The Relationship between Variations in the Gulf of Mexico Loop Current and Straits of Florida Volume Transport

GEORGE A. MAUL
Atlantic Oceanographic and Meteorological Laboratory, National Oceanic and Atmospheric Administration, Miami, Florida

FRED M. VUKOVICH
Science Applications International Corporation, Raleigh, North Carolina

(Manuscript received 10 September 1991, in final form 23 March 1992)

ABSTRACT

Twelve years of monthly mean positions of the northern boundary of the Loop Current in the eastern Gulf of Mexico from satellite and in situ data have been compared with coincident 1977–1988 estimates of volume transport in the Straits of Florida in the subseasonal frequency band 15⁻¹ to 5⁻¹ cycles per month. Volume transport estimated from Cuba minus Florida sea level difference in this frequency band accounts for 69% of the variance in volume transport estimated from the Florida–Grand Bahama Island submarine cable. On average, the Loop Current has a dominant period of 11 months whereas the volume transport is dominated by annual spectral energy; little significant coherence squared occurs between them. The maximum northward penetration of the Loop Current occurs on average in winter when the volume transport is a minimum, but this is an artifact of the sampling epoch. This negative relationship is most pronounced for 1979–1981 when transport is characterized as unimodal, but for 1984–1985 and 1987 the Loop Current and volume transport are more in phase, bimodal, and transport and position tend to have more semiannual energy. In this subseasonal band, the volume transport undergoes a significant change in the phase of its annual cycle after 1985 as compared with 1977–1984. For the twelve years considered in this study, the ensemble correlation between monthly position of the Loop Current and volume transport is essentially zero.

1. Introduction

The literature contains many studies on the evolution of the Loop Current in the Gulf of Mexico (Leiper 1970; Behringer et al. 1977; Maul 1977; Molinari et al. 1977; Vukovich et al. 1979; Vukovich and Crissman 1986; Vukovich 1988). The results from these studies suggest that when the Loop Current makes a deep penetration into the eastern Gulf of Mexico, a portion of the current separates, creating an anticyclonic ring. The period for separations is highly variable, ranging from 6 to 17 months, having an average period of about 10–11 months. The average period has little practical significance since the actual period only occasionally equals the average period. Some investigators have found the predominant or average ring-separation period to be as small as 8–9 months (Maul et al. 1985) and as large as 12 months (Sturges and Evans 1983), depending on the time period investigated.

One of the forcing mechanisms in the Gulf of Mexico (Fig. 1) is the transport associated with flow through the Yucatan Channel into the eastern Gulf and out through the Straits of Florida (Ichie 1962; Reid 1972; Hurlburt and Thompson 1980, 1982). Molinari et al. (1978) concluded that the seasonal intrusion of the Loop Current is found to vary directly with the geostrophic transport through the Yucatan Channel, and that the transports through the Yucatan Channel and Straits of Florida were in phase and had the same magnitude. Schott et al. (1988) have indicated that the volume transport in the Straits of Florida ranges from $20 \times 10^6$ m$^3$ s$^{-1}$ to $40 \times 10^6$ m$^3$ s$^{-1}$ with a mean of $30.5 \times 10^6$ m$^3$ s$^{-1}$ and a standard deviation ($\sigma$) of $\pm 3.0 \times 10^6$ m$^3$ s$^{-1}$; the month-to-month deviation from the annual cycle was about $\sigma = \pm 1.0 \times 10^6$ m$^3$ s$^{-1}$. Molinari et al. (1985) report that the variance in the volume transport is greater than 30% of the mean flow with transients approaching 40% of the mean (see also Molinari 1987). Nineteen percent of the variance in the winter was concentrated in the two-day to ten-day period band compared to only 7% in the summer (cf. Lee and Williams 1988).

Though the transport is highly variable, Hurlburt and Thompson’s (1980, 1982) numerical model for the Gulf of Mexico, using a constant transport of approximately $30 \times 10^6$ m$^3$ s$^{-1}$, shows that eddy shedding can be simulated in the model with eddy-separation...
statistics not significantly different from those determined from in situ data, that is, an eddy shedding period of about 11 months. Using the Bryan–Cox Model driven by the mean wind-stress curl, Sturges and Welsh (1991) report eddy shedding at 7-month intervals, but their (steady) model transports are ~40% too weak. Reduced transport reported by Sturges and Welsh may be due to the exclusion of synoptic and mesoscale wind variations (Veronis 1970) and/or the thermohaline component of Gulf Stream flow (Schmitz and Richardson 1991). Molinari and Morrison (1988) contend that much of the intrusion variability is associated with the angle at which the current enters the Gulf at the Yucatan Channel. The question, however, remains what effect, if any, does the variable nature of the transport have on the cycle of the Loop Current. This paper endeavors to shed some light on that relationship.

