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Initial Observations of the Subsurface Structure and Short-Term Variability of the Seaward Deflection of the Gulf Stream off Charleston, South Carolina

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A recurring seaward deflection of the surface layer of the Gulf Stream has been observed near 32°N latitude off the coast of the southeastern United States. It has been suggested that a ridge and trough bottom feature (the so-called 'Charleston bump') on the upper continental slope off the Georgia/South Carolina coast produces the deflection through a bottom steering effect. Present data indicate that the deflection is great enough to direct the Gulf Stream's shoreward surface thermal front to the east, and even south of east, about 70% of the time. Air-deployed expendable bathythermograph surveys have been made with sufficient coverage to provide several synoptic, three-dimensional views of the Gulf Stream's thermal frontal zone in the region between Savannah, Georgia, and Cape Hatteras, North Carolina. These views show the subsurface structure of the seaward deflection to exhibit large short-term variability. During wintertime conditions (February 1979) the greatest deflection (>090° true) of the near-surface front occurred at a time when the deeper front was more aligned (~080° true) with local topography. Within the few days following this observation the deflection angle at all depths decreased to near or below 070° true. Two large-amplitude Gulf Stream meanders progressed northeastward away from the deflection region during this time period. Deflection angles at all levels during late summertime conditions (November 1979) were observed to be near 070° true. A simple, kinematical model which incorporates growing, propagating Gulf Stream meanders is proposed to explain the deflection's short-term variability. A dome-shaped volume of cold water was observed to be located over the upper continental slope immediately downstream of the deflection. The existence and persistence of this cold dome suggest that upwelling is important in its maintenance, a hypothesis consistent with its hydrographic properties.

INTRODUCTION

A recurring seaward deflection of the surface layer of the Gulf Stream has been observed near 32°N latitude off the coast of the southeastern United States. The deflection is evident in many satellite views of the Gulf Stream's surface temperature field, such as the example shown in Figure 1. This image, taken on April 8, 1977, by the NOAA 5 satellite, shows the seaward deflection to be noticeable near 32.5°N offshore of Charleston, South Carolina (CHS). A train of three large-amplitude, northeastward propagating meanders may be seen downstream of the deflection. Although early in situ data occasionally indicated the presence of the deflection [cf. *Singer et al.*, this issue], it was not until numerous sea surface temperature (SST) images from satellites were available that the persistence and latitude-specific location of the deflection became apparent [cf. *Pashinski and Maul*, 1973].

Legeckis [1976, 1979] has suggested that a ridge and trough bottom feature (the so-called 'Charleston bump') situated on the upper continental slope off the Georgia/South Carolina coast produces the deflection through a bottom steering effect. He cited the conservation of potential vorticity as the controlling dynamical mechanism. *Brooks and Bane* [1978] have presented data which indicate that the deflection is great enough to direct the Gulf Stream's shoreward surface thermal front to the east, and even south of east, about 70% of the time. Several studies [*Brooks and Bane*, 1978; *Pietrafesa et al.*, 1978; *Legeckis*, 1979] have shown the location of the deflection to be consistently within 30′ latitude of 32°N. *Maul et al.* [1978], *Bane and Brooks* [1979], and *Legeckis* [1979] have also shown that the lateral variability of the position of the Gulf Stream increases markedly within about 200 km immediately downstream of the deflection. They have suggested that this is due to the rapid growth of northeastward propagating Gulf Stream meanders and that the high meander growth rate is 'triggered' by the deflection process.

In a review of historical and recent hydrographic observations in the region of the Gulf Stream deflection, *Singer et al.* [this issue] have provided evidence which suggests seasonal changes in the degree of the deflection. Their data presentation suggests that (1) an offshore trend of the Gulf Stream flow is a persistent feature, even at depth, in the deflection region, (2) upwelling-induced doming of the 15°C isothermal surface is common seaward of the 200-m isobath and along the shoreward edge of the Gulf Stream between 31.5°N and and 34.5°N, with the most frequent doming occurring off Long Bay, and (3) the seasonal changes in the degree of deflection may be associated with seasonal changes in Gulf Stream transport and in the general circulation pattern in the North Atlantic Ocean.

We have recently made subsurface current and temperature observations with sufficient coverage to provide several synoptic, three-dimensional views of the Gulf Stream in the region between Savannah, Georgia, and Cape Hatteras, North Carolina. In an earlier paper [*Bane et al.*, 1981], which will be referred to herein as BBL, we presented a description of two large-amplitude meanders as they propagated northeastward away from the deflection region along the Carolina continental margin during February 1979. The skewed wave-like structure of the meanders was observed to be vertically coherent within the upper 400 m, thereby supporting the conjecture that the satellite-observed meander patterns in

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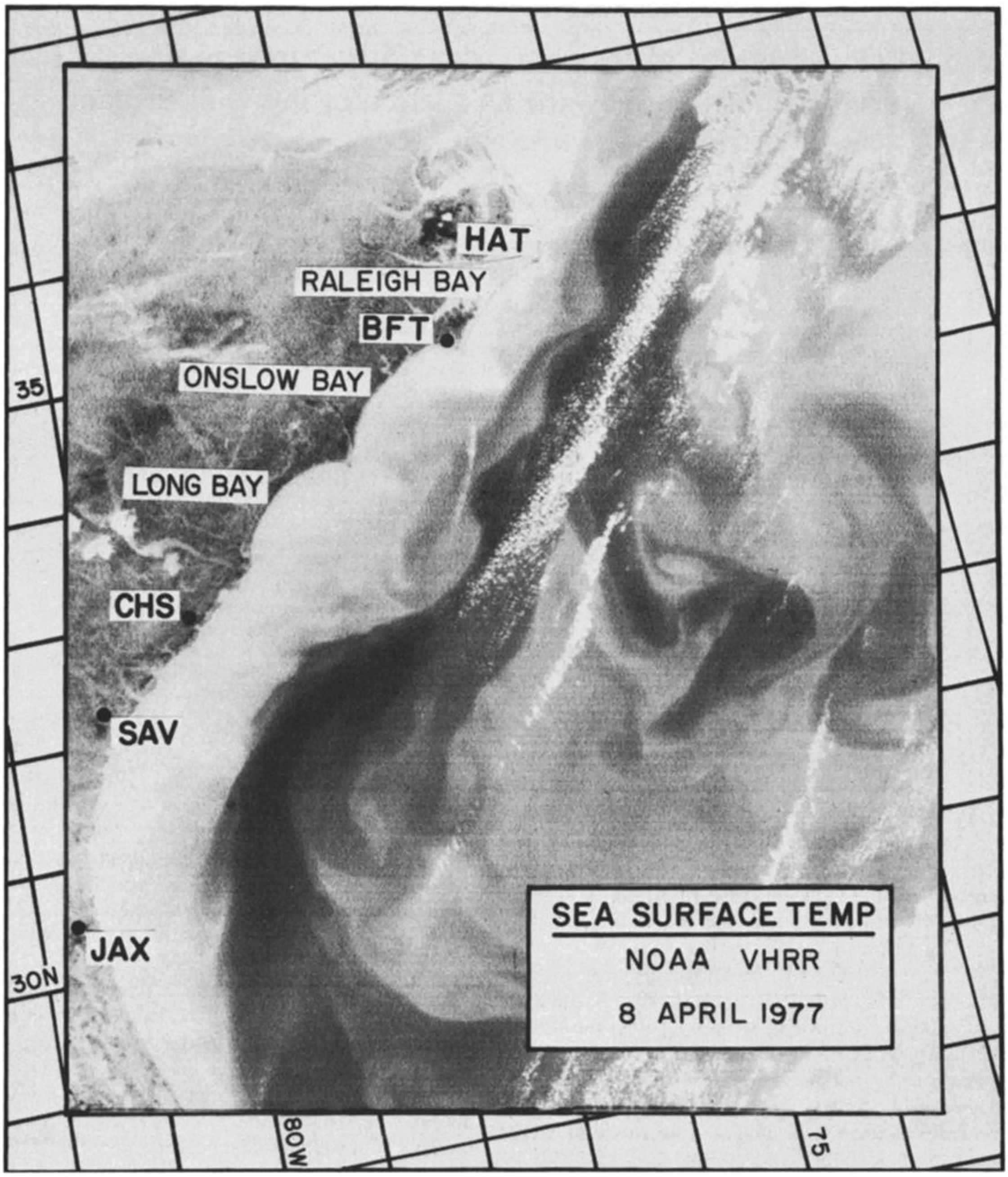

