Temporal and Spatial Characteristics of Summer Upwelling along Florida's Atlantic Shelf[1]

NED P. SMITH

Harbor Branch Foundation, Inc., Fort Pierce, FL 33450

(Manuscript received 10 November 1982, in final form 25 April 1983)

ABSTRACT

Temperature data from shelf waters along Florida's Atlantic coast are used to characterize upwelling during the summer of 1980. Bottom temperatures, recorded at seven stations across the shelf and during 14 weekly cruises between early July and mid-September, show a continual cross-shelf movement of the isotherms, but only one primary upwelling event, during the first three weeks of August. Upwelling ends with an exceptionally rapid warming over a one-week period. The largest net temperature increase of about 10°C occurs at mid- and near-bottom depths over the middle shelf. Temperature-recorder data from four stations spaced along the 10 m isobath suggest that upwelling events arrive on the inner shelf along relatively restricted sections of coastline and persist between one and three weeks. Surface-drogue data reveal an increase in current speed coinciding with lowest bottom temperatures. This lends support to the likelihood that the Florida Current is the primary cause of upwelling in Florida Atlantic shelf waters.

1. Introduction

The Atlantic coast of Florida is one of a relatively few east-coast settings which experiences well-defined and recurring seasonal upwelling. Effects have been reported in terms of anomalously low multi-year monthly-mean surf temperatures in summer months (Green, 1944; Taylor and Stewart, 1958). More recently, current and wind data were combined with temperature data to describe temperature variations along a cross section extending seaward to the shelf break off Cape Canaveral (Leming, 1979). Results were used to postulate upwelling as a response to seasonal variations in coastal wind patterns.

Two recent investigations (Smith, 1981, 1982) have called into question the concept of summer upwelling along Florida's Atlantic coast in response to a wind-driven, seaward-directed Ekman transport. Near-bottom temperatures from the 10 m isobath were compared with both longshore and cross-shelf components of wind stress, and coherence values were not statistically significant over time scales normally associated with meteorological forcing. On the other hand, variations in near-bottom longshore flow in mid-shelf waters were coherent with variations in near-bottom temperatures over time scales in excess of approximately two days. The phase lead of long-period increases in northward flow over decreases in temperature was ~90°.

Several explanations have been offered for east-coast upwelling even in the absence of wind-stress forcing. Hsueh and O'Brien (1971) have described upwelling in response to a northward flowing longshore coastal current. A breakdown in geostrophy in the lowest layers occurs when a boundary current comes in contact with a continental shelf. The local dominance of the shoreward-directed pressure gradient moves relatively cool water up the shelf and forces a compensating seaward return flow in the surface layer. Along the east coast of Florida, this process is a distinct possibility in view of the proximity of the Florida Current (Richardson *et al.*, 1969; Vukovich *et al.*, 1979). Nautical charts indicate that the mean position of the axis of the Florida Current in this part of the Straits of Florida is about 60 km offshore, but this may vary significantly. Unpublished data from the shelf break at latitudes 27°25′N and 27°35′N (Kerr, 1980) suggest that the cyclonic front moves onto the outer shelf aperiodically during summer months at least, and bursts of northward current speed are recorded at both near-surface and near-bottom levels.

Blanton *et al.* (1981) have described an alternate mechanism, also in response to a longshore current. Upwelling occurs when absolute vorticity is conserved in a current moving along a shelf with diverging isobaths. Smith (1982) has reported upwelling in mid-shelf waters along a section of the Florida east coast where the angle between the 20 m and 50 m isobaths is ~30°. The Florida continental shelf broadens in a northward direction (Fig. 1). The coastline is oriented approximately 340–160°, while the 100 m isobath lies nearly north–south. The shelf break occurs at the coast at latitude 26°45′N (Palm

[1] Harbor Branch Foundation, Inc., Contribution No. 334.

