frequently found in sediments. Work presented here does not disprove the earlier hypothesis that temporary cysts may cause shellfish toxicity. However, temporary cysts were not seen in the sediments and we believe that toxicity was caused by the large numbers of toxic resting cysts present.
7. E. S. Gilfillan, J. W. Hurst, S. A. Hanson, C. P. LeRoyer III, unpublished report to the New England Regional Commission, Boston, Mass., April 1976.
8. D. Wall, R. R. L. Guillard, B. Dale, *Phycologia* **6** (2/3), 83 (1967).
9. Concentrations of cysts were often in excess of 100 per slide as compared with 5 to 20 per slide in samples from other areas.
10. Cysts with intact cell contents included four species of *Gonyaulax*, three species of *Protoperidinium*, and a species of *Scrippsiella*.
11. We used a micropipette to pick off cysts and cleaned them by several transfers through drops of distilled water. Clean cysts were concentrated by centrifugation and rinsed three times with distilled water with centifugation. Then 509 cysts were sonicated vigorously, acidified, and injected into mice (Jackson strain) with the standard PSP bioassay. Isolated cysts produced classical signs of toxicity, yet the death time was not within the standard limits. Sieved sediments containing 14,700 cysts (cyst numbers were estimated on the basis of counting 0.1 ml of the 15-ml total sample) were then analyzed according to the same procedure, divided into four parts, and injected into four mice; the death times (267 sec/19.0 g, 261 sec/19.0 g, 250 sec/19.5 g, and 239 sec/19.5 g) were well within the standard limits. Since isolated cysts proved to be toxic, we assume that toxicity in sieved sediment was caused by the included cysts, but the theoretical possibility that other particles in the sediment were significantly toxic cannot be discounted.
12. We induced temporary cysts (*5*) from motile cells by subjecting cultures growing at 18° to 5°C. Both temporary cysts and motile cells were filtered onto Gelman glass-fiber filters and ground with 0.1*N* HCl with a tissue homogenizer. We then refiltered this solution and injected it into mice (Jackson strain), using the standard PSP bioassay.
13. If cysts break down to release toxins in human digestion, even intact cysts in the stomach contents of ingested shellfish could cause PSP; moreover, it seems likely that cysts may break down in shellfish digestion since *G. excavata* cyst walls are less resistant to chemical and biological degradation than those of most other dinoflagellates. Chemical treatment of sediments for palynological preparation destroy *G. excavata* cysts; in naturally occurring sediments *G. excavata* cysts apparently break down and are lost whereas most other cysts persist into the fossil record.
14. B. Dale, *Rev. Palaeobot. Palynol.* **22**, 39 (1976).
15. K. A. Steidinger, *Environ. Lett.* **9**, 129 (1975).
16. Cysts collected on 4 October 1977 lacked conspicuous red-pigmented cell inclusions previously described for mature *G. excavata* resting cysts (*5*), whereas most had developed this by 21 November 1977 and virtually all cysts had developed this by 17 December 1977. By the 30 January 1978 collection, cyst contents darkened and showed Brownian-like motion.
17. We periodically isolated resting cysts from the sediments and tested for viability by placing cysts at conditions of light and temperature known to induce excystment (*5*). Several excysted from sediment collected on 30 January 1978 and tested viable on 6 February 1978, suggesting a mandatory resting period of at least 4 months.
18. It should not be presumed that possible dangers would be avoided because dumping dredged-up sediment at sea would bury or dilute any cysts present. Cysts would sediment out with the fine silt fraction after dumping and thus would usually settle at or near the sediment surface.
19. We thank M. L. Brann, R. Bryer, C. Lewis, F. Mague, and C. Mickelson for field and laboratory assistance. We thank Drs. T. Braarud, R. C. Dugdale, J. Gray, G. Hasle, I. Morris, E. Paasche, T. T. Packard, and C. S. Yentsch for constructive criticisms of the manuscript. This work was supported in part by Food and Drug Administration contract 223-76-2311, National Institute of Environmental Health Sciences contract ESO-1329-01A1, National Science Foundation contract OCE-76-10518, Norwegian Research Council for Science and Humanities contract D40.31-15, and Maine Department of Marine Resources contract 4-77. Bigelow Laboratory contribution No. 77023.