Fig. 1. Sea surface temperature image taken on April 8, 1977, by the very high resolution radiometer the NOAA 5 satellite. The east coast of the United States from south of Jacksonville, Florida (JAX), to north to Cape Hatteras, North Carolina (HAT), and the adjacent ocean are shown. The warm surface temperatures in the Gulf Stream make it discernible as a dark gray band running generally northeastward through the image. The seaward deflection of the Gulf Stream is clearly evident near 32°N latitude where the stream's shoreward surface thermal front is oriented east-west. Three large-amplitude meanders may be seen northeast of the deflection. (Also shown along the coast are Beaufort, North Carolina (BFT), Charleston, South Carolina (CHS), and Savannah, Georgia (SAV).)

the SST field are surface signatures of subsurface meander patterns. (Using later data from the same area, *Brooks and Bane* [1981] demonstrated the correlation between subsurface current fluctuations and the passage of a SST meander pattern. Further analysis of our 1979 data has shown that both aircraft- and satellite-observed meander patterns in the SST field correspond closely to subsurface meander patterns to depths of at least 400 m [*Bane and Legeckis*, 1981; *Seay and Bane*, 1981].)

The observations also revealed the subsurface structure of the seaward deflection of the Gulf Stream off Charleston. Unlike the meanders, the deflection was not always vertically coherent in its structure. It was reported in BBL that the Gulf Stream's shoreward surface thermal front was oriented approximately east-west on February 10, 1979. With increasing depth, however, the front became more aligned with the local isobaths. Observations made in the same area a few days later showed only a slight seaward deflection of the Gulf Stream at any level within the upper 400 m. During the interim the two aforementioned meanders had propagated northeastward away from the deflection region. The suggestion was made in BBL that a relatively sharp seaward deflection of the surface layer of the Gulf Stream may be associated with the late stages of a meander passage through the region near 32°N.

The present paper describes, in greater detail than was provided in BBL, the structure and short-term variability of the seaward deflection of the Gulf Stream during the February 1979 observational period. (In this paper, 'short-term' refers to periods of several days.) Additional observations made in the same area during November 1979 are also discussed. The following sections present a quantitative description of the Gulf Stream's thermal structure during periods of strong and weak deflection and show that the February and November periods were characterized by relatively high and relatively low degrees of deflection variability, respectively. Possible relationships between the deflection process and the Gulf Stream meander field are also discussed. The hydrographic conditions found in the Gulf Stream during the February observational period were typical of the wintertime regime, with the permanent thermocline extending to the ocean surface, thereby forming a strong surface thermal front along the inshore edge of the Gulf Stream. During November the conditions were typical of late summertime, with the permanent thermocline intersecting the upper continental slope near 100-m depth and with weak temperature gradients existing within the upper layer.

TEMPERATURE MEASUREMENTS

Thirteen aircraft surveys of the temperature field within the upper 400 m of the Gulf Stream frontal zone were made as part of the Gulf Stream Meanders Experiment. The surveys were conducted along the continental margin between Savannah, Georgia, and Cape Hatteras, North Carolina, during 1979. Eight daily flights were made between February 9 and 18, and five between November 21 and 29. Aircraft temperature surveys were chosen as the best method for providing rapid three-dimensional measurements of a large area of the Gulf Stream in a region where significant variations can occur within a few days time. Surface temperature data were collected with a precision radiation thermometer (PRT), and subsurface temperature profiles were measured with air-deployed expendable bathythermographs (AXBT's). Each flight obtained temperature data along several (four to ten) cross-stream lines spaced 50 km apart. AXBT drops were usually made at 12.5-km intervals along each cross-stream line. Complete data sets are documented in the reports by *Bane et al.* [1980] and *Bane and Brooks* [1981].

The data to be described here have resulted primarily from the AXBT drops. The surface temperature data taken with the PRT show a close correspondence to the near-surface AXBT data, except that the PRT surface temperatures are consistently cooler than the AXBT near-surface (1-m level) temperatures by about 1°C. The horizontal temperature patterns that were contoured from either the PRT data or the near-surface AXBT data show no important differences.

DEFLECTION STRUCTURE AND VARIABILITY

Using over 100 satellite SST observations, *Legeckis* [1979] has determined that the orientation angle of the Gulf Stream's western surface thermal front in the deflection region varies from 060° to 120° clockwise from true north, with an average orientation of 083°. He reported that significant variations in frontal orientation may occur within a period of a few days, and he noted the similarity between this time scale and typical meander periods. With the exception of only a few serendipitous views of the horizontal subsurface structure of the Gulf Stream in this area, observations of the seaward deflection have been restricted to the surface layer.

During eight of our February and November 1979 aircraft surveys we collected data sufficient to determine the orientation angle of the Gulf Stream's thermal front throughout the upper 400 m in the deflection region between 31.5°N and 32.5°N. Figure 2 is a plot of the frontal orientation angle (deflection angle, for convenience) at several levels on each of these eight surveys. Because of the 12.5-km cross-stream spacing of the AXBT stations the deflection angle may be determined only to within a certain range. (Occasionally, the station spacing would vary owing to poor data recovery from

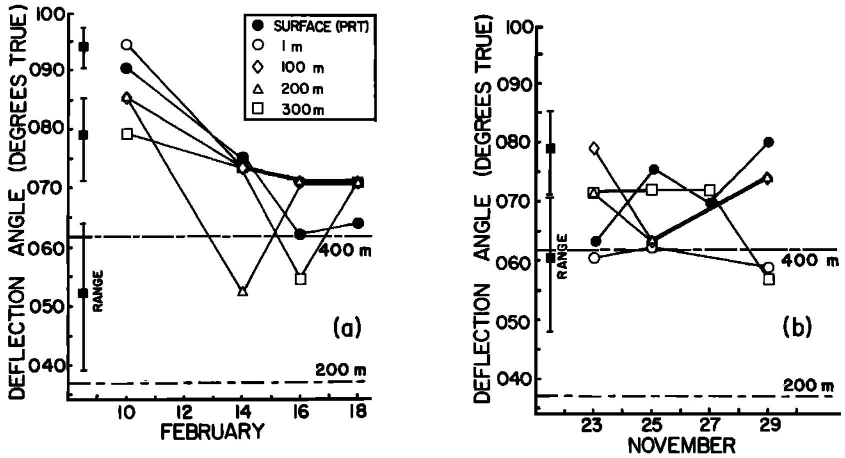

Fig. 2. Orientation angle (clockwise from true north) of the Gulf Stream thermal front at several levels during (*a*) the February and (*b*) the November 1979 AXBT survey periods. The curves show the deflection angles that would have existed if the front had passed midway between each AXBT station pair used to define a frontal location. The range bars along the left side of each graph indicate the typical uncertainty in angle determination, which is smaller for higher deflection angles. The orientation angles of the 200-m and 400-m isobaths in the deflection region are also shown.

