OCS Study
MMS 87-0006

Gulf of Mexico Physical Oceanography Program Final Report: Year 4

Volume I: Executive Summary

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

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EXECUTIVE SUMMARY

I. INTRODUCTION

In 1982, Minerals Management Service (MMS) initiated a multi-year program under contract with Science Applications International Corp. (SAIC) to study the physical oceanography of the Gulf of Mexico as part of its outer continental shelf environmental studies program. This particular program, called the Gulf of Mexico, Physical Oceanography Program (GMPOP), has two primary goals:

- Develop a better understanding and description of conditions and processes governing Gulf circulation, and
- Establish a data base which could be used as initial and boundary conditions by a companion MMS funded numerical circulation modeling program.

The area to be studied emphasizes the deeper Gulf and those shallower regions where conditions may be directly or indirectly affected by patterns associated with or originating in the deeper Gulf. This multi-year, phased program will investigate the eastern and western Gulf separately (Figure 1.1-1). This report presents results from three years of observations in the eastern Gulf.

1.1 Program Participants

Science Applications International Corp., the prime contractor for the GMPOP, is working with a team of scientists from SAIC, universities, and institutes to study physical oceanographic processes and conditions in the Gulf. The present report is an addendum or supplement to the Years 1 and 2 Final Report. As such the primary participants during this third eastern Gulf year differed somewhat from the first two years. However, material developed by Years 1 and 2 principal investigators is used and incorporated into presentations in this report.

Presented below is a list of participating scientists and a brief description of their technical involvement during Program Year 4:

- Mr. J. Miller (U. of Miami) and Dr. L. Atkinson (Old Dominion University) - Hydrographic and kinematics of Loop Current (LC) boundary events.
- Dr. J. Lewis (SAIC) - Kinematics and dynamics of the Loop Current and LC eddies.
- Dr. W. Sturges (FBN Oceanography) - Lower frequency wind and Loop Current forced West Florida Shelf circulation.
- Dr. G. Lagerloef (SAIC) and Dr. P. Hamilton (SAIC) - Inertial currents on the West Florida Shelf.

The above are the primary authors of the Year 4 report.

