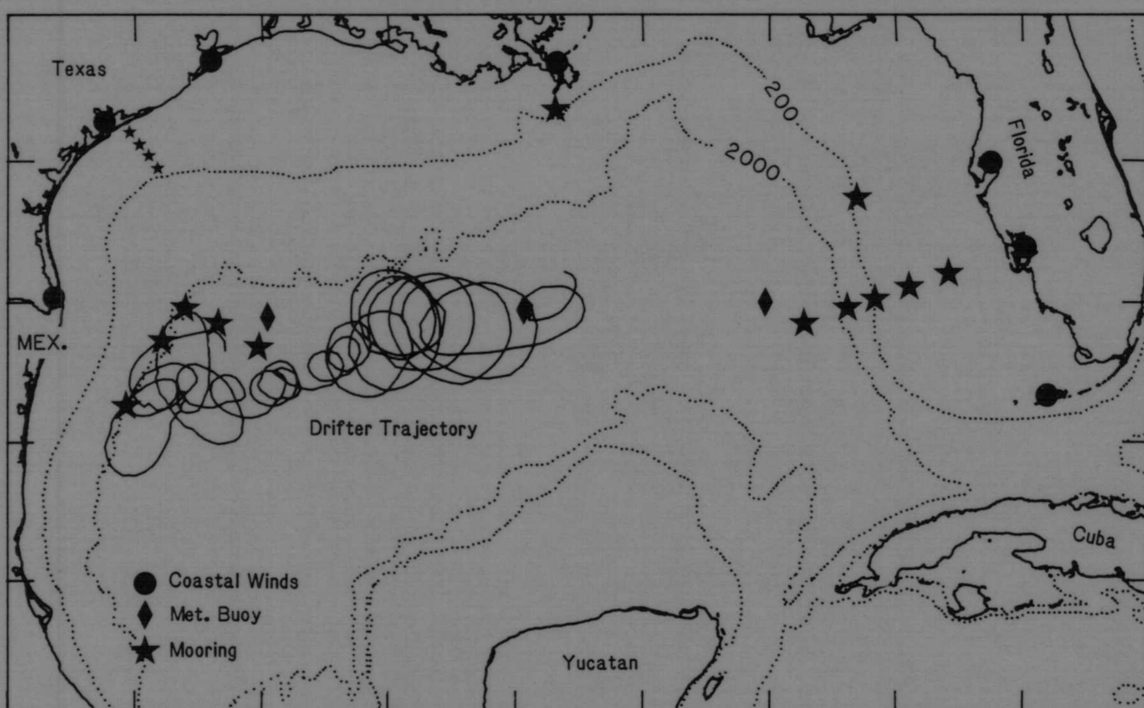
OCS STUDY
MMS 85-0093

Gulf of Mexico Physical Oceanography Program Final Report: Years 1 and 2

Volume I: Executive Summary



U.S. DEPARTMENT OF THE INTERIOR / MINERALS MANAGEMENT SERVICE

OCS STUDY
MMS 85-0093

GULF OF MEXICO PHYSICAL OCEANOGRAPHY PROGRAM FINAL REPORT YEARS 1 and 2

VOLUME I: EXECUTIVE SUMMARY

Program Manager:
Evans Waddell, Ph.D.
Science Applications International Corp.
Raleigh, North Carolina 27606

Project Officer:
Murray L. Brown, Ph.D.
Minerals Management Service
Gulf Regional OCS Office

Prepared by :
Science Applications International Corp.
under
Contract No. 14-12-0001-29158

for

Minerals Management Service
Gulf of Mexico Regional OCS Office
Department of the Interior
3301 N. Causeway Blvd.
Metairie, Louisiana 77843

February, 1986

SAIC Report No. SAIC-86/1022

TABLE OF CONTENTS

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 (GOMPOP), 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). This report presents results from the first two of three years of observations in the eastern Gulf. At present, MMS plans are for a year of comprehensive measurements in the central and western Gulf followed by a year of Gulf-wide observations. Note that some measurements made and analyzed during the first two years are directed toward developing a better understanding of western Gulf conditions and processes, e.g. Loop Current eddies.

1.1 Program Participants

Science Applications International Corp., the prime contractor for the GOMPOP, is working with a team of scientists from universities, institutes and companies to study physical oceanographic processes and conditions in the Gulf. Presented below is a list of these scientists, as well as a brief statement of their general area of technical involvement:

- Dr. L. Atkinson (Old Dominion University) - Hydrographic conditions on the outer west Florida shelf and adjacent slope and Loop Current waters.
- Dr. J. Lewis (SAIC) - Kinematics and dynamics of Loop Current eddies in the central and western Gulf.
- Dr. W. Sturges (FBN Oceanography) - Subsurface currents on the west Florida shelf and slope.
- Dr. F. Vukovich (Research Triangle Institute - RTI) - Satellite thermal imagery of the Loop Current and associated features, e.g. boundary features and spin-off eddies.
- Dr. W. Wiseman (Louisiana State University) - Subsurface currents on the Louisiana outer shelf.

