GULF STREAM MEANDERS ALONG THE CONTINENTAL MARGIN FROM THE FLORIDA STRAITS TO CAPE HATTERAS

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Abstract: A rapid increase in the magnitude of Gulf Stream meanders downstream of a seaward deflection of the Stream off Charleston, South Carolina, has been indicated by an analysis of the shoreward surface thermal front of the Stream. The sixty four cases examined show that lateral movements of the Stream from Charleston to Cape Hatteras may be as great as 40 km from the mean, whereas upstream of Charleston the movements are generally less than 15 km in amplitude. This difference points to the importance of the deflection of the Stream by a bottom feature off Charleston in producing Gulf Stream meanders.

Introduction

The existence of Gulf Stream meanders along the continental margin from the Florida Straits to Cape Hatteras has been recognized for several decades. Meanders of the Stream have been observed in density and current data (*Fuglister and Worthington,* 1951; *Webster,* 1961; *Lee and Atkinson,* 1977) as well as in satellite views of sea surface temperature (SST) patterns (*Legeckis,* 1975, 1979; *Maul, et al.,* 1978). The meanders are characterized by lateral shifts of the Stream, which may be as great as forty kilometers from its mean position. The alongshore structure of the meanders inferred from SST patterns may be wavelike or eddylike, and these perturbations have been observed to move downstream with speeds on the order of 40 cm sec $^{-1}$ (*Legeckis,* 1975).

A typical example of the SST structure in this region is shown in Fig. 1. The large undulations evident in the strong, shoreward thermal front between the warm Gulf Stream surface waters and the relatively cold shelf waters indicate a subsurface cross-slope movement of the Stream which results from the meandering path taken by the core of the Stream. Three common features of the SST field in this region are exhibited in Fig. 1. The first is the relative "smoothness" of the shoreward surface thermal front between the Florida Straits and about 32°N. Relatively small (*ca.* 10 km) lateral movements of the Stream occur here, with spin-off eddies occasionally developing into elongated patterns with shelf/slope water apparently being entrained into the edge of the Gulf Stream. *Lee* (1975) and *Lee and Mayer* (1977) have described these eddies and believe they evolve from growing instabilities, which may initially be wind induced.

The second feature to note is the seaward deflection of the surface front at about 32°N latitude. This deflection has been observed in the subsurface temperature structure (*Fuglister and Voorhis,* 1965) and repeatedly in SST patterns (*Brooks and Bane,* 1978). *Legeckis* (1976) has suggested that the deflection is due to the Stream flowing around a bulge in the continental slope off Charleston, South Carolina, in a manner consistent with the conservation of potential vorticity. *Brooks and Bane* (1978) have presented quantitative evidence that the deflection is a remarkably persistent feature which often directs the surface thermal front due east, and occasionally south of east. They found that the mean latitude plus or minus one standard deviation for the eastward deflection of the thermal front was 31°59'N ± 23'. The mean is designated Θ_E in Fig. 1. This position for the deflection supports the hypothesis that it is associated with the ridge and trough bottom structure off Charleston. This previously unnamed feature has become known as the "Charleston bump." Using sub-bottom seismic data, *Ewing et al.* (1966) suggested that the feature may be an eroded area of the southwestern flank of a geologic structure known as the Cape Fear Arch.

The third portion of the SST field of interest is the region downstream of the deflection. The frontal meanders that occur in this area appear in satellite SST patterns to have consistently greater cross-slope displacements than those upstream of the deflection. This suggests the generation of a wake phenomenon downstream of the Charleston bump.

The purpose of this letter is to present data that describe the path of the Stream from the Florida Straits to Cape Hatteras and give quantitative support to the observation that the meanders downstream of Charleston are of distinctly greater amplitude than those upstream.

Sea Surface Temperature Analysis

In an attempt to quantify the relative strength of Gulf Stream meanders along the continental margin, 64 Experimental Ocean Frontal Analysis (EOFA) SST composites, produced weekly by the U.S. Naval Oceanographic Office, were analysed. The composites span the time period from 5 January 1977 to 29 March 1978. For this analysis, fourteen sections were constructed. They are spaced at about 80 km intervals along the 200 m depth contour, with each section oriented perpendicular to that contour (Fig. 2).

