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# On the variability of the Loop Current in the Gulf of Mexico

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ABSTRACT

It is of considerable interest to know to what extent offshore currents may drive flows on the continental shelf. We have used the northernmost position of the Loop Current, from hydrographic data, to piece together a time series 13 years long. This record samples the lowest frequencies well but undersamples the amplitude of variations with periods of ~8 months by a factor of 2. The "annual" variation of the Loop Current appears to be a relatively broad spectral peak rather than a sharp spectral line. We find as much power at periods near 30 months as at periods near a year; this is a new result. Both bands seem to be, at least in part, wind forced. There are also fluctuations having periods near 8 months, and this may be a beat frequency. As the 30-month and annual signals drift in and out of phase over ~5 years, the envelope of the 8-month signal varies from zero to a maximum of ~2.5 degrees of latitude, peak-to-peak, which is the same as the range of the 30-month signal.

Our primary finding is that the north-south fluctuations in Loop Current position are correlated with sea level at the coast and presumably with coastal currents. The results are essentially the same using tidal data at either St. Petersburg or Key West. The phase delay is such that the inferred southerly flowing currents on the shelf reach a maximum before Loop Current position reaches its maximum northern position, by 1 to 3 months. If the Loop Current is inherently unstable, as the numerical model of Hurlburt and Thompson (1980) suggests, the wind forcing may merely set the frequency of the variability. Observations at the outer edge of the West Florida Shelf have shown flow to the south of 10 to 20 cm/sec, persistent over many months, which is consistent with this model.

## 1. Introduction

The currents in the eastern Gulf of Mexico are dominated by the Loop Current, which enters the Gulf through the Yucatan Straits and leaves between Key West and

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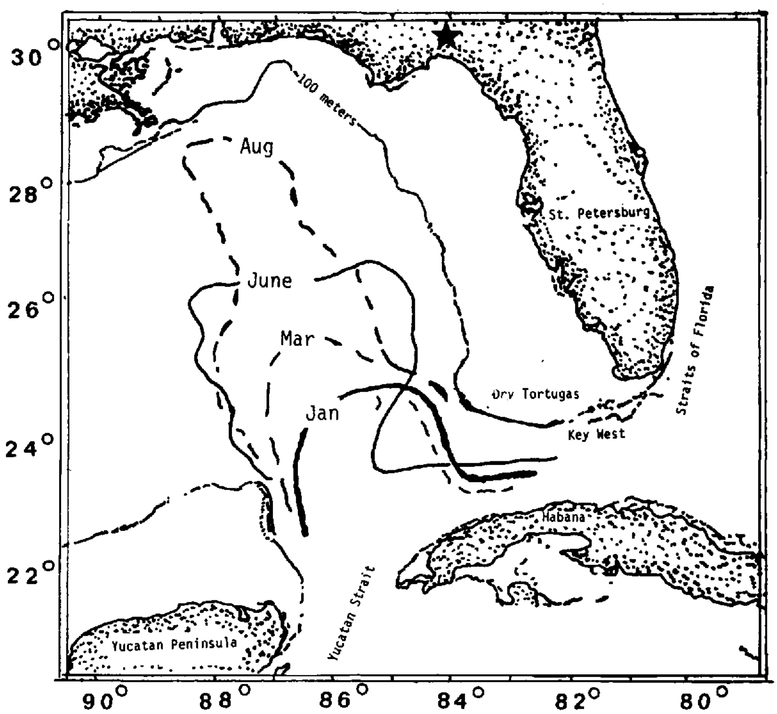



Figure 1. Series of positions of the Loop Current in the Gulf of Mexico in 1973. After Maul, 1977. The paths are the location of the 22° isotherm at 150 m.

Cuba. The variability of the Loop Current has been studied by many authors (e.g., Molinari *et al.*, 1977, 1978; Soong, 1978). Figure 1 shows several positions of the Loop Current as an intrusion develops (Maul, 1977). Leipper (1970) proposed that the intrusions have a predominantly annual cycle.

