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Julie McClean-Padman
Old Dominion University

Larry P. Atkinson
Old Dominion University, latkinso@odu.edu

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Observations of a Cyclonic Ring–Gulf Stream Coalescence Event Over the Blake Plateau

JULIE MCCLEAN-PADMAN AND LARRY P. ATKINSON

Department of Oceanography, Old Dominion University, Norfolk, Virginia

Hydrographic data collected in September 1980 over the Blake Plateau were analyzed using a combination of empirical search and inverse techniques. Five sections, extending from the continental shelf break eastward across the Blake Plateau, were positioned at approximately 1° intervals between 28° and 32°N. The empirical search procedure was applied to four closed regions (boxes), constructed from adjacent sections, where each region was assumed to consist of two conservative layers. Five geostrophic velocity sections were obtained using the average optimum reference level for the four boxes. The inverse technique provided barotropic correction velocities that caused all layers to conserve mass. The sections and the resulting transport streamline fields revealed the presence of a cyclonic feature whose meridional and zonal extent was about 200 km in both directions. This feature was shown to be a coalescing Gulf Stream ring in a late stage of decay. Water mass analyses, current meter data, and earlier studies were used to support this hypothesis. The cyclonic advection of Gulf Stream water around the ring formed a meander in the eastern Gulf Stream wall. Topography appeared to be affecting this flow, suggesting that other rings entering the region would be similarly influenced. Evidence of recurring rings at or near this location and hence, meanders of the eastern Gulf Stream wall, was found in hydrographic data collected by NOAA over a 12-month period from 1965 to 1966. These data suggested that two such events, lasting about 4 weeks each, occurred during this period. The frequency of these events was in agreement with earlier findings, while the duration of these events was supported by current meter observations.

1. INTRODUCTION

The Blake Plateau, a terrace lying adjacent to the southeastern U.S. continental shelf, extends northward from the Bahamas to Cape Hatteras (Figure 1). The circulation over the plateau is dominated by the Gulf Stream, which flows north through the Straits of Florida and along the outer edge of the continental shelf. Past studies in the area concentrated on the flow near the Gulf Stream [*Atkinson et al.*, 1985]. Less attention, however, has been paid to the circulation east of the Gulf Stream over the central and outer plateau. Cold-core, cyclonic rings formed from large 200- to 300-km diameter meanders of the Gulf Steam north of Cape Hatteras have been observed, on occasion, to encroach the Blake Plateau and coalesce with the Gulf Stream [*Cheney and Richardson*, 1976; *Richardson et al.*, 1978]. *Lee and Waddell* [1983] reported prolonged southward currents lasting up to 40 days with speeds in excess of 0.3 m s^{-1} over the bottom of the mid-plateau to the east of the Gulf Stream. They suggest that the flow may be associated with coalescing eddies, or with the southward undercurrent that has been observed beneath the Gulf Stream off Cape Hatteras [*Richardson*, 1977].

In this paper we present the results of a study where empirical search and inverse techniques were used to derive the circulation over the Blake Plateau from a series of conductivity-temperature-depth (CTD) sections. *Wunsch* [1978] determined the general circulation of the western North Atlantic by applying inverse techniques to deep hydrographic data. *Fiadeiro and Veronis* [1983] used a combination of empirical search and inverse techniques to obtain the circulation and heat flux in the same region. These methods have also been used to obtain the circulation in the Caribbean Sea [*Roemmich*, 1981], the South Atlantic Ocean [*Fu*, 1981] and the Gulf of Mexico [*Hofmann and Worley*, 1986]. The empirical search procedure, based on hydrographic data and the dynamic method, provides a good estimate of the level of no motion and thereby avoids the use of an assumed reference level. The minimum energy solution of the inverse method is used to improve this estimate.

The goal of this study was to determine the circulation over the Blake Plateau from a hydrographic data set collected in September 1980 (Figure 2). Water mass analyses, current meter data, and earlier studies [*Cheney and Richardson*, 1976; *Richardson et al.*, 1978] suggested that the cyclonic feature observed over the plateau in the September 1980 data was a coalescing Gulf Stream ring in a late stage of decay. This study represents the first detailed CTD survey of a coalescence event in this region. A correlation was noted between the plateau topography and the trajectory of the meander of the eastern wall of the Gulf Stream arising from the cyclonic advection of Gulf Stream water around the cold-core ring. This suggests that other rings in the region will be similarly affected, resulting in a recurring meander of the eastern Gulf Stream wall. Current meter and ancillary hydrographic data were used to provide evidence that rings occur in this region about twice per year, with a typical duration of 4 weeks.

The data used in this paper are presented in section 2. The empirical search, error analysis, and inverse techniques are discussed in section 3, while the application of these methods to the Blake Plateau data set are found in section 4. Velocity sections and transport streamline fields obtained from the empirical search and inverse techniques are presented in section 5. Causes for the observed circulation features are discussed in section 6, while section 7 contains a summary and conclusion.

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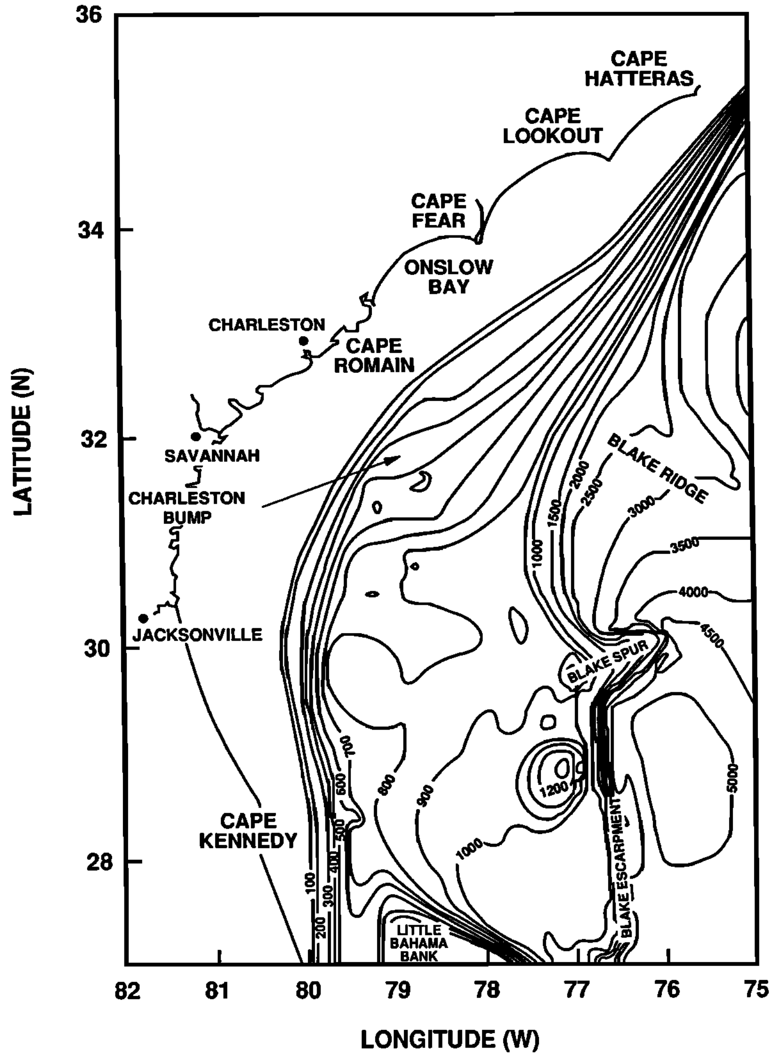

Fig. 1. Bathymetry and topographic features of the Blake Plateau.

