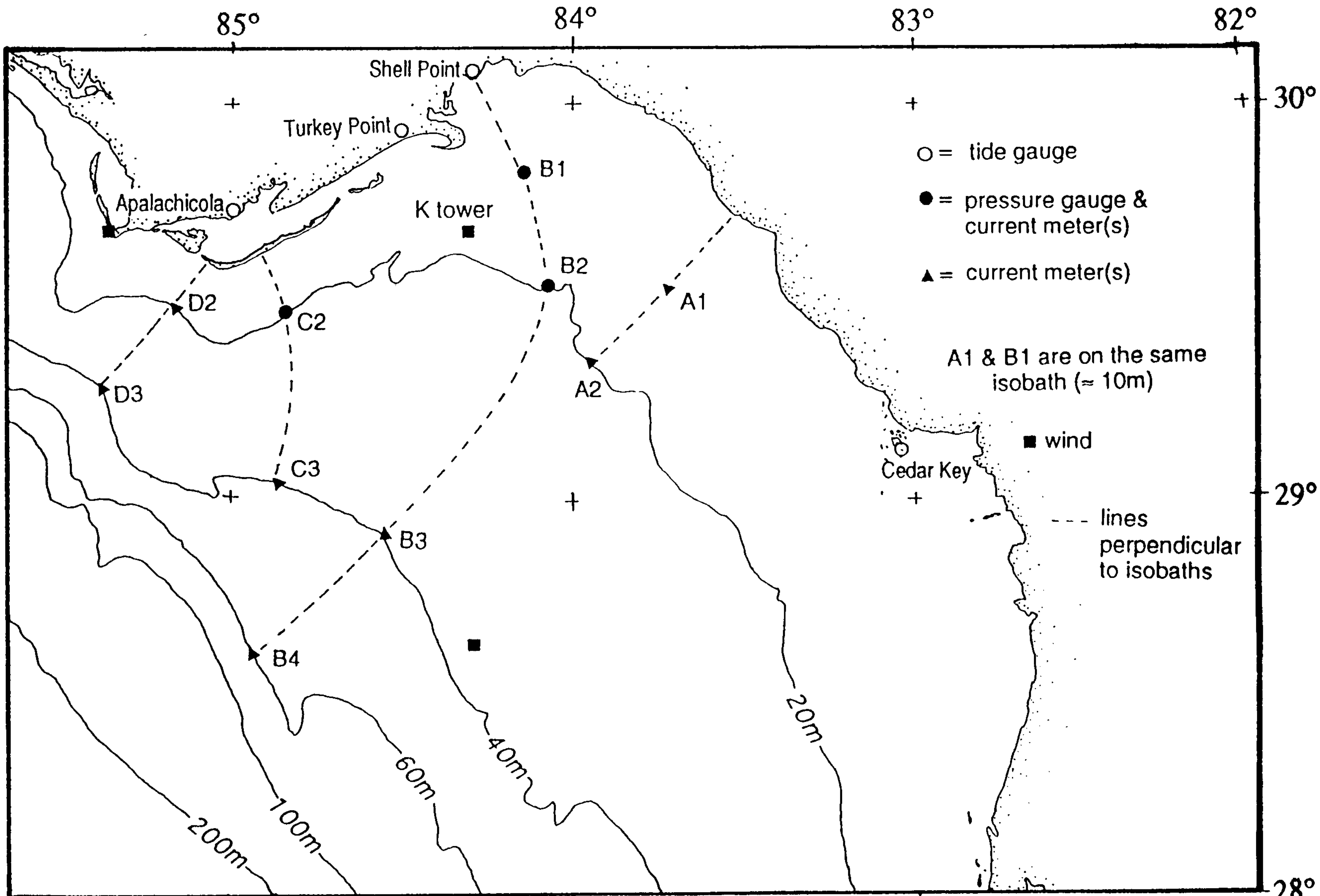

Figure 81. Proposed measurements on Florida's Big Bend shelf.

Meteorology Experiment

by
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The meteorology of the NEGOM can be closely linked to the physical oceanographic processes in the Gulf of Mexico and this coastal region. The current availability of meteorological information is limited. One can acquire information from land-based meteorological monitoring stations maintained by the National Weather Service (NWS) (Boothville, LA; Mobile, AL; Pensacola, Fl and Tampa, FL), and the Coastal Marine Automated Network (C-MAN) (Southwest Pass, LA; Dauphin Island, AL, Cape San Blas, FL and Venice, FL) along the coast of the NEGOM region. Gulf-based meteorological information is from the National Data Buoy Center (NDBC) buoys (42007: 30.1N 88.8W; 42001: 26N 89.7W; 42002: 26N 93.5W). These buoys are inadequately spaced to provide good coverage of any gradients occurring across the NEGOM continental shelf, although they may provide adequate alongshore coverage. The existing buoys are located on the far west NEGOM inner shelf and in the central Gulf of Mexico, much too far to document shelf processes. The existing buoy compliment could be supplemented by additional, long-duration meteorological buoys at 29N 88W and 28N 86W. These locations are seaward of the shelf break and approximately straddle the DeSoto Canyon. These additional two buoys would provide critical information along the open boundary of the NEGOM.

The following meteorological experiments are presented not as a complete suite of possible experiments, but as a starting point of discussion. These experiments certainly reflect a physical oceanography perspective.

1) Air Mass Modification by the Loop Current

The warm waters of the western Gulf of Mexico were found to modify 'return flow' during the GUFMEX program in the late 1980's (Lewis *et al.,* 1989). The polar and continental air masses that moved out over the Gulf of Mexico and then returned to the continental US were warmed and moistened. The Loop Current is a warm ocean current in the eastern Gulf of Mexico that aperiodically exhibits northward intrusions. At times these intrusions extent up to and interact with the continental shelf waters of the NEGOM. Air masses that move over the Loop Current and then flow over the coastal NEGOM regions and the southeastern US ought to have different weather characteristics dependent upon the position of the Loop Current. Molinari (1987) found that air masses passing over 'deep' Loop Current intrusions have 1^{o}C and 1g/kg greater increases of temperature and moisture than air masses passing over 'shallow' intrusions. These differences ought to be observable in the mixing ratios of air masses over land. This experiment would make use of climatic and synoptic land based NWS meteorological data in conjunction with satellite sea surface temperature (SST) imagery that would quantify the position and extent of northward intrusion of the Loop Current and then relate the air mass modification to changes in the regional weather. Air mass modification would be determined from sea surface temperature corrections and vertical profiles of temperature and humidity. The former would be an inverse atmospheric satellite correction problem, the latter would need routine shipborne atmospheric soundings or a platform capable of short duration manned occupation.

2) Atmospheric Boundary Layer Modifications

Recent studies have indicated that wind velocity and temperature fields are modified by the presence of the coast (*e.g.*, the Coastal Ocean Dynamics Experiment [CODE] Beardsley *et al.*, 1987, Zemba and Friehe, 1987). Other studies have indicated that variations occur across ocean fronts (Hsu *et al.*, 1985). Given that the NEGOM is a region with seasonal shelf-break oceanic fronts, aperiodic Loop Current fronts and the land-sea interface, a number of questions arise pertaining to the modifications of the atmospheric boundary layer. Changes of meteorological parameters and the atmospheric boundary layer with the passage of atmospheric fronts across the land-sea interface, Loop Current fronts, and seasonal shelf-break fronts in the NEGOM would be the focus of this experiment.

The NEGOM region provides a compact region in which to mount a field experiment to monitor the passage of atmospheric fronts in great detail. The field project would consist of synoptic meteorological field sampling (surface wind velocity, air and sea temperature, atmospheric pressure, humidity, and vertical soundings of temperature, moisture and wind velocity) across these frontal zones. These would be obtained using a variety of means: shipboard surveys across oceanic fronts would provide detailed pictures of changes in the atmospheric boundary layer; time series of the spatial gradients of meteorological parameters would enable sequences of atmospheric fronts to be evaluated and the magnitudes to be related to the presence and magnitudes of oceanic fronts; satellite determination of oceanic fronts (using thermal, visible and color sensors) would enable the spatial and temporal variability of the oceanic fronts to be related to the episodic atmospheric frontal modifications in the sea surface.