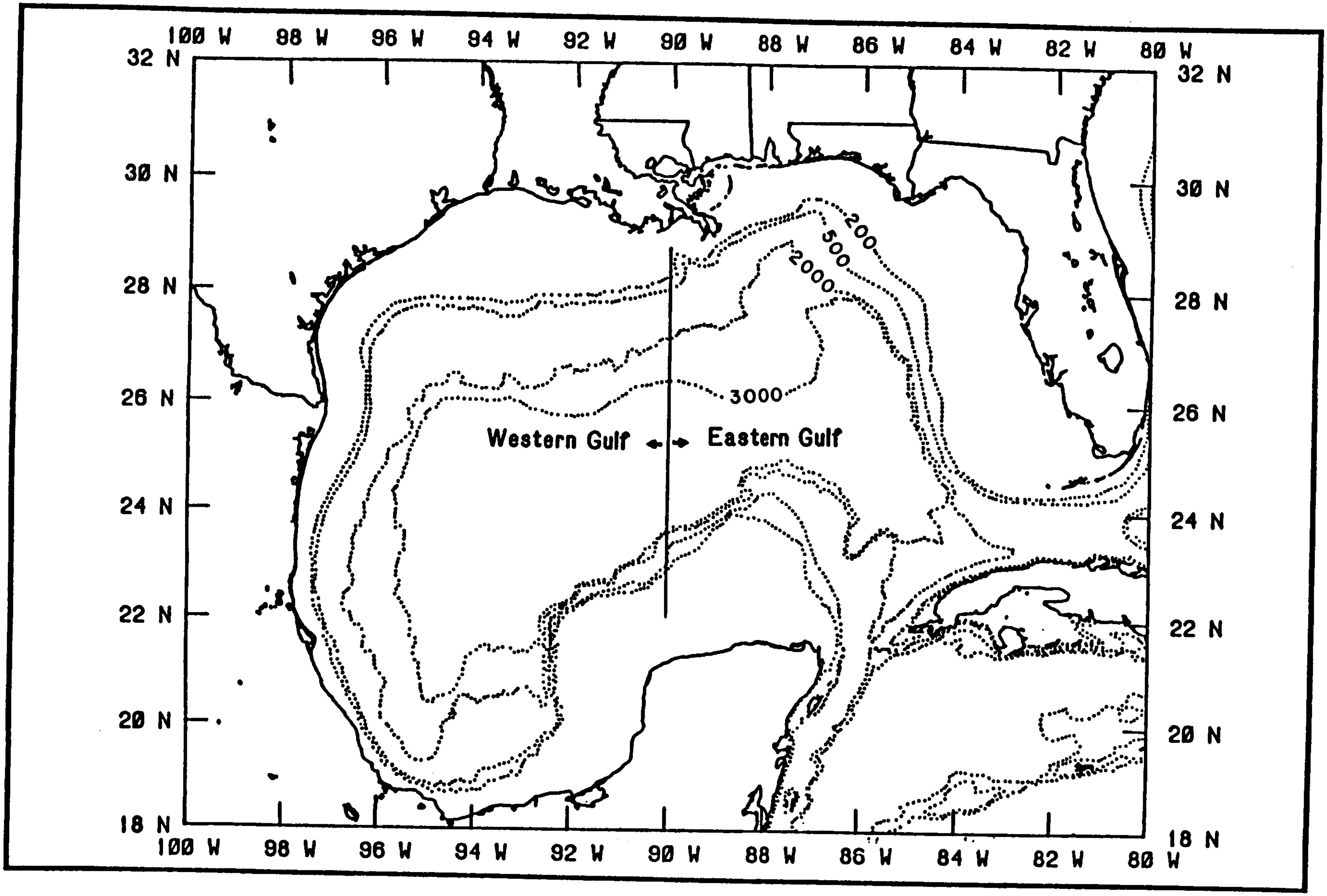


Figure 1.1. Gulf of Mexico bathymetric map showing the nominal partition of the eastern and western Gulf of Mexico study areas. This also partitions the emphasis on the Loop Current and Loop Current eddies.

The above indicates the primary responsibility; however, each investigator uses many aspects of the program data base to identify key patterns and features. An additional program element which is available to all PI's is the MMS funded Ship-of-Opportunity Program which provided both regular periodic and one-time temperature sections across or through the Gulf.

J. Karpen, an SAIC physical oceanographer, is Data Manager for the GOMPOP. As such he has worked closely with the above scientists to provide needed data analysis and resulting data products. Dr. E. Waddell (SAIC) is Program Manager for the GOMPOP.

1.2 Program Tasks

The above program participants undertook the following tasks during Years 1 and 2:

- Statistical and kinematic characterization of the Loop Current boundary and associated features using satellite thermal imagery.
- Documentation of historical trajectories of Loop Current eddies.
- Evaluate Lagrangian drifter trajectories to deduce kinematic and dynamic characteristics of Loop Current eddies.
- Three hydrographic surveys to document regional conditions and/or characteristics associated with Loop Current boundary features.
- Measure and utilize subsurface current/temperature and pressure on the west Florida shelf, slope and rise, on the outer portion of the Louisiana shelf and across the south Texas shelf. In addition, and as appropriate, coastal and at-sea winds and coastal water levels were used in conjunction with subsurface *in situ* observations in developing an improved understanding of the circulation patterns and processes active in each of the areas mentioned above.
- Obtain and utilize temperature profile data taken along transects as part of a Ship-of-Opportunity Program.

The complete data set was available to and used by each of the scientific principals; however, each tended to emphasize those observations with which he was most closely associated.

The satellite thermal imagery was analyzed by RTI. Lagrangian drifter analysis was done cooperatively by SAIC and the University of South Florida. All subsurface currents, temperature, pressure, coastal water level, winds, and hydrographic analysis were done by SAIC as part of the program's centralized data management and analysis structure.

II. TECHNICAL DISCUSSION

2.1 Introduction

Presented below are summaries of material presented in Chapter 4, Vol. 2 of this report. Such synopsis can not be comprehensive, but rather identifies and relates key insights or understandings. In such limited space no effort is made to verify items discussed. For a more complete discussion, the reader is directed to Vol. 2 of this report.

2.2 Lagrangian Drifters

The paths, translation velocities, local vorticity and horizontal deformation rates have been calculated from Lagrangian observations for three large anticyclonic Gulf of Mexico rings (e.g. Figure 2.2-1). Within the capabilities of the data base and the analysis routine, it is now established that:

- The paths of the three rings across the central Gulf to the continental slope off Mexico are virtually identical.

- For Rings 1599 and 3374, there was evidence of strong ellipticity developing as these rings approached the continental slope. The axis of orientation was approximately NE-SW.

- After encountering the continental slope in the western Gulf and migrating to the north, the centers of both Rings 1599 and 3374 were very close. The vorticity and deformation rates were not substantially different from those at mid-Gulf.

- Trajectories indicated a ring life span of approximately 9 to 13 months, with a persistence off the Mexican coast of 3 to 5 months.

The trajectory of a fourth drifter not seeded in a ring still shows strong anticyclonic motion. The SST data for the period that this last drifter was deployed show the interaction of three anticyclones in the western Gulf. The drifter circles all three anticyclones and shows, along with the SST data, the coalescing of two of the anticyclones.

The dynamics calculations show vortex stretching of the ring centers that oscillates in size in a period of 10 to 20 days. However, even greater variations in angular momentum appear to be associated with the wobble of the ring centers. These dynamic similarities along with the strong kinematic similarities indicate that there is a primary mechanism for steering the rings which dominates other processes such as different initial mass and velocity fields and different wind forcing. This is encouraging for the modeling of Loop Current rings in that one may concentrate on defining that principle mechanism in the best manner possible. It is conjectured that this mechanism is bottom topography.