2. Data

Hydrographic and nutrient observations were collected between September 3 and 14, 1980, along seven sections extending from the southeastern U.S. continental shelf break eastward across the Blake Plateau (Figure 2). The sections were positioned at approximately 1° intervals between 27° and 33°N. Along-section spacing was approximately 19 km for depths less than 200 m, and 37 km in the deeper waters over the plateau. The sections were collected from north to south, and each section took about 1.5 days to complete. Only stations with bottom depths greater than 100 m were used in the following analyses, thus eliminating stations in the vicinity of stress boundaries where geostrophy fails. Measurements were made to within a few meters of the bottom in water depths of less than 1200 m. Several stations were located in depths of about 2000 m, in which case measurements were made to within 200 m of the bottom.

Temperature and salinity observations were made with a Plessey 9400 CTD system. Water samples were collected for nitrate, phosphate, silicate, and dissolved oxygen. The sampling depths were at 100-m intervals from the surface to the bottom of the profile, with an additional sample at 50 m. Further descriptions of data calibration and reduction are given by *Atkinson* [1983].

3. Methodology

3.1. *Empirical Search Techniques*

The aim of the analysis techniques used in this paper was to estimate the depth-dependent velocity field throughout the array of hydrographic stations over the Blake Plateau. Hydrographic data have been routinely used to estimate the current component normal to the line between two stations by assuming geostrophy and a level of no motion in the dynamic calculation. More recently, acoustic doppler current meter profilers (ADCPs) have been used to provide upper layer velocities during hydrographic cruises. Since this technology was not developed at the time of the hydrography cruise discussed here, we chose to use the empirical search technique developed by *Fiadeiro and Veronis* [1982, 1983] to obtain a reference surface for the geostrophic calculation. The technique, which is discussed in detail in these papers, is designed to avoid the ad hoc assumption of a level of no motion by providing an empirical estimate that is consistent with mass conservation and geostrophy.

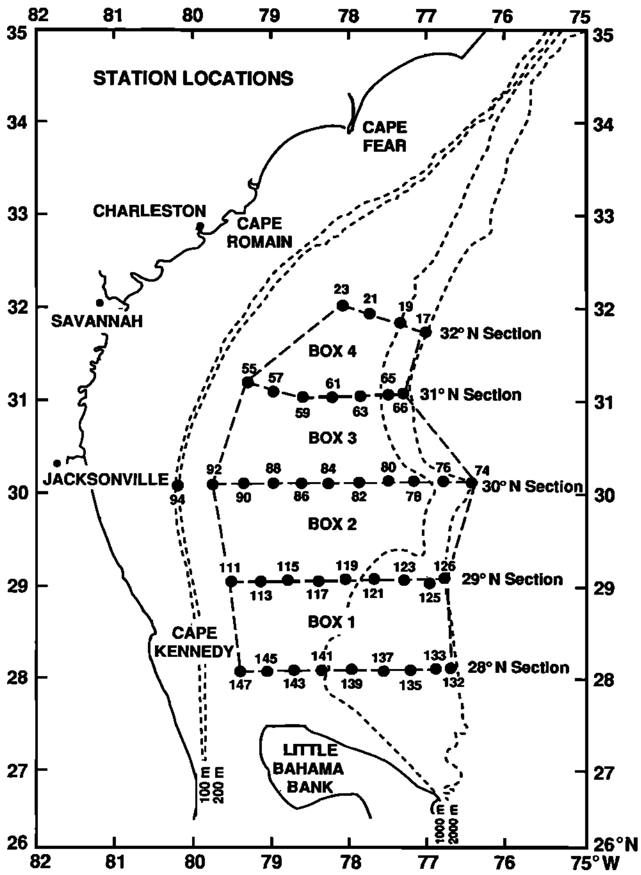

Fig. 2. The Blake Plateau hydrographic stations. Dashed lines encompassing closed regions define "boxes" for empirical search and inverse techniques.

The empirical search methodology requires several assumptions to be valid in the particular case being studied. It is assumed that an array of hydrographic stations can be constructed such that the net flow out of the enclosed "box" is zero, satisfying the continuity equation. It is also assumed that the hydrographic stations constitute a synoptic set and that geostrophy is valid. Finally, a reference level of no motion, which may be either a depth or a particular isopycnal surface [*Fiadeiro and Veronis*, 1982] is assumed to exist within the "box." An enclosed box may be formed entirely from hydrographic stations [*Fiadeiro and Veronis*, 1983], or coastal boundaries may be used to provide partial closure of the box [*Fiadeiro and Veronis*, 1982]. The technique finds the reference level by evaluating the net volume transport into the closed box for a range of plausible reference levels. The optimum reference level is considered to be that which produces the minimum mean square transport residual.

To apply this technique to hydrographic data, conservative layers are identified using water mass analysis. Conservative layers are layers whose volume-integrated properties such as density, temperature, and salinity are assumed to be invariant with time, implying that there are no fluxes of these properties between layers. The data are interpolated onto an evenly spaced vertical grid and extrapolated to the ocean bottom. Boxes are formed from the stations, and geostrophic velocities and volume fluxes relative to the surface are calculated in the layers between station pairs. This total volume flux, relative to the surface is

$$T_{rj} = \sum_{i=1}^{n} \int_{z_{j+1}}^{z_j} v_{ri}\, dz\, \Delta x_i \qquad j = 1, 2, 3, \cdots, m \qquad (1)$$

where n and m are the number of station pairs around the box and the number of layers, respectively; v_{ri} is the relative geostrophic velocity; z_j is the top of the jth layer; and Δx_i is the station separation.

The empirical search for the optimum reference level is then performed by treating successively deeper density or depth levels as the reference level. The relative net transport is calculated at each level, from which we obtain the mean square transport

$$T_r^2 = \sum_{j=1}^{m} T_{rj}^2 \qquad (2)$$

which is a measure of the extent to which the volume flux divergence through the box boundaries vanishes. The depth or density level at which T_r^2 is a minimum is considered to be the reference level and is as close to the level of no motion as can be obtained by this method.

The best empirical estimate will not satisfy mass constraints perfectly [*Fiadeiro and Veronis*, 1982]. Errors are introduced by the measurement errors in the hydrographic data and station positions, the extrapolation techniques used to synthesize hydrographic data to the full depth of the water column, the lack of synopticity of the data set, and the assumption of geostrophy. The latter two sources cannot be evaluated in the present study; however, the noise level on estimates of T_r^2 resulting from the first two error sources will be discussed in the following section. If the minimum T_r^2 is greater than this noise level, the mass flux divergence can be minimized by the addition of a spatially dependent barotropic flow. This barotropic correction can be estimated by the inverse method to bring the transport imbalance within the limits set by the sampling errors.

3.2. *Error Analysis*

As was discussed above, the empirical search technique finds the optimum level, either in depth or density, at which T_r^2 is a minimum for a particular data set. To determine a criterion for acceptable T_r^2 values (data that require no barotropic correction), the effect of measurement noise needs to be assessed. This was evaluated by rerunning the empirical search on data simulated from the addition of random noise to the original hydrographic data set.

