JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 92, NO. C10, PAGES 10,845–10,852, SEPTEMBER 15, 1987

Near-Bottom Cross-Shelf Heat Flux Along Central Florida's Atlantic Shelf Break: Winter Months

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Near-bottom current and temperature data from a 154-day period in winter 1984–1985 are combined to investigate cross-shelf heat fluxes along central Florida's Atlantic coast between 27° and 30°N. Temperature and current time series recorded at the shelf break exhibit considerable variability over time scales of the order of 1–2 weeks. Low-frequency temperature fluctuations, superimposed onto a seasonal cooling of approximately 0.4°C/week, decrease from south to north. Cross-shelf motion results in little net displacement at latitudes 27° and 30°N but results in considerable net shoreward displacement at latitude 28°N. Cross-shelf heat flux is shoreward at all study sites, but values decrease approximately linearly from south to north. The study shows that a shoreward flux of relatively cool water can continue through winter months in the vicinity of Cape Canaveral. Compared with summer upwelling in the same area, the characteristic time scale is considerably shorter because the heat flux appears to be related to frontal eddies embedded in the cyclonic shear zone of the Florida Current rather than to seasonal variations in volume transport combined with a westward shift of the axis of the Florida Current.

1. INTRODUCTION

A series of hydrographic studies over the past 40 years has documented the annual recurrence of anomalously low water temperatures over the inner shelf along the Atlantic coast of Florida in midsummer months. *Green* [1944] published a brief note which established the existence of low surf temperatures during June, July, and August, with minimum values at 29°N. *Taylor and Stewart* [1959] confirmed that summer upwelling occurred consistently, though to varying degrees, between 27° and 30°N, and they hypothesized that a principal cause in this east coast setting was the seasonal shift of winds into the southeasterly quadrant. *Leming* [1979] combined wind records with temperature, salinity, and current data to investigate individual upwelling events in the vicinity of Cape Canaveral (latitude 28°30′N). Results lent support to the hypothesis that the wind played a significant role in forcing upwelling.

Two more recent field studies conducted south of Cape Canaveral at about latitude 27°30′N produced evidence that the Florida Current may be important in explaining summer upwelling as well. *Smith* [1981] compared time series of inner shelf water temperature with time series of cross-shelf and longshore wind stress and with time series of longshore currents from midshelf waters. Lower temperatures were considerably more coherent with longshore currents, and minimum temperatures lagged slightly behind strongest northerly flow. Upwelling favorable wind stress coincided with some upwelling events, but on average, wind stress forcing seemed to play a secondary role south of the cape. A follow-up study [*Smith*, 1983] reinforced the suggestion that the main midsummer upwelling event, lasting 1 to 3 weeks, occurs with the strongest longshore flow at the shelf break. *Hsueh and O'Brien* [1971] have described a mechanism which can explain upwelling in east coast settings. A departure from geostrophic flow occurs in near-bottom layers, and a locally dominant pressure gradient deflects water landward when a northerly flowing current is retarded by the outer shelf or upper slope. These conditions exist when the Florida Current meanders to the western side of the Straits of Florida.

Chew and Bushnell [1987] have reported results of a study which relate directly to the lateral movement of the axis of the Florida Current and which are helpful in explaining the occurrence of sustained upwelling in summer months. They note that highest volume transports in the Florida Straits characteristically occur in midsummer months [*Niiler and Richardson*, 1972] and then show that the Florida Current should exhibit a negative (anticyclonic) curvature bias at times of high transport. Such a relationship would shift the axis of the Florida Current westward in summer months, bringing stronger longshore flow to the Florida shelf break. Ageostrophic flow in the benthic boundary layer would then deflect relatively cool water shoreward.

Field studies conducted north of Cape Canaveral and in the Georgia Bight suggest two additional upwelling mechanisms, both related to circulation. *Blanton et al.* [1981] have proposed that upwelling can occur in response to longshore flow when absolute vorticity is conserved in shelf waters with diverging isobaths. This mechanism is not seasonal; thus it may explain areas of persistent upwelling. *Lee and Atkinson* [1983] and *Atkinson* [1985] have described upwelling off the Georgia coast, occurring with the passage of frontal eddies. The characteristic time scale may be just a few days, depending on the speed of the Gulf Stream. In this case, lowest temperatures occur with lowest longshore current speeds, during the passage of cyclonic perturbations embedded in the quasi-steady flow.