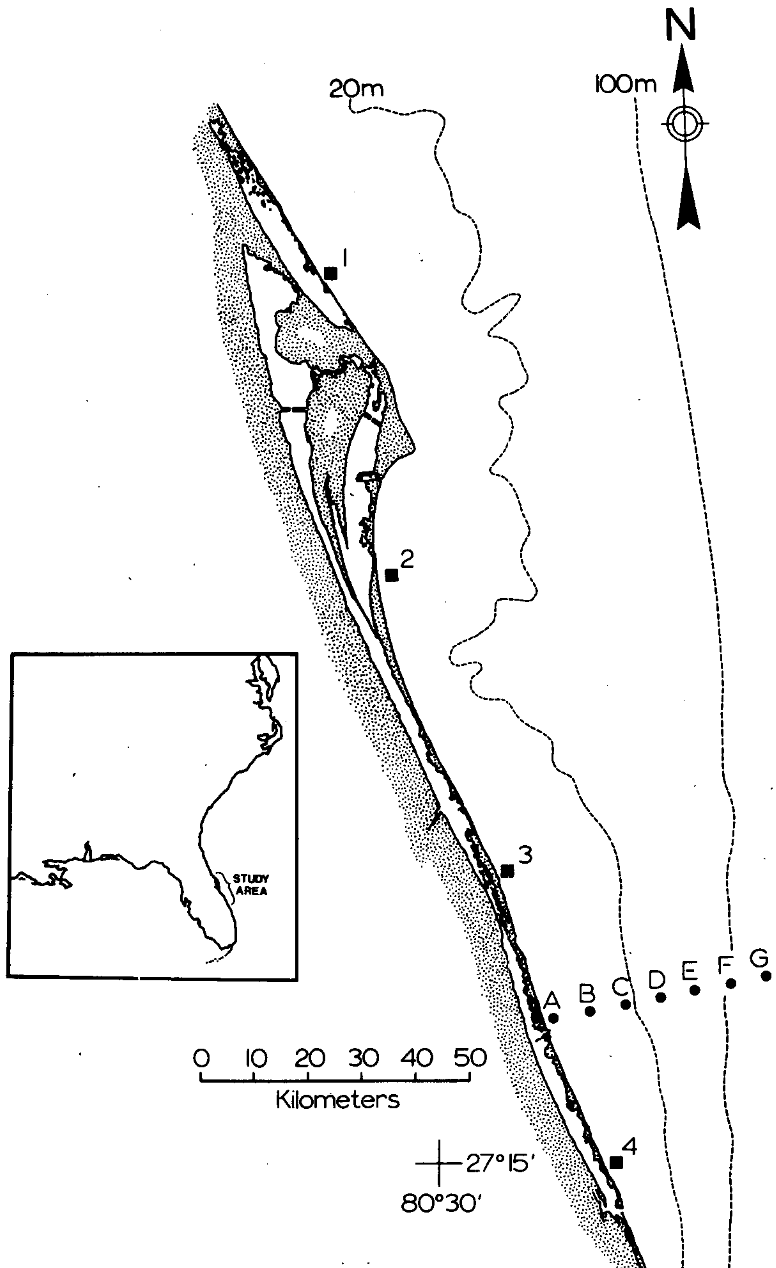

FIG. 1. Locations of hydrographic stations A–G and temperature-recorder stations 1–4 off the Atlantic coast of South Florida. Insert shows study area along the coast of the southeastern United States.

Beach) and is found just over 40 km offshore at latitude 28°30′N (Cape Canaveral). At latitude 27°30′N, the shelf is ~30 km in width, the shelf break occurs at about the 60 m isobath, and the cross-shelf gradient over the middle shelf is approximately 2.2 m km^{-1}.

The likelihood that the Florida Current plays a major role in explaining upwelling in Florida Atlantic shelf waters, during summer months at least, prompted a follow-up study in the summer of 1980. The field experiment included weekly cruises along a transect extending seaward 41 km to the shelf break (Fig. 1). Temperature cross sections traced the arrival and retreat of cool water associated with upwelling events between early June and mid-September 1980. Furthermore, four temperature recorders were spaced at 56 km (0.5° of latitude) intervals along the coast to determine the spatial representativeness of inner-shelf temperature data recorded at a single location.

Data relating the Florida Current to upwelling events were provided by surface-drogue drift vectors, originating at the outermost station of the transect.

