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Low-frequency current variability and spin-off eddies along the shelf off Southeast Florida

by Thomas N. Lee\textsuperscript{1} and Dennis A. Mayer\textsuperscript{2}

\textbf{ABSTRACT}

Time series analyses of current meter records from a 6-element box array installed on the narrow shelf (<5 km) off Miami, Florida revealed two distinct current regimes. Current oscillations at the shelf break (30m isobath) appeared to be primarily produced by Florida Current spawned events, such as low frequency (periods of 2 days to 2 weeks) wave-like meanders of the Florida Current and the transient occurrence of small diameter spin-off eddies, both of which may be indirectly related to wind forcing. Velocity fluctuations along the shallow inner shelf (6m isobath) were primarily in direct response to the local wind stress. The transition between current regimes occurred within the array east-west spacing of 2 km. Current fluctuations were observed to propagate to the north at speeds ranging from 20 to 100 cm/sec and were highly coherent over the 10 km north-south array spacing for all periods greater than 2 days. Along-shelf current oscillations were mutually coherent with fluctuations in the cross-stream current measured near the Florida Current axis, and with the east-west component of the local winds, at periods of about 2 and 9 days. Cyclonic spin-off eddies appear to evolve from growing barotropic instabilities (meanders), which may initially be wind induced. They manifest themselves as warm, southward-oriented, tongue-like extrusions of Florida Current water onto the shelf. Eddy diameters range from 10 to 30 km and they extend to a depth of approximately 200m. These features occur on the average of once per week and have a life span of about 1 to 3 weeks. They contribute to shelf water mass exchange and Florida Current energy dissipation.

1. Introduction

In a recent review of continental shelf circulation, Niiler (1975) stressed the highly variable nature of horizontal currents responding energetically to atmospheric forcing, eddies and long waves from the deep sea, and tidal phenomena. He noted that the rms of these fluctuations, on time scales of a few hours to 10 days, typically exceed the seasonal means.

Lee (1970; 1975) found the high current variability on the shelf off Pompano

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Figure 1a. Plan view of Florida Straits showing the location of the current meter box array, Terrace mooring, and the sea level and wind stations.

Figure 1b. Bottom profile of Florida Straits with current meter locations and mean temperature and current distributions based on University of Miami and Nova University observations during summer 1974.

Figure 2. Current and wind roses from 3 HrLP data for the period 9 February to 5 June, 1973 (see Table 1 for details); x is the location of the wind and sea level recorder.

and Boca Raton, Florida to be primarily governed by "spin-off eddies" (small diameter, cyclonic, edge-eddies) and horizontal wave-like meanders of the Florida Current front, with time scales ranging from 2 to 10 days. Mayer and Hansen (1975) observed that nearshore currents off Miami (depths <10m) were strongly correlated with the local wind stress. The shelf break (30m isobath) is approximately 3.5 km from the beach off Miami, which is about twice the shelf width off Boca Raton. This suggests that nearshore currents off Miami are somewhat isolated from events occurring along the shelf break.

2. Measurements

Eight current meters were deployed in an elongated $2 \times 10$ km box array on the continental shelf off Miami Beach in February, 1973 as part of a continuation of a southeast Florida coastal program begun in 1971 (Mayer and Hansen, 1975). The program was designed to provide information on circulation and exchange processes
Table 1. Mooring information and record lengths for filtered time series from current meter box array.

<table>
<thead>
<tr>
<th>Station</th>
<th>Water Depth (m)</th>
<th>Instrument Depth (m)</th>
<th>3 HrLP* record length</th>
<th>40 HrLP record length</th>
<th>40 HrHP record length</th>
<th>Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>M11</td>
<td>6.1</td>
<td>4.9</td>
<td>2878</td>
<td>2743</td>
<td></td>
<td>25°52.9'N 80°6.4'W</td>
</tr>
<tr>
<td>M12</td>
<td>32.0</td>
<td>13.7</td>
<td>2885</td>
<td>2750</td>
<td></td>
<td>25°52.9'N 80°5.2'W</td>
</tr>
<tr>
<td>M31</td>
<td>7.3</td>
<td>6.1</td>
<td>7271</td>
<td>7136</td>
<td></td>
<td>25°50.8'N 80°6.3'W</td>
</tr>
<tr>
<td>M2T (Top)</td>
<td>30.8</td>
<td>13.7</td>
<td>6774</td>
<td>6639</td>
<td></td>
<td>25°50.6'N 80°5.1'W</td>
</tr>
<tr>
<td>M3SM (Middle)</td>
<td>30.8</td>
<td>22.9</td>
<td>2926</td>
<td>2791</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M3SB (Bottom)</td>
<td>30.8</td>
<td>29.0</td>
<td>1150</td>
<td>1080</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M21</td>
<td>5.8</td>
<td>4.6</td>
<td>2879</td>
<td>2744</td>
<td></td>
<td>25°47.8'N 80°6.6'W</td>
</tr>
<tr>
<td>M22</td>
<td>32.0</td>
<td>13.7</td>
<td>2925</td>
<td>2790</td>
<td></td>
<td>25°47.4'N 80°5.1'W</td>
</tr>
<tr>
<td>Wind</td>
<td></td>
<td></td>
<td>3258**</td>
<td>3123</td>
<td></td>
<td>25°46'N 80°7.6'W</td>
</tr>
</tbody>
</table>

* Note: All data have time interval of 1 hour; All start times for 3 hr. low-passed (HrLP) data were 0800 GMT, 6 Feb. '73; All start times for 40 HrLP and high-passed (HP) data were 0800 GMT, 9 Feb. '73.
** Wind data have been 5 HrLP.

peculiar to this narrow, shallow shelf. The location of the current meter array relative to the Florida Straits geometry and mean temperature and current fields is shown in Figs. 1a, 1b, and 2. The local isobaths are aligned in approximately a north-south direction near the measurements. Station coordinates, depths, and record lengths are given in Table 1. The box array was maintained for approximately 4 months over the winter and early spring. Stations M21 and M22 were maintained through December, 1973 with a single current meter on each, providing about 9 months of data.