Since the data set upon which to establish the kinematics of Loop Current rings is rather limited, it is recommended that additional rings be seeded with Lagrangian drifters, particularly any rings that take a more northerly

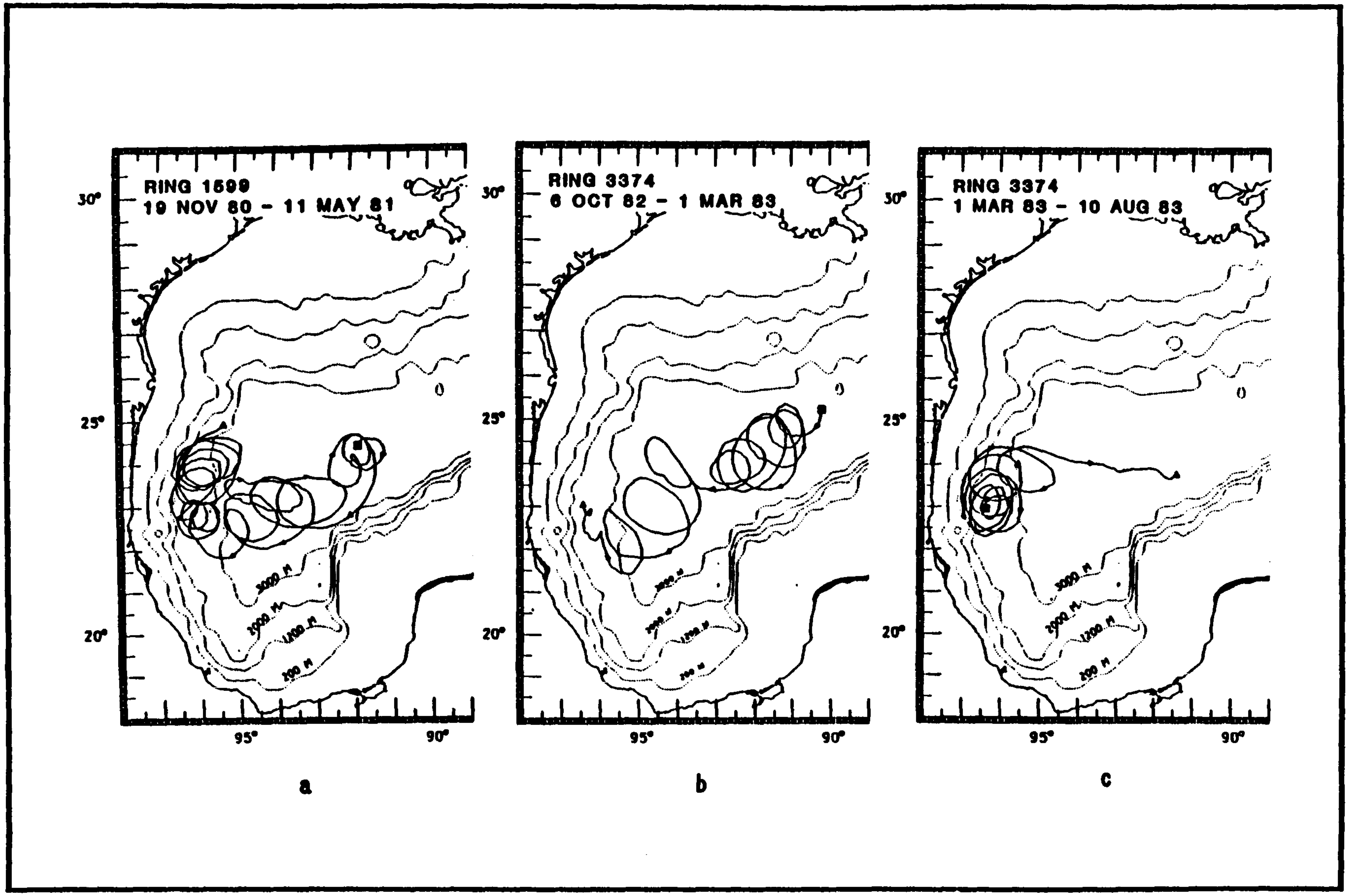


Figure 2.2.1. Trajectories for Drifters (a) 1599, and (b) and (c) 3374. Depth contours are in meters. The square and triangles denote the start and end positions, respectively.

route across the Gulf of Mexico. This information would provide an indication of the frequency and characteristics of anomalous ring movement.

Continuation of the kinematic and dynamic analyses of Rings 1599, 3374, and any future rings that are tracked is also recommended. In particular, further study is needed for the spatial and temporal variations of ring vorticity, ecsentricity, and orientation as well as the effect the motion of the ring center has on angular momentum balance. Moreover, the topographic steering effect could be considered with the appropriate angular momentum balances.

2.3 Sea-Surface Temperature/Satellite Imagery

2.3.1 Loop Current Boundary Eddies

Maximum fluctuation of boundary positions based on 1980-84 data occurred near the northern boundary of the Loop Current (LC) which was most often located between 27°N to 28°N. Generally, western LC boundary fluctuations are relatively smaller and less frequent than northern and eastern fluctuations.

At the sea surface, eastern LC cold-core perturbations, on the average, have an along-stream dimension of 190 km, an across-stream dimension of about 130 km (Figure 2.3-1) and a speed which ranges from 6 to 24 km day^{-1}. Once established, the boundary eddies have a variable evolution and "life-span", which seem in part dependent on interaction between features (e.g. merging) and the west Florida slope. Duration of the eddies was also dependent on where they formed. As might be expected, those forming on the LC northern boundary lasted longest. Well-resolved boundary eddies which reached the southwest corner of the west Florida slope tended to become quasi-stationary, while some grew in size and others dissipated. Available satellite imagery does not show these features moving into or through the Florida Straits.

Although evolutionary, LC boundary eddies seem to have some general characteristics:

- The LC front exhibits a wave-like configuration with the wave crest tending to evolve by northward (upstream) growth of a warm filament.
- A pool of cooler water is located between the filament and the LC proper.
- Limited satellite imagery and in situ current data suggest a northward motion in part of the filament, although the Eulerian magnitude and direction of this flow are probably affected by the feature's downstream advection speed.
- A filament can have along-stream dimension as large as several hundred kilometers.
- The across-stream LC, cold-pool, filament structure supports a cyclonic circulation which is geostrophically driven.