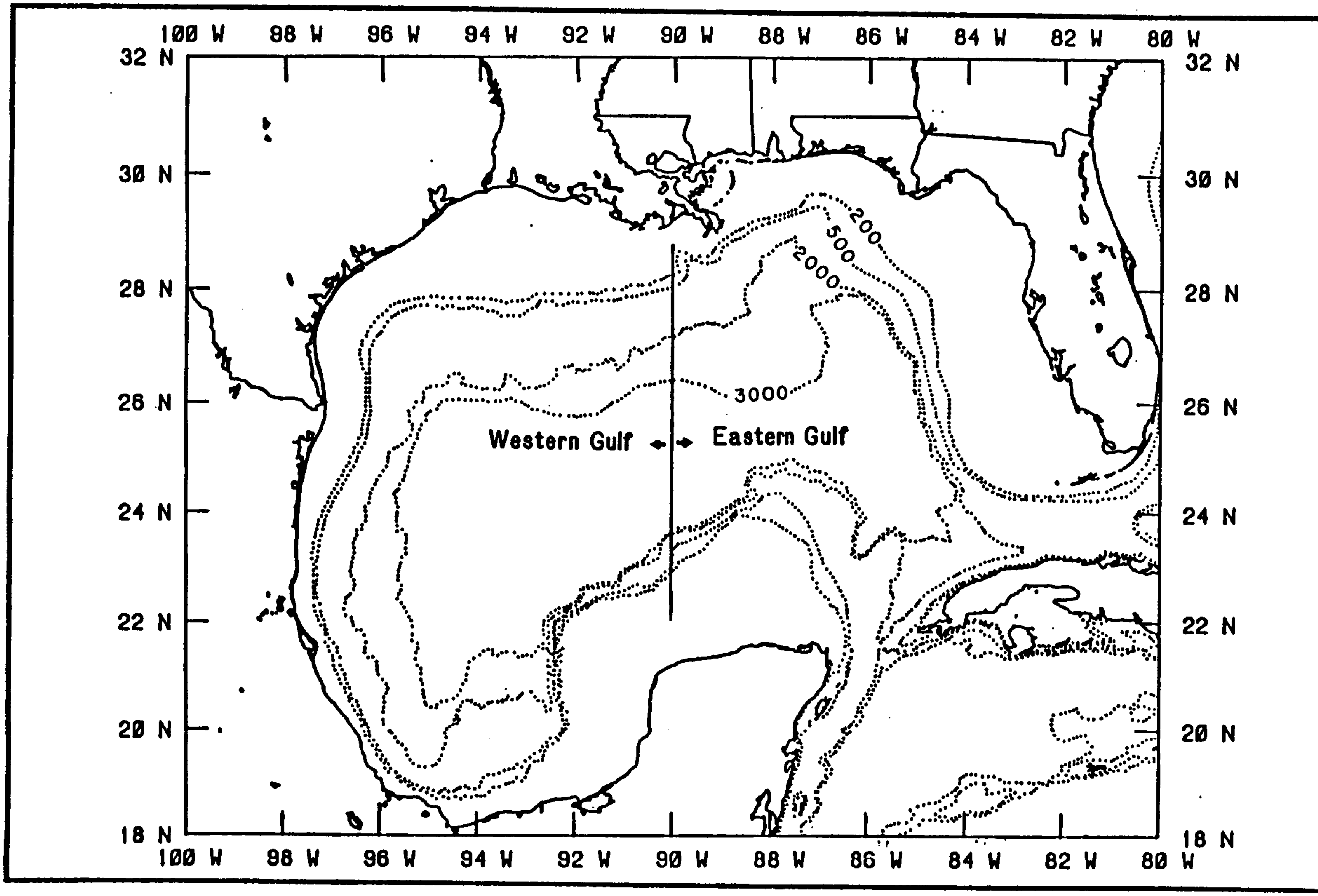

Figure 1.1-1. Gulf of Mexico bathymetric map showing the nominal partition of the eastern and western Gulf of Mexico study areas. This also partitions the emphasis on the Loop Current and Loop Current eddies.

The above indicates the primary areas of responsibility. In so doing, each investigator used elements of the available three-year, multivariate data base to help resolve and identify key patterns and processes. In addition, Mr. R. Wayland (SAIC) is Data Manager for Yr. 4 of GMPOP. As such he has worked closely with the above scientists to provide needed data analysis and data products. Dr. E. Waddell is Program Manager for GMPOP.

1.2 Program Tasks

The above program participants undertook the following primary scientific efforts during Program Yr. 4:

- Kinematic and hydrographic characterizations of Loop Current boundary features, e.g., waves, filaments or perturbations.

- Comparative kinematics and dynamics of the Loop Current and a LC eddy as indicated by drifting buoy trajectories.

- Further discrimination and characterization of West Florida Shelf circulation patterns, e.g., inertial currents, wind and Loop Current forced currents.

During Year 4, the new data included a third year of subsurface current/temperature and pressure and additional drifter trajectories. To accomplish these tasks, data from all three program years were available to and used by the investigators. Aspects of these elements may have been addressed using two years of data. With access to the more comprehensive data sets, additional insights could be developed.

II. TECHNICAL DISCUSSION

2.1 Introduction

The following summarizes key material developed and described in Vol. II, Chapter 4, of this report. Such a synopsis cannot be comprehensive but rather identifies and describes the more relevant and important insights. No effort is made in this summary to verify or prove the points discussed. For that more detailed level of presentation the the reader is directed to Vol. II of this report.

2.2 Lagrangian Drifters

During Year 4, GMPOP had a unique opportunity to compare the simultaneous motions of drifters located in a Loop Current eddy that had just pinched off and in the reminent Loop Current (Figure 2.2-1). This comparison included both kinematic and dynamic analyses and descriptive characterizations of these two features, with special emphasis on the rotational aspects of both. It is important to note that the LC eddy described (Buoy No. 3378) continued to move westward and provided the basis for a uniquely extensive and comprehensive, multivariate study of Loop Current eddies which will be described in detail in a report concerning Program Year 3. The present information serves to characterize some initial eastern Gulf aspects of that fairly complete LC eddy life cycle.

In the present study, primary data sources were weekly composite sea-surface temperature (SST) maps, MMS-funded ship-of-opportunity (SOOP) expendable bathythermograph (XBT) transects, and the ARGOS drifting buoy trajectories. The period of time presented extends from mid-June through September, 1985. The setting for the comparative information is as follows:

- Buoy 3354 was deployed in mid-June in what was believed to be at the center of a pinched off LC eddy. In fact, separation was not complete and this buoy moved southeastward. While this was occurring and being monitored in real time, it was realized that a completed break-off had not been "seeded" and another drifter was released in what was believed to be an eddy in mid-July. Thus, from mid-July through September, 1985, buoys were entrained in the eddy and the Loop Current.

Several key aspects resulting from trajectory analysis are:

- The separated ring was initially ellipical but evolved into a more circular shape within about 2 revolutions of buoy placement. This may be part of the "relaxation" phase seen in anticyclonic rings in the Gulf Stream region.

- For both the eddy and in the closed anticyclonic feature embedded in the Loop Current, there was a current shear so that period of rotation got longer with proximity to the eddy center. This is consistent with the expectation of higher speed current being localized nearer the outer edge of an eddy and the LC.

