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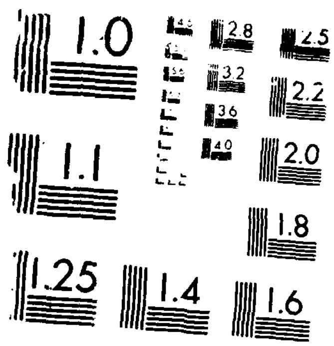

RESOLUTION TEST CHART

FINAL TECHNICAL REPORT

Office of Naval Research Contract
Number N00014-77-C-0354

Submitted by

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University of North Carolina
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This report is the Final Technical Report for the ten-year-long Office of Naval Research Contract Number N00014-77-C-0354 to the University of North Carolina at Chapel Hill. Dr. John M. Bane, Jr., Professor in the Marine Sciences Program, was Principal Investigator for the entire contract period, which began on 1 April 1977 and terminated on 31 March 1987. Total award for this period was $1,039,448.40.

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1. INTRODUCTION

This is the Final Technical Report for the ten-year-long Office of Naval Research Contract Number N00014-77-C-0354 to the University of North Carolina at Chapel Hill. Dr. John M. Bane, Jr., Professor in the Marine Sciences Program, was Principal Investigator for the entire contract period, which began on 1 April 1977 and terminated on 31 March 1987. Total award for this period was $1,039,448.40. The internal account number at the University of North Carolina began as 1-0-110-3262-SD033 and was changed to become 5-0-110-3262-35706 about mid-way through the contract period.

This contract supported research on the physical oceanography of the Gulf Stream, which included several sub-projects (each referred to herein as a project). Each project will be discussed individually below. Data and scientific results from the first three projects have been documented in data reports, analyzed in graduate student theses, reported at national and international meetings, and/or published in refereed scientific journals. A list of these is given for each individual project. Results from the final project supported by this contract are discussed in detail, since they have not been completely documented in reports and publications yet, although some presentations at meetings have been made.

Projects A and B were conducted in collaboration with Professor David A. Brooks of the Department of Oceanography, Texas A and M University. Additional funding from the National Science Foundation's Physical Oceanography Program supported this participation. Project D was conducted in collaboration with Profesor D. Randolph Watts, Graduate School of Oceanography, University of Rhode Island. He was supported by the Physical Oceanography Programs of the National Science Foundation and the Office of Naval Research.

2. RESEARCH PROJECTS

A. A Theoretical Study of Topographic Rossby Waves Trapped over the Continental Slope in the Gulf Stream (Work began 1 April 1977)

Several theoretical models of subinertial waves propagating in the Gulf Stream were developed during this project. The barotropic model studied by Brooks (1978, 1979) indicated that southward propagating continental shelf waves (CSW's) may be responsible for the subtidal sea level oscillations recorded at coastal stations along the North Carolina coast. The more general, baroclinic (two-layer) model developed by Bane (1980) revealed a number of trapped-wave modes that may progress along the continental margin, and suggested that quasi-geostrophic edge waves (QGEW's) and complementary mode edge waves (CMEW's) are also candidate mechanisms for causing the coastal water fluctuations. A new frontal-trapped wave (FTW) was revealed in this model, and is characterized by a band of large-amplitude current fluctuations along the cyclonic side of the Gulf Stream and non-dispersive propagation. These properties are similar to those of the large-amplitude meanders of the Stream measured during the observational portion of the next project (section B below), although phase speeds differ. The continuously stratified baroclinic model constructed by Luther and Bane (1980) also supports FTW's, as well as one CSW mode. Strong mode-coupling in this model produces a family of dispersion curves which demonstrates the possibility of hybrid waves in the Gulf Stream; that is, coupling of a CSW and a FTW may give rise to a wave which appears to be a CSW over the continental shelf, but also has large-amplitude motions in the Gulf Stream frontal zone typical of a FTW. These stable wave studies led into our later theoretical investigations of unstable wave motions in a baroclinic Gulf Stream (under NSF sponsorship).

Results from this project were published as follows:

Journal Articles

Brooks, D.A., and J.M. Bane: Gulf Stream Deflection by a Bottom Feature off Charleston, South Carolina. *Science, 201(4362)*, pp. 1225-1226, 1978.

Bane, J.M.: Lee Topographic Rossby Waves in the Gulf Stream. In: *Symposium on Long Waves in the Ocean, Manuscript Report Series No. 53*, National Research Council of Canada, pp. 173-180, 1979.

Bane, J.M. and D.A. Brooks: Gulf Stream Meanders along the Continental Margin from the Florida Straits to Cape Hatteras. *Geophys. Res. Letters, 6 (4)*, pp. 280-282, 1979.

Brooks, D.A.: Coupling of the Middle and South Atlantic Bights by Sea Level Oscillations. *J. Phys. Oceanogr., 9*, pp. 1304-1311, 1979.

Brooks, D.A.: Shelf Waves: Do They Modulate the Gulf Stream? In: *Symposium on Long Waves in the Ocean, Manuscript Report Series No. 53,* National Research Council of Canada, pp. 162-172, 1979.

Bane, J.M., and Y. Hsueh: On the Theory of Coastal-Trapped Waves in an Upwelling Frontal Zone. *J. Phys. Oceanogr., 10(2),* pp. 270-285, 1980.

Bane, J.M.: Coastal-Trapped and Frontal-Trapped Waves in a Baroclinic Western Boundary Current. *J. Phys. Oceanogr., 10(10),* pp. 1652-1688, 1980.

Technical and Data Reports

Brooks, D.A.: Long Wave Coupling of the Mid- and South Atlantic Bights Forced by the Atmosphere. *Texas A and M Univ. Report No. 79-3-T,* 119 pp., 1979.

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Bane, J.M.: Baroclinic Topographic Rossby Waves in a Sheared, Baroclinic Western Boundary Current. *Trans. Amer. Geophys. Un., 58(12),* p. 1158 (abstract). Paper presented at the AGU Fall Annual Meeting, December 6, 1977.

Bane, J.M.: Gulf Stream Fluctuations along the Continental Margin: Observations and Theory. *Trans. Amer. Geophys. Un., 60(7),* p. 90 (abstract). Paper presented at the AGU Fall Annual Meeting, December 5, 1978.

Bane, J.M.: Density Fronts in Coastal-Trapped Wave Models: The Complementary Mode. *Ocean Modelling, 26,* pp. 3-5, 1979.

Bane, J.M., and D.A. Brooks: Gulf Stream Meanders along the Continental Margin from the Florida Straits to Cape Hatteras. *Trans. Amer. Geophys. Un., 60(16),* p. 205 (abstract).

Luther, M.E., and J.M. Bane: Coastal-Trapped Waves in a Continuously Stratified Western Boundary Current. *Ocean Modelling, 25,* pp. 6-8, 1979.

Luther, M.E., and J.M. Bane: Coastal-Trapped Waves in a Continuously Stratified Western Boundary Current. *Trans. Amer. Geophys. Un., 60(46),* p. 848 (abstract). Paper presented at the AGU Fall Annual Meeting, December 6, 1979.

Bane, J.M.: Coastal-Trapped and Frontal-Trapped Waves in a Baroclinic Western Boundary Current. *Trans. Amer. Geophys. Un., 61,* p. 260 (abstract). Paper presented at the AGU Spring Meeting, Toronto, May 23, 1980.

Theses

Du, Chen-San: Some Aspects of the Theory of Topographic Rossby Waves in a Baroclinic Boundary Current. 1980, 65 pp.

Luther, Mark E.: Coastal-Trapped and Frontal-Trapped Waves in a Continuously Stratified Western Boundary Current. 1980, 77 pp.

B. Observations of Topographic Rossby Waves and Gulf Stream Meanders along the Continental Slope (Work began 1 April 1978)

The observational phase of this project took place during calendar year 1979. The core of the experiment consisted of four taut-wire moorings, which supported a total of ten Aanderaa RCM-4 current meters. The moorings were deployed over the 200 and 400 meter isobaths during the period from 16 January to 15 May, 1979, and again from 5 August to 17 November, 1979 (Figure 1). Shipboard hydrographic surveys were made in the vicinity of the moorings during each deployment and recovery cruise. Two series of AXBT flights were conducted to rapidly map the thermal structure in the upper 400 meters of the Gulf Stream frontal zone between Savannah, GA, and Cape Hatteras, NC. Eight flights were made between 9 and 18 February, and five flights were made between 21 and 29 November.

Two large-amplitude meanders were mapped during the February flights, with the flight on 11 February giving the best coverage of these events. The temperature data clearly show the skewed, wavelike meander patterns that were in the Stream, and the filament of warm Gulf Stream water which trailed each meander crest. [*Note: A meander crest (trough) is taken to be the shoreward-most (seaward-most) excursion of the Stream along one meander length.*] The space-time views of these two particular meanders are the most comprehensive that we obtained during the field study (Figure 2). A complete description is given in Bane, Brooks and Lorenson (1981).

An overview of the combined theoretical and observational results from the first two projects may be seen by considering the frequency vs. wavenumber (period vs. wavelength) diagram in Figure 3. This is a composite plot of the observed period-wavelength points for the dominant sub-intertial motions that have been observed along the Carolina continental margin, along with the theoretically determined dispersion curves for the stable, sub-inertial waves which may propagate in that domain. The dispersion curves in the upper half of the dispersion diagram were calculated with the baroclinic model of Bane (1980), using the wintertime Onslow Bay topography/density/current regime. Three types of waves are possible. The barotropic waves are continental shelf waves (CSW) and quasigeostrophic edge waves (QGEW). One frontal-trapped wave (FTW) exists, and has non-dispersive propagation and baroclinic velocity structure. The three solid circles in the upper

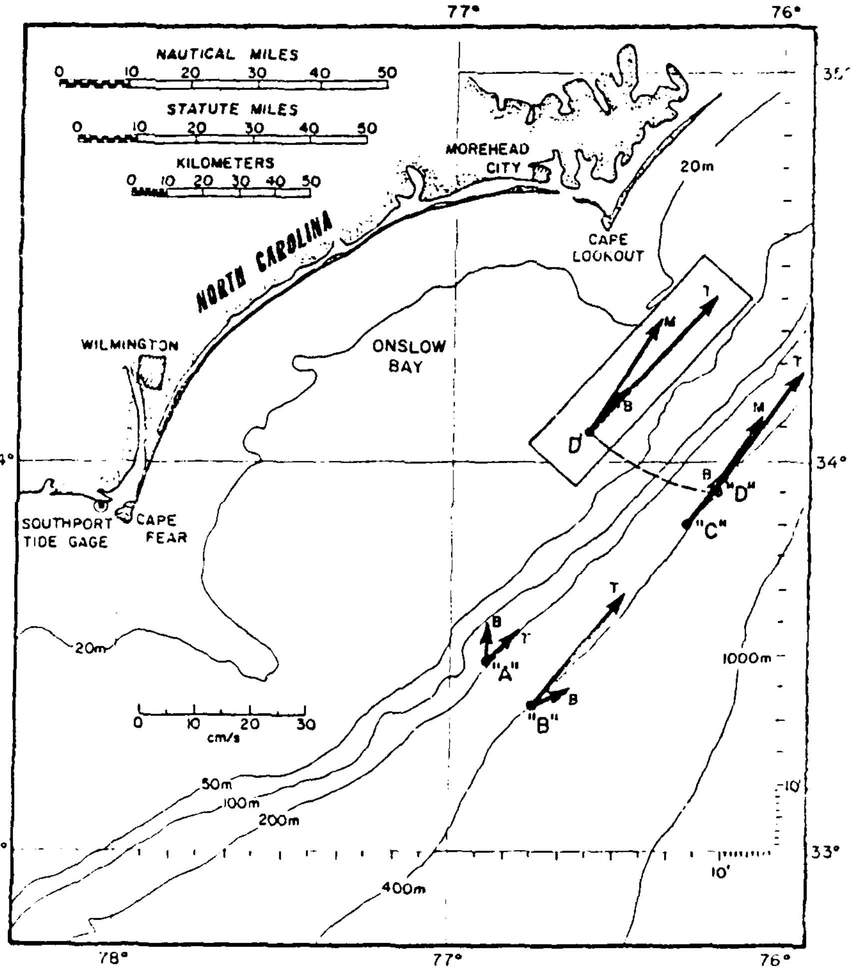

Figure 1. Details of the moored array over the Onslow Bay upper continental slope, which was in place for two four-month-long periods in 1979. Moorings A, B, C, and D are shown, along with the mean currents from measurements made between mid-January and mid-May of that year. Instruments at the top (T), middle (M) and bottom (B) positions on the moorings are indicated.