Aanderaa model RCM-4 current meters with a 10-min. sampling interval were used exclusively. The deeper stations (~30m) M12, M22, and M32 were of a taut wire, subsurface-float design. Station M22 had three meters in the vertical, the uppermost being approximately at mid-depth. The shallow stations (~6m) M11, M21, and M31 were all fixed tripods that mounted the meters approximately 1m above the bottom.

3. Data processing

All data were filtered to remove noise and to partition into distinct frequency bands. Three basic filters were used: 3 hr. low-pass (HrLP), 40 HrLP, and 40 hr. high-pass (HrHP). A period of 40 hrs., which falls within a spectral gap, is used to distinguish conceptually between slowly and rapidly varying processes; the latter includes tidal and inertial frequencies with periods less than 2 days but longer than 3 hrs. Table 2 summarizes the transmission characteristics of each filter. Current
Table 2. Characteristics of the digital filters used for smoothing time series data.

<table>
<thead>
<tr>
<th></th>
<th>3 HrLP (hr)</th>
<th>5 HrLP (hr)</th>
<th>40 HrLP (hr)</th>
<th>40 HrHP (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 db point</td>
<td>1/2 amplitude</td>
<td>2.5</td>
<td>5.0</td>
<td>37</td>
</tr>
<tr>
<td>1/10 amplitude</td>
<td>2.0</td>
<td>4.0</td>
<td>30</td>
<td>48</td>
</tr>
</tbody>
</table>

Meter data were first smoothed with the 3 HrLP filter then resampled hourly. The resultant time series were then filtered with the 40 HrLP and 40 HrHP to examine low and high frequency processes separately.

4. Statistics

Statistics were computed from the basic time series and are tabulated in Table 3. In addition to the means, the low and high frequency variances were calculated for the velocity component time series $u(+east)$ and $v(+north)$. The ratio of high passed variance ($HPV$) to total variance ($TV$), and the ratio of $TV$ to the squared mean speed ($\nu^2$) are also given. The former ratio indicates the percentage of high frequency energy in the records, and the latter ratio is of interest in analyzing the dispersion of materials.

Momentum flux calculations were computed from the velocity data and are summarized in Table 4. It is convenient to represent the velocity time series in terms of three time scales:

$$\vec{w} = \langle \vec{w} \rangle + \vec{\tilde{w}} + \vec{w}'$$

where $\vec{w} = u$ or $v$. The symbol $\langle \rangle$ is a time average over the record length. The overbarred term ($\vec{\tilde{w}}$) signifies the 40 HrLP data minus the mean, thus representing the slowly varying or low frequency processes. The primed terms ($\vec{w}'$) are 40 HrHP data and represent the rapidly varying or high frequency processes. The time averaged momentum flux, or Reynolds stress, is expressed as:

$$\langle \vec{w} \vec{w} \rangle = \langle \vec{w} \rangle \langle \vec{w} \rangle + \langle \vec{\tilde{w}} \vec{\tilde{w}} \rangle + \langle \vec{w}' \vec{w}' \rangle$$

Tables 3 and 4 indicate that the box array spanned two very different flow regimes. In the shallow water, mean currents were essentially zero, whereas, at the deeper stations, a net northerly flow of nearly 20 cm/sec existed. A summary of the 3 HrLP direction data is given in Fig. 2. These polar frequency distributions contain both low and high frequency processes within 10 degree class intervals. Flows at the offshore stations had a considerable bias toward the north, while those nearshore were bimodal (north and south). Approximately 70 to 75% of the total variance at the shelf break was produced by current fluctuations which had periods longer than 40 hrs. In the shallow water about 50 to 60% of the total variance was produced by low frequency currents. Also, the momentum flux ($\langle \vec{v} \vec{v} \rangle$ and $\langle v' v' \rangle$) was considerably larger at the deeper stations.
Table 3. Statistics of 3 HrLP, 40 HrLP, and 40 HrHP current meter time series.