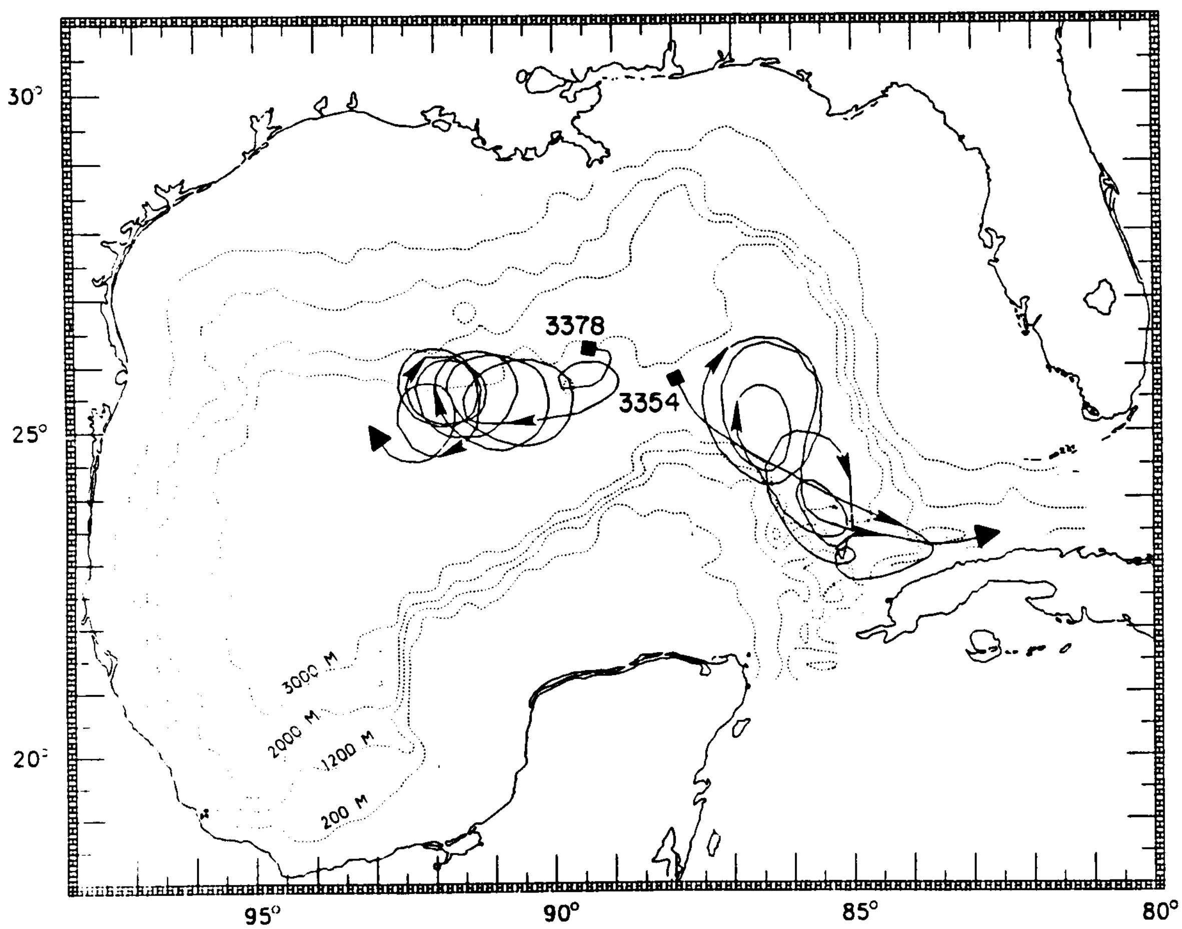

Figure 2.2-1. Trajectories of Drifter 3354 (in the Loop Current) from mid-June through mid-September, 1985 and Drifter 3378 from mid-July through mid-September. The square indicates the deployment position and the large triangle the final position used in this report.

- Drifter velocities, which varied from 30-90 cm s^{-1} depending on drifter location, seemed to decay slightly with "age". It is quite possible that drifters were never entrained in the higher speed core associated with the zone of stronger shear.

- In both features the buoys indicated closed circulation features. This is expected in the eddy but was previously undocumented in the LC.

The motion of the LC drifter suggests that at least during part and possibly all of a LC eddy shedding cycle, a recirculating anticyclonic (clockwise) gyre is embedded within the Loop Current. Motion of Buoy 3354 indicates that this pattern occurred at least during and immediately following eddy separation. Other buoy data as yet unpublished suggests this embedded anticyclonic feature may exist prior to completion of eddy separation (personal communication, Forristall).

A key point is that the basic closed pattern of clockwise rotating water may exist regularly in that region interior to the higher speed flow regimes and can develop at least during or immediately after LC eddy separation. This circulation pattern was maintained as the LC built northward so that within approximately 1.5 months the LC had the northward extension combined with an anticyclonic rotation pattern which forms the basis for subsequent eddy separation. These drifter trajectories did not suggest what may cause eddy separation to be initiated.

Documentation of this internal LC recirculation points to the need for further drifter deployments in the LC to evaluate the presence and characteristics of this pattern.

2.3 Loop Current Boundary Features

As part of the Year 1 and 2 Final Report an initial analysis of combined hydrographic and Acoustic Doppler Current Profiles (ADCP) was made (Figure 2.3-1). However, timing of that report and the need for software development and data processing resulted in a preliminary discussion. The important ADCP portion of that cruise was an added measurement which was available only because the vessel to be used happened to have one on board at the time and SAIC's technical team was experienced in its use. During the cruise both individual transects and time series of transects were made.