2. Loop current data processing

The variations of the Loop Current's northern boundary were obtained using a "wave staff" technique for a 12-year time frame (1977–1988). Frontal analyses were developed in the eastern Gulf of Mexico on relatively clear-sky days using NOAA infrared imagery; in situ data were used during the summer when satellite infrared data were not useful, and in all months between 1981–1987 to supplement the satellite data. The distance between the northernmost position of the Loop Current and 30°N latitude was determined. All distances obtained in a given month were then averaged to produce monthly averaged values of the distances. From four to ten frontal analyses were available in each month from the satellite data over the 12 years, but generally only one analysis per month was available from in situ data in the summer. Loop Current positions were checked against the extensive ship-of-opportunity data available during 1981–1987; in all cases the comparisons between the surface manifestation in the hydrographic data and that in the satellite data were very good.

The average distance for each year was calculated and subtracted from each of the corresponding monthly values to produce detrended displacements using a sign convention of positive displacements to the north. The data were then bandpass filtered to remove spectral energy outside the range $15^{-1}$ to $5^{-1}$ cycles per month (cpm); this frequency range is chosen to be compatible with the subseasonal bandwidth (called BW1) used in estimating volume transport from sea level difference (see section 3).

The bandpass-filtered Loop Current displacements are shown by the solid line in Fig. 2. It can be seen that the principal variation is a quasi-periodic cycle of the Loop Current northern boundary. The eddy separation process generally occurs when the Loop Current reaches its most northward position. In the separation process, the main Loop Current reforms south of the eddy, typically making an anticyclonic turn toward the Florida Keys from the Yucatan Channel; however, it must be noted that ring separation did not occur in every case when the Loop Current reached a peak northward position in a given year. The data in Fig. 2 indicate that the amplitude of the cycle of Loop Current displacements was slightly larger from 1977 to 1982 than from 1983 to 1988.
3. Straits of Florida transport data

Volume transport in the Straits of Florida was calculated using a multifrequency model (Mayer and Maul 1991) from sea level data at Siboney (near Havana, Cuba) and Key West, Florida. These data were used instead of the volume transport measurements (Larsen and Sanford 1985) of the Florida Current made by the submarine cable from Jupiter, Florida, to Settlement Point in The Bahamas (Fig. 1) because application of the sea level data provided transport estimates over the 12 years of this study and cable measurements only provide transport data for a 6.5-year time frame (1982–1988). The time series of mean monthly transport in the Straits of Florida based on sea level difference (SLD) data are shown by the dashed line in Fig. 2. These data have been bandpass filtered to provide a compatible dataset for comparison with the Loop Current positions.

The monthly mean sea level data at Key West had several gaps due to equipment failure, but none of the gaps were more than six months long, usually only one or two months long. The gaps were filled by least squares fitting Key West to Miami and replacing the missing values; the high linear correlation coefficient \( r \) between Key West and Miami \( (r = 0.91) \) assured meaningful data replacement. The SLD, Siboney minus Key West, was then bandpass filtered identically to the filtered Jupiter–Settlement Point cable data, and a volume transport time series was calculated; the parameters are given in Table 1, and the transport estimates are given in Table 2. Figure 3a shows the volume transport from both the cable and SLD model. We note that \( |H|_{\text{annual}} \) herein is \( \sim 45\% \) larger than given in Mayer and Maul (1991) for the straits at 27°N; this is approximately as expecte from the difference in cross-sectional area at the two SLD sites and the geostrophic assumption for surface current speeds. Since 69% of the variance in BW1 volume transport estimated from the cable is accounted for in the SLD model, we conclude that BW1 Siboney minus Key West is a useful indicator of Gulf of Mexico outflow.

The inflow, however, is the driving force of the Gulf Loop Current, and this is the Yucatan Current. From continuity considerations, one expects that the inflow must equal the outflow on long time scales, but on monthly time scales this may not be the case. To test this we have plotted in Fig. 3b the SLD from both the Straits of Florida (Siboney minus Key West) and the

### Table 1. Subseasonal frequency response function for smoothed BW1 (365-1 - 183-1 cpd). Abbreviations: bandwidth (BW), cycles per day (cpd), frequency (\( f \)), frequency response function amplitude (|\( H \)|) and phase (\( \phi \)), record length (\( L \)), variance reduction (\( VR = 100\% \)), and standard error estimate (\( \epsilon \)).

| \( f \) (cpd) | \( |H| \) \((10^6 \text{ m}^3 \text{ s}^{-1} \text{ cm}^{-1})\) | \( \phi \) (deg) | Notes |
|--------------|---------------------------------|-------|---|
| 365.25-1     | 0.335                           | 8     | SLD leads modeled cable by 8 days |
| 243.50-1     | 0.259                           | 17    | SLD leads modeled cable by 11 days |
| 182.62-1     | 0.234                           | 34    | SLD leads modeled cable by 17 days Inversion BW = 396-1 - 183-1 cpd; \( L = 78 \) months; \( VR = 69\% \); \( \epsilon = \pm 0.8 \times 10^6 \text{ m}^3 \text{ s}^{-1} \) |
TABLE 2. Estimates of Florida Current volume transport (10^6 m³ s⁻¹) based on monthly mean sea level difference Siboney (Cuba) minus Key West (Florida) in smoothed subseasonal BWI (365⁻¹ − 183⁻¹ cpd).