Some studies of the Loop Current suggest that each large penetration leads to formation of a ring (Hurlburt and Thompson, 1980; Molinari *et al.*, 1978). One motivation for this study, therefore, was a desire to know the variability of the Loop Current for application to questions of the rate of ring formation.

A second motivation for this study was that we know little about the flow on the west Florida continental shelf and the extent to which it is forced by the Loop Current. Because the cross-shelf momentum balance is approximately geostrophic, sea-level observations at the coast, when adjusted to uniform atmospheric pressure, are widely recognized to be a good measure of currents on the continental shelf. It is important to keep in mind the various kinds of mechanisms that cause sea-level variations (e.g., Chelton and Davis, 1982). But the dominant effect arises from coastal currents; this has been confirmed for currents driven by synoptic wind events (Smith, 1974) and for mean monthly data (Reid and Mantyla, 1976) (see also Noble and Buttman, 1979 and Mitchum and Sturges, 1982).

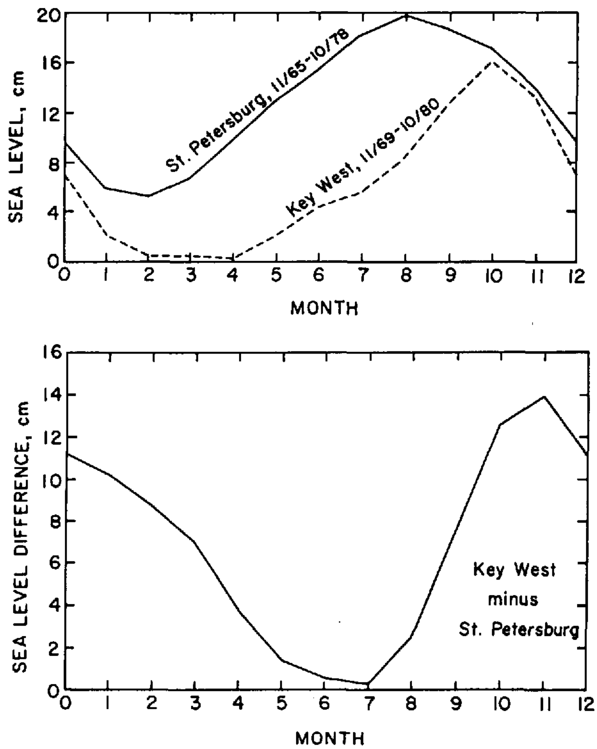



Figure 2. (a) Mean annual sea level signals adjusted to constant atmospheric pressure, at Key West and St. Petersburg, Florida. The monthly values are the means of the Jan., Feb., . . . from the original low-passed series. The time base used for each series is shown. Each curve has an arbitrary zero; they are displaced from each other for clarity. (b) The annual variation of the sea-level difference signal, Key West minus St. Petersburg, using the 9 available years of overlapping data.

With this in mind, we have compared the positions of the Loop Current with sea-level data, in hopes of learning about the underlying forcing mechanism.

## 2. Sea-level data

Tide-gauge data available to us are of two types: hourly heights, available on magnetic tape for certain years, from the National Ocean Survey, NOAA, and monthly means. We have used the filtered hourly heights exclusively. The mean monthly values contain a small amount of energy aliased from the 2 to 10-day wind-driven events. On a wide continental shelf, these events have amplitudes ~30 cm and are not well filtered by the "monthly means."

Using data from St. Petersburg and Key West, Florida, we first adjusted for atmospheric pressure by the inverted barometer method. The hourly tidal heights are filtered to remove energy at periods shorter than two months by a low-pass filter (eg., Bloomfield, 1976; the frequency response falls to 0.5 at periods near 100 days, and goes to zero at 56 days). The sea-level data are then subsampled "monthly," every 365.25/12 days. The mean annual cycle of sea level at the two stations is shown in Figure 2a, including the annual cycle of their difference. The yearly high in October at Key West is typical of tidal stations on the U.S. east coast (e.g., Fernandina, Norfolk) as well as along the Mexican Gulf Coast. The yearly high in the late summer at St. Petersburg is more in keeping with the annual cycle of stored heat. Although July is the lowest month for the average difference, the July value is actually the year's low in only two cases of the 9-year data used here, because of year-to-year variability; the July mean has a standard deviation of ~3 cm.