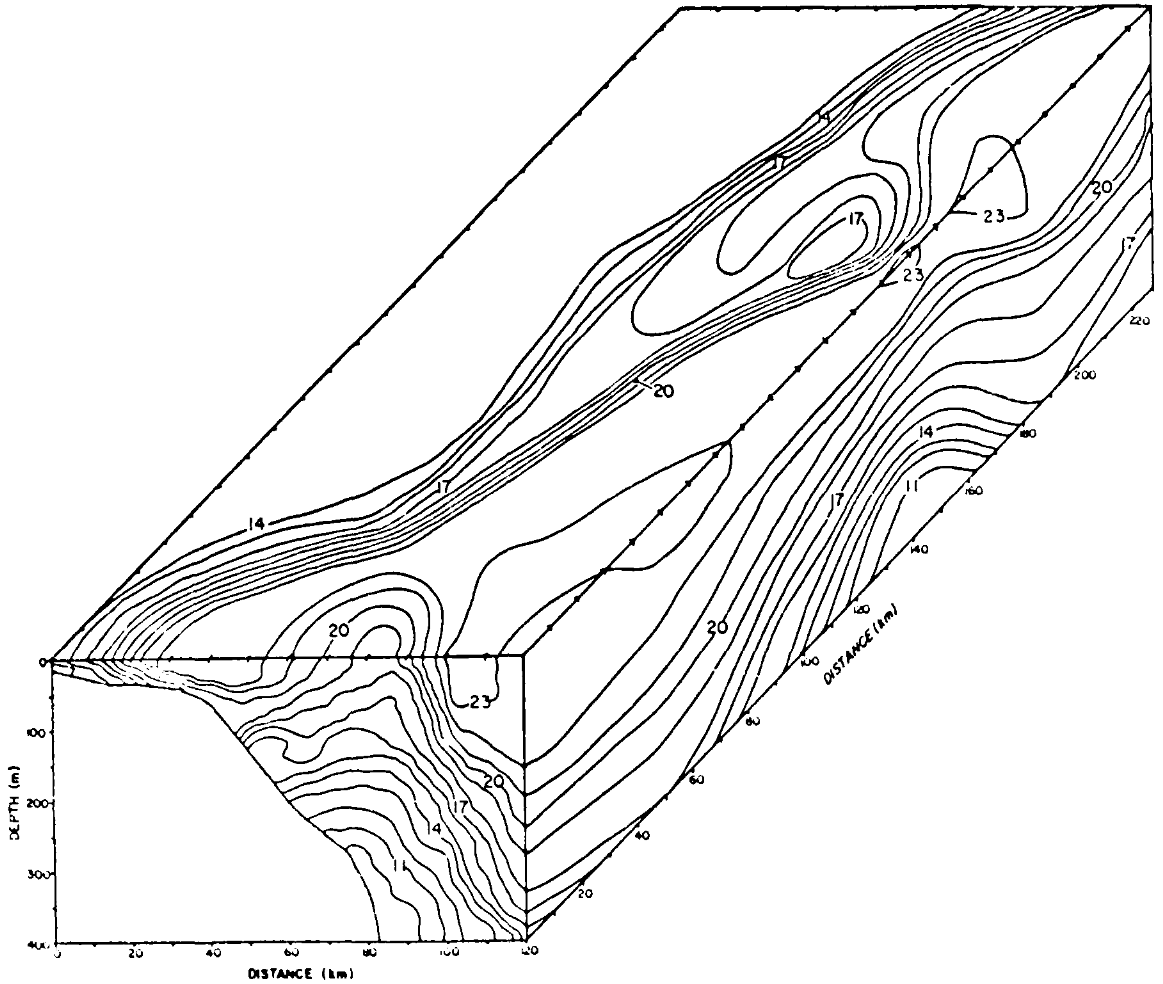

Figure 2. An extensive, three-dimensional view of two large-amplitude Gulf Stream meanders which progressed along the Carolina Continental Margin during February 1979. These data, from our 11 February AXBT survey, demonstrate the skewness of this type of meander. A warm filament trails each of the meander crests. The southern filament has been "sliced" through vertically revealing the shallowness of the filament, and showing the dome of cool water which has upwelled to fill the volume between the upper slope and the main body of the Gulf Stream.

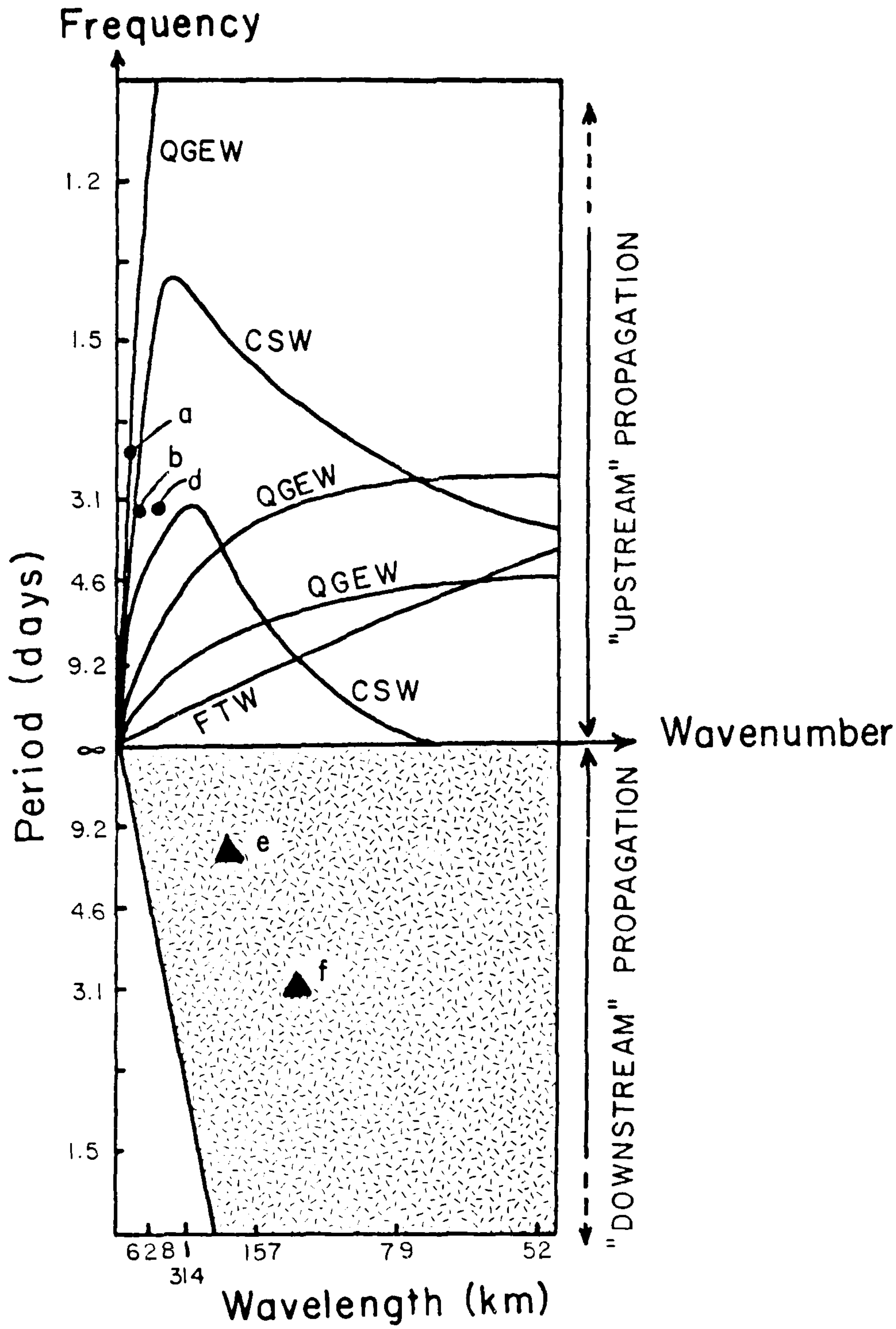

Figure 3. Frequency-wavenumber diagram giving an overview of the combined theoretical and observational results from the first two projects. The dispersion curves in the upper half-plane are for the three coastal-trapped wave components which may propagate along the continental margin past Onslow Bay in a typical wintertime density/current regime (after Bane, 1980). The wave components are: barotropic continental shelf waves (CSW), barotropic quasi-geostrophic edge waves (QGEW), and baroclinic frontal-trapped waves (FTW). The frequency-wavenumber points for fluctuations observed off Onslow Bay are denoted as follows: a, b and d are coastal sea level oscillations, probably due to CSW's and QGEW's; the triangles e and f are large-amplitude Gulf Stream meanders and smaller amplitude oscillations.

half-plane (a, b, d) indicate the period-wavelength points for the subtidal coastal sea level oscillations reported by Brooks (1978). The proximity of these points to the dispersion curves for the fastest QGEW and CSW suggest that these modes are most likely responsible for the oscillations. Cross-shelf structure of the wave amplitude function for each of these wave types shows a maximum at the coastline, consistent with the observations. Little interaction between these waves and the Gulf Stream is expected upstream of Cape Hatteras due to the rather wide continental shelf (*cf.* Bane, 1980).

The period-wavelength points corresponding to the two dominant Gulf Stream meander types observed during the GSME are denoted by the solid triangles. Triangle e represents the more energetic, large-amplitude meanders, such as the two described in Bane, Brooks and Lorenson (1981). These meanders typically have periods near 8 days and wavelengths of about 200 km. Triangle f represents smaller amplitude oscillations which have periods near 3 days and wavelengths near 100 km. The time series and the frequency spectra for the horizontal velocity component measured by the B-top instrument during the January-May period clearly show the signatures of these two meander types (Figure 4).

Each meander type was observed to propagate in the northeastward, or "downstream" direction. Waves which fall in the shaded portion of the lower half-plane in Figure 3, as do the Gulf Stream meanders, have downstream phase speeds within the range of the mean current speed. This suggests the possibility of wave instabilities. The skewness of the large-amplitude wave meander patterns observed during the GSME also suggests a flux of energy between the mean and fluctuation energy "partitions" in the Stream (Brooks and Bane, 1981). The fact that the meander period-wavelength points fall into the shaded portion of the dispersion diagram also indicates the importance of advection by the mean flow in the meander dynamics. The lack of significant correlation between Gulf Stream fluctuations off Onslow Bay and coastal sea level fluctuations, reported by Brooks and Bane (1981), suggests little shelf-wide motion associated with the meander field. Taken together, this implies that the typical topographic Rossby wave modes found over continental shelves (e.g., CSW's and QGEW's) are probably not responsible for Gulf Stream meanders. The FTW components found in the theories of Bane (1980) and Luther and Bane (1980) seem to have structural properties similar to meanders but the propagational properties differ.