Upwelling studies south of Cape Canaveral had been restricted largely to summer months and primarily to inner shelf and midshelf waters, until a 16-month field study sponsored by the Minerals Management Service, U.S. Department of the Interior, began in March 1984 [*Maul*, 1985]. Of particular interest, within the context of upwelling, was the deployment of current meters along the shelf break between 27° and 30°N from October 1984 to March 1985. It

Paper number 7C0499.
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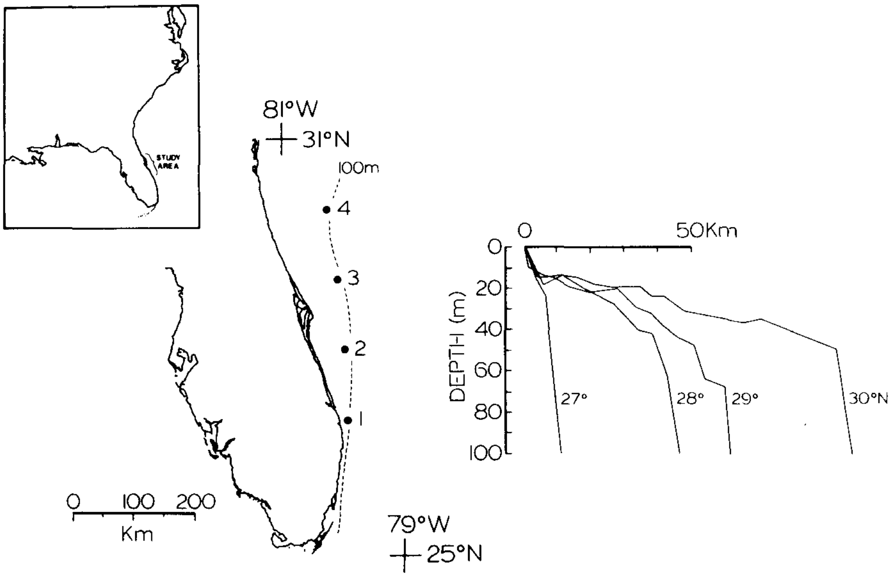

Fig. 1. Locations of shelf break stations 1–4 off Florida's Atlantic coast. All stations are on the 75-m isobath. The insert shows the study area along the southern coast of the United States; the figure to the right is a composite of cross-shelf profiles passing through the four study sites.

is along this 335-km section of coastline that the continental shelf widens from just a few kilometers at 27°N to nearly 100 km at 30°N (Figure 1). Current and temperature time series from this study extended results from earlier studies in a spatial sense by involving stations at the shelf break and in a temporal sense by considering winter months.

Results from this winter period suggest that upwelling events continue throughout the year. The nature of upwelling events seems to change appreciably from summer to winter months, however, as the time scale decreases from weeks to days. Instead of one or two major pulses of cold water, cross-shelf heat fluxes in winter months occur as a series of relatively minor events. Results indicate that periods of cooler water at the shelf break are related more consistently to periods of relatively slow longshore motion. Thus upwelling seems to be associated with frontal eddies. Data also show a north-to-south increase in thermal activity over time scales of several days and in the magnitude of the cross-shelf heat flux along this relatively short segment of coastline.

2. The Data

Current meter and temperature data were obtained from four locations (Figure 1) during a 154-day period of time from October 9, 1984, through March 11, 1985. Stations 1, 2, 3, and 4 were at latitude 27°, 28°, 29°, and 30°, respectively. Current meters were moored 3 m above the bottom in 75 m of water. The four cross-shelf profiles at the right side of Figure 1 indicate that the 75-m isobath is found at or slightly beyond the shelf break. Deployment and recovery of the taut-line moorings, and data translation were performed by General Oceanics, Inc. (Miami, Florida). Current data from the 72-m level at station 3 (29°N) were judged unreliable. Thus only the data from stations 1, 2, and 4 were used to quantify cross-shelf near-bottom heat fluxes.

General Oceanics Mark I Niskin winged current meters were used to record both temperature and current speed and direction at hourly intervals. The instrument tilt accuracy is ±0.5°; the direction accuracy is ±2°. The accuracy of the temperature sensor is ±0.25°C, according to instrument specifications. The time series used for analysis and plotting were smoothed using a 40-hour low-pass Lanczos filter with a cosine taper. Energy density spectra (not shown) show a sharp decrease in energy density values at periodicities in excess of approximately 1.5 days (36 hours).

3. Results

3.1. *Temperature Data*

Data were recorded during a period of time which coincided with the cooling phase of the annual temperature cycle. Figure 2 is a composite, showing the low-pass-filtered, near-bottom temperatures from the three current meters used in the study. In all three plots, the secular decrease in temperature stands out prominently. Seasonal cooling, quantified by the linear trend of the data shown in Figure 2, results in a temperature decrease of slightly less than 0.4°C per week at these three locations (see Table 1). Superimposed onto the seasonal trend, however, is a low-frequency variability with maxima and minima spaced approximately every 6–8 days. This low-frequency variability is distinctly greater at station 1 than at either station 2 or station 4: it is 20% greater if one uses the standard deviation of the low-pass-filtered temperatures as a measure of thermal variability.