<table>
<thead>
<tr>
<th>Year</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>1966</td>
<td>-0.46</td>
<td>-0.23</td>
<td>-0.32</td>
<td>-0.53</td>
<td>-0.38</td>
<td>0.27</td>
<td>0.98</td>
<td>1.10</td>
<td>0.42</td>
<td>-0.60</td>
<td>-1.17</td>
<td>-0.89</td>
</tr>
<tr>
<td>1967</td>
<td>-0.07</td>
<td>0.58</td>
<td>0.62</td>
<td>0.19</td>
<td>-0.17</td>
<td>-0.07</td>
<td>0.34</td>
<td>0.58</td>
<td>0.30</td>
<td>-0.35</td>
<td>-0.90</td>
<td>-0.94</td>
</tr>
<tr>
<td>1968</td>
<td>-0.48</td>
<td>0.15</td>
<td>0.56</td>
<td>0.63</td>
<td>0.51</td>
<td>0.36</td>
<td>0.25</td>
<td>0.11</td>
<td>-0.07</td>
<td>-0.26</td>
<td>-0.41</td>
<td>-0.54</td>
</tr>
<tr>
<td>1969</td>
<td>-0.68</td>
<td>-0.77</td>
<td>-0.60</td>
<td>0.01</td>
<td>0.95</td>
<td>1.79</td>
<td>1.96</td>
<td>1.22</td>
<td>-0.18</td>
<td>-1.54</td>
<td>-2.22</td>
<td>-1.99</td>
</tr>
<tr>
<td>1970</td>
<td>-1.10</td>
<td>-0.04</td>
<td>0.84</td>
<td>1.41</td>
<td>1.65</td>
<td>1.54</td>
<td>1.02</td>
<td>0.16</td>
<td>-0.81</td>
<td>-1.50</td>
<td>-1.66</td>
<td>-1.28</td>
</tr>
<tr>
<td>1971</td>
<td>-0.61</td>
<td>0.05</td>
<td>0.57</td>
<td>0.93</td>
<td>1.15</td>
<td>1.19</td>
<td>0.96</td>
<td>0.44</td>
<td>-0.25</td>
<td>-0.89</td>
<td>-1.29</td>
<td>-1.37</td>
</tr>
<tr>
<td>1972</td>
<td>-1.13</td>
<td>-0.58</td>
<td>0.20</td>
<td>1.03</td>
<td>1.58</td>
<td>1.55</td>
<td>0.90</td>
<td>-0.05</td>
<td>-0.77</td>
<td>-0.90</td>
<td>-0.57</td>
<td>-0.24</td>
</tr>
<tr>
<td>1973</td>
<td>-0.31</td>
<td>-0.73</td>
<td>-1.01</td>
<td>-0.62</td>
<td>0.47</td>
<td>1.69</td>
<td>2.24</td>
<td>1.69</td>
<td>0.35</td>
<td>-1.01</td>
<td>-1.71</td>
<td>-1.66</td>
</tr>
<tr>
<td>1974</td>
<td>-1.21</td>
<td>-0.75</td>
<td>-0.33</td>
<td>0.30</td>
<td>1.26</td>
<td>2.17</td>
<td>2.31</td>
<td>1.26</td>
<td>-0.64</td>
<td>-2.34</td>
<td>-2.77</td>
<td>-1.69</td>
</tr>
<tr>
<td>1975</td>
<td>0.12</td>
<td>1.45</td>
<td>1.58</td>
<td>0.74</td>
<td>-0.14</td>
<td>-0.32</td>
<td>0.17</td>
<td>0.62</td>
<td>0.40</td>
<td>-0.45</td>
<td>-1.20</td>
<td>-1.15</td>
</tr>
<tr>
<td>1976</td>
<td>-0.29</td>
<td>0.69</td>
<td>0.98</td>
<td>0.43</td>
<td>-0.36</td>
<td>-0.57</td>
<td>0.04</td>
<td>0.91</td>
<td>1.14</td>
<td>0.35</td>
<td>-0.95</td>
<td>-1.77</td>
</tr>
<tr>
<td>1977</td>
<td>-1.47</td>
<td>-0.25</td>
<td>1.02</td>
<td>1.51</td>
<td>1.09</td>
<td>0.27</td>
<td>-0.33</td>
<td>-0.44</td>
<td>-0.28</td>
<td>-0.20</td>
<td>-0.31</td>
<td>-0.46</td>
</tr>
<tr>
<td>1978</td>
<td>-0.42</td>
<td>-0.18</td>
<td>0.11</td>