The primary focus of the May, 1984 cruise on which the hydrography and current profiling were accomplished was to document and better understand the interaction processes of the LC and the adjacent West Florida Shelf (WFS) waters. Prior studies in this region and elsewhere clearly pointed to boundary wave perturbations and frontal eddies as important interaction mechanisms. Fortunately, this study benefited from previous Gulf Stream (GS) studies which are dynamically similar to the LC situation. These studies have shown that GS and quite probably LC forcing of circulation can be very important on the outer shelf. The LC has the added degree of variability that both its N-S extent and E-W position can vary which effects the governing interaction and exchange processes on the outer WFS.

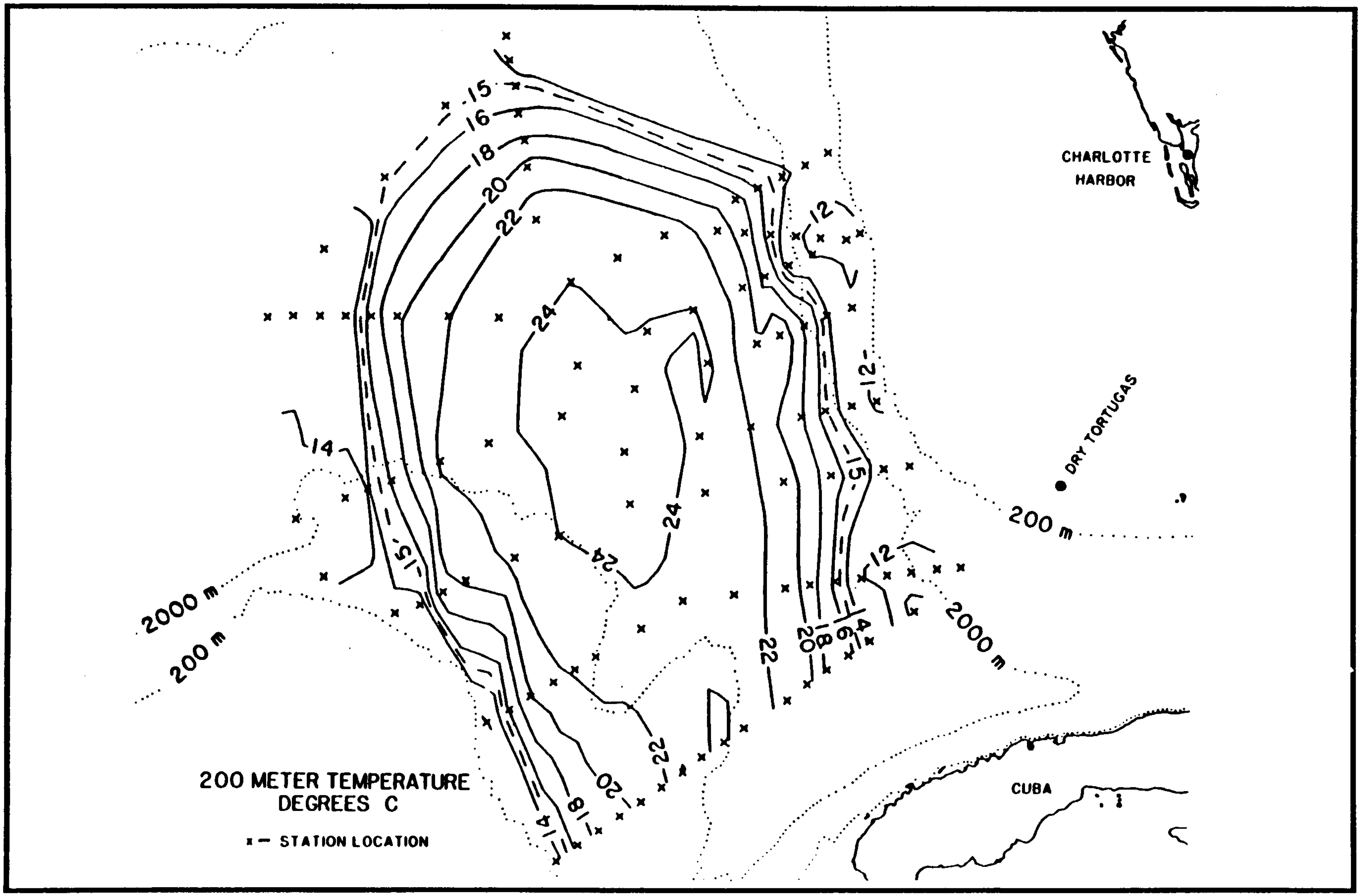

Figure 2.3-1. The general Loop Current configuration during the acoustic doppler current profiling and hydrographic cruise. Note the several cold pools on the eastern boundary which are probably associated with waves and the cold perturbation southwest of the Dry Tortugas.

