An Investigation of Summer Upwelling Across Central Florida’s Atlantic Coast: The Case for Wind Stress Forcing

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ABSTRACT


Three water temperature time series are used to characterize seasonal upwelling off Florida’s central Atlantic coast. Data recorded near the bottom at a mid-shelf study site indicate fluctuations in temperature of 4–8 °C, probably representing upwelling intrusions, occurring over time scales on the order of several days to about a week during May, June and early July of 1986. During the same time period, data from two inner-shelf study sites show a relatively steady seasonal rise in temperature with little indication of upwelling. A major upwelling event, beginning in mid July and lasting approximately three weeks, appears in all three records. At the mid-shelf site, the event is characterized by an abrupt decrease of nearly 12 °C followed by a gradual recovery period. Over the inner shelf, temperature decreases more slowly and returns relatively rapidly to values characteristic of the summer season. Calculations indicate that upwelled water moves along and across the shelf to the northwest at 10–13 cm sec⁻¹. Meteorological data indicate that wind plays a significant role in driving the observed upwelling.

ADDITIONAL INDEX WORDS: Upwelling, Florida’s Atlantic coast, wind stress, Florida Current, spectral analysis.

INTRODUCTION

The Atlantic coast of central Florida is one of only a few east-coast regions having well-defined summer upwelling. Studies over the past 50 years have documented the along-shelf distribution of anomalously low midsummer surf temperatures (GREEN, 1944; TAYLOR and STEWART, 1958), the ephemeral nature of individual upwelling events (SMITH, 1983) and the special case of upwelling in response to the passage of a hurricane (SMITH, 1982). The across-shelf structure of upwelling patterns has been described using temperature profiles taken synoptically from the coast to the shelf break (LEMING, 1979; SMITH, 1981, 1982). The more recent studies incorporated wind and current meter data and emphasized the role that the Florida Current plays in forcing shelf upwelling. Wind forcing was explored by SMITH (1981), but inner shelf, near-bottom temperatures were incoherent with both along-shelf and across-shelf wind stress components.

The significance of summer upwelling in this area is twofold. First, upwelled water reduces inner-shelf water temperatures approximately 10 °C, from midsummer maximum values of 28–30 °C. During periods of upwelling, temperatures decrease to values more characteristic of early winter or early spring months. Lower temperatures are largely confined to the lower part of the water column. Surface temperatures decrease only slightly, as a result of intense solar heating.

The combination of local heating by insolation in surface layers and advective cooling in near-bottom layers results in a mid-depth thermocline that may be as strong as 2–3 °C m⁻¹. Second, the upwelling process provides an exchange mechanism for replacing coastal water with open ocean water. Dissolved and suspended material (e.g., nutrients, plankton, and larvae) can be transported the entire width of the continental shelf. ATKINSON et al. (1978) and PAFFEHHOFER (1980) have shown high chlorophyll and dense phytoplankton and zooplankton populations resulting from the shoreward transport of nutrients at near-bottom levels during Gulf Stream intrusions onto the Florida shelf. Differences in phytoplankton across the shelf before and after the onset of upwelling have been described by GREEN (1979).

Most shelf upwelling studies utilize temperature profiles from across-shelf transects to define upwelling patterns. For example, SMITH (1981, 1982) compiled weekly temperature cross-sections to describe the occurrence of midsummer upwelling events in Florida shelf waters south of Cape Canaveral. Across-shelf transects provide useful information on the low-frequency temporal variability of upwelling events, as well as on the fraction of the water column occupied by upwelled water. Higher-frequency temporal variability cannot be quantified in this way because of the relatively slow speed of most survey vessels.

The purpose of this paper is to use three temperature records collected simultaneously during the summer of 1986 to describe spatial and temporal characteristics of seasonal upwelling off the central Florida Atlantic coast. The time series
used in this study provide information over the shorter time scales often missed by shipboard studies. Spectral analysis shows the time scales over which mid-shelf and inner-shelf temperature variations are coupled by upwelling events, the shoreward propagation speed of the intruding water and the role of wind forcing.