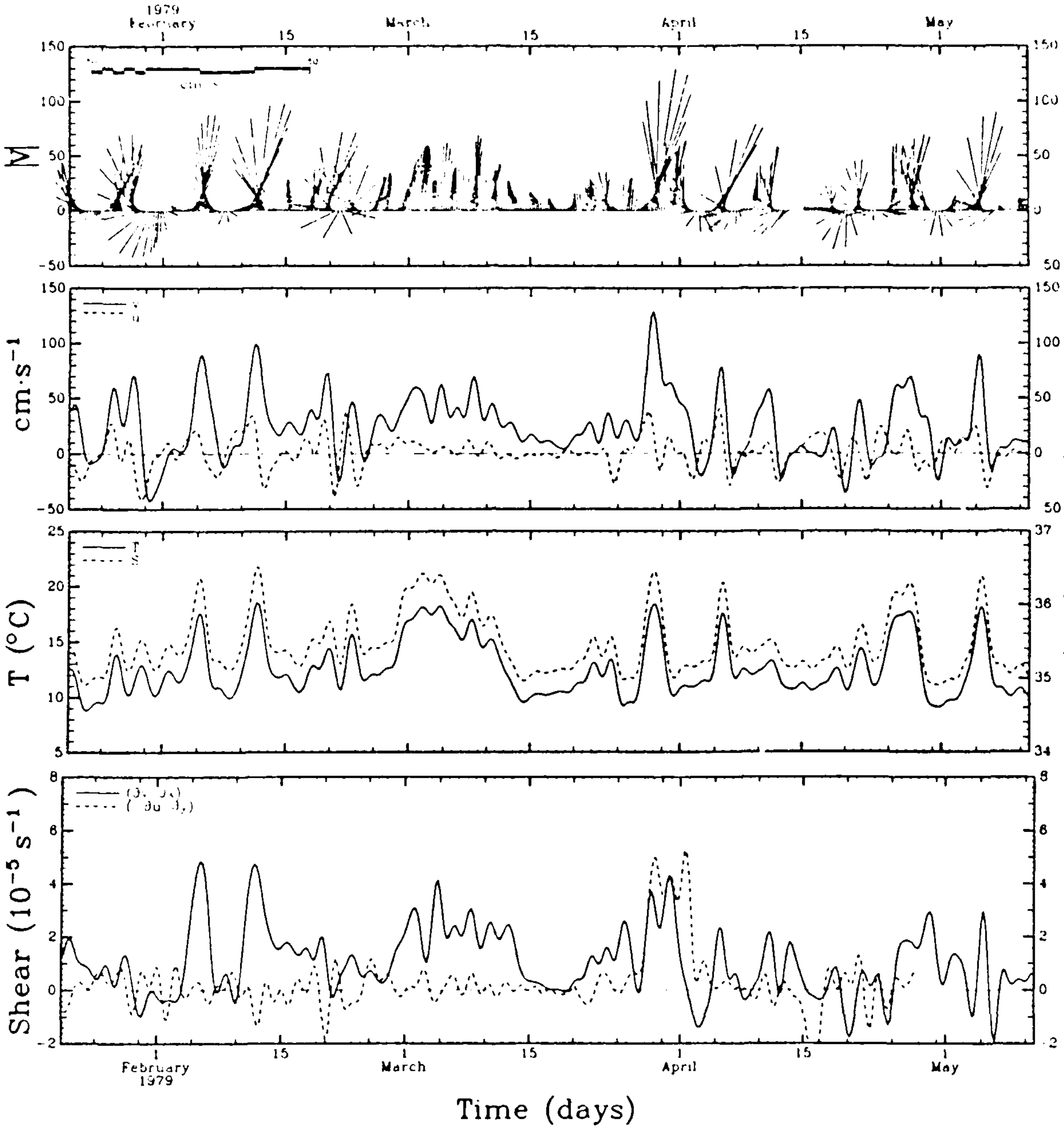

Figure 4a. Forty hour low-pass filtered time series of velocity vectors and components (u and v), temperature (T) and salinity (S) from the B-Top instrument for the January-May 1979 mooring period. Velocity vectors (top panel) pointing toward the top of the figure correspond to downstream flow. The bottom panel shows the relative velocity components due to the horizontal shear, estimated by the moored array. Prominent oscillations occur at periods near 8 days.

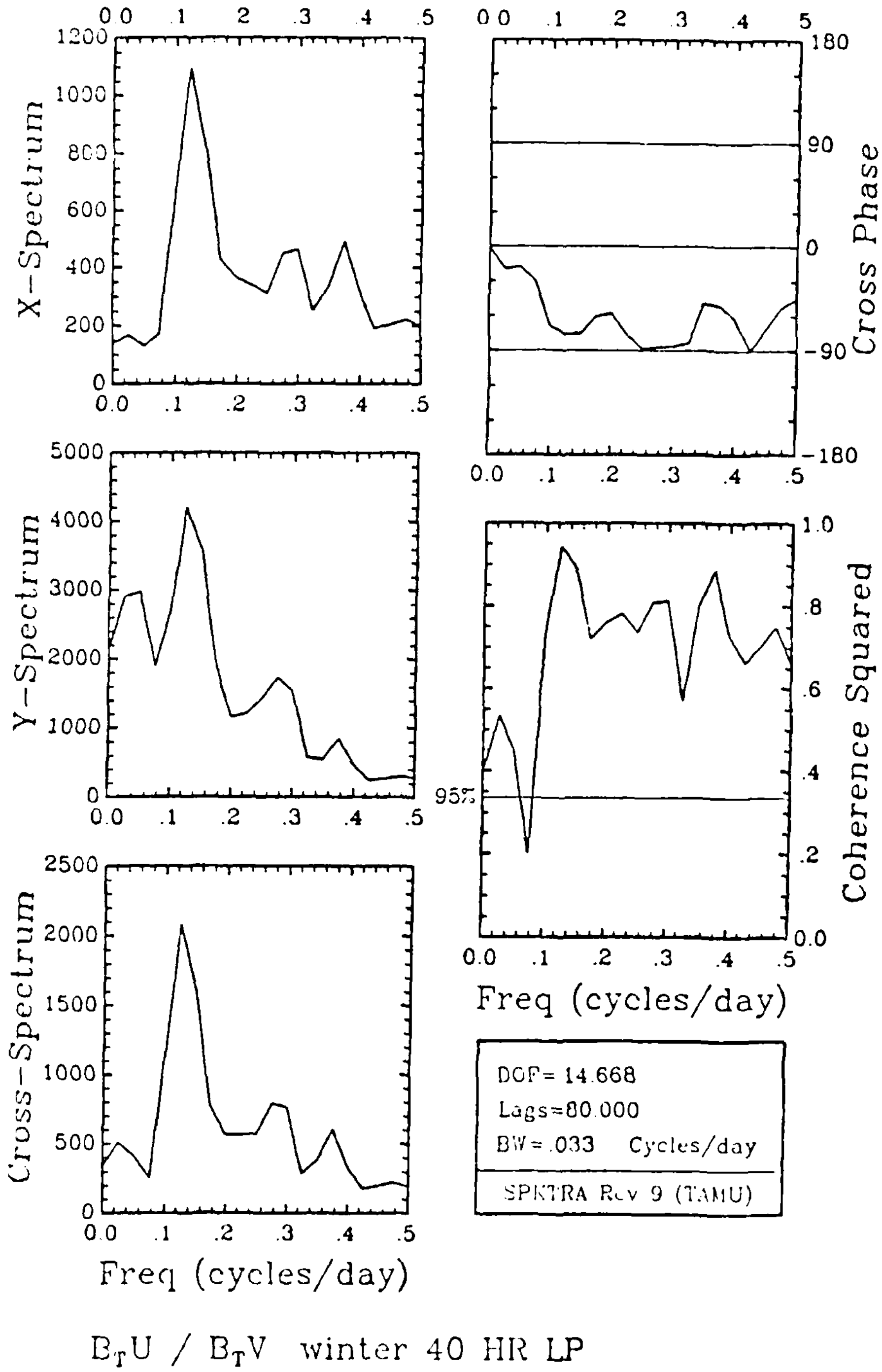

Figure 4b. Spectral properties of the 40 hour low pass filtered offshore (u) and downstreram (v) velocity components measured at the B-Top instrument during the January-to-May 1979 mooring period (see Figures 1 and 4a). The most energetic fluctuations were eight-day-period meanders, which were characterized by large variations in the v component. The B-Top v spectrum (denoted Y-Spectrum here) shows spectral peaks at 8.0 days and 3.6 days. The cross phase of about -70° in the 0.10-0.18 cycle/day band shows that u leads v by less than one quarter period, so the large amplitude meander velocity components are not in quadrature. The 0.26-0.30 cycle/day band shows cross phase to be near -90°, implying a typical progressive wave motion.

The B-top instrument was moored at 250 meters depth over the 390 meter isobath. The signatures of several large-amplitude meanders (corresponding to triangle e in Figure 3) consist of in-phase increases in alongshore velocity (v) and temperature (T). Two of the largest amplitude meanders passed B-top on 5 and 11 February (see Figure 4a). These are the two meanders shown in Figure 2. Smaller amplitude oscillations (corresponding to triangle f in Figure 3) occurred in all variables throughout most of the mooring period. The February AXBT data revealed that only a slight meander pattern in the subsurface temperature field accompanied these motions.

B-top time series data suggest that periods of large-amplitude meander activity are separated by less energetic periods. For example, no large-amplitude meanders were recorded at B-top during the interval between 24 February and 27 March. In an effort to study the energetics of the Stream during the mooring period, and to assess the importance of meanders in the energy transfer processes, the terms in the energy equation were calculated. Energy flux terms were calculated in two manners: First, fluxes were determined for the entire period. Second, the records were divided into four equal-length series and fluxes calculated for each of the approximately month-long periods. These calculations consistently indicate that energy is being converted from meander kinetic energy (KE) and (available) potential energy (PE) to mean KE and PE off Onslow Bay. They also indicate that the meanders play an important role in the energy transfer processes. The succeeding observational study in the Gulf Stream along the southeastern United States, described in section C below, focused on the energy transfer processes and sought to determine the extensive alongshore propagation and coherence of the meander field.

Results from this project were published as follows:

Journal Articles

Bane, J.M., D.A. Brooks, K.R. Lorenson, and C.M. Seay: Three-Dimensional View of a Gulf Steam Meander between Savannah, GA and Cape Hatteras, NC. *Gulfstream, 6(5)*, pp. 3-7, 1980.

Bane, J.M., D.A. Brooks, and K.R. Lorenson: Synoptic Observations of the Three-Dimensional Structure and Propagation of Gulf Stream Meanders along the Carolina Continental Margin. *J. Geophys. Res., 86(C7)*, pp. 6411-6425, 1981.

Brooks, D.A. and J.M. Bane: Gulf Stream Fluctuations and Meanders over the Onslow Bay Upper Continental Slope. *J. Phys. Oceanogr., 11(2)*, pp. 247-256, 1981.

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Chew, F., J.M. Bane, and D.A. Brooks: The Propagation of a Cold-Dome Meander: A Conceptual Model. *Proc. Workshop Gulf Stream Struc. Var.*, Univ. North Carolina, pp. 63-68, 1982.

Bane, J.M.: Initial Observations of the Subsurface Structure and Short-Term Variability of the Seaward Deflection of the Gulf Stream off Charleston, South Carolina. *J. Geophys. Res., 88(C8)*, pp. 4673-4684, 1983.

Brooks, D.A., and J.M. Bane: Gulf Stream Meanders off North Carolina During Winter and Summer 1979. *J. Geophys. Res., 88(C8)*, pp. 4633-4650, 1983.

Hood, C.A. and J.M. Bane: Subsurface Energetics of the Gulf Stream Cyclonic Frontal Zone off Onslow Bay, North Carolina. *J. Geophys. Res., 88(C8)*, pp. 4651-4662, 1983.

Legeckis, R., and J.M. Bane: Comparison of the TIROS-N Satellite and Aircraft Measurements of Gulf Stream Surface Temperatures. *J. Geophys. Res., 88(C8)*, pp. 4611-4616, 1983.

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Chew, F., J.M. Bane, and D.A. Brooks: On Vertical Motion, Divergence and the Thermal

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Bane, J.M., D.A. Brooks, and M.J. Ignaszewski: The Gulf Stream Meanders Experiment - Hydrographic Data Report, *R/V Endeavor* Cruises EN-040 and EN-045. *Texas A and M Univ. Report No. 80-11-T*, 170 pp., 1980.

Brooks, D.A., J.M. Bane, and M.J. Ignaszewski: the Gulf Stream Meanders Experiment - Hydrographic Data Report, *R/V Endeavor* Cruises EN-031 and EN-037. *Texas A and M Univ. Report No. 80-1-T*, 145 pp., 1980.

Brooks, D.A., J.M. Bane, R.L. Cohen, and P. Blankinship: The Gulf Stream Meanders Experiment - Current Meter, Atmospheric and Sea Level Data Report, January to May, 1979, Mooring Period. *Texas A and M Univ. Report No. 80-7-T*, 264 pp., 1980.

Luther, M.E., and J.M. Bane: Coastal-Trapped and Frontal-Trapped Waves in a Continuously Stratified Western Boundary Current *Univ. North Carolina Report No. CMS-80-1*, 77 pp., 1980.

Bane, J.M. and D.A. Brooks: The Gulf Stream Meanders Experiment - AXBT/PRT Data Report, *R/A Seascan* Flights, 21-29 November 1979. *Univ. North Carolina Report No. CMS-81-1*, 174 pp., 1981.

Brooks, D.A., J.M. Bane, R.L. Cohen, and P. Blankinship: The Gulf Stream Meanders Experiment - Current Meter, Atmospheric and Sea Level Data Report, August to November, 1979, Mooring Period. *Texas A and M Univ. Report No. 81-3-T*, 183 pp., 1981.

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Bane, J.M., and D.A. Brooks: Three Dimensional, Mesoscale Characteristics of the Temperature Field in the Gulf Stream Frontal Zone South of Cape Hatteras. *Trans. Amer. Geophys. Un.*, *60(46)*, p. 859 (abstract). Paper presented at the AGU Fall Annual

Meeting, December 6, 1979.

Brooks, D.A., and J.M. Bane: Gulf Stream Meanders and Low Frequency Currents over the Continental Slope off Onslow Bay, NC. *Trans. Amer. Geophys. Un., 60(46)*, p. 859 (abstract). Paper presented at the AGU Fall Annual Meeting, December 6, 1979.