3) Regional Cyclogenesis

The presence of shelf-break oceanic fronts in the western Gulf of Mexico enhances the frequency of winter and spring frontal over-running along the Louisiana coast and ultimately in regional cyclogenesis (Hsu, 1992). These fronts constitute open Gulf-shelf water temperature differences that are much greater than those at the land-sea interface, these temperature differences lead to increases in atmospheric convective instability and vorticity. The presence of seasonal temperature gradients along the NEGOM shelf-break, a relationship between these oceanic fronts and the Loop Current position, and the fact that the DeSoto Canyon allows warm open Gulf waters to bisect the NEGOM in winter and spring, all imply that the NEGOM is also a region of enhanced cyclogenesis. An experiment should determine the relationship between seasonal shelf-break oceanic fronts, frontal over-running and cyclogenesis in the NEGOM region. Some basic questions should be addressed. What is the relationship between NEGOM frontal over-running and regional extratropical cyclogenesis? Does seasonal variation of shelf-break front strength or position by Loop Current intrusions increase the likelihood of frontal over-running or regional cyclogenesis?

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Historical Hydrographic Data Experiment

by
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This experiment proposes to collate and analyze existing hydrographic data for the NEGOM to determine the climatology and the variability of hydrographic fields, and the location and persistence of physical oceanographic features. When hydrographic data is simply defined as temperature, salinity and density data there are numerous things that can be learned from existing data. However, it should be recognized that the definition could be expanded to include transparency, dissolved oxygen, nutrients, trace metals, and many other water column parameters. Many hydrographic data sets exist that were never fully analyzed. There were few, if any, shelf wide surveys; surveys were usually short duration and of limited areas. Data collected for individual cruises can be combined with data from other cruises and analyzed as a larger group. The last organization of information in this region was almost 20 years ago (the MAFLA study). There certainly has been more data collected since then.

Existing hydrographic data will be identified by querying regional scientists, regional state and federal agencies and laboratories, data depositories, and regional Gulf of Mexico University and laboratory libraries. Data would be assembled at a primary location and a comprehensive data base established. This alone would require a dedicated data manager.

Analysis of the salinity/temperature/density fields would provide, in addition to horizontal distribution climatologies, the location of observed features such as fronts. Anecdotal evidence is not adequate when describing position and duration probabilities. There must be systematic determination of the location of these features, their vertical extent, and whether they are linked to the topography. There needs to be statistical documentation of the persistence of fronts, whether they are seasonal, long lived or transitory. Distinctions between salinity and temperature fronts should be determined. The relationship between the fronts in the NEGOM and the Loop Current needs to be investigated and quantified. Are there regions that fronts occur only when the Loop Current is near the shelf? Does the nature of the fronts change with the proximity of the Loop Current?

The analysis of vertical profiles of salinity/temperature/density should describe the climatic distributions of characteristic or mean profiles, and the variation that occurs about the mean vertical profiles. Regional and seasonal locations of halo-, thermo-, and pycnoclines should be determined. This analysis should be expanded to include derived parameters such as mixing depth and stratification parameters. The location and timing of upwelling and downwelling should be identified, as well as correlated to the climatic meteorology.

Analysis of the density data should be expanded to include computation of geopotential fields and the estimations of the baroclinic circulation. Limitations to this type of analysis is the spatial and temporal data coverage. But seasonal or persistent cyclonic and anticyclonic features should be determined for the NEGOM as they were for the northwest Gulf of Mexico (Cochrane and Kelly, 1986).

Analysis of the temperature data should be expanded to included regional heat budgets. The transfer of heat between the Loop Current and the NEGOM may be determined as a heat flux divergence term. Certainly climatic data could be used in a heat budget analysis. This type of analysis has been performed for the northwest Gulf of Mexico (Etter *et al.,* 1986).

An analysis of the NEGOM region freshwater content would enable estimates of residence times, fates and distributions of the various fresh water inputs. Freshwater content can be determined as the difference between *in situ* salinity and a reference salinity. The Mississippi River is the single largest source of freshwater, but the coastal rivers and the groundwater flow combine to add an influential amount of fresh water to the NEGOM. By accounting for the freshwater flux to the region, various determinations of freshwater residence time can be estimated. This type of analysis has been performed for the Louisiana Texas shelf in the northwest Gulf of Mexico (Dinnel and Wiseman, 1986). River flows are adequately monitored, but groundwater flow to the region may not be. Volumetric analysis of fresh water in the coastal regions can be related to river flux and the ground water flux estimated by residual.

There are many questions that the analysis of historical hydrographic data could address. Some additional examples: Are there persistent circulation features in the region? Does the Loop Current influence shelf-break frontal features? Is there upwelling/downwelling in the NEGOM region? Does it have seasonality or regionality? Is the DeSoto canyon a conduit for exchange?

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A Strawman Plan for the Northeastern Gulf of Mexico Physical Oceanography Workshop, April 5-7, 1994, Tallahassee, Florida

Monitoring the Frequency and Structure of Loop Current Related Intrusions onto the Slope and Shelf in the Northwestern Gulf of Mexico

by
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Background

The Mississippi-Alabama Marine Ecosystem Study (MAMES) was conducted during 1988 and 1989 on the continental shelf and slope between the Mississippi Delta and DeSoto canyon. During this study, Vastano *et al.* (1991) used satellite imagery to monitor the Loop Current and count the filaments that meander northward from it. Although their census found warm intrusions in the MAMES to be frequent, an exact count for the whole study period could not be made by thermal imagery because intermittent cloud cover and the relatively isothermal sea surface conditions during July through September interrupted the continuity of their observations.

Kelly (1991) supplemented the search for intrusive events by studying the 40-hour, low-passed time series of temperature recorded at 150 m and 426 m by two current meter moorings on the 430-m isobath. He found that every intrusion counted in the census by satellite corresponded to a temperature increase above the mean in one or more of the subsurface temperature series. The increase persisted for at least ten days and reached a peak deviation of at least one degree. Using these criteria he found additional periods of warm intrusions in the subsurface temperature series. The combination of satellite imagery and sub-surface temperature data covered a total of 798 days. Intrusions were found during eleven periods of time, totaling 355 days, or forty-four percent of the time.

Three of the five, roughly semi-annual, hydrographic surveys conducted during the study also encountered warm intrusions. The combination of satellite imagery, hydrographic surveys and sub-surface moorings suggested that the east-west spatial scale of the intrusions was on the order of 30-45 km. The vertical extent of the warm intrusions was variable, reaching to 426 m in some cases and at least 150 m in others.

Proposed Study

The results of the MAMES study suggest that Loop Current related intrusions are a frequent and important forcing factor for the waters over the mid- to outer continental shelf and slope on the Northeastern Gulf of Mexico. The objectives of this strawman proposal are to maintain a fairly complete census of the frequency and duration of warm intrusions and to detail their vertical structure. This would be accomplished through a combination of satellite imagery, sub-surface temperature recorders, and rapid ship surveys using CTD casts and ADCP transects. Such a census would complement and support any other studies conducted in this region.

Although subsurface moorings could include other types of sensors, such as current velocity and conductivity, temperature sensors would appear to provide the most cost-effective data set. Eleven sub-surface temperature moorings would cover the 500-m isobath between about 85° and 88° 30' W, *i.e.,* Tampa and the Mississippi Delta, with an along-isobath spacing of about 50 km (see Figure 82). The principal mooring components would be an acoustic release, a number of temperature sensors and a data logger. The top of the mooring should be kept relatively deep to reduce the risk of interference from shipping and fishing. The MAMES results suggest that almost all intrusions reach at least to 150 m. An alternative would be to construct the mooring with two data logging sections. The shallower portion, above 150 m say, would be designed to break free before the whole mooring could be dragged. Deployment intervals could be long, and servicing could be accomplished on cruises of opportunity.

This proposal assumes that satellite thermal imagery would be acquired routinely by another component that would provide this study with relatively cloud-free images. Image processing to obtain the type of information required for the census can be accomplished on most workstations using data visualization software such as PV-Wave.