DATA AND METHODS

Three bottom-mounted thermographs were used to investigate summer upwelling. An Endeco Type 109 thermograph was positioned in 25 m of water over the mid-continental shelf, 24 km offshore at 27°43.0’N, 80°07.6’W (Figure 1). Inner shelf temperatures were recorded off Sebastian Inlet, and Fort Pierce Inlet using Sea Data Model TDR-3 temperature/pressure recorders. The Sebastian Inlet station was in 13 m of water, 1.7 km offshore (27°51.8’N, 80°25.9’W) and 35 km west-northwest of the mid-shelf site. The Fort Pierce station was in 10 m of water, 2 km offshore (27°28.4’N, 80°15.9’W), 31 km south-southwest of the mid-shelf site. Bottom temperatures were recorded every two hours at the mid-shelf study site and hourly at the inner-shelf sites. All three records began on April 3, 1986. The mid-shelf and Sebastian Inlet data continued through September 25; the Fort Pierce Inlet record ended on July 25, 1986. The accuracy of both instruments is 0.2 °C, according to manufacturers’ specifications.

Hourly wind speeds and directions were recorded 60 m above sea level from June 1 through July 21, 1986 at the Florida Power and Light Hutchinson Island nuclear power plant (Figure 1). The weather station is less than 100 m from the coast and well suited for estimating over-water wind conditions. Observed wind speeds were reduced to their 10-m equivalent, assuming a logarithmic profile and a dynamic roughness of 0.025 cm (ROLL, 1965). Adjusted winds were converted to wind stress using the method described by Wu (1980). Hourly wind stress vectors were plotted head-to-tail to construct a progressive vector diagram.

Temperatures and wind stress components were smoothed with a 39-weight Doodson-Warburg numerical filter (GROVES, 1955) to remove high-frequency fluctuations. The half-power point of the filter is at a period of 55 hours. Spectral analysis of smoothed mid-shelf water temperature and wind stress (LITTLE and SHURE, 1988) was used to investigate the role wind forcing plays in summer upwelling. Statistically significant coherence levels (PANOFSKY and BRIER, 1958) reveal the time scales over which shelf upwelling responds to coastal zone winds. Phase spectra indicate the time lag between wind forcing events and the arrival of upwelled water. The magnitude of the transfer function quantifies the change in near-bottom water temperature that occurs in response to wind forcing.

RESULTS

Figure 2 combines the temperature records from the three study sites. The dominant feature in the mid-shelf data (Figure 2a) is an upwelling event occurring from mid July through August. Temperatures decrease from just over 25 °C to a minimum of 14 °C in ten days. After an increase of 4 °C over the next five days, temperatures remain within about 1 °C of 18 °C for the next three and a half weeks. During the last half of August, temperatures increase to near 26 °C. During May and June, and again in mid September, brief periods of upwelling are recorded approximately biweekly. These events last 3–10 days and reduce the near-bottom temperature 4–6 °C.

The temperature time series recorded at the inner-shelf site near Sebastian Inlet (Figure 2b) shows a different pattern. The major upwelling event of July and August begins with a gradual decrease in temperature from 26 °C to 19 °C over a five-week period, followed by a relatively abrupt increase to a mid-summer maximum temperature of 28 °C. The temporary cooling events apparent in the mid-shelf temperature record are either absent or much less pronounced in the inner-shelf time series.

The abbreviated record from the inner-shelf site off Ft. Pierce Inlet shows a pattern similar to that recorded off Sebastian Inlet, 47 km to the north-northwest. Temperature increases from the end of April through early July. A one-week period of cooling in early June probably represents an intrusion of upwelled water. Although the Ft. Pierce record ends in late July, it contains the first part of the July–August upwelling event recorded at the other two study sites. Temperatures decrease gradually from 27 °C to 22 °C during the last half of July, much like the decrease recorded off Sebastian Inlet.

Figure 1. Study area on the Atlantic shelf of central Florida. Diamonds represent locations of thermographs and the circle shows the location of the meteorological station on Hutchinson Island.
To better understand temporal relationships, 31-day segments of data from each site have been isolated and plotted on the same time axis (Figure 3). The decrease in temperature during the first week of July, and again at the start of the major upwelling event, occurred simultaneously at the mid-shelf site and the Ft. Pierce inner-shelf site. Near-bottom temperatures off Sebastian Inlet decreased only slightly in early July, and temperature variations were delayed by about four days.