<td>0.34</td>
<td>0.53</td>
<td>0.73</td>
<td>0.86</td>
<td>0.67</td>
<td>0.01</td>
<td>-0.93</td>
<td>-1.58</td>
<td>-1.49</td>
</tr>
<tr>
<td>1979</td>
<td>-0.66</td>
<td>0.40</td>
<td>1.05</td>
<td>1.05</td>
<td>0.69</td>
<td>0.44</td>
<td>0.48</td>
<td>0.51</td>
<td>0.14</td>
<td>-0.70</td>
<td>-1.53</td>
<td>-1.76</td>
</tr>
<tr>
<td>1980</td>
<td>-1.15</td>
<td>-0.04</td>
<td>0.92</td>
<td>1.34</td>
<td>1.25</td>
<td>1.00</td>
<td>0.78</td>
<td>0.51</td>
<td>-0.04</td>
<td>-0.87</td>
<td>-1.65</td>
<td>-1.95</td>
</tr>
<tr>
<td>1981</td>
<td>-1.56</td>
<td>0.65</td>
<td>0.44</td>
<td>1.41</td>
<td>2.09</td>
<td>2.30</td>
<td>2.81</td>
<td>0.58</td>
<td>-1.07</td>
<td>-2.38</td>
<td>-2.66</td>
<td>-1.80</td>
</tr>
<tr>
<td>1982</td>
<td>-0.40</td>
<td>0.63</td>
<td>0.86</td>
<td>0.65</td>
<td>0.72</td>
<td>1.13</td>
<td>1.98</td>
<td>0.48</td>
<td>-1.80</td>
<td>-3.51</td>
<td>-3.57</td>
<td>-3.57</td>
</tr>
<tr>
<td>1983</td>
<td>-1.96</td>
<td>0.34</td>
<td>2.07</td>
<td>2.62</td>
<td>2.21</td>
<td>1.39</td>
<td>0.54</td>
<td>-0.31</td>
<td>-1.13</td>
<td>-1.66</td>
<td>-1.54</td>
<td>-0.79</td>
</tr>
<tr>
<td>1984</td>
<td>0.06</td>
<td>0.37</td>
<td>0.00</td>
<td>-0.46</td>
<td>-0.17</td>
<td>1.05</td>
<td>2.38</td>
<td>2.61</td>
<td>1.18</td>
<td>-1.23</td>
<td>-3.13</td>
<td>-3.34</td>
</tr>
<tr>
<td>1985</td>
<td>-1.88</td>
<td>0.18</td>
<td>1.64</td>
<td>2.01</td>
<td>1.63</td>
<td>1.05</td>
<td>0.48</td>
<td>-0.22</td>
<td>-1.07</td>
<td>-1.65</td>
<td>-1.39</td>
<td>-0.23</td>
</tr>
<tr>
<td>1986</td>
<td>1.11</td>
<td>1.64</td>
<td>0.89</td>
<td>-0.56</td>
<td>-1.58</td>
<td>-1.41</td>
<td>-0.26</td>
<td>0.91</td>
<td>1.34</td>
<td>1.01</td>
<td>0.51</td>
<td>0.30</td>
</tr>
<tr>
<td>1987</td>
<td>0.24</td>
<td>-0.21</td>
<td>-1.22</td>
<td>-2.21</td>
<td>-2.25</td>
<td>-0.90</td>
<td>1.24</td>
<td>2.88</td>
<td>3.04</td>
<td>1.73</td>
<td>-0.13</td>
<td>-1.51</td>
</tr>
<tr>
<td>1988</td>
<td>-1.97</td>
<td>-1.76</td>
<td>-1.28</td>
<td>-0.69</td>
<td>0.11</td>
<td>1.10</td>
<td>1.87</td>
<td>1.88</td>
<td>0.98</td>
<td>-0.35</td>
<td>-1.33</td>
<td>-1.48</td>
</tr>
<tr>
<td>1989</td>
<td>-0.91</td>
<td>-0.15</td>
<td>0.37</td>
<td>0.57</td>
<td>0.62</td>
<td>0.54</td>
<td>0.19</td>
<td>-0.46</td>
<td>-1.06</td>
<td>-1.02</td>
<td>-0.08</td>
<td>1.27</td>
</tr>
<tr>
<td>1990</td>
<td>2.01</td>
<td>1.40</td>
<td>-0.33</td>
<td>-2.01</td>
<td>-2.43</td>
<td>-1.29</td>
<td>0.54</td>
<td>1.78</td>
<td>1.73</td>
<td>0.72</td>
<td>-0.30</td>
<td>-0.67</td>
</tr>
</tbody>
</table>