Some data about the vertical structure of intrusions would come from the temperature moorings. More detail about their structure could be obtained by rapid response surveys on small vessels of opportunity. Vessel requirements could be minimized by using an internally recording CTD and a programmable rosette sampler (to eliminate the need for conducting cable and slip rings). The addition of an ADCP would further enhance information about the structure. Not all intrusions would be surveyed; budget considerations would limit the number of cruises.

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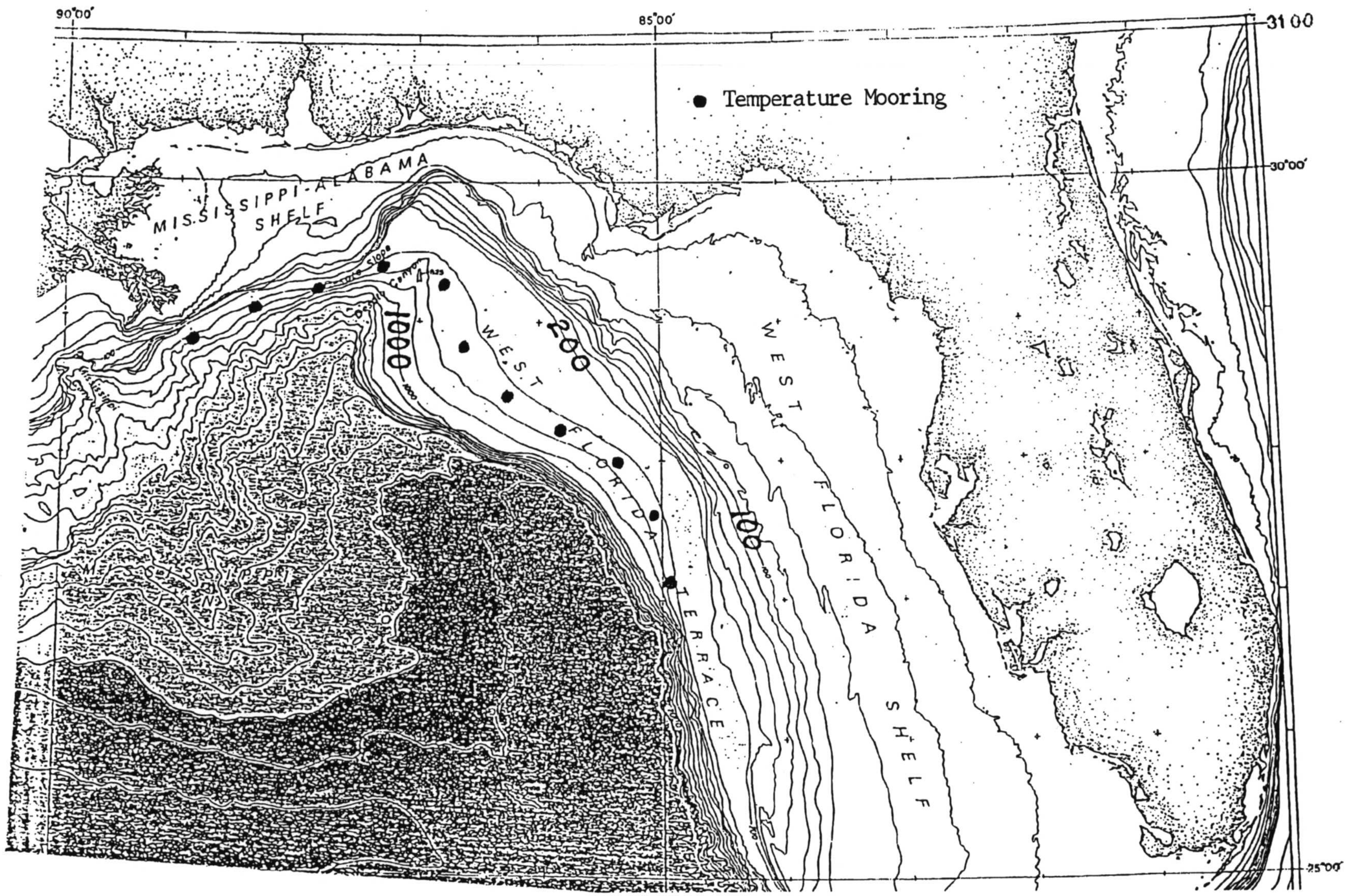

Figure 82. Proposed measurements on the NEGOM continental slope.

Buoyancy-Driven Exchange and the Fate of Fresh Water Discharged onto the Mississippi-Alabama Continental Shelf: Inner- to Mid-Shelf Experiment

by
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River run-off along the eastern portion of the northern Gulf of Mexico is highly variable. The Mississippi River dominates the region with an average discharge of over 14,000 m^3 sec^{-1}. However, most of this run-off flows westward onto the Louisiana shelf. The Mississippi-Alabama shelf is still dominated by Mississippi River run-off followed in importance by that of the Alabama and Tombigbee rivers. These rivers converge to form the Mobile River System flowing into Mobile Bay, Alabama. Average discharge into Mobile Bay is approximately 2,220 m^3 sec^{-1}. West of Mobile Bay to Chandeleur Sound, numerous rivers contribute an average discharge of just over 1,220 m^3 sec^{-1}, the largest coming from the Pascaguola and Pearl rivers. To the east of Mobile Bay run-off from the Florida Panhandle is considerably lower, collectively averaging less than 800 m^3 sec^{-1}. Most of the local runoff is thus onto the inner- to mid-shelf region south of Alabama and Mississippi and east of Louisiana.

Exchange between Mobile Bay and the shelf mainly occurs through a single pass. Therefore, fresh water is introduced to the shelf offshore of Alabama principally through the formation of a brackish water coastal plume or as a discrete fresh water source. On the hand, along the Mississippi coast, multiple passes associated with Mississippi Sound results in more of a "leaky", line or distributed source introduction of fresh water to the shelf. It is anticipated that the fate of this fresh water will be controlled by the following: (1) the development of a seasonal buoyancy-driven coastal current; (2) relatively slow cross-shelf exchange via mixing; and (3) more rapid cross-shelf exchange driven by either episodic wind events or intrusions onto the shelf of Loop Current filaments. A prominent characteristic of this shelf relative to the fate of the fresh water is the abrupt 90^o change in the east-west orientation of the Mississippi-Alabama barrier island coastline to the north-south trend of the Chandeleur Islands and Mississippi birdfoot delta coastline.

The fate of fresh water and the dynamics of the coastal current system are important for a variety of reasons. The fresh water effluent from the river carries both nutrients to the coastal waters and pollutants from the petroleum industry and other industry within state waters onto OCS waters. The frontal boundary associated with the coastal current is a barrier to encroachment of both offshore oil spills and estuarine dependent eggs and larvae into the productive estuaries and marshes of the coastal states.

Specific questions to be resolved include:

1. What is the role of pressure gradients built up in the corner region between the Missssissippi-Alabama barrier islands and the Chandeleur Islands in the dynamics of the coastal current in front of the island chains?

2. Is cross-frontal exchange between the mid- and inner-shelf an important process or does water simply flow cyclonically around the shelf to merge with the Mississippi River effluent?

3. If cross-frontal mixing does occur, is it primarily driven by upwelling favorable winds, by instabilities in the flow, or by intrusions of Loop Current waters onto the shelf?

Minimal requirements for a field program to support these experiments would likely include fixed mooring arrays in an along-shelf/cross-shelf cross (+)-configuration, both monthly and 7-10 day intense hydrographic/ADCP ship surveys, satellite coverage and airborne salinometer surveys. In addition, coastal and offshore wind and sea level data will be required.