The general pattern has wave-like oscillations in the LC boundary propagating southward (downcoast). This caused a corresponding E-W oscillation of this boundary. In the wake of a wave crest, investigators have often found a cyclonic (counter clock-wise rotating) eddy consisting of relatively cool (geostrophically upwelled) water surrounded on the downstream and shoreward sides by a relatively thin filament of LC water. This filament seems to grow as it migrates downstream. However, evaluation of thermal imagery has not shown that such features "turn the corner" and move through the Florida Straits as an identifiable feature.

One other feature, which is often seen in IR imagery and was sampled during this cruise, was a large cold perturbation located southwest of the Dry Tortugas.

2.3.1 Cold Perturbation

Within the cold feature, as expected, cyclonic circulation occurred with strongest currents closest to the LC boundary. Across this boundary into the LC very strong shear occurs with speeds increasing to four knots on the northern side of the perturbation. Note that the higher speed core current which occurs fairly close to the thermal boundary of the LC must change direction by almost 180° in going around the southwestern end of the cold perturbation and exiting the Gulf via the Florida Straits.

On a subsequent survey (about 2 weeks later) the plan view and location of the perturbation had changed although the domed isotherms presisted. Its southwestern most extension had moved eastward and retained high velocity flows (greater than 3 knots) just seaward of the LC boundary.

2.3.2 Frontal Eddies

The May 1984 cruise (CF8405) documented a filament and adjacent boundary current at a horizontal resolution appropriate to discern internal velocity patterns (Figure 2.3-2). Analysis suggest that at least in a documented early stage of filament evolution, recirculation did not occur within the filament and the flow field extended from the surface to near the bottom. Circulation patterns similar to that mentioned above continued throughout a time series of transects taken during partial passage of this boundary wave and associated filament. These observations are consistent with theories which describe frontal eddies as upwelling vortices generated in the lee (downstream) of southward propagating onshore meanders of the Loop Current front.

2.4 West Florida Shelf Circulation Pattern

2.4.1 Introduction

Subsurface currents used in the present study were measured at a variety of shelf, slope and deep water locations (Figure 2.4-1). Because of the vertical extent, resolution and temporal coincidence different combinations of observations were used in the discussion of eastern Gulf circulation patterns.