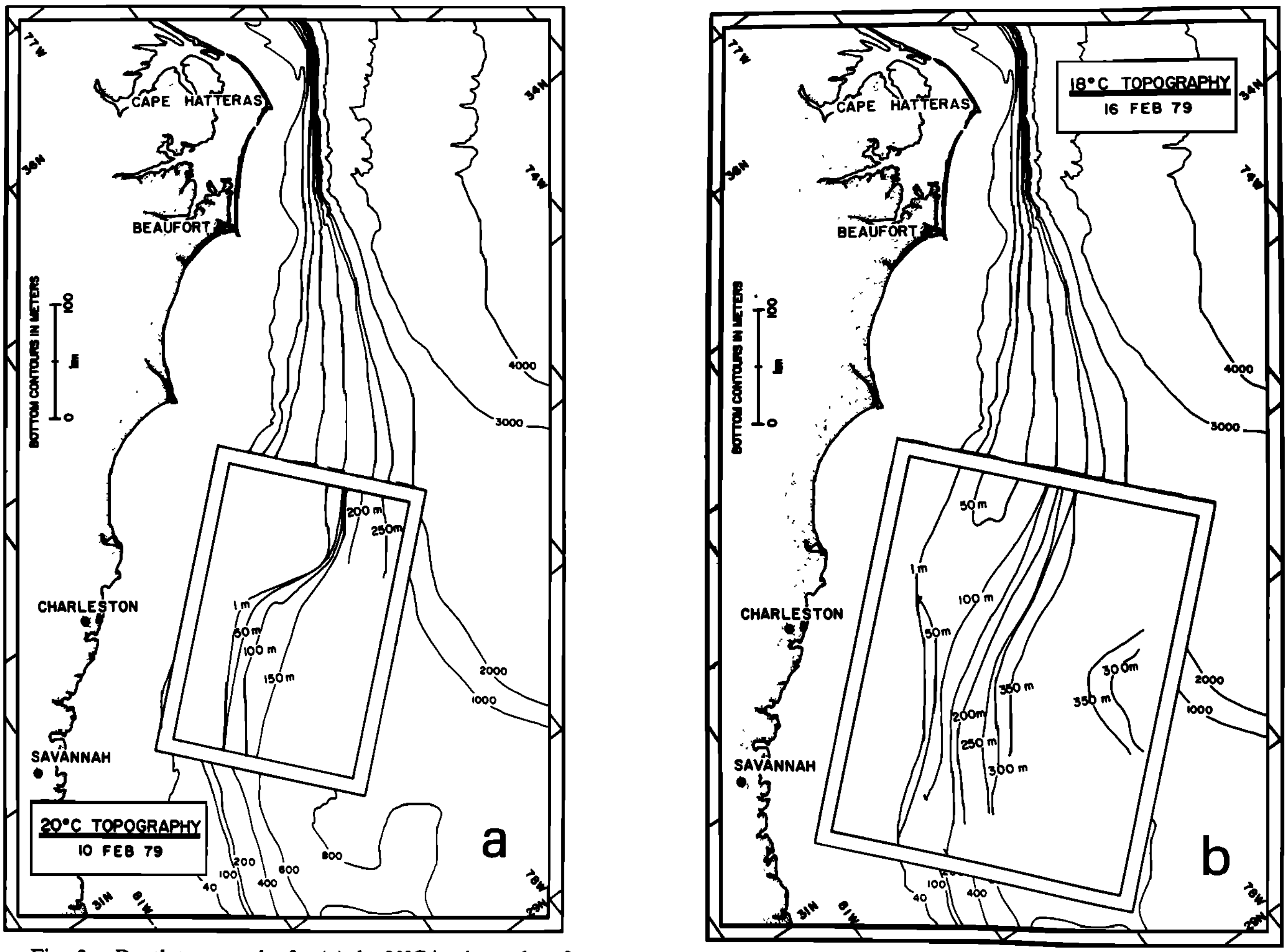

Fig. 3. Depth topography for (*a*) the 20°C isothermal surface on February 10, (*b*) the 18°C isothermal surface on February 16, and (*c*) the 18°C isothermal surface on November 29. These surfaces display various aspects of deflection angle and structure. On February 10 the deflection angle was high at every level, yet there was considerable vertical structure in the deflection. On both February 16 and November 29 the deflection angles were low at all levels, even though wintertime conditions prevailed during February and summertime conditions during November. (Figure 3*a* is after *Bane et al.* [1981].)

an AXBT or to alteration of the survey grid in order to conserve AXBT probes.) The curves show the deflection angles which would have existed had the thermal front passed halfway between each station pair. Typical range bars are plotted to illustrate the uncertainty in determining the deflection angle due to the station spacing.

SST data taken with the PRT during the surveys give a more accurate measure of the deflection angle at the surface. Angles derived from these data compare well with the angles calculated from the 1-m level AXBT data for the February period, since each PRT-derived angle is within the appropriate 1-m level range bar. During November, however, the PRT-derived angles and the 1-m AXBT-derived angles occasionally show greater differences. This is probably due to the small temperature gradients which existed in the upper layer during November as compared to February (compare, for example, Figures 6*b* and 7*b*), thereby making it difficult to determine surface front locations accurately.

Considerable vertical variation of the deflection angle was observed on February 10, with the deflection angle decreasing with increasing depth. The observed deflection angle was also greatest at all levels at that time. The vertical structure of the deflection on February 10 is illustrated by the topography of the 20°C isothermal surface shown in Figure 3*a*. The deflection angle at the surface was near 095°, less than the

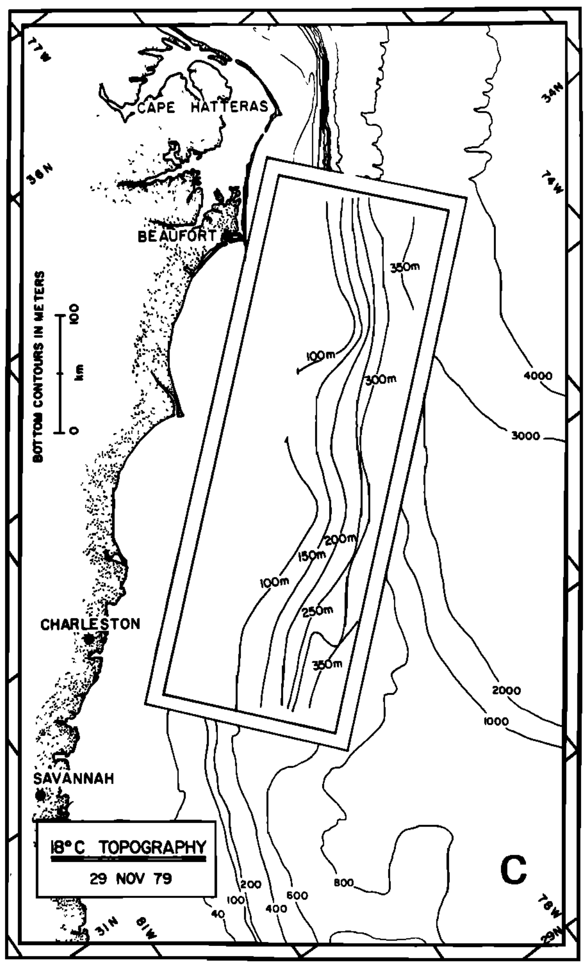

Fig. 3. (continued)

120° maximum surface deflection angle which *Legeckis* [1979] observed in satellite SST images. At 300 m depth the deflection angle was near 080°. During the few days following February 10 the deflection angle decreased, and the vertical structure in the deflection lessened considerably. These features are evident in Figure 3*b*, which shows the 18°C topography on February 16. Together these observations suggest that vertical structure in the deflection (such as that observed on February 10) may be associated with the transition from high to low deflection angle and that such a transition may occur rapidly (e.g., within a few days).