<table>
<thead>
<tr>
<th>Station</th>
<th>Mean Temp. °C(±.05)</th>
<th>Mean North Component cm/sec(±1.0)</th>
<th>Mean East Component cm/sec(±1.0)</th>
<th>(HPV) Variance (µ²)</th>
<th>(LPV) Variance (µ²)</th>
<th>Squared Mean Speed (cm/sec)²</th>
<th>Total Variance (TV)</th>
<th>TV/µ²</th>
</tr>
</thead>
<tbody>
<tr>
<td>M₃₁</td>
<td>24.37</td>
<td>0.0</td>
<td>0.0</td>
<td>72.0</td>
<td>84.0</td>
<td>~1.0</td>
<td>.46</td>
<td>156</td>
</tr>
<tr>
<td>M₁₂</td>
<td>24.50</td>
<td>13.0</td>
<td>1.0</td>
<td>145.0</td>
<td>308.0</td>
<td>170.0</td>
<td>.32</td>
<td>2.7</td>
</tr>
<tr>
<td>M₂₁</td>
<td>26.32</td>
<td>0.0</td>
<td>0.0</td>
<td>57.0</td>
<td>67.0</td>
<td>~1.0</td>
<td>.46</td>
<td>124</td>
</tr>
<tr>
<td>*M₂₃</td>
<td>24.27</td>
<td>-1.0</td>
<td>1.0</td>
<td>64.0</td>
<td>89.0</td>
<td>1.4</td>
<td>.42</td>
<td>109</td>
</tr>
<tr>
<td>M₂₃T (Top)</td>
<td>26.43</td>
<td>18.0</td>
<td>0.0</td>
<td>206.0</td>
<td>654.0</td>
<td>324.0</td>
<td>.24</td>
<td>2.7</td>
</tr>
<tr>
<td>*M₂₃T (Top)</td>
<td>24.88</td>
<td>15.0</td>
<td>0.0</td>
<td>140.0</td>
<td>370.0</td>
<td>225.0</td>
<td>.27</td>
<td>2.3</td>
</tr>
<tr>
<td>M₂₃M (Middle)</td>
<td>24.25</td>
<td>10.0</td>
<td>1.0</td>
<td>97.0</td>
<td>190.0</td>
<td>101.0</td>
<td>.34</td>
<td>2.8</td>
</tr>
<tr>
<td>M₂₃B (Bottom)</td>
<td>23.97</td>
<td>7.0</td>
<td>1.0</td>
<td>29.0</td>
<td>57.0</td>
<td>50.0</td>
<td>.34</td>
<td>1.7</td>
</tr>
<tr>
<td>M₃₈</td>
<td>24.45</td>
<td>1.0</td>
<td>0.0</td>
<td>65.0</td>
<td>96.0</td>
<td>1.0</td>
<td>.40</td>
<td>161</td>
</tr>
<tr>
<td>M₃₉</td>
<td>24.62</td>
<td>21.0</td>
<td>-1.0</td>
<td>161.0</td>
<td>499.0</td>
<td>442.0</td>
<td>.24</td>
<td>1.5</td>
</tr>
<tr>
<td>Wind</td>
<td>133.0±10.0</td>
<td>-258.0±10.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* These statistics are computed based on first 2750 points or approximately the first 4 months, otherwise statistics are based on the record lengths in Table 1.

The Reynolds stress estimates of Table 4 indicate a northward momentum flux toward the west of about -10 cm²/sec² for both the low and high frequency currents with little horizontal variability over the array. These estimates are believed...
Table 4. Statistics of momentum flux time series (cm²/sec²).

<table>
<thead>
<tr>
<th></th>
<th>40 HrLP (± 10%)</th>
<th>40 HrHP (± 10%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \langle \tilde{v} v \rangle )</td>
<td>( \langle \tilde{u} u \rangle )</td>
</tr>
<tr>
<td>( M_{12} )</td>
<td>78.0</td>
<td>6.0</td>
</tr>
<tr>
<td>( M_{12} )</td>
<td>304.0</td>
<td>5.0</td>
</tr>
<tr>
<td>( M_{22} )</td>
<td>61.0</td>
<td>6.0</td>
</tr>
<tr>
<td>*( M_{22} )</td>
<td>84.0</td>
<td>5.0</td>
</tr>
<tr>
<td>( M_{22T} ) (Top)</td>
<td>648.0</td>
<td>7.0</td>
</tr>
<tr>
<td>*( M_{22T} ) (Top)</td>
<td>365.0</td>
<td>5.0</td>
</tr>
<tr>
<td>( M_{22M} ) (Middle)</td>
<td>188.0</td>
<td>2.0</td>
</tr>
<tr>
<td>( M_{31} ) (Bottom)</td>
<td>91.0</td>
<td>4.0</td>
</tr>
<tr>
<td>( M_{32} )</td>
<td>494.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>

* These statistics are computed based on first 2750 points or approximately the first 4 months, otherwise statistics are based on record lengths in Table 1.

5. Comparative analysis

Time series of 6-hourly current vectors, local wind, and adjusted sea level are shown in Fig. 3 for the 40 HrLP series. Coastal currents were primarily aligned with the isobaths (north-south). Currents at the shelf break (meters \( M_{12}, M_{22T}, M_{22M}, M_{22B}, \) and \( M_{32} \)) display considerable variability with fluctuation amplitudes ranging from 50 to 100 cm/sec over time scales of about 2 days to 2 weeks. These oscillations are visually coherent along the shelf break over the array spacing (10 km) and appear, for the most part, to be barotropic due to the high vertical similarity (\( M_{22T}, M_{22M}, \) and \( M_{22B} \)). Cyclonic (anticlockwise) current reversals, such as the one coded EDWARD on \( M_{32} \), appear to be a common occurrence along the shelf break. These events were described as Florida Current spin-off eddies by Lee (1975) and will be discussed in more detail in a later section. It is difficult to detect any persistent visual correlation between shelf break currents and the local winds or sea level. A seasonal change in wind intensity occurred near the end of April with the cessation of the weekly migration of cold fronts without any apparent change in current variability.
In the shallow nearshore waters, currents had high along-shelf coherence over the array ($M_{11}$, $M_{21}$, and $M_{31}$) and were more clearly correlated with local winds. Visual similarity between currents at the inshore and shelf break stations is weak. The mean current along the inner shelf was approximately zero and the amplitude of the fluctuations ranged from 10 to 30 cm/sec. Current directions paralleled the coast, either to the north or south, depending on whether the wind had a component from the south or north, respectively, similar to the findings of Murray (1975). There was also a marked decrease in current speeds which occurred at the time of the summer decrease in wind speeds. Mofield and Mayer (1976) used a
Figure 4. Spectra $M_{12}$ vs. $M_{32}$ (cm$^2$/sec$^2$/CPD) of 40 HrLP v-component series for the period 9 February to 5 June, 1973. Number of data points = 331; sample interval = 8 hrs.; lags = 56; degrees of freedom = 15.8; bandwidth = 0.035 CPD.