NEGOM Innershelf Experiment

by
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Introduction

Very little is known about the circulation on the NEGOM innershelf. In the littoral zone of the western NEGOM (Alligator Point to Cape San Blas) a westward drift is inferred from sand migration patterns along beaches (Rizk, 1985). However, seaward of littoral zones to the outer limit of the innershelf -- the 20-meter isobath -- there is only information offshore of Alligator Point (Marmorino, 1983, Harkema *et al.*, 1991, 1992, 1993, 1994). Here from the mid innershelf (depth ≈ 10 m) to the outer innershelf (depth ≈ 20 m), the hydrography is often estuarine-like with a fresher layer overlying a salty layer. The flow in the lower layer at the 18 m isobath has a distinct inshore component consistent with the estuarine hydrographic setting (*ibid.*), as well as being consistent with the US southeastern innershelf which also displays an estuarine hydrography (Menzel, 1993). The flow in the upper layer has a distinct onshore component, again being consistent with estuarine hydrography (Marmorino, 1983, Harkema *et al.*, 1991, 1992, 1993, 1994); however, unlike the US southeastern innershelf it typically turns left rather than right looking off-shore. Weatherly and Thistle (1994, manuscript) suggests that the flow in the upper layer may be remotely wind-driven.

Experiment

It is proposed that the currents and hydrography be measured along three sections in the NEGOM. One section would be off of St. George Island, the second off of Apalachee Bay and the third nominally off Deadman Bay (see Figure 83). Each section would be monitored for a year.

Currents It is proposed that ADCPs be set nominally at 9m and 18m depth along the three sections. The ADCPs would be bottom mounted within heavy frames to minimize the chance of being snagged by trawlers (the NEGOM innershelf is heavily trafficked by shrimp trawlers). They offer the possibilities of: (1) profiling from ≈ 1 m depth to ≈ 1 m above the bottom (2) sampling at fast enough a rate (≈ .25 Hz) to average out wave motions (3) having sufficient battery capacity to be left out for a year, (4) having the option of downloading data, via diver attached cable, every time the ADCP is inspected, (5) resisting marine fouling of the sensors over a year's deployment (personnel communication, William Jones of the NW Florida Water Management Bureau, Quincy, FL).

In shore of the ≈ 9m isobath it is proposed that flows be estimated periodically with drogued surface drifters.

Hydrography Hydrographic transects across the innershelf along each section at least once bi-monthly are proposed.

Other Tallahassee, FL wind data available from NOAA should be adequate. (A coastal or offshore site would be preferable if it becomes available.) Wave data could be measured periodically at each ADCP site using an existing wave/pressure gauge at FSU.

We note finally that four of the proposed current meter mooring sites are the same as those proposed in this Meeting for the study of "Flow on Florida's Big Bend Shelf". Furthermore, the hydrographic sections are also shoreward extensions of sections also proposed in that study.

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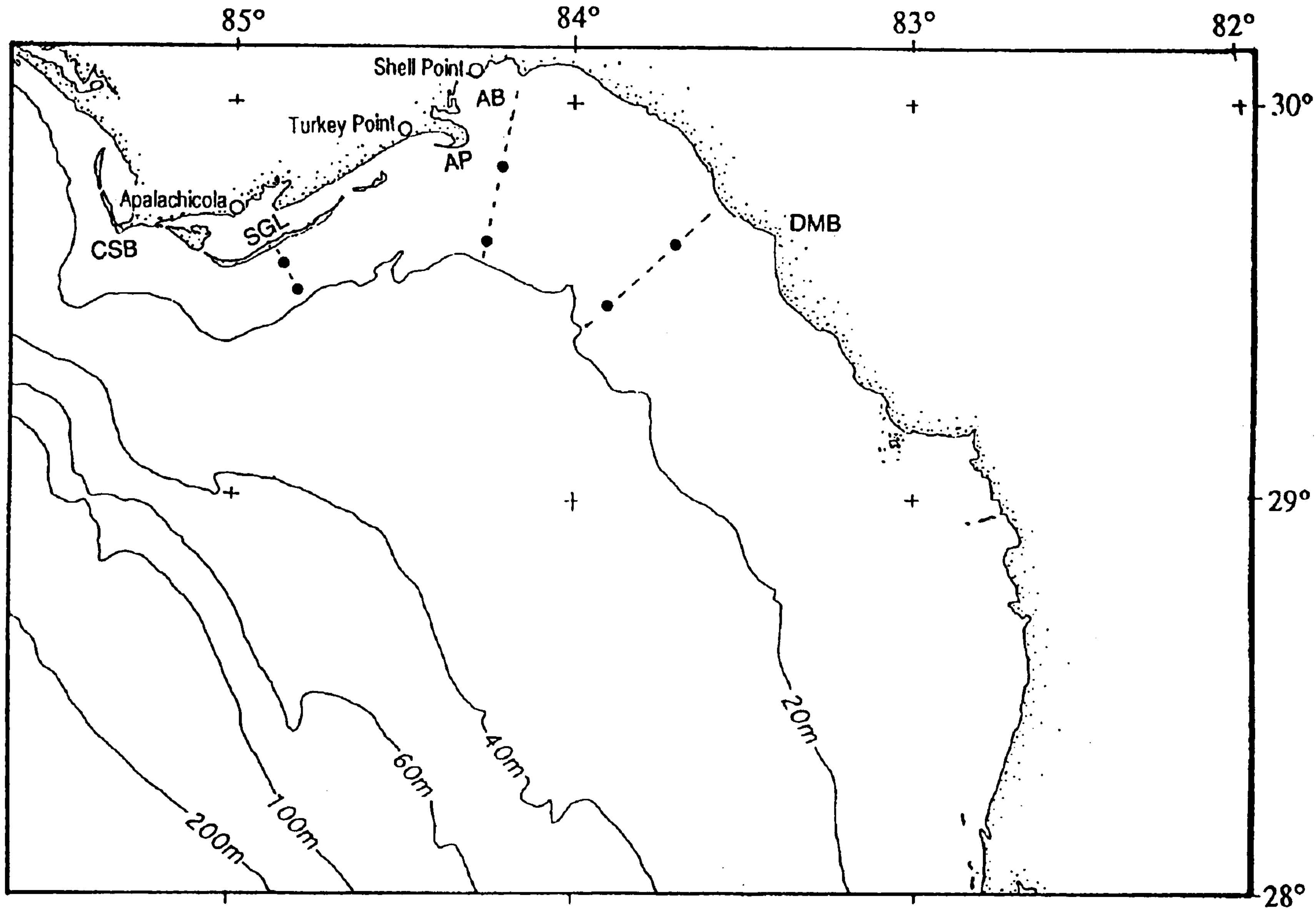

Figure 83. Proposed moorings and hydrographic sections for NEGOM innershelf experiment.

Apalachicola River Plume Experiment

by
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It has been estimated that about 80% of the Apalachicola River discharges into the Gulf of Mexico through West Pass, a channel between Little St. George and Vincent Islands (personal communication, William Jones, NW Florida Water Management Bureau, Quincy, FL). The major objective of the experiment would be to study the fate of Apalachicola River plume which exits West Pass, with a subsidiary objective to infer the fates of the remaining Apalachicola River plumes, those exiting the other channels between the barrier islands separating this river from the Gulf of Mexico (Indian Pass, West Pass, Government Cut, East Pass, Dog Island Pass).

The fresh water input to the NEGOM inner shelf appears sufficient to give it an estuarine character, both in its hydrography and circulation, out to about the 20m isobath (Harkema *et al.*, 1991, 1992, 1993, 1994). It is proposed to make bi-monthly hydrographic sections for one year to study the plume which presumably is a significant source of fresh water to the NEGOM inner shelf. Initially a survey track as indicated in Figure 84 is proposed; this track would likely be modified based on results of the initial surveys. Several drogued surface drifter studies are recommended to study how well Lagrangian data agrees with inferred flow patterns.