Yucatan Channel (Cabo San Antonio minus Progreso) for the period 1966–1990. Figure 3c shows the cross correlation between the two SLD records, and although the maximum correlation \( r = 0.53 \) is not very high, the two SLD series are clearly without significant lags or leads between them. The relationship between SLD and transport in the Yucatan Channel is probably not as robust as in the Straits of Florida because the Yucatan Channel is much deeper, but the essential issue summarized in Fig. 3 is that the sea level difference between Siboney and Key West is a viable estimator of Gulf Loop Current inflow/outflow.

4. Results

a. The spectrum of variability

Spectral variability of the Loop Current boundary and of Straits of Florida volume transport is shown in Fig. 4. The boundary variability peaks at 0.09 cpm, an 11-month period. The transport variability peaks at 0.08 cpm with secondary peaks at 0.13 and 0.17 cpm; 12-, 8-, and 6-month periods, respectively. Thus transport is dominated by spectral energy at the annual frequency but Loop Current energy is clearly centered at a period of 11 months (cf. Vukovich 1988; Jacobs and Leben 1990). Little statistically significant coherence squared between the two series is worth noting (cf. Sturges and Evans 1983; Maul et al. 1985). Comparing Figs. 4 and 2, it appears that the Loop Current and the transport move in and out of phase once in this particular 12-year period, and this is consistent with a frequency difference \( \Delta f = 11^{-1} - 12^{-1} = 0.0076 \) cpm in the dominant cycle of each record.

We also joined the Loop Current boundary record from Molinari and Morrison (1988) to our record to form a 24-year gappy time series. Analyses parallel to those already discussed were performed without any particularly diverse results. A spectral estimate using the methods discussed in Maul et al. (1985) for gappy records was also calculated (not shown), and except for a clearer separation between the 12-month peak in transport and the 11-month peak in Loop Current position \( \Delta f = 0.0069 \) cpm the result is not significantly different from that illustrated in Fig. 4.

Spectra of these data do not show the typical “redness” because we investigate only BWI. Trends of the position of the Loop Current in the eastern Gulf based on annual averaged displacements (not shown) indicate that, from 1977 to 1985, the annual mean position of the Loop Current shifted northward. From 1985 to 1988, the annual mean position moved to the south. It is interesting to note that at the same time that the Loop Current was shifting northward, the north wall of the Gulf Stream between 65° and 75°W was also shifting northward. Vukovich (1990) has indicated that the annual average volume transport in the Straits of Florida was increasing in the early 1980s, reached a peak in 1985, and decreased thereafter.
position in the Gulf of Mexico in winter when the Straits of Florida transport is near a minimum. Eddy separation from the Loop Current normally takes place when the Loop Current reaches its maximum northward position. The data further indicate that the Loop Current reaches its maximum southward position in the summer when the Straits of Florida transport is a maximum. This is quite the opposite of the description of Leipper (1970).

This average relationship (Fig. 5) can be very misleading. To further explicate the true nature of the co-

b. Year-to-year variability

Figure 5 presents the average annual cycle of the Loop Current boundary and Straits of Florida transport based on the 12-year (1977–1988) dataset. It is obvious from the figure that the average annual cycle of the Loop Current boundary and the Straits of Florida transport are negatively correlated. These data indicate that the Loop Current has a maximum northward po-

FIG. 3. (a) Modeled BW1 (396⁻¹ − 183⁻¹ cpd) sea level difference Siboney (Havana), Cuba minus Key West, Florida (solid line) and subseasonal volume transport from the Florida–Bahamas submarine cable (dashed line). (b) Sea level difference Siboney minus Key West (solid line) and Cabo San Antonio minus Progreso (dashed line). Both records are based on monthly mean sea levels at the respective stations. (c) Cross correlation between monthly mean Siboney minus Key West sea level and Cabo San Antonio minus Progreso sea level.

FIG. 4. (a) Spectrum of Loop Current position (solid) and spectrum of Straits of Florida volume transport (dashed). (b) Coherence squared (solid) and phase (dashed); phase 0°–360° normalized on 0–1; degrees of freedom: 6; coherence squared 95% significance level: 0.776.

FIG. 5. Twelve-year (1977–1988) average of the annual cycle of the Loop Current position (km) and for the Straits of Florida volume transport (10⁶ m³ s⁻¹); r = −0.3; n = 12.
A simple explanation of the relationships in Figs. 5 and 7 can be made by taking an 11-month cycle and computing a mean annual cycle based on a 12-year record. For the Loop Current position during 1977–1988, we calculate the least-squares maximum period as \( \omega = 1.0684 \, \text{cpy}, \) with position \( b(t) \) in kilometers to be

\[
b(t) = 66.2 \cos(2\pi \omega t - 175.7°),
\]

where \( t \) is the Julian Year (i.e., 1974.95). For the time frame 1977–1988, if one computes 144 values of \( b(t) \) for 12 monthly bins, the mean annual curve of \( b(t) \) is a maximum in winter and a minimum in summer. Therefore the preceding equation does seem to agree with the eddy separation events from 1965–1977 documented in Molinari et al. (1977). If the data were collected for the 12-year period 1971–1982 instead of 1977–1988, the mean annual Loop Current position and the mean annual volume transport would be in phase (i.e., \( r > 0 \)). Thus, the relationships in Figs. 5 and 7 appear to be an artifact of the time frame used in this study.