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Gulf Stream Deflection by a Bottom Feature off Charleston, South Carolina

Abstract. *A topographic feature on the continental slope off Charleston at 32°N persistently deflects the Gulf Stream seaward, with the inshore surface thermal front deflected east or south of east in 27 of the 39 cases examined. Meanders often form downstream of the deflection, suggesting that the "Charleston bump" induces Gulf Stream fluctuations.*

A frequent seaward deflection of the Gulf Stream occurs over a ridge and trough bottom irregularity in the continental slope at about 32°N off Charleston, South Carolina. Satellite observations of sea-surface thermal patterns show a considerable difference in the magnitude of the Gulf Stream fluctuations upstream and downstream of the "Charleston bump," with greater fluctuations occurring downstream. The winter example in Fig. 1 shows large undulations most evident in the shoreward thermal front between the warm Gulf Stream surface waters and the relatively cold shelf waters (*1*). The existence of Gulf Stream meanders in the South Atlantic Bight has been recognized for several decades (*2*), and several theories have been advanced, with varying degrees of success, to explain their generation, propagation, and decay (*3*). However, persistence of the deflection off Charleston (*4*), its association with a bottom irregularity (*5*), and its potential significance in modifying the downstream character of meanders (*6*) have only recently been appreciated.

Surface isotherms are known to be reasonably well correlated with the deeper hydrographic and velocity structure of the Gulf Stream in the South Atlantic Bight (*7*), and the inshore surface thermal front in Fig. 1 may be associated with the shoreward edge of subsurface Gulf Stream flow. The Stream extends essentially to the bottom in this area (*8*) and thus must make dynamical adjustments as it flows over bottom topography. The simplest application of the vorticity conservation theorem predicts a seaward curvature of the Stream when it flows over a bump on an otherwise featureless continental slope.

The detailed bottom topography including the region enclosed in a box in Fig. 1 is shown in Fig. 2 (*9*). The crest of the ridge runs approximately transversely to the Stream as it enters the boxed area, and turns generally eastward farther offshore, trending toward the Blake Outer Ridge. A narrow trough or channel traceable to the base of the Blake Plateau at a depth of about 2 km runs eastward on the downstream side of the ridge. Ewing *et al.* (*10*) suggested that the ridge and trough system off Charleston may be a result of erosion along the southwestern flank of a geologic structure known as the Cape Fear Arch, which extends seaward toward the Blake Outer Ridge. Uchupi (*11*) sug-

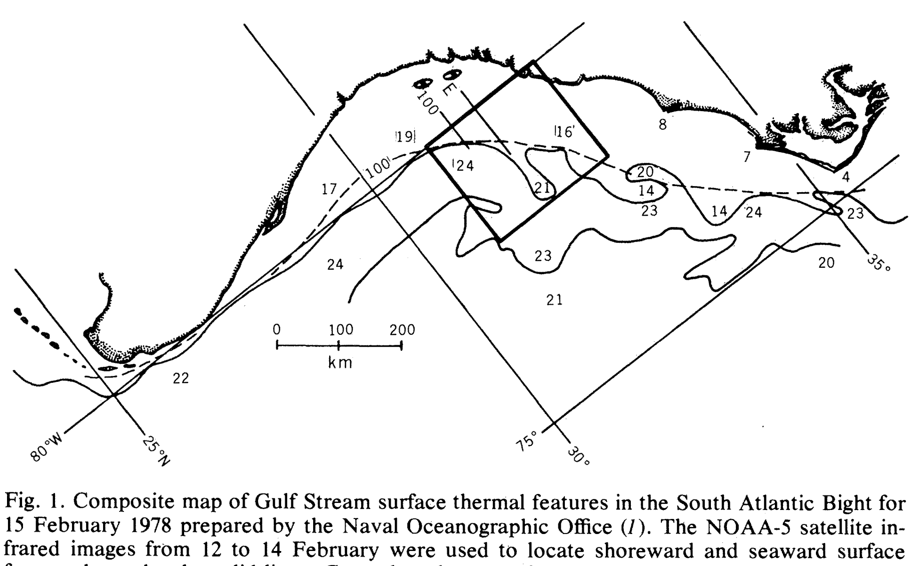

Fig. 1. Composite map of Gulf Stream surface thermal features in the South Atlantic Bight for 15 February 1978 prepared by the Naval Oceanographic Office (*1*). The NOAA-5 satellite infrared images from 12 to 14 February were used to locate shoreward and seaward surface fronts, shown by the solid lines. Ground-truth sea surface temperatures (degrees Celsius) are shown for comparison with the frontal structure. Symbols: θ_{100} is the latitude at which the inshore front turns seaward of the 100-fathom contour shown by the dashed line, and θ_E is the latitude at which the front reaches an eastwardly deflection. The detailed bottom topography in the region in the box is shown in Fig. 2.