Observations showed that some filament-like features extended to depths of 350 m. When associated with a strong density field, such a filament may

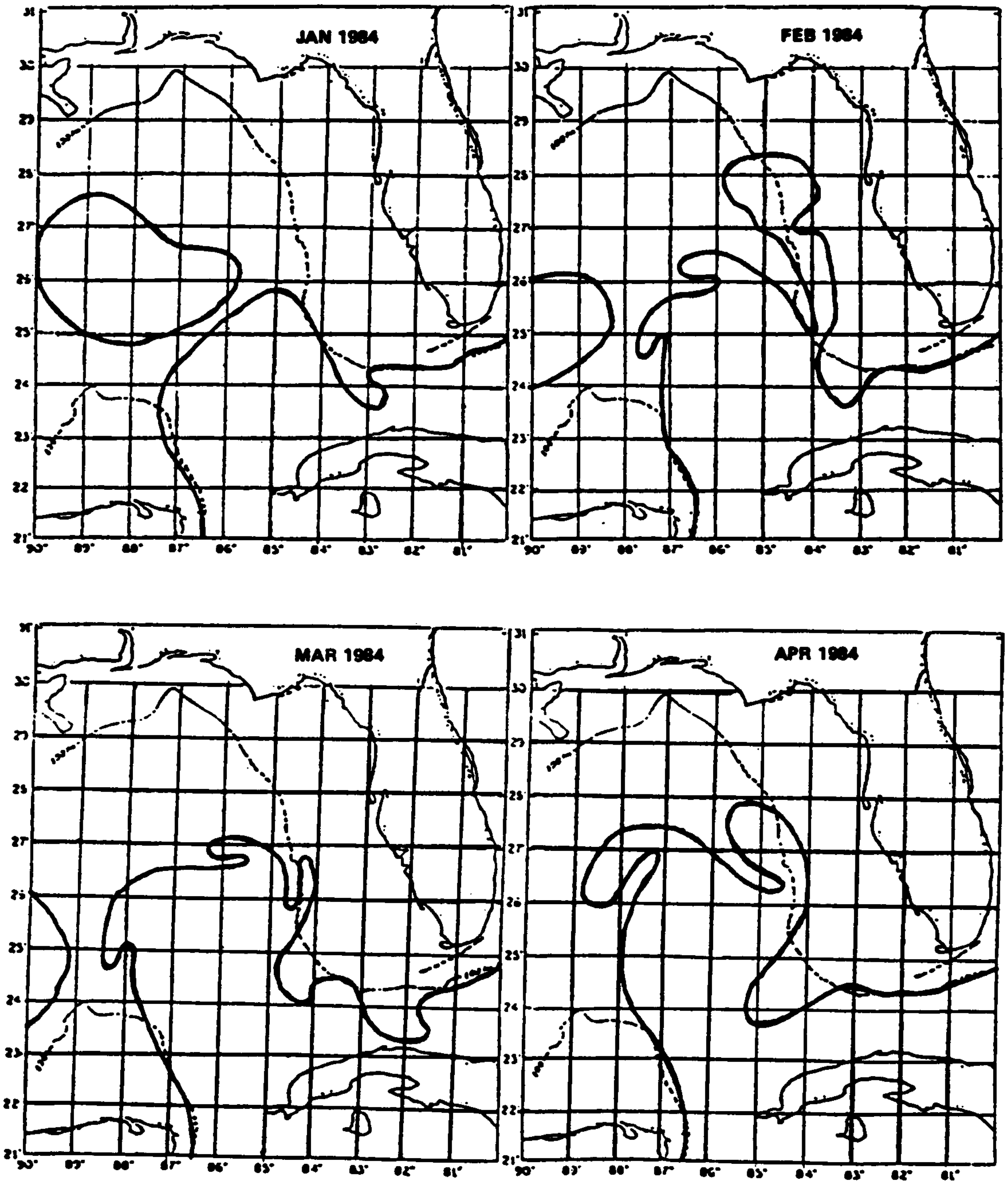


Figure 2.3.1. Monthly frontal analyses in the eastern Gulf of Mexico derived from NOAA and GOES satellite data (January through April 1984). This frontal map portions the Loop Current water from the ambient Gulf water. Cold-core boundary eddies of various scales and configurations are evident.

internally support an anticyclonic geostrophic flow with strongest currents closest to the fronts.

Some warm filaments (and LC origin water) may have contributed water to the west Florida shelf. This conjecture results from circumstances which are not completely documented and hence involve some deduction rather than being derived from satellite-tracked features.

In May, detailed hydrographic surveys were conducted under support from several agencies, especially MMS (See Section 4.4, Vol. 2). During March through May 1984, a cold-core perturbation was tracked. Several time surveys were made through the feature. This feature moved along the LC boundary until reaching the region southwest of the Dry Tortugas where it stagnated and tended to erode with the associated decrease in surface and subsurface expression. This change was clearly evident from several surveys through the feature. Note that such a fairly stationary cold-pool or cold-dome southwest of the Dry Tortugas is seen often in satellite images.

2.3.2 Loop Current Eddies/Rings

Movement of several LC eddies has been evaluated using drifting buoys (Section 2.2). A more descriptive inventory from satellite imagery provides information on typical dimensions, speeds and trajectories. Typical translation velocities as determined from available imagery range from 2-5 km day^{-1} with a diameter ranging from 150 to 300 km. The latter tend to decrease from separation through westward movement. Such break-off eddies are believed to be a major contributor of momentum and heat to the western Gulf.

Satellite imagery combined with SOOP observations has helped identify sequential separation and movement of major LC eddies. Historical imagery suggests three general trajectories of eddy centers which seem to originate at similar locations with Path 1 in Figure 2.3-2 to the southwest predominating.

Eddy translation velocity which had an overall mean of 5 km day^{-1} oscillated from 1 to 8 km day^{-1}, on the average, at periods of 40 to 100 days which was approximately in-phase with linear trajectories. Note that these data were not all from sequential observations because of the inherent intermittency of thermal imagery.

Limited available sea-surface temperature maps showed an approximately 50% reduction in surface area of the eddies in the first 150 days and a 70% reduction in 300 days. This decrease in size appeared to occur through erosion at eddy boundaries and by separation of smaller spin-off eddies. These are mechanisms for removal of momentum and mass since the boundary erosion occurs by creation of streamers or filaments.

2.4 Hydrography

Three hydrographic surveys were conducted with the objective of either:

- Documenting regional salinity, temperature and nutrient fields, or
- Characterizing, in detail, conditions or processes associated with Loop Current boundary and related eddies or perturbations.

