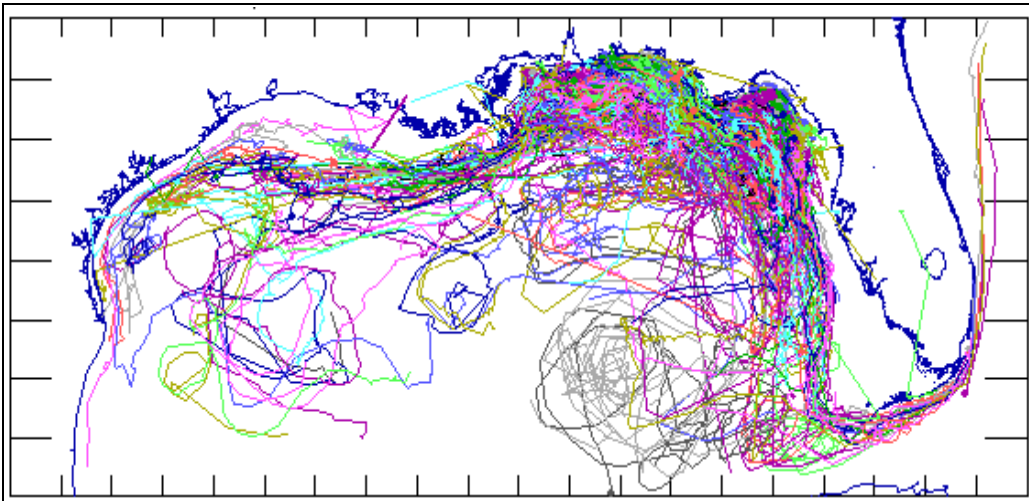


Northeastern Gulf of Mexico Inner Shelf Circulation Study



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Northeastern Gulf of Mexico Inner Shelf Circulation Study

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About the Cover

The map of drifter tracks in the Gulf of Mexico shown on the cover of this report was prepared by Dr. Walter Johnson, the COTR for this Cooperative Agreement. All the drifter tracks for the 13-month long series of drifter deployments are shown. The drifters were deployed in depths of 50m or less along the upper west coast of Florida between Cedar Key and Pensacola. They spread over the full Gulf and into the open Atlantic.

Acknowledgements

This project was carried out cooperatively between MMS and Scripps Institute of Oceanography, The Florida State University, and The University of South Florida. Dr. Walter Johnson, MMS, while not officially an author of this report, made major contributions to this project. Dr. Alexis Lugo-Fernandez of the New Orleans office and Dr. Ronald Lai, Washington, D.C., were also instrumental in major ways that enabled the success of the work, providing both technical and administrative support. We are deeply grateful for their contributions to the project.

At Scripps, P. Niiler was assisted by Dr. Carter Ohlman, who made major contributions to the work. The assistance of Sharon Lukas, Judy Illeman-Gaukel and Andy Sybrandy is acknowledged throughout the progress of the SCULP experiments. The drifters were the work of Technocean, Inc., of Cape Coral, Florida, as mentioned in the text.

At Florida State University, W. Sturges was assisted by Mr. Jianguo Wang, who provided significant, ongoing scientific programming assistance. The current meters were launched and recovered with the assistance of David Hunley, the Senior Engineer at the FSU Current Meter Facility, together with Ken Jones and Nick Wooten, NWFRWQM, as well as by Mr. C.J. DeHaan. We especially wish to thank Mrs. Diane Stuart for administrative oversight.

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Executive Summary

This report presents the results of an experiment involving several hundred satellite-tracked surface drifters used, together with an auxiliary series of moored current meters and meteorological buoys, to measure the near-shore circulation in the coastal waters of the Northeastern Gulf of Mexico. The drifter experiment was performed under the direction of Dr. P. P. Niiler of Scripps. Each weekly set of results, determined by satellite, was mapped in near-real time by Dr. Walter Johnson of the Minerals Management Service (MMS) and then made available to interested parties on a web page set up for this project at <http://gulf.ocean.fsu.edu>.

In support of the oil and natural gas leasing activities in the Gulf of Mexico, the MMS has funded a number of intensive studies of the circulation of the US coastal economic zone. This study, termed *SCULP – II*, obtained and analyzed data from 342 ARGOS-tracked CODE-type drifters off the northwest coast of Florida between February 6, 1996 and June 28, 1997.

These drifters were deployed from aircraft to 26 stations on the continental shelf by the manufacturer, Technocean, Inc., with a 99% success rate. The average at-sea life of a drifter that survived the air deployment was 73 days. Over a 12-month period at periods of approximately every two weeks a new drifter was deployed by parachute to one of these 26 stations if no drifter was found within a 5-km distance. In all, 25,100 one-day average displacements were obtained. The processed data on drifter location and velocity was transmitted in near real time to MMS/HQ and has been in use there in oil-spill modeling activities for the past four years. Abstracts of the scientific publications that have resulted from these data refer to specific dynamical inferences drawn from these data. This report presents a summary of the statistical analyses.

The displacements of the drifters on the West Florida Shelf were variable in time and occurred principally along bottom topographic contours. The monthly mean currents were the strongest along the shelf break and west of Cape San Blas. Significant mean flows occurred on the shelf break to the south or southeast and near shore along the

Florida panhandle to the west. Across-shelf currents were strongest off Cape San Blas and the Mississippi Sound. The largest excursion from the general oscillating drift pattern occurred in early October 1996 when, during a tropical storm, 35 drifters moved with speeds in excess of 50 cm/sec westward from the West Florida Shelf past the Mississippi River delta as far as the Louisiana-Texas shelf. One unexpected finding was a “forbidden” zone that emerged north of the Florida Bay, south of Tampa Bay, suggesting that a region exists where no drifters ventures.

About 47% of the velocity variance can be explained by spatial-scale coherent patterns that occupy the entire horizontal extent of the northeast Gulf shelf. The spatial correlation scale of the along-topography currents along isobaths is about 50 km in water depths between 10-30m and 350 km in water depths of 50-80m. Both local winds and remote forcing from the Loop Current were shown to produce the observed strong events in the large spatial-scale flow patterns. The region of the shelf between 100m and 30m depth exhibited no annual mean velocity, but drifters from that region were ejected to all four corners of the Gulf of Mexico in less than 120 days by short-lived strong events in circulation.

In addition to the surface drifters program, a program of moored current meters was carried out cooperatively between Florida State University and the University of South Florida. The mooring program was designed to supplement previous moored current data as well as to complement the drifter study. These results are described in detail in Section III.

It is of considerable scientific and engineering interest to know how the measurements taken from the two different observation systems compare; this study is described in Section IV. The two different sets of measurements agree quite well in the expected ways and show the expected shear and veering within boundary layers.

Discussed in Section V is an issue of considerable practical interest and a fundamental question: whether if the wind blows at a certain speed in a given location we can then compute the near-surface currents with any reasonable accuracy. The answer is "yes," and the coefficients we obtained are presented here. The results have been presented in near-real time on a

web page, <http://gulf.ocean.fsu.edu>, as mentioned above, and it is our expectation that this page will be maintained for several years beyond the formal end of the study. The mooring program on the west Florida shelf has been continued under the ECOHAB study, and these results are maintained and made available to interested parties on the web page: <http://ocg6.marine.usf.edu> .

Over the past few decades, we have learned to compute the purely wind-driven currents on the continental shelves quite well. Numerical models are beginning to be able to include the influence of offshore eddy-like features on shelf currents. One awkward technical problem still remains, however, because much of our knowledge of the eddies beyond the shelf break depends on results of satellite altimetry. We learned from the MMS-sponsored DeSoto Canyon study that a dominant eddy size is in the 100-150 km range. Casual study of the ground tracks of the Topex (altimeter) satellite shows that eddies of this size can fit comfortably inside the track-line pattern in such a way that they remain essentially hidden from view. And since many energetic events of shelf currents seem to be driven by these offshore eddies, a very great deal remains to be learned about the shelf currents along the Florida coast.

I. Introduction

This report presents the results of an experiment involving more than 300 satellite-tracked surface drifters used together with an auxiliary series of moored current meters and meteorological buoys to measure the near-shore circulation in the upper waters of the Northeastern Gulf of Mexico. The drifter experiment was conducted under the direction of Dr. P. P. Niiler of Scripps. Each weekly set of results, determined via ARGOS satellite, was mapped in near-real time by Dr. Walter Johnson, MMS, and made available to interested parties on a web page, <http://gulf.ocean.fsu.edu>, that was established for this project. As the project developed, both the near-surface data collected by the drifters and the currents measured at the fixed moorings were made available on that web page. It is our intention to maintain this web page and make the data and primary plots available for at least two years after the end of the project.

The primary purpose of this experiment was the measurement of near-shore surface currents at depths of less than 50 -100m. The drifters perform this work with great accuracy in the upper meter of the water column. This work and the results are described in the Section II of this report. The current meter moorings and some brief results are described in Section III.

It is of great interest to know how the measurements taken from the two different observation systems compare; this is described in Section IV. An issue of considerable practical interest, and fundamental question, discussed in Section V, is whether if the wind blows at a certain speed in a given location, we can then compute the near-surface currents with any reasonable accuracy. The answer is "yes", and the coefficients we obtained are presented here.

Section IV presents an initial list of the reports and publications that have come from this work. In Appendix A we show a lengthy series of plots that describe the observations of currents at a selection of the various moorings. The initial copies of this report also include a compact disk that contains the data from the drifters, the current meter experiments, and the figures from the web page.

Section II. The Drifter Experiment

Also known as the

“SURFACE CURRENT LAGRANGIAN-DRIFT PROGRAM”

SCULP – II

II.1 Summary of the Drifter Work

In support of the oil and natural gas leasing activities in the Gulf of Mexico, the Minerals Management Service (MMS) has funded a number of intensive studies of the circulation of the US coastal economic zone. In this study, termed *SCULP – II*, data were obtained and analyzed from 342 ARGOS-tracked, CODE-type drifters off the northwest coast of Florida in the period February 6, 1996 to June 28, 1997. These drifters were deployed from aircraft to 26 stations on the continental shelf by the manufacturer, Technocean, Inc., with a 99% success rate. The average at-sea life of a drifter that survived the air deployment was 73 days. Over a 12-month period, at periods of approximately every two weeks, if no drifter remained within 5 km of any one of these 26 stations on the continental shelf a replacement drifter was deployed by parachute. In all, 25,100 one-day average displacements were obtained. The processed data on drifter location and velocity was transmitted in near-real time to MMS/HQ and has been in use there for the past four years in oil spill modeling activities. Abstracts of the scientific publications that have resulted from these data refer to specific dynamical inferences drawn from them. This is a summary report of the statistical analyses.

The displacements of the drifters on the West Florida Shelf were variable in time and occurred principally along bottom topographic contours. The monthly mean currents were the strongest along the shelf break and west of Cape San Blas. Significant annual mean flows were on the shelf break to the south or southeast and near shore along the Florida panhandle to the west. Across-shelf currents were strongest off Cape San Blas and the Mississippi Sound. The largest excursion from the general oscillating drift pattern occurred in early October, 1996 during a tropical storm when 35 drifters moved with speeds in excess of 50 cm/sec westward from the West Florida Shelf past the Mississippi River delta to the Louisiana-Texas shelf. A “forbidden zone where no drifter ventures” emerged north of the Florida Bay,

halfway to Tampa Bay, a region to About 47% of the velocity variance can be explained by spatial-scale coherent patterns that occupy the entire horizontal extent of the northeast Gulf shelf. The spatial correlation scale of the along-topography currents along isobaths is about 50 km in water depths between 10-30m and 350 km in water depths of 50-80m. Both local winds and remote forcing from the Loop Current were shown to produce the observed strong events in the large spatial-scale flow patterns. The region of the shelf between 100m and 30m depth exhibited no annual mean velocity, but drifters from that area were ejected to all four corners of the Gulf of Mexico in less than 120 days by short-lived, strong events in circulation.

II.2. Background

Direct observations of the circulation on the continental shelf of the Gulf of Mexico have been going on since the early 1970s. Since that time, the MMS has sponsored several efforts to collect and synthesize these data (Niiler and Koblinsky, 1978) and to carry out comprehensive field studies where circulation data were lacking (LATEX, 1995). Of primary importance were data on the movement of the very-near-surface water parcels that could be used most directly to assess the fate of spilled oil. MMS has also sponsored the development of numerical models of the surface circulation on continental margins, and data sets were needed to assess their validity and usefulness in modeling particle dispersal in the Gulf of Mexico (Herring et al., 2001). To help accomplish these objectives, a field program entitled “Surface Current and Lagrangian-Drift Program (SCULP)” commenced in June 1993 to deploy and analyze data from arrays of ARGOS fixed-surface drifters in the US economic zone of the Gulf to observe the patterns of near-surface Lagrangian displacement and circulation. This is a report on the overview of the data synthesis of SCULP II that was carried out on the west Florida and Alabama continental shelves from February 1996 to June 1997.

The data in this study were obtained with air-deployed ARGOS-tracked drifters similar to CODE drifter developed by Davis (1985). The objective of SCULP-II was to observe the monthly to seasonal time-scale evolution of the circulation on the entire northeast Gulf of Mexico shelf. Drifters released in this area were transported in several surprising ways to other distant parts of the Gulf, resulting in a more comprehensive description than originally planned, especially of the appearance and mechanisms of the forcing of strong currents along the shelf break.

The experimental plan was to fly over a 26-station pattern on the shelf, between 50m depth and the coast twice a month and parachute a drifter on to any station where none was found within a 5-km distance. In this way, an array of drifters was maintained over the shelf for a 12-month period. Each month, the processed data was forwarded to MMS/HQ so that the cooperating scientists at MMS could use these in near-real time for analyses relative to potential oil spills. (The complete processed file has also been released by MMS/HQ for public use.) Section 2 describes the drifters and the data processing. Section 3 describes the monthly mean drifter displacements, velocity and the velocity variances. In Section 4 are derived several characteristics of coherent patterns of flow. The abstracts of the published papers that deal with several dynamical causes for the observed flow patterns are presented in a later chapter of this report.

II.3. The methods and data processing

i) The drifters: Technocean, Inc. of Cape Coral, Florida, built the drifters used in this study (Figure 1). These were packed in a folded configuration in soluble cardboard "coffins" and made air-deployable by the use of degradable cotton parachutes. The tubular PVC body of the drifter, from which the self-deploying arms emanate after the coffin disintegrates in seawater, contains the ARGOS transmitter, controller and batteries. The overall dimension of the square, cross-shaped drogues was 92 cm high and 100 wide. The controller within the drifter shut off the power after 120 days of transmission. The design and testing of these devices was done in SCULP I (Niiler et al., 1997). Their half-life at sea was 73 days. The slip of these drifters as a function of wind speed or sea-state is not known quantitatively, but is estimated by Davis (1984) to be less than 3 cm/sec in the coastal upwelling winds off northern California.

A 26-station deployment pattern was laid out over the northeast Florida shelf (Figure 2). The deployments were carried out by a crew supervised by Technocean, Inc in a twin-engine Piper-Navajo aircraft operated by Cherry Air of Lafayette, LA on a schedule specified several days before by the PI's at the Scripps Institution of Oceanography (SIO). Cherry Air made 23 flights commencing on 5 February 1996. It began the first deployment with 15 drifters at the easternmost stations, to which the 11 westernmost stations were added by 2 April 1996 after it became apparent that drifters moved rapidly westward to the Mississippi Sound, the objective being to obtain a complete data set during the time that these currents would

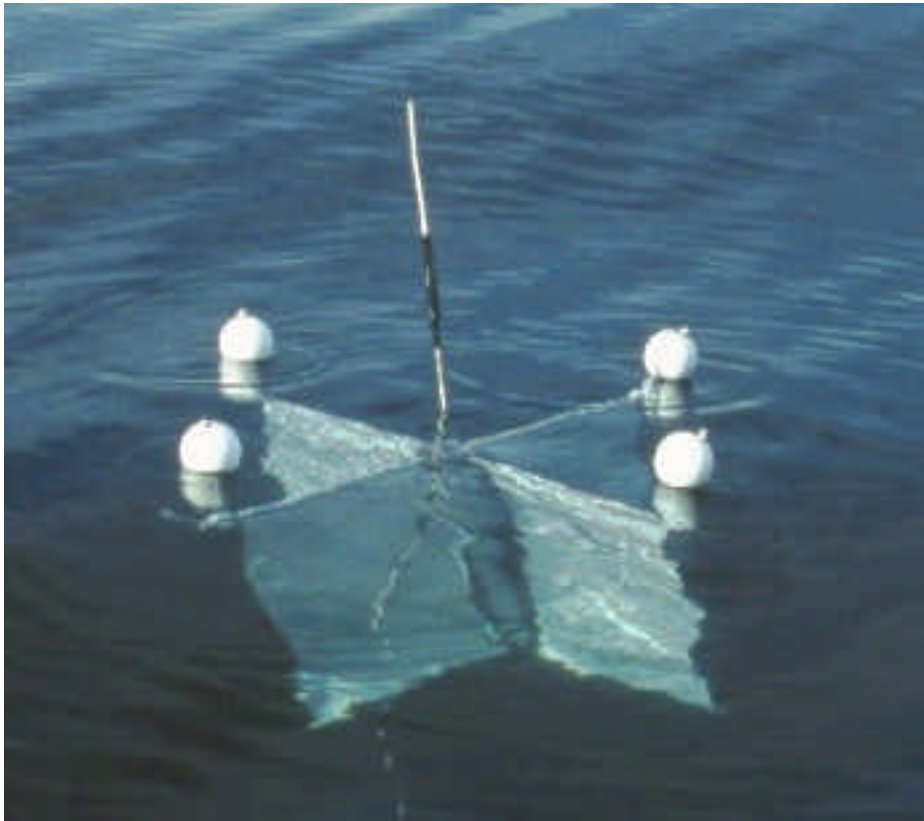


Figure 1. SCULP drifter. The four rectangular vanes are each 50 cm wide by 90 cm tall.

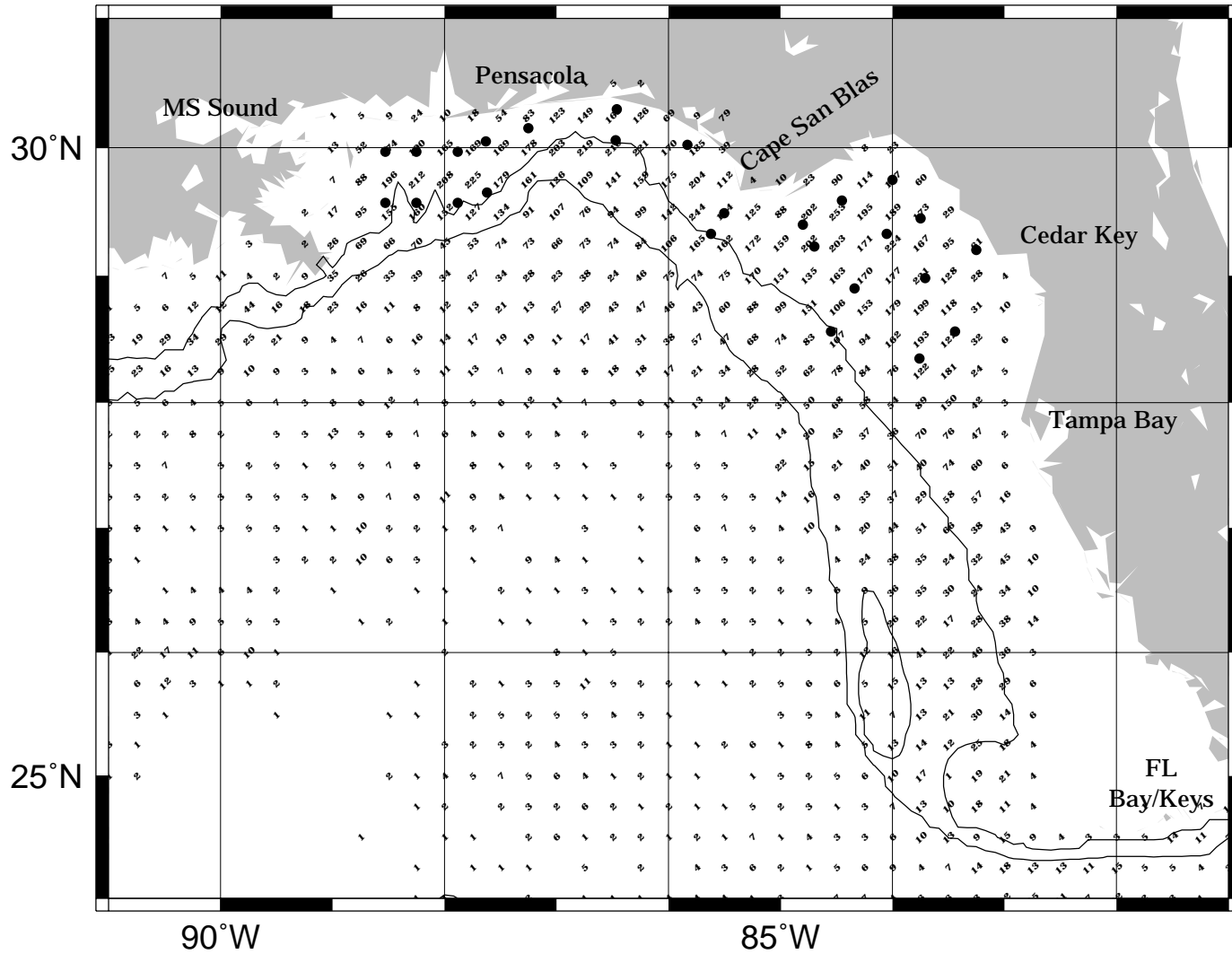


Figure 2. Number of daily averaged surface current observations from Lagrangian drifters in 0.25 x 0.25 degree bins. Drifter deployment locations are indicated with circles. Bathymetry contours are shown at 50 and 200 m.

reverse. Fully loaded, the plane could carry 20 drifters at a time, but usually only 10-18 drifters were required to re-initialize the array every two weeks. In the 12-month period, the plane deployed 344 drifters, of which 342 (99%) produced data.

ii) Data Processing: Once a month, Service Argos delivered to Technocean, Inc. a data tape that contained the times of ARGOS receptions and derived locations of the drifters and estimated to have a minimum uncertainty of 300m. Technocean produced processed data from the raw data tapes. This raw location data was put into correct time sequence and de-spiked with an algorithm, which eliminated displacements that yielded velocities in excess of 250 cm/sec. Observations with less than 15 min. time separation from different satellites were averaged together. Next, an analytic correlation function was computed every day from the Fourier transform of a model spectrum based on 10 days of unequally spaced data centered on the day of observation (VanMeurs, 1996). This correlation function was used to produce an interpolated location time series, sub-sampled every three hours. Velocity components were computed from center time differences. Daily average locations and velocities are used in this presentation.