## 3. Loop Current data

From available hydrographic data, we have determined in any given month the northernmost position of the Loop Current. Historically this has been chosen as the position of the 20° isotherm at 150 m (e.g., Fig. 1). The resulting data set, from a variety of sources (Molinari and Mayer, 1980; Molinari, 1977; National Oceanographic Data Center) is shown in Figure 3. The positions based on hydrographic data represent an attempt—even perhaps a crude one—to piece data together to form a time series. During months when the data base is poor, whether to use the resulting data becomes somewhat subjective. We have chosen, when in doubt, to omit a monthly data point when the hydrographic data were sparse. The smoothed monthly positions are from a natural cubic spline fit to the observations.

As will be shown later, the majority of the energy in the Loop Current fluctuations is at periods of a year or longer. During the first six years of the record there are only 22 data points, so the average effective Nyquist is approximately $(6.5 \text{ mo})^{-1}$. During the last six years, however, the effective Nyquist is near $(3.8 \text{ months})^{-1}$ so the fluctuations having periods near 7 to 8 months are much better resolved. For most of the record one feels that the signal is reasonably—if not ideally—resolved. Because the sampling is more frequent in recent years, the later parts of the record are used in determining phase information at periods shorter than a year. The spline fit overshoots in late 1967 but otherwise seems reasonable. Although the Loop Current rarely extends beyond 28N, excursions as far north as 30 degrees have been observed (Huh *et al.*, 1981).

After this manuscript was essentially completed, a new set of observations reported by Molinari and Mayer (1982) came to our attention. The data in their Figure 5 extend the range shown in our Figure 3.

Weekly summaries of Loop Current positions as determined from satellite infra-red data are made available by the National Environmental Satellite Service, Miami, Florida. Dr. George Maul has kindly made available to us his own "archive" (since 1976) of these positions. Vukovitch *et al.* (1978) have also reported positions using the satellite IR data. The satellite IR data are not useful in the summer months, but from October through May provide data in segments of ~8 months duration. Unfortunately, the weekly plots available to us merely show a "path" and do not allow the high resolution available in the original data.

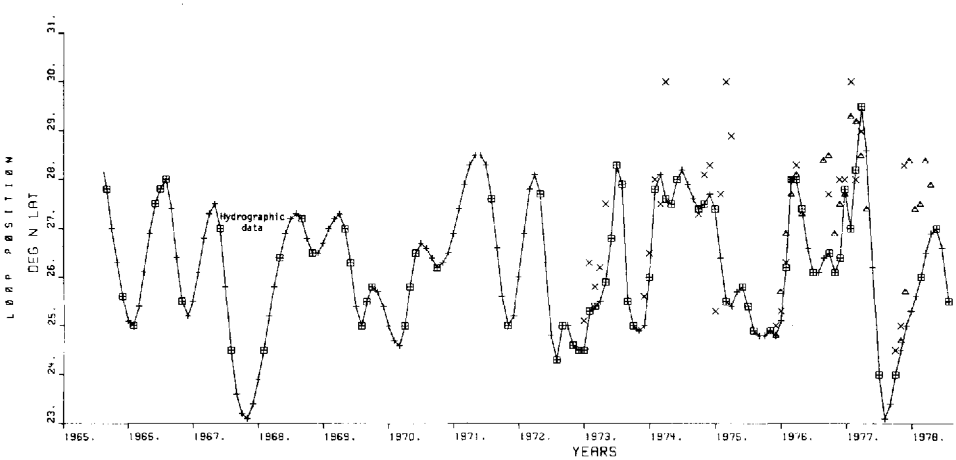



Figure 3. Positions of the northern edge of the Loop Current from a variety of data. The time series of monthly points used (plus signs) is interpolated by a cubic spline fit through the available hydrographic data (squares). The positions obtained from sea-surface infra-red data are shown by X (Vukovitch *et al.*, 1978) and triangles (from weekly NOAA/NESS maps, generously provided by G. Maul).