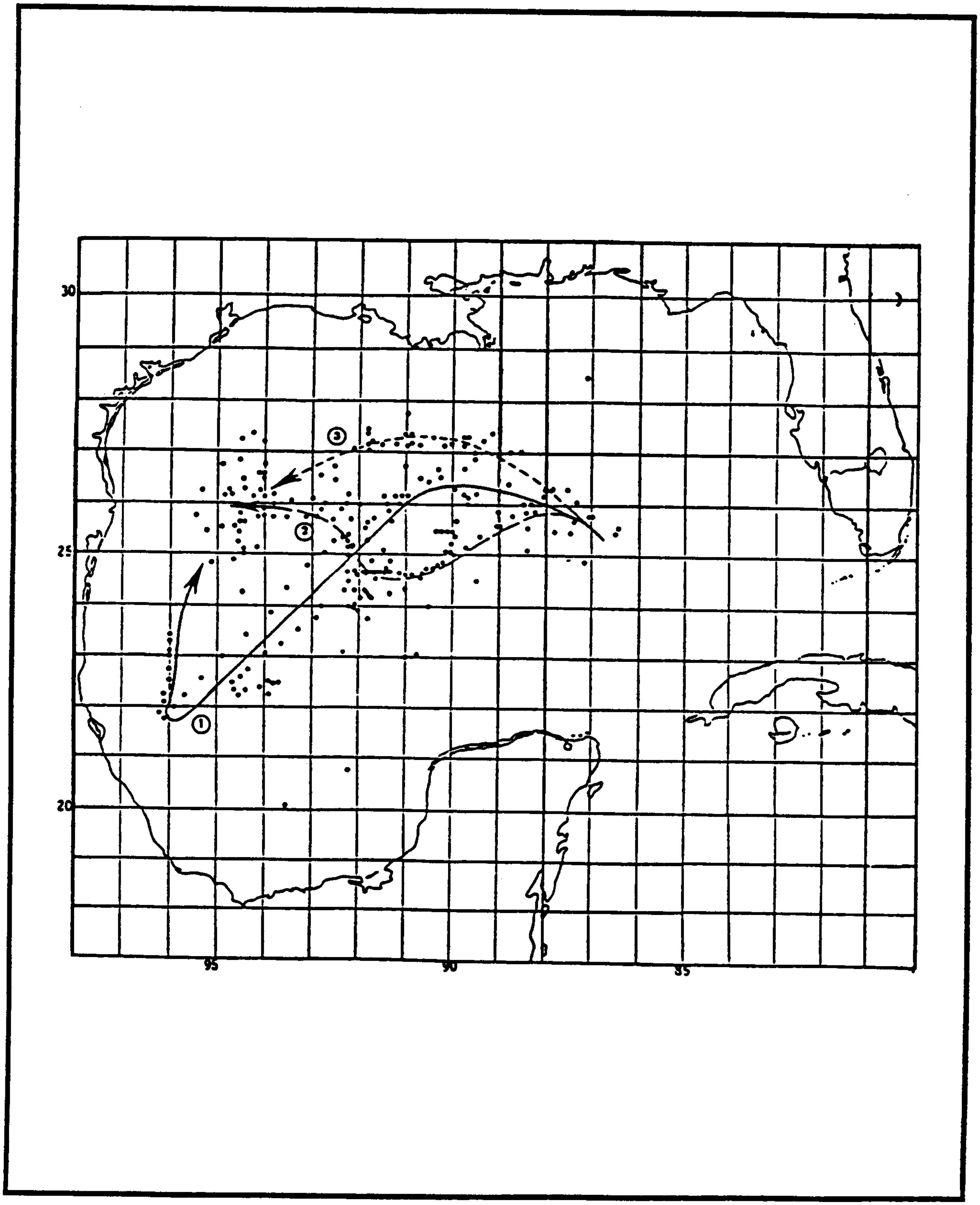


Figure 2.3.2. Characteristic paths of warm rings in the western Gulf of Mexico and the position of warm ring centers obtained using GOES and NOAA satellite data for the period from 1973 to 1984.

Observations during these surveys were supplemented by available SOOP temperature transects from several sources. Cruises were planned for periods when it was expected that satellite thermal imagery would provide guidance in selecting station locations.

All cruises provided information on conditions in proximity to the LC boundary or front which expanded or verified our understanding of local kinematics and related fields. Higher speed currents were generally located in a 100-150 km near-surface band which was adjacent to the LC frontal boundary. Maximum speeds near or at the surface decreased by approximately 50% or more in the upper 250 m (Figure 2.4.1). Along the eastern boundary this zone moved laterally and was over or very near the shelf break while at other times it could be over 100 km seaward of the shelf break. On the western side of the northern Yucatan Straits, the high speed zone was consistently "up against" the fairly steep slope.

Preliminary acoustic doppler current profiler data suggests that a very sharp shear occurs in the LC along-front velocity component. This may well occur even in summer/early fall when there is no lateral surface temperature gradient and very weak gradients above the seasonal thermocline.

Interior to the higher velocity band, geostrophically estimated currents were considerably weaker while still supporting a general anticyclonic flow. Some evidence suggests the near-surface interior flow may not always parallel the higher speed flow region which could allow recirculation.

Two surveys provided information on a transect through the base of the Loop Current which showed that inflow was more concentrated that outflow. Some data suggests that the Yucatan Straits may support a time-dependent bidirectional exchange but with a net inflow.

Cold pools associated with the LC eastern boundary could extend to considerable depth with isotherm doming evident at over 500 m (Figure 2.4.2). Associated boundary filaments could be deep or shallow. These boundary features tended to upwell cooler nutrient-rich water from the upper slope onto the shelf and thus may play an important role in the magnitude and distribution of west Florida shelf productivity. On one cruise, a cross-shelf near-bottom cool water mass with a local isolated chlorophyll and nutrient maxima was documented, which suggests that upwelled water may at times be advected well onshore with only weak mixing occurring.

T-S, as well as other scatter plots (e.g. nutrients), showed fairly predictive relationships within LC water which was below the seasonal thermocline. As might be expected it is similar to that found in the Gulf Stream. In filaments and outside the LC influence a wide scatter occurred. The expected shelf horizontal/vertical seasonal temperature stratification occurred: vertical stratification with weak or absent horizontal gradients in summer, vertically well-mixed shelf water with stronger horizontal gradients from the shoreline to LC boundary.