Luther, M.E., J.M. Bane, and D.A. Brooks: Rotary Spectra of Gulf Stream Meanders over the Continental Slope off Onslow Bay, North Caroina. *Trans. Amer. Geophys. Un., 61*, p. 261 (abstract). Paper presented at the AGU Spring Meeting, Toronto, May, 1980.

Bane, J.M., D.A. Brooks, and K.R. Lorenson: Synoptic Observations of the Three-Dimensional Structure, Propagation and Evolution of Gulf Stream Meanders along the Carolina continental Margin. *Bull. Amer. Meteor. Soc., 61* (abstract). Paper presented at the Third Conference on Atmospheric and Oceanic Waves and Stability, San Diego, January 19, 1981.

Bane, J.M., and R.V. Legeckis: Comparison of Aircraft and TIROS-N Satellite Thermal Infrared Measurements of the Gulf Steam. *Trans. Amer. Geophys. Un., 62*, p. 295 (abstract). Paper presented at the AGU Spring Meeting, Baltimore, May 26, 1981.

Seay, C.M., and J.M. Bane: On the Usefulness of Remotely Sensed Sea Surface Temperature Patterns as Indicators of Subsurface Meanders in the Gulf Stream. *Trans. Amer. Geophys. Un., 62*, p. 302 (abstract). Paper presented at the AGU Spring Meeting, Baltimore, May 27, 1981.

Hood, C.A., and J.M. Bane: Subsurface Energetics of the Gulf Stream Cyclonic Frontal Zone off Onslow Bay, North Carolina. *Trans. Amer. Geophys. Un., 62*, p. 926 (abstract). Paper presented at the AGU Fall Annual Meeting, San Francisco, December 3, 1981.

Brooks, D.A. and J.M. Bane: Gulf Steam Meanders off North Carolina: A Seasonal Comparison of their Observed Characteristics. *Trans. Amer. Geophys. Un., 63*, p. 362 (abstract). Invited Paper presented at the AGU Spring Annual Meeting, Philadelphia, June 4, 1982.

Theses

Lorenson, Karen R.: Three-Dimensional, Mesoscale Characteristics of the Gulf Stream

Thermal Frontal Zone South of Cape Hatteras. 1980, 181 pp.

Luther, Mark E.: Coastal-Trapped and Frontal-Trapped Waves in a Continuously Stratified Western Boundary Current. 1980, 77 pp.

Hood, Carroll A.: Subsurface Energetics of the Cyclonic Gulf Stream Frontal Zone off Onslow Bay, North Carolina. 1981, 57 pp.

Seay, Cynthia M.: Characteristics of the Gulf Stream Sea Surface Temperature Field Between Savannah, Georgia and Cape Hatteras, North Carolina. 1981, 115 pp.

C. An Observational Study of Gulf Stream Deflection and Meander Energetics along the Continental Margin (Work began 1 April 1981)

During the period September 1981 through April 1982, the Gulf Stream Deflection and Meander Energetics Experiment (DAMEX) was conducted in the region of the Stream's seaward deflection, off Charleston South Carolina at about 32° N latitude. This experiment was designed to study the deflection process and its relationship to Gulf Stream variability. In this project, we collected data which suggest that the deflection of the Stream has a bimodal character, and that the nature of the low frequency variability of the Stream in the region from the Charleston bump to Cape Hatteras varies between the two states of deflection. In DAMEX papers, we describe these observations (Bane and Dewar, 1987), discuss the energetics of the Stream in this region (Dewar and Bane, 1985), and analyze the dynamical balances and vertical velocities in Gulf Stream fluctuations (Osgood et al, 1987).

DAMEX was composed of three observational components. (1) Current meters and bottom pressure gauges were supported on seven moorings for the seven-month-long DAMEX period, which began in September, 1981; (2) a CTD survey was made in the deflection region during September, 1981; and (3) four AXBT surveys were conducted along the Gulf Stream in an area which encompassed the deflection region in March, 1982. The seven instrument moorings comprised the central DAMEX component, and they were grouped into two smaller three-mooring arrays and one single mooring (Figure 5a). The southernmost array, E, contained three moorings with two current meters each, and was located about 90 km southwest (upstream) of the bump. The center array, F, also consisted of three moorings with two current meters each, and it was located roughly 90 km northeast (downstream) of the bump. Bottom pressure gauges were mounted on two of the F moorings. A single mooring, G, with two current meters was positioned off Onslow Bay. Arrays E and F were moored in areas which had not previously been sampled, while the G mooring was placed at a site studied earlier, during the 1979 mooring period (see Section B, above).

The three moorings in each of the E and F arrays were placed in an 'L' configuration, with one mooring on the 300 m isobath and two on the 400 m isobath. In each array the shallow mooring was identified as the '1' mooring, the one directly downslope from this as the '2' mooring, and the one alongslope to the north or northeast as the '3' mooring. The top (bottom) current meter at each mooring, including G, was placed

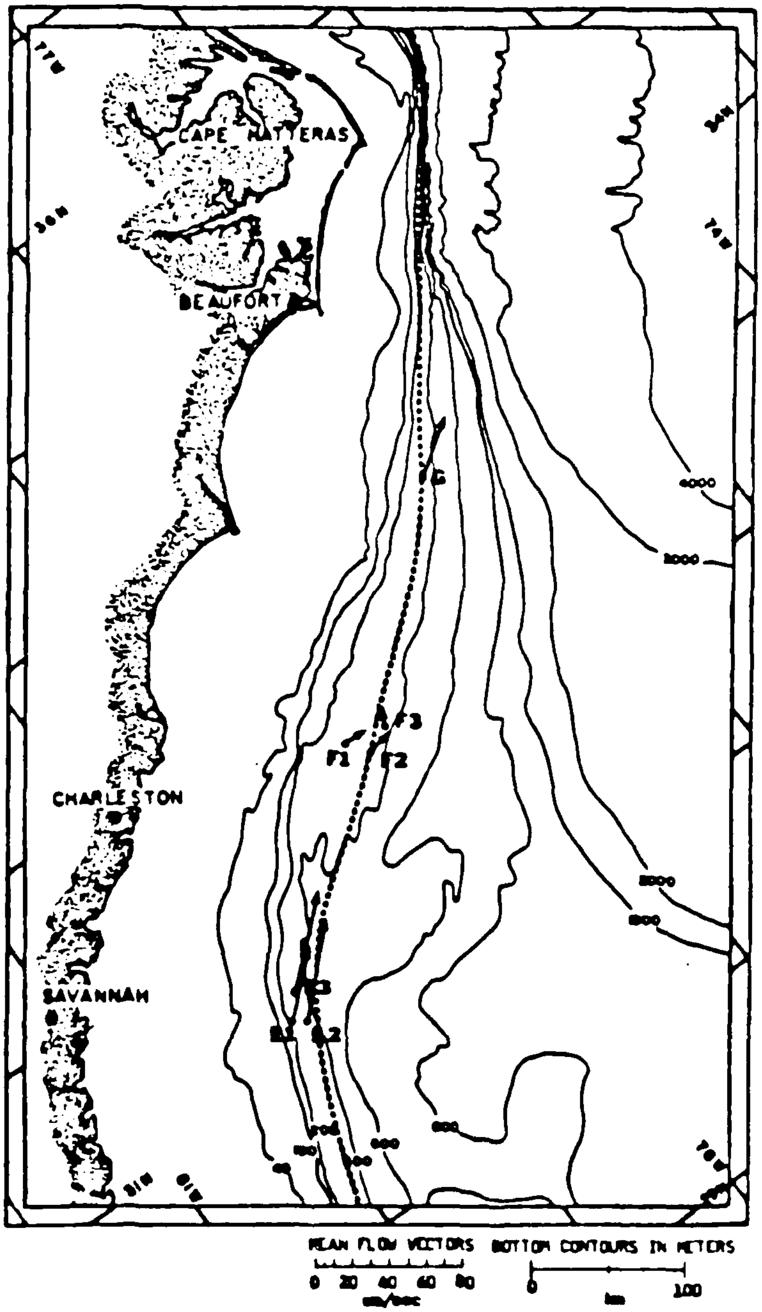


Figure 5a. Mean flow vectors for the DAMEX array during the September 1981 through April 1982 mooring period. The dotted line is the mean position of the Gulf Stream's shoreward surface thermal front.

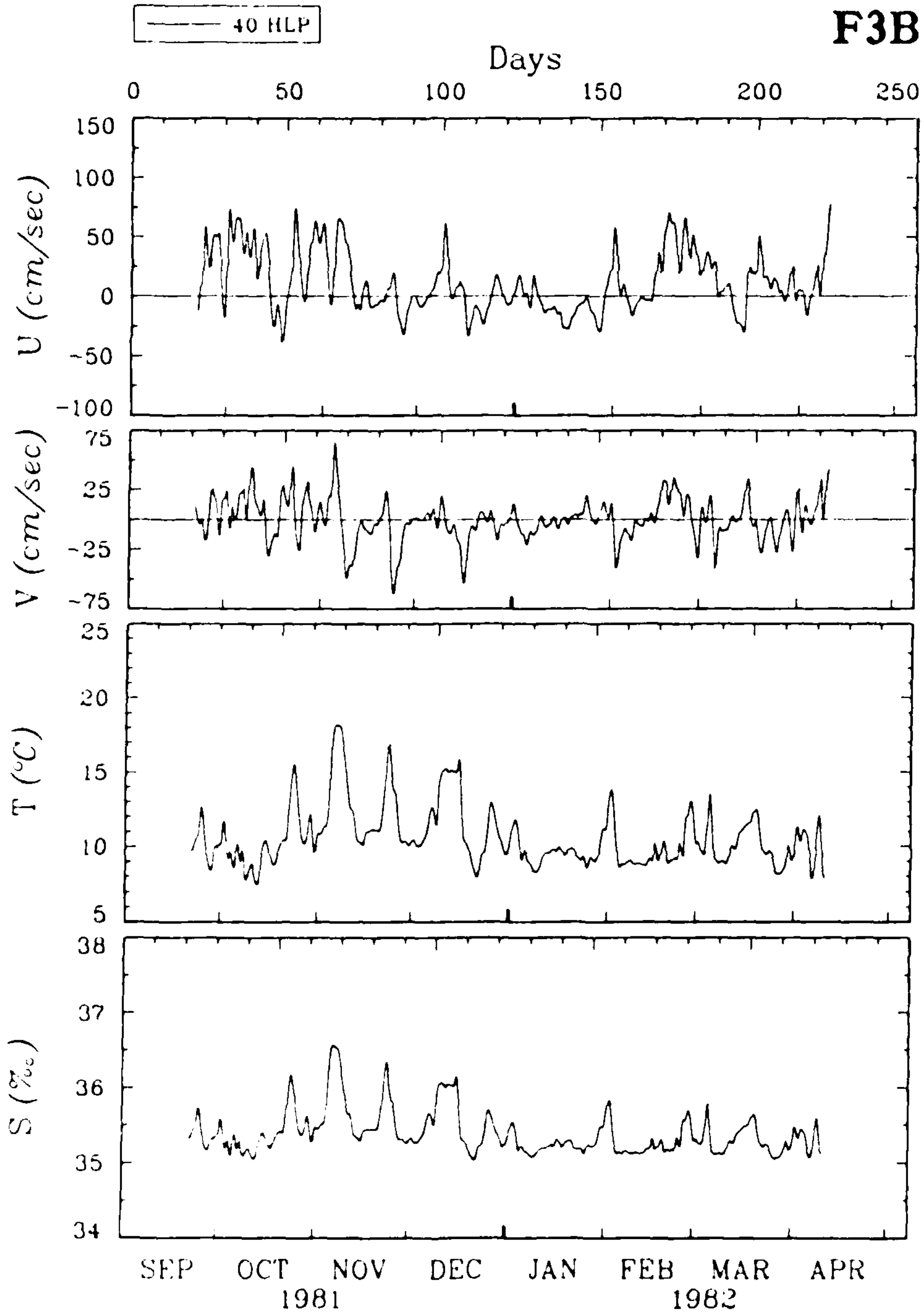


Figure 5b. Forty hour low-pass filtered time series of downstream speed (v), cross-stream speed (u), temperature (T) and salinity (S) for the F3B instrument in the DAMEX array. Note the change to lower frequency fluctuations in mid October, and then the change back to highter frequencies at the end of January. These changes in fluctuation character were due to the Gulf Stream shifting from a weakly deflected state to a strongly deflected state in mid October, and then back to a weakly deflected state in Late January

at a nominal depth of 210 m (270 m). Each instrument is referred to by a unique name which denotes its array, mooring and instrument location. For example, E1T (E1B) is the current meter at the top (bottom) position on the E1 mooring.