2. Observations

Hydrographic cruises were conducted on 5 June, and then weekly from 26 June through 18 September. Temperature profiles at seven stations equally spaced between the 10 and 180 m isobaths were used to construct cross sections from the inner shelf to the shelf break. Temperatures were digitized at intervals ranging from 1 to 3 m, depending upon the thermal structure of the water column. Instrumentation used to measure temperature included a Beckman Model RS5-3 Field Salinometer, a Martek TDC Metering System, a Plessey Model 9060 Salinity/Temperature/Depth Profiling System, and Sippican R-603 Expendable Bathythermograph System. Temperatures were verified at the surface and 0.5 m above the bottom (except at the outermost station) with reversing thermometers. Temperature profiles and cross sections should be accurate to ±0.2°C.

Surface currents were determined from drogue drifts, originating at the outermost station on the transect. Positioning at the start and end of the trajectory was by LORAN-C aboard R.V. *Sea Diver*. Drifts were over an approximately 1 h period, and starting and ending positions were determined to the nearest 0.1 μs. This represents an accuracy of ~ ±1.0 cm s^{-1}, depending upon the LORAN line used and the time interval over which the drogue was in the water.

Bottom temperatures were recorded continuously at four stations, using ENDECO Inc., Type-109 film-recording thermographs, from 5 June through 13 September, 1980. Temperatures averaged over 2 h periods were used to calculate the daily-mean values that were used in turn to trace low-frequency variations in temperature along the 10 m isobath. Temperature-recorder data are accurate to within ±0.2°C, according to instrument specifications.

3. Results

Results of the 1980 upwelling study are put in perspective nicely with a plot of the bottom temperatures from the profiles at each of the seven stations along the transect, and from each of the 14 cruises between 5 June and 18 September. Fig. 2 contains isotherms of bottom temperatures as a function of distance from the coast, depth and time; cruise dates are entered along the time axis. The plot shows a continual cross-shelf movement of the isotherms, as relatively cool water first advances toward the coast, then retreats seaward.

The data reveal a single, major upwelling event. Isotherms start moving shoreward in late June though cooling over the inner and middle shelf is interrupted

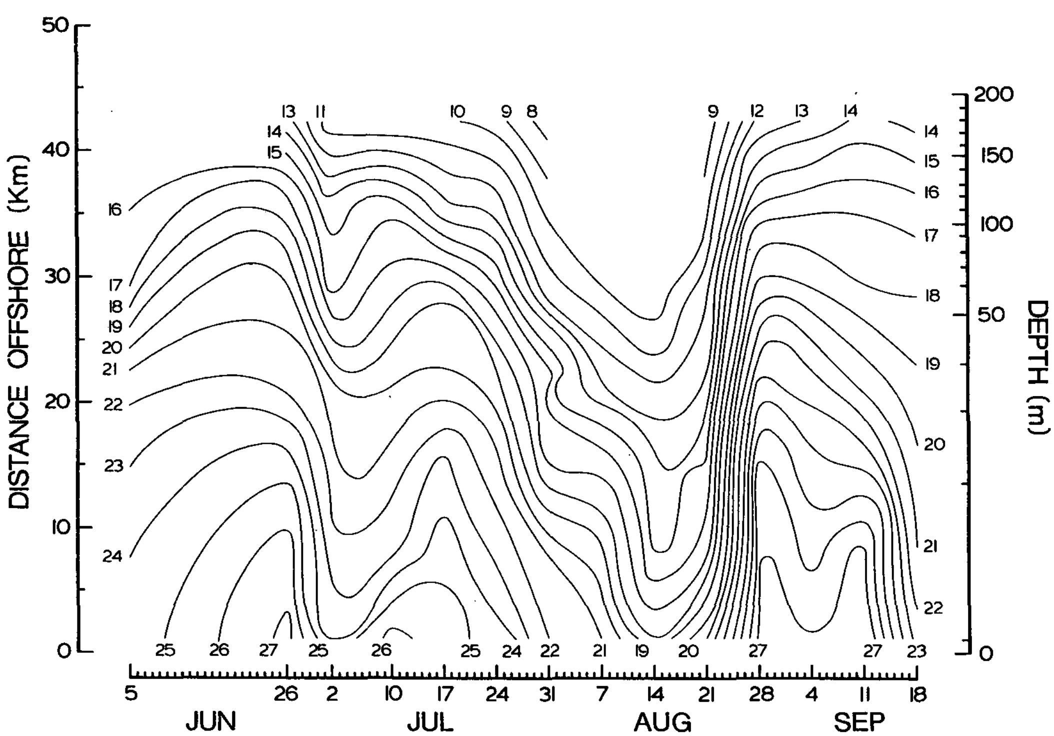

FIG. 2. Time-distance plot, showing isotherms of bottom temperatures (°C) measured at stations A–G, 5 June through 18 September 1980.