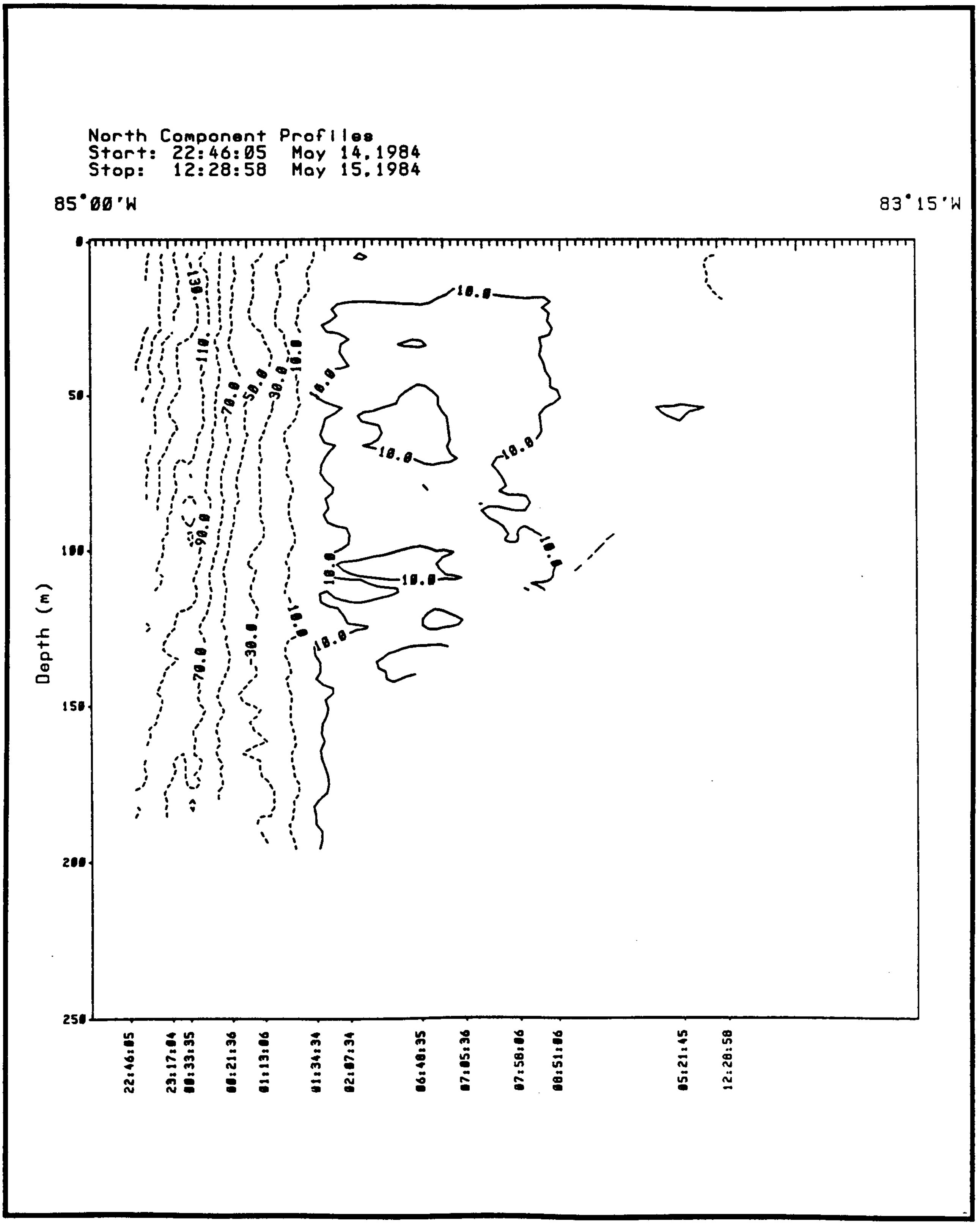

Figure 2.3-2. A cross section of the cyclonic shear boundary on the eastern Loop Current boundary (negative velocities are southward or downcoast). The weaker northern flow east of the high velocity southerly flow was probably associated with a filment. The maximum down cast velocity is greater than 190 cm sec^{-1} ($\geq$ 4 kts.). The horizontal scale in this figure is 105 nautical miles. Most of the horizontal shear occurs in less than 20 nautical miles.

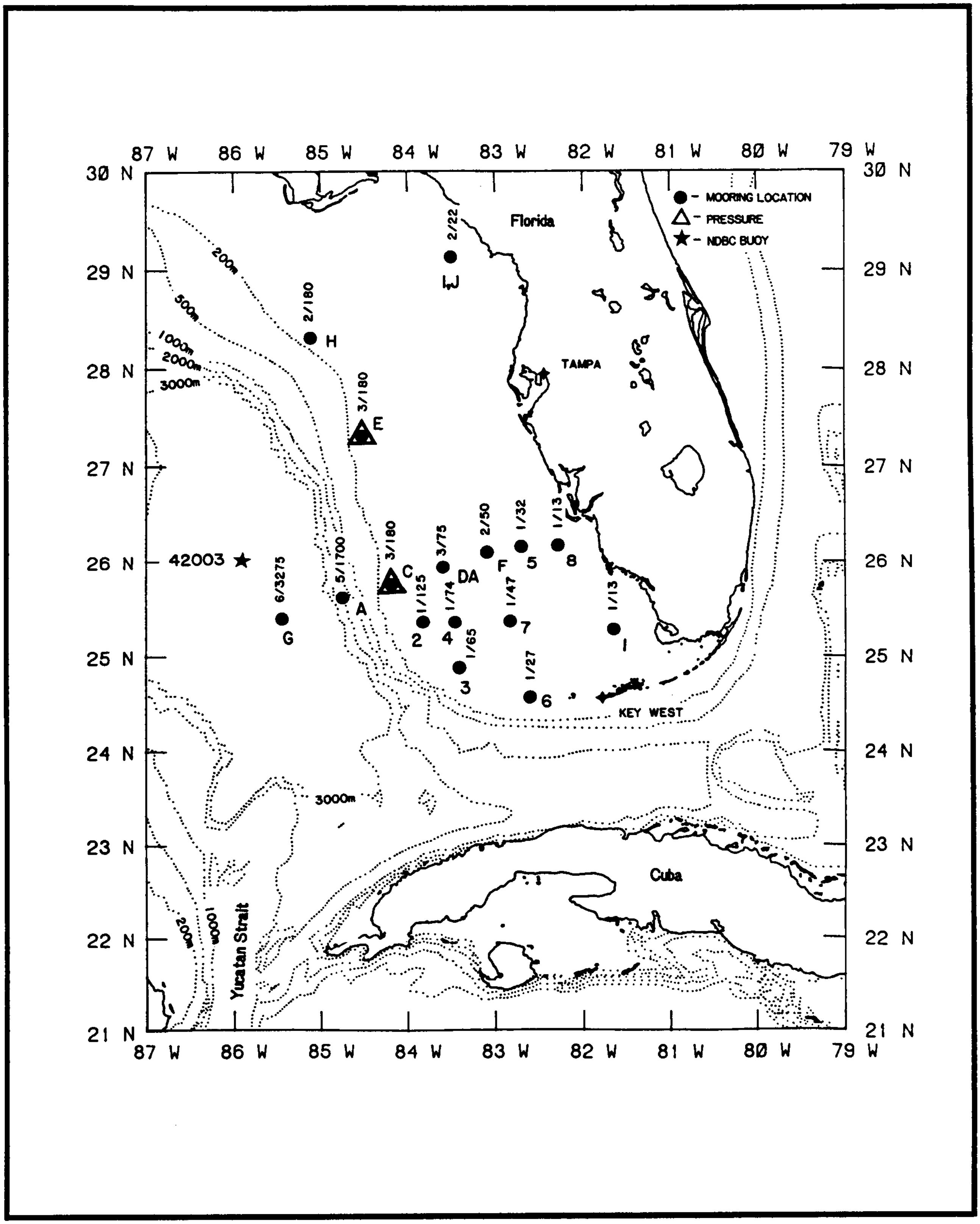

Figure 2.4-1. Map showing the location of the various subsurface current measurements made during or available to the GMPOP. Moorings 1-8 were near-bottom current meters deployed by Environmental Science and Engineering, Inc. under a concurrent MMS-funded benthic field measurement program.