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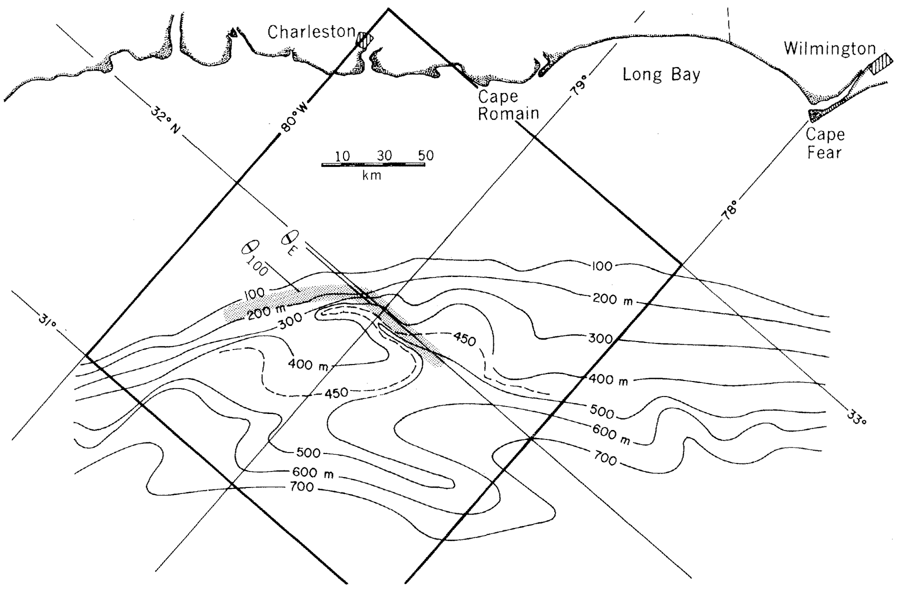

Fig. 2. Bottom topography including the boxed region in Fig. 1, showing the ridge and trough irregularity off Charleston known as the "Charleston bump." The contours in meters were interpolated from the original chart (*9*), which was contoured with an interval of 25 fathoms (45.7 m). The mean position of the inshore surface thermal front suggested by $\bar{\theta}_{100}$ and $\bar{\theta}_E$ is shaded.

gested that the Gulf Stream may have been deflected southeastward by the ridge during a lower stand of sea level.

To test the persistence of the topographic deflection process, 39 surface thermal composites spanning the period 6 April 1977 to 1 March 1978 were examined. The composites were produced by the Naval Oceanographic Office at approximately weekly intervals, except for the latter half of November and all of December. Since the inshore surface thermal front is the most discernible Gulf Stream feature in the composites, it was used to estimate where the Stream began its seaward deflection by noting the latitude (θ_{100}) at which the front crossed the 100-fathom (183-m) contour (the only contour shown on the composites). In 37 (95 percent) of the composites, θ_{100} occurred inside the boxed region. In the remaining two cases, the front was offshore of the chosen isobath but still meandered seaward in the boxed region. In 27 (69 percent) of the composites, the deflection was sufficient to direct the Stream eastward or even south of east, and in those cases the latitude (θ_E) at which the front first reached its eastward direction was also recorded. The mean latitudes ± 1 standard deviation are $\bar{\theta}_{100} = 31°49' \pm 20'$ and $\bar{\theta}_E = 31°59' \pm 23'$. When compared with the topography in Fig. 2, these results suggest that the deflection of the Stream is a remarkably persistent feature associated with the ridge and trough bottom structure off Charleston. The mean frontal path suggested by $\bar{\theta}_{100}$ and $\bar{\theta}_E$ is shown by shading in Fig. 2. After being deflected over the ridge, the front often follows the trough offshore 50 to 100 km.

Although the Stream deflection off Charleston seems to be a quasi-stationary feature, the wave or eddy-like meanders in the lee of the ridge have been observed to drift slowly downstream at 30 to 40 km/day (*12*). Cyclonic cold-core eddies with alongshore scales of 100 to 150 km and apparent inshore currents setting southwestward are often observed to form along the inshore edge of the Stream. Three or four such eddies are suggested in Fig. 1. Southward setting eddy currents in this area were impediments well known to early sailors northward bound; John White in 1590 gave the first written account of their presence and advised vessels to stand well off to sea where a "much swifter" current could be found to aid their passage (*13*).