References

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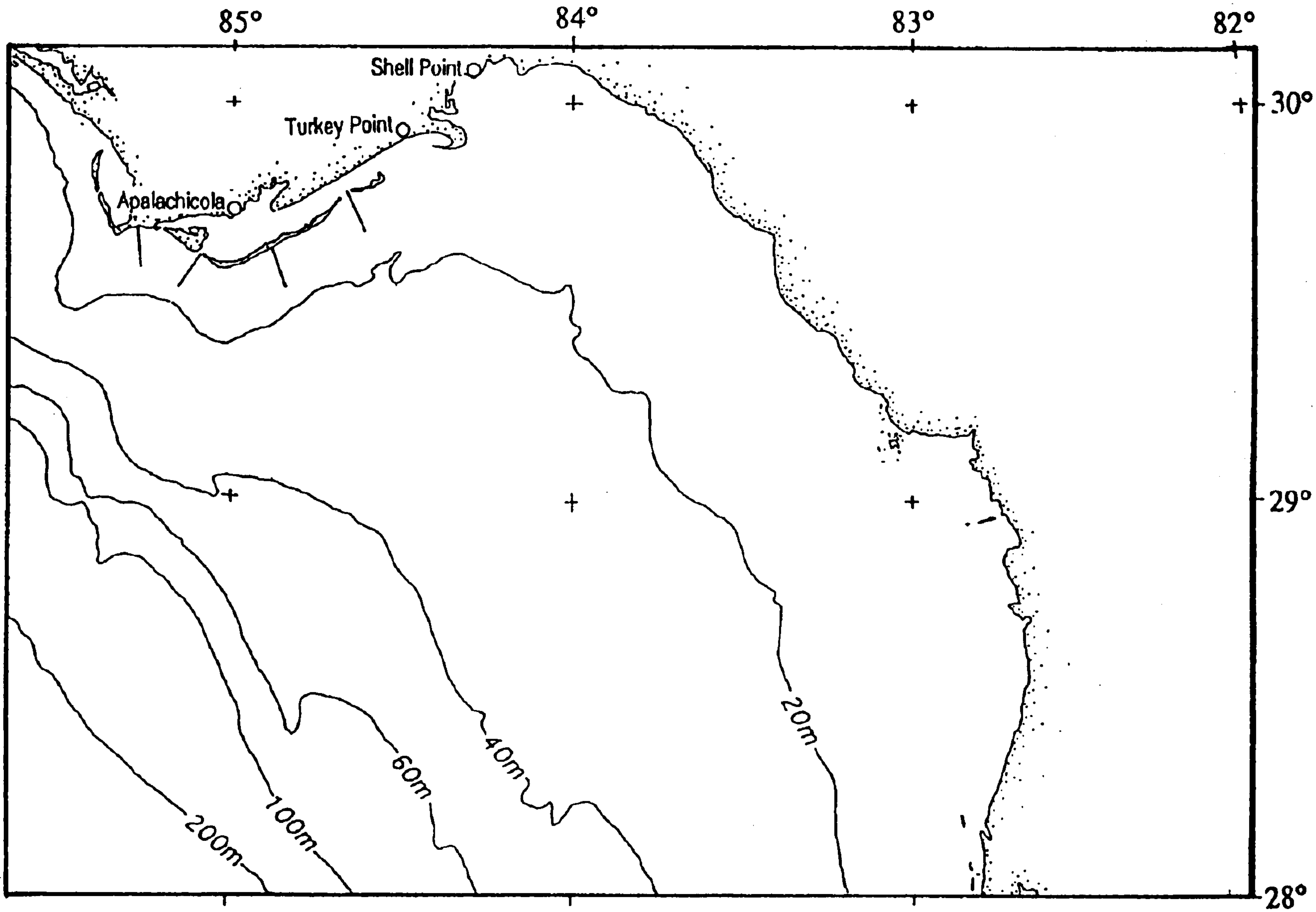

Figure 84. Proposed initial hydrographic sections for Apalachicola Plume study.

Strawman Plans for the Northeastern Gulf of Mexico Physical Oceanography Workshop, April 5-7, 1994, Tallahassee, Florida

The Fate of Mississippi River Effluent on the Mississippi-Alabama Shelf

by
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A single year's worth of carefully executed monthly hydrographic surveys in the late sixties indicated a persistent eastward transport of low salinity water from the Mississippi River along the shelf break. Depending on the season, these surface waters appeared to turn cyclonically onto the mid and inner shelf at different distances downstream from the delta. Because of the large area of surface water influenced by these low salinities, its capacity to transport large volumes of dissolved and particulate materials and the important frontal convergence zones associated with these waters, it is important to understand how characteristic this one year of data may be and what dynamical balances might have controlled the flow of the near-surface waters as they were moved against the climatological winds.

It would seem important to determine

* the characteristic flow patterns of low salinity waters from the eastern passes of the Mississippi River,

* the balance of forces controlling the flow of these waters,

* the depth of such flows, and

* the fate of these waters.

A minimal experiment would involve a single mooring along the shelf break with an upward-looking ADCP and a near-surface salinometer string supplemented by periodic hydrographic/ADCP cruises, satellite coverage and airborne salinometer surveys. The duration of the experiment should attempt to include high discharge conditions during periods with and without deep Loop Current intrusions into the northeastern Gulf.

Subsequent data analysis should determine the persistence of eastward flow at the shelf break and its dynamics. Is it a geostrophic flow? Is it intimately linked to the interaction of Loop Current eddies with the shelves of the northern Gulf? If so, must the linkage be local? Both satellite data and field measurements suggest strong eastward transport when the Loop Current or its eddies are interacting locally with the Mississippi-Alabama shelf, but numerical models also suggest that as Loop Current eddies spin down in the 'eddy graveyard' of the northwestern Gulf, there is increased eastward flow along the upper slope of the entire northern Gulf. If the plume recurves cyclonically onto the shelf, is this an inertial response or is it due to momentum transfer from the prevailing southeasterly winds? What balance of forces determines whether surface waters are entrained offshore along the edge of the Loop Current or its associated eddies? Satellite images, occasional drifters and salinity anomalies on the inshore edge of the Loop Current/Gulf Stream system all indicate that shelf waters of the northeastern Gulf can be entrained and advected through the Florida Straits during periods of deep Loop Current intrusion. It is not as clear whether such events occur at other times.

Strawman Plans for the Northeastern Gulf of Mexico Physical Oceanography Workshop, April 5-7, 1994, Tallahassee, Florida

Analysis of Historical Satellite Data Sets

by
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Prior to initiation of field efforts, a significant amount of information concerning the physical and biological patterns of variability on the shelves of the northeastern Gulf of Mexico may be derived from a careful statistical analysis of historical satellite data sets. Potentially the most useful are the thermal and visible AVHRR images from the NOAA satellites and the colour imagery from the Coastal Zone Colour Scanner (CZCS). Of equal dynamical importance will be an analysis of historical altimeter data.

Sea surface temperature fields derived from properly analyzed AVHRR thermal channel data provide data for a variety of different types of analyses during those times of the year when a significant thermal contrast is apparent between the surface waters of the shelf and slope:

* Statistical description of the scales and patterns of thermal fronts,

* Zeroeth-order estimates of the baroclinic pressure field on the west Florida shelf during the well-mixed winter season, and

* Possible estimates of the mesoscale circulation fields over the shelf using feature tracking techniques as demonstrated by Vastano in recent experiments on the Texas shelf and the Mississippi-Alabama shelf. The daily repeat orbits of the NOAA satellites effectively filters out tidal-inertial motion in the northernmost portion of the study area.

During the summer months when thermal contrasts between the various shelf waters are small, analysis of the visible data still allows description of the scales and patterns of flows fields associated with turbidity such as effluent plumes from the larger river systems. The downstream effects of the effluent from such systems may still be visible in the CZCS data sets after the turbidity signal has dissipated. The CZCS data will also delineate patterns of motion associated with the Loop Current such as shelf edge interactions, spin-off eddies and their interaction with the shelf as they trace non- conservative biomass indicators.

Evidence is accumulating from recent studies of altimetric data that these data sets can provide useful information concerning the variability of sea surface height over the continental shelf and slope. Consequently, a careful analysis of both the GEOSAT and TOPEX/POSEIDON data sets should be undertaken early in the course of any large program to study the shelves of the northern Gulf.

The time scales which can be resolved from these three different types of satellite data range from the daily to the interannual. Resolvable spatial scales range from shelf-wide scales to a few kilometers. Problems with cloud cover associated with thermal and visible imagery can be overcome using compositing, objective analysis, and dynamical interpolation. Expected products will be descriptions, visual and statistical (probability distributions, EOF patterns), of features as well as more complicated estimates of velocities and pressure gradients which might serve as input to model forcing or calibration.