The location of the inshore surface temperature front as depicted in each EOFA composite was used as an indicator of the Stream's position. Due to the occasional presence of eddylike filaments along this front, the choice of front location was not always unique. Two positions were used to locate the front for those times when the frontal line crossed a section more than once. The first method used the actual front position closest to shore. The second position was found for a frontal line which was smoothly contoured through the filaments near what appeared to be the main edge of the Stream. This was done to provide a more conservative estimate of the magnitude of the meandering of the bulk of the Stream.

The mean position of the front for each data set was calculated, and the mean front using method 1 data is shown in Fig. 2. The mean front from method 2 was not found to be significantly different from this. The effect of the frequently occuring seaward deflection off Charleston is noticeable near sections 7 and 8. The mean front position is slightly north of the bump there. This is due primarily to the influence in the averaging process of those times when the Stream is deflected only slightly or not at all.

The standard deviation of the front position may be used as an indicator of the strength of Gulf Stream meander activity in this region. Two curves of position standard deviation vs. section were found, and are displayed in Fig. 3. The curve shown with open boxes was determined by using data from the first method of defining the front position, while the curve with solid triangles was found from the second method data set. The distribution of the relative strength of meander activity, as indicated by these curves, is consistent with the previous discussion. The greatest meander amplitudes seem to occur between sections 8 and 13 where the standard deviation is greatest. Even the more

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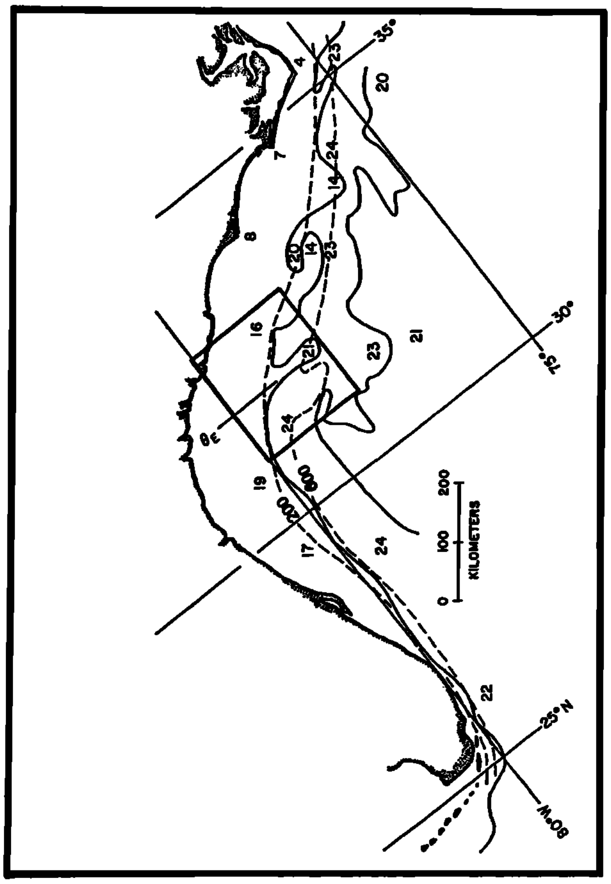

Fig. 1. Composite sea surface temperature map of the Gulf Stream region along the continental margin of the U.S. for 15 February 1978. The map was derived from one of the experimental Ocean Frontal Analysis charts prepared weekly by the U.S. Naval Oceanographic Office. The NOAA-5 satellite infrared images from 12-14 February were used to locate shoreward and seaward surface fronts, shown by the solid lines. Ground-truth sea surface temperatures (degrees Celsius) are shown to highlight the frontal structure. The symbol Θ_ϵ denotes the latitude at which the front reaches its eastward deflection. The 200 m and 600 m bottom contours are shown by the dashed lines. The "Charleston bump" is indicated by the shape of the 600 m isobath near 32°N. (After *Brooks and Bane*, 1978.)

conservative method 2 results show the standard deviation there to be about twice the average standard deviation found for sections 1 through 7. The rapid increase evident in both curves from section 7 to section 8 implies that the strong downstream meanders are generated in this area, probably as a wake "behind" the Charleston bump.