The current meters measured horizontal velocity, temperature and conductivity at 30-minute intervals from the middle of September, 1981 to the middle of April, 1982. The data were low pass filtered to remove tides and internal waves by using a modified Lanczos filter with a quarter-power point at forty hours. The resulting forty hour low passed (40 HRLP) time series averaged 200 days in length and had an effective sampling interval of six hours. This processing follows that of our earlier study (*cf* Brooks et al, 1981). A full documentation of all DAMEX mooring data and processing techniques is given in Bane and Dewar (1983).

Fluctuations of the Gulf Stream changed in character twice during the seven-month DAMEX mooring period. The oscillations observed at each current meter mooring were predominantly in the 4- to 8-day period band prior to November and after January, while during the November-through-January interval they were of distinctly lower frequency, with periods ranging approximately from 14 to 20 days. These changes were most noticeable at Array F (Figure 5b), although they are obvious at the other locations as well. Our analysis indicates that these dramatic changes were associated with differences in the degree of deflection of the Gulf Stream at the Charleston bump.

We will refer to the configuration of the Gulf Stream prior to mid-October and after January as the "weakly deflected" state, and to its configuration during the mid-October-through-January period as the "strongly deflected" state. Two satellite images of the sea surface temperature (SST) field taken during DAMEX show the two deflection states quite nicely (Figure 6). They are the AVHRR images for 3 December 1981 and 2 March 1982, which are typical of the strongly and weakly deflected states, respectively. The primary difference between the images is the offshore position of the main body of the Gulf Stream just downstream of the Charleston bump. In the weakly deflected state, the Stream's shoreward SST front is everywhere shoreward of the 600 m isobath upstream of Cape Hatteras. In the strongly deflected state, the shoreward SST front (and thus the entire width of the Gulf Stream) is seaward of the 600 m contour by at least 50 km for that portion of its path just downstream of the bump. We have found this to be a good "rule of thumb"; namely, if the Gulf Stream's

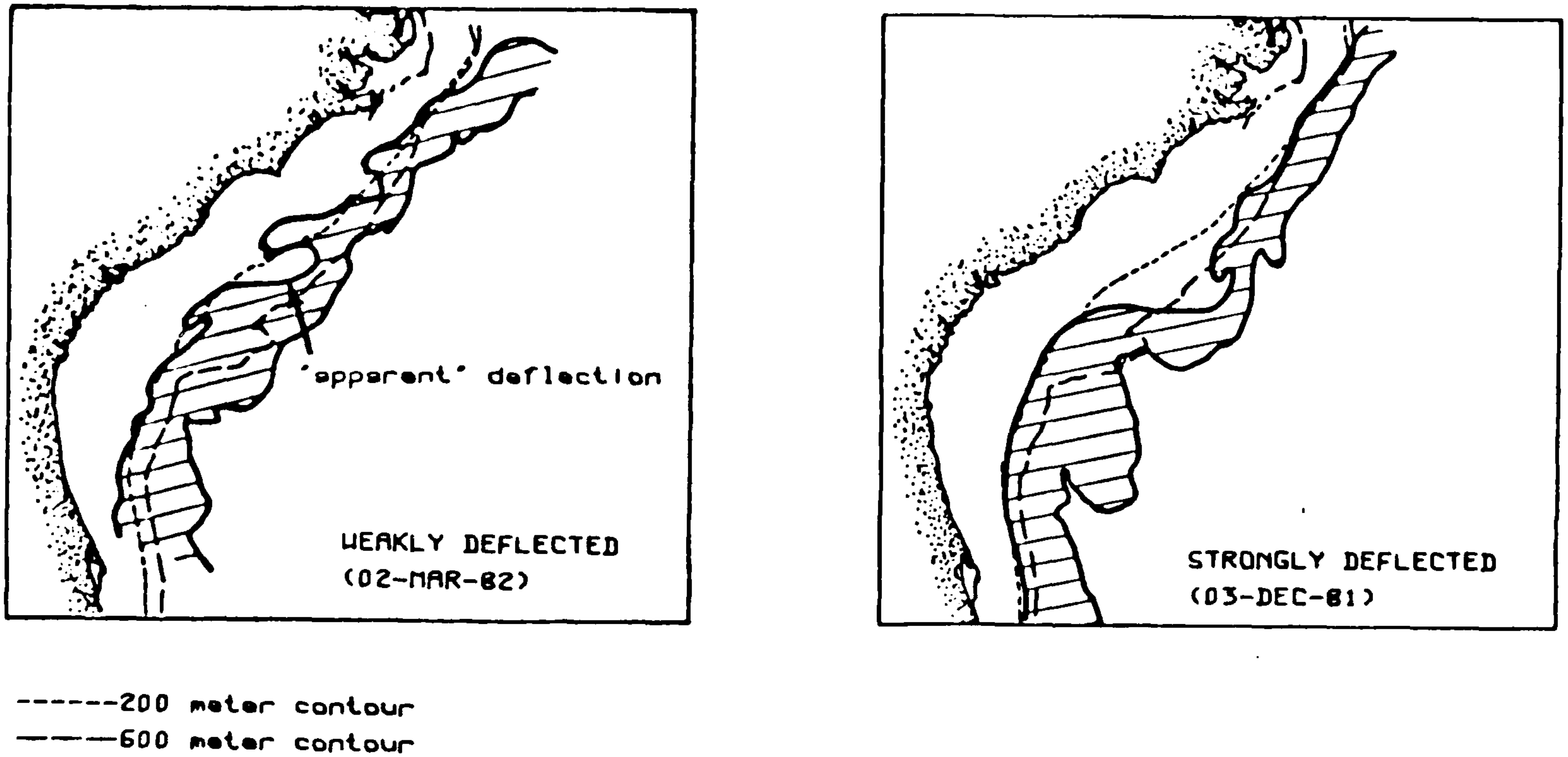


Figure 6. Satellite views of the Gulf Stream for a typical weakly deflected state and a typical strongly deflected state, both observed during DAMEX.

shoreward SST front in the first several tens of kilometers just downstream of the Charleston bump is seaward of the 600 m isobath, then we consider the Stream to be in its strongly deflected state.

There is a noticeable difference in the Stream's meander patterns between the two states of deflection. Downstream of the bump, several of the typical meander/frontal eddy patterns and their associated warm filaments occur in the weakly deflected example of 2 March. In contrast, the path of the Stream in that region in the strongly deflected case of 3 December is a rather smooth arc. The Stream leaves the deflection region flowing eastward well past the 600 m isobath, and then it turns gradually northward towards Cape Hatteras. Earlier observations of the flow over the continental shelf and upper slope in this region have shown that there is a quasi-stationary, cyclonic circulation pattern (the so-called "Charleston Gyre") positioned shoreward of the Gulf Stream's arcuate path in this state. We found meander-like fluctuations to occur in the Charleston to Cape Hatteras region during a period of strong deflection in DAMEX. Such meanders of the Gulf Stream jet have lateral amplitudes greater and phase speeds slower than do the more commonly observed meander/frontal eddy patterns. Data presented below show this meander motion to result in a quite convoluted, sometimes "sawtooth" pattern in the Gulf Stream's path, resulting in very strong anticyclonic flow around each meander crest. To distinguish this type of meander motion from the meander/frontal eddy motions which occur when the Stream is only weakly deflected, we will refer to the larger amplitude meanders observed during the strongly deflected period of this study as the DAMEX meanders.

The record-long mean velocity vectors show the effect of the seaward deflection at the F moorings (Figure 5a). Relatively low mean velocities occurred there, and were due to the shift of the Stream away from Array F during the strongly deflected state. This greatly reduced the mean downstream speed there for the mid-October through January period. Because these moorings were sometimes in, and sometimes out of the Stream, the essentially eastward means at F1T and F2B may not be reliable indicators of the longer term mean path of the main Stream in this area. For comparison, the mean path of the shoreward SST front as indicated by Bane and Brooks (1979) is oriented near 060° True there. The Array F mean velocities are more suggestive of the cyclonic flow around the southern edge of the Charleston Gyre.

Results from this project were published as follows:

Journal Articles

Bane, J.M., and M.H. Sessions: A Field Performance Test of the Sippican Deep Aircraft-Depolyed Expendable Bathythermograph. *J. Geophys. Res., 89(C3)*, pp. 3615-3621, 1984.

Bane, J.M., and W.K. Dewar: Biomodality in the Gulf Stream? *Gulf Stream Workshop Proc.*, Univ. Rhode Island, pp. II.116-II.126, 1985.

Dewar, W.K., and J.M. Bane: An Analysis of Gulf Stream Mean Flow Energetics off Charleston, South Carolina. *Gulf Stream Workshop Proc.*, Univ. Rhode Island, pp. II.256-II.273, 1985.

Dewar, W.K., and J.M. Bane: The Subsurface Energetics of the Gulf Stream near the Charleston Bump. *J. Phys. Oceanogr., 15(12)*, pp. 1771-1789, 1985.

Bane, J.M., and W.K. Dewar: Gulf Stream Mean Flow and Variability near the Charleston Bump. *J. Geophys. Res.* (submitted).

Osgood, K.E,. J.M. Bane and W.K. Dewar: Momentum Balances and Vertical Velocities in Gulf Stream Meanders. *J. Geophys. Res.* (in press).

Technical and Data Reports

Bane, J.M.: A Field performance Test of the Sippican Aircraft-Deployed Expendable Bathythermograph. *Univ. North Carolina Report No. CMS-83-1*, 85 pp, 1983.

Bane, J.M., and W.K. Dewar: The Gulf Stream Deflection and Meander Energetics Experiment - Current Meter and Bottom Pressure Gauge Data Report for the September 1981 to April 1982 Mooring Period. *Univ. North Carolina Report No. CMS-83-2*, 481 pp, 1983.

Notes and Published Abstracts

Bane, J.M. and W.K. Dewar: Gulf Stream Mean Flow and Variability near the Charleston Bump. *Trans. Amer. Geophys. Un.*, 65, p. 931 (abstract). Paper presented at the AGU Fall Annual Meeting, San Francisco, December 3, 1984.

Dewar, W.K. and J.M. Bane: The Subsrface Energetics of the Gulf Stream near the Charleston Bump. *Trans. Amer. Geophys. Un.*, *65*, p. 931 (abstract). Paper presented at the AGU Fall Annual Meeting, San Francisco, December 3, 1984.

Cordova, L. and J.M. Bane: The Gulf Stream's Western Surface Temperature Front Between Cape Canaveral and Cape Hatteras, 1976-1978: Basic Statistical and Principal Component Analyses. 158 p. *Trans. Amer. Geophys. Un.*, *66*, p. 1284 (abstract). Paper presented at the AGU Ocean Sciences meeting, New Orleans, Jan. 14, 1986.

Osgood, K.E. and J.M. Bane: Vertical velocities and the Momentum Balance in the Gulf Stream. *Trans. Amer. Geophys. Un.*, *66*, p. 1277 (abstract). Paper presented at the AGU Ocean Sciences meeting, New Orleans, Jan. 14, 1986.

Theses

Cordova, Leonidas: The Gulf Stream's Western Surface Temperature Front Between Cape Canaveral and Cape Hatteras, 1976-1978: Basic Statistical and Principal Component Analyses. 1984, 158 pp.

Osgood, Kenric E.: Vertical Velocities and the Momentum Balance in the Gulf Stream. 1986, 67 pp.

D. Observations of the Current Structure and Energetics of Gulf Stream Fluctuations Downstream of Cape Hatteras (Work began 1 October 1983)

During 1984, an array of five current meter/bottom pressure gauge moorings and twenty inverted echo sounders (IES) was maintained in the Gulf Stream region 150-500 km northeast of Cape Hatteras. The mooring locations are shown in Figure 7. The five current meter mooring sites each had four levels instrumented from 500 m below the surface to near the bottom. An IES with a bottom pressure gauge was located at the base of each mooring.

This was an extremely successful field program. We used a high performance design for the current meter moorings, which allowed them to extend high into the strong current. This was the first 3-dimensional array of current meters to span through the main thermocline and strong vertical shear in a region where the Gulf Stream flows in deep water. To withstand the strong currents, each mooring was constructed with small diameter (3/16") jacketed wire to reduce drag, and high floatation (*ca.* +2000 lbs. positive buoyancy). These high performance, "stiff" moorings survived a one-year deployment with little indication of adverse effects. The tilting of the moorings due to currents was well within design specifications for Aanderaa current meters, and the amount of vertical excursion was even somewhat lower than the design target. We safely recovered all of the moorings and instruments, and achieved a data return of 85% for velocity and 90% for temperature. The IESs were recovered in both January and May 1985, with only one instrument loss and one data tape failure (both from the second deployment period) for a data success rate of 95% on the 19-month-long combined records. The failure of the electrical circuitry controlling one of the five bottom pressure gauges resulted in a data return of only 80%. However all the bottom temperature sensors functioned properly, yielding a 100% data recovery.