Measurement errors in the hydrographic surveys occurred in station position, sensor depth, temperature T, and salinity S. Depth errors were incorporated into errors in T and S, based on the local mean vertical gradients of these properties. With the depth error incorporated, rms errors in T and S for the present data set were 0.1°C and 0.02 psu, respectively. A position error of 1 km in both latitude and longitude for each station was based on a ship drift of up to 0.5 m s^{-1} for the 30 min taken to complete a single hydrographic station. Both CTD and position errors were assumed to be normally distributed with the above standard deviations. Simulations were run on 100 "noisy" data sets for box 1 (Figure 2), and the reference level at which the mean T_r^2 for the 100 runs was a minimum was chosen as the best estimate

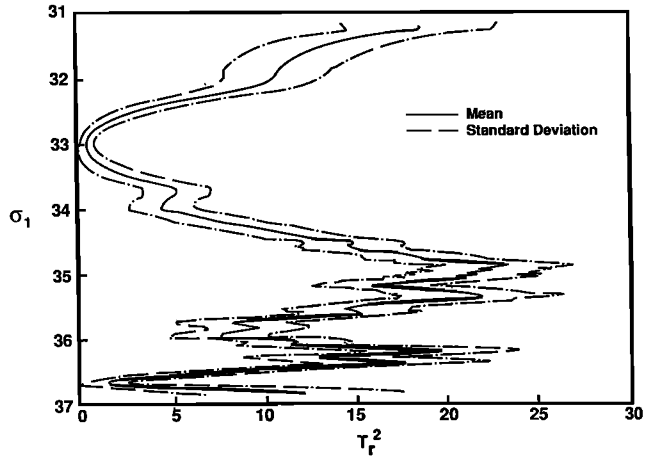

Fig. 3. Mean (solid line) ± 1 standard deviation (dash-dot lines) of the mean square transport, T_r^2, for 100 runs.

for the surface of no motion (Figure 3). Potential density referenced to 1000 m, σ_1, was used as the vertical coordinate because the layers were not distributed uniformly in depth. We chose twice the standard deviation of T_r^2 at the optimum reference level as the noise attributable to measurement error. In the present study, this value was 2.5 Sv^2 (1 Sv = 10^6 m^3 s^{-1}). That is, a mean square transport imbalance of less than 2.5 Sv^2 at the optimum reference level was consistent with measurement noise, and no further correction was required.

If the minimized T_r^2 exceeds 2.5 Sv^2, however, the imbalance was assumed to be the result of an unsatisfactory estimate of the reference level. In this case, the true reference level was estimated by adding a spatially dependent barotropic correction velocity to the geostrophic velocity field.

3.3. *Inverse Analysis*

In the inverse method, mass conservation is satisfied by adding a spatially dependent barotropic correction velocity, b_i, to the geostrophic velocities, v_{ri}, calculated relative to the empirical search reference level, i.e.,

$$\sum_{i=1}^{n} \int_{z_{j+1}}^{z_j} (v_{ri} + b_i)\, dz\, \Delta x_i = 0 \tag{3}$$

Using (1), this expression becomes

$$\sum_{i=1}^{n} b_i \Delta z_j \Delta x_i = -T_{rj} \tag{4}$$

where Δz_j is the thickness of the jth layer and $\Delta z_j \Delta x_i$ is the area of the jth layer between station pairs. Substituting A_{ij} for $\Delta z_j \Delta x_i$, equation (4) becomes

$$\sum_{i=1}^{n} A_{ij} b_i = c_j \tag{5}$$

where $c_j = -T_{rj}$ (the transport imbalance in each layer). In matrix notation (5) is

$$\mathbf{A} \cdot \mathbf{b} = \mathbf{c} \tag{6}$$

The solution to (6) can be found using singular value decomposition. The details of this solution method are discussed by *Wunsch* [1978] and *Fiadeiro and Veronis* [1982]. The solution yields the barotropic correction vector **b**, which has a separate value for each station pair. This solution represents the minimum correction and is intended primarily to account for the transport errors resulting from deviations of the reference surface from an isopycnal surface (or a particular depth). This correction is assumed to be the most physically realistic.

Large, coherent barotropic flows through the system may not be accounted for by this method. *Roemmich* [1981] discusses this situation using a model where two hydrographic sections run from a coastline to a common point in the mid-ocean. Many station pairs are assumed to exist but two have identical depth and layer thickness. He states that the solution elements will, by symmetry, be equal in terms of the mass flux constraints. If the station pairs are located on different sections and an arbitrary, large mass flux passes through them, the flux will not be determined by this method if it is the same at the two station pairs. This flow can be accounted for by further constraining the model with measured data anywhere on the perimeter of the box.

4. APPLICATION TO THE BLAKE PLATEAU

To apply these methods to the Blake Plateau, conservative layers were identified and closed regions formed from the hydrographic data. Details of these procedures, the extrapolation of data from the maximum common sample depth to the average bottom depth between stations, and the application of the empirical search and inverse techniques to the Blake Plateau data set are discussed below.

4.1. *Conservative Layers*

To locate potentially conservative layers, water masses over the Blake Plateau were identified in vertical salinity sections (Figure 4) using *Atkinson*'s [1983] potential temperature–salinity (θ-S) relationship for this data set. The salinity S of Subtropical Underwater is between 36.6 and 36.8 psu: this signature was found over the entire plateau seaward of the Gulf Stream in the top 200 m of the water column. Western North Atlantic Water [*Armi and Bray*, 1982] is found below the Subtropical Underwater. We regarded this water mass as ambient Blake Plateau water. Antarctic Intermediate Water (S between 34.84 and 34.88 psu) was found by *Atkinson* [1983] at several stations in water depths greater than 700 m.

The first layer was chosen to incorporate Subtropical Underwater and the surface water above it. A sufficiently thick upper layer was chosen to reduce the effect of nonconservative transport processes at the air-sea interface [*Fiadeiro and Veronis*, 1982]. The second layer extended from the bottom of the Subtropical Underwater to the seafloor and consists of Western North Atlantic Water. A third layer was not constructed from the Antarctic Intermediate water, as it did not completely cover the region. The surface σ_1 = 34.4 separated the two layers.

4.2. *Extrapolation Scheme and Closed Regions*

One of the major assumptions of the methods used in this analysis was that the hydrographic survey adequately re-