2.5 Currents

Because wind stress can be an important circulation producing mechanism, an examination of certain aspects of the wind field is an essential first-step,

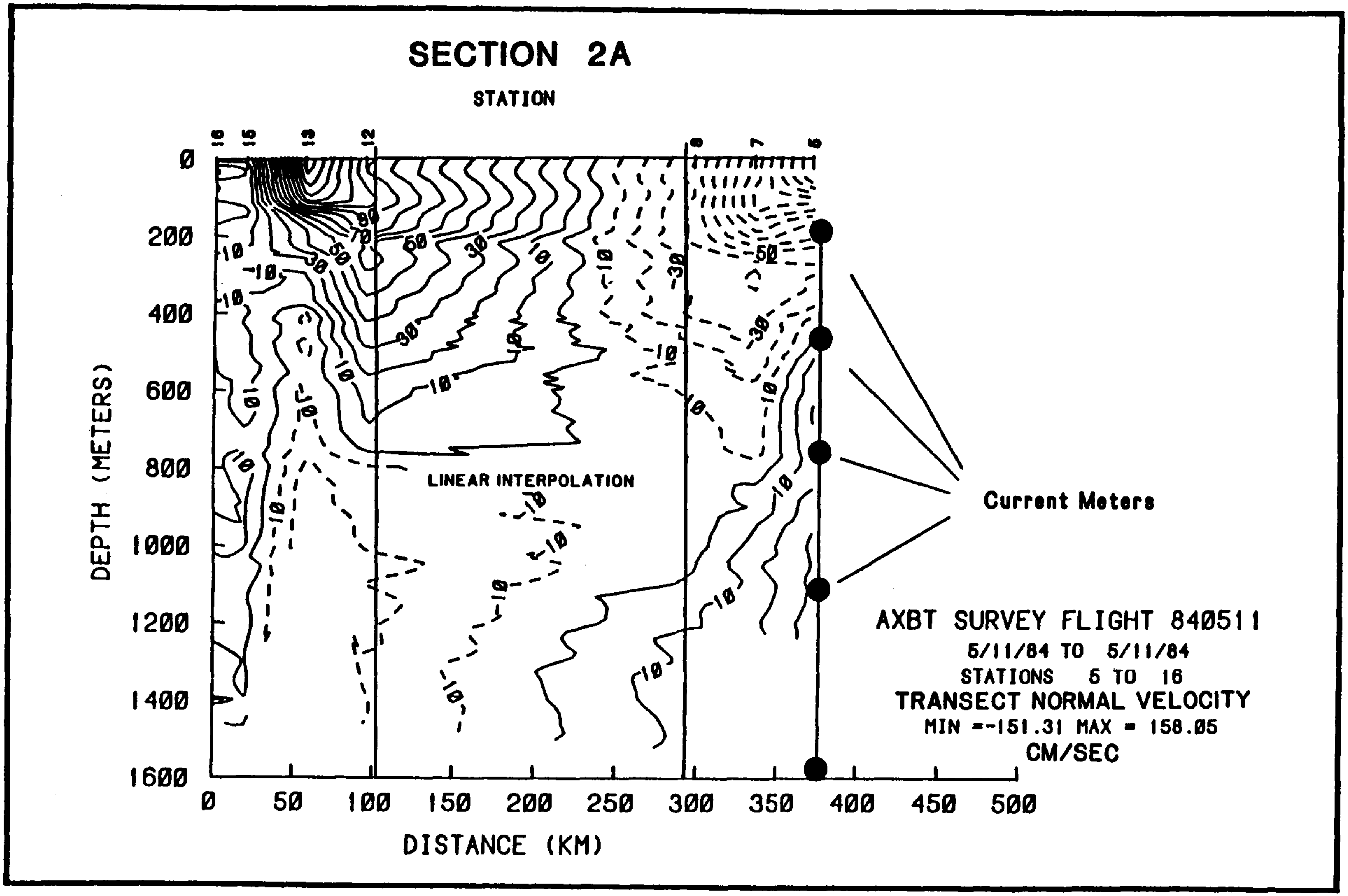


Figure 2.4.1. Contours of transect normal velocity component from AXCP's. The horizontal velocity distribution may tend to spread because of interpolation. The actual velocity magnitude is an estimate, however, relative velocity (i.e. shear) should be fairly accurate. Solid lines are velocities to the north (into page); dashed lines are to the south (out of page).