The following data sets were derived at SIO and linearly interpolated on to the drifters' daily average locations: (a) the 0.08 degree resolution TOPO .08 bottom topography, (b) bottom topography gradient vector, computed from 0.25 latitude x 0.25 longitude sub-sampled bottom depth data, (c) long-topography and cross-topography velocity vectors.

The data density map on a 0.25 degree resolution (Figure 2) shows that the largest number of daily average observations come from a region shallower than 50 m. This was no surprise, as the deployment stations were shallower than 50m. Drifters cross over to the shelf break with ease as the region between 50m and 200m depths appears contain about 50% of the data even though they were not deployed there. The statistics of flow will be developed for all 0.25 x 0.25-degree regions if there were more than 5 one-day average observations in them.

II.4. Circulation patterns

The ensemble of drifter tracks (Figure 3) shows that while the predominant motion is along the shelf, drifters cross isobaths and become

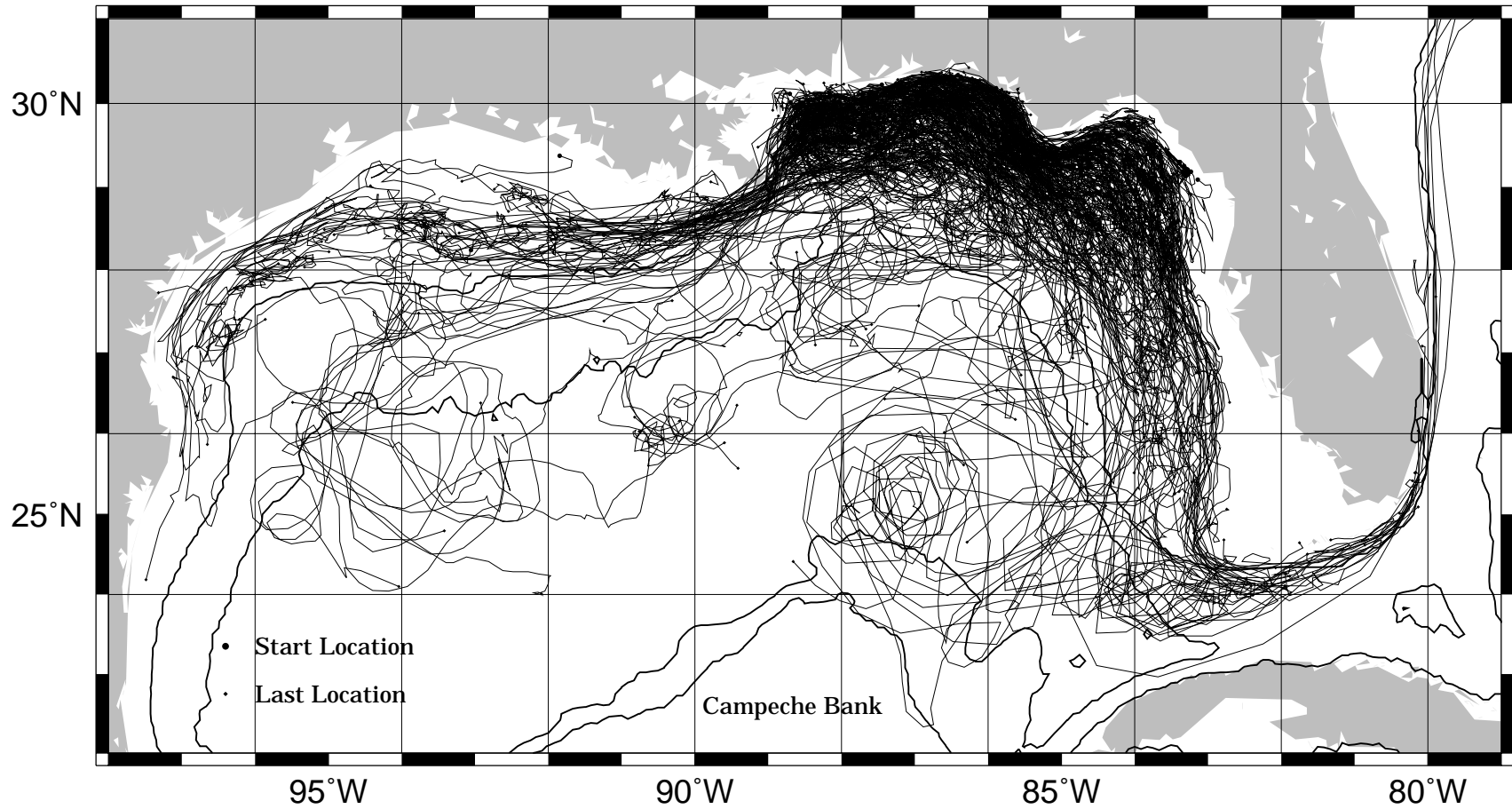


Figure 3. Tracks for each of the 342 drifters deployed during the SCULP-II experiment. Starting (ending) locations are shown with circles (diamonds). Bathymetry contours are shown at 200 and 2000 m.

entrained in the circulation patterns in the deep Gulf (Ohlmann et al., 2001) or cross the outflow of Mississippi River to the Louisiana-Texas (LATEX) shelf (Ohlmann and Niiler, 2001). Prominent in this display is a "forbidden zone" on the west Florida in the coastal waters (shallower than 10m) and a large area of the shelf directly north of the Florida Keys, nominally the Florida Bay (Yang et al., 1999). On their passage southward to join the Florida Current some are entrapped into cyclonic eddies emanating from the westernmost tip of the Florida Keys and are transported by these eddies to the Campeche Banks. Several of these drifters are also entrained into the shoreward side of the Florida Current or a jet along the shelf escarpment (Hetland et al., 1999). These latter, together with the drifters that move southward at the 50m isobath in the fall and winter seasons, travel to the North Atlantic or become entrained into the spin-off eddies on the shelf off eastern Florida or the Florida Keys. Thus it is seen that particles from the deployment region traverse the entire Gulf of Mexico and the US economic zone of bounding Florida on a time scale of less than 120 days.

A variety of shorter-period circulation phenomena are displayed in monthly tracks (Figure 4). Note that drifters on large segments of the shelf appear to move together, with reversals on time scales shorter than a month. The large displacements often occur during ten-day and even smaller periods. The largest coherent excursions occur in October '96 and November '96, when drifters move rapidly westward across the mouth of the Mississippi. Of the 342 drifters deployed, 59 travel westward across 90W to the LATEX shelf. These motions reflect wind-forced motions that have synoptic meteorological time scales and have been reported from analyses of current meter data (e.g., Niiler, 1975). During the months of November through March, drifters moved southward on the west-Florida shelf in a well defined "stream" just shoreward of the 50m depth contour, the explanation for which has not emerged from dynamical considerations.

In July 1996 a strong jet to the south was centered on the shelf-break at 150m depth. This feature could have been related to the encroachment of the Loop Current on the Tortugas shelf (Hetland et al., 1999). In the period of April-October, there was a general westward movement of drifters south of the Florida Panhandle and west of Cape San Blas. This coastal flow to the west in water depth less than 20 m was most well organized in June 1996 when the coastal winds in this area are strongly from the east.

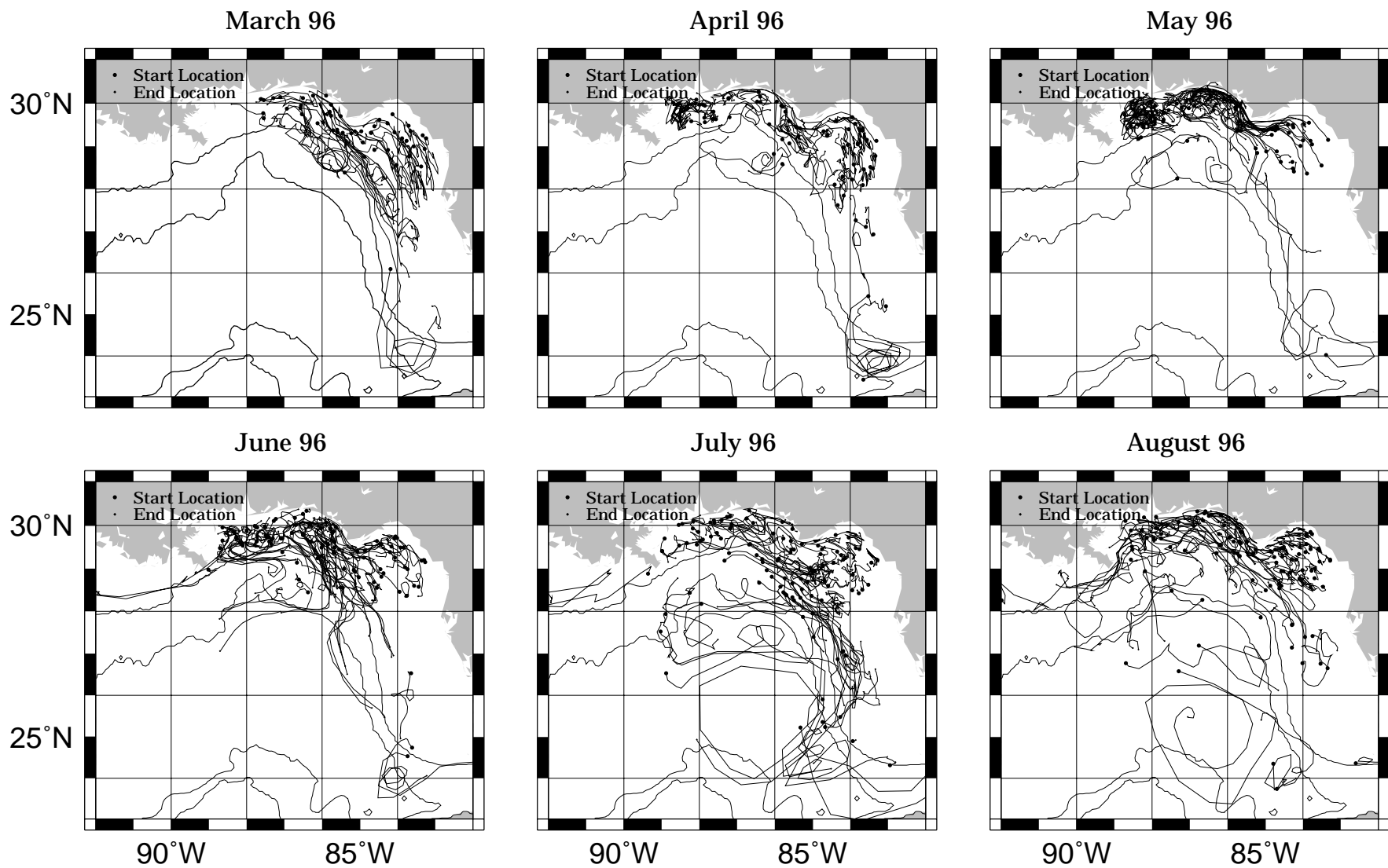


Figure 4. SCULP-II drifter tracks shown by month for a complete year (from March 96 through February 97). Starting (ending) locations on the first (last) day of each month are in denoted with circles (diamonds). Bathymetry contours are shown at 200 and 2000 m.

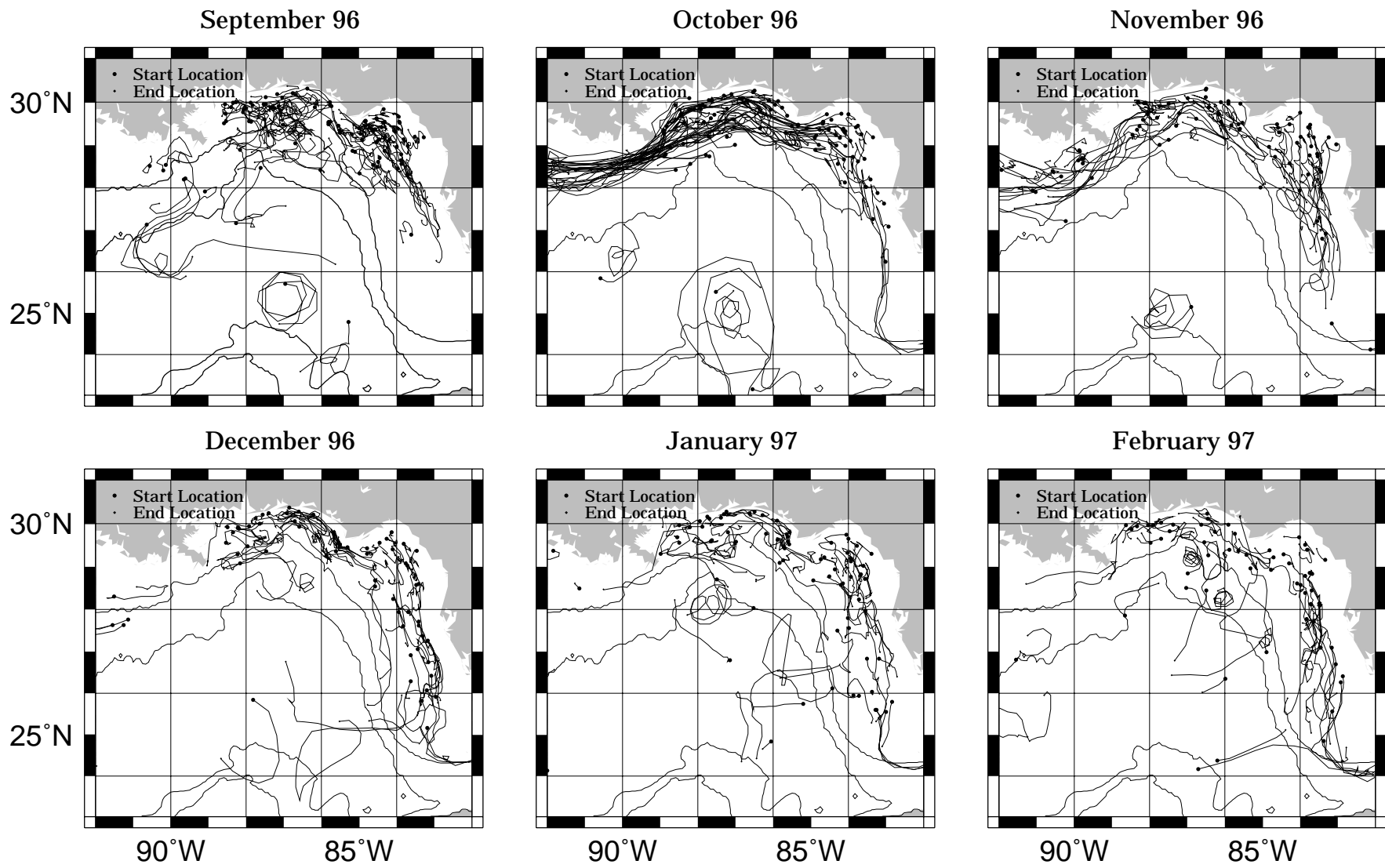


Figure 4 continued.

The sequence of events that compose the October 1996 movement of 35 drifters from the shelf south of the Panhandle to the LATEX shelf was clearly related to forcing by the tropical storm "Josephine" (Figure 5). Between October 3 and October 10, the entire west Florida shelf from Tampa Bay to the Mississippi Sound is accelerated to the west during the strong tropical storm (Ohlmann and Niiler, 2001). Similar movements occur in the period of November. 15-30 when 12 drifters make a rapid excursion to the west. These rapid displacements, with daily movements in excess of 100 km/day across the mouth of the Mississippi River, had not been known before these drifter data were assembled.

In summary, the drifter displacements appeared to be characterized by 6-12 day vacillation along the shelf isobaths. In the winter months a persistent stream toward the south, just east of the 50m isobath. Occasional strong events occur during which the waters across the entire width of the shelf participate in the motion, either forced locally by storms or by Loop Current interactions with the shelf. The dispersions of drifters over large distances were caused primarily by these events.

II-4. Velocity statistics

The monthly mean velocity vectors (Figure 6) show that the strongest currents were found in water depths greater than 200 m. On the shelf, several spatially-coherent patterns appear in all months except April, May and September. In these months the mean velocity field was weak and contained many small spatial-scale features. In the months of August, October, November and January, large velocities in excess on 40 cm/sec, were observed to the west past the mouth of the Mississippi River. In April and May, monthly mean velocities in excess of 20 cm/sec were observed directly west of Cape San Blas. Because of the predominance of strong events with time scales shorter than a month, a smooth seasonal cycle cannot be defined well from viewing these data directly, but such a cycle may have existed on the northeast Gulf Shelf in 1996-97, as seen in the analysis below.

The annual mean velocity map, made from the entire record length of data (Figure 7), shows the strong currents that were caused by the short lived events discussed above. From this picture it is apparent that drifters cross the shelf break at the head of the DeSoto Canyon along the westernmost margin

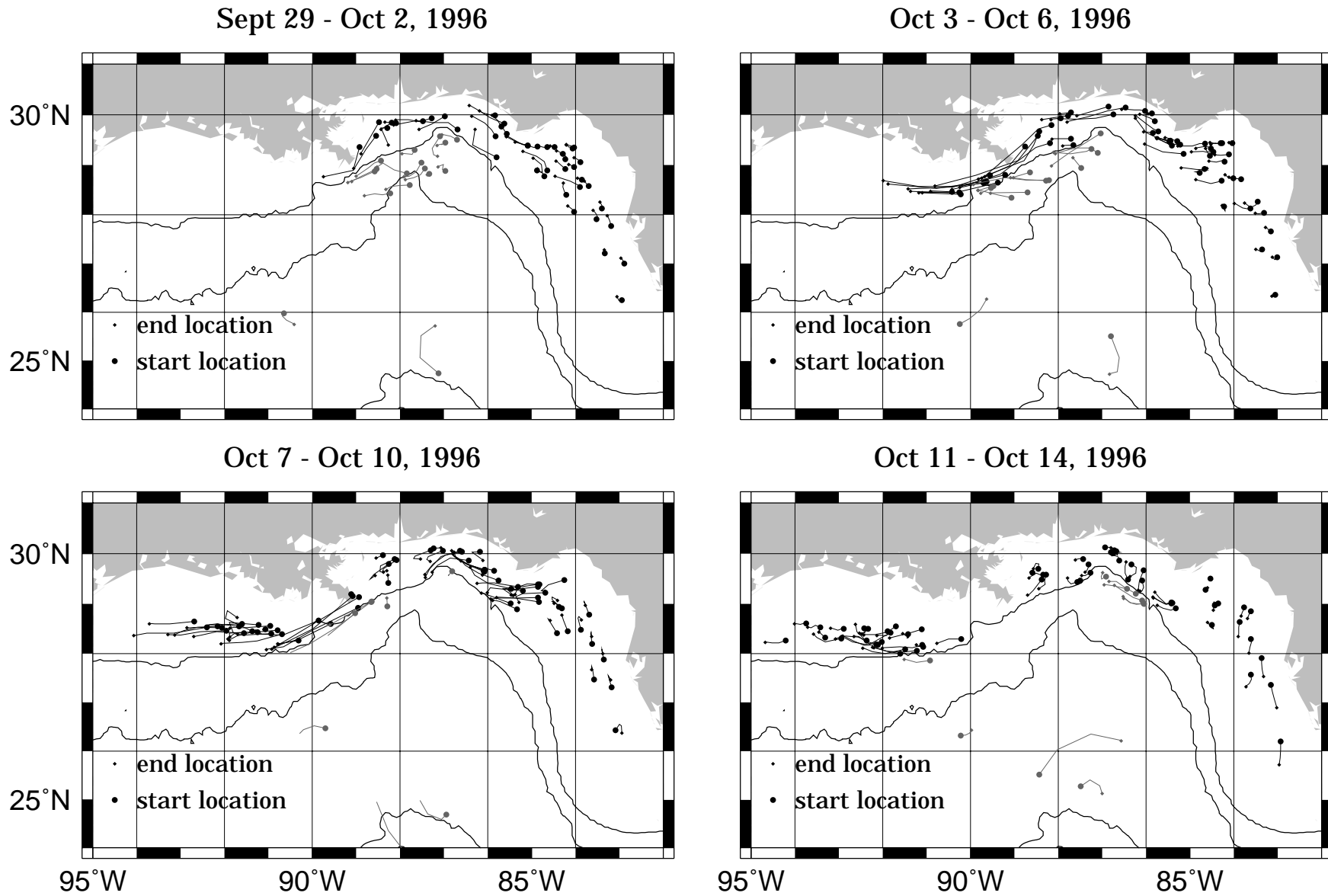


Figure 5. SCULP-II drifter tracks recorded from a) 29 September 1996 through 2 October 1996, b) 3 October through 6 October 1996, c) 7 October through 10 October 1996, and d) 11 October through 14 October 1996. Drifter tracks over the continental shelf (water depths < 200 m) are illustrated in black. Tracks for regions offshore of the shelf-break (> 200 m) are gray. Starting (ending) drifter positions are denoted by circles (diamonds). Bathymetry contours are shown at 200 and 2000 m.