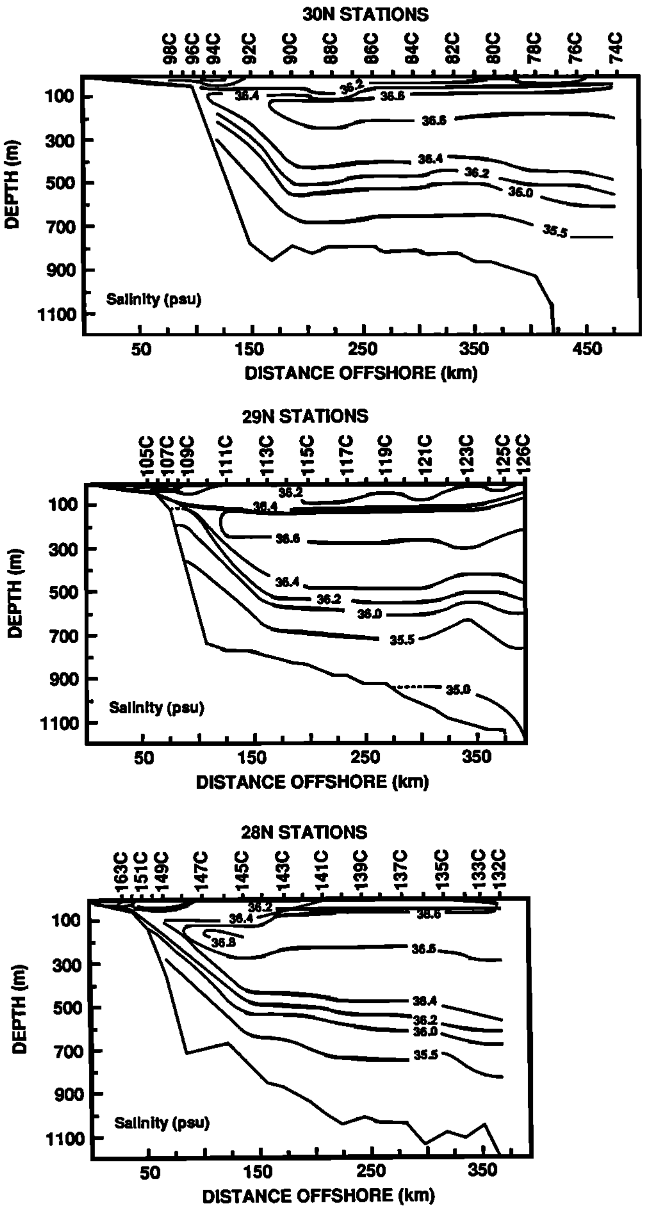

Fig. 4. Salinity sections over the southern and central Blake Plateau at 28°N, 29°N, and 30°N. Contour interval is 0.2 psu above 36.0 psu and 0.5 below it.

TABLE 1. Transport Imbalances, Residual Transports and Optimum Sigma Surfaces for Boxes 1 to 4

Box	Transport Imbalance, Sv	Residual Transport ΣT_{rj}^2, Sv^2	Optimum Sigma Surface σ_1
1	−1.12	2.85	36.63
2	1.20	0.77	35.64
3	−0.13	0.04	35.97
4	−0.08	0.01	35.51

solved all the volume flux into a closed region; that is, no significant flux into the sample box took place above or below the box. As a result, if the hydrographic profiles did not reach the bottom, it was necessary to extrapolate the data so that this constraint was satisfied. Over the plateau, hydrographic data were collected to within a few meters of the bottom except at the most seaward stations, where the flow beneath the lower sampling limit of the CTD was assumed to be negligible. Hence it was only necessary to extrapolate the maximum common sample depth to the average common bottom depth between station pairs for the calculation of relative geostrophic velocities. The extrapolation scheme, used by *Hofmann and Worley* [1986], locates the density value at the maximum sample depth of the shallower station in the density profile of a deeper station along the hydrographic section. The deeper portion of the density profile is then added to the profile at the shallower station. *Hofmann and Worley* [1986] state that the scheme preserves the continuity and slope of the existing density field without requiring that the nature of the velocity field or the shear be specified, as is required by the schemes discussed by *Fiadeiro and Veronis* [1983].

Regardless of the scheme chosen, these methods do not work well in regions of sharply sloping topography and strong currents [*Fiadeiro and Veronis*, 1983]. Hence the extrapolation of data at stations located over the continental slope is likely to produce questionable results. In this data set the scheme was forced to extrapolate over at least half the depth of the water column between station pairs over the strongly sloping bathymetry on the inshore side of the plateau (for example, stations 92 and 94 in Figure 2). Since the currents and anomalous hydrographic properties associated with the Gulf Stream extend to the seabed in this region (station 92), there is potential for considerable error arising from this extrapolation technique. We have therefore excluded these stations from the closed regions (boxes) that were formed for the empirical search procedure (see Figure 2). Consequently, the Gulf Stream was only partially resolved in the following analyses.

Four closed regions were constructed from the hydrographic station configuration in Figure 2. Each box was formed by connecting the most landward and seaward stations in adjacent sections. Box 1, for example, was constructed by joining stations 147 and 111 and stations 132 and 126 in the 28° and 29°N sections. A box was not formed from the 27°N section (across the Straits of Florida) and the 28°N section, as the ship did not traverse the region between station 132 and Little Bahama Bank. A box was not constructed from the 32° and 33°N sections, since all the stations in the latter section lie over sharply sloping topography.

The configuration of the closed regions discussed above resulted in the inverse method's being unable to find any coherent barotropic flow in the closed regions. Station pairs occurring at the same offshore distance in parallel sections had roughly the same area in water depths less than 1200 m. Any barotropic flow passing through similar pairs on parallel sections would therefore not affect the mass flux constraints and hence would not be included in the inverse solution.

4.3. *Empirical Search and Inverse Techniques*

The empirical search was applied to all of the boxes in Figure 2. To account for the varying vertical density gradient, the step size of the vertical coordinate (σ_1) was varied, resulting in a vertical resolution of approximately 20 m. The minimum mean square transports (Table 1) arising from the empirical search in boxes 2, 3, and 4 were well within the

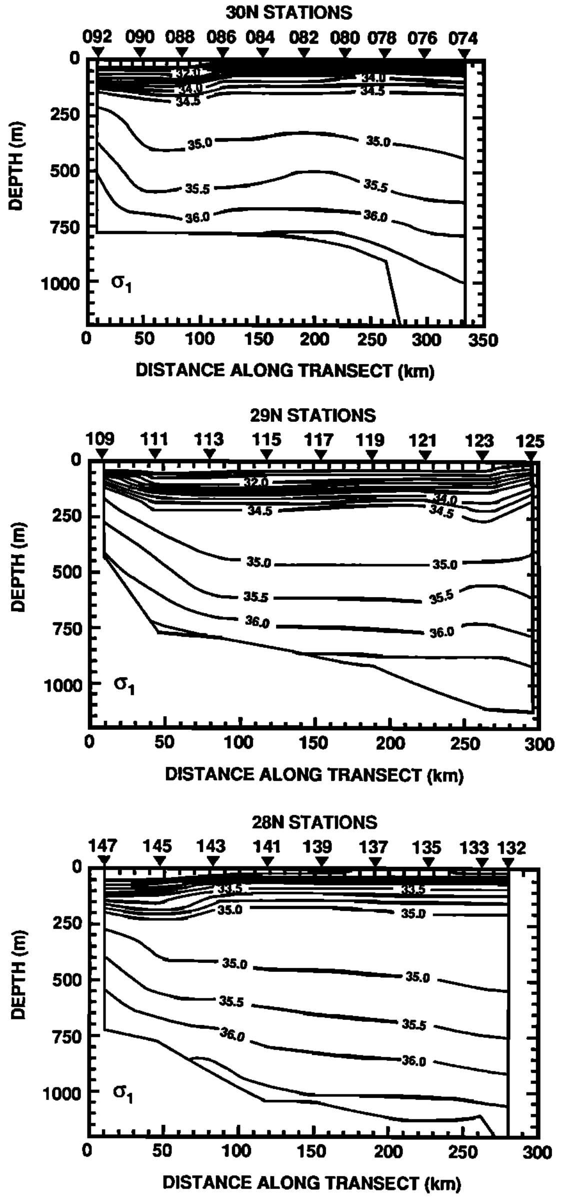

Fig. 5. Sections of σ_1 over the southern and central Blake Plateau at 28°N, 29°N, and 30°N. Contour interval is 0.5.

maximum allowable error of 2.5 Sv^2, while that in box 1 exceeded the noise level.