Strawman Plans for the Northeastern Gulf of Mexico Physical Oceanography Workshop, April 5-7, 1994, Tallahassee, Florida

Shelf Scales of Variability

by
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No theoretical dispersion relationship exists relating the spatial and temporal scales of motion on the shelves of the northeastern Gulf of Mexico. Neither do there exist sufficient measurements to define the spatial and temporal scales of the energy containing eddies over the shelf. It is known that coherence scales of horizontal motion are generally short. Analysis of satellite imagery has indicated that, at least on the Mississippi-Alabama shelf, meso-scale motions of a few tens of kilometers diameter are characteristic features of the near-surface flow field. Furthermore, the spatial scales of the shelf itself are sufficiently small that modest flows can advect properties across the shelf in only a few days.

In order to understand the aliasing associated with hydrographic cruise data and to limit the sampling required to adequately monitor these shelves, a study should be carried out to define the time and space scales associated with the meso-scale eddies of the shelf and to determine their origin. Such a study would include

* quasi-Lagrangian surface drifters with GPS location capabilities,

* rapid surveys of the velocity and hydrographic fields using ADCP, CTD and/or a SeaSoar type instrument, and continuous mapping of the near-surface fields, and

* high-resolution satellite and airborne monitoring of the sea surface.

Analysis should focus on determination of the size, intensity and persistence of meso-scale patterns. While there is existing evidence for near-surface flows, it is not clear whether these are surface-trapped features or penetrate deeply into the water column. The origin of the flows should also be illuminated. Do they result from the wind stress field or from horizontal shear? Are they more intense during the winter or when the Loop Current is deeply intruded into the Gulf?

APPENDIX B. Agenda

Northeastern Gulf of Mexico Physical Oceanography Workshop

Tuesday, April 5, 1994

8:00-9:00 Registration, coffee, bagels & fruit

Everglades Auditorium

9:00-9:05 Welcome to Tallahassee - Dean L. Abele, College of Arts & Sciences

9:05-9:15 Introduction and Announcements - Dr. A. Clarke & Dr. M.Brown

9:15-9:20 Organization of the Workshop - Dr. Allan Clarke

Session 1 Overview of the Physical Oceanography and Meteorology on the West Florida, Alabama and Mississippi Shelves in the Study Region
Session moderator: Dr. K. Brink

9:20-9:50 Overview of the physical oceanography of the Mississippi-Alabama shelf in the study region by W. Schroeder, S. Dinnel, F. Kelly & W. Wiseman.
Part I - Dr. W. Schroeder

9:50-10:20 Overview of the physical oceanography of the Mississippi-Alabama shelf in the study region by W. Schroeder, S. Dinnel, F. Kelly & W. Wiseman.
Part II - Dr. W. Wiseman

10:20-10:40 Coffee Break

10:40-11:30 Overview of the physical oceanography of the Florida shelf in the study region - Dr. A. Clarke

11:30-11:50 The influence of the Loop Current on the shelf circulation in the study region by F. Kelly & A.C. Vastano. - F. Kelly

Tuesday, April 5 (continued)

11:50-12:10 Overview of the meteorology in the study region. - Dr. P. Ruscher

12:10-1:40 Lunch

Session 2 Recent Measurements/Challenging Problems in the Study Region
Session moderator: Dr. R. Garvine

1:40-2:00 Relationship of primary production to physical oceanography in the Northeastern Gulf of Mexico - Dr. S. Lohrenz

2:00-2:20 U.S.G.S. coastal studies in the Northeastern Gulf of Mexico - Dr. G. Gelfenbaum

2:20-2:40 Recent current meter measurements on the shelf off Pensacola - Dr. W. Sturges

2:40-3:00 Satellite results for the Northeastern Gulf of Mexico - Dr. K. Carder

3:00-3:20 Shelf circulation and grouper recruitment - Dr. C. Koenig

3:20-3:40 Coffee break

3:40-4:00 Fresh water input from springs - Dr. W. Burnett

4:00-4:20 Surface drifters - Dr. P.P. Niiler

Northeastern Gulf of Mexico Physical Oceanography Workshop

Tuesday, April 5 (continued)

4:20-4:40 The Florida Marine Research Institute Coastal Ocean Study and SEAMAP by Dr. K. Haddad - Dr. C. Tomas

4:40-5:00 Some recent measurements from Florida Marine Research Institute's coastal ocean study - Dr. C. Tomas

5:00-7:00 Reception at the Conference Center

Wednesday, April 6

7:45-8:30 Coffee, doughnuts

Everglades Auditorium

8:30-8:35 Announcements, overview of the day - Dr. A. Clarke

Session 3 Logistics and Ongoing/Planned Measurements of Relevance to the Study Region

Session moderator: Dr. L. Atkinson

8:35-8:55 Management & logistical lessons learned during LATEX by W. Nowlin & D. Wiesenburg - Dr. D. Wiesenburg

8:55-9:05 Operational oceanographic data management in the Gulf of Mexico by Dr. D.R. McClain - Dr. M. Brown

9:05-9:25 Scientific results of LATEX relevant to the proposed study - Dr. R. Reid

9:25-9:45 Surface current measurements using HF Doppler radar - Dr. H. Graber

Wednesday, April 6 (continued)

9:45-10:05 Planned navigation tower and Doppler radar measurements in the Northeastern Gulf of Mexico - Dr. K. Kloesel

10:05-10:25 U.S. southeast continental shelf inner shelf processes relevant to the northeastern Gulf of Mexico inner shelf - Dr. J. Blanton

10:25-10:45 Coffee break

Session 4 Modeling of the Region

Session moderator: Dr. K. Brink

10:45-10:55 Needs of MMS/the Oil Spill Risk Analysis model - Dr. R. P. LaBelle

10:55-11:05 Results for the NEGOM using the Dynalysis Model by Dr. R.C. Patchen & Dr. J. Herring - Dr. R. Patchen

11:05-11:25 A 3-D model of GOM and shelves - Dr. L. Oey

11:25-11:45 Regional modelling in the northeastern Gulf of Mexico - Dr. J.K. Lewis

11:45-12:05 A wind-driven shelf flow model - Dr. A. Clarke

12:05-1:40 Lunch

Northeastern Gulf of Mexico Physical Oceanography Workshop

Wednesday, April 6 (continued)

Session 5 Development of an Experimental Plan

1:40-2:05 Some strawman experimental plans - Dr. W. Wiseman

[These plans are meant to stimulate discussion and help generate good ideas. They may be changed completely in the subsequent breakout and plenary sessions.]

2:05-2:10 Conference participants proceed to 3 breakout rooms (see Breakout Room Assignment sheet)

2:10-3:30 Breakout room discussion: Strengths and weaknesses of the strawman plans/Development of different experimental plans

Breakout room chairmen: Dr. K. Brink, Dr. R. Garvine, Dr. L. Atkinson

3:30-3:50 Coffee break

3:50-5:00 Further breakout room discussion in the 3 breakout rooms

5:15-6:15 Executive Meeting of the Program Manager (leader/facilitator), COTR and the Breakout Room Chairmen
Topic: Discussion and summary of breakout room ideas

Thursday, April 7

7:45-8:30 Coffee, doughnuts

Everglades Auditorium

8:30-10:00 Workshop Reports - Dr. K. Brink, Dr. R. Garvine, Dr. L. Atkinson

10:00-10:20 Coffee break

10:20-11:50 Plenary discussion of the workshop reports/Formulation of an experimental plan

11:50-12:00 Closing remarks - Dr. M. Brown

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RADAR OBSERVATIONS OF COASTAL CURRENTS OFF THE ALABAMA-FLORIDA SHELF

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Filaments from the Loop Current frequently meander northward and intrude the shelf and coastal waters via the DeSoto canyon off the coast of Pensacola. To understand how these intrusions interact and/or influence the shelf flow in this region we propose to measure the surface vector current field with an HF Doppler radar from two shore stations located at the barrier islands near Pensacola. The radar observations would also be used to intercompare drifter measurements and provide critical background conditions to explain the tracks of drifters.