first-order autoregression technique to determine the longshore current response at $M_{21}$ and $M_{32}$ to the longshore component of the wind during the winter. He found that approximately 60% of the low frequency (periods longer than 40 hours) current variability at the inner shelf and about 12% at the shelf break were accounted for by the local wind.

Sea level set-up (set-down) at the coast appears, for the most part, to be correlated with southward (northward) winds, which is in agreement with Ekman-type downwelling (upwelling) found by Brooks and Mooers (1977). This is illustrated during February 9 to March 11, March 21 to 26, and May 1 to 16.

6. Spectrum analysis

Spectrum and cross-spectrum analyses were performed on selected time series pairs from Fig. 3 using standard Fourier transform methods (Jenkins and Watts, 1968). Only the v-component spectra are shown for they contained most of the variance, due to the north-south current alignment with the isobaths. Currents at the shelf break display four broad-band spectrum peaks centered at periods of 2.3, 3.1, 9.3, and 18.7 days (Fig. 4). At the 95% significance level, low frequency fluctuations were extremely coherent over the 10 km north-south array separation for all periods greater than two days, which account for about 75% of the total vari-
Figure 5. Spectra $M_{32}$ vs. $M_{31}$ (cm$^2$/sec$^2$/CPD) of 40 HrLP v-component series for the period 9 February to 5 June, 1973. Number of data points = 331; sample interval = 8 hrs.; lags = 56; degrees of freedom = 15.6; bandwidth = 0.036 CPD.

Since the phase is positive for all cross-spectrum peaks, the oscillations occurred at the southern location first, which indicates a northward propagation for all low frequency motions. The periods of the coherent peaks, their coherency, phase, and 95% phase confidence limits are given in Table 5. Also shown are the corresponding wave lengths, phase speeds, and amplitudes computed over the array.

In the cross-shelf direction the only significant coherence occurred at a period of 2.2 days (Fig. 5); however, if an 80% significance level were used, then motions with periods of 2.5, 4.1, and 18-37 days would also be considered coherent. The phase is approximately +90° for all frequencies greater than 0.15 CPD, which indicates that fluctuations in the shallow water lead by about 1/4 wavelength. In the

Table 5. Linear wave properties computed from the spectra of $M_{32}$ and $M_{12}$.

<table>
<thead>
<tr>
<th>Period (days)</th>
<th>(coherence)$^2$</th>
<th>Phase</th>
<th>95% confidence limit for Phase</th>
<th>Wave Length (km)</th>
<th>Phase Speed (cm/sec)</th>
<th>Amplitude (cm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.7</td>
<td>.96</td>
<td>4.3°</td>
<td>±2°</td>
<td>905</td>
<td>+56</td>
<td>11</td>
</tr>
<tr>
<td>9.3</td>
<td>.92</td>
<td>22.7°</td>
<td>±3°</td>
<td>160</td>
<td>+20</td>
<td>14</td>
</tr>
<tr>
<td>3.1</td>
<td>.87</td>
<td>17.7°</td>
<td>±6°</td>
<td>263</td>
<td>+98</td>
<td>13</td>
</tr>
<tr>
<td>2.3</td>
<td>.88</td>
<td>27.9°</td>
<td>±6°</td>
<td>129</td>
<td>+65</td>
<td>20</td>
</tr>
</tbody>
</table>
Figure 6. Spectra $M_{31}$ vs. Miami Beach wind (cm$^2$/sec$^2$/CPD) of 40 HrLP $v$-component series for the period 9 February to 5 June, 1973. Number of data points = 328; sample interval = 8 hrs.; lags = 56; degrees of freedom = 15.6; bandwidth = 0.035 CPD.

9 to 12 day period band, oscillations at the shelf break lead by about 45°. It is again obvious that the temporal behavior of currents over the inner shelf was strikingly different from that measured at the outer shelf. The most energetic currents along the inner shelf had periodicities ranging from 4.6 to 6.2 days with a peak at 5.3 days. At the outer shelf the spectral peaks occurred at different periods with considerably higher amounts of energy.

Alongshore currents in the inner shelf waters were highly coherent with the $v$-component of the local wind for all periods longer than 3.5 days (Fig. 6). The similarity of the shape of the energy spectra and the near zero phase lags suggests that low frequency currents in these shallow waters are primarily driven by the local wind stress. In comparison, at the shelf break, the $v$-component wind was only significantly coherent (95% level) with alongshelf currents at a period of 4.1 days, with strong indication of significant coherence at 18.6 days (Fig. 7). However, the $u$-component wind was significantly correlated with current modulations at the outer shelf with periods of 37.3 and 9.3 days (Fig. 8). In addition, at periods of 4.7 and 2.2 days, the coherence is very near the 95% significance level. At the 5 day period the $u$-component wind was nearly in phase with the $v$-component current, whereas at the 9 day period the wind led by about 90° (2.2 days).