As was reported in BBL, two large-amplitude Gulf Stream meanders were observed progressing northeastward away from the deflection region subsequent to February 10. Figure 4 is a composite of 1-m level AXBT data from the surveys of February 10 and 11. The composite shows how the Gulf Stream may have appeared on February 10, with the two meanders immediately downstream of the sharp surface deflection. This extensive view reveals that the deflection at the time of these observations formed the trailing portion of the trough which followed the second meander crest. (In this paper, as in BBL, a meander crest (trough) is taken to be the shorewardmost (seawardmost) excursion of the Gulf Stream along one meander length.) This overall structure is strikingly similar to that show in the satellite SST image in Figure 1, which was taken almost 2 years prior to the 1979 AXBT surveys. The decrease in the deflection after February 10 occurred as these meanders progressed northeastward at speeds near 35 km d^{-1}. According to the AXBT data and moored current meter data collected over the upper continental slope off Onslow Bay, these were the last large-amplitude meanders to progress through this region for almost a month [BBL; *Brooks and Bane*, 1981]. Relatively low deflection angles persisted through February 18, the early portion of this 'low-meander-activity' period.

Even with low deflection angles, a cross-isobath orientation of the front existed through at least February 18. Figure 2*a* shows the deflection angle to be about 070° at most levels on February 16 and 18, implying a seaward flow of the Gulf Stream away from the outer shelf edge and approximately following the 400-m isobath. The 200-m isobath is oriented at about 037°, and the 400-m isobath at about 062° in this region. The deflection angles near 070° observed on February 16 and 18 are similar in magnitude to the 064° orientation of the average SST front in the deflection region reported by *Bane and Brooks* [1979] but are somewhat less than the 083° average surface deflection angle reported by *Legeckis* [1979]. (This apparent discrepancy between 'average deflection angles' disappears with the realization that the numbers from the other two studies are different quantities. More specifically, *Bane and Brooks* [1979] show the 'average' surface front constructed from 64 individual views. The 064° orientation angle was then calculated for this average picture. On the other hand, *Legeckis* [1979] determined the orientation angle of over 100 instantaneous views of the deflection and then averaged these angles.) Collectively, these data suggest that the front in the deflection region was situated in its 'average' low-meander-activity configuration on February 16 and 18, with a slight seaward trend that it most likely due to topographic steering. This indicates that at all levels above 400 m the average front in the deflection region follows essentially the same seaward trend as the average SST front found by *Bane and Brooks* [1979] (see Figure 8).

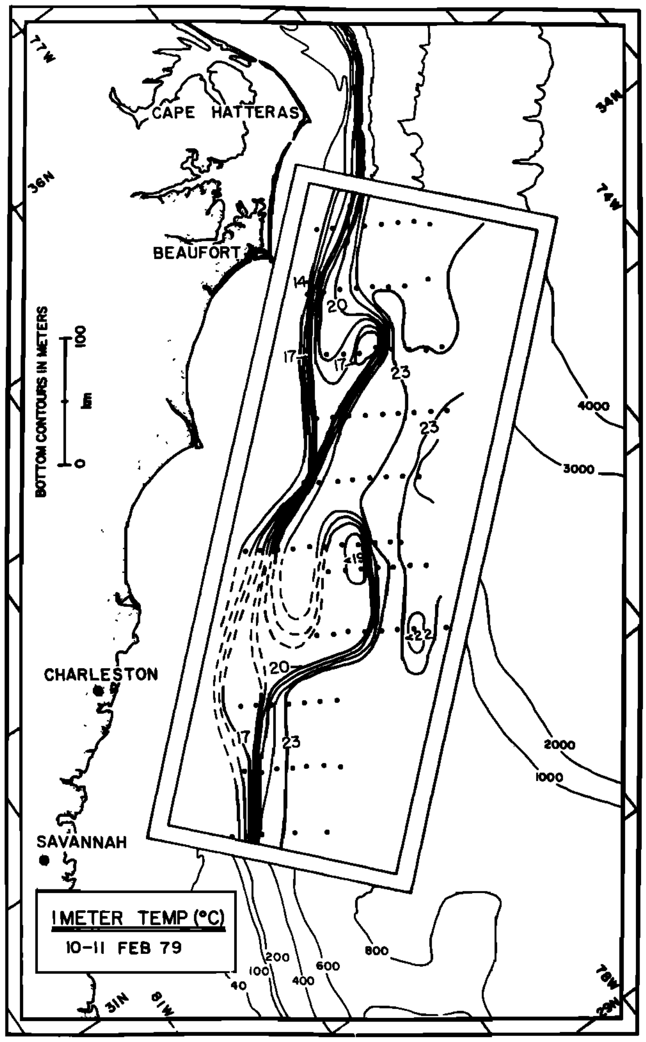

Fig. 4. An extensive horizontal temperature section constructed from AXBT data collected on February 10 and 11. This composite was made by moving the February 11 data, which were gathered in the northern portion of the study area, 30 km 'upstream' to account for the propagation of the two meanders in that area between February 10 and 11. This view shows the two meanders progressing away from the deflection region [after *Bane et al.*, 1981].

During the November AXBT surveys the front was oriented near 070° at all levels in the deflection region (Figure 2*b*). No significant vertical structure is suggested by these data, since subsurface deflection angles are never separated by more than a set of range bars. The topography of the 18°C isothermal surface in the deflection region on November 29 (Figure 3*c*) is typical of all of the AXBT data sets collected during this period and exhibits both low deflection angles and little vertical structure in the deflection.

Subsurface current and temperature fluctuations measured by our upper slope instrument array moored off Onslow Bay suggest that meanders with periods near 6 days were passing through the array from late October until the instruments were recovered on November 19 [*Brooks et al.*, 1981]. Data from the DMSP satellite and our aircraft surveys detected meanders with alongshore wavelengths near 180 km to be progressing through the study area through November 29. One such meander may be seen with its crest positioned near the southern end of Onslow Bay in Figures 3*c* and 7*a*. These data describe a situation which is in contrast to the February observations, with little vertical structure and variability occurring in the deflection during a time when meanders were progressing northeastward away from the deflection. These differences may be associated with the different hydrographic regimes that prevailed during the two survey periods. One must be extremely cautious, though, to realize that the number of observations made to date of the deflection process and its effects on the meander field are far too few to give a complete and reliable description of the phenomena.

THE COLD DOME

One result of the seaward deflection of the Gulf Stream which may have important regional oceanographical consequences is the existence of a volume of cool water just downstream of the deflection. According to our AXBT surveys, the cool water is normally situated between the upper continental slope and the main body of the Gulf Stream in the area where it arcs from its deflected, seaward trend cyclonically back toward the north, approximately offshore of Long Bay (see Figure 1). The subsurface thermal structure of this water volume is domelike, and the term 'cold dome' is chosen to refer to this feature.

Using historical data, *Singer et al.* [this issue] have described the hydrography of the cold dome. They found conclusive evidence for the dome in six of seven sections off Long Bay (the seventh section was not extensive enough to define the dome), thereby attesting to its persistence. Temperature, salinity, and nutrient properties indicated that upwelling is probably important in the maintenance of the dome. They also found evidence that doming occurs less frequently farther downstream from the deflection/cold dome region, but the doming there is probably due to the cold core cyclonic frontal eddies which travel downstream in the troughs of propagating Gulf Stream meanders [BBL; *Lee et al.*, 1981].