Spectral analysis [*Brown*, 1977] of low-pass-filtered temperatures brings out several interesting features involving the interrelationships of these time series at selected pairs of stations. Results are summarized in Table 2. Near-bottom temperature fluctuations at stations 1 and 2 were highly coherent over all time scales in excess of about 5 days and weakly coherent at periodicities of approximately 2.5 days. In all cases, temperature variations at station 1 led those at station 2, suggesting that the Florida Current was playing a

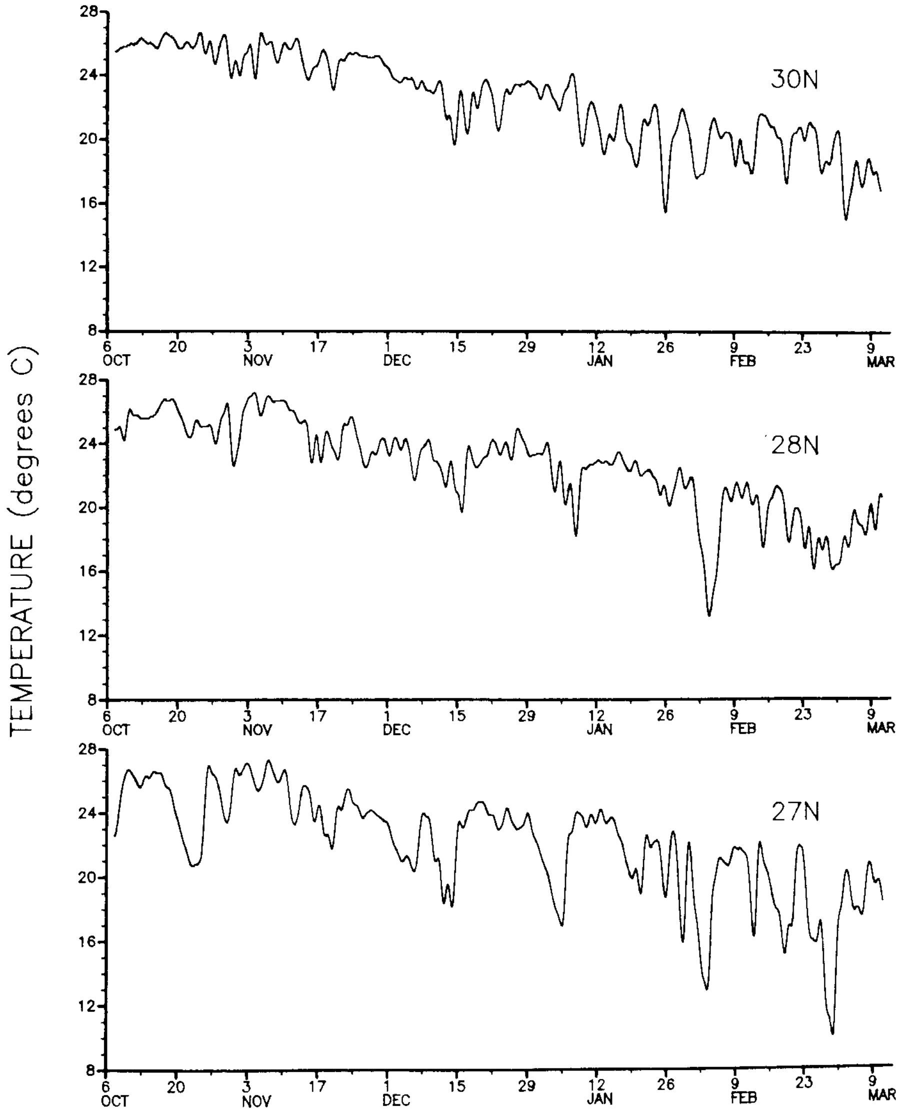

Fig. 2. Low-pass-filtered near-bottom temperatures recorded at stations 1, 2, and 4 from October 9, 1984, through March 11, 1985.

role in the south-to-north appearance of relatively cool water. Temperature variations at stations 1 and 4 and at stations 2 and 4, involving study sites south and north of the cape, were somewhat less coherent. That, combined with inconsistencies in phase relationships and an apparently greater coherence between stations 1 and 4 than between stations 2 and 4, cast doubt upon the significance of the computed station-to-station coherences on opposite sides of the cape.

TABLE 1. Summary of Selected Statistics of Temperature (T) and Cross-Shelf Current Component (u) Time Series, Recorded at the 72-m Level, October 9, 1984, Through March 11, 1985

Station	Mean T, °C	s.d.	ΔT/week	Mean u, cm/s	$\overline{u'T'}$, cgs
4	22.6	2.8	−0.39	+0.3	+0.7
2	22.6	2.8	−0.37	−7.4	+4.6
1	22.0	3.3	−0.39	0.0	+7.5

The standard deviation (s.d.) of the temperature was computed from the low-pass-filtered time series; positive currents indicate seaward flow. the data from station 3 were judged unreliable.

3.2. *Current Data*

The cross-shelf component of the near-bottom current at the three study sites is represented by the cumulative net displacement plots shown in Figure 3. The displacement associated with a given hourly observation is determined from the product of the current component speed and the time interval that it represents. By definition, positive displacements indicate seaward flow. A crucial preliminary step in the calculation of cross-shelf displacement is the estimation of the orientation of the 75-m isobath in the vicinity of the study site. This was especially difficult to determine at station 2 because of a series of shelf-break bathymetric features [*Avent et al.*, 1977; *Thompson and Gilliland*, 1980]. Near latitude 28°N these features are known as the Sebastian Pinnacles and have a maximum relief of 25 m. The extent to which these features may have influenced individual soundings used to determine the orientation of local isobaths is unknown. Soundings appearing on navigational charts normally used in these shelf waters were used to draw isobaths.