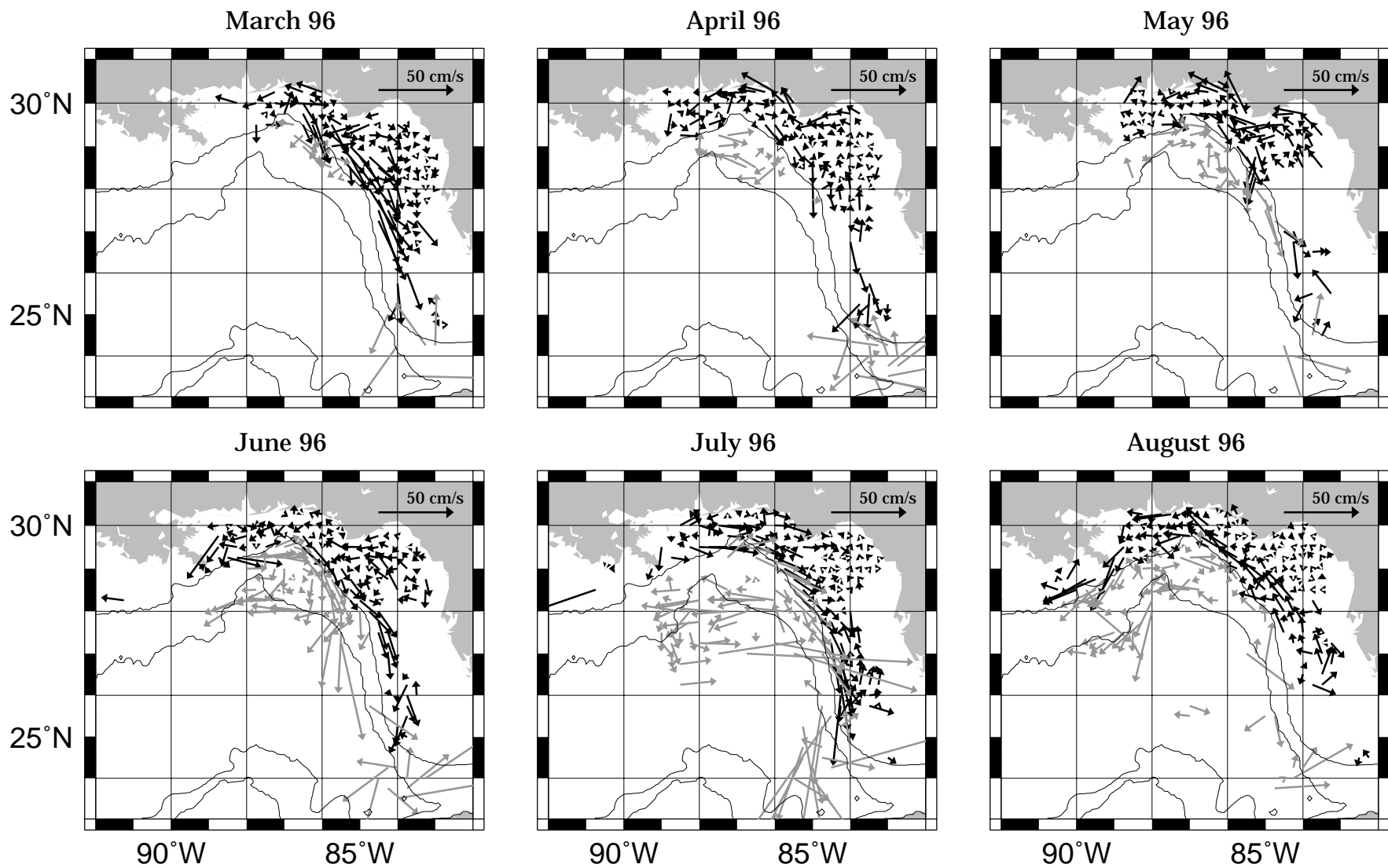


Figure 6. Monthly mean surface current vectors computed from SCULP-II drifter data. Mean velocities are calculated for 0.25×0.25 degree bins over a complete year (March 96 through February 97). Velocity vectors over the continental shelf (water depths < 200 m) are illustrated in black. Vectors for regions offshore of the shelf-break (> 200 m) are gray. Bathymetry contours are shown at 200 and 2000 m.

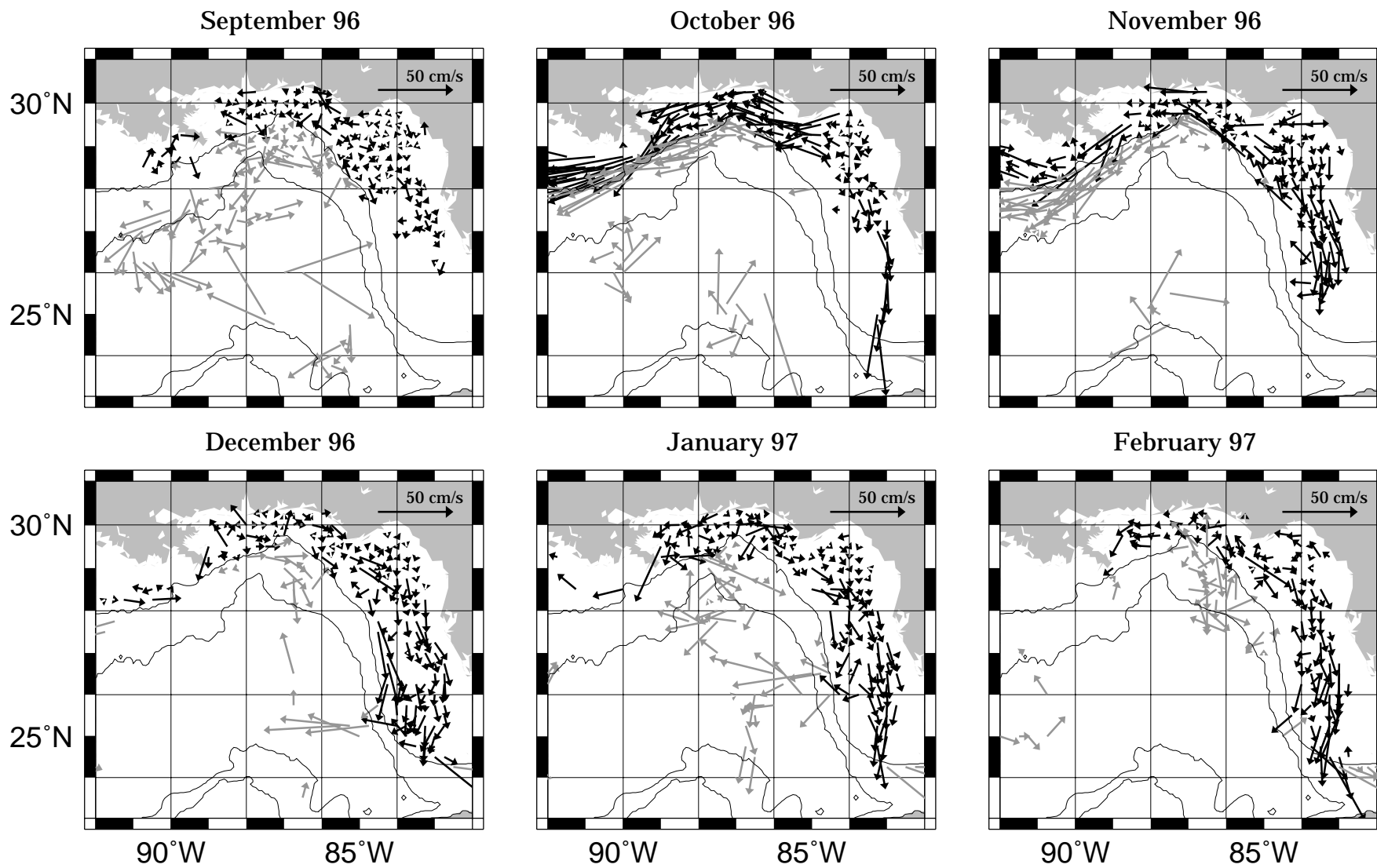


Figure 6 continued.

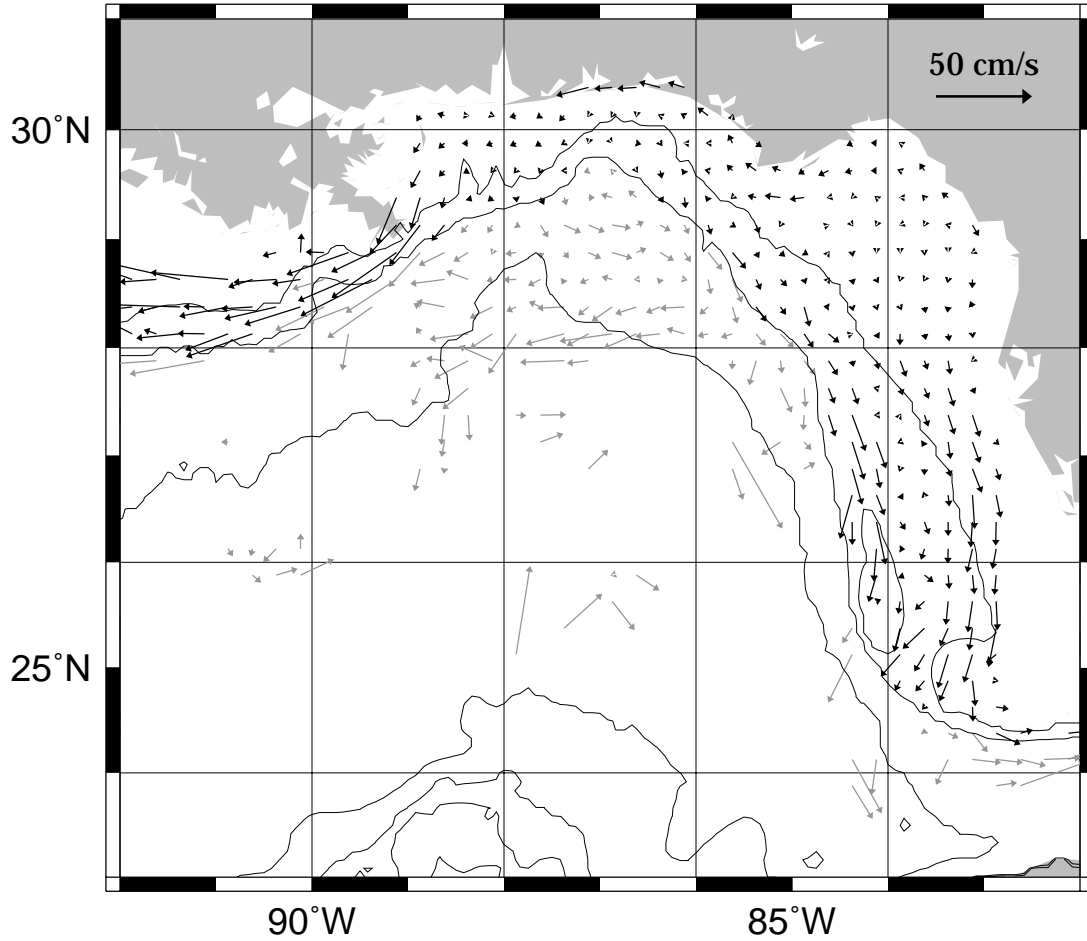


Figure 7. Mean surface current vectors from the SCULP-II drifter data. Mean values are calculated for 0.25×0.25 degree bins with 5 or more observations. Vectors inshore (offshore) of the shelf-break (200 m) are shown in black (gray). Bathymetry contours are shown at 50, 200, and 2000 m.

of the Mississippi Sound and directly west of the Dry Tortugas. The jet just shoreward of the shelf break was not due to the local presence of the Loop Current along the shelf, but is a shelf circulation feature caused by the interaction of the Loop Current with the shelf near the Tortugas in June 1996 and July 1996. On the central shelf, where the deployment strategy obtained a uniformly sampled data set, no resulting significant mean currents were displayed. When Figure 7 is viewed together with Figure 2 it is apparent that the strong mean circulation features here were not sampled as well as on the northeast shelf, and drifters entered these features only when they were carried away from the deployment area. These mean current features could well be a result of the biased sampling that resulted from the fact that drifters were not deployed on a regular basis in the regions where they occurred. It is quite remarkable, however, that the mid-shelf region of no mean flow was able to eject drifters to the four corners of the Gulf via Lagrangian transport processes of short-lived, strong events on a time scale less than 120 days. Thus the value of a limited number of time series of currents taken on this shelf at various fixed locations for deriving conclusions on the fate of oil must be questioned severely.

Though it will be obvious to the reader, perhaps we should emphasize this last point. A mean signal emerges in this data set, but in many of the regions there are only a very few observations. One should be very reluctant, therefore, to interpret any mean value based on fewer than perhaps 100-150 samples as being well observed. Furthermore, it is essential to be aware that the mean from even the best-sampled regions are a mean *for this time period only*. A long-term mean (assuming that one exists that is different from zero) would have to be established from data taken in many different years. We are beginning to assemble enough data – both of wind and of currents – to estimate how long this might require, but at this writing it remains an open question.

The variance ellipses (Figure 8) demonstrate that the variance along the bottom contours was larger than across bottom contours. The major axes of the variance ellipses, however, show a consistent counterclockwise rotation relative to the bottom contours. This could well have been due to the Ekman currents driven by winds that crossed isobaths. The smallest variances were found in the shallow water between Cape San Blas, Cedar Key and Tampa Bay. Variance in 50 m depths west of Cape San Blas was as vigorous as that on the shelf break. The topography of De Soto Canyon is only weakly felt in the relative different rotations of the variance ellipses on either side of the

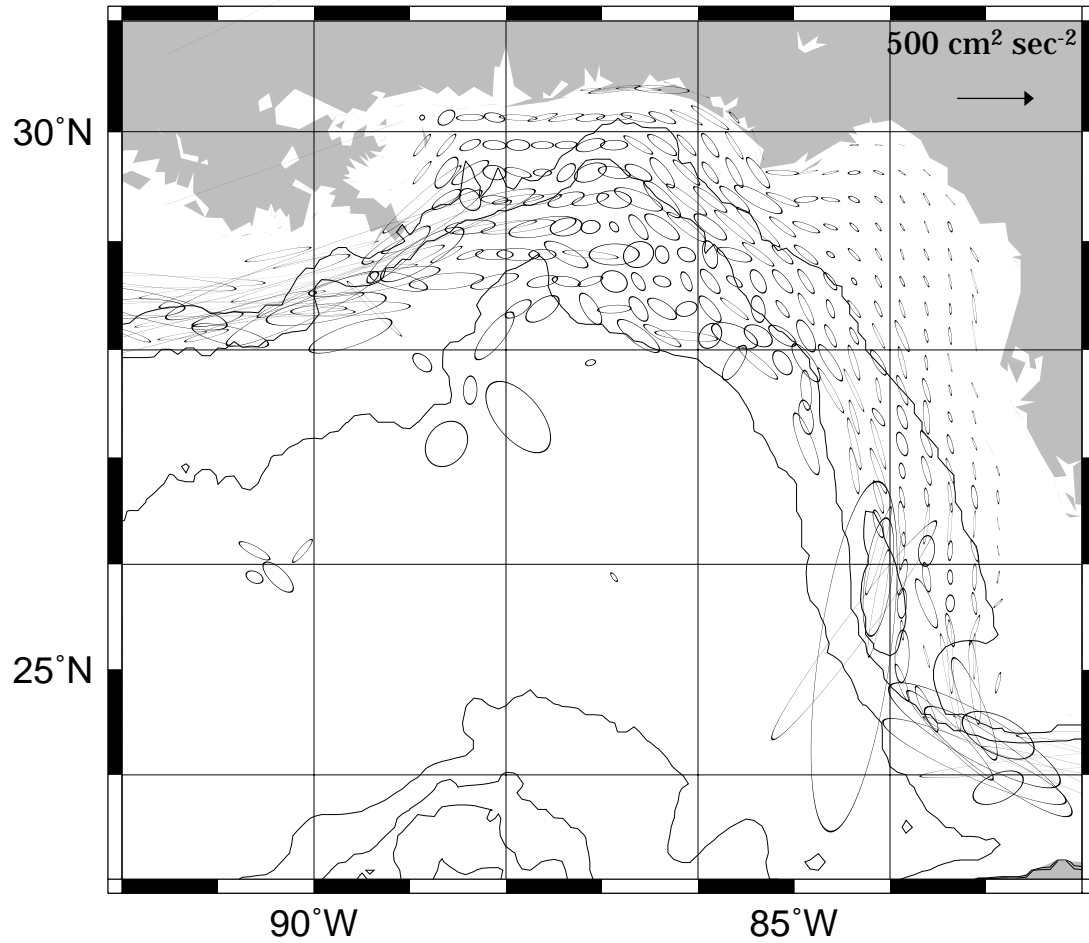


Figure 8. Velocity variance ellipses computed from SCULP-II drifter data. Ellipses are calculated from daily averaged velocity values for 0.25 x 0.25 degree bins with 5 or more observations. Bathymetry contours are shown at 50, 200, and 2000 m.

Canyon wall. Drifters move across these walls without much regard to the severe changes of topography that occur below.

The vector EOFs of velocity computed from the shelf less than 100m depth show that a pattern that was unidirectional and encompasses the entire shelf (Figure 9) accounts for 47% of the variance (Figure 10). The four principal EOFs account for a total of 75% of the variance and account for 100 km spatial scales of flow along topography. The time series of the amplitude of the principal mode has energy on time scales of 5 days and larger. It also reflects the strong wind events that caused the rapid movement of drifters toward the Mississippi Sound in October and November of 1996.

The second principal EOF mode appears to have a shift in August from a predominantly positive value to a negative value and is perhaps the best representation of the "seasonal cycle" of the circulation. This pattern shows convergence toward Cape San Blas from both sides of the Cape with a strong current to the northwest on its western side.

The residual of the energy, 25% of the initial energy, after the currents composed of the four principal modes were subtracted, still shows a preponderance of motion along topographic contours (Figure 11). This represents spatial scale motions with coherence scales less than 50 km, or two grid points of the averaging scale used. Thus there were significant energetic motions, such as the coastal current west of Cape San Blas, that were not coherent with the rest of the motions on the shelf on a 100 km spatial scale and were not well represented in the principal modes. There were motions that were not well represented by the decomposition of the principal components. The assumption of separability into functions of space and time in constructing EOFs may not be valid here.

To characterize the space and time scales of motion, the auto-correlation function of the along-topographic current was computed as a function of time lag and spatial lag along topographic contours (Figure 12). Significant differences occur in the transition from 10-30 m depth region to 100-150 m depth region. The time scales of coherence increase from 10 days to 15 days and then decrease to 7 days. The space scales increase from 25 km to 300 km and then decrease to 100 km. In summary, the currents in shallow water persist for 10 days, but have short space scales along topographic contours. On the mid-shelf, the time scale is several weeks and the space scales encompass the entire study area. On the shelf break the time scales are much reduced, as are the space scales, perhaps due to the small scale eddies of the shelf-break region. There is a tendency of the signals to propagate to the west along the mid-shelf, much more slowly than continental shelf waves would in this region.

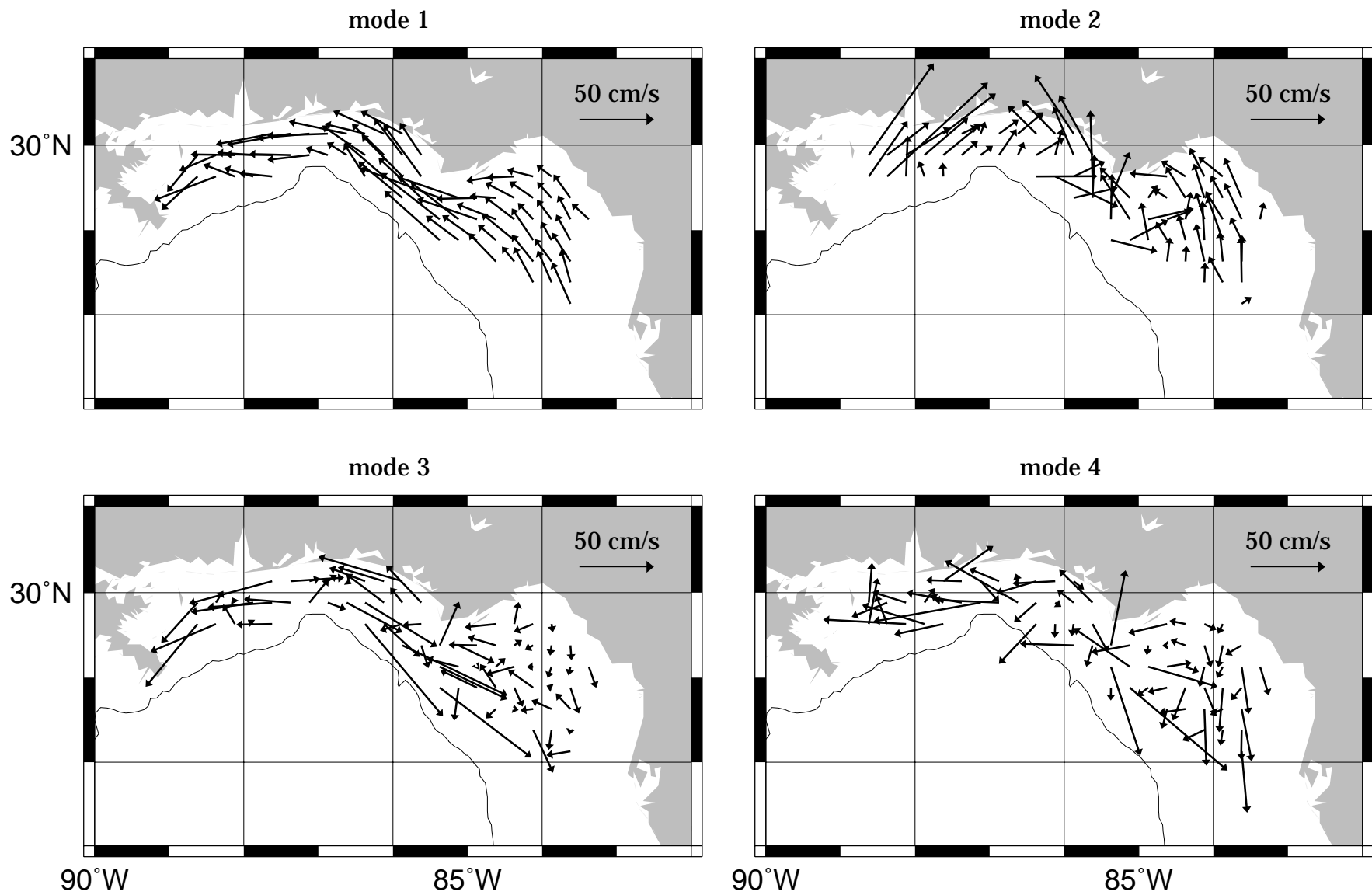


Figure 9. Spatial patterns of the first four empirical orthogonal eigenfunctions. EOFs are calculated with daily average velocity data on a 0.25 x 0.25 degree grid. Modes 1 through 4 explain 47.2, 12.3, 8.5, and 6.2% of the variance, respectively. The 200 m isobath is shown.