We also experienced a high level of success in our seven scheduled AXBT mapping flights. All but one of these flights were made aboard a Naval Research Laboratory P-3, with the remaining one flown aboard a NOAA P-3. Over 100 AXBT's were deployed per flight.

(1) The Current Meter Records. The moored array was located in a region where Gulf Stream meanders are known to propagate and grow in the downstream direction. In

Figure 7, solid circles on lines B and C denote current meter moorings. Aanderaa current meters were placed at nominal depths of 500 m, 1000 m and 2000 m from the surface and 500 m from the bottom (D-500) on each mooring, and they recorded current speed, current direction, and temperature at one-hour intervals.

Figures 8a through 8d show the mean flow vectors at the four levels. During much of 1984, the Stream flowed along a course which was north of its usual path. This condition resulted in our array being positioned within the anticyclonic side of the Stream, as may be seen in the 500 m and 1000 m mean currents shown in Figures 8a and 8b. The northernmost mooring (C1) was essentially at the Stream center during much of the deployment period. By contrast, the near-bottom currents (Figure 8d) at the two southern moorings show the presence of a deep southwestward mean flow, counter to that of the surface Gulf Stream.

Times series of the forty hour low-pass (40 HRLP) filtered downstream speed (u), cross-stream speed (v), and temperature (T) measured by the four instruments on mooring B2 are shown in Figures 9a through 9d. Mooring B2 was the westernmost in the array, located near 35.6 N and 73.5 W. The depth of the top instrument is also shown in the top panel in Figure 9a, to provide an indication of the mooring's performance (r.m.s. vertical excursions of about 60 m at the mean depth of 440 m, excursion range from 350 to 585 m).

Several aspects of the Gulf Stream environment during 1984 may be seen from visual inspection of the Figure 9 time series. The uppermost instrument on B2 was on the southern fringes of the strong current during the first and last portions of the period, while from about year-day 120 to day 350 the Gulf Stream had moved far enough south that its high velocity core flowed through the array near mooring B2. A general decrease in temperature was seen at all levels of B2 during this period, associated with the southward, shift throughout the water column, of the baroclinic temperature field along with the current.

Two strong events occurred near day 115 and day 265 in the B2-1 record. Using velocity and temperature signatures at this instrument, plus delay times between instruments on the other moorings, it was determined that these events were cold-core, cyclonic eddies moving to the northeast. Satellite data confirm that the events were cold-core Gulf Stream rings coalescing with the main current and

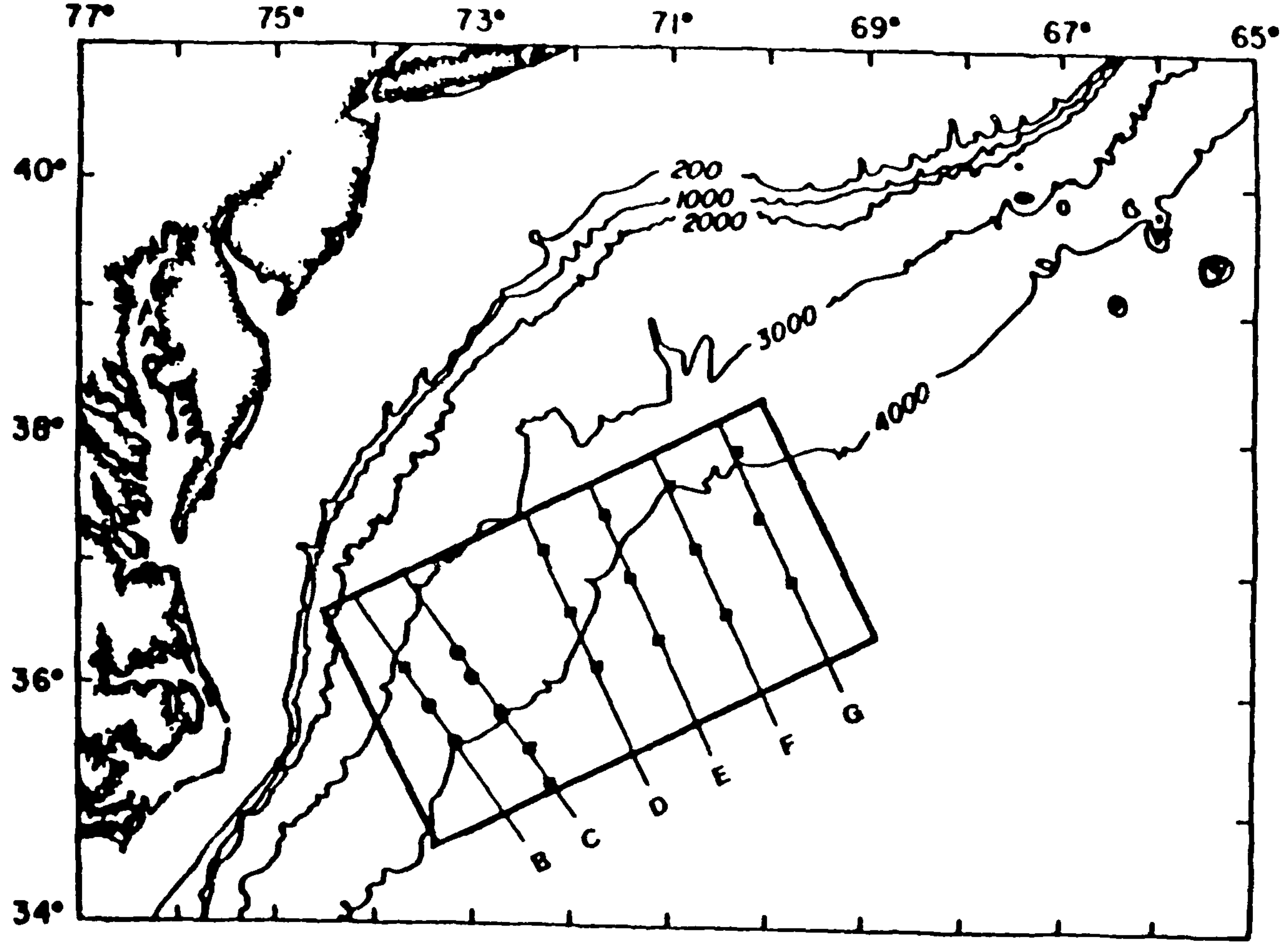


Figure 7. IES sites (boxes and circles) along line B through G were occupied during 1984. Current meter moorings as well as IES were located at the sites shown by the solid circles.

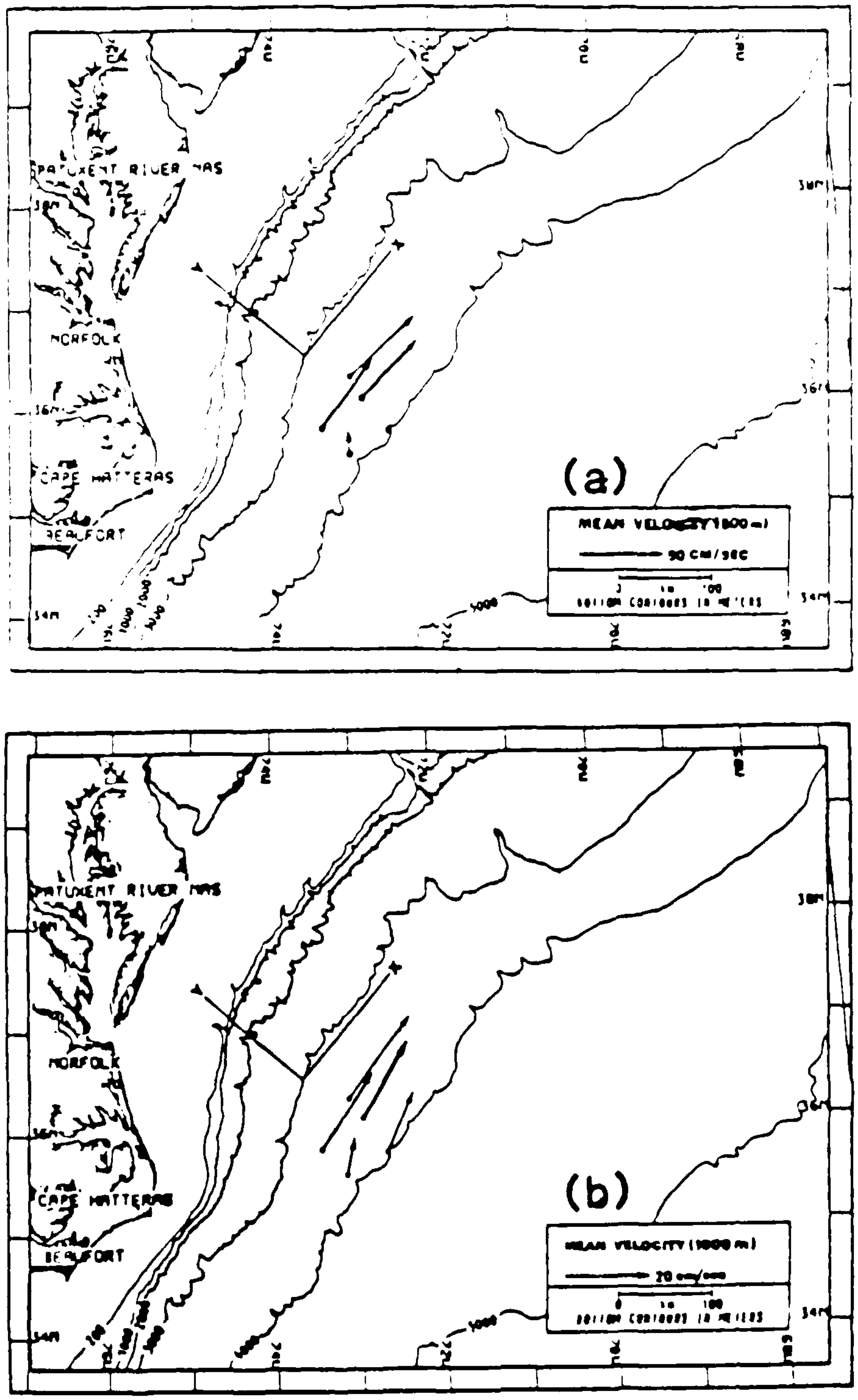
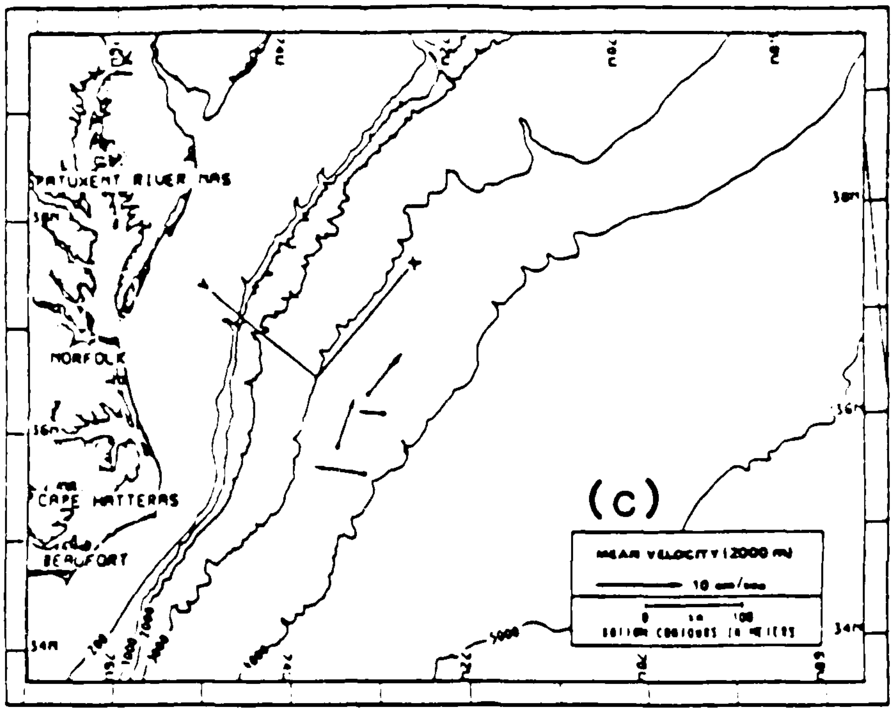


Figure 8. One-year-long mean velocities in the study area for instruments moored at nominal depths of (a) 500m, (b) 1000m, (c) 2000m, and (d) 500m above the bottom.