TABLE 2. Summary of Statistically Significant Coherences of Cross-Shelf Current Components (Upper Right) and of Temperatures (Lower Left) Recorded at the 72-m Level, October 9, 1984, Through March 11, 1985

	Station 1		Station 2		Station 4	
Station 1	· · ·		0.25–0.35	(6.5–7.4)*	0.25–0.41	(7.4–12.9)†
Station 2	0.30	(2.6)*	· · ·		0.26–0.27	(1.6–1.7)*
	0.27–0.70	(>5.2)*				
Station 4	0.32	(2.0)*	0.28	(7.4)†	· · ·	
	0.29–0.40	(3.4–4.0)†				
	0.25	(8.6)*				

Coherences of 0.25 or greater are significant at the 95% confidence level. Periodicities, in days, are noted in parentheses. More specific phase information is included in the text.

* Phase lead at the more southerly station.

† Phase lag at the more southerly station.

Additional soundings were obtained at the times of current meter installation only to verify a water depth of 75 m.

The three plots of near-bottom cross-shelf displacement show considerable differences, considering the relatively short distances separating the stations. Cross-shelf flow at 30°N exhibits a tendency toward seaward (increasingly positive) displacements through much of the study period. Early and late in the record, onshore flow occurs for periods of 3–4 weeks, but displacements increase irregularly from mid-November through mid-February. At latitude 28°N, little cross-shelf displacement in either sense is calculated for the first 8 weeks, but this is followed by a steady and relatively

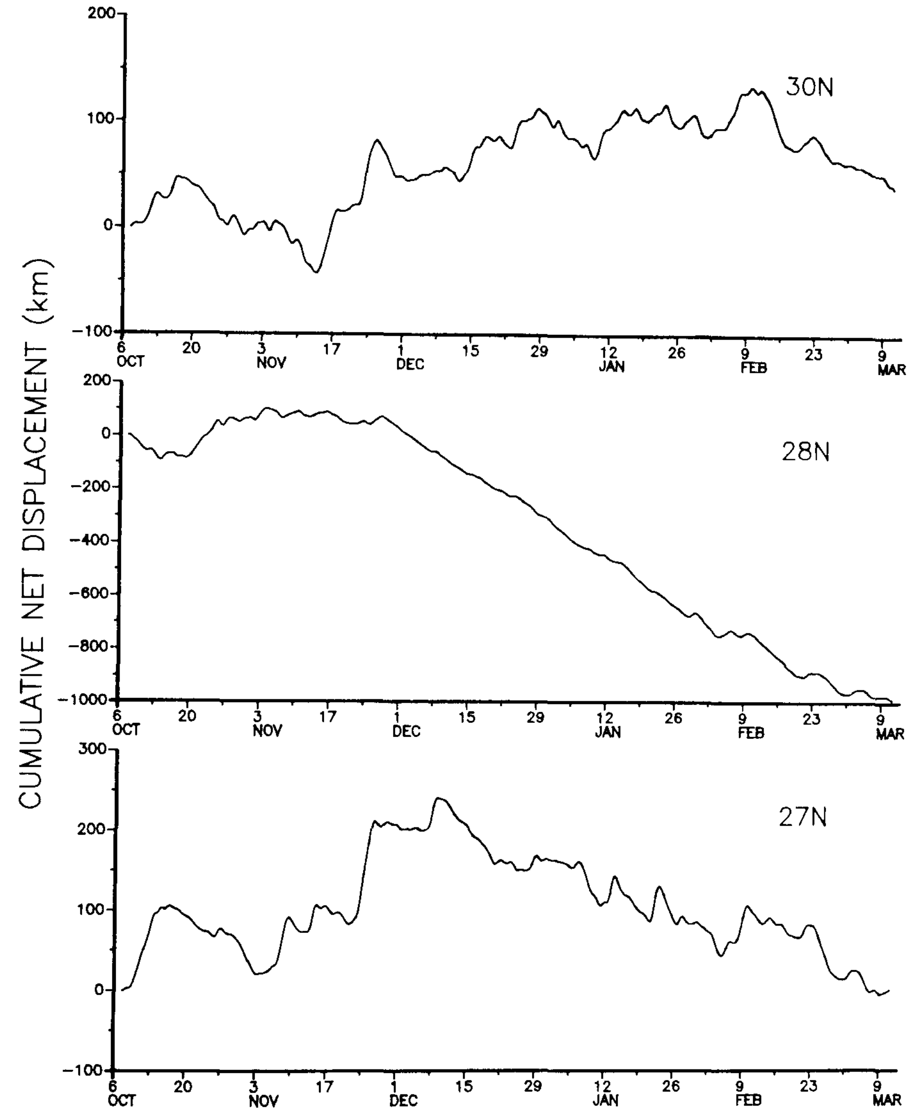

Fig. 3. Cumulative net cross-shelf displacement, calculated from low-pass-filtered near-bottom currents recorded at stations 1, 2, and 4 from October 9, 1984, through March 11, 1985.

rapid decrease in net displacement through the end of the record. Such a pattern would result from a mean shoreward cross-isobath flow of nearly 14 cm/s. The magnitude of the associated onshore motion calls into question the choice of orientation for the 75-m isobath at this location. An incorrect orientation, in either sense, would have the effect of introducing a slope in the plot or altering a valid linear trend. For the latitude 27°N data, there is no clear trend in the plot. Instead, there is a tendency for increasing displacements during approximately the first half of the record, followed by decreasing displacements through the latter half.