In Figure 3, we see that when the "Loop" does not extend far into the basin, or when the Loop is in a growth phase, the IR data agree well with the positions obtained from hydrographic data. When the Loop Current has developed a large intrusion, however, the agreement between the two data sets is poor. There are many months where hydrographic data show positions of the Loop Current that are in major disagreement with the northernmost path as deduced from the surface IR information. In order to maintain a consistent data base, therefore, we have used only the positions based on hydrographic data. It is well known that there are frequently several "fronts" in IR imagery on the inshore side of the Gulf Stream, and in any analysis one must be careful to choose the appropriate one. It has been observed, using ship-based data, that when the Loop Current has a large excursion the surface (warm) expression of the current may be substantially farther north than the core of the current as indicated by the position of mid-thermocline isotherms (W. Merrill, personal communication).

It seems useful to compare the two data sets, which were determined independently. Using only the 33 months where there are data in both series, the difference between the two shows a range of 2.2 degrees in one direction (satellite ~ farther north) to 1.0 degree in the other, with a standard deviation of 0.9 degrees. These comments are not intended to be unnecessarily critical of the very valuable satellite IR data but to make an attempt to compare these two sets which we usually assume give the same information.

Figure 4 shows the mean annual signal of Loop Current positions. The mean annual cycle has a range of only 1.6 degrees of latitude, which is less than half the range shown in Figure 1. Obviously there is a great deal of year-to-year variation.

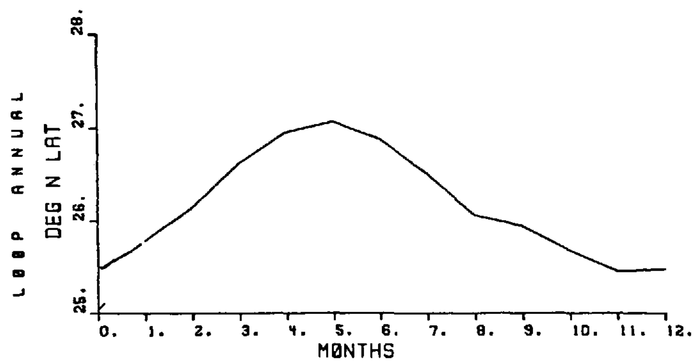


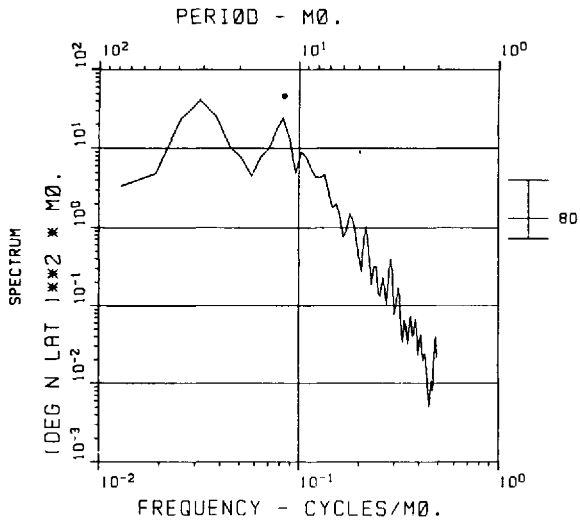

Figure 4. Annual cycle of the Loop Current, using the data shown in Figure 3.

Molinari *et al.* (1978) show estimates of the mean monthly dynamic height maps. These show average Loop Current positions from March through June near 27N. (We could hardly expect much disagreement, as the two sets of information are from a single data base.)

The Loop Current spectrum (Fig. 5a) suggests that there is variability associated with an annual cycle, but not in the sense of a sharply-tuned tone which emerges high above the background, as in sea level (5b). The energy in the broad band near 30 months is greater (but not significantly so) than at 1 year. The spectrum of the last 6 years, which has the best sampling, shows a decay of $\sim f^{-3}$ between periods of a year and four months. The high resolution of Figure 5a shows a region of energy at periods of ~7 to 9 months, slightly above the background. In this band of energy no single estimate is significantly above the background, yet over ~6 bands it is found to be coherent with sea level.