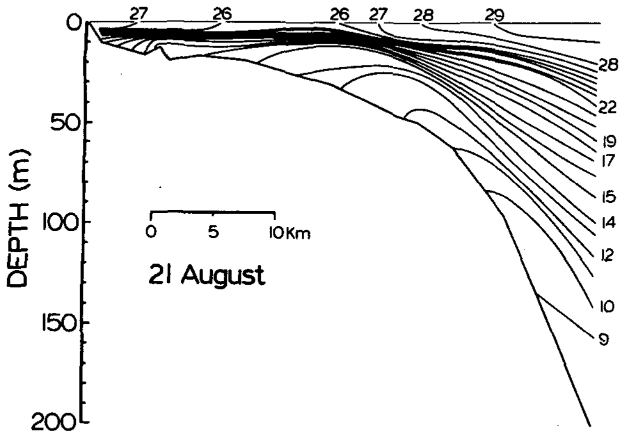

FIG. 3. Cross sections of temperature (°C) from stations A–G, 21 August 1980.

for about two weeks in mid-July. There is some suggestion that another upwelling event was starting in mid-September, but weekly cruises were terminated at that time, and thus the spatial and temporal extent cannot be characterized. A remarkable feature of the plot is the rapid warming recorded across the entire shelf between 21 and 28 August. This marks the end of the major upwelling event. Near-bottom temperatures increase ~10°C over the inner and middle shelf. Warming may have been somewhat more rapid, but the presence and absence of the upwelled water can be confirmed only by the profiles available from cruises on these two dates.

Lowest temperatures along the entire transect are recorded in mid-August; temperatures over the inner shelf decrease briefly to just under 19°C. Lowest recorded temperatures over the shelf break were just under 8°C. Minimum values were probably lower, but they were not recorded because of instrument failure on two consecutive cruises.

The temperature cross sections constructed from profiles obtained on the 21 and 28 August cruises are helpful for describing the two-dimensional structure of the water column across the shelf for both upwelling and post-upwelling conditions. Fig. 3 is the cross section constructed from the 21 August temperature data. Cool water has moved onto the inner shelf, and a well-developed thermocline is found at a depth of 10–15 m. The thermocline extends intact out to approximately 27 km from the coast. There isotherms diverge in the vertical and descend. This thermal structure is probably related to the Florida Current. There is a slight onshore-directed surface temperature gradient, with temperatures over the inner and middle shelf generally 2–3°C lower than over the outer shelf and continental slope.

The temperature cross section constructed from profiles collected on 28 August (Fig. 4) shows considerable warming through most of the transect. Only surface waters over the shelf break have remained at about the same temperature. The seasonal thermocline is poorly defined. Isotherms over the outer shelf tilt upward toward the coast, but this feature has decreased over the preceding week. An onshore-directed temperature gradient persists over the outer and middle shelf, with surface temperatures decreasing a full 2.5°C between the shelf break and a point 20 km from the coast.

Fig. 5 shows the net temperature change, from 21 to 28 August. Net warming was determined by subtracting temperatures recorded at a given station and depth on 21 August from those recorded the following week at the same location. Positive values indicate an increase in temperature over this period. Maximum warming of as much as 12°C is indicated at a depth of about 20 m over the middle shelf. This is due in part to the degradation of the thermocline. The advective transport of relatively warm water into the study area cannot be investigated with the available data. Within 30 km of the coast, near-bottom warming is consistently in excess of 8°C. In sharp contrast with the substantial net warming recorded below about the 10 m level, near-surface warming during this period is relatively slight. Maximum warming was 2.2°C at a point 13 km from the coast, and there was even a slight cooling recorded 27 km from the coast near the shelf break.