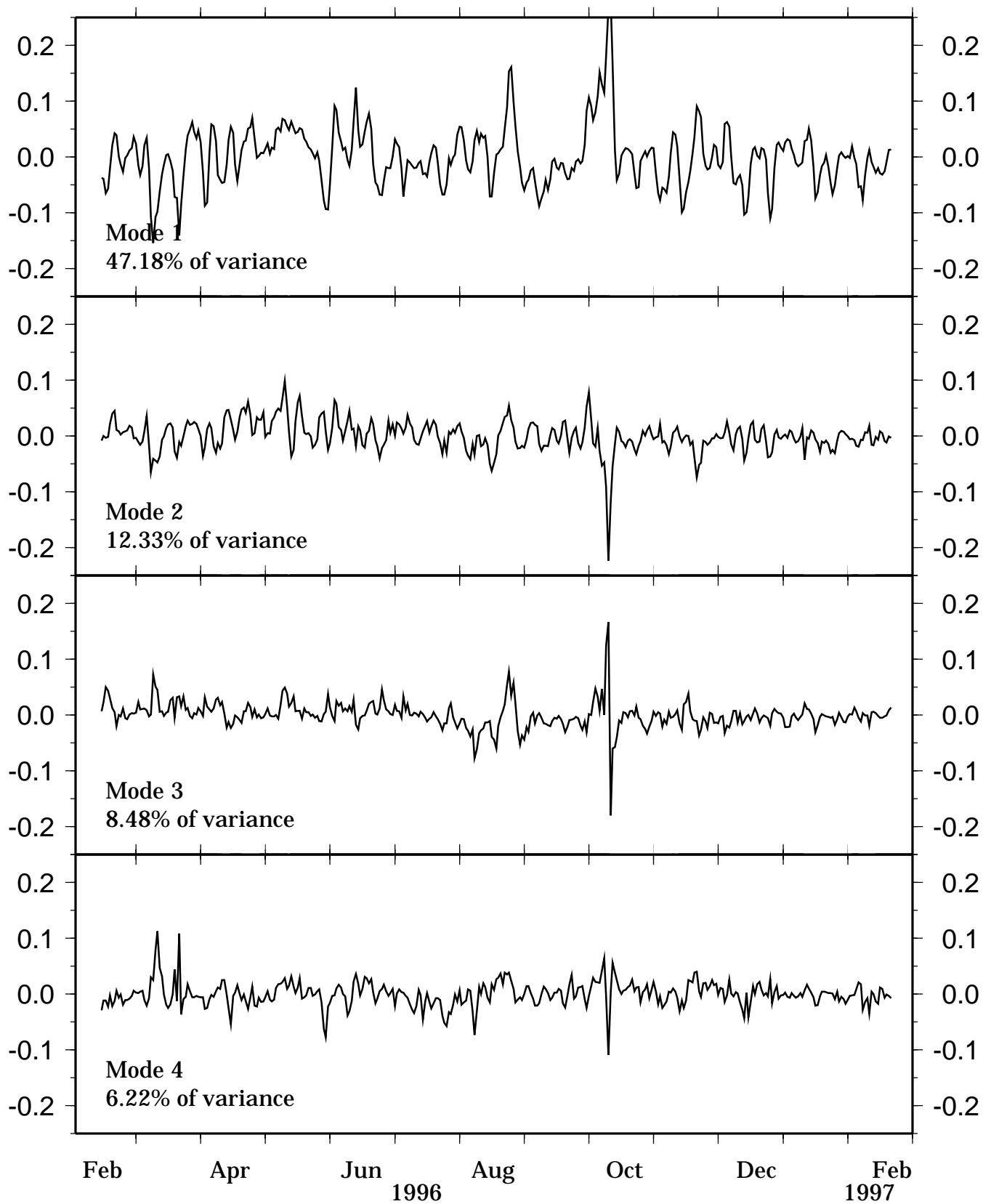


Figure 10. Temporal amplitudes corresponding to the first 4 spatial EOF modes shown in Figure 9.

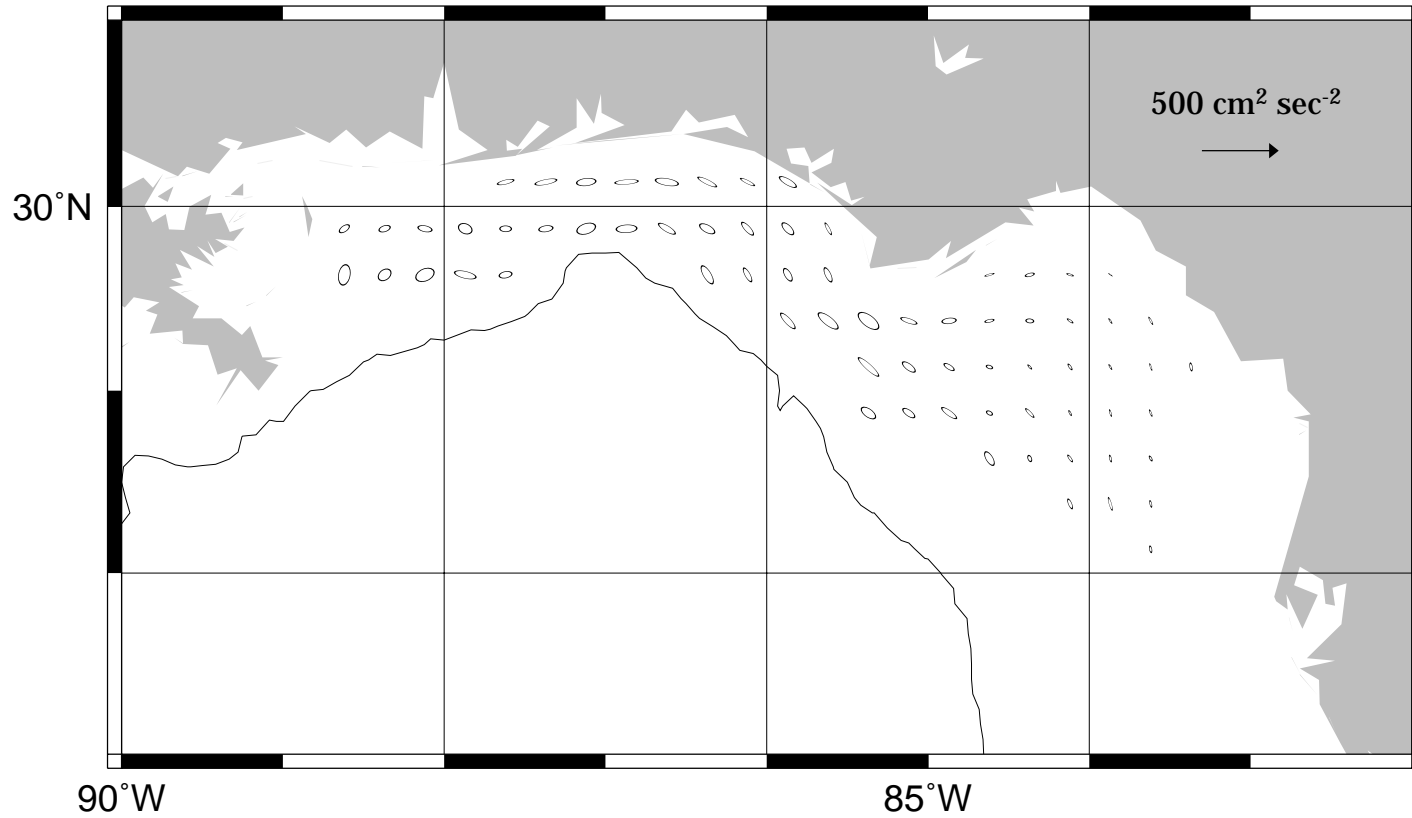


Figure 11. Variance ellipses computed for differences between daily average surface velocities from drifter data on a 0.25×0.25 degree grid, and velocities computed from the first four modes of the EOF analysis. The 200 m isobath is shown.

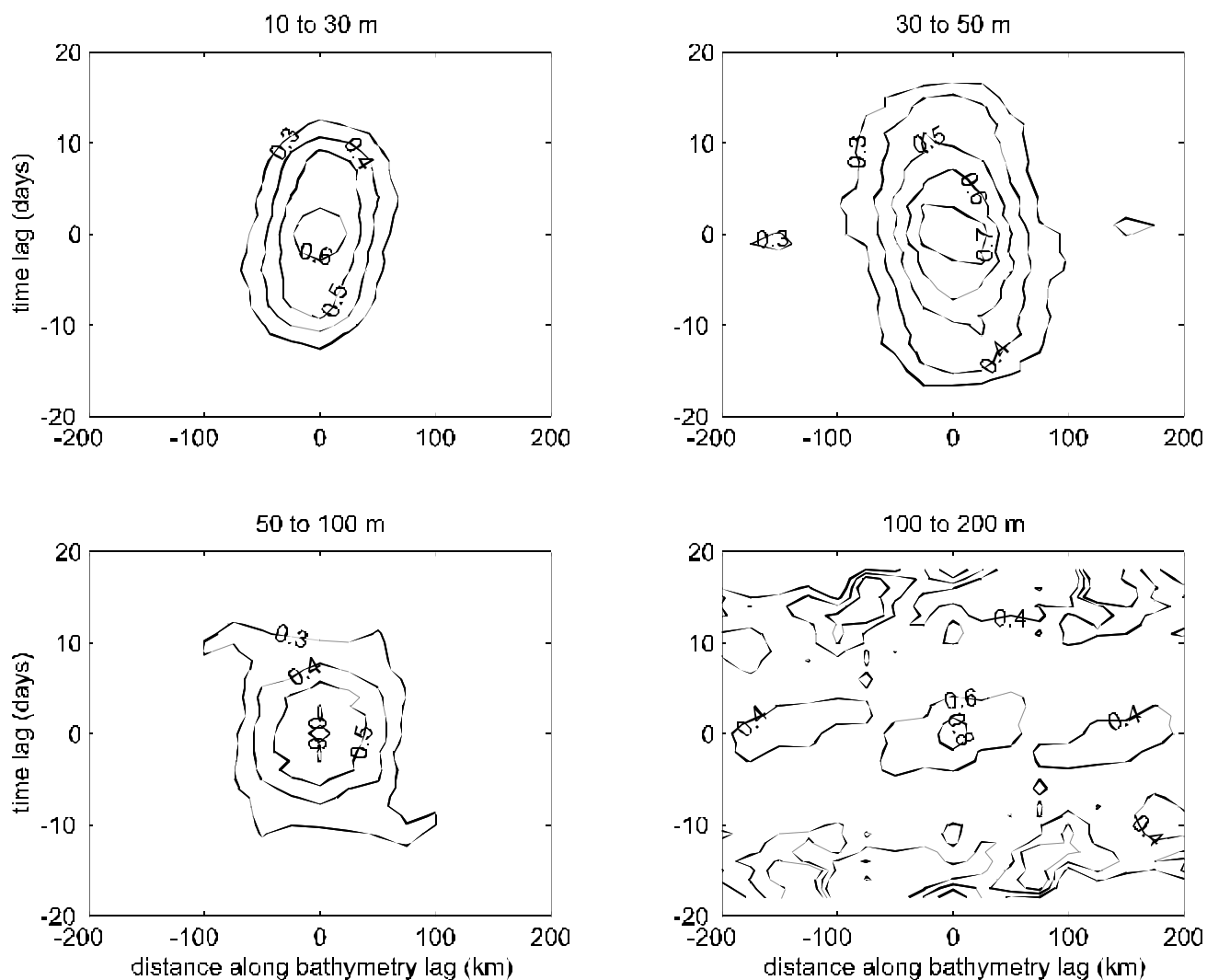


Figure 12. Normalized autocovariance for the along-shore velocity component in the depth regions a) 10 to 30 m, b) 30 to 50 m, c) 50 to 100 m, and d) 100 to 200 m. The autocovariance is lagged in space and time. Daily average velocity values for bins bounded by the upper and lower isobaths considered, and extending 25 km along the mean depth between isobaths, are used in the calculation. Covariance values are smoothed in time using a 5-day running mean prior to contouring.

III. The Moored Current Meter Experiment

The primary focus of the NEGOM program was the surface drifter experiment to observe currents very near the sea surface. An auxiliary experiment involving moored current meters, as described here, was included for several reasons. First, there is the basic question: Do the measurements from drifters tell us the same things as measurements from moorings? Second, as is well known, the moorings provide continuous observations at a point, while drifters provide sequential observations at many points. The Eulerian and Lagrangian frameworks provide complementary observations, but they are qualitatively different, and by having both kinds of observations we hoped to be able to map the velocity fields with better accuracy and resolution. Third, there is a great deal of existing data from moored instruments. Having at least a minimal set of moored observations here to augment the drifters provides a means of insuring continuity between the new work and historical archived results.

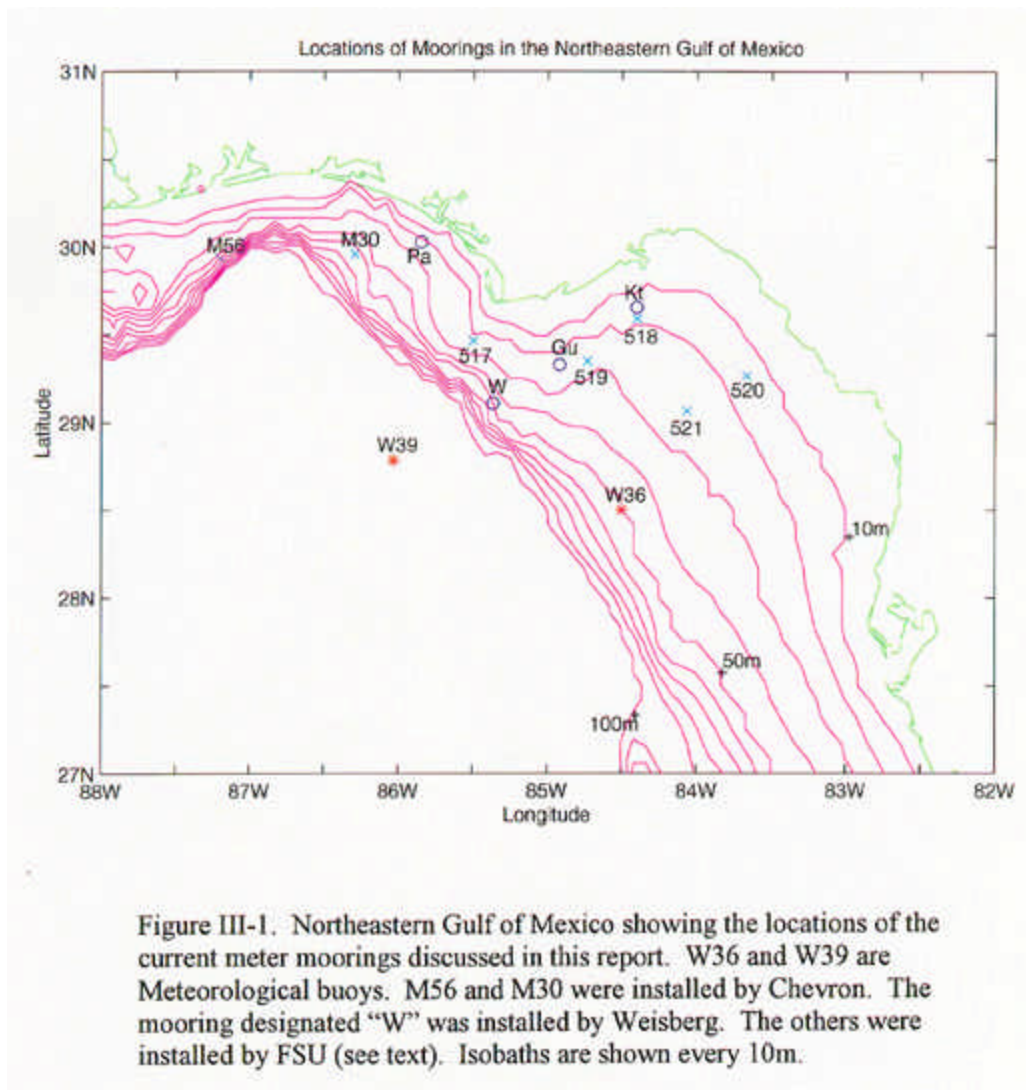
Figure III-1 shows the location of a variety of moored instruments. W36 and W39 were meteorological buoys, provided by the NDBC. M56 and M30 were multi-instrument moorings installed by Chevron, Inc. at the head of DeSoto Canyon prior to the beginning of the drifter experiment. M30 was set using MMS equipment, so the data are publicly available. The data from M56, however, were still proprietary at this writing.

Moorings 517 – 521 were simple moorings with a single near-bottom S4 current meter set 4 m above the bottom. These moorings suffered from frequent encounters with fishing trawlers. As a result, moorings designated **Kt** (K-tower), **Gu** (Gulf) and **Pa** (Panama) were set with an upward-looking acoustic Doppler current meter (ADCP) on the bottom, in trawl-proof housings. These were set by the Current Meter Facility at Florida State University.

The mooring designated simply as “W,” on the 50-m contour, was set by an instrument group headed by Weisberg at the University of South Florida.

Figure III-2 shows a set of time lines of the mooring emplacements. Figure III-3 shows the design of Weisberg’s mooring, in which the adcp was placed at the sea surface.

An extensive set of plots of current measurements is given in Appendix A. Further analyses and comparisons are given in the next two sections of this report. A few brief results are given here as an example of the nature of the results.



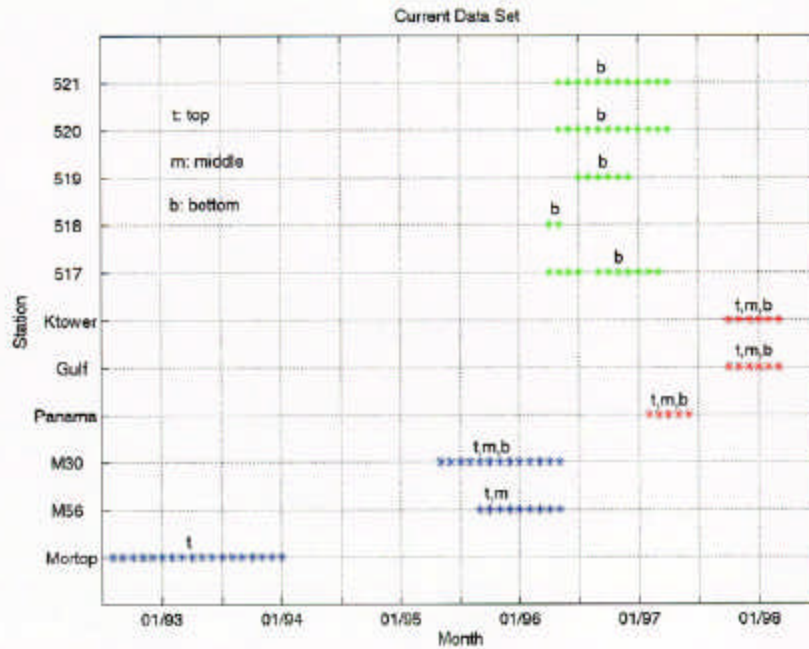


Figure III-2. Mooring deployment time lines. Red markers indicate bottom-mounted ADCPs, Green indicates a single S4 mounted 4 m above the bottom; Blue indicates a mooring with several instruments in the vertical. Mortop was on a mooring very near M56.

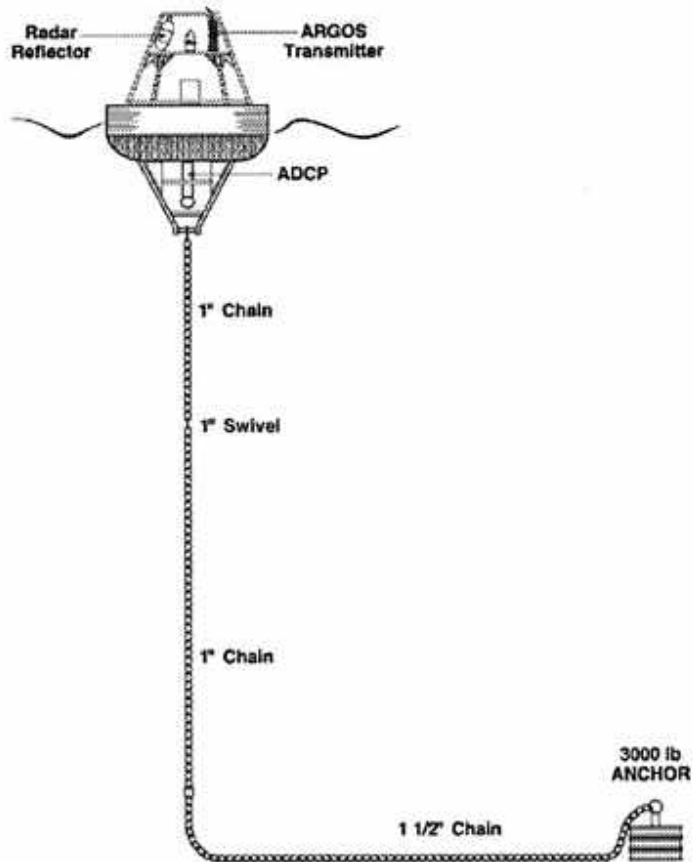


Figure III-3. The deployment of the mooring at 50m depth, marked by "W" on figure III-1, installed by Weisberg's group at the University of South Florida.

One of the fundamental findings of wind-driven coastal currents is that they have a characteristic oscillatory nature, as described in the section on Drifter Results. Figure III-4 shows a set of variance ellipses for results at the near-bottom currents. The arrows show the means for the duration of the mooring settings, and the ellipses show the variance in the “wind-driven band” of periods longer than 30 hours (to suppress tides and inertial motions) out to periods of 20 days. Figure III-5 shows equivalent results as measured in the middle of the water column by the (bottom-mounted) adcp instruments. It is clear that the wind-band variance is very large in comparison with the weak mean signals. Figure III-6 shows the large variance in the tidal-inertial band – also as measured in the middle of the water column.