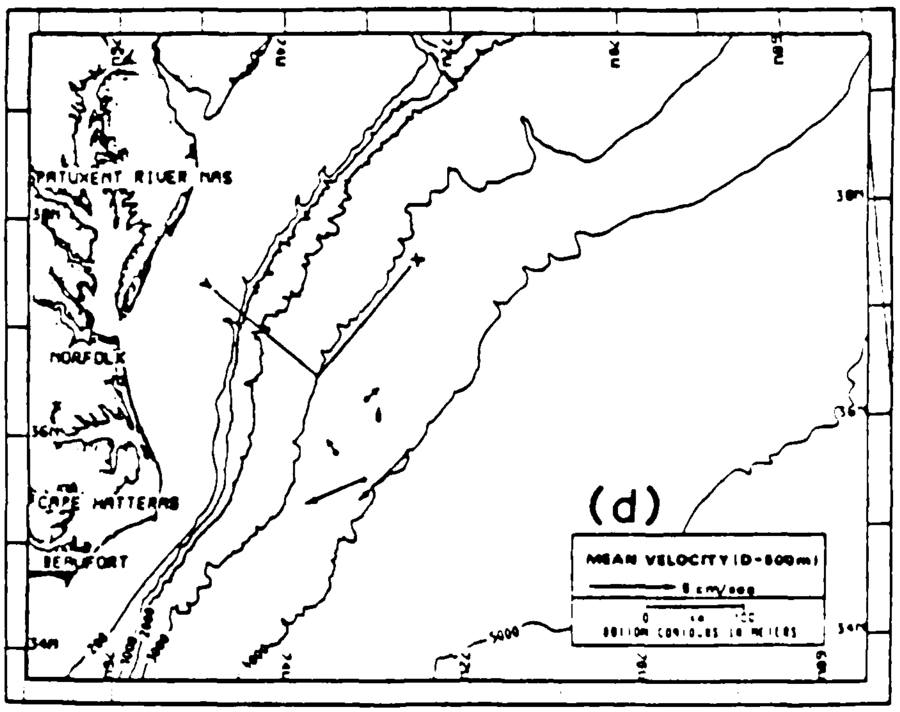


Figure 8. (continued)

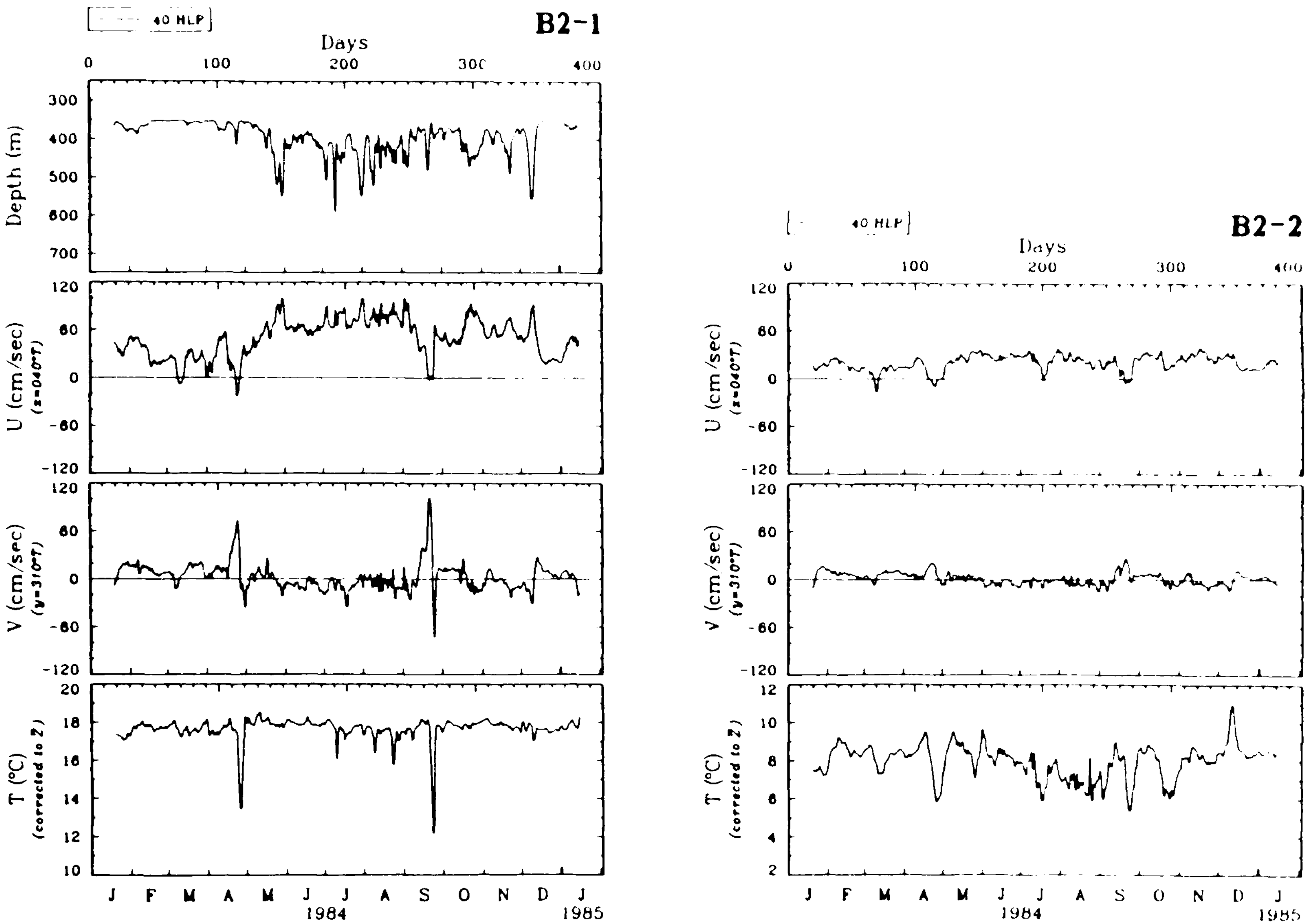
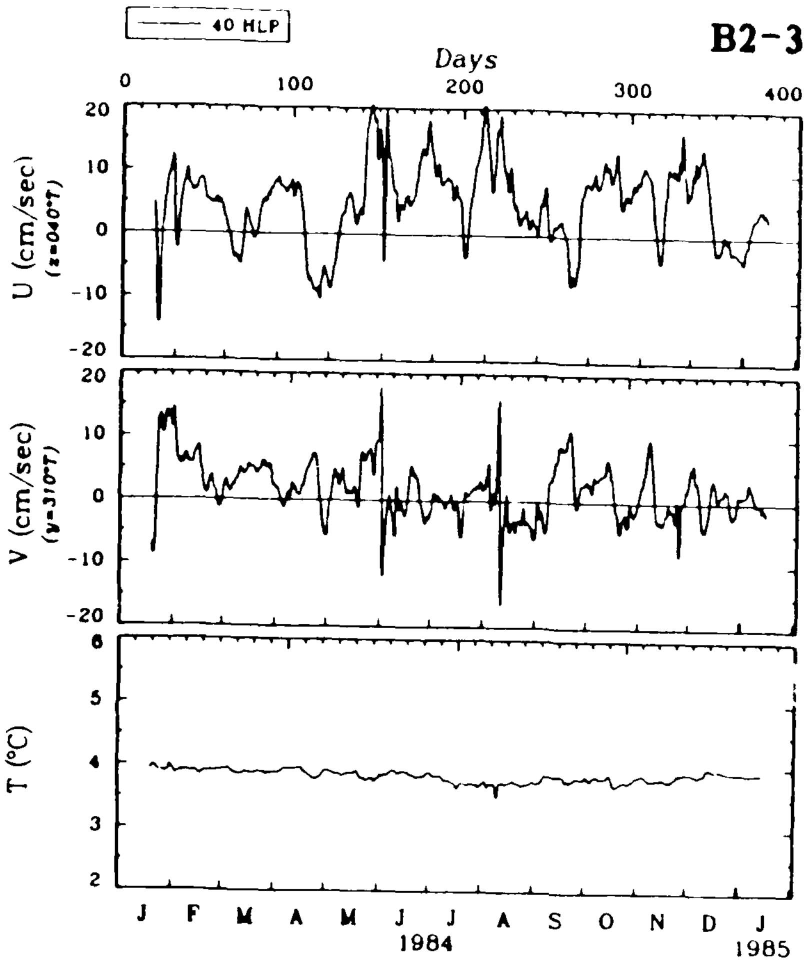


Figure 9. Forty-hour low-passed time series of downstream (u) and cross-stream (v) velocity components, temperature (T) and instrument depth (top meter only) for the B2 mooring. Nominal instrument depths are 500 m (B2-1), 1000 m (B2-2), 2000 m (B2-3), and 500 m above the bottom (B2-4).



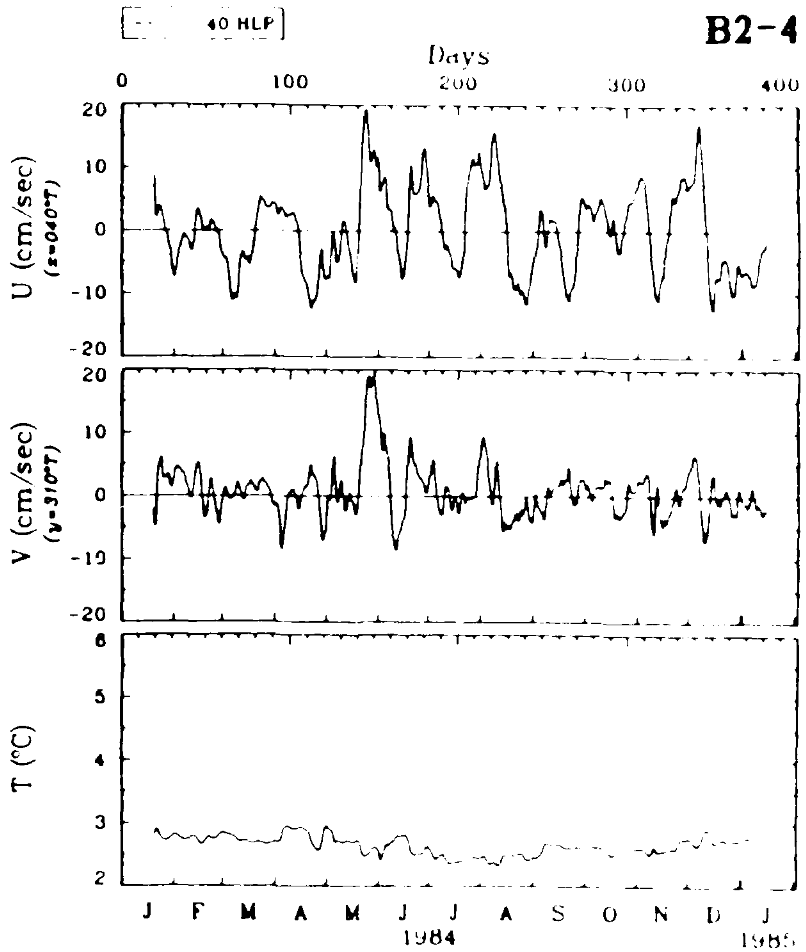


Figure 9. (continued)

[illegible] Stream

[illegible] mid-depth velocity fluctuations may be seen at the 2000 m level (Instrument B2-[illegible]) near days [illegible] and 220. These are caused by cyclonically swirling, submesoscale coherent vortices (SCVs) transiting through the array. Each of these eddies was about [illegible] km in diameter, and had swirl velocities exceeding 15 cm/sec. At least eleven other SCVs were observed by this array.

With the exception of the cold-core rings, the largest and most energetic isolated eddy to be observed was an anticyclonically rotating mid-depth warm eddy which progressed northeastward through the array, just on the Sargasso Sea side of the Gulf Stream. The eddy extended from at least the 500 m level to the near-bottom instrument levels, and was about 120 km in diameter. It left its signature in the B2, B3, C2, and C3 mooring instruments near year day 345. Temperature and velocity fluctuations due to this eddy may be seen in the time series in Figure 9 for several levels of the B2 mooring. These fluctuations occurred as the northern side of the eddy, which was closest to the Gulf Stream, passed over this mooring. There were no observed sea surface temperature characteristics discernible by satellite, further indicating that this energetic eddy was concentrated below the surface. Remarkably, about two weeks after this eddy had exited the array, the C3 mooring data show that it reversed its course and was travelling southwestward back through the array at the end of the experiment period. Phase speed was estimated to be about 15 km/day during each of the eddy's transits through the array area. Due to its position on the seaward side of the Stream, this eddy was definitely not a warm core Gulf Stream ring. Its origin remains unknown at this point in time.