To examine the data in more detail, the 12-year dataset was separated into two 3-year sets (1979–1981 and 1984–1985 + 1987); the first 3-year epoch is of maximum negative correlation, and the second 3-year epoch is of the maximum positive correlation; that is, we do a superposed epoch analysis (Panofsky and Brier 1958). The average annual cycles for the Loop Current and for the Straits of Florida transport based on the two 3-year datasets are given in Fig. 7. The average that is based on the 1979–1981 epoch indicates that the Loop Current reached its maximum northward position in the Gulf of Mexico during winter when the Straits of Florida transport was near a minimum. For the epoch when transport and Loop Current position are positively correlated (Fig. 7b), the Loop Current and the transport seem to have a bimodal shape, but for the Loop Current position the primary mode occurs first in time, and for the transport it follows the secondary mode.

The 3-year averaged data also indicate changes in the annual cycle for Straits of Florida transport. The volume transport peaked in late spring/early summer when the Loop Current had a minimum penetration and peaked in midsummer when the Loop Current had its maximum penetration in spring (cf. Figs. 7a and 7b). The transport was about 25% stronger during the epoch when \( r > 0 \) than during the \( r < 0 \) epoch. It should also be noted that transport lags Loop Current penetration for the 1984–1985, 1987 epoch, which is counterintuitive if one regards the Yucatan Current as forcing the Gulf Loop Current cycle.
correlation between monthly mean Loop Current position and volume transport for 1977–1988 is \( r = -0.15 \), that is, the variation of the Loop Current penetration into the Gulf and that for the Straits of Florida transport are essentially uncorrelated.

c. Comparison with numerical models

Two numerical models, the NORDA/JAYCOR model (Hurlburt and Thompson 1980; Wallcraft 1986) and the Bryan–Cox model (Sturges and Welsh 1991), can produce eddy shedding with a constant Yucatan Current transport. The NORDA/JAYCOR model gives an eddy-shedding periodicity essentially the same as that found from observations (i.e., 11 months) using a constant transport of \( 30 \times 10^6 \) m³ s⁻¹ (see Fig. 8), suggesting that a variable transport is not necessary to produce a reasonable Loop Current evolution. It should, however, be noted that for the 10 years of model calculations presented in Fig. 8, the eddy-shedding period and the amplitude of the penetration do not vary to any great extent from year to year, whereas observations (Fig. 2) indicate that both vary appreciably from year to year.

The 11-month period for the eddy shedding in the Gulf from observations is representative of the average situation, whereas in the model result in Fig. 8, the eddy-shedding period is nearly constant. In one version of the NORDA/JAYCOR model in which the shelf depth in the Gulf was shallower (~200 m) than this version, the model results had an overall range for the eddy shedding of about 10 months (A. Wallcraft, personal communication). In that case the eddy-shedding interval ranged from 14 to 24 months over a 10-year period, with most of the intervals greater than 18 months, which by no means conforms with observations since the maximum eddy-shedding time interval in the observed data is 17 months.

d. Comparison with analytic models

We now turn attention to the linear potential vorticity conserving physics between the velocity (V) in the Yucatan Channel and the Loop Current position. Molinari and Morrison (1988) argued that the Loop Current penetration distance \( b \) into the Gulf of Mexico at the Yucatan Channel is correlated with the direction angle \( \theta \) of the Yucatan Current according to Reid’s (1972) equation:

\[
b(\theta, V) = [(1 - \cos \theta) \times 2V/\beta]^{1/2},
\]

where \( \beta \) is the latitudinal variation of the Coriolis parameter. Molinari and Morrison did not vary \( V \) in their analysis, but showed that for reasonable depth-averaged values \( V = 0.1 \) to 0.5 m s⁻¹, the predicted penetration distance was in agreement with the observed \( \theta \) value. We have computed the multiple correlation between \( b, \theta \), and \( V \) using Molinari and Morrison’s values of \( b(\theta, V) \) and \( \theta \), and the relationship between \( V \) and volume transport (Table 2) from Maul et al. (1990). At 95% confidence, only \( b \) and \( \theta \) are statistically significant; \( (1 - \cos \theta)^{1/2} \) accounts for only 18% of the variance of \( b(\theta, V) \). The reasons are myriad, not the least of which is the application of linear theory to a highly nonlinear problem.