To illustrate the nature of the large variability of the flow in comparison with the mean, Figure III-7 shows a plot from the Chevron moorings south of Pensacola. With approximately 30 months of data, we might expect that a mean flow either to the west or the east might emerge. The “x” values are the monthly means; the dashed lines show the standard deviation of the monthly means. The monthly values range from -7 to 19 cm/sec, and the over-all mean is 1.5 cm/sec. The individual monthly mean values are essentially independent (as the autocorrelation goes to zero in about 30 days) so the standard error of the mean is less (by the square root of 30) than the standard deviation shown by the dashed lines. It thus appears that although the mean flow is ~ 1.5 cm/sec (positive, to the east), and significantly different from zero by 5 standard errors, the flow in *any given month* is likely to be significantly different from the long-term mean.

The importance of this result bears further explanation. During a given wind event, the wind-induced flow can be computed fairly well (as shown in section V). It is a “meaningful question” to inquire about the flow from a given wind event. However, it is a much less meaningful question to inquire about the “mean flow” in general. No clear seasonal signal emerges from the results shown in Figure III-7. And while the slightly positive mean flow (to the east) seems to be significantly above the noise, we would be reluctant to assume as certain that a repeated set of observations would give a similar mean unless we could be assured that the wind forcing would be similar. We note that the mean flows from the drifter experiment (Fig 7, Section I) are also not significantly different from zero.

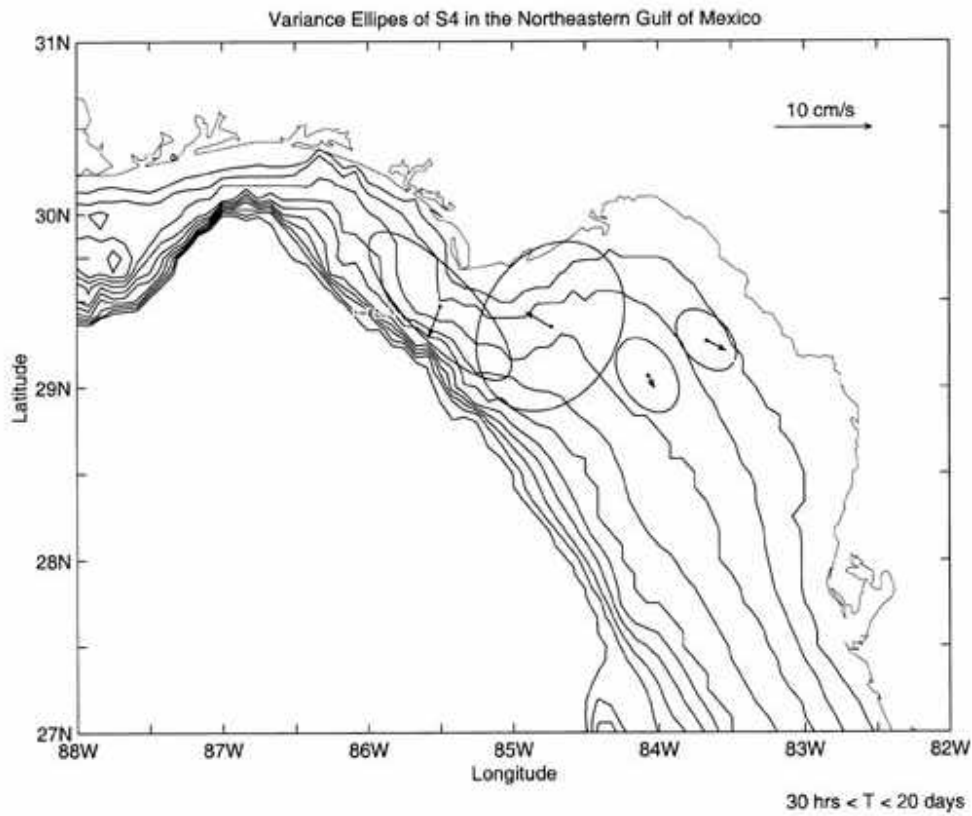


Figure III-4. Variance ellipses computed from the observations at the S4 moorings (see Figure III-1). The mean over the record is shown by the small arrow. These are from data taken 4m above the bottom. The data are filtered to suppress power at periods shorter than 30 hours and longer than 20 days, in order to concentrate on the “wind-driven band.”

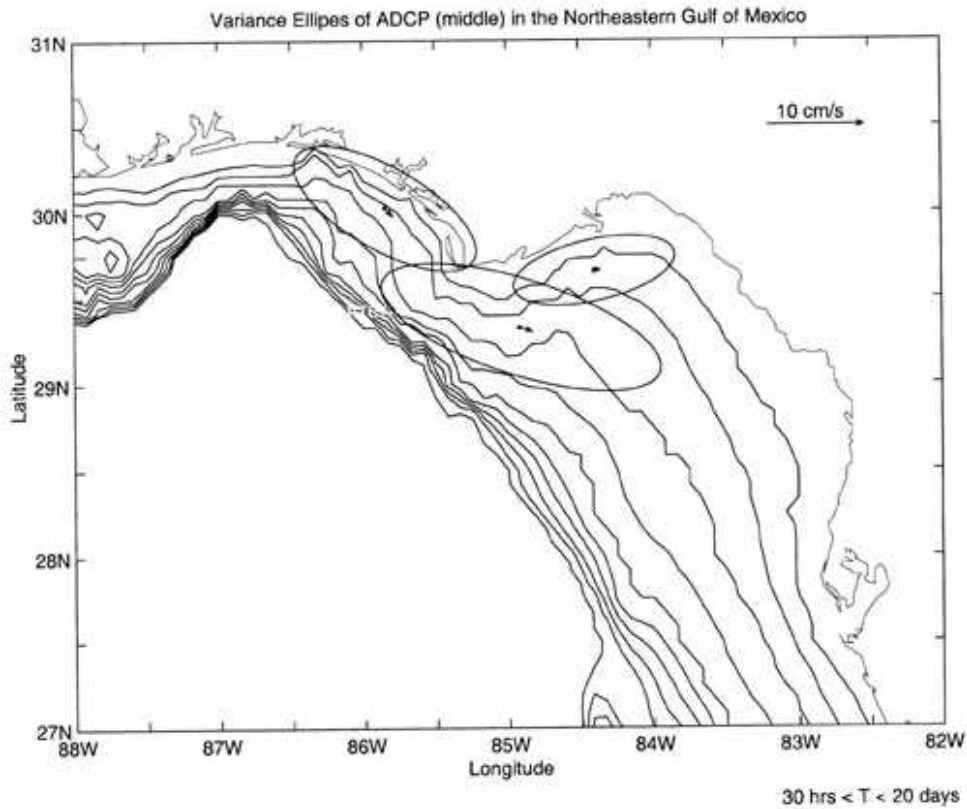


Figure III-5. Variance ellipses, as in Figure III-4, but computed in the middle of the water column from the ADCP data. These data are also band-passed as in III-4.

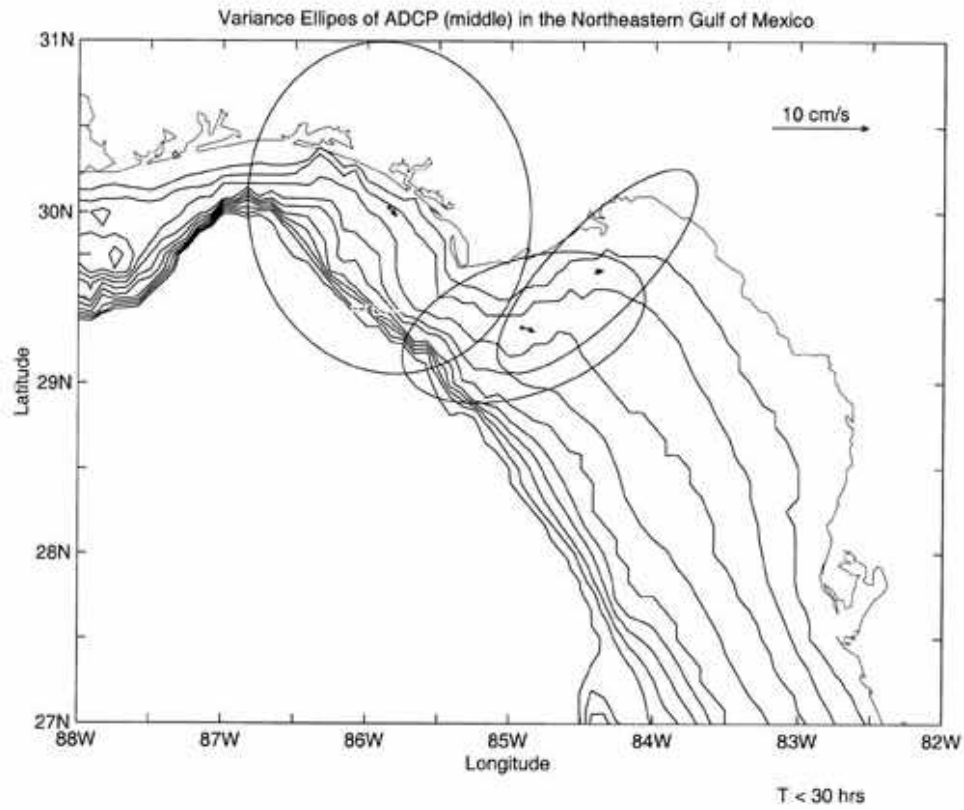


Figure III-6. Variance ellipses, as in Figure III-5, computed in the middle of the water column from the ADCP data, but for the velocity fluctuations at periods shorter than 30 hours. This includes tides and inertial motions.

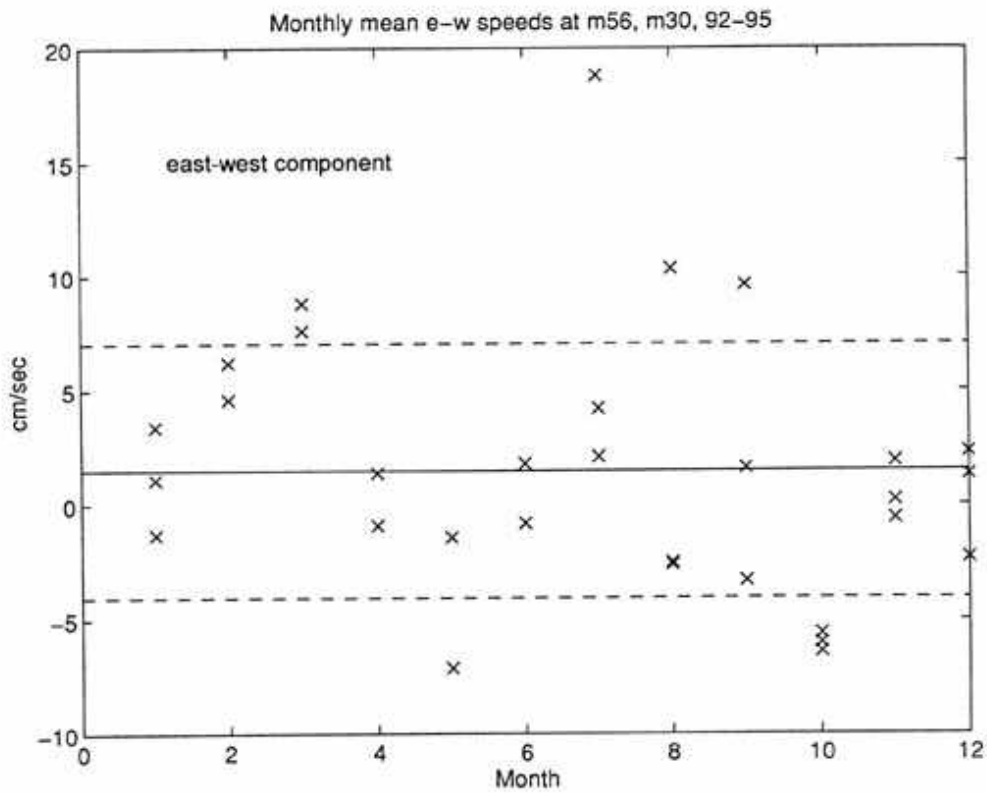


Figure III-7. Monthly mean currents – east-west component -- over a period of roughly 3 years at Moorings M30 and M56 (see Figure III-1). The full line at ~ 1.5 cm/sec is the over-all mean; the dashed lines show the standard deviation of the monthly values.

III.1 Winter versus Summer

Figures III-8 through III-10 show a set of comparisons between observations made in the winter versus those in the summer. Each panel shows two months of data from the winter and then data from two months in the summer. These results, while typical, are from the ADCP offshore of Panama City. The figures are for results at 2m (in the uppermost bin from the ADCP), from near the middle of the water column, and from a bin approximately 3 m above the bottom. We see the characteristic result of strong currents in the winter, weaker currents in the summer. The frontal systems come through a periods of 3-10 days, making the flow oscillate from one direction to the other. The prominent directions on the stick diagrams can be taken to be “alongshore.” The velocity observations are made throughout the water column, but the temperature (bottom panel) is measured within the ADCP housing, at the bottom, and thus are the same in all three figures.

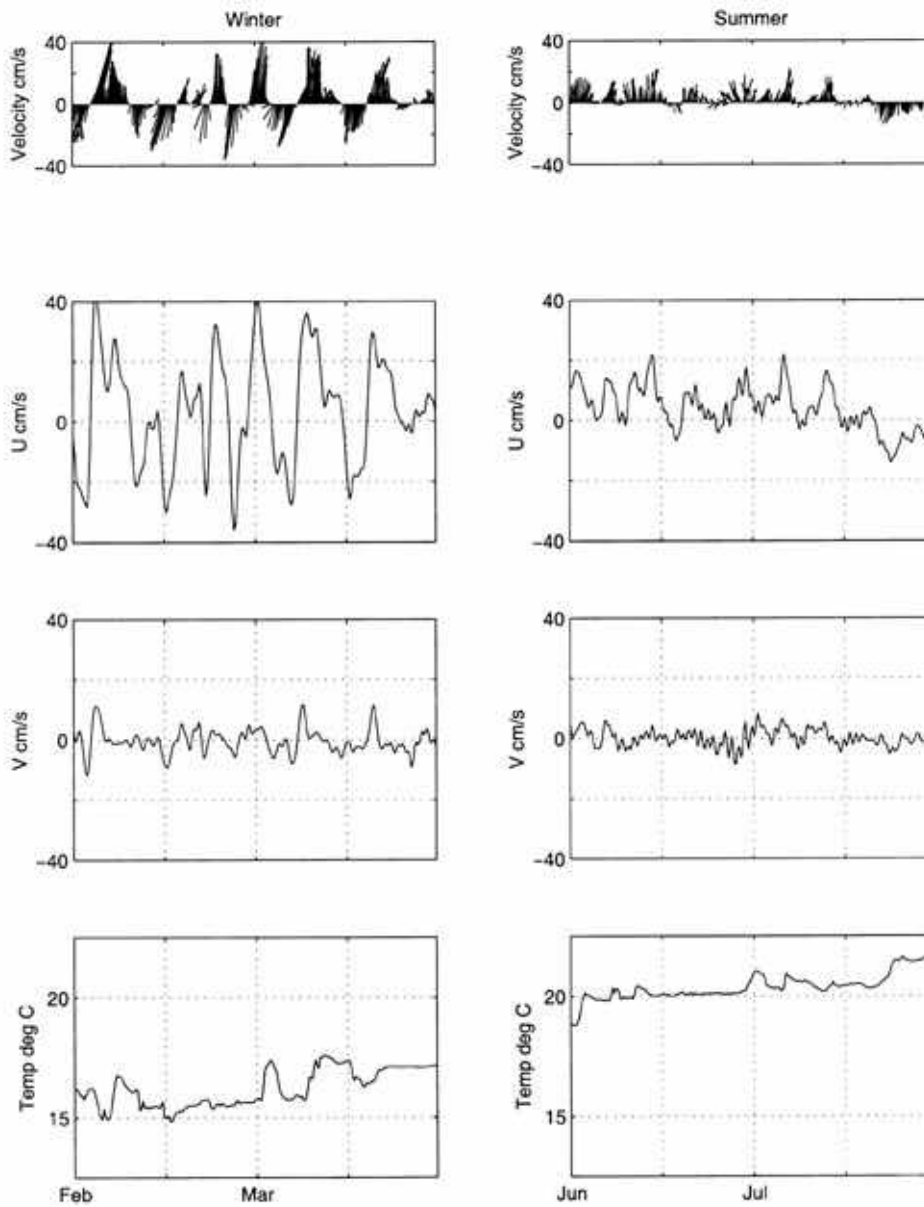


Figure III-8. A comparison of winter (02/01/98-03/31/98) and summer (06/01/98-07/29/98) currents offshore of Panama City at the upper-most useful bin from the ADCP, ~2m depth. These values have been 48-hr low passed. In the stick plots, "up" is alongshore, 310°. The bottom plot is temperature at the ADCP, on the bottom.

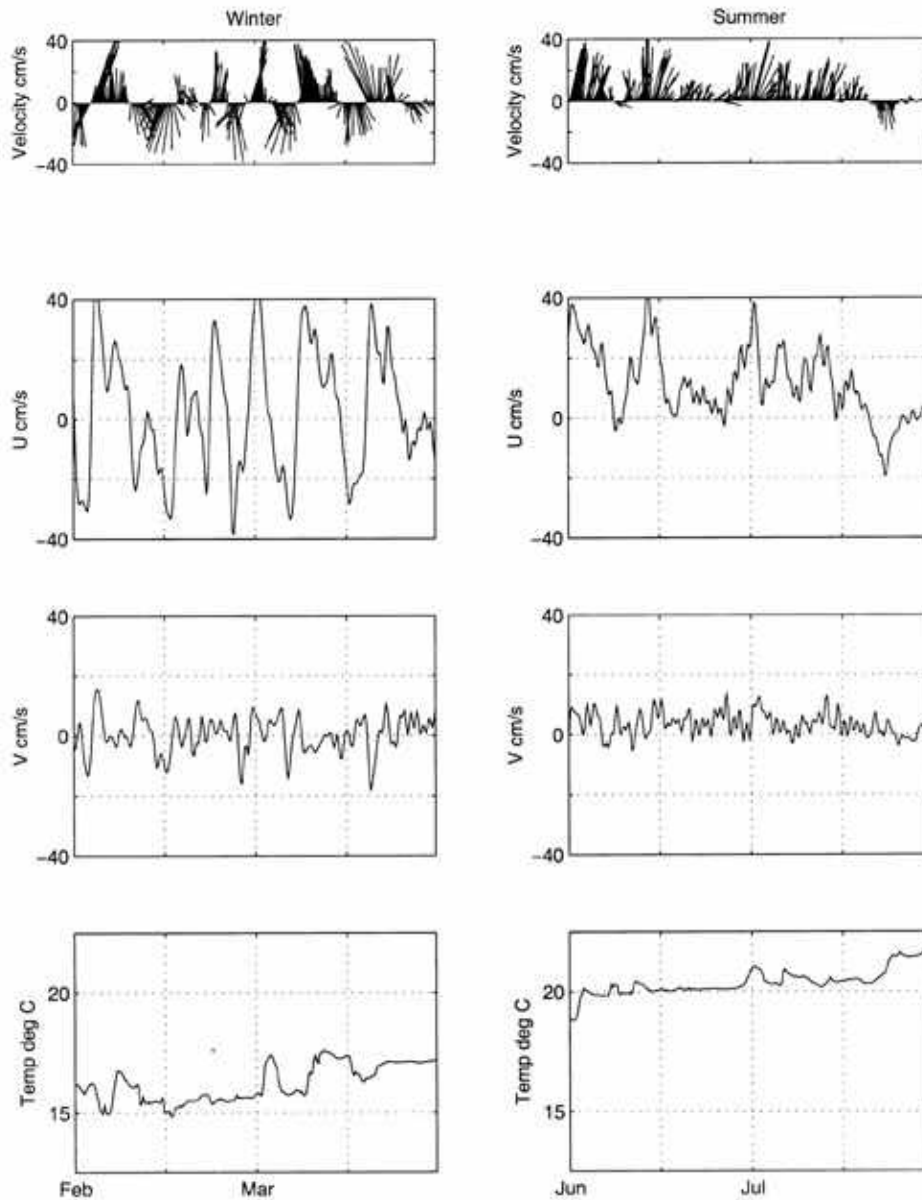


Figure III-9. A comparison of winter (02/01/98-03/31/98) and summer (06/01/98-07/29/98) currents offshore of Panama City at a mid-depth bin from the ADCP, ~ 12m depth. These values have been 48-hr low passed. In the stick plots, "up" is alongshore, 310°. The bottom plot is temperature at the ADCP, on the bottom.