The clear signature of topographic Rossby wave motions may be seen in the B2-4 time series. These waves had dominant periods near thirty days and usually had the strongest flow along rather than across isobaths. They were most energetic following the cold-core ring passage of day 115 when the Gulf Stream was centered near mooring B2. The excellent spatial coverage of this array has provided for very nice length scale and propagation determinations for these topographic Rossby waves. Figure 10 shows the variance ellipses for the lower frequency (periods longer than 10 days) and higher frequency (4 to 10 day periods) waves. Also shown for each frequency band is a phase propagation vector computed from one triplet of current meters within the array. Phase speeds were found to range from about 2 km/day for

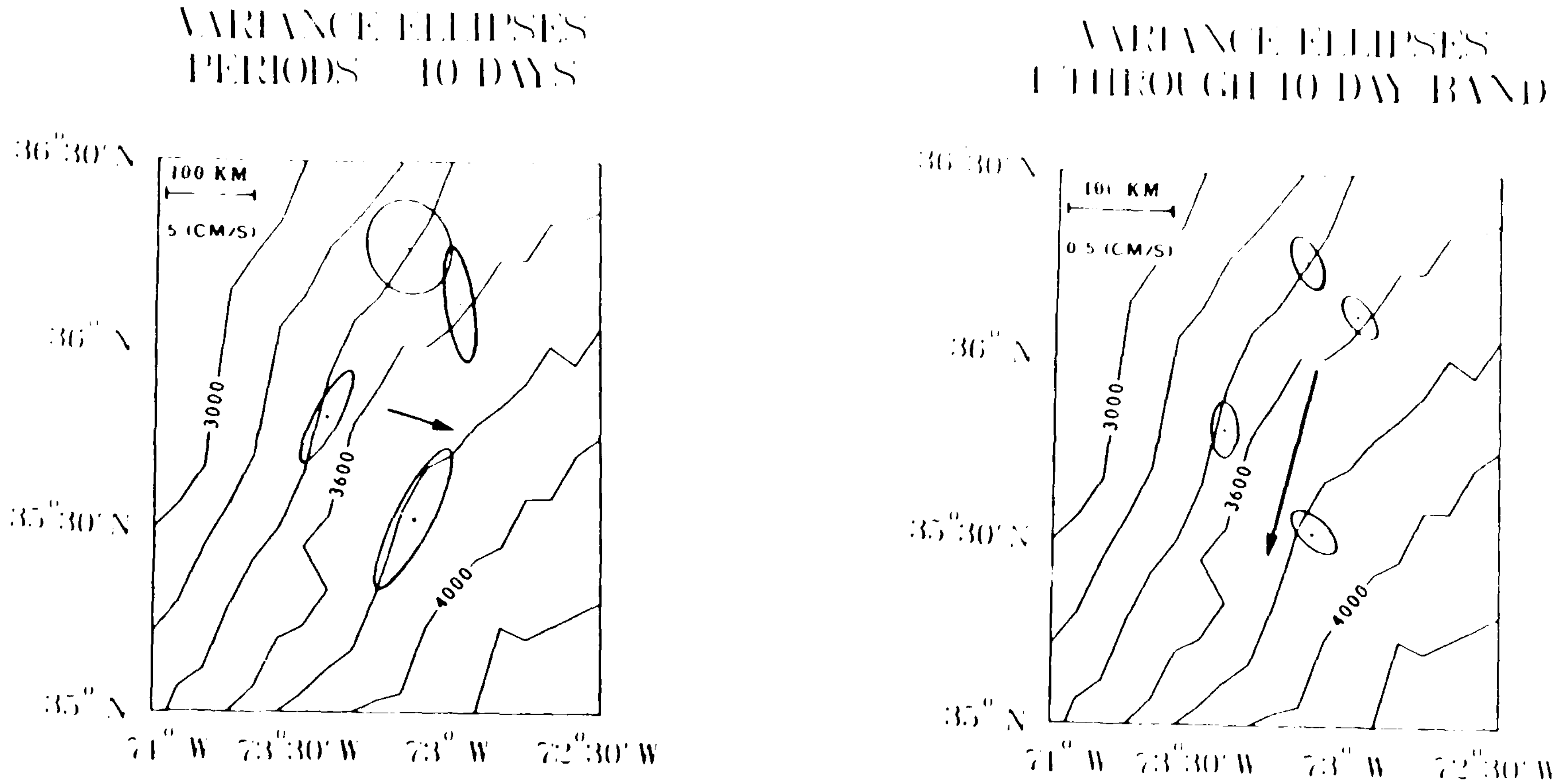


Figure 10. Variance ellipses computed for the deepest meter on 4 of the moorings (C3-4 excluded). The ellipses, given in standard deviation units, show the orientations of the fluctuation velocities for lower frequencies (10-64 day period band, left panel) and higher frequencies (4-10 day band, right panel). The arrows show phase propagation directions determined from the B2-B3-C2 triple of current meters. The length of each arrow is proportional to the wavelength of the dominant wave. These variance and propagational properties are consistent with topographic Rossby wave motions in this area.

the 64-day period waves to near 15 km/day for the 13-day period waves, values that are consistent with those found farther to the east during earlier studies.

A "cartoon" summarizing these results and showing the variety and complexity of the motions observed with this array is given in Figure 11. This level of variability and large number of different phenomena were not previously expected in this region. The results also strongly suggest that energetic eddy/Stream interactions, such as the two cold-core ring/Gulf Stream interactions that we observed in 1984, may play a fundamental role in inducing rapid changes in the Stream's path and variability, and that the effects of such changes may last for a time period much longer than that required for the change itself. These properties of the Gulf Stream environment point to the necessity of observing the Gulf Stream and surrounding waters with sufficient spatial and temporal coverage if one wishes to gain a complete understanding of the system.

(2) *Energetics of the Gulf Stream from this Current Meter Array.* We have performed an analysis of the Gulf Stream's energetics using data from the current meter array. The essential result for the mid-level portion of the anti-cyclonic flank of the Gulf Stream jet (about 400 m depth) is that both barotropic and baroclinic energy transfers occur from the mean flow to the fluctuations. The barotropic mechanism is found to be the dominant one, consistent with earlier finding for 68W, but in contrast to earlier results for 73W. The low amount of barocline energy transfer in our array of limited cross-stream extent reflects the low density fluctuations and mean density gradients within the mid-level anti-cyclonic shear zone due to the presence of 18-degree water there (see Figure 8a). Another way to view this is that the more strongly sloping isopycnals on the cyclonic side of the Stream will support greater baroclinic energy conversions than the weak baroclinity within the 18-degree water on the anticyclonic side. Thus, our array measurements favor the barotropic conversions.

One important aspect in the assessment of the Gulf Stream's energetics and dynamics from current meter data in this fashion is the error in estimating each of the terms in the pertinent balances. The three sources of error are (i) measurement error due to the accuracy and positioning of the instruments, (ii) finite differencing error that arises when estimating gradients from Eulerian time series, and (iii) the statistical error of estimate of any quantity. The energetics analysis from this array has pointed

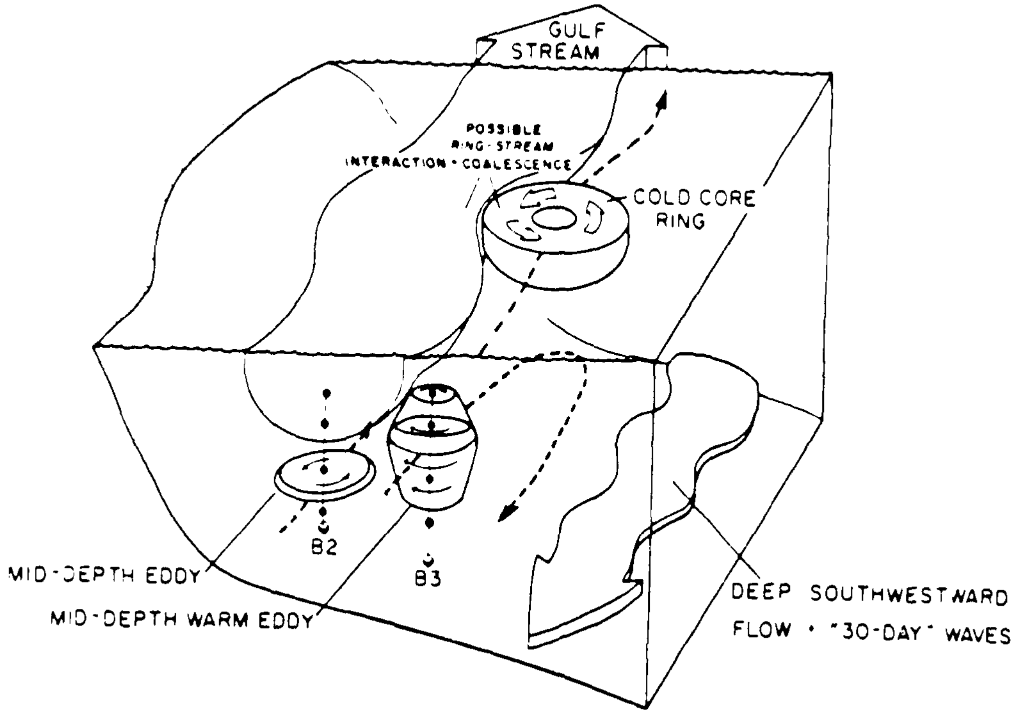


Figure 11. A cartoon summarizing the variety of motions observed by the 1984 Gulf Stream array. The Gulf Stream jet occupied the upper 1000 m, and a deep western boundary undercurrent flow was seen over the 4000 m isobath. The dominant mesoscale eddy types were cold-core Gulf Stream rings, two of which coalesced with the Stream in the array area, and one anticyclonically rotating mid-depth warm eddy which moved through the array twice. Numerous submesoscale coherent vortices (mid-depth eddy near B2 in this cartoon) passed through the array. Both cyclonically and anticyclonically swirling submesoscale vortices were seen. Deep topographic Rossby wave motions occupied the lower waters, from about the base of the permanent thermocline to the bottom. Waves with periods ranging from 4-days to at least 60-days were detected, with the 30-day waves having generally the greatest energy density. This summary illustrates the complexity and diversity of the motions in the region of this array.

once again to the fact that the largest contributor to the total error is the statistical error of estimate. With one year of data, we have been able to compute energy flux terms that are usually significantly different from zero, although this is not true for all the largest terms. Even the ones that are significant sometimes barely exceed the statistical error level. This is due entirely to the length of the data sets. We know from our spectral calculations (and simple visual inspection of the time series) that there are long period motions occurring in the Gulf Stream system. We must collect data sets of sufficient duration to observe a representative sample of these motions if their energetics and dynamics are to be understood.

Results from this project are still under analysis at the writing of this report. Preliminary results have been published as follows:

Journal Articles

Bane, J.M., and D.R. Watts: Recent Current Measurements in the Gulf Stream Downstream from Cape Hatteras. *Gulf Stream Workshop Proc.*, Univ. Rhode Island, pp. II.127-II. 134.

Pickart, R.S., D.R. Watts, and J.M. Bane: Labrador Sea Water and the Gulf Stream at Cape Hatteras: Results from a Moored Experiment. *J. Geophys. Res.* (submitted).

Technical and Data Reports

Bane, J.M., D.R. Watts, L.M. O'Keefe and R.S. Ault: The Gulf Stream Dynamics Experiment - Current Meter Data Report for the January 1984 to January 1985 Mooring Period. *Univ. North Carolina Report No. CMS-87-3*, 1987 (in preparation).

Notes and Published Abstracts

Bane, J.M. and D.R. Watts: The Gulf Stream Downstream from Cape Hatteras: The Current and Its Events During 1984. *Trans. Amer. Geophys. Un.*, *66*, p. 1276 (abstract). Paper presented at the AGU Ocean Sciences meeting, New Orleans, Jan. 14, 1986.

Watts, D.R. and J.M. Bane: Mapping Gulf Stream Meanders: Objective Analyses from an IES Array Compared with AXBT and XBT Surveys. *Trans. Amer. Geophys. Un.*, *66*, p. 1277 (abstract). Paper presented at the AGU Ocean Sciences meeting, New Orleans, Jan. 14, 1986.

Theses

Blanton, Sankey L.: Vertical Velocities in the Deep Gulf Stream (in progress).

O'Keefe, Lucy M.: An Energetic, Anticyclonic Mesoscale Eddy near the Deep Gulf Stream (in progress).

Schultz, John R.: Topographic Rossby Waves Beneath the Deep Gulf Stream (in progress).

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