The optimum reference levels for the four boxes corresponded to σ_1 surfaces with values between 35.51 and 36.63. All these isopycnal surfaces were close to the bottom or intersected it (Figure 5). The empirical search therefore was finding either the plateau floor or a nearby isopycnal surface as the reference surface across the entire plateau. As a result, the four reference levels were averaged to give a mean reference surface of $\sigma_1 = 35.95$ for the plateau region. The validity of this reference surface for the entire plateau was checked by performing an empirical search on a single box encompassing boxes 1 to 4. The reference surface obtained for this large box was $\sigma_1 = 35.73$, which was comparable to the σ_1 value for the mean reference surface. The mean square transport for the large box at the optimum reference surface was 0.47 Sv^2. The mean square transports associated with the mean reference surface for the individual boxes are listed in Table 2: in boxes 1 and 2 they are greater than the maximum allowable error; hence the inverse correction was applied to these boxes. For analytical consistency, the correction was also applied to boxes 3 and 4.

5. Results

Vertical sections of cross-transect velocity obtained from the empirical search and inverse techniques were used to identify circulation features over the Blake Plateau. Transport streamlines, constructed from the depth-integrated velocity fields provided an additional view of this circulation.

5.1. *Velocity Sections*

Velocity sections from box 1, over the southern plateau, are shown in Figures 6*a* and 6*b*. The Gulf Stream was identified at stations 147 and 145 in the 28°N section (Figure 6*a*) and at stations 111 and 113 in the 29°N section (Figure 6*b*). Only part of the Gulf Stream flow was captured in these sections owing to the limitations of the extrapolation scheme discussed above. East of the Gulf Stream in the 28°N section a band of southward flow extended to depths of 200 m. At the surface, this southward flow covered a distance of up to 2 station spacings (about 40 km) with a maximum surface speed of 0.45 m s^{-1}. Farther eastward, the flow was northward throughout the water column with speeds no greater than 0.15 m s^{-1}. In the 29°N section a weak southward flow (<0.1 m s^{-1}) in the top 150 m of the water column was located just east of the Gulf Stream. Farther seaward a northward flow of similar magnitude was seen. Over the outer plateau (station 121 to 126), a cyclonic feature extending from 250 to 800 m depth was observed. The maximum southward flow at these depths was 0.1 m s^{-1}, while the strength of the adjacent northward flow was 0.25 m s^{-1}. The 29°N σ_1 section (Figure 5) showed a convergence of the isopycnals between stations 123 and 125 at middepths.

In the 30°N section (midplateau), part of the Gulf Stream was resolved in the vicinity of stations 88, 90, and 92 (Figure 6*c*). Adjacent to it, a cyclonic feature occupying the entire plateau was seen. This feature consisted of a southward flow with a maximum surface velocity of about 0.55 m s^{-1} and a weaker (0.20 m s^{-1} at the surface) but more vertically extensive, northward return flow over the outer plateau. The vertical extent of this feature was about 800 m and it extended over 7 station spacings (about 250 km). The 38°N σ_1 section (Figure 5) showed a doming of the isopycnals in the lower half of the water column at the center of this feature.

Over the northern plateau (31°N section, Figure 6*d*), the Gulf Stream was again partially resolved between stations 55 and 59. Lying adjacent to it was a shallow (<200 m), southward flow (<0.25 m s^{-1}) whose surface extent covered 2 station spacings (70 km). Seaward of this southward flow, there was a northward flow with velocities less than 0.20 m s^{-1} and horizontal and vertical extents of 50 km and 200 m, respectively. Over the edge of the plateau there was a partially resolved southward flow. In the 32°N section (Figure 6*e*), part of the Gulf Stream was seen together with a weak (no greater than 0.10 m s^{-1}), southward flow extending to 100 m.

5.2. *Transport Streamlines*

The nature of the circulation over the Blake Plateau was determined by calculating transport streamlines from the

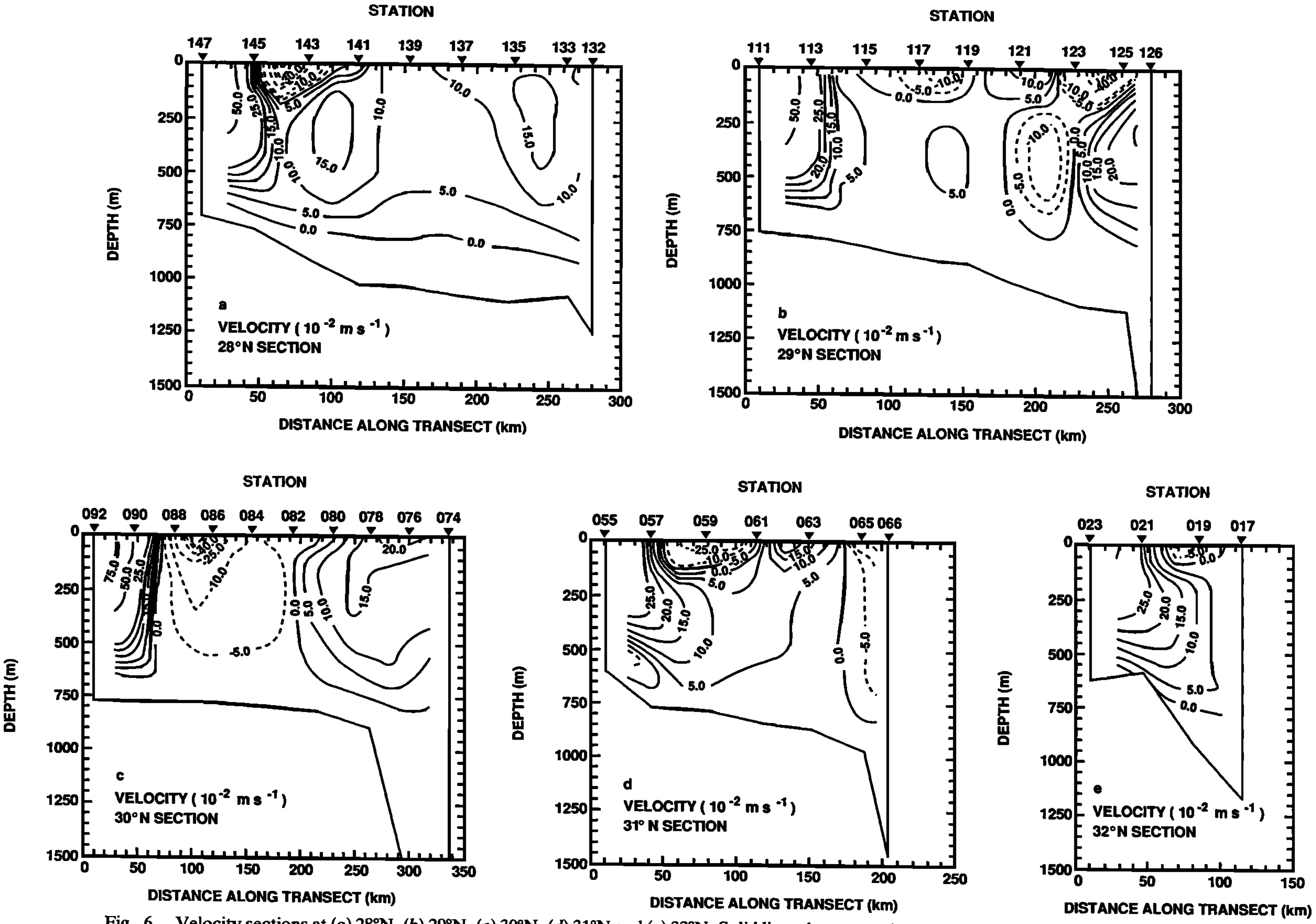

Fig. 6. Velocity sections at (*a*) 28°N, (*b*) 29°N, (*c*) 30°N, (*d*) 31°N and (*e*) 32°N. Solid lines denote northward velocities; dashed lines denote southward velocities. The contour interval in 10^{-2} m s^{-1} is variable.