Low frequency current oscillations are not restricted to the continental shelf.
Lee & Mayer: Low-frequency current variability

Figure 7. Spectra $M_{32}$ vs. Miami Beach wind (cm$^2$/sec$^2$/CPD) of 40 HrLP $v$-component series for the period 9 February to 5 June, 1973. Number of data points = 328; sample interval = 8 hrs.; lags = 56; degrees of freedom = 15.6; bandwidth = 0.036 CPD.

Similar phenomena have been observed in a two-year deep current record obtained from the seaward edge of the Miami Terrace (approximately 26 km east of the box array; see Figs. 1a and 1b), located near the mean current axis of the Florida Current (Düing, Mooers, and Lee, this issue). Significant coherence occurred between the $u$-component current at this location and the $v$-component current at the shelf break for periods of 2.3 to 2.5 days and 9.3 to 12.4 days, with fluctuations at the current axis leading (Fig. 9). Comparisons with the $v$-component current from the Terrace break are not shown, but they revealed high coherence at periods of 2.3 to 2.5 days, 3.7 and 5.3 days, whereas it was low at periods of 9.3 to 12.4 days. Düing, Mooers, and Lee also observed significant coherence at periods in the 9.3 to 12.4 day range between the $v$-component current at the Terrace break and the east-west wind stress ($\tau_e$) with the wind leading by about 90°. This is very similar to the correlation found at the shelf break with the east-west local wind.

Low frequency current fluctuations, with periods ranging from 2 days to 2 weeks, are a persistent feature of the Florida Current time domain. They were first observed by Pillsbury (1890) and later by Parr (1937). Webster (1961a) found a 7-day meander of the Florida Current front off Onslow Bay with amplitudes up to 10 km. He discovered the meander to be well correlated with onshore winds computed from north-south pressure differences that were lagged by 4.5 days, which is
Figure 8. Spectra $M_{32} (v)$ vs. Miami Beach wind ($u$-component) (cm$^2$/sec$^2$/CPD) of 40 HrLP time series for the period 9 February to 5 June, 1973. Number of data points = 328; sample interval = 8 hrs.; lags = 56; degrees of freedom = 15.6; bandwidth = 0.036 CPD.

again similar to our results and those of Düing, Mooers, and Lee. Schmitz and Richardson (1968) reported the Florida Current to be meandering on a one-week time scale with amplitudes of about 5 km in the Florida Straits. Mooers and Brooks (1977) analyzed temperature records near Miami and found several-day oscillations with amplitudes of 2 to 3°C. Düing (1975) conducted profiling from four anchored ships off Miami and noted a current modulation with 4 to 6 day time scales that was interpreted as a northward-traveling barotropic wave superimposed on the mean baroclinic current profile. The wavelength was estimated between 160 and 240 km and the phase speed was reported to be about +50 cm/sec.

It is evident that at least part of the low frequency current oscillations over the shelf are connected to similar features in the Florida Current over the Miami Terrace (Fig. 9), both of which appear to be related to wind stress. A mechanism which could account for these observations was discussed by Brooks (1975), viz., the fluctuating wind stress can produce a surface onshore-offshore Ekman transport which results in deep motions across steep bottom topography and mean current shear. As a consequence, relative vorticity is generated, which can propagate as topographically trapped waves (shelf waves). With a mean northward flow, the first two barotropic longwave modes travel to the south, with shallow water on the right. However, the shortwaves and higher modes can travel north.
Figure 9. Spectra Terrace Break Meter (u-component) vs. M\textsubscript{32} (v-component) (cm\textsuperscript{2}/sec\textsuperscript{2}/CPD) of 40 HrLP time series for the period 9 February to 18 April, 1973. Number of data points = 205; sample interval = 8 hrs.; lags = 56; degrees of freedom = 9.8; bandwidth = 0.036 CPD.

7. Seasonality

After removal of the box array, moorings M\textsubscript{21} and M\textsubscript{22} were maintained for an additional 5 months, producing record lengths of approximately 9 months. Time series of 4-hourly current vectors from these locations, along with local wind and unadjusted sea level, are shown in Fig. 10. The long current records were broken into three seasonal subsets, labeled A, B, and C, of 100 days duration and 15 days overlap. Simple statistics of these 40 HrLP series are given in Table 6.

Table 6. Basic statistics of seasonal subsets of the long 40 HrLP current series.

<table>
<thead>
<tr>
<th>Mooring</th>
<th>Data Set</th>
<th>u (cm/sec)</th>
<th>v (cm/sec)</th>
<th>Stand. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>M\textsubscript{21} A</td>
<td>Min.</td>
<td>Max.</td>
<td>Mean</td>
<td>Min.</td>
</tr>
<tr>
<td>M\textsubscript{22} A</td>
<td>-9</td>
<td>7</td>
<td>-0.3</td>
<td>2</td>
</tr>
<tr>
<td>M\textsubscript{21} B</td>
<td>-4</td>
<td>6</td>
<td>-0.4</td>
<td>2</td>
</tr>
<tr>
<td>M\textsubscript{22} B</td>
<td>-8</td>
<td>7</td>
<td>-0.4</td>
<td>3</td>
</tr>
<tr>
<td>M\textsubscript{21} C</td>
<td>-8</td>
<td>11</td>
<td>-0.5</td>
<td>3</td>
</tr>
<tr>
<td>M\textsubscript{22} C</td>
<td>-10</td>
<td>8</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>
Figure 10. Time series of 4-hourly current vectors, 6-hourly wind vectors, and unadjusted sea level over the period 9 February to 3 December, 1973. The current and sea level data have been smoothed with a 40 HrLP filter. The wind record is 6-hour averages from 3-hourly Miami airport readings; speed scales are given by the magnitude of the arrows: 50 cm/sec for current and 5.4 m/sec for wind; seasonal subsets are designated by A, B, and C.