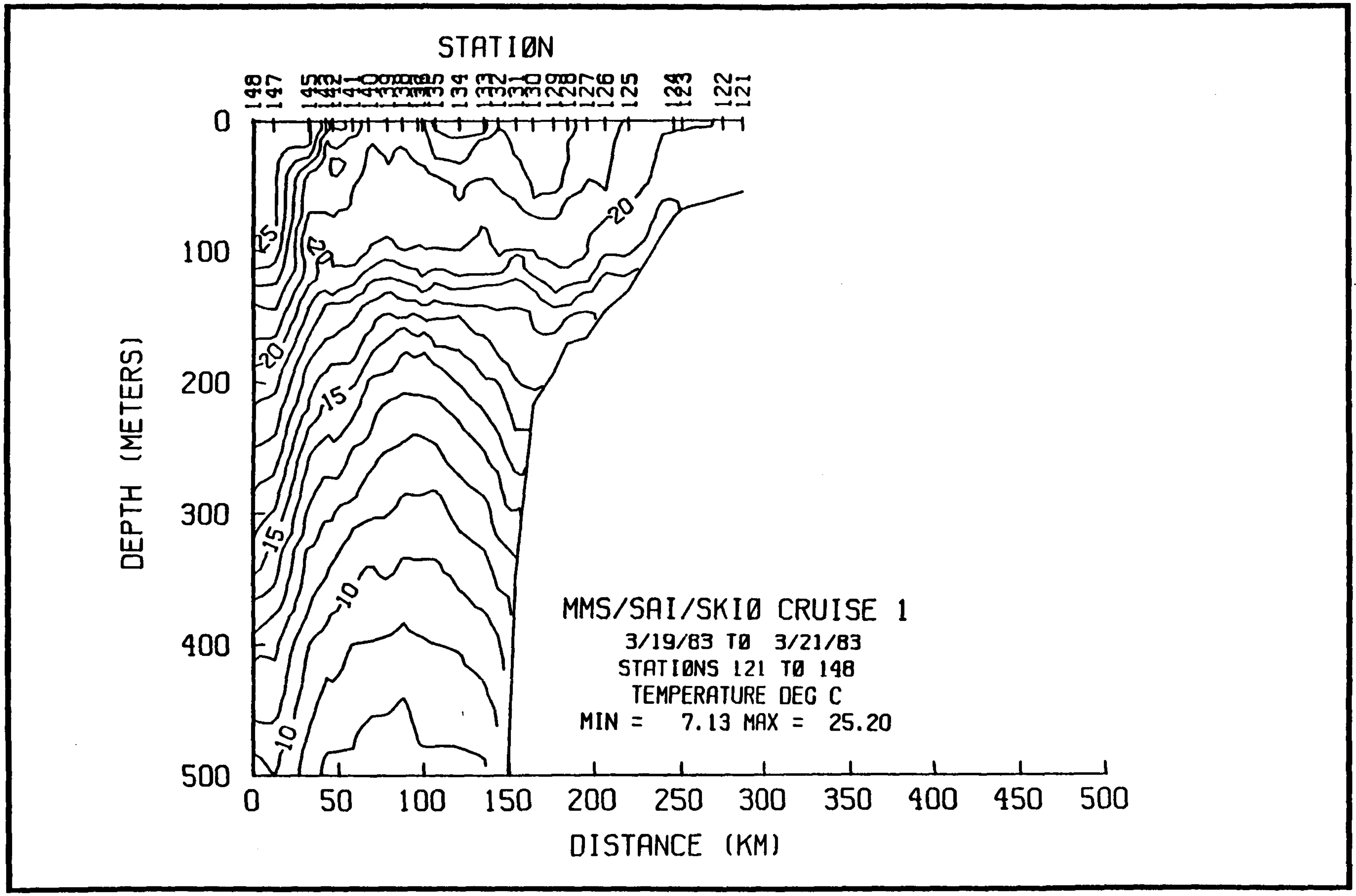


Figure 2.4.2. Domed isotherms associated with an apparent cold pool. Note the relatively warm surface waters approximately over the shelf break.

prior to attempting to resolve couplings between currents and winds. Over the west Florida shelf, especially the southern half, winds are spatially coherent both along and across shelf, although Key West (i.e. the south) is generally more energetic than coastal and at-sea measurements to the north (Figure 2.5-1).

As expected, conditions vary seasonally with winter winds being more energetic. The most apparent variability is associated southward propagating frontal systems which become increasingly vigorous during winter and tend to recur on a 3 to 10 day period. The wind and cool air mass systems tend to mix and cool the entire water column. The seasonal onset of frontal passage and the interfrontal period are respectively somewhat delayed and longer in the more southern portions of the study area.

During summer, analyses suggest that some wind forcing may propagate south to north. However, such systems are relatively less energetic and hence less effective in driving currents. In addition, summertime strong vertical stratification resulting from heating the upper portion of the water column helps reduce the effectiveness of wind forcing.

Initial analysis of shelf currents indicates that between 40-60% of the variability is in the higher frequency band (3-40 hrs) with some records having 80% of variance in the period band for selected (yet substantial) intervals (Figure 2.5.2). The diurnal-semidiurnal mixed tide (diurnal slightly dominant) contributes relatively little to the current field ($\sim$5%). The bulk of the remaining fluctuations appears to be associated with inertial currents which may be initiated with relatively rapid wind stress associated with frontal passage. However, this mechanism does not seem sufficient to explain the omnipresent, rotary, anticyclonic motion which seems to intensify under summer stratified conditions. It would seem that any effort at characterizing shelf circulation patterns would have to account for inertial current patterns.

The across-shelf mooring placement did not provide information regarding currents on the inner shelf where winds are expected to be strong; however, available observations indicated that the maximum measured wind induced currents were found approximately at mid-shelf and decreased offshore.

The low-frequency portion of current variability was not well resolved nor consistently associated with an identifiable forcing mechanism. Clearly, the Loop Current can penetrate well onto the shelf and dominate the velocity and temperature fields. The more proximate the LC is, the more influential. When well offshore or to the south the direct LC influence is not apparent. Thus, we might expect a low-frequency current signal on the outer shelf/slope which reflects both the north-south and east-west motion of the LC. In addition when the LC is adjacent to the slope, cold-core boundary perturbations can have a considerable influence on circulation. These features are discussed in detail in several sections of this report.

Evidence to date suggests that circulation fields may be weak-sense stationary (i.e. the first two moments become time invariant) for averaging periods on the order of two years, at least the two years studied. Continuing measurements will help identify if this is an artifact of the particular period or a more fundamental characteristic of the environment. It should be