Temperature-recorder data collected along the 10 m isobath (see Fig. 1) have been combined in Fig. 6 to show in a qualitative way the onset and disappearance of upwelling events over the inner shelf along this part of the coast. Daily average temperatures were calculated from two-hourly values, and isotherms were contoured from the daily averages. Isotherms perpendicular to the time axis indicate simultaneous warming or cooling along the enclosed segment of coastline; isotherms paralleling the time axis reveal distinctly different hydrographic conditions at adjacent stations. Isotherms forming closed

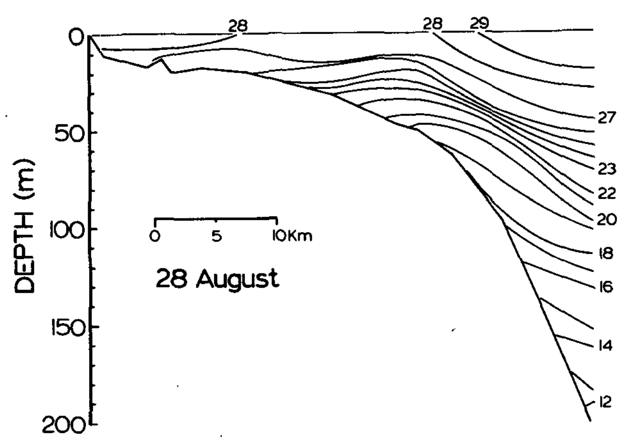

FIG. 4. As in Fig. 3, but on 28 August 1980.

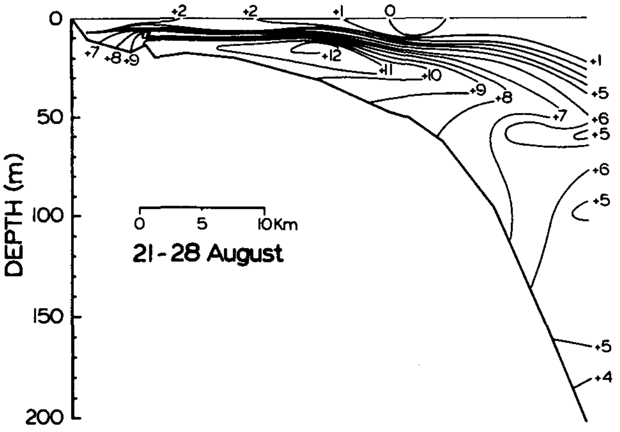

FIG. 5. Temperature changes (°C) from 21 to 28 August 1980. Positive values indicate a net warming.

loops indicate upwelling events that are both localized in space and transient in time.

Fig. 6 shows examples of isotherms oriented along both the time and space axes, but isotherms forming closed loops are more characteristic of the time and place of the study. Upwelling events tend to last on the order of 1–3 weeks over the inner shelf, and often a temperature minimum is recorded at only a single station. Inner-shelf bottom temperatures remain generally above 25°C at all four stations through the first week in July. At that time, water temperatures at Station 2, just south of Cape Canaveral, decrease to 20°C and remain low through the end of the month. During the last half of July, cool water is recorded at Stations 1 and 4, and finally at Station 3—at a time when warming is occurring at Station 2. Minimum temperatures at all four locations are slightly below 18°C, occurring generally during the last few days of July and the first half of August.

Bottom temperatures at Station 2 increase to characteristically non-upwelling levels during the first week in August. Within the following two weeks, similar warming is recorded at the other three stations. Except for a brief cooling at Station 1 in early September, inner-shelf bottom temperatures increase to what appear to be the annual maxima of around 27–28°C.

As noted previously, at the seaward end of the transect, a surface drogue was set adrift and recovered approximately one hour later. The mean Lagrangian surface-current vector was calculated from the end points of the trajectory. Results appear in Fig. 7; starting points are offset for clarity and plotted above the cruise dates along the time axis. All current directions are within ±14° of a heading of 355°, indicating strong bathymetric steering. Surface current speeds evolve through a cycle which includes an irregular increase in weekly drift speeds from early July through mid-August, a sharp decrease during the last part of August, and a second increase indicated over the last portion of the study. No information is available to quantify the near-bottom velocity, given only the surface current. The vertical structure of the current is unknown. Drogue data are presented only as additional evidence linking upwelling with variations in the Florida Current. If there is a consistent similarity in the near-surface and near-bottom currents, then the drogue data are compatible with earlier results (Smith, 1981, 1982) which suggest that the Florida Current is a primary driving force for upwelling along this part of the coastline.