Two other features of the Gulf Stream system in this region are suggested by Fig. 3. The gradual increase in standard deviation from section 1, located at the northern end of the Florida Straits, to section 7 may result from spatially growing long waves in that portion of the Stream (*cf. Hogg*, 1976). Another possible explanation is that the meander activity is simply supressed in the southern sections due to the confinement of the Stream just south of there by the Florida Straits. The rapid decrease in both curves near section 14 may be due to the narrowness of the continental margin off Cape Hatteras, thereby reducing the scale of the cross-slope motions of the Stream. Furthermore, since the Stream flows away from the continental slope after passing Cape Hatteras, the fluctuations must transition from shelf/slope modes to deep water modes which have less topographic control. This transition appears to be characterized by a decrease in meander amplitude.

It is not known if the filamentous eddies on the inshore side of the Stream are a distinctly different phenomenon than the wavelike meanders, or perhaps represent a later stage of development of a Gulf Stream fluctuation. Information concerning the strength and occurrence of eddies may be obtained from the EOFA analysis. A measure of the horizontal excursions of the eddies is given by the difference between the two curves in Fig. 3. An estimate of the rate of occurrence of eddies is obtained by simply determining the percent of composites in which an eddy crosses a section. This percent is plotted in Fig. 4 for each section. The indications are that both eddy strength and occurrence are significantly greater downstream of the Charleston bump. However, due to difficulty in detecting the smaller scale eddies that form upstream of the bump, the estimate of eddy occurrence in that region may be unrealistically low.

Discussion

A rapid increase in the magnitude of Gulf Stream meanders downstream of a seaward deflection of the Stream off Charleston, South Carolina, has been indicated by an analysis of the shoreward surface thermal front of the Stream. Lateral movements of the Stream from Charleston to Cape Hatteras may be as great as 40 km from the mean, and are characterized by eddies or filaments occurring from 10 to about 50 percent of the time. Upstream of Charleston the movements are generally less than 15 km in amplitude with eddies occurring less than 10 percent of the time. These differences point to the importance of the

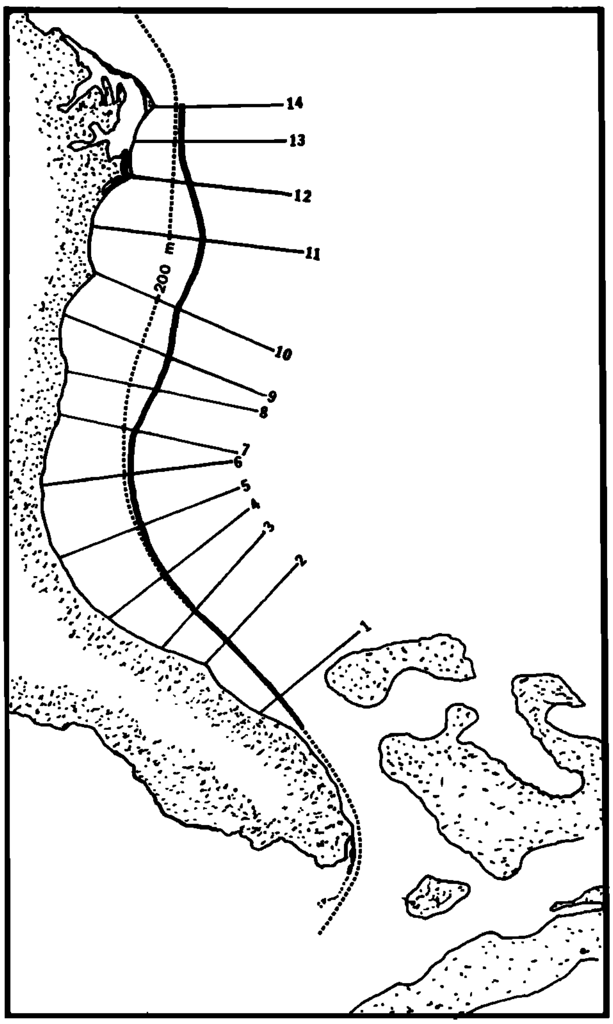

Fig. 2. The fourteen sections constructed perpendicular to the 200 m isobath for the analysis of the position of the Gulf Stream surface thermal front. Spacing between the sections is approximately 80 km, except in the region of the Carolinas where the sections are placed either at a Cape or midway between two Capes. The solid line is the mean position of the front for the 64 SST composites.