As suggested earlier (Fig. 3), the intense current variability at the shelf break is persistent throughout the year and shows little visual correlation with the local winds, which display a marked seasonal behavior. Currents at the inner shelf were

Figure 11. Spectra $M_{21}$ vs. $M_{22}$ (cm$^2$/sec$^2$/CPD) of 40 HrLP $v$-component series for the period 9 February to 12 November, 1973. Number of data points = 817; sample interval = 8 hrs.; lags = 56; degrees of freedom = 38.9; bandwidth = 0.036 CPD.
highly influenced by the local wind during the two winter seasons of February through April and October through November. During the summer the smaller amplitude fluctuations appear to be related to events at the shelf break. There was a significant increase in the northerly mean current at the shelf break in the summer. A similar summer increase has been observed at the shelf break off Boca Raton, Florida by Lee (1975). These observations may reflect the summer maximum Florida Current volume transport reported by Niiler and Richardson (1973) and later confirmed by Mooers and Brooks (1977). Mean currents in the inner shelf were near zero for all seasons.

Cross-spectrum analyses were conducted with the \( v \)-component time series from the inner shelf and shelf break locations for the total record (Fig. 11) and seasonal subsets (Figs. 12, 13, and 14). Distinct energy peaks become lost in spectra of the total records due to the event nature of the fluctuations which occur with many different time scales and tend to produce a red spectrum when analyzed together. The cross-shelf coherence computed over the 9 months of data is above the 95% significance level for most of the low frequency spectrum except for periods of about 5 days. The negative phase indicates that fluctuations occurred first at the inner station. Spectra of the winter subset (Fig. 12) are essentially the same as that of Fig. 5, where it was shown that the 5 day peak in the inner shelf was associated...
with a similar period motion in the local winds. The 9 day peak at the shelf break was coherent with the \( u \)-component of the wind and the \( u \)-component of the current at the Miami Terrace break. In subset B (summer) current oscillations at the inner shelf, with periods of about 9 days, now appear as a well-defined energy peak and are coherent with similar fluctuations at the shelf break (Fig. 13). These changes are probably due to the decrease in local wind forcing which occurs with the discontinuance of winter cold fronts. The spectra of subset C (part summer and winter) do not contain any pronounced energy peaks, which reflects the mixture of time scales that are occurring during this period (Figs. 14 and 10). These numerous differences in spectra of the total data set and seasonal subsets indicate that low frequency current modulations in the shelf waters occur as transient phenomena in response to event-type forcing, such as the passage of cold fronts, which may in turn generate meanders and eddies. Thus, the shape and partition of energy in a current spectrum is to some degree dependent on the time period of the measurements. However, the statistics of the current and momentum flux time series averaged over the total record and the first 4 months showed little variation (Tables 3, 4, and 6).

8. Spin-off eddies

One of the most pronounced features of the current observations is the large
number of current reversals that do not appear to be either directly tide- or wind-
induced (Figs. 3 and 10). Similar events were previously observed off Pompano and
Boca Raton, Florida and were termed “spin-off eddies” (Lee, 1970; 1975). These
disturbances were described as small diameter (10-30 km), cyclonic edge-eddies
which form along the inshore front of the Florida Current and travel northward
through the coastal waters. Vortices of this type have been frequently observed in
frontal regions of strong horizontal shear (Spilhaus, 1940; Von Arx, Bumpus, and
Richardson, 1955; Bang, 1971; 1973). Remote satellite thermal imagery clearly
displays these features to be tongue-like, Gulf Stream extrusions coupled to a trail-
ing band of shelf or slope waters (NOAA-NESS, 1974; DeRycke and Rao, 1973;
Maul, Norris, and Johnson, 1974; Stumpf and Rao, 1975; Legeckis, 1975).

Spin-off eddies leave their signatures in a current meter record as a strong cy-
clonic reversal which is many times accompanied by an advection of heat and salt
from the Florida Current. Fig. 10 indicates that approximately 45 reversals oc-
curred during the total measurement period or, on the average, about one per week.
However, it is difficult to determine from current meter records alone if a reversal
was produced by an eddy or a propagating wave.

On February 22 and 23 the 3-dimensional thermal field of a well-developed spin-
off eddy was mapped during its northward passage through the current meter array.
This event is designated EDWARD in Figs. 3 and 10. Mapping was performed

Figure 14. Spectra M_x C vs. M_y C (cm²/sec⁷/CPD) of 40 HrLP v-component series for the
period 29 July to 6 November, 1973 (summer and fall subset C). Number of data points =
300; sample interval = 8 hrs.; lags = 56; degrees of freedom = 14.3; bandwidth = 0.036 CPD.
daily off Miami and Fort Lauderdale by running a saw-toothed cruise tract with a continuously recording surface thermosalinograph on a rapid vessel. A series of XBT's were released on each leg perpendicular to shore. A composite surface thermal map was constructed by translating the daily thermal maps northward at the speed of the anomaly as measured by the current meter array (Fig. 15). Mapping of the eddy event took approximately one day, from 1130 hours on the 22nd to 1200 hours on the 23rd. EDWARD appears as a warm, tongue-like southward extrusion from the Florida Current, coupled to an entrainment of cooler shelf water.
Figure 16. Time series of one-hour values of 3 HrLP current and wind vectors during the passage of a spin-off eddy (EDWARD).

along the southern boundary. This configuration is very similar to the “shingle” (Von Arx, Bumpus, and Richardson, 1955) structure observed from satellites. The oblong-shaped eddy traveled toward the north at approximately 39 cm/sec, with a length of about 34 km and width of 23 km. The northward speeds computed from the current meter array and daily displacements of the thermal maps were in good agreement. There appears to be a smaller distortion of the surface front about 80 km to the north. This feature was also observed to produce a current reversal and may be an initial growth stage of an edge-eddy. Both disturbances were associated with a larger wave-like meander of the front which had a length of 84 km and appeared to propagate to the north at the same speed as EDWARD, which indicates a period of 2.2 days.