The progressive vector diagram of wind stress (Figure 4) shows wind stress into the southwest quadrant during the first and last weeks of June. During mid-June and most of July, wind stress was toward the northwest. Given the orientation of the coastline and isobaths (340°–160°), Ekman transport in surface layers will be seaward, and this favors wind-forced upwelling (CSANADY, 1984).

The temperature record from the mid-shelf study site was used to investigate the response to wind forcing. This thermograph was in the best position to record the advance and retreat of cold water across the continental shelf. A qualitative comparison of mid-shelf temperature and cumulative wind stress (Figures 2a and 4) reveals that the two transient cooling events recorded during the third week in June and the first week in July correspond in time with wind stress favorable for upwelling. Similarly, the major upwelling event (starting about July 10) coincides with a period of sustained northwestward wind stress.

Results of the spectral analyses indicate that the 205°–205° wind stress component is the most coherent with mid-shelf bottom temperature. Figure 5 shows the coherence spectrum and the spectra of the phase and magnitude of the transfer function. The coherence spectrum shows values above the
ture. Over these same time scales, the magnitude of the transfer function ranges from 0.045–0.090 dynes cm⁻² per °C. Comparison of the spectral densities of these two time series (not shown) suggests that wind forcing explains virtually all of the near-bottom temperature variability over time scales of 3–5 days.

**DISCUSSION**

The temporal and spatial variability observed in this upwelling study is similar to that observed from previous summer upwelling studies conducted along Florida’s central Atlantic Coast (Smith, 1981; Pitts, 1993). A major upwelling event, crossing the entire shelf and decreasing temperatures 6–10 °C for several weeks, is common for mid to late summer; although, it may impact only a few tens of kilometers of coastline at any one time (Smith, 1983). Before and after the major upwelling, transient upwelling events occur over the inner shelf, but they seem to be more pronounced and more frequent in mid-shelf and outer-shelf waters (Smith, 1981).

One of the significant differences between the three temperature records involves the low-frequency fluctuations in temperature during the first three months of the study. Low-frequency variations are less common and less distinct at the two inner-shelf sites. Temperature fluctuations in the mid-shelf record occur over time scales of about a week and almost certainly represent the advance and retreat of upwelled water that does not reach the inner shelf. Smith (1981, 1982, 1983) has shown that the shoreward movement of cold water does not always involve the entire shelf. Intrusions of cold water may reach only the outer-shelf or mid-shelf regions, particularly north of Cape Canaveral where the continental shelf broadens. It is likely that a thermograph located at the outer shelf during this study period would have recorded additional and more intense upwelling episodes.

Low-frequency upwelling events occur in some form throughout the year in this region, though effects are much more apparent during summer months when pre-upwelling and upwelling temperature differences are greatest. Smith (1987) used bottom temperature and current data from three locations along the shelf break to document temperature fluctuations during winter months between 27° and 30° N. His study documented a shoreward flux of relatively cool water, but the characteristic time scale was considerably shorter than that associated with summer upwelling. In winter, the upwelling process is driven by the passage of frontal eddies through the study area, rather than by a seasonal shift in the axis of the Florida Current or upwelling favorable winds. During winter months, upwelled water is also less likely to move onto the middle and inner shelf.

The coincidence of temperature fluctuations at the mid-shelf and Fort Pierce Inlet sites during July suggests the leading edge of intruded upwelled water is oriented northeast-southwest. Temperature fluctuations at the Sebastian inner-shelf study site are delayed by approximately four days. Given the horizontal separation of our three stations, the data suggest that the intrusion moves at a speed of 10–13 cm sec⁻¹. These calculations are in good agreement with the ±5–10 cm sec⁻¹ along-shelf current speeds recorded at a

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![Figure 5](https://example.com/figure5.png)

Figure 5. Coherence, phase and transfer function spectra of low-pass filtered wind stress (205°–025° component) and mid-shelf temperatures. Hatched line represents 95% confidence limit.