We made a brief attempt to determine quantitatively the effects of the gappy data on the results. Using, for comparison, the complete sea-level record at St. Petersburg, we deleted data points to make it gappy in the exact way the Loop Current record is. It was then interpolated, using the cubic spline fit, and the cross-spectra computed between the two records—one original, and one gappy but filled in. The frequency response is near one, with departures of ~10% for periods longer than 9 months; there is an abrupt decrease from 0.9 to 0.5 near 9 months. The phase shifts were ~10°, for

Figure 5. (a) Spectrum of Loop Current position, using 13 years of monthly interpolated data as shown in Figure 3. The spectral estimates have been smoothed by only a single Hanning pass, and the original series was tapered 10%. Data base is 9–65 through 8–78. The dot at 12.0 months shows the unsmoothed, original variance at a year. (b) Spectrum of low-passed sea level at St. Petersburg, Florida, adjusted to constant atmospheric pressure. The (relatively sharp) low-pass filter has the quarter-power point at 100 days (see text). Calculations performed as in (a). (c) Spectrum of Loop Current northerly position from 5 segments (each 32 weeks long) of weekly data. Each segment was tapered 50%, and then Bartlett averaged.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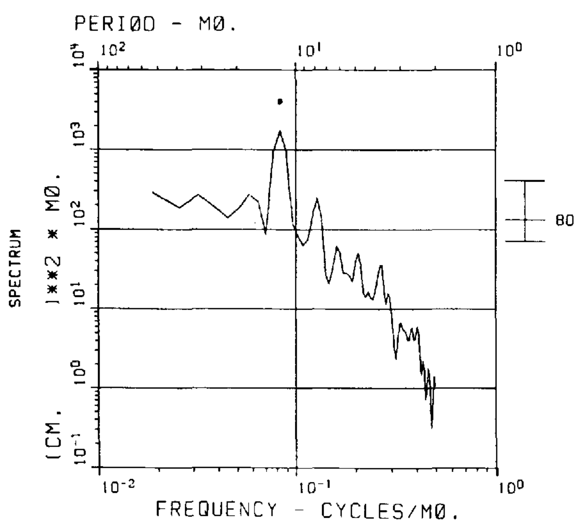
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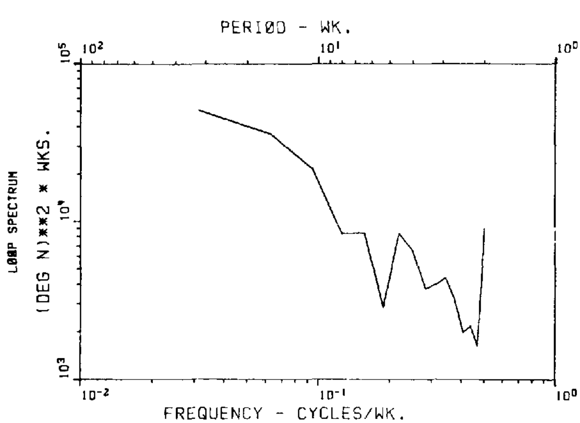
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periods longer than 7 months, and had opposite signs near 30 and 8 months. We conclude that the errors from gappy data seem less than the phase uncertainties of the basic spectral calculations.

The energy in the band near 30 months is a new result. Although the 13-year record is not really "long" compared with the 30-month signal, there are about 10 degrees of freedom. The peak-to-peak signal in this band is ~2.5 degrees of longitude, which is nearly twice the mean annual signal. A very-low-pass-filtered plot of data shows a maximum excursion in late 1966 or early 1967, late 1968, early 1971, late 1974, and late 1976. These are of course consistent with Figure 3. When this signal is in phase with the annual variability the Loop Current intrusion is large, and conversely.

At the suggestion of a reviewer, the interpolated data points in 1967, '71, and '77 were modified by a smooth fit, "hand-forced" through the data, with the purpose of reducing the overshoots. The energy at periods of 1 year or longer was reduced by ~10% or less—but for periods of 2–4 months was increased. However, the overshoots by the original spline fit did not enhance the 30-month band relative to the annual.