4. Discussion

The longshore gradients in bottom temperature, as revealed in the plot of inner-shelf temperature-recorder data (Fig. 6), suggest that one cannot use temperature profiles from a single transect to characterize upwelling along the central Florida Atlantic coast in general. Upwelled water moving shoreward affects segments of coastline that may be only a few tens of kilometers in length. Information on the spatial ex-

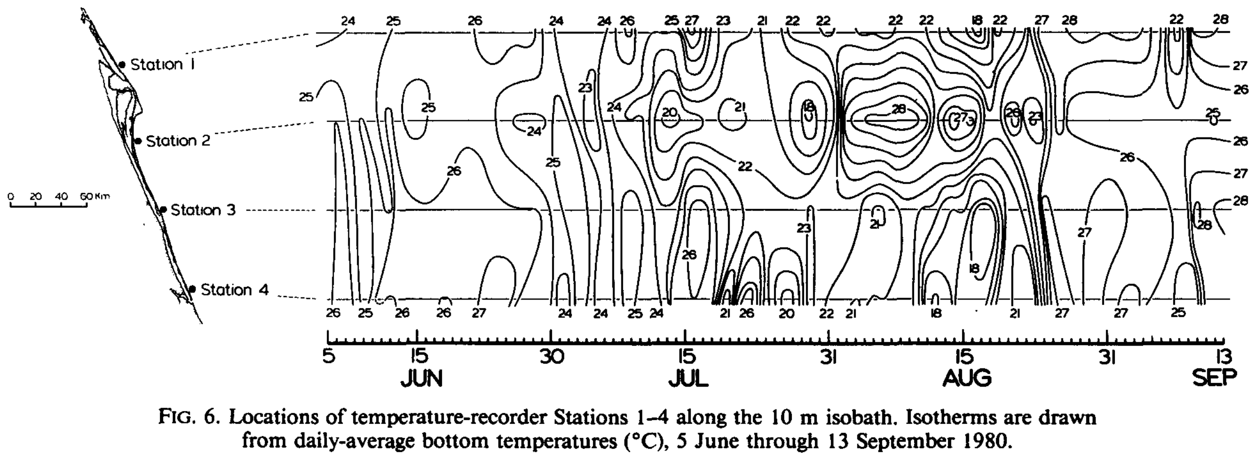

FIG. 6. Locations of temperature-recorder Stations 1–4 along the 10 m isobath. Isotherms are drawn from daily-average bottom temperatures (°C), 5 June through 13 September 1980.

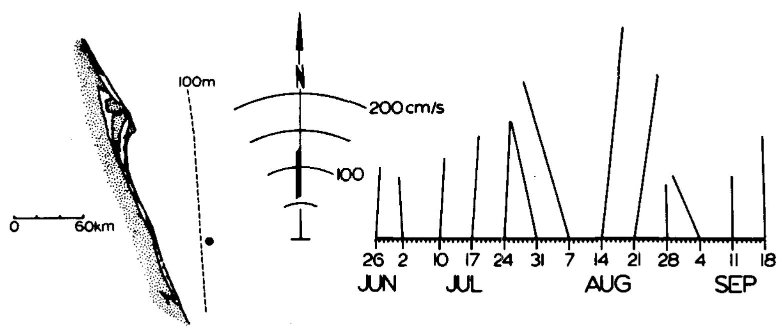

FIG. 7. Stick diagram of surface-drogue drifts, originating at station G (solid circle) 26 June through 18 September 1980. Current vectors are averaged over ~1 h.

tent of upwelling events is provided by the 1980 temperature-recorder data only in those cases when the cool water reached the inner shelf. In this study, as in earlier studies (Smith, 1981, 1982), one does not find evidence that an upwelling event ended before cool water reached the inner shelf, but this possibility cannot be ruled out. Thus, to adequately document the temporal and spatial aspects of upwelling, a substantial data base must be assembled, involving repetitive hydrographic data from a series of transects.

The surface drogue data lend support to the hypothesis that the Florida Current provides a primary driving force for coastal upwelling in this area, rather than wind stress (Smith, 1981). The plot of current speed versus time (Fig. 7) suggests a very close relationship between increases in current speed to the north and the shoreward movement of isotherms (Fig. 2). Clearly the drogue and temperature data reflect conditions at opposite ends of the approximately 180 m water column, and the vertical structure of the western edge of the Florida Current was not investigated as part of the 1980 upwelling study. While a forcing mechanism for coastal upwelling cannot be confirmed in this study, the qualitative comparison is encouraging.