Reid (1972) also stresses that the relation \( b^2 = (1 - \cos \theta) \times 2V/\beta \) only holds true for the deep water region and that \( b^2 \) is measured from the northern edge of the Yucatan Channel; however, the most energetic flow is on the western side of the Yucatan Channel, and the complete potential vorticity conservation equation, \( (\xi + f)/H = \text{const} \), should be invoked in order to account for the variation in bottom topography \( (H) \). Assuming that the relative vorticity \( \xi \) is constant, the topographic beta effect \( (\beta_H) \) is derived from \((d/dy)\xi/H\) as

\[
\beta_H = (f/H) dh/dy,
\]

and we compare this with the planetary beta, \( \beta_p = df/dy \). For the Yucatan Channel, \( \beta_p \approx 2 \times 10^{-13} \) cm⁻¹ s⁻¹. Using \( dh/dy = 500 \) meters per degree of latitude and \( H = 500 \) m, \( \beta_H = 5 \times 10^{-12} \) cm⁻¹ s⁻¹. In view of the results of Molinari and Morrison (1988) and the ratio \( \beta_H/\beta_p \approx 25 \), we argue that the effect of bottom topography is important even in linear theories (cf. Ichiye 1962; Reid 1972) of Loop Current penetration into the Gulf of Mexico.

e. Complex demodulation

We summarize the behavior of the volume transport and of the Loop Current penetration during the 1977–1988 time frame, with a complex demodulation (Bloomfield 1976). A complex demodulation gives information on the temporal behavior in amplitude \( (A) \) and phase \( (\phi) \) of a given harmonic of the form

\[
y_1(t) = A_i \cos(2\pi\omega t - \phi_i).
\]
Fig. 8. (a–l) Sequence of twelve monthly sea surface heights (SSH) from the NORDA/JAYCOR (Hurlburt and Thompson 1980) numerical model. Model parameters are: $A = 300 \text{ m}^2 \text{s}^{-1}$; $C_p = 2 \times 10^{-3}$; $\rho_0 = 4.5 \times 10^{-3}$ s$^{-1}$; $g = 9.8 \text{ m} \cdot \text{s}^{-2}$; $\beta = 2 \times 10^{-11} \text{ m}^{-1} \text{s}^{-1}$; $H_1 = 200 \text{ m}$; $H_2 = 3450 \text{ m}$; $g' = 0.03(H_1 + H_2)/H_2 \text{ m}^2 \text{s}^{-1}$; $\rho = 10^{-3} \text{ kg} \cdot \text{m}^{-3}$; $\Delta x, \Delta y = 0.2^\circ$. Contour interval is 5 cm; solid lines are positive SSH anomalies; negative SSH anomalies are dashed.

Figure 9a shows the variations in the amplitude and phase of the annual harmonic ($\omega = 12^{-1} \text{ cpm}$) for Straits of Florida transport ($i = T$); Fig. 9b shows the same result for Loop Current position ($i = LC$). For these 1977–1988 transport data, the phase of the transport annual harmonic is fairly steady at $\phi_T \approx 135^\circ$. 
until 1986, but the amplitude $A_T$ varies by more than a factor of two, with a maximum in 1982 and a minimum in 1986. The phase of the Loop Current $\phi_{LC}$ steadily drifts through $\sim 360^\circ$ in the 12-year record, which is approximately as expected from the difference frequency between $12^{-1}$ and $11^{-1}$ cpm; $A_{LC}$ also shows considerable variability and for the most part is anti-correlated with $A_T$.

The behavior of $\phi_T$ after 1985 (Fig. 9a) warrants further consideration because it represents a change in

FIG. 8. (Continued)
the time of maximum transport. Figure 3a shows somewhat of a mismatch in the modeled BW1 transport and BW1 SLD during 1986, and at first it appeared that it was a tracking error. We therefore calculated a complex demodulation of the subseasonal volume transport from the cable (not shown) and found that the cable data too had an increase in phase of ~120° in 1986 and 1987 over the phase for 1982–1985. Similarly, we performed a complex demodulation of the 1966–1990 BW1 SLD transport estimate (Table 4) and note that from 1966 to 1985, $\phi_{\text{annual}}$ was as steady as shown for 1977–1985 in Fig. 9a. We conclude that the different shape of the volume transport cycle shown in the superposed epoch analysis (cf. Figs. 7a and 7b) is not an artifact of the model, but represents real year-to-year variability in the volume transport, and that there seems to be substantial change in the transport behavior between 1966–1985 and 1986–1990.

5. Summary and discussion

Twelve years (1977–1988) of NOAA satellite/hydrographic data and sea level difference were used to study the relationship between the subseasonal cycle of the Gulf of Mexico Loop Current northernmost position (boundary) and Straits of Florida volume transport. It was found that over the 12-year time frame, the annual mean northern boundary of the Loop Current shifted backward in time relative to the annual transport cycle. The maximum northward position of the Loop Current in the Gulf of Mexico occurred, on the average, in winter during 1979–1981, and in early summer during 1984–1985, 1987. Concurrent shifts of the time of maximum southward position of the Loop Current in the Gulf of Mexico also were noted. The amplitude of the cycle of the Loop Current was larger during the 1979–1981 epoch compared to the 1984–1985, 1987 epoch.

Changes in the annual cycle of Straits of Florida transport were also observed, but were not as pronounced as that for the cycle of the Loop Current position. The time of minimum transport occurred, on average, in the autumn throughout the twelve years; the maximum transport occurred in the summer. The late summer transport was 25% greater when the Loop Current was also at a maximum latitude in late spring/early summer; however, even when the correlation between the Loop Current penetration and transport was positive, the Loop Current penetration led transport in phase by about three months.