A blow-up of the 3 HrLP current and wind data recorded during the passage of EDWARD is shown in Fig. 16. Data from current meter M_{22T} are not shown for it was not operating properly at this time. Except for a small reversal near the 23rd, the local winds were light and steady (~ 5 m/sec toward the south) over the duration of the eddy and show no direct connection. The northward movement of the event is clearly evident in the shelf break records. Currents along the inner shelf
Figure 17. Temperature profiles through a spin-off eddy; section (A), 22 February, 1130-1155; section (B), 22 February, 1220-1236; section (C), 22 February, 1324-1343; section (D), 23 February, 1040-1108; section (E), 23 February, 0936-1014; arrows indicate XBT stations.

appear to be unaffected by EDWARD, indicating that it did not extend into these shallow depths (~ 6m).

The passage of a spin-off eddy also produces a strong vertical distortion of the thermal field over the slope and terrace (Figs. 17, 18a, 18b, and 18c). The up-lifted isotherms associated with the cyclonic circulation of EDWARD created a cool surface band of 23°C water near the center of the vortex. The warmer water within the southward extruding tongue is part of a homogeneous layer approximately 80m deep. The convergence of the southerly and northerly flows at the southern boundary produces an extremely turbulent surface disturbance line that is clearly visible.
Figure 18a. Composite map of surface temperature (°C) contoured from thermosalinograph data recorded continuously along a saw-toothed cruise track on February 22 and 23. XBT stations are marked with an X.

Figure 18b. Composite map of temperature (°C) at the 50 m depth, contoured from XBT data obtained on February 22 and 23. XBT stations are marked with an X.

Figure 18c. Composite map of temperature (°C) at the 100m depth, contoured from XBT data obtained on February 22 and 23. XBT stations are marked with an X.
Effects of the eddy appear to extend to a depth of about 200-220m where the isotherms tend to become horizontal.

9. Eddy model

Since it is difficult to obtain synoptic measurements of spin-off eddies, Lee (1975) developed a kinematic model that uses current meter data to predict the horizontal dimensions, phase speed, and circulation of an eddy. This approach was used with good results on 7 vortices measured off Boca Raton; however, the only parameters available for model verifications were the observed currents and phase speeds. The event shown in Figs. 15 and 16 can be used to check the spatial predictions as well. Briefly, the model consists of a linear combination of a moving vortex pair with a uniform background current. The resulting flow is 2-dimensional in the $x$-$y$ plane, with $y$ positive to the north and $x$ positive to the east. A vortex pair was used in order to account for the influence of the coastline (Lamb, 1945) for, when com-
bined with a uniform current, this becomes analogous to a single moving vortex in a flow near a boundary. As an eddy passes a fixed current meter, the recorded time series should resemble this combined motion.

Current meter data (M₂, 3 HrLP) recorded during the passage of EDWARD were tested with the above model. The actual and predicted currents as shown in Fig. 19 appear to be reasonably similar. In addition, the model predicts the eddy to have a width of 21 km, length of 36 km, phase speed of 40 cm/sec to the north, and a circulation of \(4.5 \times 10^2\) cm\(^2\)/sec. These estimates are within 8% of the measured values, which is a good agreement and further substantiates the model's ability to give a reasonable representation of spin-off eddies.

10. Eddy formation

There are several candidate mechanisms that may be responsible for edge-eddy formation. Eddies are known to form in the wake of topographic anomalies, are at times generated by wind, and can form from growing instabilities. It is well documented in the literature that mesoscale eddies (rings) form east of Cape Hatteras from the growth and detachment of large-scale Gulf Stream meanders (cold core rings: Fuglister, 1971; Barrett, 1971; Parker, 1971; warm core rings: Saunders, 1971; Thompson and Gotthardt, 1971; Gotthardt, 1973). The meanders can be initiated by winds or thermohaline processes and then grow to detachment due to instabilities in the basic zonal flow (Saltzman and Tang, 1975).