An increase in current speed may indicate a general acceleration of the Florida Current; alternately it may reflect the westward migration of a meandering current axis. Several previous studies have provided information on the nature of meanders in the Florida Current. Vukovich *et al.* (1979) documented a meandering of the streamlines with satellite imagery, and drogue drifts have been used (Richardson *et al.*, 1969; Chew and Berberian, 1970) to quantify both the wavelength and the amplitude of the meanders. Wavelengths vary considerably but are generally on the order of 100–200 km. Chew and Berberian found an amplitude of 5 km in the Florida Straits; Webster (1961) reported an amplitude of 10 km off Onslow Bay (34°N).

The nature of these meanders bears directly upon the nature of upwelling. Specifically, the curvature of the streamlines, combined with the bathymetry of the outer shelf, determines the length of coastline that will receive the influx of cool water. The time scales associated with the evolution of the meanders, along with the lateral movement of the axis of the current, will determine the lifetime of an upwelling event. The longshore translation of a meander, again combined with outer-shelf bottom topography, will influence the longshore movement of the region of lowest temperatures. However, this will be influenced by the circulation over the inner shelf as well. The 1980 data indicate relatively limited sections of coastline experiencing upwelling at any given time. The longshore extent of upwelling is less than about 100 km. The wavelength of the meanders may be considerably greater. The 100 km length scale refers only to that segment of the meander in contact with the outer shelf.

The rapid warming along the transect noted between 21 and 28 August is the dominant feature of the time-distance plot (Fig. 2). It is not clear from the available data how common it is for the entire shelf to experience such a rapid change, but the temperature-recorder data indicate that local warming and cooling occur over the inner shelf with some regularity. Fig. 6 shows that a warming of 7°C in less than 3 days was recorded at Station 4 in late August, and that near-bottom temperatures increased by 5°C in just over a day in early August at Station 2. Similarly, rapid warming of nearly 6°C in two days occurred at Station 1 in early September, following the last brief period of cooling recorded during the study. Periods of near-bottom cooling can be rapid as well.

The impression created by combining the data from the 1980 study is that upwelling along the Atlantic coast of central Florida appears in the form of tongues of relatively cool water moving up over the shelf break and onto the middle and inner continental shelf. Here and in previous studies (Smith, 1981, 1982), whenever cool near-bottom water is detected over the inner shelf, it exists in a continuous near-bottom layer across the entire shelf (Fig. 3). The relative minima appearing in Fig. 6 are isolated on a time–space plot, but not in x-y coordinates. Thus, relatively cool water over the inner shelf is probably not an isolated water mass spun off of the Florida

Current. Rather, it can be traced back into the Current as an uninterrupted layer.

The nature of upwelling along the central Florida Atlantic coast appears to be significantly different in two respects from the upwelling described for Georgia shelf waters by Lee and Brooks (1979): Upwelling events off Florida are longer-lived, and the variations in current speed and temperature are inversely related, rather than directly related. Upwelling events in shelf waters off Florida may span time intervals of up to three weeks. Farther north, off Georgia, relatively low water temperatures are more transient in nature, with quasi-periodic minima lasting on the order of 3–4 days.

In Florida shelf waters, temperature minima follow increases in current speed. This relationship was quantified at statistically significant levels using mid-shelf data from two study sites (Smith, 1981, 1982), and it is shown qualitatively in Fig. 7. Lee and Brooks (1979) have noted that a decrease in longshore flow to the north over the outer shelf is followed by a decrease in temperature. This relationship has been interpreted in terms of meanders in the Gulf Stream, but upwelling occurs when the cyclonic shear zone shifts laterally in a seaward direction. An observed cyclonic rotation in the current vectors suggests that spin-off eddies may be passing through the study area, and that the upwelling might be in the cold core of the eddies.

Meanders may be important for Florida shelf upwelling as well, but the triggering mechanism appears to be a shoreward shift in the axis of the Florida Current. The cross-shelf extent of the cold-water layer over the Florida shelf would seem to rule out eddies, which are characteristically elongated in the longshore direction. Certainly, there is no reason to expect upwelling to occur in the same form everywhere, but it is unusual to find two seemingly quite different mechanisms occurring along adjacent sections of coastline.