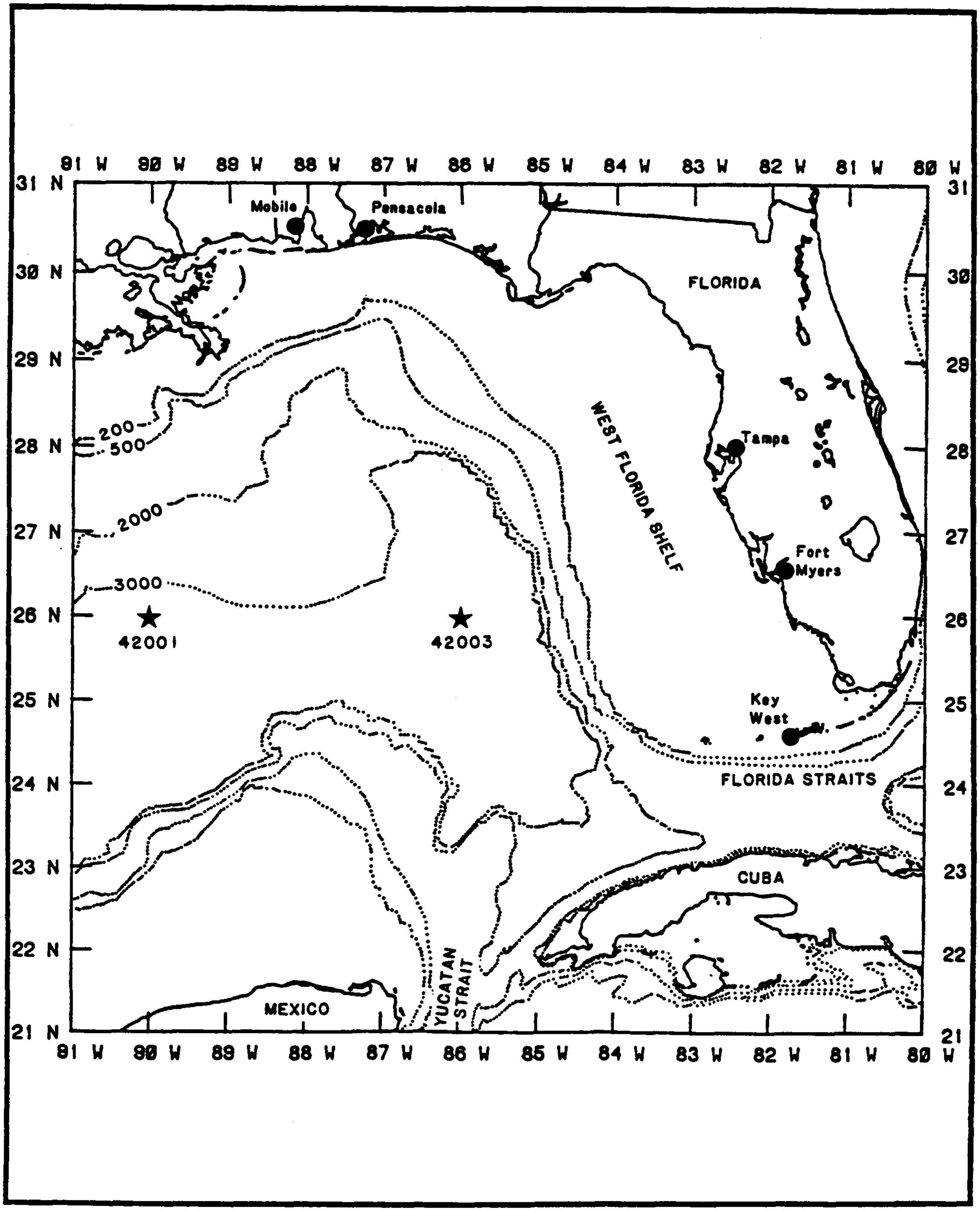


Figure 2.5.1. Available eastern Gulf meteorological data. Dots indicate NWS coastal stations; stars indicate NOAA/NDBC meteorological buoys.

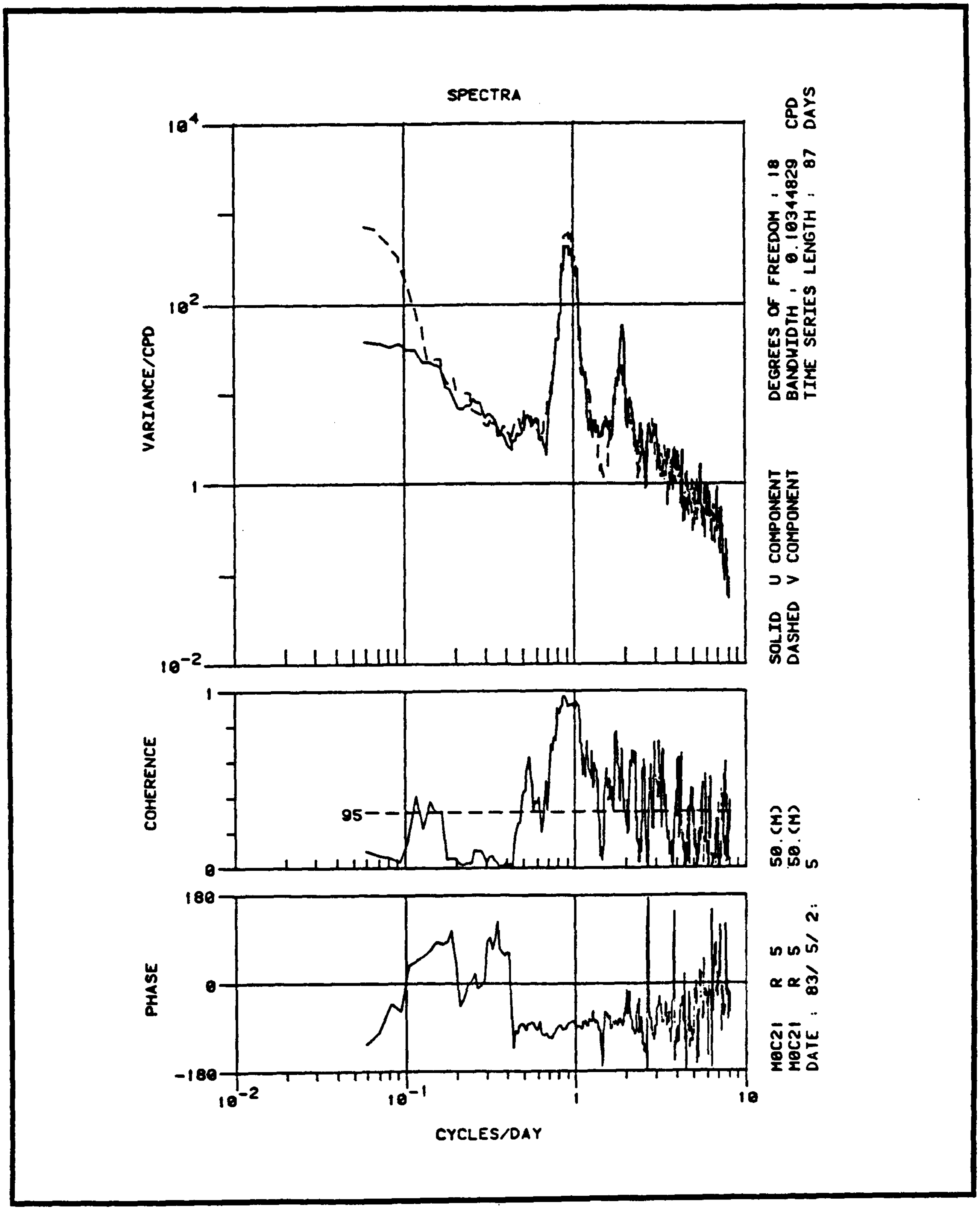


Figure 2.5-2. Spectra of along-isobath (V) and across-isobath(U) velocity components and coherence squared and phase between these variables. Note the shift to low-frequency of the approximately diurnal peak due to inertial currents. As expected in such motion U and V are highly coherent and 90° out-of-phase.

noted that generally the mean or average current is small compared to the variable component. Most long-term averages indicated a net southward directed flow suggesting a corresponding volume flux.

Several efforts to isolate and identify currents due to shelf waves proved inconclusive or unsuccessful.

The Department of the Interior Mission

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

The Minerals Management Service Mission

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

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

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