A second series of coherence and phase spectra was computed from cross-shelf current components alone at the three pairs of stations. Station separation, coupled with the mean along-isobath current speeds of approximately 50 cm/s, determined probable times needed to advect frontal eddies or other perturbations embedded within the along-isobath flow from one station to another. This focused attention on periodicities of several days and longer. Cross-shelf motion at stations 1 and 2 was related at statistically significant levels over time scales of from 5.5 to 7.5 days, with a consistent phase lead at station 1. Cross-shelf variability at stations 2 and 4 was coherent over a more restricted range of time scales, centered at 5 days, but station 4 lagged again, as expected. The broadest band of coherent cross-shelf motion, 7.5 to 10.5 days, was found for stations 1 and 4. The consistent phase lead of variations at station 4, however, cast some doubt on how these two time series are related.

3.3. *Heat Flux Calculations*

Time series of temperature and cross-shelf current components from any given location provide the basis for the investigation of cross-shelf heat flux in general and upwelling events in particular. In both current and temperature time series, however, the linear trend should be removed. Seasonal warming and cooling, not related to upwelling, can dominate temperature records; unknown irregularities in local bathymetry can effect a trend in the record of cross-shelf motion. Thus the linear trend was removed from all six time series before proceeding with the analysis of cross-shelf heat fluxes. The focus of the study was correspondingly narrowed to time scales on the order of days to weeks.

A common measure of heat flux is the quantity $\overline{u'T'}$ where u' is the deviation from the mean cross-shelf current of a given hourly value, and T' is a similar deviation, or perturbation, from the mean temperature. The overbar indicates a time average. Values for $\overline{u'T'}$ were calculated with data from all three stations, and results indicate a seaward flux of heat and a shoreward flux of relatively cool water during this winter study period and over the time scales which survived the detrending and low-pass-filtering operations. At station 1, $\overline{u'T'}$ was 7.5 (cgs units). Values were lower at the two more northerly stations. At station 2 and station 4, values were 4.6 and 0.7, respectively. This rather uniform northward decrease in cross-shelf heat flux corresponds with the south-to-north decrease in thermal activity shown in Figure 2.

A visual representation of the cross-shelf heat transport occurring during this time period is provided by Figure 4. Temperatures have been converted to heat content, in calories. In these plots, the products of the heat content and cross-shelf current speed are summed from 1 hour to the next to quantify the cumulative flux of heat across the shelf break rather than the mean value. Some features seen in the plots of cross-shelf current components reappear in Figure 4. The quasi-periodic nature of cross-shelf heat transport is a prominent characteristic at stations 1 and 4. Some similarity appears in the plots for stations 1 and 2 during December and January: both show a tendency toward decreasing values. A net import or export of heat across the shelf break (quantified above by the perturbation products) is not apparent in any of these plots, because the longer-term residuals are small compared with shorter-period variability.

3.4. *Relationship of Temperature With Current*

Spectral analysis which combined current and temperature data from a given station involved first the cross-shelf (Table 3*a*) and then the along-isobath (Table 3*b*) components of the near-bottom current. At station 4, coherence spectra computed with the cross-shelf components showed spectral peaks in excess of the 95% confidence level at time scales of slightly over 1.5 days (just beyond the reach of the low-pass filter) and again at 2.0–3.0 days. A third region of relatively high coherence appeared over time scales of 4.0–6.5 days. It is probable that the relatively shorter time scales are associated with frontal eddies [*Lee*, 1975; *Lee and Mayer*, 1977]. The longer time scales may be related to the meandering of the streamlines. At station 2 the cross-shelf flow was coherent with temperature only at a period of 6.5 days; again warming followed an increase in seaward flow. At station 1 a distinct coherent relationship appeared at periodicities of between 2.7 and 2.9 days, but in this case u lagged slightly behind T.

The final aspect of this study involved the phase relationship of periods of relatively cool water and periods of relatively strong or weak along-isobath flow. This bears directly upon the dynamics associated with winter shelf break upwelling. Spectral analysis, using the low-frequency temperature and along-isobath current time series, suggests a pattern decidely different from that found in midsummer months [*Smith*, 1981] and reveals substantial longshore variability. Results from station 1 (Table 3*b*) indicated statistically significant coherence levels at periodicities of approximately 1.8 and 2.8 days. In both cases, higher water temperatures consistently followed stronger current speeds.