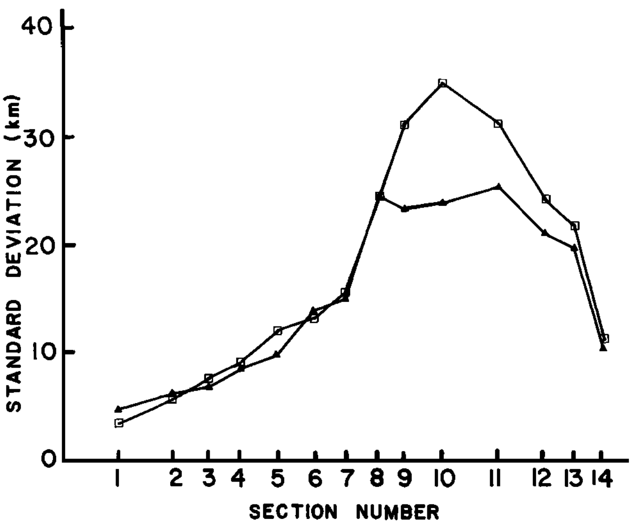

Fig. 3. The standard deviation of the surface front position for each section, in km. Spacing of the section numbers along the horizontal axis is proportional to the spacing of the sections along the mean frontal line (Fig. 2). The curve defined by the open boxes results from using the inshore most crossing of the frontal line on each section. The curve with solid triangles is from calculations using the "smoothed" front.

deflection of the Stream by the Charleston bump in producing Gulf Stream meanders.

Topographic Rossby waves constitute one class of oceanic long wave motion possible over a sloping bottom such as the continental margin along the southeastern United States. It is not known whether the Gulf Stream meanders in this area fall into this class, or are controlled by other dynamics, for example baroclinic instability (*Orlanski and Cox*, 1973). For topographic Rossby waves to be induced in the Stream by the Charleston bump, it is necessary to have a downstream flux of wave energy (i.e. downstrem group velocity). Numerical models of stable barotropic and baroclinic topographic Rossby waves in the Gulf Stream have been developed (*Brooks and Mooers*, 1977; *Bane*, 1977). Dispersion curves from those studies show that group velocities in the downstream direction are possible for both modes. Upstream as well as downstream phase propagation is allowed for the barotropic waves, whereas only downstream phase propagation was found for the

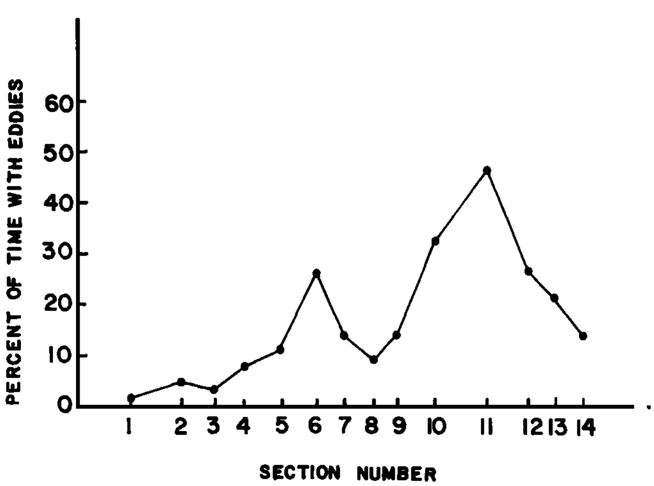

Fig. 4. Percent of composites in which a filamentous eddy crossed each section. The occurrence of an eddy is defined to be when the frontal line crosses a section more than once.

baroclinic waves. These properties suggest the possibility of a topographic Rossby wave wake in the Gulf Stream downstream of the Charleston bump.

Futher analysis of two years of Gulf Stream SST patterns south of Cape Hatteras is in progress and will reveal more of the spatial and temporal details of the fluctuations in this area. Additionally, a field program to directly measure *in situ* current and temperature fluctuations along the Gulf Stream front is being conducted and should produce data valuable in resolving the subsurface nature of, and the dynamics controlling Gulf Stream meanders along the continental margin.

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