Several of our AXBT surveys were extensive enough to synoptically map the structure of the cold dome. Displayed in Figures 5–7 are horizontal and vertical temperature sections through the cold dome on three different days. As discussed above, these days represent three different regional conditions. February 10 and 16 (Figures 5 and 6) were both characterized by typically wintertime thermal structure; however, the Gulf Stream was sharply deflected (at least in the shallower layers) on February 10, while it was showing an almost average deflection angle on February 16. Thermal conditions on November 29 (Figure 7) were typical of late summertime, and the Gulf Stream was oriented with an almost average deflection angle. On each day, however, the cold dome was found situated in essentially the same location. Within the limits of these observations it appeared also to have had the same general geometrical structure on each of these days.

The horizontal temperature sections in Figures 5*a*, 6*a*, and 7*a* show the cold dome to be centered near 32.5°N, 78°W. Figure 7 displays the general shape of the cold dome. Although the less extensive surveys of February 10 and 16 do not reveal the northeastern extent of the dome, data from flights conducted to the north on the days just preceding or following those days show the typical arcuate pattern similar to that in Figure 7*a* [*Bane et al.*, 1980].

The vertical cross-stream and along-stream sections (Figures 5*b*, 5*c*, 6*b*, 6*c*, 7*b*, and 7*c*) clearly display the domelike structure of the isothermal surfaces. Each cross-stream line (designated line M during the surveys) appears to have come close to slicing through the dome's center on each date. In these figures the 17°C isothermal surface represents a reasonable upper limit to the dome's extent. Taking this to be the case, the cold dome extends upward to a depth of about 70 m on each section. Using data from November 29, the volume bounded by the 17°C isothermal surface, the upper continental slope, and the 400-m depth level (the lower limit of our data coverage) is estimated to be 4×10^{12} m^3. (This rough computation assumes an alongshore extent of the cold dome of 150 km, which is necessary since the 17°C surface may not always intersect the upper continental slope at the northern and southern extremes of the dome.)

Considering just the thermal structure described above, a cyclonic eddylike flow around the cold core of the dome may be anticipated. Along the shoreward Gulf Stream front, however, the topographies of isopycnal surfaces are not always similar to those of isothermal surfaces due to salinity variations through the front [cf. *Lee et al.*, 1981]. Thus our AXBT data are only suggestive of this horizontal circulation pattern.

THE SEAWARD DEFLECTION: AN ALTERNATIVE HYPOTHESIS

The seaward deflection of the Gulf Stream near 32°N is a recurring and latitude-specific feature of the boundary current. The deflection's characteristics provide circumstantial evidence that it is the result of bottom steering by a topographically high feature on the upper continental slope off Charleston, South Carolina. Nonetheless, short-term variability observed in the structure and magnitude of the deflection is presently not satisfactorily explained by a simple bottom steering mechanism.

An alternative hypothesis for the seaward deflection may be advanced which incorporates meander propagation and amplification as well as bottom steering. In concert, all available evidence points to a slight mean seaward flow of the Gulf Stream near 32°N. The average orientation angle of the Gulf Stream's thermal front appears to be approximately 070°–080° true near 32°N; thus the Gulf Stream crosses the trend of the upper continental slope isobaths at an angle of about 10°–40° there. Between the Florida Straits and Cape Hatteras the bottom slope along the 400-m isobath reaches a minimum in the deflection region. This is due to a general divergence of isobaths toward this area when approaching from either the north or the south [cf. *Uchupi*, 1968]. As the Gulf Stream flows northward from the Florida Straits, it encounters progressively smaller bottom slope. According to stability studies [*Orlanski*, 1969; *Ikeda*, 1981] this will tend to destabilize the stream. Small meanders which were initiated in the Gulf Stream south of the deflection region [cf. *Lee*, 1975; *Lee and Mayer*, 1977; *Lee et al.*, 1981] may then be amplified as they progress northward toward the deflection region. According to surface meander patterns, meander growth rates are enhanced in the deflection region, possibly because of a combination of the small bottom slope and the mean seaward flow of the Gulf Stream there.

Assume for the moment that a train of meander patterns is progressing along the average path of the Gulf Stream and that the lateral amplitude of each meander increases as it progresses. Each wavelike meander pattern superimposed on the mean Gulf Stream path will cause the orientation of the stream's instantaneous front to differ, in general, from

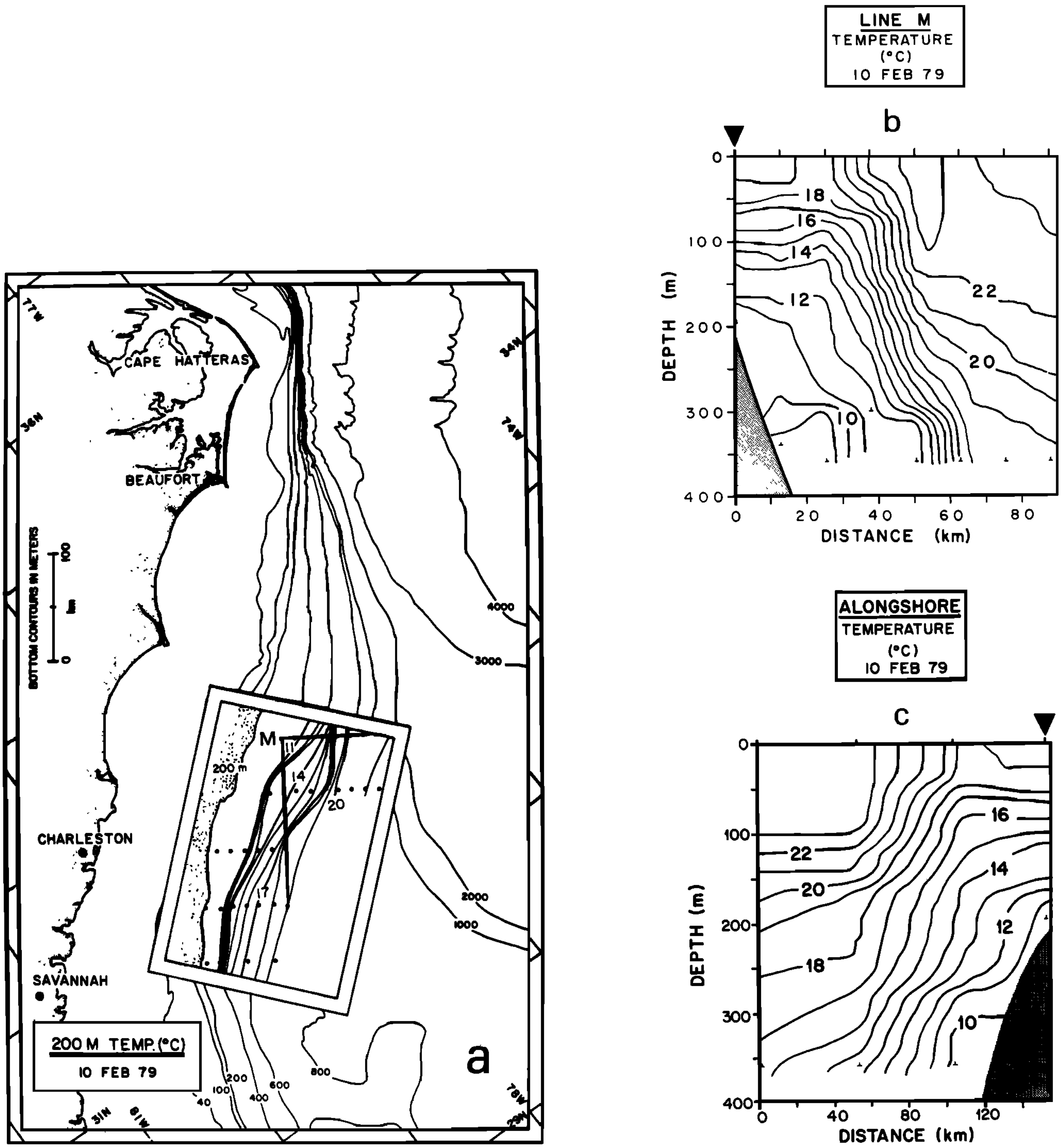

Fig. 5. Temperature sections which reveal the structure of the cold dome on February 10. On the 200-m level horizontal temperature section (Figure 5*a*) are shown the positions for the cross-stream line, line M (Figure 5*b*), and the along-stream section (Figure 5*c*). The along-stream sections are views looking generally northwestward. The solid triangles on the vertical sections indicate their common station.