At station 2 the phase relationship of along-isobath current and temperature variations in the near-bottom layer reversed abruptly at periodicities longer than about 5.5 days. At shorter time scales, increases in along-isobath current led periods of warming. Peaks in the coherence spectrum occurred at approximately 2 days, 2.5 days, and again at 5 days. Over time scales longer than about 5.5 days, however, increases in longshore flow consistently led occurrences of relatively cool water. In the long-period part of the spectrum, coherence values remained relatively low.

At station 4 the relationship between near-bottom along-isobath motion and temperature was most clearly defined. Over all time scales, an increase in along-isobath flow led an increase in temperature, and in two broad spectral bands (at about 1.5 days, and again between 2 and approximately 6 days) the coherence was highly significant. The phase relationship, involving relatively strong along-isobath flow leading relatively warm water, suggests that the mechanism most responsible for cross-shelf heat fluxes is one involving frontal eddies along the cyclonic shear zone of the Gulf Stream.

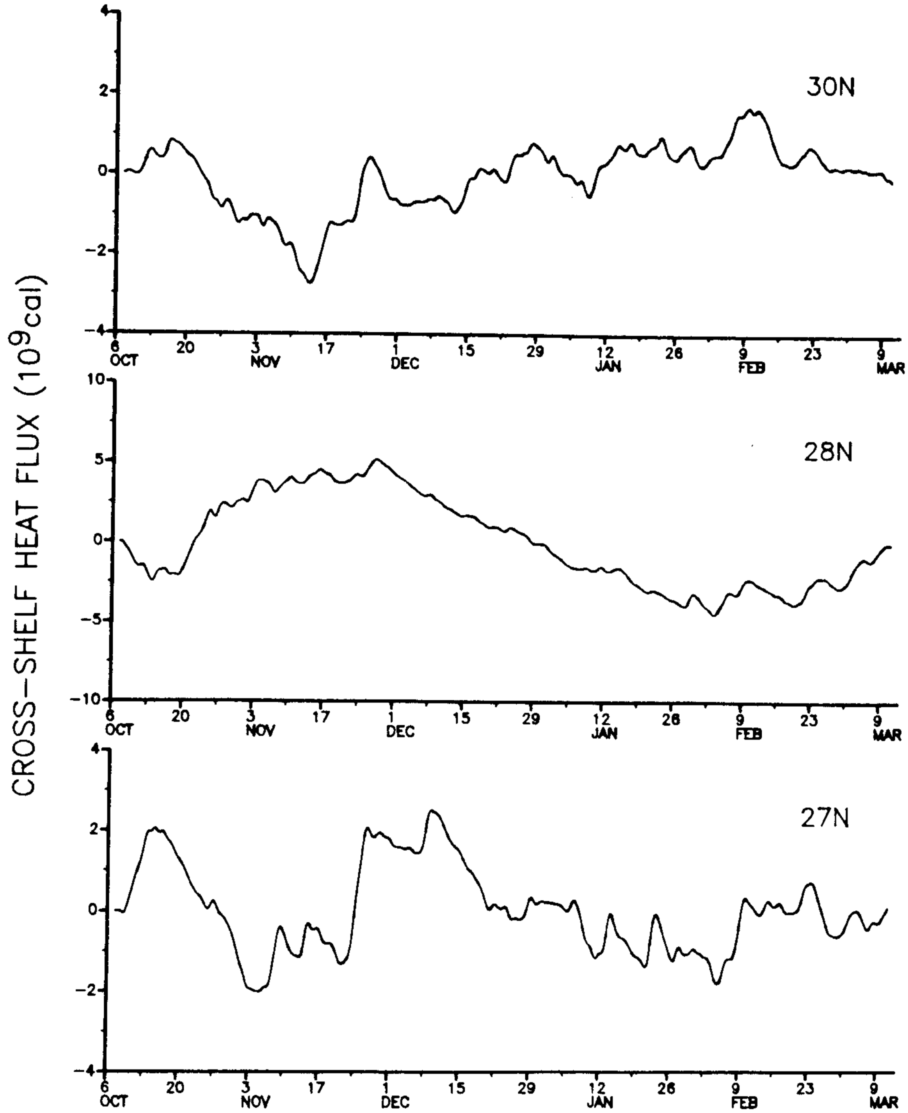

Fig. 4. Cumulative net cross-shelf heat flux at stations 1, 2, and 4, computed from detrended and low-pass-filtered near-bottom temperatures and cross-shelf current components from October 9, 1984, to March 11, 1985.

4. Discussion

Perhaps the most significant finding to come out of this work is that upwelling persists through winter months in the vicinity of Cape Canaveral, albeit in a different form and to a lesser extent than during summer months. There is no evidence yet to suggest how far upwelled water moves shoreward across the shelf. It is unlikely to penetrate beneath the 12°–14°C water commonly found over the inner shelf during midwinter to late winter. But at the shelf break it appears that upwelling continues throughout the year, even if its cause changes. Thus upwelling along central Florida's Atlantic coast is considerably less seasonal than was previously suggested [*Smith*, 1981, 1983].