A question which remains unanswered after nearly 40 years of investigating Florida's Atlantic coast upwelling is whether or not the phenomenon is in fact seasonal. If, as suspected, upwelling occurs primarily in response to the Florida Current, rather than in response to the coastal wind field, there is no reason to expect that upwelling is restricted to summer months. It would be best defined at that time, because of the summer maximum in volume transport (Niiler and Richardson 1973) and because of the greater thermal contrasts between the subsurface water moving up the slope and the inner-shelf water it is replacing. Further, it is conceivable that the "seasonal" label has persisted on account of the dominance of studies conducted during summer months, when weather is more conducive to field work. Atkinson *et al.* (1978) have documented Gulf Stream intrusions in April off St. Augustine, 280 km to the north, and have questioned the concept of seasonality.

Indeed, the character of coastal upwelling might change during the colder months. The greater density of the isopycnal inner-shelf water column in winter months may effect a hydrodynamic barrier which cannot be undermined by intermediate water layers from farther offshore. Upwelled water of 18–20°C, which would be relatively cool in summer months, would be similar in temperature to inner-shelf waters in mid-winter (Smith 1981). At such times, although the forcing would be present for upwelling, the response would be restricted to middle- and outer-shelf waters. Additional work in other seasons will be required along this part of the coast as well before one can reject the long-held concept of seasonality.

Acknowledgments. The author expresses his appreciation to George Kierspe, Lew Gilliland and Mark Sternberger for their assistance on the hydrographic cruises, and in installing and recovering the temperature recorders. Mark Sternberger digitized the temperature profiles and constructed the temperature cross sections.

REFERENCES

Atkinson, L., G-A. Paffenhöfer and W. Dunstan, 1978: The chemical and biological effect of a Gulf Stream intrusion off St. Augustine, Florida. *Bull. Mar. Sci.*, **28**, 667–679.

Blanton, J., L. Atkinson, L. Pietrafesa and T. Lee, 1981: The intrusion of Gulf Stream water across the continental shelf due to topographically-induced upwelling. *Deep-Sea Res.*, **28A**, 393–405.

Chew, F., and G. Berberian, 1970: Some measurement of current by shallow drogues in the Florida Current. *Limnol. Oceanogr.*, **15**, 88–99.

Green, C., 1944: Summer upwelling—northeast coast of Florida. *Science*, **100**, 546–547.

Hsueh, Y., and J. O'Brien, 1971: Steady coastal upwelling induced by an along-shore current. *J. Phys. Oceanogr.*, **1**, 799–810.

Kerr, G., 1980: Low-frequency current variability on the continental shelf off Fort Pierce, Florida. M.S. thesis, Florida Institute of Technology, Melbourne, 91 pp.

Lee, T., and D. Brooks, 1979: Initial observations of current, temperature and coastal sea level response to atmospheric and Gulf Stream forcing on the Georgia Shelf. *Geophys. Res. Lett.*, **6**, 321–324.

Leming, T., 1979: Observations of temperature, current and wind variations off the central eastern coast of Florida during 1970 and 1971. NOAA Tech. Memo. NMFS-SEFC-6, 172 pp.

Niiler, P., and W. Richardson, 1973: Seasonal variability in the Florida Current. *J. Mar. Res.*, **31**, 144–167.

Richardson, W., W. Schmitz and P. Niiler, 1969: The velocity structure of the Florida Current from the Straits of Florida to Cape Fear. *Deep-Sea Res.*, **16** (Suppl.), 33–39.

Smith, N., 1981: An investigation of seasonal upwelling along the Atlantic coast of Florida. *Ecohydrodynamics*, J. C. J. Nihoul, Ed., Elsevier, 79–98.

——, 1982: Upwelling in Atlantic shelf waters of South Florida. *Florida Sci.*, **45**, 125–138.

Taylor, C., and H. Stewart, 1958: Summer upwelling along the east coast of Florida. *J. Geophys. Res.*, **64**, 33–39.

Vukovich, F., B. Crissman, M. Bushnell and W. King, 1979: Gulf Stream boundary eddies off the east coast of Florida. *J. Phys. Oceanogr.*, **9**, 1214–1222.

Webster, F., 1961: A description of Gulf Stream meanders off Onslow Bay. *Deep-Sea Res.*, **8**, 130–143.