Shay *et al.* (1993) has shown that the long-time series data acquired by HF radar as a function of space at 700 grid points are crucial to improve our understanding the complex coastal ocean (Brink *et al.*, 1992) especially since Eulerian surface currents cannot be measured by conventional measurement techniques. In concert with aircraft, drifter, mooring, and ship-based observations, these data can be used to isolate upper ocean physical processes and gain insight into the evolution of complex surface features. Furthermore, the surface current measurements from the radar can be processed to reveal tidal components, mean flow characteristics, near-inertial flow, as well as the Stokes drift and Ekman fields when combined with wave and wind field observations.

The use of an HF radar offers many advantages over standard methods including the short time required and insensitivity to meteorological conditions and optical transmittance. The ability to sample a wide region in a short period of time and provide current vector maps in near real time would significantly enhance any field measurement program in providing the latest information to guide ships for hydrographic/ADCP surveys or for rapid response sampling by small vessel of opportunity and to aircraft for the deployment of either drifter or expendable AXCPs and AXBTs. Such maps could also be superimposed onto AVHRR thermal imagery on cloud-free or partially cloudy times to correlate SST features with the surface flow pattern. Radar observations can also be made in adverse weather conditions that would not allow small vessel operation. Measurements can also be made on cloudy days that would inhibit spaceborne or airborne observations from visible and infrared sensors. The calculation of the Doppler frequency spectra is not dependent upon materials in the water column and consequently could be used when sediment or biological material would be present. This may be important in regions of significant sediment inflow from rivers (Apalachicola) or deltas (Mississippi), or when biological activity is high.

The RSMAS dual-frequency ocean surface current radar (OSCR) utilizes HF (25.4 MHz) and VHF (49.9 MHz) radio frequency to map surface current patterns over a large area in coastal waters. The shore-based radar system consists of two units (Master and Slave) which are deployed several kilometers apart. Each unit makes independent measurements of current speed along radials emanating from its phased-array antenna system. The data are then combined via UHF or telephone communication to produce accurate vector currents (speed and direction) and display them in near real time. The measurements can be made simultaneously at up to 700 grid points either at 1 km (HF mode) or 250 m (VHF mode) resolution. The range of the radar would extend about 45 km offshore and the two stations would be about 30 km apart. One vector current map is produced every 20 minutes.

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Ocean models used for analysis and prediction of surface waves (including surf), currents (wind-driven), and water level (surge) are forced primarily by the time-space evolution of surface winds. It has long been recognized that uncertainties in surface marine wind fields specified from typical historical and climatological meteorological data are the primary source of error in ocean model generated data (*e.g.*, Cardone *et al.*, 1990). This deficiency has been highlighted with the hindcasts in the SWADE IOP-1 event of October, 1990 (Graber *et al.*, 1991 and Cardone *et al.*, 1994). On the other hand, since ocean wave models are very sensitive to such errors in the atmospheric forcing, they could be used as indicators of the fidelity of the wind field (*e.g.*, Bauer *et al.*, 1992).

There is also a substantial growth in evidence that the presence of waves on the ocean surface influence the calculation of wind stress in two ways:

(1) Experimental results have shown that the aerodynamic drag coefficient depends on sea state, because the roughness of the sea surface is coupled to waves (for a detailed review see Donelan, 1990). Such a relationship might be intuitive from studies of fluid flow over solid walls, but in practice a description of the sea surface roughness is complicated by the fact that waves are mobile and constantly evolving in space and time.

(2) Recent observations suggest that the direction of the surface wind stress is not co-aligned with the direction of the wind when swell and/or large wind waves are present (Geernaert, 1993). Swell waves propagate in directions independent of the wind direction and it is believed that swell-induced orbital velocity modulations of roughness steer the direction of the stress towards the wave direction.

While dissipation by wave breaking from whitecapping to the more ubiquitous microscale breaking is the least known source term in ocean wave models, its effect on mixed-layer dynamics cannot be denied. Sufficient experimental evidence exists that large contributions of momentum are injected by breaking waves into currents within the upper layer. Simple calculations of the available energy flux from a breaking wave suggest that it is substantially larger than typical values used in mixed layer models. Field measurements (Graber *et al.*, 1994) under breaking waves show energy dissipation rates an order of magnitude higher than the traditional wall layer estimates. The depth over which breaking directly affects mixed layer dynamics is an issue which needs to be resolved. Laboratory results indicate that the injection of bubbles due to breaking penetrates to depths of several times the wave height.

It is obvious from the above statements that surface waves play a crucial role in air-sea interaction for specifying the correct wind and wind stress vector which drive ocean models and in mixed-layer dynamics to estimate the wave-induced momentum flux into the upper layer and the depth of the mixed layer.

Therefore, we propose to deploy three modified NDBC 3-m discus buoys like those deployed during the Surface Wave Dynamics Experiment (SWADE) (Weller *et al.* 1991) and the High-Resolution Remote Sensing Program (HIRES) (Herr *et al.* 1991). The buoys were deployed for the purpose of continuously monitoring the directional wave field and the surface fluxes. Shipboard measurements of heat, humidity and momentum fluxes suffer from severe flow distortion effects and cannot be considered accurate. However, with these buoys, Anctil et al. (1994) have made the first reported attempt to obtaining direct estimates of the air-sea fluxes from measurements made on a small surface-following buoy. The buoys would be equipped with a sonic and/or K-Gill anemometer, a humidity sensor (Licor) and a motion sensing package in addition to the standard NDBC payload (Steele *et al.* 1992). Furthermore, a three-axes sonic current meter could be deployed in the mooring line at a depth of 10 m to provide near-surface measurements of horizontal and vertical currents, temperature, pressure and density.

The deployment sites of the buoys should be chosen when (1) the region and focus of the NEGOM field program is defined and (2) in concert with existing operational buoys and platforms from NDBC and the offshore industry as well as the C-MAN stations. The experimental objective of these buoys is to maximize the observations of the meteorological conditions in the NEGOM as accurately described by the strawman "Meteorological Experiment" by Scott P. Dinnel.

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SURFACE CIRCULATION OF THE EASTERN GULF SHELF

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The Alabama-Florida shelf has complicated space-time variable circulations. Forcing of these patterns are due to tides, winds, river flux and Loop Current eddies all of which change their intensity and time and space scales through seasons. The spatial patterns of the shelf response can be very complex, depending on the stratification on the shelf and the relative strengths of the forcing functions. The time scale of response of the circulations can be as short as several hours during the passage of storm systems or several months as is attributed to the evolution of the Loop Current intrusions into the northern Gulf. The complexity of the shelf response is further enhanced by highly variable topography and irregular coastline. Observations of circulation in this area are scant and those that exist are not well suited for analysis of the fate of man-made substances in the study area. A measurement program, using air-deployed surface drifters, is proposed which would allow the determination of space-time evolving patterns of circulation over the continental shelf and provide a data set for a direct assessment of the fate of particles released in the surface waters of the continental shelf.

The scientific issues are:

1) What are the spatial and temporal patterns of surface velocity?
(Can we make a map of surface currents on the entire shelf?)

2) What is the character of dispersion - random/shear/jets?
(Will maps of velocity be good enough to replicate dispersion?)

3) What is the difference between observed and modeled velocity?
(Is the difference random or does it have "structures"?)

4) What is the fate of particles released from several sites?
(Are there "accretion" zones and "forbidden" zones?)

The program would begin with a design study of the drifter sampling array; approximately 200 drifters would released over the winter season, which is the strongest synoptically wind forced season. After the array is designed, a two year systematic measurement program will follow.

SAR IMAGERY

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Figure 85 is a SEASAT SAR image of the water surface in the Gulf of Mexico (**cloud penetrating**) taken on August 1978. It is centered at 27°55'N 83°57.7'W, with 100 x 100 km size (see map, Figure 86). The satellite velocity is towards 341°, as marked on the left side of the image (below the wedge). Resolution is about 30m. Image brightness increases with the intensity of short waves, roughly 20 cm long, in the area.