The more or less consistent phase lead of seaward flow over near-bottom warming (Table 3*a*) identifies upwelling as

TABLE 3*a*. Summary of Coherence and Phase Relationships for Cross-Shelf Current Components *u* and Temperatures *T* Recorded at the 72-m Level

Station	Periodicity, days	Coherence	Phase Relationship
4	1.6–1.8	0.25–0.48	*u* leads *T* by 1.7–2.3 days
	2.0–3.0	0.28–0.45	*u* leads *T* by 0.8–1.4 days
	4.0–6.5	0.25–0.36	*u* leads *T* by 0.6–0.7 day
2	6.5	0.28	*u* leads *T* by 2.2 days
1	2.7–2.9	0.41	*u* lags *T* by 0.1–0.2 day

Coherences greater than 0.25 are significant at the 95% confidence level. Stations are listed in reverse order to correspond with Figure 1.

TABLE 3*b*. Same as for Table 3*a*, But With Along-Isobath Current Components *v* and Temperature *T*

Station	Periodicity, days	Coherence	Phase Relationship
4	1.6–1.8	0.45–0.60	*v* leads *T* by 0.2 day
	2.1–5.7	0.33–0.53	*v* leads *T* by 0.3–0.8 day
2	1.8–2.0	0.31–0.32	*v* leads *T* by 0.3–0.4 day
	2.3–2.5	0.29–0.35	*v* leads *T* by 0.2 day
	5.2	0.28	*v* leads *T* by 0.1 day
	17.2–25.8	0.25	*v* lags *T* by 3.8–4.5 days
1	1.8	0.25	*v* leads *T* by 0.2 day
	2.7–2.9	0.33–0.39	*v* leads *T* by 1.2–1.3 days

the source of the cool water recorded at all three stations. During midwinter months, it is conceivable that transient periods of lower near-bottom temperature could occur at the shelf break as a seaward directed density flow, following the passage of more intense cold fronts. Cooling over the inner shelf would be greater than cooling at the shelf break, and this could provide an alternate source of relatively cool water. The phase relationship between temperature and cross-shelf flow would be reversed, however, and this does not generally appear to be the case. Relatively cool water arrives with seaward directed flow only at station 1.

A seasonal shift in wind direction along the central Florida Atlantic coast may relate both directly and indirectly to the seasonal variation in the nature of cross-shelf heat flux. The mean surface wind direction recorded from Palm Beach to Daytona Beach (the approximate bounds of the study area) is generally out of the northeasterly quadrant from October through March and out of the southeasterly quadrant during the rest of the year [*National Oceanic and Atmospheric Administration*, 1977, 1982]. Thus along this roughly north-south coastline, one would expect a seasonal variation in cross-shelf Ekman transport. In summer months, southeasterly winds would force a northerly directed shelf circulation and an offshore-directed Ekman transport in surface layers. The Ekman transport would tend to aid coastal upwelling, explaining the prolonged upwelling events commonly observed from late July through late August [*Smith*, 1981, 1983]. The pattern would reverse in winter months. In particular, a shoreward directed Ekman transport would inhibit sustained periods of upwelling, and the dominant time scale would shift to that characteristic of frontal eddies being carried through the study area by the Florida Current.

A seasonal variation in wind-driven shelf circulation could also produce a lateral displacement in the axis of the Florida Current. In winter months, a southerly transport of water along this wedge-shaped shelf (Figure 1), together with the decrease in transport and cyclonic curvature noted earlier, would tend to displace the axis of the Florida Current eastward. An eastward displacement would both reduce ageostrophic cross-isobath flow at the shelf break as a very long period upwelling mechanism and leave more room for frontal eddies to develop to the west of the Florida Current, especially in the southern part of the study area. Furthermore, the combination of the northerly flowing Florida Current and a southerly directed shelf circulation would increase cross-isobath shear and thus encourage the formation of frontal eddies along the western fringe of the current.

Further north, in the South Atlantic Bight [*Lee et al.*, 1985], the shelf is considerably broader, and the mean position of the Gulf Stream lies further offshore throughout the year. In spite of seasonal variations in transport and east-west meanderings of the axis, lateral constraints on frontal eddies are minimal in the absence of a nearby coast. Frontal eddies appear to serve as the dominant upwelling mechanism throughout the year. In general, it seems both logical and probable that the frontal eddy and ageostrophy mechanisms play important roles when and where conditions are favorable.

Significant longshore variability in several forms is apparent even along the relatively short section of coastline investigated in this study. It is probable that this is a direct result of the longshore variation in the width of the shelf (Figure 1), but this is a subject for a more highly-focused future study. Low-pass-filtered temperature variation (Figure 2) show a distinct decrease from station 1 to station 4. The cumulative cross-shelf displacement and the cumulative cross-shelf heat flux (Figures 3 and 4) show significant differences between adjacent stations but no consistent trends. A south-to-north decrease reappears in the $\overline{u'T'}$ perturbation products, however, with highest values at station 1 coinciding logically with the greatest thermal activity.