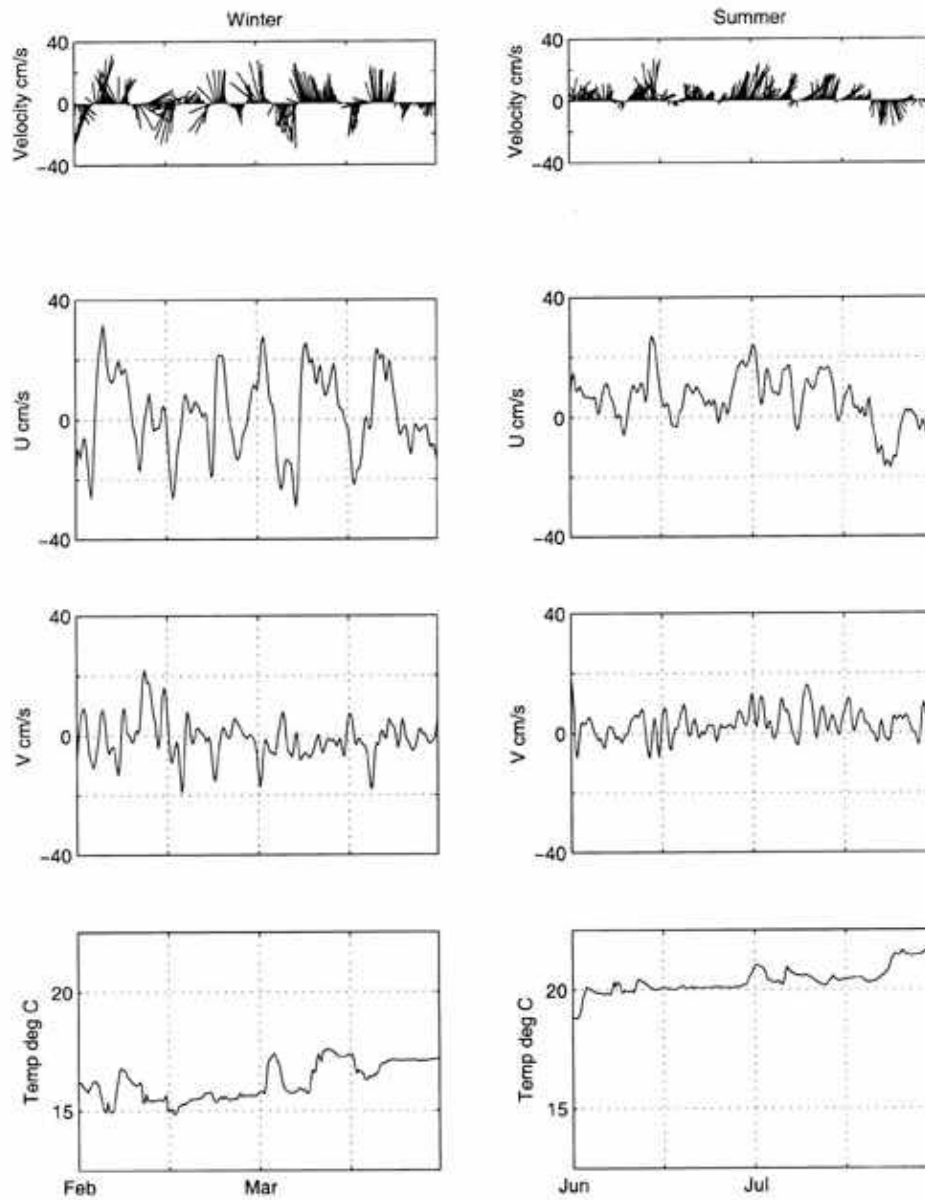


Figure III-10. A comparison of winter (02/01/98-03/31/98) and summer (06/01/98-07/29/98) currents offshore of Panama City at the deepest useful bin from the ADCP, ~ 23m depth. These values have been 48-hr low passed. In the stick plots, "up" is alongshore, 310°. The bottom plot is temperature at the ADCP, on the bottom.

IV. Comparing Drifter Results and Current-Meter Results.

If we wish to understand the environmental impact of a contaminant at the sea surface, it is clear that we need to know and understand the velocity in the uppermost layers of the ocean. Historically, however, we have had velocity data almost exclusively from moored current meters. Therefore it seems important to examine whether these two types of data “see the same thing.”

We realize of course that these two different measures of currents can not possibly give identical results. Moorings down in the water column are much less able to measure the effects of the upper Ekman layer. Moreover, in the NEGOM experiment, our measurements for most of the duration of the drifter experiment were only 4 m above the bottom and therefore in the bottom boundary layer. The near-bottom currents will be strongly constrained by topography – much more so than the upper layer flow measured by the drifters.

For this reason we have made the following comparisons. The two moorings 520 and 521 (as seen in Figure III-1) are the ones with the smoothest local bottom topography and therefore the most likely to show good comparisons. We first determine a “longshore” direction from maps of local bathymetry, and orient the current meter results so as to be aligned in a longshore coordinate system. We then rotate the coordinate system of the drifter velocities (at the same location) to determine the angle of maximum correlation between the two. Figure IV-1 shows how the correlation changes as a function of this angle (here measured counter-clockwise, relative to East). The purpose of showing this (rather bland) result is to emphasize that picking exactly the right angle is not crucial; 10° or so in either direction is barely noticeable on this plot.

Mooring 521 is in a region of relatively straight isobaths at a depth of approximately 26m. The S4 current meter here is 4 m above the bottom and is therefore likely to be in the bottom boundary layer.

Figure IV-2 shows the primary result, a scatter plot with a correlation coefficient of 0.66. Using a linear least squares fit such that

$$\text{Speed at the current meter} = k * \text{speed of the drifter} + \text{offset} \quad (IV-1)$$

we find that the coefficient here between drifter and near-bottom current is 0.31 (dimensionless), with an offset of -1.1 cm/sec. In other words, if the drifter, at the surface, shows a velocity of 10 cm/sec, we would expect, on the

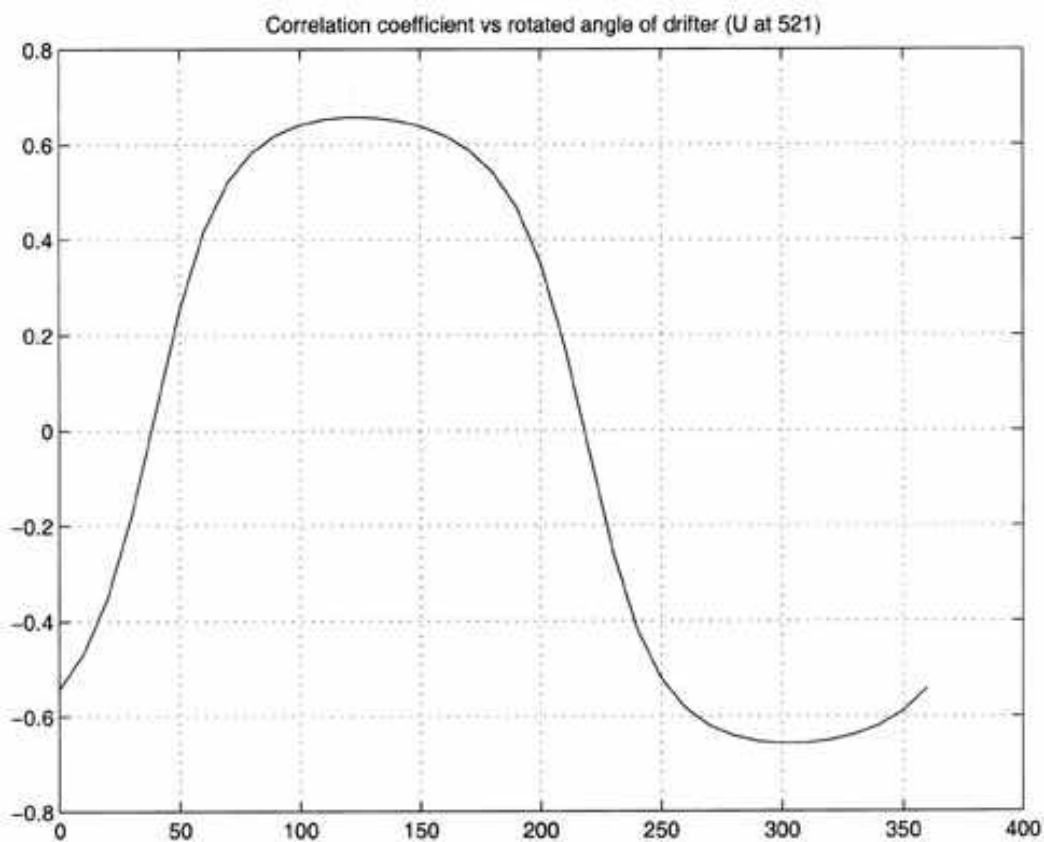


Figure IV-1. A plot of the correlation coefficient, as a function of angle, between the longshore current at Mooring 521 (4 mab) and the currents observed by the drifters passing overhead. The drifter angle is held fixed and the current direction of the drifters is varied.

Scatterplot of U between S4(521) and Drifter (Corr = 0.65774)

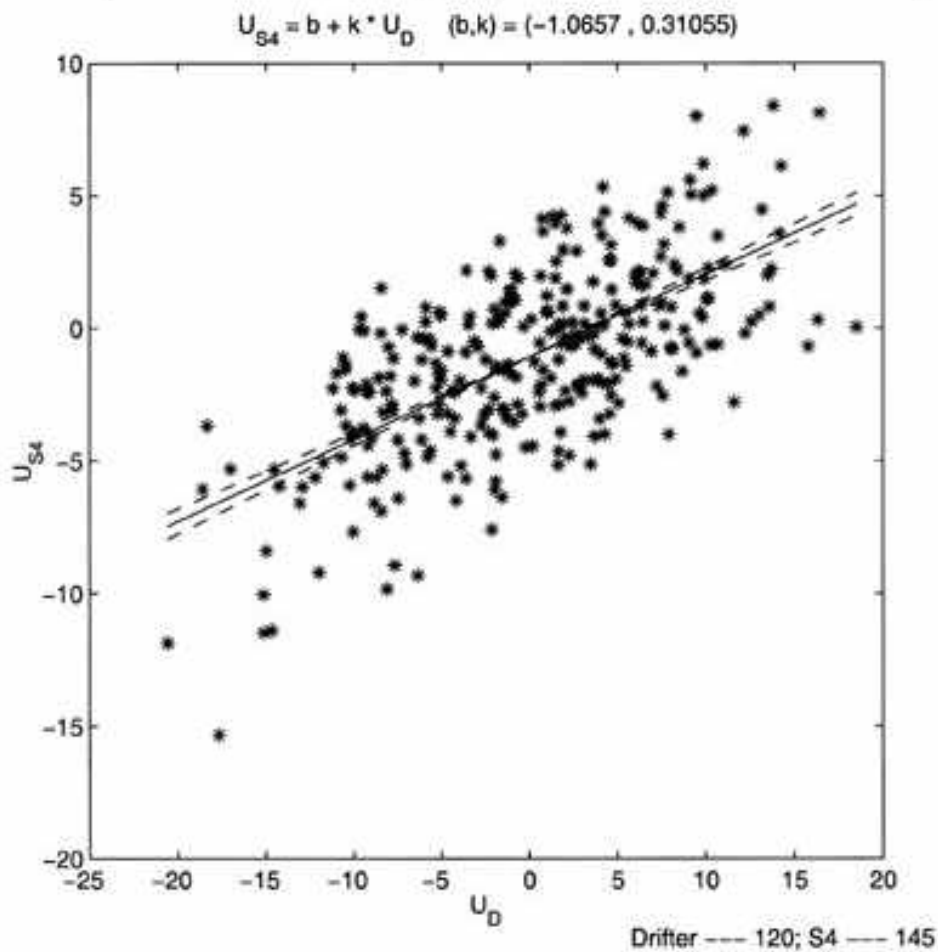


Figure IV-2. A scatter plot showing the daily values of current measured by the mooring 521 and those measured by the drifters just above it, using the angle of maximum correlation found in Fig. IV-1. The alongshore angle is taken to be 120° measured counter-clockwise from East.

average, a velocity of only 3 cm/sec at the near-bottom current meter. The speeds here (for Figure IV-2) are daily fits for the drifters, as described in Section II, and “daily” filtered to suppress tides at the current meters. The dashed lines about the least-squares fit show an estimate of the uncertainty of the slope (k) as determined by the Bootstrap method.

Figure IV-3 gives a comparison of the longshore speeds as seen by the current meter with the actual observation times when drifters were close to the mooring. We see that the drifter observations, as seen by the current meters, do a very good sampling job for the times when they are present.

Figures IV-4 and IV-5 show equivalent results for mooring 520, which was inshore of 521. The observed speeds in shallower water are somewhat greater. Table IV-I summarizes these results. The offset speeds of (-) 1-2 cm/sec suggest either that when the wind stops the flow at the current meters does not stop as quickly as the drifters do, or that there is a small mean flow even in the absence of wind. These observations, however, are quite limited, and with an over-all scatter of ~20 cm/sec the mean is of questionable value, although the linear coefficient between the two variables is significant.

Table IV-I. Relationship between daily mean longshore speeds at moored current meters (4 m above bottom) and speeds measured by the drifters.

	Depth	<u>Heading for max R</u>		R	k	veering angle
		Bottom	Drifter			
Mooring 520	17m	305°	340°	.63	.53	35°
Mooring 521	27m	305°	330°	.66	.31	25°

Several features emerge from these comparisons. In shallow water (520) the offset angle appears slightly greater, although these calculations are done with only a resolution of 10°. This can be the effect of the higher speeds at 520, giving rise to greater veering in the bottom boundary layer. The coefficient (k) is much greater at 520. This suggests that higher speeds in the upper Ekman layer are influencing the lower layers to a greater extent at 520

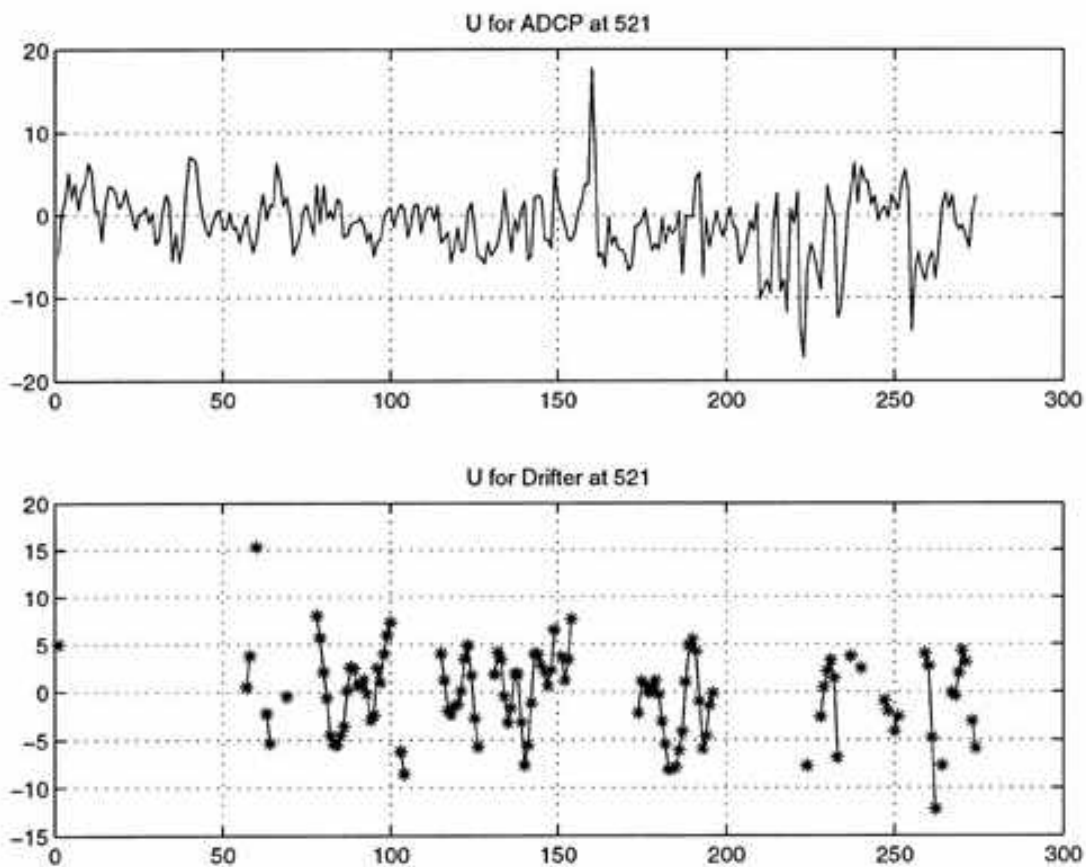


Figure IV-3. The daily longshore velocity component as measured at Mooring 521 (upper) along with that measured by the drifters (lower plot) when simultaneous observations occurred.

Scatterplot of U between S4(520) and Drifter (Corr = 0.62703)

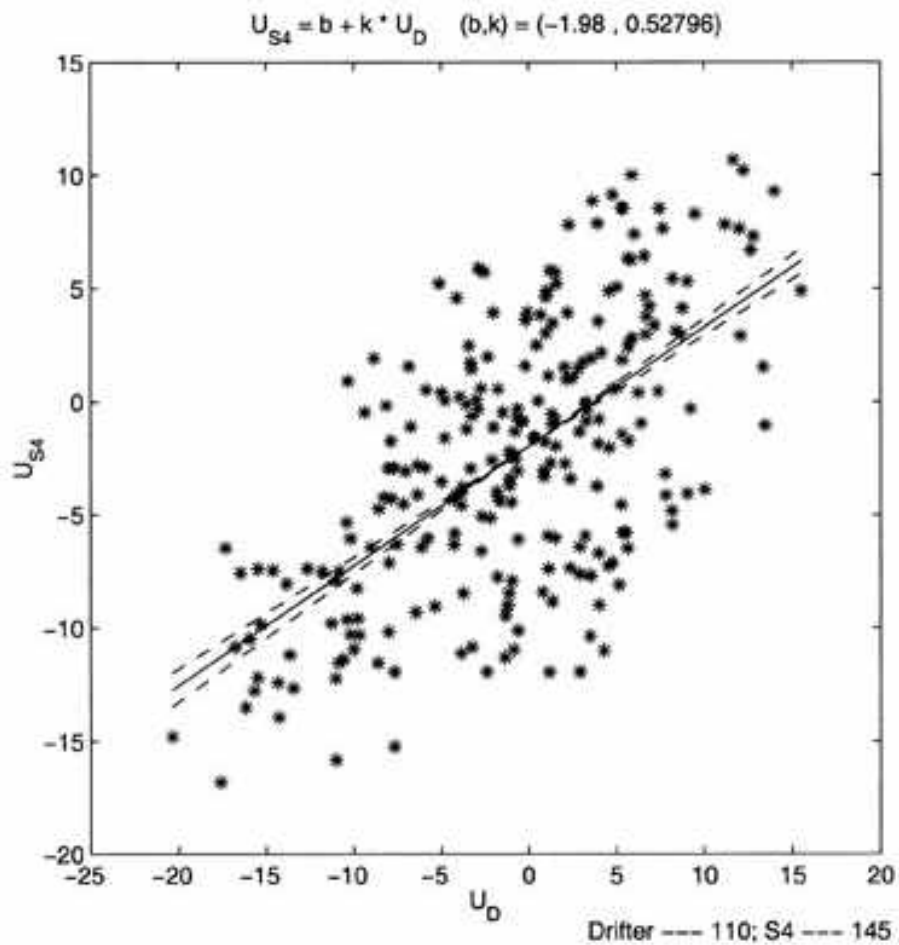


Figure IV-4. A scatter plot showing the daily values of current measured by the mooring 520 and those measured by the drifters just above it, using the angle of maximum correlation. The longshore angle here is taken to be 110° measured counter-clockwise from East.

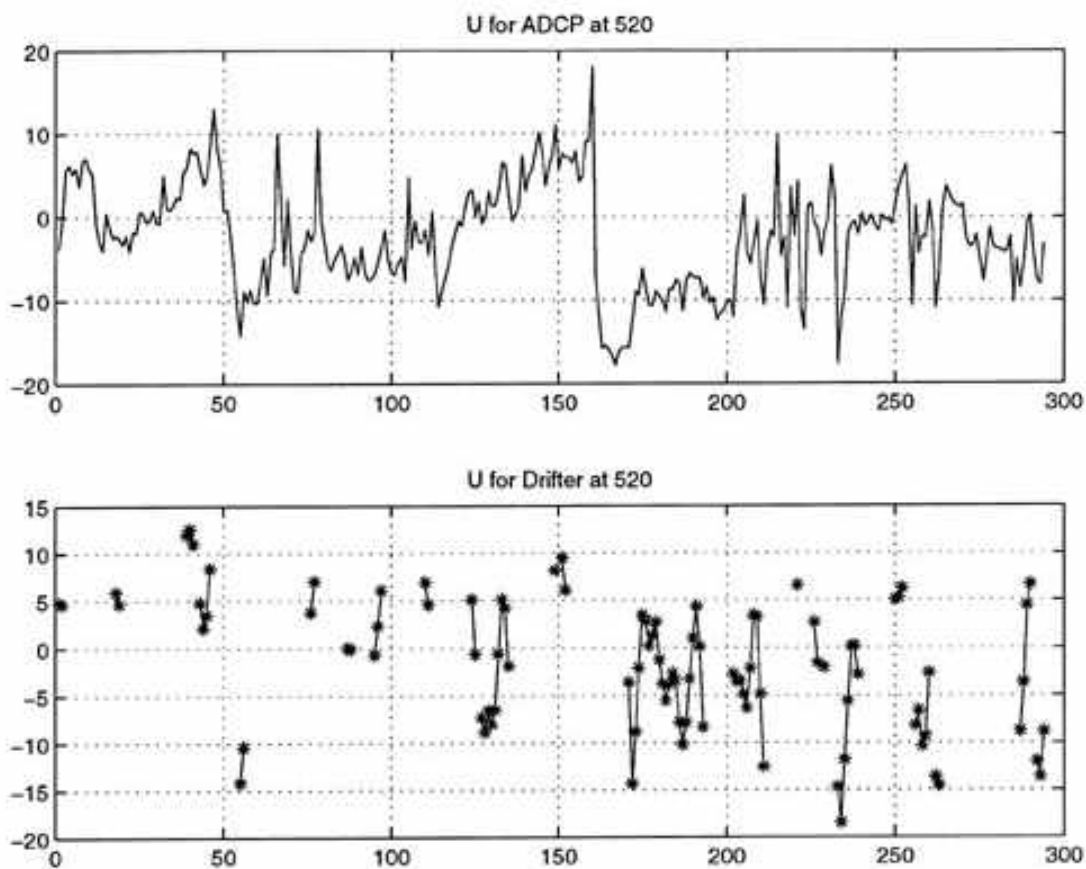


Figure IV-5. The daily longshore velocity component as measured at Mooring 520 (upper) along with that measured by the drifters (lower plot) when simultaneous observations occurred. Similar to III-3.

than at 521. The nice result, however, is that – despite an expected amount of scatter in the observations, the two kinds of measurements do tend to “see the same thing” rather well in the longshore direction.

Similar calculations were made for the cross-shore component of velocity, which were not reliably coherent. The correlation coefficients were -0.02 (at 520) and -0.16 (at 521). Part of this lack of correlation is that the upper veering to longshore winds is to the right of the wind at the top, and to the left at the bottom. When the winds are not blowing strongly, there is little or no veering to the right at the surface.

It will be shown in the next section that the cross-shelf velocity component, as determined by the drifters, actually is found to be coherent with the wind forcing. However, the angle of the wind must be adjusted differently for the cross-shelf component than for the alongshore component.