Figure 5c shows a spectrum from weekly paths using Satellite IR data, from the archive provided by G. Maul. Figure 5c was processed differently from 5a, b. There were 5 data segments of weekly data, each 32 weeks long. A 50% taper was used to suppress leakage, and the spectra were Bartlett averaged. Most of the energy is in the band between 2 and 5 months. The annual cycle and lower frequencies are suppressed by the processing. The power near 1 month is only ~one-third the power from 2–5 months, and is more than a full decade below any signals we will deal with in this paper. We conclude that aliasing by monthly data is not a serious problem in this data set, for periods of 8 months and longer.

## 4. Coherence between Loop Current position and sea level

We have calculated cross spectra between the Loop Current positions (Fig. 3) and sea level. Figure 6 shows that coherence is found in two bands—near 8 months, and near 30 months. For the calculations shown, the annual signal and its harmonics are removed from the tide gauge data before spectral smoothing (except for the results at 12.0 months). There is physical justification, of course, for removing the annual cycle of stored heat (~10 cm) from the tidal data. The annual signals appear highly coherent between all variables.

Near periods of 8 months, the phase delay between the Loop Current and sea level is essentially identical at both coastal stations. The coherence is higher at Key West. However, there is little sea-level power at these frequencies.

At the longest periods, the Loop Current position shows higher coherence with sea level at St. Petersburg. The phases are similar at both locations.

Figure 6 also shows the phases at the annual period. Because the annual cycle of stored heat (as shown in Fig. 2) is so large, it is difficult to remove this signal with any degree of confidence. The values for phase and gain are shown, but their interpretation is obscure. The phase at Key West seems consistent with the other frequencies.