The general conclusion which can be drawn from this study is that a shoreward flux of relatively cool water continues intermittently through winter months along the central part of Florida's Atlantic coast, but the dynamics driving this process may be quite different from that which predominates in the same area in summer months. A discrete major cooling event, lasting 2–4 weeks, such as that found consistently in early August to mid-August [*Smith*, 1981, 1983] did not appear in the winter data. Instead, the dominant time scale shifted to the 2- to 6-day band. This shorter time scale, coupled with the phase lead of stronger along-isobath flow over warmer temperature, suggests that near-bottom heat flux is associated with the movement of frontal eddies through the study area. Thus in summer, upwelling appears to be related more to the mean flow; in winter it appears to be associated with frontal eddies embedded within and carried along by the mean flow.

Acknowledgments. The Florida Atlantic Coast Transport Study was funded by the Minerals Management Service, U.S. Department of the Interior, and administered by Florida Institute of Oceanography through State of Florida contract DOI/MMS 14-12-0001-30082. Current meter moorings were deployed and recovered, and initial data reduction was performed by General Oceanics, Inc., of Miami, Florida. Preliminary data processing was by Science Applications, Inc., of Raleigh, North Carolina. Patrick Pitts plotted the data shown in Figures 2–4 and computed the coherence and phase spectra. Elizabeth Smith and Paul Mikkelsen assisted with the programming needed to calculate the perturbation products and cross-shelf heat fluxes. Harbor Branch Oceanographic Institution contribution 568.

REFERENCES

Atkinson, L. P., Hydrography and nutrients of the southeastern U.S. continental shelf, in *Oceanography of the Southeastern U.S. Continental Shelf, Coastal and Estuarine Sci.*, vol. 2, edited by L. P. Atkinson, D. W. Menzel, and K. A. Bush, pp. 77–92, AGU, Washington, D. C. 1985.

Avent, R. M., M. E. King, and R. E. Gore, Topographic and faunal studies of shelf-edge prominences off the central Eastern Florida coast, *Int. Revue Gesamten Hydrobiol.*, *62*, 185–208, 1977.

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

Brown, M. B. (Ed.), *Biomedical computer programs, P-Series, Health Sciences Computing Facility, UCLA*, 880 pp., University of California Press, Berkeley, 1977.

Chew, F., and M. H. Bushnell, Changing transport and curvature bias: A new type of meandering in the Florida Straits, *J. Geophys. Res.*, *92*, 9503–9513, 1987.

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

Hsueh, Y., and J. J. O'Brien, Steady coastal upwelling induced by an along-shore current, *J. Phys. Oceanogr.*, *1*, 180–186, 1971.

Lee, T. N., Florida Current spin-off eddies, *Deep Sea Res.*, *22*, 753–763, 1975.

Lee, T. N., and L. P. Atkinson, Low-frequency current and temperature variability from Gulf Stream frontal eddies and atmospheric forcing along the southeast U.S. outer continental shelf, *J. Geophys. Res.*, *88*, 4541–4567, 1983.

Lee, T. N., and D. A. Mayer, Low-frequency current variability and spin-off eddies along the shelf off southeast Florida, *J. Mar. Res.*, *35*, 193–220, 1977.

Lee, T. N., V. Kourafalou, J. D. Wang, W. J. Ho, J. O. Blanton, L. P. Atkinson, and L. J. Pietrafesa, Shelf circulation from Cape Canaveral to Cape Fear during winter, in *Oceanography of the Southeastern U.S. Continental Shelf, Coastal and Estuarine Sci.*, vol. 2, edited by L. P. Atkinson, D. W. Menzel, and K. A. Bush, pp. 33–62, AGU, Washington, D. C., 1985.

Leming, T., 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., 1979.

Maul, G. A., FACTS: The Florida Atlantic Coast Transport Study, *Eos Trans. AGU*, *66*, 434–435, 1985.

National Oceanic and Atmospheric Administration, Local climatological data, Daytona Beach, Florida, National Climatic Center, Asheville, N. C., 1977.

National Oceanic and Atmospheric Administration, Local climatological data, West Palm Beach, Florida, National Climatic Center, Asheville, N. C., 1982.

Niiler, P. P., and W. S. Richardson, Seasonal variability of the Florida Current, *J. Mar. Res.*, *31*, 144–167, 1972.

Smith, N. P., An investigation of seasonal upwelling along the Atlantic coast in Florida, in *Ecohydrodynamics*, edited by J. C. J. Nihoul, pp. 79–98, Elsevier, New York, 1981.

Smith, N. P., Temporal and spatial characteristics of summer upwelling along Florida's Atlantic shelf, *J. Phys. Oceanogr.*, *13*, 1709–1715, 1983.

Taylor, C., and H. Stewart, Summer upwelling along the east coast of Florida, *J. Geophys. Res.*, *64*, 33–39, 1959.

Thompson, M., and L. Gilliland, Topographic mapping of shelf-edge prominences off southeastern Florida, *Southeast. Geol.*, *21*, 155–164, 1980.

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(Received January 16, 1987;
accepted March 3, 1987.)