2.4.2 Inertial Current

Higher frequency motion (periods $\leq$ 1.5 days) contribute a large portion of the current fluctuations and hence kinetic energy (Figure 2.4-2). In the absence of direct Loop Current forcing the high frequency fluctuations may account for 50-85% of the total energy at the measurement location. The clearly dominant high frequency motion is due to inertial currents, with tides representing a much smaller contribution.

It is assumed that the measured inertial currents are initially forced by mechanisms which have a duration less than the 27 hour inertial period. This is generally assumed to be wind forcing. However, it should be noted that substantial inertial currents have been documented in LC eddies in the western Gulf.

A summary of primary points and conclusions concerning inertial currents on the West Florida Shelf are presented below:

1. Inertial currents were prominent at all locations studied in the West Florida Shelf mooring array, and were quite energetic, with peak amplitudes from 15 to 30 cm s-1, and occasionally greater.

2. The amplitudes were intermittent in time and space, as is commonly observed for inertial currents in general. Amplitudes commonly peaked at different times at different depths of the same mooring string, as is consistent with models. Amplitudes were also not well correlated between mooring locations separated by 70 kilometers except during isolated events forced by major storms.

3. Mid-depth maxima of inertial amplitudes were common at moorings which sampled near the base of the mixed layer, suggesting that peak amplitudes were associated with the pycnocline. This was consistent with the model of Gill, but not with those of Kundu.

4. Moorings on the shelf (D and F) showed noticeable increases in inertial amplitudes during summer. This occurred even as 40-hour low-pass winds diminished in summer. However, vertical stratification and diurnal wind amplitudes were both generally greater in spring or summer, possibly accounting for the increased inertial amplitudes.

5. Two hurricanes in 1985 (Elena and Kate) had similar tracks and produced sharp peaks of inertial amplitudes at all sites (up to a maximum of 42 cm s^{-1} at C1 from a base amplitude of 15 to 20 cm s^{-1}). Hurricane Kate produced the largest inertial amplitude peak measured for the three-year data set at the deeper moorings (A, C and E).

6. The 100-m depth amplitude at Mooring E modulated strongly for two months after the passage of Kate. This was uncharacteristic of the response to the earlier storm, Elena, and of the responses at the other moorings to Kate. Similar modulations were noted at other moorings, but not in response to an intense storm.