We also should point out one detail of these calculations. In the results shown here (Table IV-I) we fixed the angle of orientation of the current meter results and rotated the drifter velocity components to find the best agreement. There is a reason for this, of course, because the current meters, near the bottom, are constrained by bottom topography. It could be argued, however, that this choice is somewhat arbitrary, and a better fit might possibly be obtained by choosing the “longshore” orientation for the drifters first, then rotating the current meter data to find an angle of orientation for maximum correlation. We did this. The results of this second calculation, however, differ from Table IV-I in only the second or third decimal place, with random signs, and so are not considered significant.

V. Practical results: Comparing Drifter Results with Wind Forcing.

In order to make comparisons between observed currents and the winds that force them, it is usual practice in a scientific experiment to deploy meteorological buoys near the experiment to measure winds. In the work described here, such buoys from the NDBC were in place.

As a general rule, however, when we wish to *use* the results of experiments such as this in broad applications, we would expect to have available only the standard weather bureau products. In order to make our results from this study applicable to calculations under those circumstances, we have done a series of calculations to determine the correlations between the drifter currents and a standard meteorological product, the so-called NCEP (National Center for Environmental Prediction, NOAA) winds. These wind data are available over the Gulf of Mexico on a grid every 2.5° in latitude and longitude. For our purposes here, we interpolated to positions midway between two standard NCEP grid locations to provide daily wind information as close as possible to offshore locations near the drifter experiment.

It is well known that for motions in the 3-10 day “weather band” coastal currents preferentially move approximately along the isobaths. Figure V-1 shows the drifter motions for March 1996 data, in which the drifter tracks obviously follow the local bottom topography in the Big Bend region north of St. Petersburg. These motions are of course consistent with the along-isobath coherence shown in Section II. For our analysis, therefore, we grouped the drifter data into two main sets appropriate to the bottom slope. One set is formed from data in the Big Bend region, between St. Petersburg and Cape San Blas, but using only data near the center of the region, avoiding the edges where the topography turns. The second data set is from the region between Cape San Blas and the western edge of the data shown in Figure V-1. The idea was to have the bottom topography be roughly similar for all the data in each group--that is, to group the data from the very wide shelf and the data from the narrow shelf region to the north separately. The data in each group were then further divided by depth.

In a manner similar to that in the previous section, we first determined the angle of wind orientation that maximizes the correlation between the NCEP daily winds and the currents from drifters. Figure V-2 shows how the correlation function changes as a function of wind rotation, from the study region to the east, in the area between St. Petersburg and Cape San Blas. For

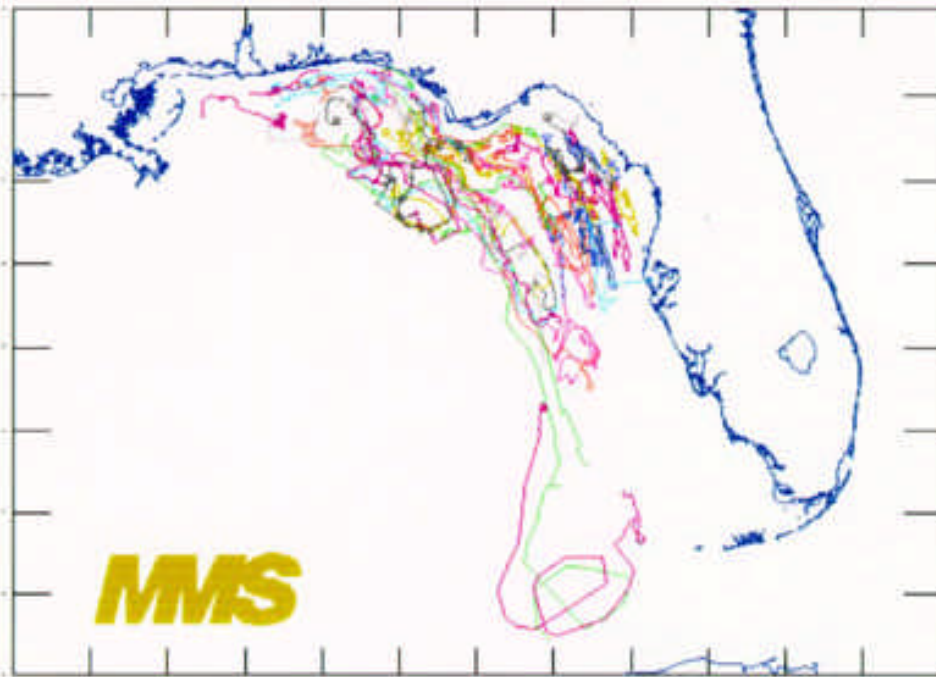


Figure V-1. Tracks of surface drifters for the month of March, 1996, taken from the web page <http://gulf.ocean.fsu.edu>. Different colors represent different individual drifters. A small square shows the beginning position for the month. The main point is that the tracks between the coast and the middle of the shelf preferentially move parallel to the bottom topography. This figure was constructed by W. Johnson, MMS.

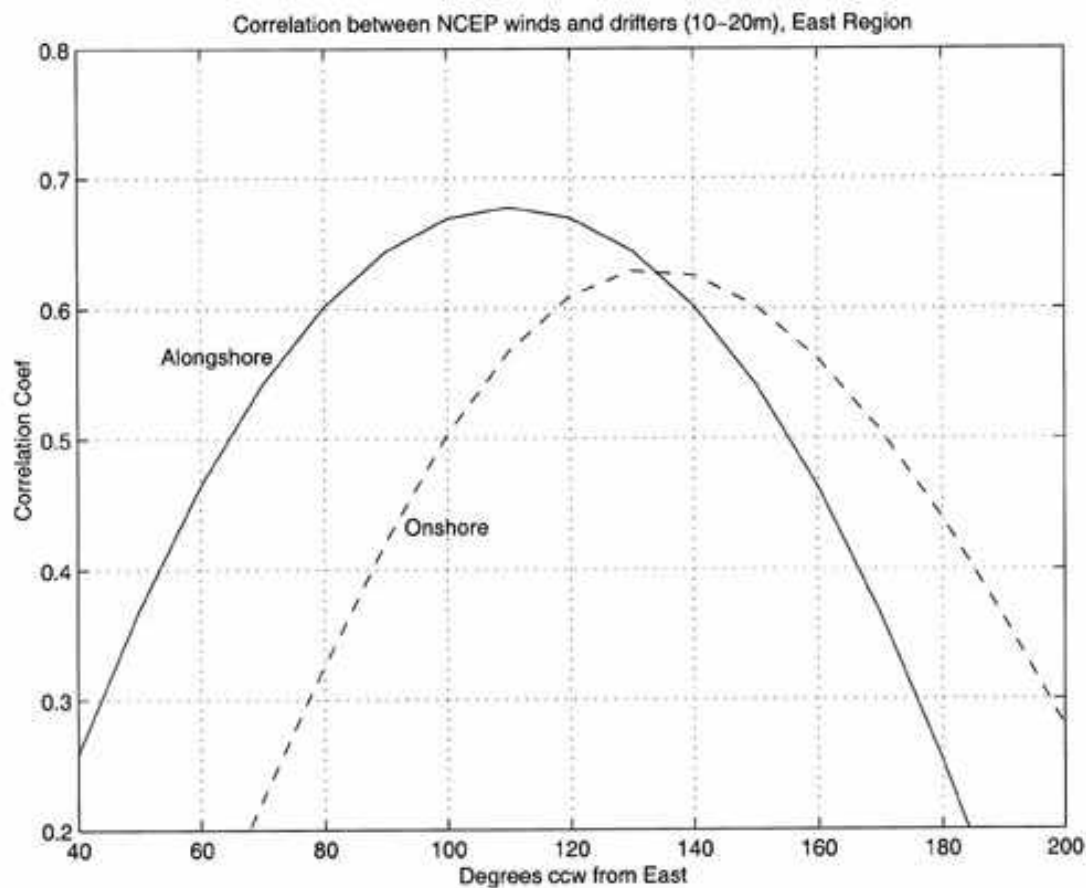


Figure V-2. The variation of the correlation coefficient between the surface drifters and NCEP winds, eastern region, for the 10-20 m depth band, as the angle between wind and drifters is varied. The x-axis is angle of rotation, counter-clockwise, relative to east.

these calculations we used a wind data set interpolated to 28.75° N, 83° W. Further explanation of the angular conventions is discussed in a later section.

Two results emerge from this figure. First, the correlations are moderately high – over 0.6 for both the longshore and the onshore components. Second, as one might have expected, the angle of rotation that gives the highest correlation for the longshore component is not the same angle that gives the highest correlation for the onshore component.

Figure V-3 shows the scatter plot of the comparison between longshore winds and longshore drifter motions. A least-squares fit through these points gives a slope of 1.06 (using cm/sec for the surface currents, m/sec for the winds). The correlation is that found at the maximum in figure V-2. The dashed lines near the best fit show an estimate of the uncertainty of this coefficient (determined by a Bootstrap method).

The intercept, -0.86, says that when the winds stop blowing there is a flow of .86 cm/sec to the northwest. For this time period. This value is slightly above the standard error of the mean, but should not be misconstrued as a generally applicable result. The winds in some other year are not likely to be the same as those for this experiment.

We performed similar calculations for the longshore motions and the onshore, or cross-shelf, motions, in both of the regions described earlier. The essential results are given in Tables V-I, V-II.

Table V-I. Correlations, R, and optimum wind angles between NCEP winds and NEGOM surface currents from drifters in the region between St. Petersburg and Cape San Blas. The isobaths are assumed to be oriented toward 327° True, hence the onshore direction is 057°. Winds are interpolated to 28.75° N, 83° W. The coefficient “k” is the linear fit between wind speed (m/sec) and currents (cm/sec)

Depth	Wind Angle for Maximum R		R _{max}		k	
	Longshore/Onshore	Longshore/Onshore	Longshore/Onshore	Longshore/Onshore	Longshore/Onshore	Longshore/Onshore
10-20 m	340	045	0.68	0.63	1.06	0.56
20-30 m	330	020	0.66	0.62	1.19	0.58
30-50 m	315	045	0.56	0.58	1.25	0.63

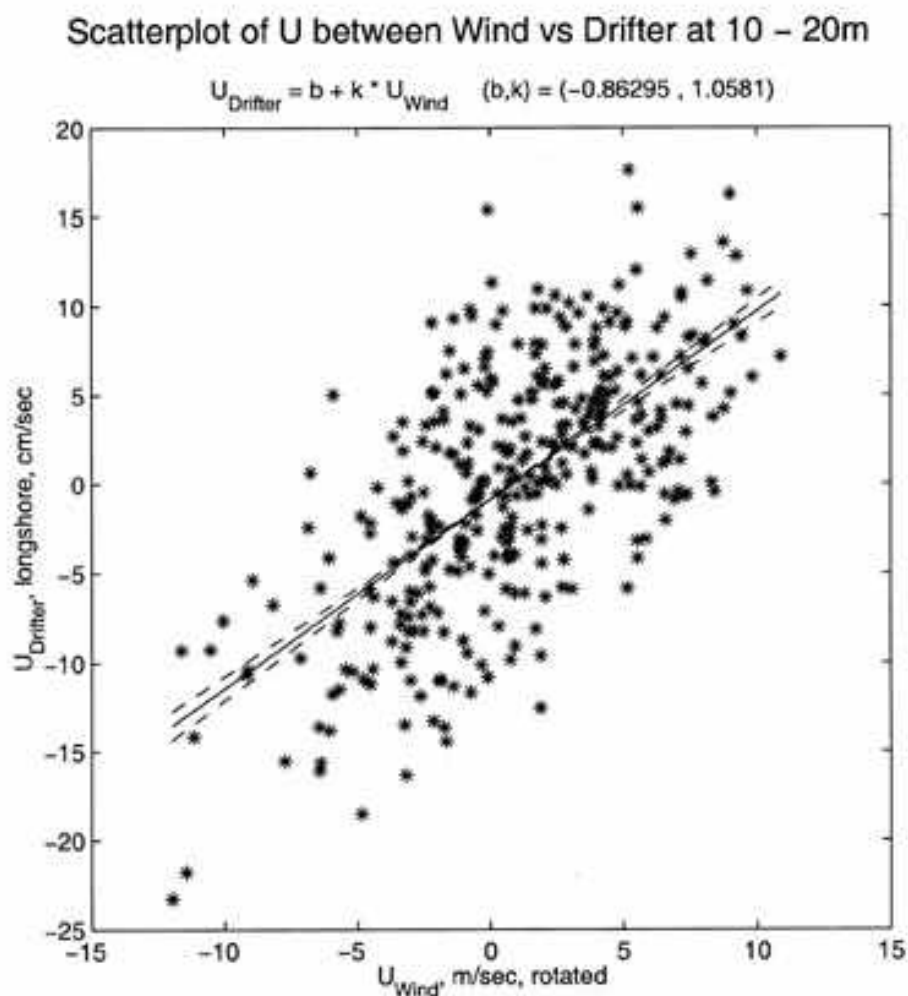


Figure V-3. A scatter plot showing wind speeds (x-axis) and drifter speeds for the longshore component in the 10-20 m depth band, eastern region, using the angle of maximum correlation as determined from Figure V-2. Note that wind is in m/sec, drifter speeds are in cm/sec.

Table V-II. Correlations, R, and optimum wind angles between NCEP winds and NEGOM surface currents from drifters in the northern region, west of Cape San Blas. The isobaths are assumed to be oriented toward 305° True, hence the onshore direction is 035°. Winds are interpolated to 30.° N, 86.25° W. The coefficient “k” is the linear fit between wind speed (m/sec) and currents (cm/sec)

Depth	Wind Angle for Maximum R		R _{max}		k	
	Longshore/Onshore		Longshore/Onshore		Longshore/Onshore	
10-30 m	295	020	0.66	0.54	2.57	0.82
30-50 m	300	000	0.57	0.38	2.20	0.68
50-100 m	285	000	0.46	0.35	1.85	0.57

V.1 Longshore coefficients.

Figure V-4 summarizes the results of the longshore comparisons. The x-axis is depth; a comparison plotted against distance offshore would show a somewhat different view, but for the present purpose the water depth is appropriate. In both the eastern and northern regions, the correlation between the winds and the drifter motions falls away smoothly with depth (or with distance offshore). The “k” values, which represent the ratio of current response to the wind forcing, show quite clearly that the speeds are higher, for the same wind speeds, by a factor of ~2 along the narrow shelf off Pensacola-Panama City compared with the wide shelf in the east. This is a well-known result, in general, but the values shown here for *surface* current speeds are a new result.

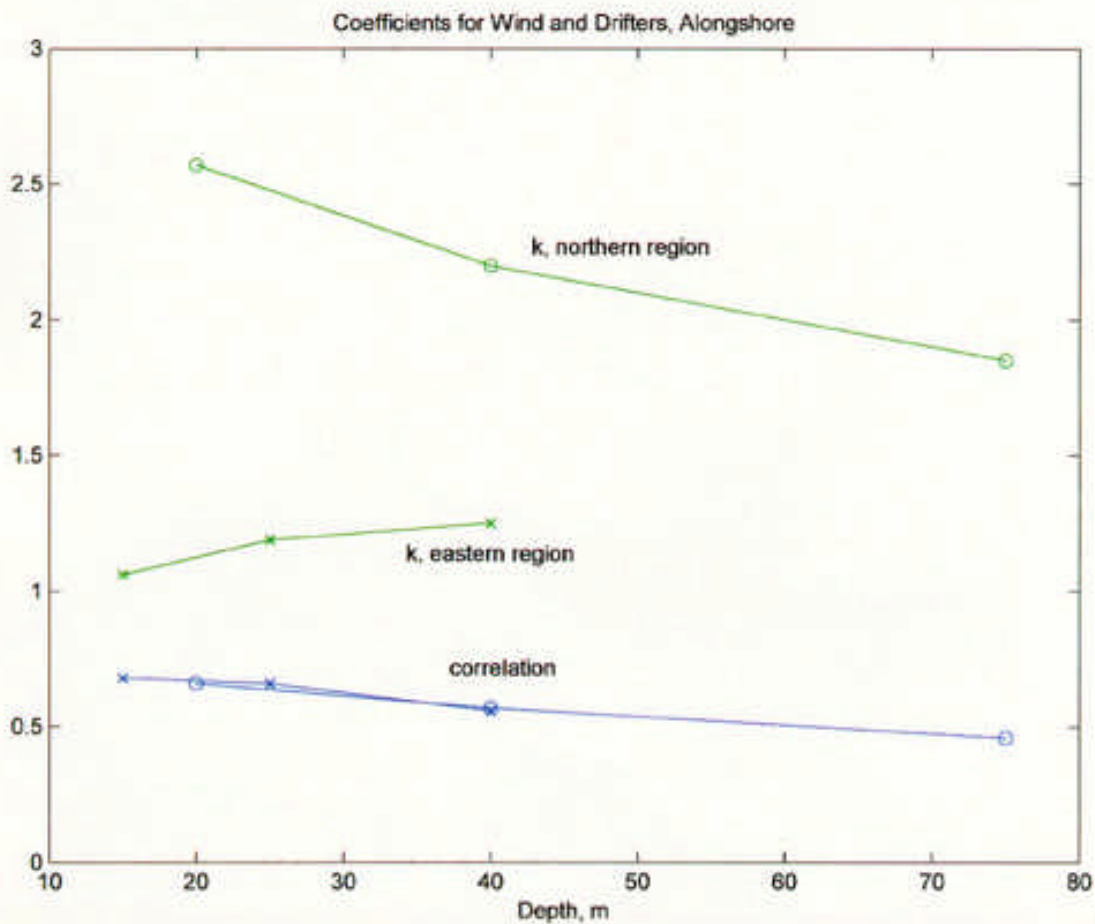


Figure V-4. The variation of correlation coefficient and wind drift coefficient, k , with distance offshore, for the longshore flow, plotted versus depth. The k values are plotted separately for the eastern and northern regions; the correlation coefficients from the two regions are indistinguishable.

V.2 Onshore coefficients.

Figure V-5 shows the equivalent plot for the Onshore comparisons. One gets the initial impression that if the x-axis were chosen to be distance offshore, a result much closer to a simple linear trend would appear. (This view is used to be consistent with Figure V-4.)

The correlation values, R , in the eastern region remain similar to those of the longshore motions, but the correlations are substantially lower. One expects that on a broad shelf, as in the east, the inshore currents are isolated from the eddy motions imposed at the shelf break. In the north, however, the region of our studies is not far from the shelf break, and offshore eddy motions affect the results here.

It may not be immediately obvious why these differences occur. Therefore, Figures V-6, V-7 show scatter plots for the longshore and onshore components of the deepest segment in the northern region. For the longshore component, the drifter speeds reach 40 cm/sec. For the onshore component, the drifter speeds are half that or less. We know from the recent, magnificent satellite observations that the eddy swirling motions are, at least to first order, approximately horizontally homogeneous. Their effect (in our calculation) is therefore larger for the onshore motions. It is not that the drifters do not perform well, but that the motions are induced by effects other than the local winds. Figure V-6 shows that the correlation drops considerably as the currents are driven by the eddy motions in addition to the winds, even for the longshore flow. For the onshore motions, however, the effect is *relatively* much larger.

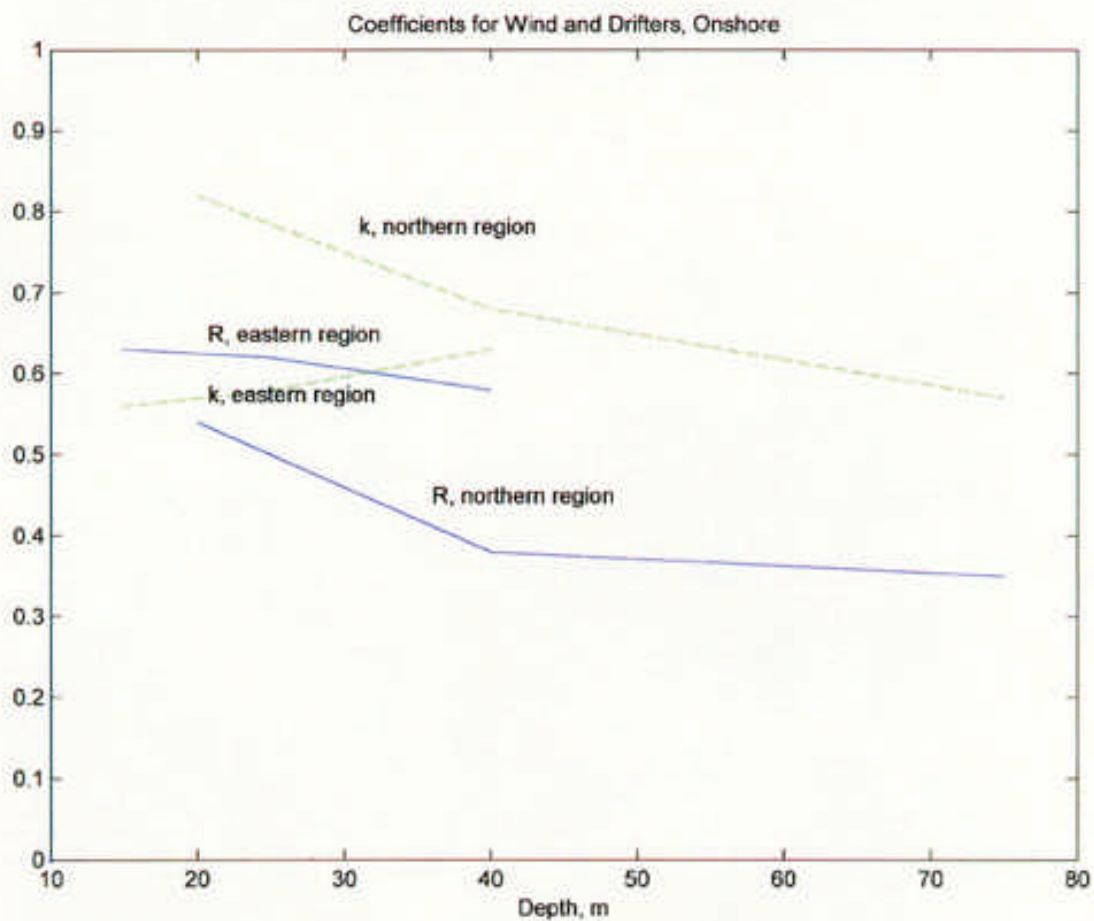


Figure V-5. The variation of correlation coefficient and wind drift coefficient, k , with distance offshore, as in V-4, but for the onshore flow, plotted versus depth. The dashed lines show the k values for the eastern and northern regions; solid lines show the correlation coefficients for the two regions.