95% confidence level over the frequency band of 0.009–0.016 cph (periodicities of 111 to 62 hours). Over this frequency band, the phase spectrum indicates that the phase lead of wind stress over temperature generally increases from 75° to 100°. Thus, wind stress forcing has a relatively constant time lead of 18–23 hours over decreases in near bottom tempera-
nearby inner shelf study site during summer months (Smith, 1982). Northerly flow increased by 5–15 cm sec^{-1} during periods of upwelling.

Whereas our spectral analysis supports a cause-and-effect relationship between wind stress and upwelling within the 3–5 day band of periodicities, other processes may be producing upwelling over these same time scales. Leming's (1979) work showed significant coherence between bottom temperature and alongshore wind stress near the 3-day periodicity; yet, he questioned whether the large fluctuations in temperature could be explained by simple wind-driven coastal upwelling. His data showed frequent periods of wind stress conducive to coastal upwelling occurring with no apparent response in temperature. The strength of the local winds was also of concern to Leming. Typical summer wind stress for this region (0.1–0.3 dyne cm^{-1}) is an order of magnitude less than that for other coastal upwelling areas. A study by Smith (1981), using spectral analysis, showed coherence values computed between wind stress and bottom temperatures to be generally well below the 95% confidence limit, particularly over the longer time scales. More recently, Pitts (1993) described a study in which upwelling events lasting several days occurred at times when winds were unfavorable to upwelling.

A number of investigators have examined alternate forcing mechanisms to explain upwelling patterns in the absence of wind stress. In shelf waters landward of a western boundary current, upwelling can occur in several ways. Bumpus (1955), working off Cape Hatteras, was the first to establish a link between the Gulf Stream and continental shelf upwelling. Later, Hsueh and O'Brien (1971) provided a theoretical framework for this process when they modeled upwelling as a dynamic readjustment in an along-shelf current. Along the Atlantic coast of Florida when the Florida Current contacts the outer shelf, the current speed and thus the Coriolis force are decreased in near-bottom layers. This leaves the shoreward-directed pressure gradient locally dominant, and cooler water is forced onto the shelf. Smith's (1981, 1982) studies of the Florida Current suggest that the major late-summer upwelling event occurs in this way. Niller and Richardson (1973) demonstrate that Florida Current volume transport is greatest in summer months, and Chew and Bushnell (1987) show that an increase in volume transport will force the Florida Current to the west side of the Florida Straits.

The lateral meandering of the Florida Current over seasonal time scales has been documented by drogue measurements (Richardson et al., 1969; Chew and Berberian, 1970) and satellite imagery (Vukovich and Crissman, 1979). Typically these perturbations have wave lengths of 100–200 km and amplitudes of 5 km. Upwelling occurs when near-bottom water is forced onto the continental shelf along the anticyclonic part of the meander. The distance it penetrates shoreward is related to the current speed at the shelf break as well as the length of time the stronger current speeds persist along a given section of the outer shelf.

Lee (1975), Lee and Mayer (1977) and Lee et al. (1991) documented the occurrence of cyclonic frontal eddies which evolve from meanders of the Florida Current. Northward-propagating eddies occur at a given location approximately once per week. They can be characterized as tongue-like protrusions of the Florida Current with diameters of 10–30 km. Of particular interest are the regions of eddy decay which seem to be associated with upwelling (Pietrafesa et al., 1985). Because eddies can extend to a depth of 200 m, they can produce regions of upwelling that move along the outer shelf, but it is not likely that upwelling of this type would be recorded at a mid-shelf study site.

Results of our 1986 study indicate that wind stress plays a significant role in forcing upwelling in mid-shelf waters. Integrating our work with previous studies, it appears that the relative importance of wind stress and western boundary currents in driving the observed upwelling can vary substantially across the shelf. Florida Current effects seem to be most important over weekly, sub-seasonal and annual time scales at the shelf break. Wind forcing becomes significant in mid-shelf waters, combining with the nonlocal effects of meanders in the Florida Current. For upwelling to reach the inner shelf, it is likely that a seasonal shift in wind direction must coincide with a seasonal shift in the position of the Florida Current. Under those conditions, upwelled water is both forced landward from the outer shelf and drawn landward by a near-surface Ekman transport.

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LITERATURE CITED