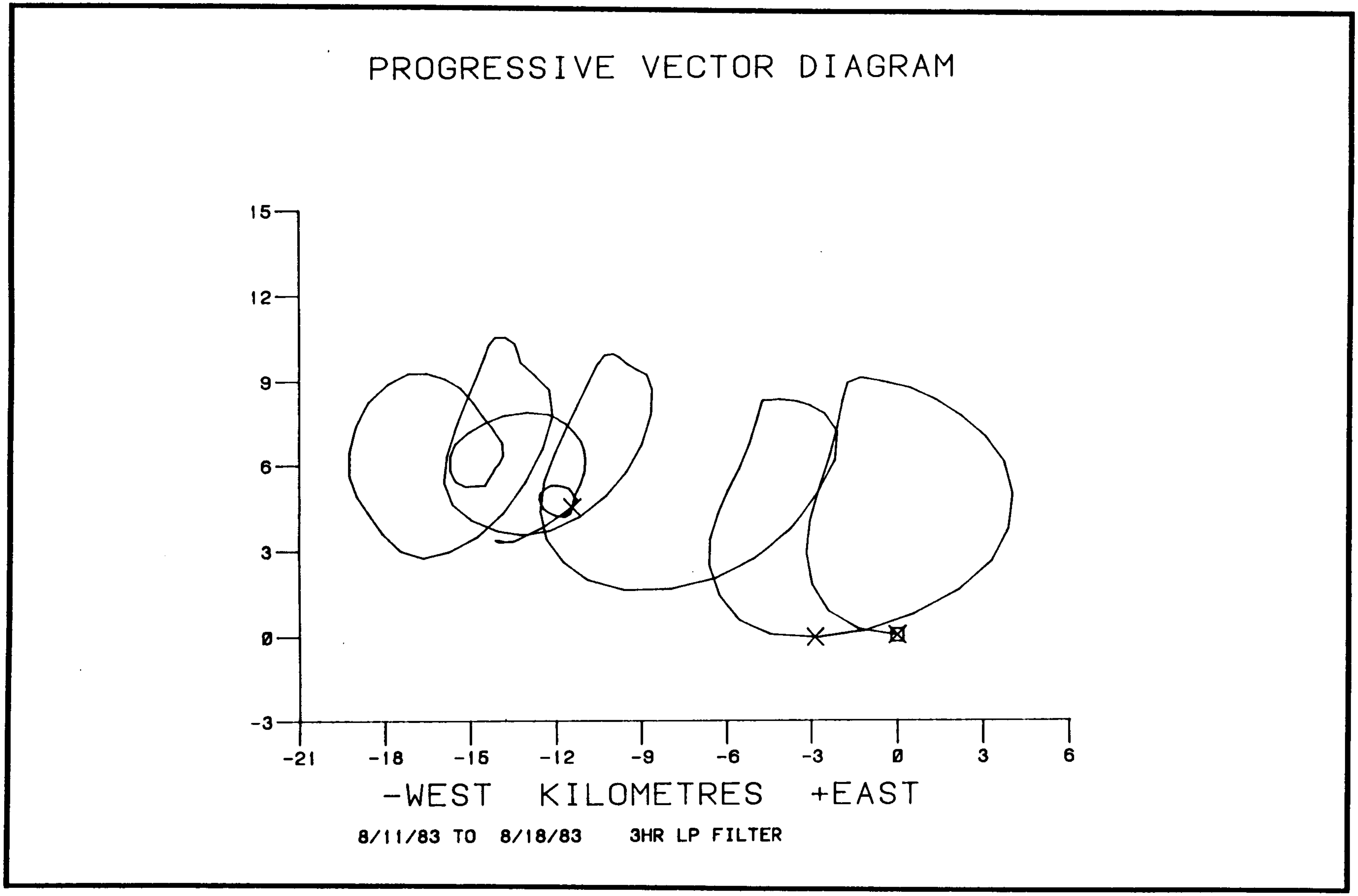

Figure 2.4-2. A progressive vector diagram illustrating the inertial circulation patterns measured on the WFS over a one week period. Note this does not illustrate particle displacement but is a means of visualizing particular flow patterns.

In general, inertial currents are important to the dynamics of the West Florida Shelf oceanography. They are energetic, with amplitudes often exceeding magnitudes of mean currents, low-frequency fluctuations and tides. They are ubiquitous in location and common throughout the year. They are undoubtedly important to the dynamics of the mixed layer and to transport and mixing processes in general.

2.4.3 Longer Period Circulation Patterns

The discussion of circulation patterns having time scales greater than approximately one day focuses on wind and Loop Current forcing. Subsurface current time series of three years and shorter were variously taken over the complete N-S extent of the West Florida Shelf and used in the present discussion. In addition compatible and coordinated wind and water level time series were used.

Previous and present examination of currents show that nearshore currents are primarily wind driven and that this forcing occurs in preferential frequency bands with the most encompassing being between 3- and 10-day periods. At periods longer than 10 days to two weeks are eddy-like motions which are typically barotropic (vertically uniform) responses to external forcing such as the Loop Current.

Availability of long and spatially diverse current and wind records permits consideration of the two-dimensional and time dependent nature of the forcing. As expected the wind signal shows a seasonal modulation with a summer minimum and fall-winter-early spring maximum. The primary signal relates to frontal passage with the more vigorous and numerous fronts occurring in the cooler seasons. Because fronts have differing intensities and different N-S penetration, the wind measurement site selected for comparison can effect the level and existance of coherence between winds and currents. Evaluation of wind-current time series showed this to be the case and depending on the frequency band different wind measurement sets should be used. This clearly points to difficulties of using a single or even several partitioned wind records to drive shelf circulation models.

This pattern of significant wind-current coherence also changes with season (with time). This is in part the result of changes in the patterns of wind systems and the inherently less vigorous summer wind forcing. In fact, even summer to summer patterns change. One recommendation for selecting winds in modeling shelf circulation is to select a period when winds and currents are highly correlated, even if for a relatively short time. This contrasts to using significantly coherent winds-currents for long time series where the significance level is reduced because of the higher degrees of freedom (i.e., the greater record length).

2.4.4 Loop Current Contribution

Comparing a time series of Loop Current boundary positions on two radial transects (one along the mooring line between 25N and 26N, and a second line approximately parallel to the first, but roughly one degree to the north) shows that for periods less than two weeks the northern line leads the southern line as would be expected for north to south advection of eddy-like features on the Loop Current boundary. At periods greater than two weeks, the LC boundary moves onshore and offshore in unision on the two transects. This might be expected to create eddy-like currents of the shelf edge.

The SW Florida shelf near-bottom current measurements and the Cedar Key moorings again reflected the importance of wind forcing as a current producing mechanism. Generally these more southerly locations experience less energetic currents. The strong wind-current coherence occurs not only in the expected 3 to 10 day band but extends to periods of 15 to 30 days.

SW Florida (ESE) and GMPOP currents were compared and suggest the presence of long coastal trapped waves. This would help explain the coherence between these two sets of measurements. For deeper currents (nearer the shelf break) currents at the two locations were less coherent in the normal wind bands with the currents to the north being much more energetic.

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