Nevertheless, volume transport in the Straits of Florida between Jupiter and Settlement Point where the submarine cable is sited, may be different from that flowing into and out of the Gulf of Mexico. Two notable channels, the Old Bahama Channel and the Northwest Providence Channel, could significantly alter the relationship between transport off Siboney–Key West or Cabo San Antonio–Progreso and transport at 27°N over the submarine cable. Net volume transport in the Northwest Providence Channel (Richardson and Finlen 1967) can be as large as the departures from the annual mean transport, as can those in the Old Bahama Channel (K. D. Leaman, RSMAS, 1991 personal communication; cf. Thompson et al. 1992).
These facts, coupled with uncertainties in estimating volume transport either by the cable or by sea level, suggest caution in interpreting a cause and effect relationship.

An important aspect of the use of satellite data to estimate Loop Current position is that the IR imagery may not reflect details that are found in the hydrography. For example, Maul (1977, his Fig. 2) shows a ring separation in progress on a map of the depth of the 22°C isotherm. The 150-m depth contour clearly shows the ring has separated; the 100-m depth contour suggests it is still attached to the main Loop Current (Fig. 8k). Analysis of satellite IR data would be most like the 100-m contour, and thus the analyst would argue that the eddy had not yet detached, but $b(\theta, V)$ in Reid’s (1972) model is probably more related to the behavior of the 150-m contour, and would be a source of discrepancy in our results, except that (section 2) for the years 1981-1987 when ship-of-opportunity in situ data were available, the satellite analysis agreed with the hydrographic data. This criticism does not, however, apply to the analysis of Molinari and Morrison (1988), and yet the correlations between $b(\theta, V)$ or $b^2$ and $V$ are no better than $r = 0.2$ in their data.

As to the question of the long-term stability of the 11-month mean Loop Current eddy-shedding period, we refer again to the work of Molinari et al. (1977). In their study, “winter intrusions” of the Loop Current were first documented; the notion of Leipper (1970) of an annual cycle with summer intrusions hitherto being conventional understanding. If our equation for the amplitude and phase of the Loop Current cycle, $b(t) = 66.2 \cos(2\pi t - 175.7^\circ)$, is stationary, then winter intrusions are a regular feature of the Gulf of Mexico’s mean cycle, and should have occurred when Molinari et al. reported them. It must, however, be reemphasized that while a systematic 11-month cycle is a feature of the NORDA/JAYCOR Model, there is significant year-to-year departure from regularity in the observed data.

The numerical models used to simulate the Gulf Loop Current have found average eddy-shedding intervals ranging from 7 to 20 months (Hurlburt and Thompson 1980, 1982; Wallcraft 1986; Sturges and Welsh 1991); in one case, a model produced an 11-month eddy-shedding interval (Fig. 8). In most cases, the models produced eddy-shedding intervals and amplitudes of penetration into the Gulf that were nearly constant. Observations, on the other hand, indicate that the eddy-shedding interval and amplitude of penetration are highly variable and that the average eddy-shedding interval has little practical significance since the actual interval seldom equals the average interval. For a 16-year duration, Vukovich (1988) showed that the average eddy-shedding interval was about 11 months ($\sigma = \pm 3$ months) and that only one interval actually equaled 11 months.

The data used herein indicate no statistically significant relationship between the cycle of the Loop Current position and the annual cycle of Straits of Florida.
volume transport. It is hoped that applications of the results of this study in a numerical model may shed light into the potential cause and effect relationship between the cycle of the Loop Current position and that for the Straits of Florida volume transport. For example, is the 11-month Loop Current cycle caused by the geometry of the Gulf of Mexico as the Hurlburt and Thompson (1980, 1982) model results suggest? Also, it has been shown that a fluctuating wind superimposed on the climatic wind can have a sizable effect on the mean transport (Veronis 1970); can this account for the difference between the observed transport and the modeled transport in the Sturges and Welsh (1991) study? Does lower transport result in a shorter eddy-shedding period? Clearly however, the simple dynamical models of Ichiye (1962) and of Reid (1972) are inadequate to explain these data.

Acknowledgments. Data from the 1965–1976 study of Molinari and Morrison (1988) were generously provided by R. L. Molinari. The NORDA/JAYCOR numerical model calculations were by R. R. Leben, and D. A. Mayer calculated the BW1 transports. We have benefited from conversations with C. G. H. Rooth, S. R. Baig, J. Miller, A. Wallcraft, and D. A. Mayer concerning this work: Sea level data used herein from the Permanent Service for Mean Sea Level was graciously supplemented by the Universidad Nacional Autonoma de Mexico, the NOAA National Ocean Service, and the Instituto Cubano de Hidrografia, and with the assistance of the Intergovernmental Oceanographic Commission of UNESCO. Cable data were provided by J. C. Larsen, NOAA Pacific Marine Environmental Laboratory.

REFERENCES