the front's mean orientation. In particular, as a meander progresses through the deflection region, both the seaward trend of the average path of the stream and the rapid amplification of the meander itself will cause the instantaneous front in some portion of the meander pattern to be oriented at a large angle relative to the local isobaths. It is possible for a meander to become large enough so that the leading portion of a crest (which is, of course, the same as the trailing portion of a trough) may cross the position of the average front at an angle sufficient to cause the instantaneous front to be oriented east-west or even to direct the front to the south of east. A simple calculation shows that a lateral sine wave pattern of 200-km wavelength and a lateral peak-to-peak amplitude of 23 km superimposed on an average front oriented at 070° will direct the instantaneous front in the leading portion of a crest along an east-west line. A

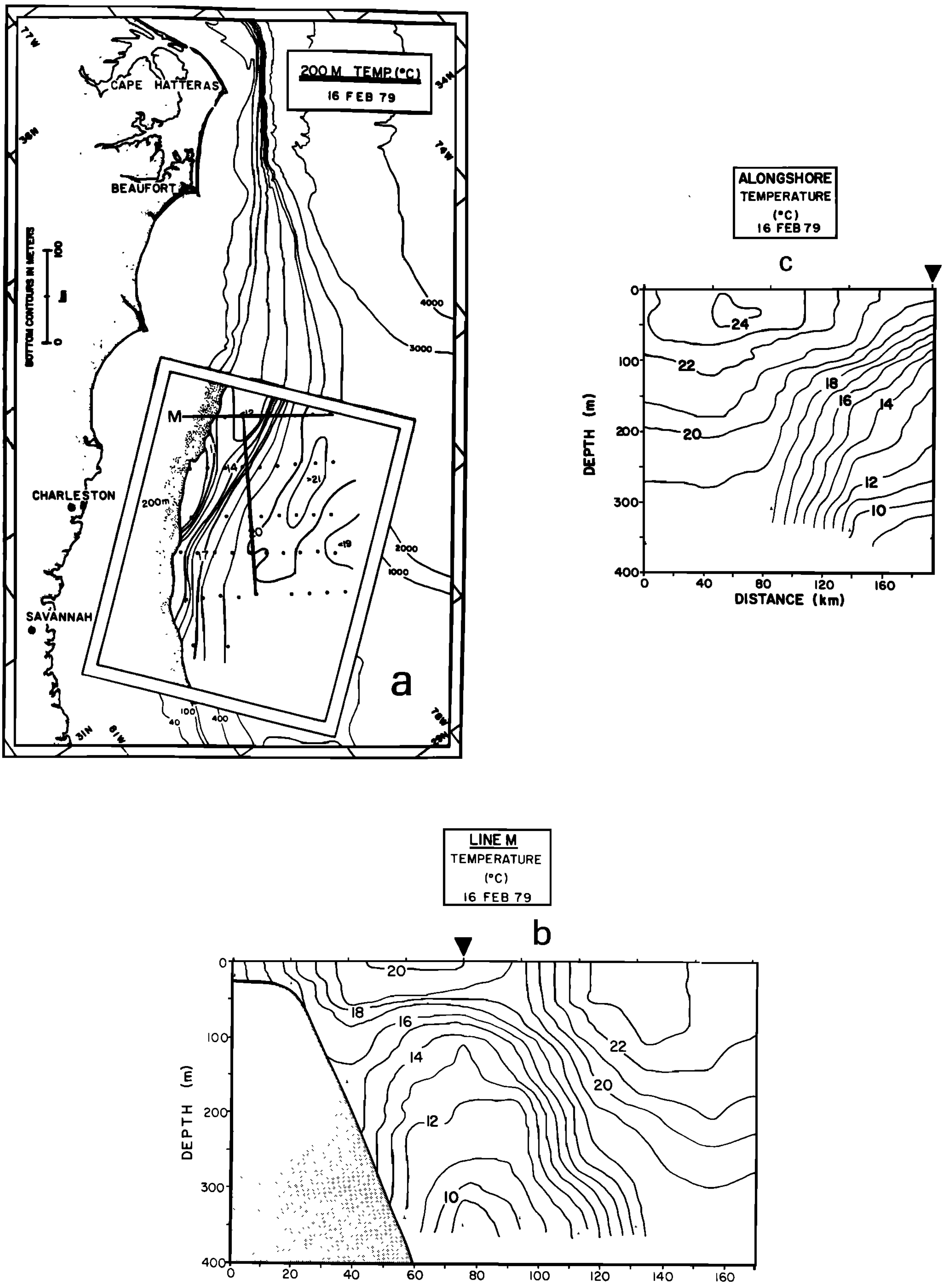

Fig. 6. Same as Figure 5 for February 16.