The similarity between the eddy scale in Fig. 1 and the alongshore separation of the four Carolina capes suggests an interaction between the eddies and the coastal boundary. A causative link between Gulf Stream eddies and the cuspate Carolina forelands was first suggested in 1895 by Abbe (*14*). He envisioned cyclonic "back-set" eddies meshed with the bays. The eddies contributed to the structure of the capes by interfering with the southwestward coastal sediment drift. Figure 1 resembles an intuitive sketch in Abbe's paper, although the eddy pattern shown here is not stationary with respect to the bays and does not always occur with such regularity. However, calculations show that stationary or nearly stationary continental shelf waves with wavelengths of about 100 km and downstream energy flux are admissible free modes of the Carolina shelf wave guide, leading to the speculation that the "Charleston bump" may resonantly force lee shelf waves in the Gulf Stream (*6*).

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References and Notes

1. The surface thermal composite maps from which Fig. 1 was derived are prepared by the U.S. Naval Oceanographic Office as an experimental ocean frontal analysis. The primary data source is the NOAA-5 satellite infrared images, from which the frontal structures shown by solid lines in Fig. 1 were contoured. Supporting data from the Coast Guard airborne radiation thermometry program and from bathythermographs have been used as "ground-truth" information wherever possible. Much more detailed temperature structure seaward and shoreward of the Stream is shown in the original composite.
2. F. C. Fuglister and L. V. Worthington, *Tellus* **3**, 1 (1951); F. Webster, *Deep-Sea Res.* **8**, 130 (1961); T. N. Lee, *ibid.* **22**, 753 (1975).
3. B. A. Warren, *Tellus* **15**, 167 (1963); P. P. Niiler and L. A. Mysak, *Geophys. Fluid Dyn.* **2**, 273 (1971); I. Orlanski and M. D. Cox, *ibid.* **4**, 297 (1973).
4. R. M. Pratt, *Deep-Sea Res.* **10**, 245 (1963); J. A. Knauss, *ibid.* **16** (Suppl.), 117 (1969); D. J. Pashinski and G. A. Maul, *Mariners Weather Log* **17**, 1 (1973).
5. R. Legeckis, *Eos* **57**, 260 (1976).
6. D. A. Brooks, *ibid.*, p. 940; J. M. Bane, Jr., *ibid.* **58**, 1158 (1977); D. A. Brooks, *J. Phys. Oceanogr.* **8**, 323 (1978).
7. F. Webster, *Deep-Sea Res.* **8**, 130 (1961); F. M. Vukovich, *J. Phys. Oceanogr.* **6**, 605 (1976); T. N. Lee and D. A. Mayer, *J. Mar. Res.* **35**, 193 (1977).
8. W. Richardson, W. Schmitz, Jr., P. P. Niiler, *Deep-Sea Res.* **16** (Suppl.), 225 (1969).
9. The bottom contours in Fig. 2 were taken from the 1970 Bathymetric Map of the Eastern Continental margin, published by the American Association of Petroleum Geologists. The original chart was contoured in increments of 25 fathoms (45.7 m); the isobaths in Fig. 2 were hand-interpolated to contours in meters.
10. J. Ewing, M. Ewing, R. Leyden, *Bull. Am. Assoc. Pet. Geol.* **50**, 1948 (1966).
11. E. Uchupi, *Southeast. Geol.* **8**, 155 (1967).
12. Analysis of daily satellite infrared images by R. Legeckis has shown that the meander patterns between Charleston and Cape Hatteras move downstream in the Gulf Stream with phase speeds of 30 to 40 km per day. A similar study of meanders upstream of Charleston is given in R. Legeckis, *Geophys. Res. Lett.* **2**, 435 (1975).
13. John White's narrative of the 1590 voyage to Virginia [in *The Roanoke Voyages*, D. Quinn, Ed. (Hakluyt Society, London, 1952), vol. 1, p. 608] states: "For from the Cape [of Florida] to Virginia all along the shore are none but eddie currents, setting to the South and Southwest."
14. C. Abbe, *Proc. Boston Soc. Nat. Hist.* **26**, 489 (1895).
15. Supported in part by Office of Naval Research contract N-00014-77-C-0354 and in part by National Science Foundation grant OCE77-20971. We acknowledge helpful discussions with G. Janowitz and L. Pietrafesa and especially with R. Legeckis. The historical research on Gulf Stream eddies was enthusiastically done by C. Knapp.

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