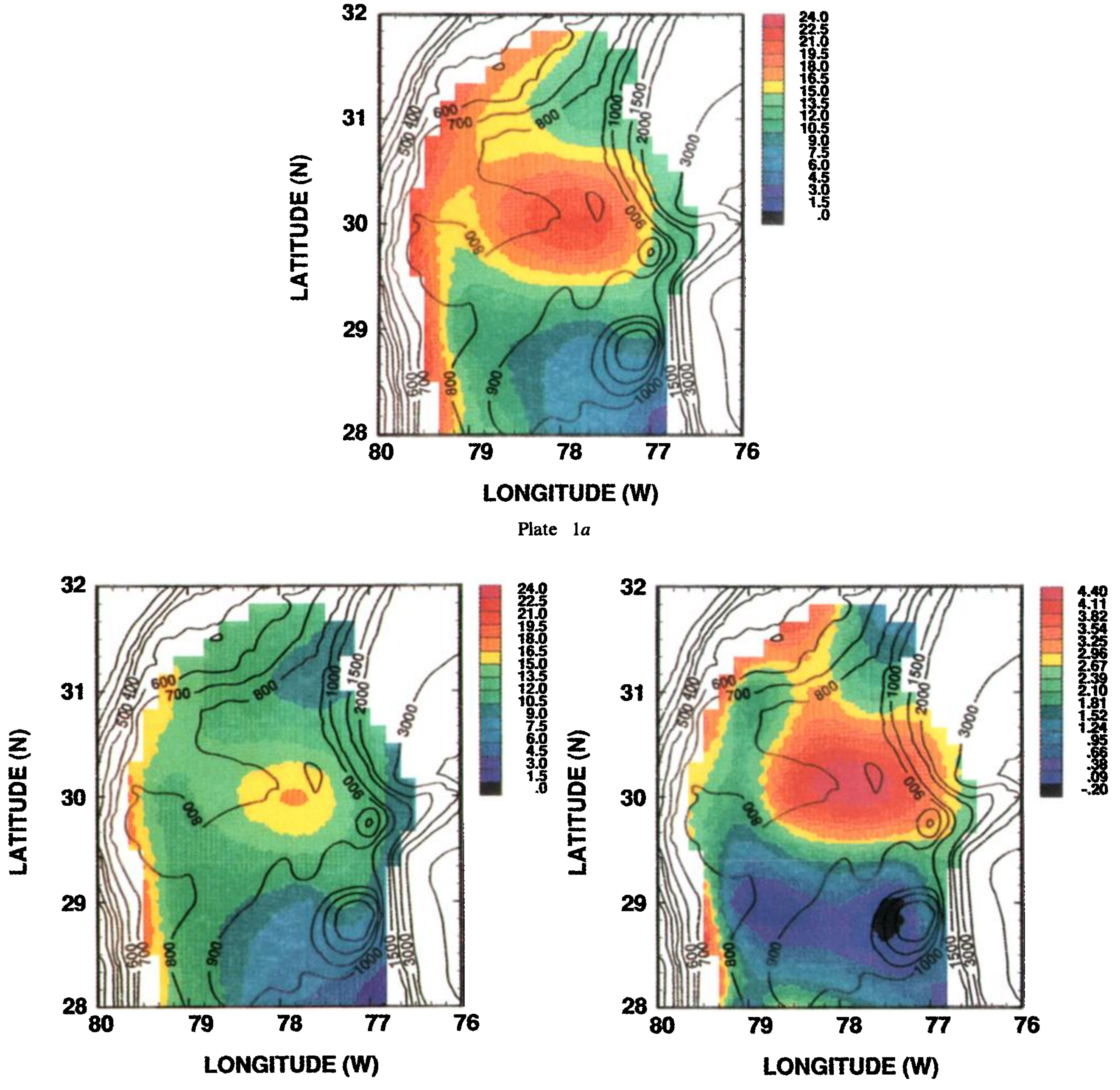

Plate 1*a*

Plate 1*b*

Plate 1*c*

Plate 1. Transport streamlines for the (*a*) total water depth, (*b*) the bottom layer (σ_1 = 34.4–36.8) and (*c*) the top layer (σ_1 = 31.2–34.4), relative to station 132. The contour interval is 1.5×10^6 m^3 s^{-1} in Plates 1*a* and 1*b*. The range of the scale in Plate 1*c* differs from that in Plates 1*a* and 1*b*, and the contour interval is variable.

velocity fields discussed in the previous section. The cross-sectional velocities were vertically integrated, and these values were summed along each section relative to station 132, the most southwesterly station of the cruise track. Streamline maps were obtained by contouring these values. An assumption of minimum streamline curvature consistent with all data points was used to smooth the stream function. Transport streamlines were calculated for the total water depth, and for each of the two layers used in the empirical search. The field obtained from integrating velocities over the total water depth is shown in Plate 1*a*. The Gulf Stream can be identified as the northward flow extending over the entire length of the western plateau (stations 147, 111, 92, and 55). Streamlines veer away from the main Gulf Stream path between latitudes 29° and 30°N and flow around a closed circulation feature centered at 30°N, 78°W (station 82). This flow can be identified in the velocity sections at 30° and 31°N (Figure 6) as a region of northward current lying seaward and adjacent to a region of southward current. A deflection of this streamline path is seen at 29°N, 77°W (the cyclonic feature centered at station 123 in Figure 6*b*) and may be associated with the underlying topography. The streamlines rejoin the main Gulf Stream over the northern plateau, forming a circulation feature whose longitudinal and latitudinal extents are both about 2°. This feature may be a decaying cold-core Gulf Stream ring that is coalescing with the Gulf Stream. This possibility will discussed in more detail in section 6. Finally, a flow toward the northeast over the Blake Escarpment is found between the 28° and 29°N sections.

The circulation in the lower layer (σ_1 = 34.4–36.80) displays a structure similar to that for the total water depth (Plate 1*b*). Again, the Gulf Stream can be seen over the western plateau, cyclonic circulation was observed over the northern and middle plateau, and a northeastward flow was found between the 28° and 29°N sections. The magnitudes of these flows were about 25% less than those for the total water depth. In the upper layer (σ_1 = 31.2–34.4) the northward flow of the Gulf Stream and the cyclonic feature over the central plateau were again seen (Plate 1*c*). To the south, an anticyclonic flow centered at about 29°N, 78°W was found. *Atkinson* [1983] has shown the water over the southern plateau to be Western North Atlantic Water; hence the feature was most probably ambient Blake Plateau water.

6. Discussion

6.1. *Comparisons With Earlier Studies*

The velocity fields and associated transport streamlines discussed above provided one realization of the circulation over the Blake Plateau during September 1980. Of particular interest was the cyclonic circulation centered at 30°N, 78°W. Such a feature has been observed previously by *Richardson et al.* [1978]. In that study they chose to use the topography of the 15° isotherm to describe the Gulf Stream and its rings. Using expendable bathythermograph (XBT), CTD, and hydrographic data collected over the period March 16 to July 9, 1975, they constructed the 15° surface seen in Figure 1*a* of *Richardson et al.* [1978]. An elevation of the 15° surface is dynamically "low" and a depression of this surface is dynamically "high." They considered the ring to be attached to the Gulf Stream and possibly coalescing with it.