Features observed in the image include:

1) Internal waves and ship wakes can be seen mostly at the top of the image (under the wedge).

2) Dark linear features in bright regions of the image. They could indicate areas of enhanced localized shear and/or surfactant materials (oil?).

3) Circulation features such as eddies, outlined by the dark linear features.

4) The brightness of the image exhibits two distinct regions, one bright and one relatively dark. This indicates a wind effect and/or a change in the air/sea temperature difference at the brightness front.

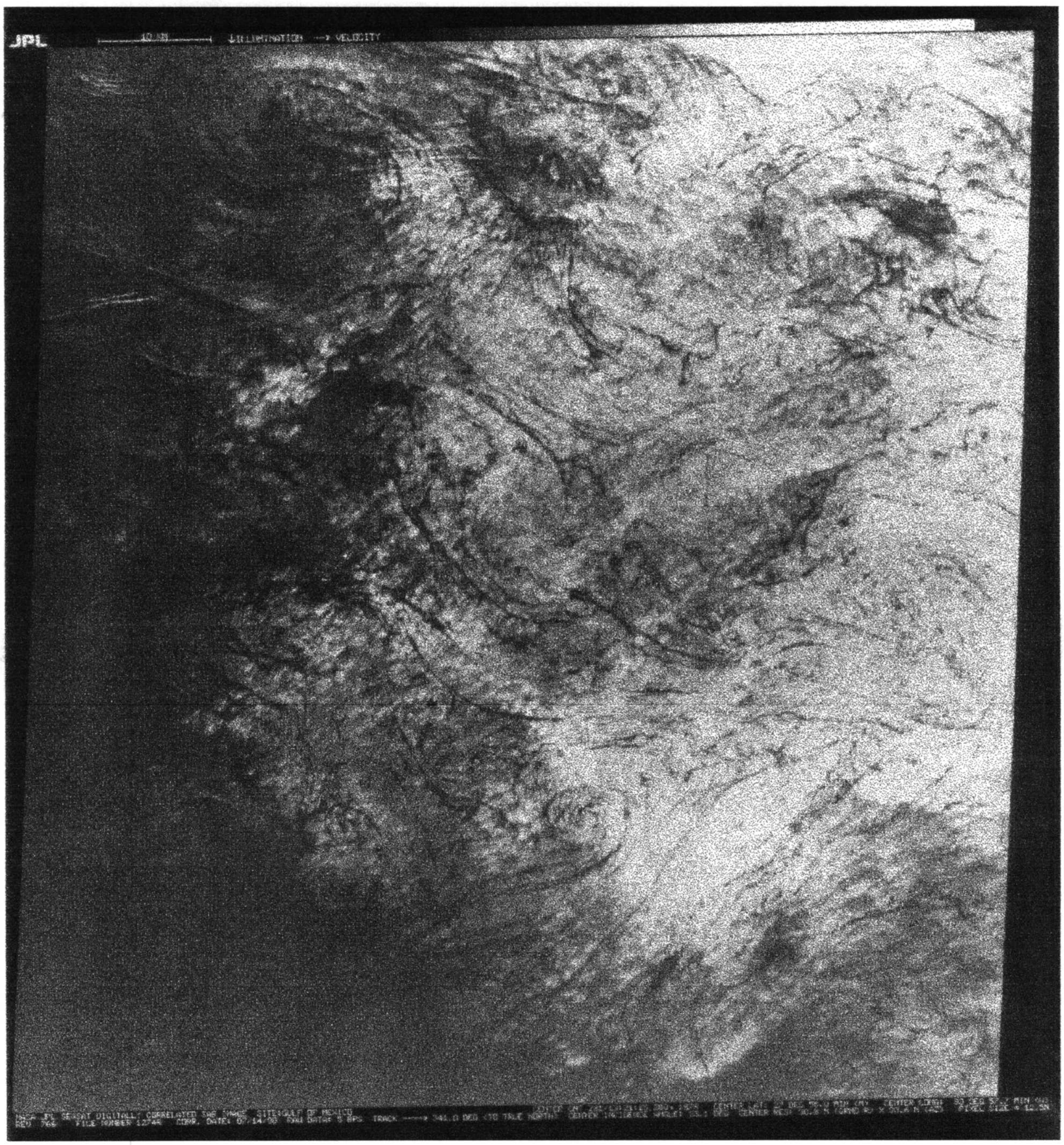

Figure 85. SEASAT SAR image.

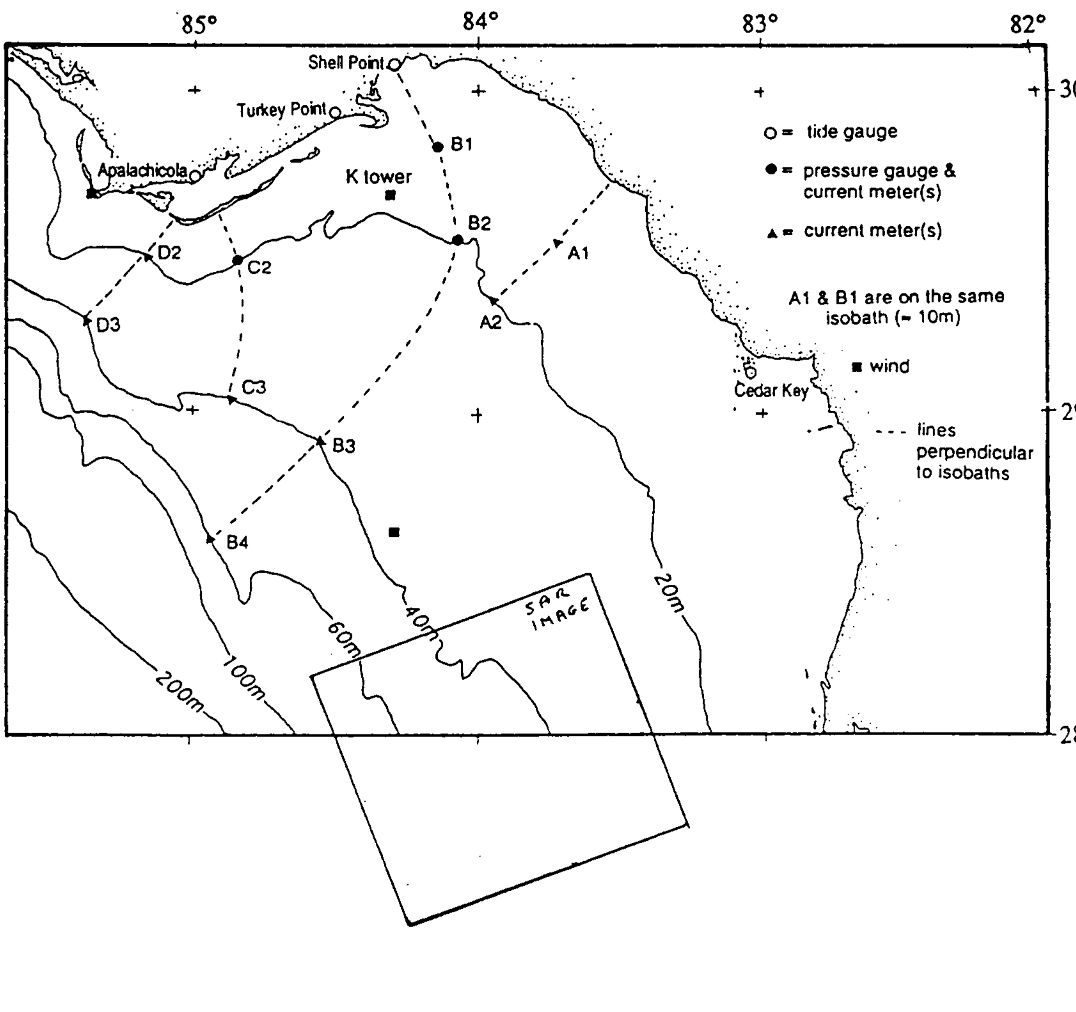

Figure 86. Map showing location of SEASAT SAR image of Figure 85.

The Department of the Interior Mission

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

The Minerals Management Service Mission

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

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

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