Similarly, smaller diameter spin-off eddies (diameter <50 km) appear to be an evolutionary stage of a rapidly growing wave-like instability of the Florida Current front. These vortices are consistently observed in regions of large horizontal shear over a wide range of different bottom topographies and at any time of year. This suggests that their generation is not likely to be due to topographic or direct wind forcing. Also, it has been shown that a small perturbation of a region of high horizontal velocity gradients can produce a rolling up of the shear zone (Rouse, 1963) which resembles the shingle structure of the Florida Current front. In a like manner, perturbations of the front have been observed to evolve into eddies in approximately 2 days (Stumpf and Rao, 1975; Legeckis, 1975). Orlanski (1969) and Orlanski and Cox (1973) demonstrated that baroclinic instabilities can develop in the Gulf Stream and may be the source of frontal meanders in the Florida Current. However, Eady (1949) and Saunders (1973) determined that the criterion for baroclinic instability of a vortex is \(R_D^2 < r^2\), where \(r\) is the eddy radius and \(R_D\) is the internal Rossby radius of deformation. For the eddy shown in Fig. 14, this ratio is approximately 3; thus, it does not appear that edge-eddies grow from amplified baroclinic waves. The criterion for barotropic instabilities to develop is satisfied if the potential vorticity distribution has one or more extrema normal to the coast (Kuo, 1949; Haurwitz and Panofsky, 1950; Lipps, 1963; Niiler and Mysak, 1971). This criterion is
met in the cyclonic shear region of the Florida Current where the instantaneous horizontal velocity profile can become strongly concave. Also, a barotropic disturbance is known to grow at the expense of kinetic energy from the mean flow (Haurwitz and Panofsky, 1950; Lipps, 1963). It was previously shown (Lee, 1975) that spin-off eddies behaved as braking mechanisms on the basic current, substantially increasing the normal energy dissipation rate of the inshore frictional region.

Due to the rapid energy dissipation, the life span of a typical spin-off eddy should be relatively short compared to the mesoscale size which can exist for years (Fuglister, 1971; Parker, 1971; Barrett, 1971). Ichiye (1966) concluded that the time ($t$) to reduce the vorticity in a small-scale Rankin type vortex (finite filament of constant vorticity surrounded by an irrotational field) to $1/2$ its initial value is given by:

$$t = \frac{L^2}{(1.82) A_H}$$

where $L$ is the horizontal scale of the eddy and $A_H$ is the horizontal eddy viscosity which he computed from the semi-empirical law $A_H = 0.01 \ L^{4/3}$. For the eddy displayed in Figs. 18a, b, and c, $L \approx 30$ km and $A_H \approx 4 \times 10^6$ cm$^2$/sec. The eddy viscosity can also be computed from the ratio of the square of the characteristic distance offshore to the center of an eddy ($X$) to the mean separation time of vorticities $T_s$, i.e., $A_H = \frac{X^2}{T_s}$, with $X = 15$ km and $T_s = 1$ week, we find that $A_H \approx 3.8 \times 10^6$ cm$^2$/sec. Using these values in eq. 3, the half-life of a 30 km scale edge-eddy is approximately 2 weeks. Satellite imagery indicates that this estimate is reasonable, for it is difficult to trace small-scale features on the Florida Current front in images taken more than 2 weeks apart.

### 11. Summary

Analysis of current meter data from the narrow continental shelf off Miami, Florida revealed that the most energetic fluctuations occurred as highly variable, low-frequency current oscillations with broad-band periods ranging from 2 days to 2 weeks. The amplitudes of these modulations were several times the means, and appear to be generated by wave-like meanders and/or eddies from the Florida Current, both of which may be causally related to wind forcing. Current fluctuations were highly coherent along the shelf break (30m isobath) over the 10 km array spacing for all periods greater than 2 days. Phase relationships indicate a northward propagation for all low frequency motions. Currents at the shelf break showed $v$-component spectrum peaks at periods of about 2, 3, 9, and 19 days that were mutually coherent with the $u$-component current near the Florida Current axis (Terrace break) and the $u$-component of the local wind at the common periods of
2 and 9 days. The v-component currents at the shelf break and at the Terrace break (Düing, Mooers, and Lee, 1977) both showed significant coherence with the east-west component of the wind around the 9 day period with the wind leading by about 90°. A similar result was found by Webster (1961a) off Onslow Bay between meanders of the Florida Current front and the east-west wind. Current oscillations along the shallow inner shelf (6m isobath) appear to be primarily driven by local winds during the winter with high coherence between the two for all periods longer than 3.5 days. The coherence between the inner shelf and shelf break locations (2 km separation) was low during this time except for periods around 2 days. During the summer, wind and inner shelf current variability decreased, whereas current variability along the shelf break remained high. In addition, current fluctuations along the inner shelf became highly coherent with those of the shelf break.

Low frequency current fluctuations are a consistent feature of the Florida Current. Oscillations over the shelf are connected to similar features over the Miami Terrace and both may be mutually related to atmospheric forcing in the form of shelf wave generation. The transient nature of the observed current modulations may, in part, be explained by the random passage of wind events, which can perturb the strongly sheared cyclonic front of the Florida Current, producing horizontal wave-like meanders (shelf-waves). Unstable barotropic modes can occur due to inflection points (potential vorticity extrema) in the horizontally sheared current, which then propagate to the north and may eventually evolve into small-scale cyclonic eddies ("spin-off eddies").

These amplified disturbances appear to dissipate kinetic energy from the mean current, behaving as braking mechanisms on the basic flow in an analogous manner as small-scale eddies in the atmosphere. Since these features occur on the average of once per week and have a life span of only about 1 to 3 weeks, their combined dissipating effect may play a significant role in the total energy balance of the Florida Current.

Edge-eddies manifest themselves as warm, southward-oriented, tongue-like extrusions of the Florida Current coupled to a trailing band of shelf or slope water. Observed eddy diameters range from 10 to 30 km and they travel to the north along the continental slope at speeds less than the mean Florida Current. They were found to extend vertically to a depth of approximately 200m. Thus, these disturbances provide a means for exchanging mass across the frontal boundary. It was estimated by Lee (1975) that the residence time of the waters on the narrow shelf off southeast Florida is largely determined by the mean separation time between spin-off eddies, or approximately one week.

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