Similarly, we constructed a chart of the topography of the 15° isotherm for our study period (Plate 2). In our figure, the 15° surface inside the cyclonic feature occurred at approximately 500 m. *Cheney and Richardson* [1976] found the 15° surface to lie at these depths in a Gulf Stream ring in a late stage of decay over the Blake Plateau. This ring was thought to have formed from a meander in the southern side of the Gulf Stream north of Cape Hatteras and was tracked by Cheney and Richardson as it moved southwest toward Florida. The vertical temperature structure through their ring over the plateau displayed isothermal doming at the ring's center in deeper water, but no thermal doming was seen in the top 300 m. We also saw doming in the lower water column at the center of the cyclonic feature (30°N, 78°W) in this analysis (Figure 5).

6.2. *Water Mass Analyses*

To confirm the hypothesis that the cyclonic feature was a decaying Gulf Stream ring we examined the distribution of oxygen anomaly (Figure 7). The oxygen anomaly is a sensitive indicator of Gulf Stream water originating from the Straits of Florida and farther south compared with Gulf Stream water of Sargasso Sea origin [*Richards and Redfield*, 1955]: the oxygen content for a given density water from the Straits of Florida is up to 1.5 mL L^{-1} deficient compared with Sargasso Water. Because of scatter in the data, first noted by Richards and Redfield, the maximum value of oxygen anomaly in the 200- to 500-m layer was plotted and contoured. Contouring was performed assuming the flow field depicted in Plate 1 was correct. This assumption allowed the extension of isopleths northeastward from the 28°N to 29°N section. The pattern supported the findings in the previous section. The core of the cyclonic feature was indeed the center of a mass of water of Sargasso Sea origin, which further confirmed its identity as a cold-core ring. Water of Caribbean origin was seen between 77° and 78°W, which indicated that the flow cyclonically advecting around the eddy originated in or south of the Straits of Florida. These results imply that a ring–Gulf Stream coalescence event was taking place, with water from the Straits of Florida flowing around the ring. Plots of salinity, nitrate, phosphate, and silicate anomaly showed the same pattern.

6.3. *Current Meter Data*

Further support for these ideas can be obtained by reconsidering the findings of *Lee and Waddell* [1983]. As was mentioned earlier, they reported periods of prolonged southward currents near the bottom at 30°N, 78°W. These currents lasted up to 40 days with speeds in excess of 0.3 m s^{-1}. Keeping in mind that these measured currents contain flow components not resolved by the methods employed above, it is likely that they form part of the flow on the western side of the cyclonic circulation of a ring such as that derived from the hydrographic data. Currents measured during the hydrographic sampling period have a persistent southward component and have speeds of about 0.3 m s^{-1}. Lee and Waddell suggest that these flows were part of cold-core eddies but are unable to be more specific owing to the lack of additional data. Our findings support their hypothesis. The moorings were in place from August 1980 to October 1981 and during that time several occurrences of southward, persistent flow of these magnitudes were measured at the location discussed above. It is reasonable to assume therefore that cold-core rings occurred repeatedly over this central region of the Blake Plateau during the deployment period.

6.4. *Role of Topography*

If the transport streamlines for the total water depth are considered in conjunction with the topography of the region (Plate 1*a*), a possible relationship between the two can be seen. The isobaths diverged over the southern Blake Plateau with the maximum divergence occurring at 30°N. They converged again in the region of the topographic irregularity known as "Charleston Bump," at about 32°N. The coalescing ring was centered over the region where the isobath divergence is a maximum. The flow appears to roughly follow the diverging and converging isobaths to the south and north. This suggests that topography affected the path of the Gulf Stream water being cyclonically advected around the ring. The smaller cyclonic feature seen in the velocity sections at 29°N, 77°W (station 123) may represent a topographic deflection of the cyclonically advecting Gulf Stream water by the closed isobaths found at this location, around which the 1000-m isobath is deflected.

The cyclonic flow of Gulf Stream water around this ring represents a seaward meander of the eastern wall of the Gulf Stream. If topography affected the direction of this flow, it is

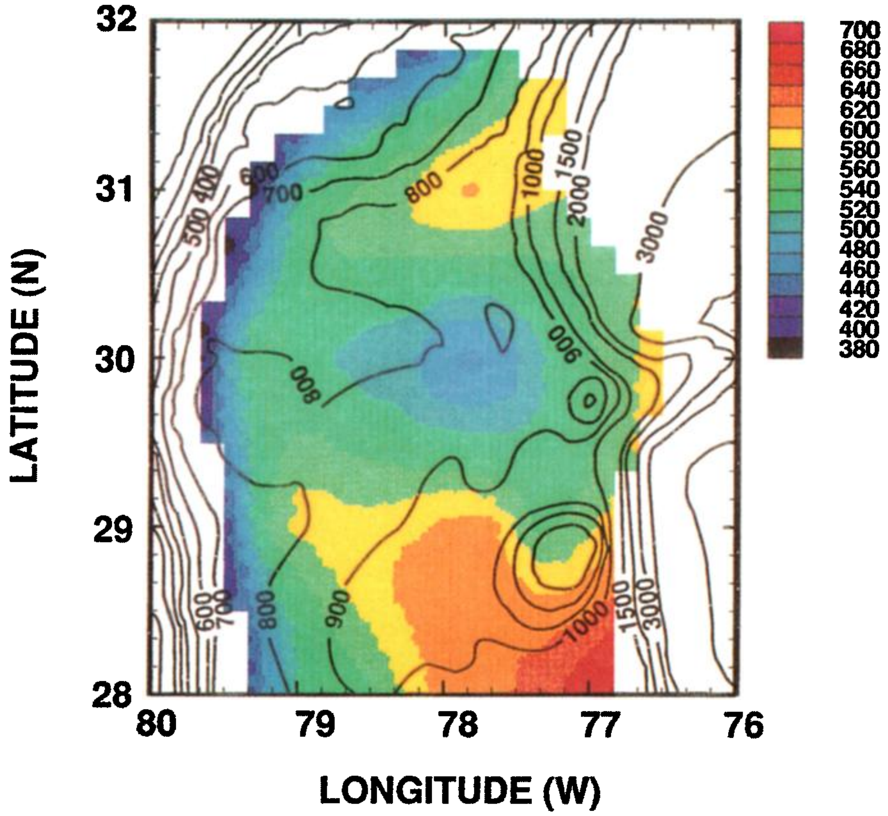

Plate 2. Depth (in meters) of the 15° isothermal surface over the Blake Plateau.

expected that other rings crossing into this region will be similarly affected and should coalesce at or near this location. Since earlier studies show that, on average, two rings invade the plateau every year and coalesce with the Gulf Stream [*Lai and Richardson*, 1977], this meander of the eastern Gulf Stream wall may be a recurring circulation feature.

6.5. *NOAA Hydrographic Data*

Further evidence of the recurrence of cold-core rings at or near this location was provided by the current meter data discussed above and a sequence of 25 biweekly NOAA hydrographic cruises from August 1965 to August 1966 [*Hazelworth*, 1976]. The NOAA cruises were conducted along a section extending from about 32°N, 79°W, to about 30°N, 78°W. This section would traverse a ring over the central plateau and should show doming as seen in the 30°N section in Figure 5. Inspection of the mean of all temperature sections from the NOAA cruises showed such a subsurface doming to be present at stations 13 to 16 (Figure 8), consistent with our hypothesis that this location is favored by eddies due to topographic control. Individual sections displayed isothermal doming occurring in the lower water column about twice during the 12-month period, with each event lasting about 4 weeks. The frequency of these events agrees well with the earlier studies [*Lai and Richardson*, 1977], while the duration of these events is supported by the current meter analysis by *Lee and Waddell* [1983].