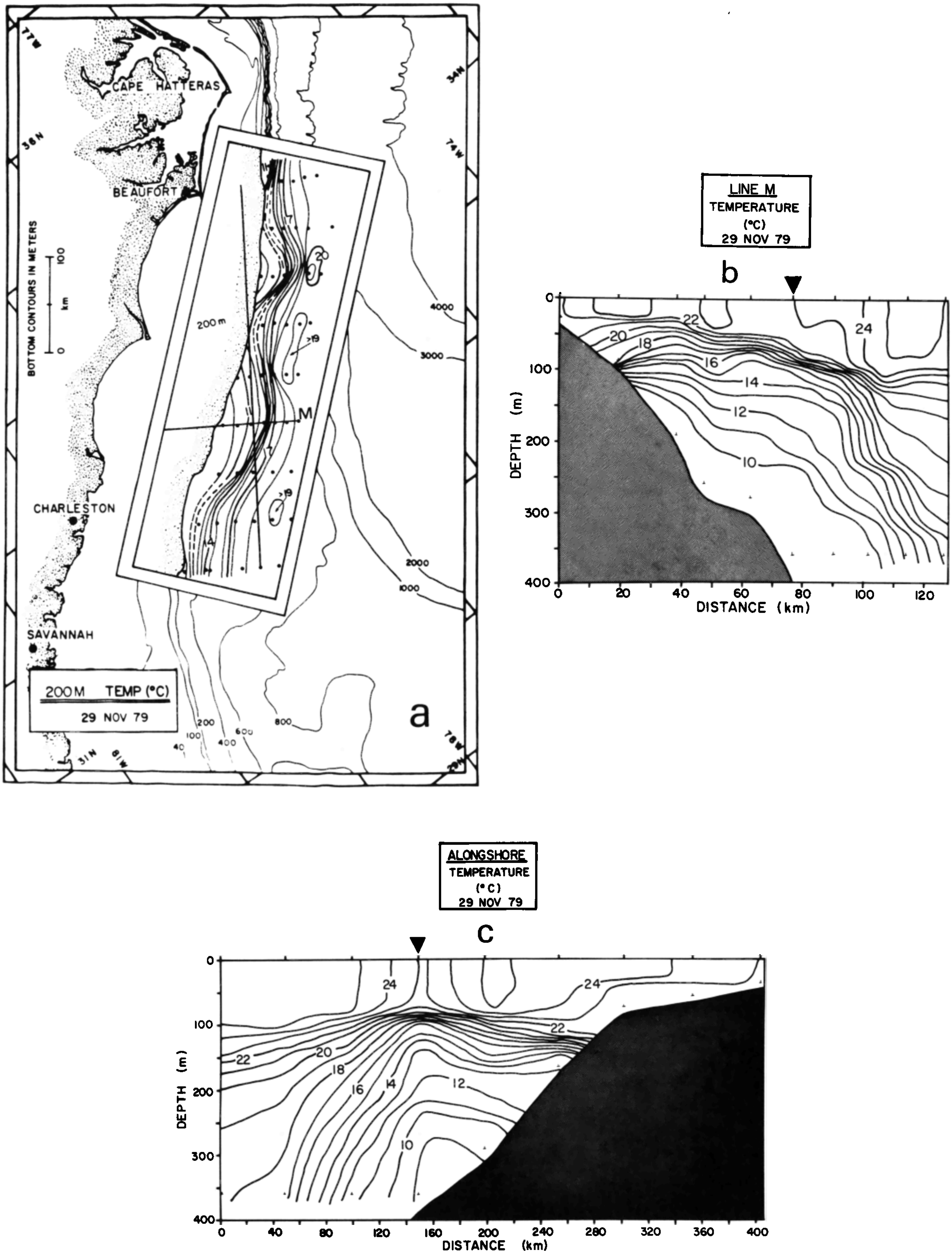

Fig. 7. Same as Figure 5 for November 29.

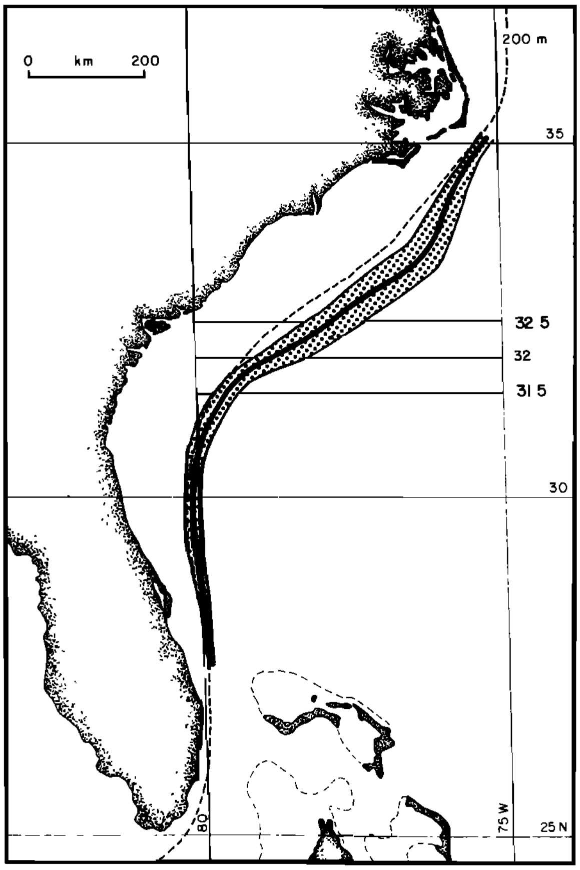

Fig. 8. The mean position ±1 standard deviation (shaded) of the Gulf Stream's shoreward surface thermal front calculated for a 64-week period by *Bane and Brooks* [1979].

peak-to-peak amplitude greater than 23 km will cause the front to be oriented at an angle greater than 090° clockwise from true north.

Peak-to-peak lateral meander amplitudes are typically less than 23 km south of 31°N and rapidly increase to near 50 km on the downstream side of the deflection region [*Maul et al.*, 1978; *Bane and Brooks*, 1979; *Legeckis*, 1979]. Taking this together with the simple kinematical discussion presented above, it may be argued that a 'severe' deflection (>090° true) of the Gulf Stream's SST front would be apparent in the region just downstream of 31°N each time a meander progressed through this area and was amplified to greater than 23 km in lateral amplitude. As a particular meander pattern progresses downstream away from the deflection region, the apparent deflection angle would lessen until the next meander crest propagated into the area from the south.

This hypothetical situation is illustrated in Figures 8 and 9. Using data presented by *Bane and Brooks* [1979], the mean position of the Gulf Stream's shoreward SST front is plotted in Figure 8 along with the standard deviation envelope of its lateral position variability. A sine wave meander pattern with an along-stream wavelength of 200 km has been plotted inside the standard deviation envelope in Figure 9. The four frames show the meander progressing downstream in 50-km steps (corresponding to quarter-period increments). Figures 9*a*–9*c* show the Gulf Stream's surface front to be deflected at an angle greater than 090° in the leading portion of meander crest A, while at the time of Figure 9*d*, meander crest B has grown to sufficient amplitude within the envelope to allow the leading portion of its crest to have a deflection angle greater than 090°. In each frame the southernmost severe deflection angle occurs within 30′ latitude of 32°N. It is the southernmost severe deflection of the front which would likely be called the 'seaward deflection of the Gulf Stream,' even though instantaneous frontal orientation angles may reach or exceed 090° in the leading portion of a meander crest northeast of there. The view of the Gulf Stream in Figure 1 displays severe frontal orientation angles not only at the site of the deflection near 32.5°N but also along the leading portions of the meander crests near 33.7°N and 34.5°N.

A comparison may be made between Figure 9 and the time series of satellite-observed frontal patterns presented by *Legeckis* [1979, Figures 9 and 10]. In his data, that section of the Gulf Stream's surface temperature front which one would call the seaward deflection of the stream was always the leading portion of a meander crest. For a 25-day period during February 1976 and a 10-day period during April 1977 (which includes the data shown here in Figure 1) the progression of the meanders through the deflection region was such that the southernmost severe deflection angle occurred first along the leading edge of one meander pattern, then along the leading edge of the following meander, and finally along the leading edge of a third meander. This sequence is consistent with the kinematical model presented in Figure 9. Thus the cause of the short-term variability in the location and orientation of the seaward deflection of the Gulf Stream near 32°N may likely be the propagation of rapidly amplifying Gulf Stream meanders through the region.

SUMMARY

The observations presented here provide an initial description of the subsurface structure and short-term variability of the seaward deflection of the Gulf Stream, which occurs near 32°N off the southeastern United States. For the two observational periods during February and November 1979, frontal deflection angles ranged from about 050° to nearly 095° clockwise from true north, and the deflection displayed variations in its vertical structure.

The greatest deflection angle at each level and the most pronounced vertical structure in the deflection were observed on February 10, which was during wintertime conditions. At that same time, two large-amplitude meanders were progressing northeastward away from the deflection region. The observations made during the few days following February 10 revealed deflection angles near 070° at all levels. It appears that the Gulf Stream was in an 'average,' low-meander-activity configuration during the later February observations.