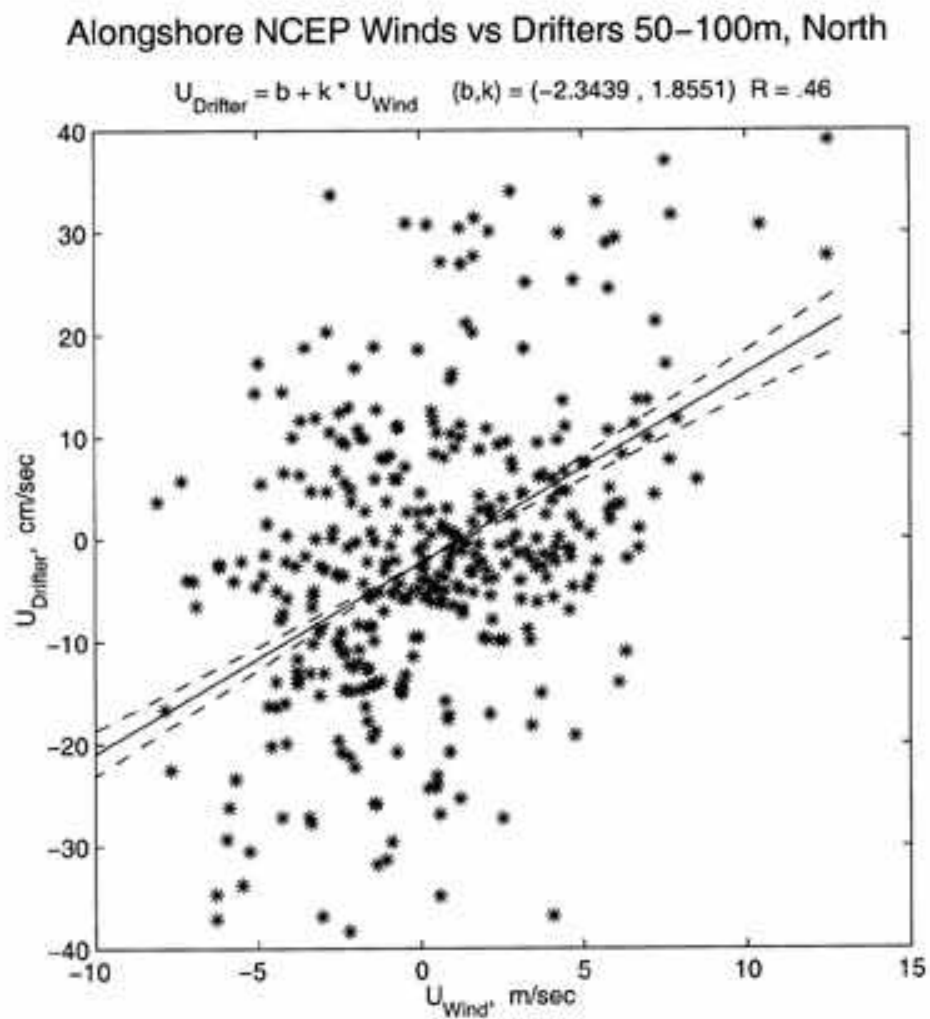


Figure V-6. A scatter plot showing wind speeds (x-axis) and drifter speeds (y-axis) for the longshore component in the 50-100 m depth band, northern region, using the angle of maximum correlation. Note that wind is in m/sec, drifter speeds are in cm/sec.

Rotated NCEP winds, vs cross-shelf Drifters, 50–100m North

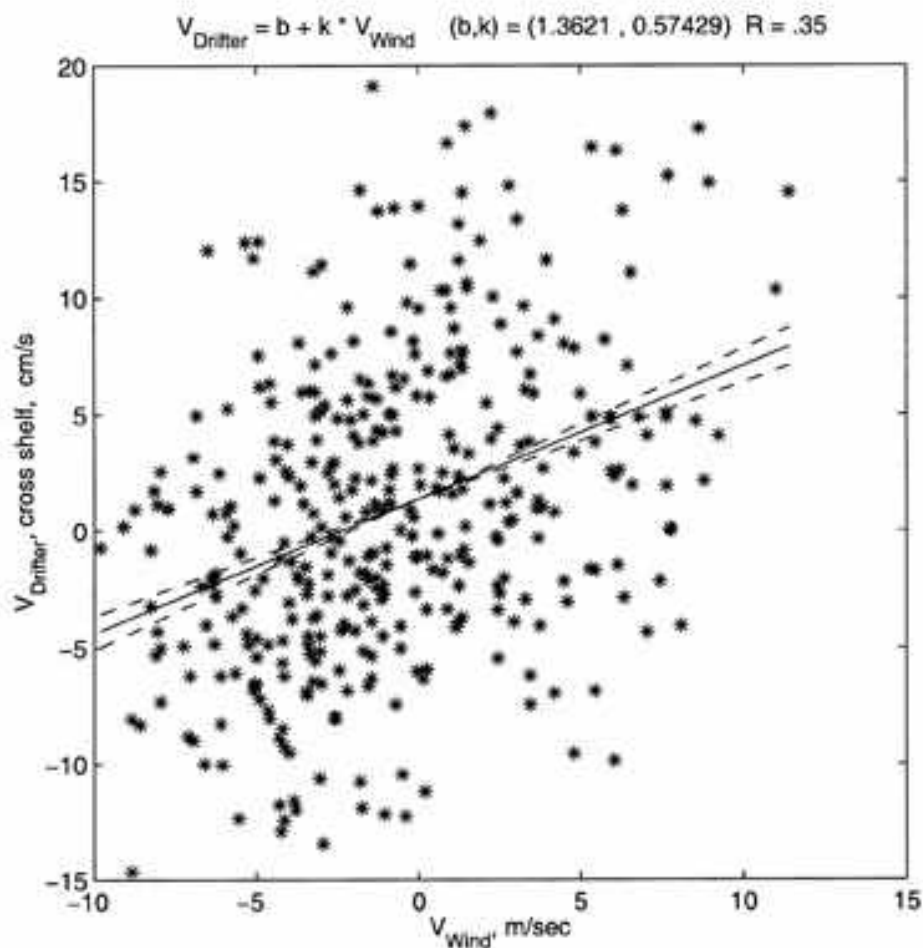


Figure V-7. A scatter plot showing wind speeds (x-axis) and drifter speeds, as in V-6, but for the onshore component in the 50-100 m depth band, northern region, using the angle of maximum correlation. Note that wind is in m/sec, drifter speeds are in cm/sec.

V.3 The Angles of rotation.

Tables V-I, V-II also show the angles at which the highest correlations are found.

Some explanation may be necessary here. For these calculations, in both cases we rotate the U wind component (originally to the east) to obtain the highest correlation for each pair. The “Longshore” plot shows the correlation between the longshore winds and the longshore currents. The “Onshore” plot shows the correlation between the onshore winds and the onshore velocity component. The angle of rotation shown on the figure however remains that of the rotation of the U wind component.

In some cases the two angles are not the same. That is, the angle of rotation that provides the highest correlation for the longshore flow is not the same as the angle of rotation that provides the highest correlation for the onshore flow. There are of course physical explanations for the differences between the two resulting angles. We know that, in general, longshore currents are driven by longshore winds, but the effect is indirect. The longshore flow results from the pressure gradient that arises from the longshore winds. Onshore motions, by contrast, require the effect of the surface Ekman layer more directly.

Figure V-2 shows that the highest correlation for longshore drifter motions are found with winds blowing toward $\sim 340^\circ$ (rotated $\sim 110^\circ$ counter-clockwise from East (we use here the oceanographic convention to describe directions)). For the calculations in the eastern region we determined that the isobaths ran along $\sim 327^\circ$ True (rotated $\sim 123^\circ$ ccw from east). Thus, the wind direction for the highest correlation is about 10° *to the right* of the isobaths. We might have assumed a priori that the optimum wind direction would be slightly to the left of the isobaths. Whether this anomalous result is from a poor choice of bottom topography direction, from uncertainties in the NCEP winds, or merely random errors, we cannot tell. However, a finding that is within 10° , which is the resolution of our calculation, is probably as good as we might expect. The essential result is that the drifters, at the sea surface, go almost directly downwind. This is in keeping with the standard coastal, longshore-flow expectation.

And perhaps we should emphasize that the close agreement between these two directions is a near-shore, shallow water result. In open water away from the coast we would expect the near-surface Ekman veering to be at least 35° or more. Careful measurements at depths as shallow as 5-10 m in deep water show veering angles as large as $65-75^\circ$ (Price et al., 1980).

For the onshore motions, however, the highest correlation (from Figure V-2) is found at an angle of $\sim 130^\circ$ to $\sim 140^\circ$ ccw from east, for the U component. Thus the result, for the onshore component, is that winds blowing toward a true direction toward 045° have the highest correlation with onshore drifter motions. The direction normal to the isobaths here, which is the direction of onshore flow, is $\sim 057^\circ$ T; thus the onshore flow is found to be $\sim 12^\circ$ to the right of the onshore wind component. Based on the result of the longshore calculations, we would expect that this value is uncertain by $\sim 10^\circ$. If the onshore current component is found to be $\sim 10^\circ$ to 20° to the right of the wind, this is in keeping with the expected veering to the right in the upper Ekman layer. In Ekman's classic result, he showed that in shallow water the angle of veering would be less than in deep water.

Section VI. An annotated bibliography of published papers, reports, and theses from this program.

He, R. and R.H. Weisberg, 2001a. Circulation and temperature budget on the west Florida shelf during the 1999 spring transition. *Cont. Shelf Res.*, in press.

We have used the present version of our POM-based model (which extends from west of the Mississippi River to the Florida Keys) to simulate the currents and temperature/salinity variations during the spring 1999 seasonal transition in response to local shelf-wide forcing by winds, surface heat flux, and river inflows. We first compare the model results with in situ data before diagnosing the model evolution. The paper supports the hypothesis of Weisberg et al. (1996) on the role of buoyancy forcing in the seasonal transitions, and it demonstrates how local forcing independent of the Loop current can account for much of the shelf circulation, in particular the "Green River" phenomenon south of Cape San Blas and the advection of Mississippi River water to the west Florida shelf.

He, R. and R.H. Weisberg, 2001b. Tides on the west Florida shelf, a model and *in situ* data comparison. In preparation, draft complete.

Here we force a regional model with a global tide model to describe the sea level and currents for the (barotropic) M2, S2, O1, and K1 constituents. We compare sea level along the coast from Mississippi to southwest Florida, and we compare velocity hodograph ellipses where available. Tidal residuals are also estimated to assess the potential for tidal rectification. A future extension of this work will be to incorporate all available data and to consider the effects of stratification.

Hetland, R.D., Y. Hsueh, R.R. Leben, and P.P Niiler, 1999: A Loop Current-induced jet along the edge of the West Florida shelf. *Geophysical Research Letters*, **26** (15), 2239-2242.

The pressure imposed upon the West Florida Shelf by the Gulf of Mexico Loop Current is found to give rise to a southward-flowing jet along the shelf edge. The pressure-induced jet is simulated by a general circulation

model of the Gulf. However, the physics causing formation of the jet are well represented by a simple continental shelf model incorporating an idealized geometry for the West Florida Shelf. The pressure response over the shelf, in an analogy to conductive heat transfer in a rod, is limited by the "insulating" effect of the steep topography of the West Florida Escarpment, which hinders the onshore spreading of the pressure influence. The shelf-edge jet is apparent in the trajectories of satellite-tracked surface drifters deployed from February 1996 through March 1997. Evidence for the requisite pressure distribution over the escarpment is provided by measurements of sea level from the satellite altimeter aboard the TOPEX/POSEIDON satellite.

Meyers, S.D., E.M. Siegel, and R.H. Weisberg, 2001. Observations of currents on the west Florida shelf break. *Geophys. Res. Lettrs.* 28, 2037-2040.

Here the authors describe observations of currents in the vicinity of the shelf break to the west of Tampa Bay. The currents there are highly variable, and the effects of the Loop Current and its eddies are sporadic. Spring and summer of 1998 exhibited large stratification over the inner-shelf, even right up to the shoreline. In situ data shows that the circulation is very sensitive to stratification. By separating the surface and bottom Ekman layers, stratification in increases across-shelf transports.

Ohlmann, C. J., P. P. Niiler, C. A. Fox and R. R. Leben, 2001: Eddy energy and shelf interactions in the Gulf of Mexico. *Journal of Geophysical Research*, **106** (C2), 2605-2620.

Sea-surface height anomaly data from satellite are continuously available for the entire Gulf of Mexico. Surface current velocities derived from these remotely sensed data are compared with surface velocities from drifting buoys. The comparison shows that satellite altimetry does an excellent job resolving Gulf eddies over the shelf-rise (depths between ~200 and 2000 m) if the proper length scale is used. Correlations between altimeter and drifter derived velocities are statistically significant ($r > 0.5$) when the surface slope is computed over 125 km, indicating that remotely sensed sea-surface height anomaly data can be used to aid the understanding of circulation over the shelf-rise. Velocity variance over the shelf-rise from the altimetry data

shows regions of pronounced eddy energy south of the Mississippi outflow, south of the Texas-Louisiana shelf, and in the northwest and northeast corners of the Gulf. These are the same locations where surface drifters are most likely to cross the shelf-rise, suggesting that Gulf eddies promote cross-shore flows. This is clearly exemplified by both warm and cold eddies. Finally, the contribution of Gulf eddies and wind stresses to changes in the mean circulation are compared. Results indicate that the eddy-generated vorticity flux to the mean flow is greater than the contribution from the surface wind stress curl, especially in the region of the Loop current and along the shelf-rise base in the western Gulf. Future modeling efforts must not neglect the role of eddies in driving Gulf circulation over the shelf-rise.

Ohlmann, J.C. and P.P. Niiler, 2001: A two-dimensional response to a tropical storm on the Gulf of Mexico shelf. *Journal of Marine Systems*, **29**, 87-99.

Surface current data from drifting buoys and remotely sensed wind data recorded over the continental shelf in the northeastern Gulf of Mexico during the passage of tropical storm Josephine in October 1996 are examined. Drifter data show the existence of a strong surface jet (velocities reaching 1 m s^{-1}) that moves up the west Florida shelf and westward along the Louisiana-Texas shelf and lasts for nearly one week. The coastal jet occurs during an intense synoptic-scale wind event where wind speeds reach 15 m s^{-1} . A simple force balance and statistical analysis are performed to assess the role of strong wind forcing. The primary balance shows an Ekman-type current. The role of local acceleration is greatest when winds are directed along bathymetry. A simple two-dimensional strongly forced shelf response model developed from the linear steady-state momentum equations also indicates larger along-shore currents due to both Ekman-type forcing by cross-shore winds and a cross-shore pressure gradient arising from conservation of mass. Model parameters fit empirically are within 15% of theoretical values. The simple model explains 30 and 46% of the variance in the observed along-shore and cross-shore surface currents, respectively.

Sturges, Wilton and Robert Leben, 2000. Frequency of Ring Separations from the Loop Current in the Gulf of Mexico: a revised estimate. *Jour. Phys. Ocean.*, **30**, 1814-1819.

The offshore forcing of the west Florida Shelf is controlled primarily by the Loop Current and its rings. In this paper we examined the frequency of variability of the Loop Current and the rate at which it sheds rings on the basis of all the ring separation data since the late 1970s.

Sturges, Wilton, and B.G. Hong, 2001. Gulf Stream transport variability at periods of decades. *Jour. Phys. Ocean.*, 31, 324-332.

In many studies of the variability of the Loop current, the basic transport of the Florida Current/Gulf stream system is taken as if it had constant transport. This study examines the longer-period variability of the Florida current. We find that the decadal scale fluctuations are larger than those of the annual cycle. The method uses model output on the offshore side of the Gulf Stream and sea level fluctuations at the coast. The results are compared with observed transport and the agreement is surprisingly good.

Walsh, J.J. K.D. Haddad, D.A. Dieterle, R.H. Weisberg, Z. Li, H. Yang, F.E. Muller-Karger, C.A. Heil, and W.P. Bissett, 2001. A numerical analysis of the landfall of 1979 red tide of *Gymnodinium breve* along the west coast of Florida - the fall/winter upwelling mode. *Cont. Shelf Res.*, in press.

This paper is an attempt at combining physical and ecological models on the West Florida Shelf. Here we attempt to simulate the evolution of the 1979 red tide, providing some insights into the joint workings of the biology and physics that culminate in near shore red tide effects.

Weisberg, R.H., B. Black, Z. Li, 2000. An upwelling case study on Florida's west coast, *J. Geophys. Res.*, 105, 11459-11469.

This paper discusses a specific case study of an upwelling event recorded both in satellite AVHRR imagery and in situ data. While upwelling (and downwelling) occur regularly on continental shelves with the passage of each weather front, rarely do all the necessary ingredients coincide to make the upwelling response visible in satellite imagery. In this case, the winds were light for several days prior to a strong, upwelling favorable wind event, and we had in situ velocity measurements for

comparison. Through a combination of data and model analyses we demonstrate the Ekman-geostrophic spin up route of the inner shelf. Using both constant density and stratified runs (stratification estimated from velocity shear by thermal wind) we describe the relative effects and explain the finding of maximum upwelling just offshore and to the south of Tampa Bay. We also explain other regions of local upwelling maxima south of Cape San Blas.

Weisberg, R.H., Z. Li, and F.E. Muller-Karger, 2001. West Florida shelf response to local wind forcing: April 1998. *J. Geophys. Res.*, in press.

Here, we describe in situ data and a numerical model simulation for the month of April 1998 and, buoyed by the fidelity between the two, use the model to analyze the dynamics. A new result is found. The data show a rectification of the inner-shelf responses to synoptic wind forcing wherein upwelling favorable winds produce disproportionately larger responses in both sea level and currents than downwelling favorable winds. Stratification accounts for the rectification, and this is most readily understood in terms of the streamwise component of vorticity. For downwelling favorable winds, the buoyancy torque due to isopycnals bending into the sloping bottom opposes the tendency by planetary vorticity tilting due to the vertically sheared coastal jet. This thermal wind effect negates the need for large relative vorticity dissipation by the across-shelf flow in the bottom Ekman layer. The opposite occurs for upwelling favorable winds. Buoyancy torque adds constructively with planetary vorticity tilting requiring larger dissipation of relative vorticity by the bottom Ekman layer. By enhancing (upwelling) or suppressing (downwelling) the bottom Ekman layer the entire response is reduced or increased, respectively.

Yang, Huijun, Robert H. Weisberg, P. P. Niiler, W. Sturges and W. Johnson, 1999: Lagrangian circulation and forbidden zone on the West Florida Shelf, *Continental Shelf Research*, 19, 9, 1221-1245.

This paper presents some recent results of drifters released on the West Florida Shelf during 1996-1997 and compares these results to the numerical model results of the wind-driven circulation. Using satellite tracked surface drifters during the one year period from February 1996 to February 1997, a drifter free region, referred to as the "forbidden zone," is found over the southern portion of the West Florida Shelf. This finding is

consistent with historical drift bottle data and with a recent numerical model study of the West Florida Shelf circulation response to climatological wind forcing. Direct drifter simulations by numerical model during March 1996 show a good agreement with both the in situ ADCP current observation and drifter observation. Three mechanisms are proposed for the observed Lagrangian features. The primarily dynamic mechanism is the along-shore wind forcing, which induces a coastal jet. This jet tends to leave the coast and the bottom, giving rise to offshore transports onshore and near-surface offshore transports. The second is the convergent coastal geometry and bottom topography for the southward flow in central shelf near Tampa Bay that enforces the coastal jet and the bottom and near-surface transport. The last is kinematic, due simply to the short along-shore Lagrangian excursion, driven by the typical synoptic weather systems. Thus near-surface shelf waters over the north may not reach the southern coast of the West Florida. The implication is that surface hazards, such as an oil spill that may occur outside of the southern West-Florida shelf, may not greatly impact the southern coastal region except Florida Keys. However the biological and chemical patches over the north that may occur in the water column such as red tides still can easily reach the southern coastal region through the subsurface and bottom waters.

MS Thesis

1) Siegel, E.M. (1999). Currents observed across the west Florida continental shelf. *Master of Science Thesis*, Department of Marine Science, University of South Florida, St. Petersburg, FL 33701, April 1999, 154pp.

This Thesis incorporates results from the MMS funded observations with other observations collected under separate funding in an attempt to provide an overview on how the currents vary across the west Florida shelf.

Technical Reports

FitzHugh, Gary, C.C. Koenig, Felicia C. Coleman, and W. Sturges, Dec. 2000. Spawning-to-nursery connection for gag: Tests of mechanisms to explain seagrass recruitment patterns. Final report, Nat. Marine Fisheries Service. 30 pp + 20 Figs.

This is a study of the recruitment of Gag Grouper on the west Florida Shelf. The data concerning wind-driven offshore surface motions were determined from the drifter results in the MMS-sponsored studies of this report.

Jones, Ken, Jianguo Wang, and W. Sturges, 1998. Observed Currents during Year 1 of the MMS Northeast Gulf of Mexico Program. Unpublished report, Dept. of Oceanography, Florida State Univ., Tallahassee, FL, 32306, January 1998.

This reports describes the basic data results from the current meter observations taken during Year 1 of the study with plots of all results.

Weisberg, R.H., J.R. Parrish, E.M. Siegel, B.D. Black, J.C. Donovan and R.D. Cole (1998). Northeast Gulf of Mexico water velocity observations: A report on data collected from a subsurface moored acoustic Doppler current profiler at 28 50'N, 84 50'W, February 1996-April 1997.

This data report provides a description of the mooring and instruments used, and gives graphical presentations of the data collected.

Web Sites

<http://gulf.ocean.fsu.edu> This site has been maintained primarily for the drifter experiment. Weekly and monthly maps of the drifter motions (Feb '95 – March '96), prepared by W. Johnson, have been kept on this web site. Access to a variety of other data, including the current meter data, are also available there.

<http://ocg6.marine.usf.edu> provides information on research performed by the USF Ocean Circulation Group. Graphical access is provided for all of the data being collected.

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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.