6.6. *Barotropic Flow and the Reference Surface*

The absolute transport of the Gulf Stream was observed by *Leaman et al.* [1989] to increase from 30 Sv at the Straits of Florida (27°N) to 94 Sv near Cape Hatteras (73°W). The increase between 27° and 29°N, however, was only 3 Sv. Of the 64 Sv increase, 12 Sv was baroclinic. The plateau circulation obtained in our analysis does not show a convergence of transport streamlines to the east of the Gulf Stream, implying that the increase in transport of the Gulf Stream over the region was primarily barotropic. Since most of the barotropic component of transport cannot be resolved with this data, an increase in transport with latitude will be similarly unresolved. The lack of evidence of an increase in the baroclinic flow component is consistent with the findings of *Leaman et al.* [1989]. Given that the total increase in transport in their study was only 3 Sv at 29°N, and that only 12 Sv of the total transport increase between 27°N and Cape Hatteras was baroclinic, the baroclinic component of the transport increase over the sampling region is expected to be small.

Since the validity of the solutions obtained in this study are dependent upon the accuracy of the estimate of the reference level, we have included a brief discussion of the reference level found by the methods used in this study. The depth of the average isopycnal reference surface $\sigma_1 = 35.95$ (Table 2) displays the same pattern as the 15° isothermal surface (Plate 2) but is deeper. It roughly follows the bottom as mentioned earlier. The reference surface is shallowest over the center of the plateau (30°N, 78.4°W) and in the main

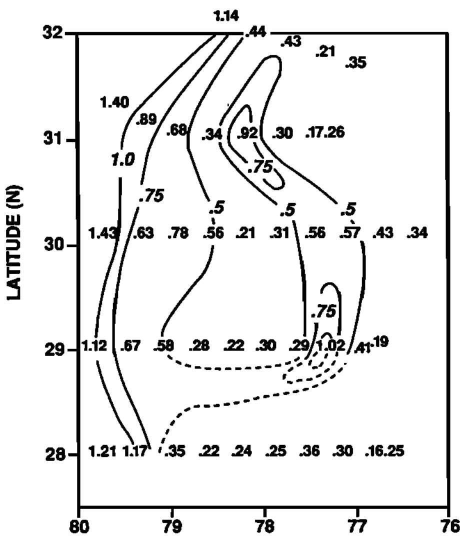

Fig. 7. Plot of maximum oxygen anomaly [*Richards and Redfield*, 1955] in the 200- to 500-m layer. Values indicate the maximum oxygen deficiency in the layer in milliliters per liter. Dashed contour lines were drawn to follow the streamlines shown in Plate 1. The Gulf Stream core is along the 1.0 mL L^{-1} isopleth.

Gulf Stream flow to the southwest. The former could be due to the doming of isopycnals, including the reference isopycnal surface, at the center of the coalescing ring. *Hofmann and Worley* [1986] found when using this method in the Gulf of Mexico that the optimum reference surface was associated with the bottom of the layer of Antarctic Intermediate Water, below which lay North Atlantic Deep Water. This result places the reference level at the boundary between the intermediate water of southern origin and the deep water of northern origin. Such northern deep water is not found over the Blake Plateau; hence the method is forced to use the bottom as the reference level.

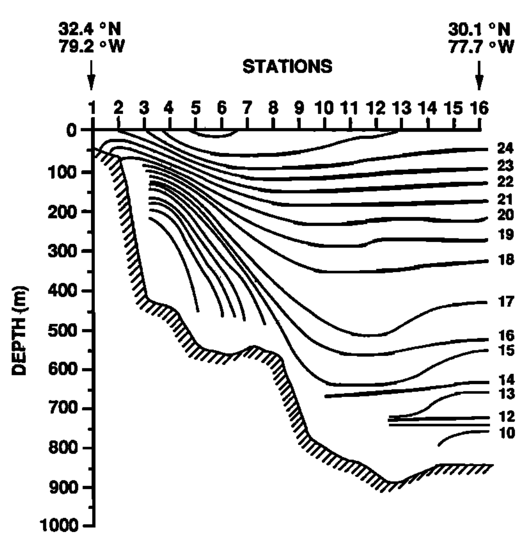

Fig. 8. Mean of all temperature (in degrees Celsius) sections from NOAA cruises [*Hazelworth*, 1976]. Stations 1 and 16 are found at 32.4°N, 79.2°W, and at 30.1°N, 77.7°W, respectively [from *Hazelworth*, 1976].

TABLE 2. Transport Imbalances and Residual Transports for Boxes 1 to 4 Using the Mean Sigma Surface σ_1 = 35.95

Box	Transport Imbalance, Sv	Residual Transport ΣT_{rj}^2, Sv^2	Mean Sigma Surface σ_1
1	−5.05	13.75	35.95
2	−0.35	2.99	35.95
3	0.53	0.31	35.95
4	−0.86	0.43	35.95

6.7. *Significance of the Study*

This study represents the first detailed CTD survey of a coalescence event in this region. Earlier studies have identified cold-core rings from XBT sections [*Cheney and Richardson*, 1976; *Richardson et al.*, 1978] but have not provided information about the plateau circulation. Even though our study provided only one realization of the circulation during this event, ancillary hydrographic data and current meter data were used to predict the frequency and duration of these events. Inshore meanders of the Gulf Stream front have been documented and explained by many investigators [e.g., *Bane and Dewar*, 1988]. The space-time properties of these meanders are explained by a skewed wave propagating downstream along a laterally sheared boundary current [*Bane et al.*, 1981]. The meander of the eastern side of the Gulf Stream suggested by this study appears to be due to a ring–Gulf Stream interaction controlled by topography and therefore represents a different dynamical process from that which is active on the western side of the Gulf Stream. A recurring Gulf Stream meander circulating in the manner observed would advect heat, salt, and nutrients away from the Gulf Stream across the Blake Plateau and then back to the main Gulf Stream flow. During its circuit, the Gulf Stream water would mix with the adjacent Blake Plateau or Sargasso Sea water and would therefore enhance property exchanges.

7. CONCLUSION

A combination of empirical search and inverse techniques were used to derive the general circulation over the Blake Plateau from a hydrographic data set collected in September 1980. The resulting velocity sections and streamlines displayed a cyclonic circulation feature over the central plateau whose latitudinal and longitudinal extent was about 2°, in each case. Water mass analysis showed Gulf Stream water circulating cyclonically around a core of Sargasso Sea water. The feature apparently was a coalescing Gulf Stream ring in a late stage of decay.

The cyclonic advection of Gulf Stream water around the ring formed a meander in the eastern Gulf Stream wall. Topography seemed to be influencing this flow, suggesting that other rings entering the region may be similarly affected. This would cause recurring meanders of the eastern Gulf Stream wall. Ancillary hydrographic data suggests that about two such events, each lasting about 4 weeks, occur each year.

Gulf Stream–ring coalescence events have been observed in detail further north of the Blake Plateau [*Richardson*, 1980]; however, over the plateau, no detailed mapping of such an event had taken place. This study has provided a realization of the circulation during these events and has implicated topography as a important factor influencing the circulation. Observations of meanders and their governing dynamics have been well documented on the western side of the Gulf Stream; here we have described and explained a meander of the eastern side of the Gulf Stream. These analyses have provided us with one example of a coalescence event; a numerical simulation of the region with realistic topography, as well as further sampling programs, would allow a more detailed analysis of these events and elucidate the role of topography.

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L. P. Atkinson and J. McClean-Padman, Department of Oceanography, Old Dominion University, Norfolk, VA 23529.

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