Late summertime thermal conditions prevailed during November. Deflection angles varied less than in February, and the structure of the deflection was always quite vertically coherent. Since meanders were observed to be progressing away from the deflection at that time, this situation is in contrast to the February observations, perhaps because of the differing hydrographic conditions. *Singer et al.* [this issue] have indicated that a relationship may exist between large (small) Gulf Stream transport in the deflection region and a high (low) deflection angle. According to this indication and the annual transport variations reported by *Fuglister* [1972], relatively low deflection angles would be expected during November, a time of small transport. This

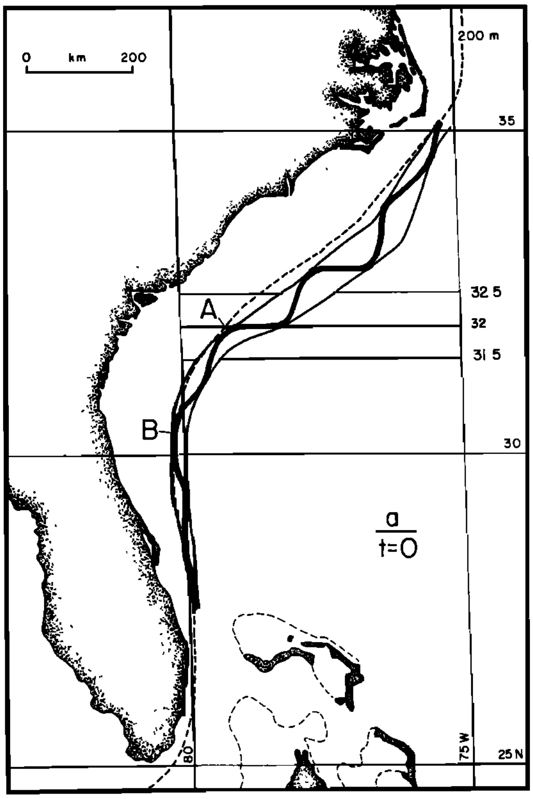

Fig. 9*a*

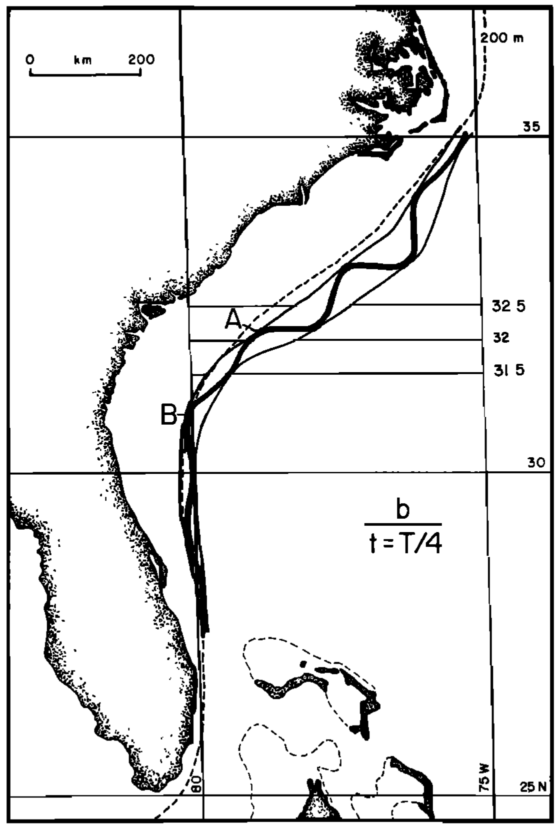

Fig. 9*b*

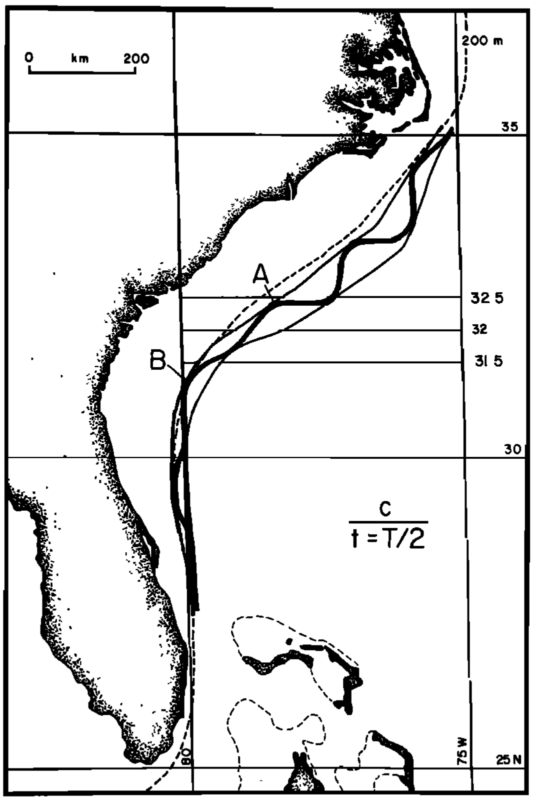

Fig. 9*c*

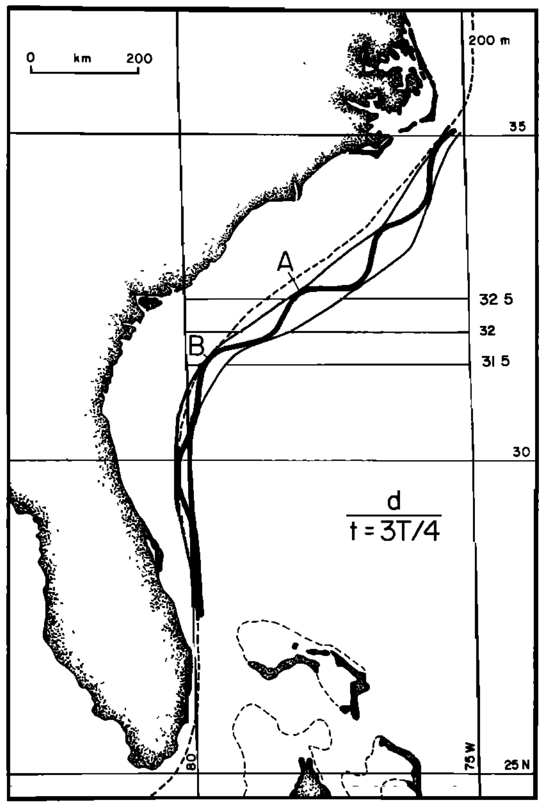

Fig. 9*d*

Fig. 9. A simple kinematical model showing 200-km wavelength sinusoidal meanders progressing along the mean frontal path shown in Figure 8. As the meanders progress through the region of amplification (where the standard deviation envelope widens rapidly between about 31.7°N and 32.5°N), the instantaneous front in the leading portion of a meander crest may be oriented at an angle greater than 090°, thereby giving a high deflection angle. The southernmost severe deflection angle always occurs between 31.5°N and 32.5°N, the latitude range of the seaward deflection of the Gulf Stream as determined from satellite SST data.

explanation does not, however, account for the differences in the short-term variability of the deflection angles between February and November 1979. Because of the relatively short time periods covered by our AXBT surveys, it remains to be determined if the observed deflection variability is representative of those times of the year.

A dome-shaped volume of cool water was observed to be located over the upper continental slope immediately downstream of the deflection. The existence and persistence of this cold dome suggest that upwelling is important in its maintenance, a hypothesis consistent with its hydrographic properties. The dome was found to contain about 4×10^{12} m^3 of water above the 400-m level and below the 17°C isothermal surface, which usually extended upward to a depth of about 70 m. The general thermal structure of the dome suggests a cyclonic flow around the cold core of water, but no conclusion regarding circulation can be based on these temperature data alone.

Variability in the degree and location of the surface manifestations of the deflection, which have been seen in satellite-observed SST images, may be explained by the propagation and amplification of Gulf Stream meanders. A simple kinematical model which uses typical Gulf Stream path and meander parameters has reproduced the severe deflection of the Gulf Stream within 30′ of latitude of 32°N, the location of the deflection region according to several analyses of satellite data.

The AXBT surveys that we conducted during 1979 have given only the first few synoptic looks at the deflection and associated cold dome. Further field observations will be required to better define the deflection process and, more important, to determine the role which is played by the deflection in causing variability in the Gulf Stream farther downstream.

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