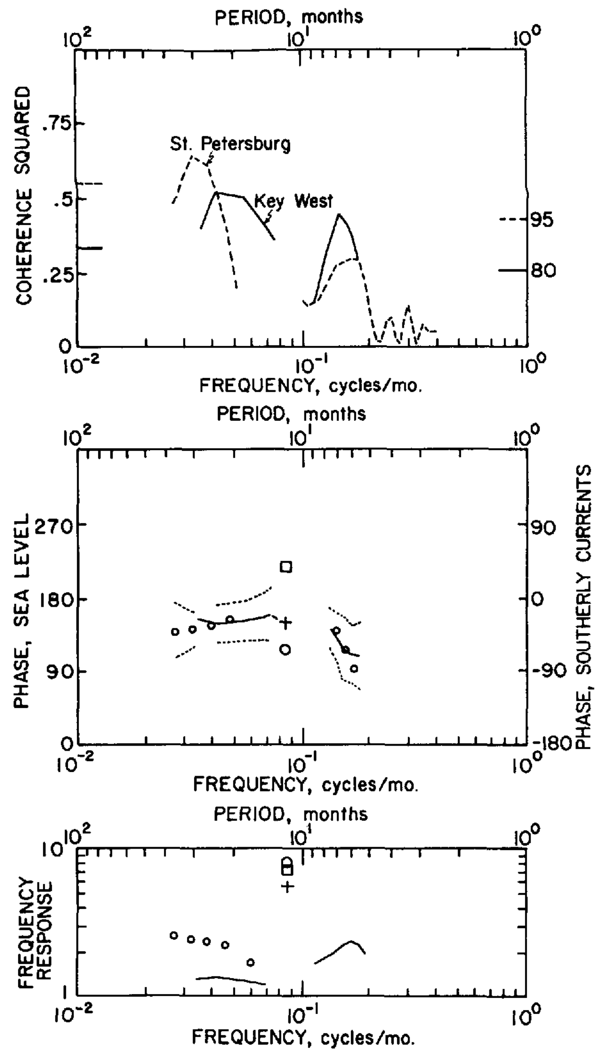


Figure 6. Cross spectra between Loop Current positions and sea level. The higher frequency band results are from the last 7 years of data, smoothed by 7 Hanning passes. The lower frequency band is from the full data set, and smoothed by only 4 Hanning passes. In the upper panel, note that the coherency confidence levels are different on either side of the figure. Center panel shows phase between the Loop Current and sea level (left-hand ordinate) and inferred coastal currents to the south (right-hand ordinate). The sign is such that if the phase is negative, the southerly currents lead the Loop Current. The Key West results are shown by the solid line and plus; St. Petersburg, circles. The 80% confidence limits are shown on the phase plot. The square symbol shows the calculation with the Key West minus St. Petersburg signal. The frequency response function, or gain, has units cm (of sea level) per degree latitude of Loop Current position. Near 8 months the St. Petersburg results are nearly identical to those for Key West and are not shown in the third panel.

The phases at the lowest frequencies are determined from 13 years of data at St. Petersburg, but 9 years at Key West owing to limitations in the tidal data. For periods shorter than 10 months we used the last 7 years of data. Because there are several lengths of record involved, there is some degree of subjectivity as to which results should be given the most weight.

It is possible that "correcting" the sea-level signals for wind effects would modify the coherence. Duttman (1981) reported the finding of coherence between sea level at St. Petersburg and the Loop Current positions. In testing to see whether this result was related to wind forcing, we found that there is little energy in the winds at Tampa (near St. Petersburg) in the 8-month band. The longshore winds were not coherent with sea level in that frequency range.

## 5. Interpretation

For a current flowing *to the south* past St. Petersburg, or to the east past Key West, an increase in current speed causes a decrease in sea level. Therefore, the phases associated with the *negative* of the sea-level signals (i.e., sea level plus 180°) are also shown in Figure 6 so we may interpret the phases in light of a longshore current.

Figure 7 shows a sketch of sea-level heights consistent with this idea. The cross section goes through both the northerly and southerly flowing portions of the Loop Current, such as the June or August positions of Figure 1. When the Loop Current is far to the north, the sea-level departure at the coast is negative. The "zero" of the figure on the offshore side is arbitrary, and the position where sea level goes through zero near the edge of the continental shelf is not known. The change in level across the Loop Current is estimated from Nowlin (1972), based on the change in dynamic height at the sea surface relative to 1500 db. At the coastal boundary there may be a *narrow* region of return flow to the north, but it is not shown in Figure 7. The present data are inadequate to resolve this feature. The sea-level height at the coast, in this sketch, is below the zero in deep water, implying a net flow on the continental shelf driven by entrainment along the coastal edge of the Loop Current. If the southerly flow were balanced by a nearshore return flow, the net sea-level departure would nearly vanish, and no coherence would be found.

The phase delays show that the longshore velocity *leads* the Loop Current position by approximately one month or more. In terms of confidence limits, there is a compromise required between increasing the record length versus using the more frequent sampling in recent years. Nevertheless, no matter which data set is used, the same result emerges. The conclusion seems clear: at all frequencies, the fluctuations in sea level, when interpreted as a southerly longshore current, *lead* the fluctuations in Loop Current position.

The phase angle at low frequencies is ~40°, or 3 months, at periods of 30 months and decreases to ~1 month at periods shorter than 20 months, with about the same time delay at periods of 8 months.

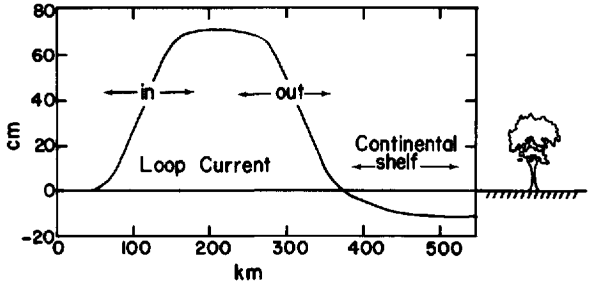


Figure 7. A sketch of the height of the sea surface through the Loop Current. The x-axis is positive to the east. The coast is at the right-hand edge of the figure.

The steady-state model of Reid (1972) suggests that the horizontal extent of penetration of the Loop Current, $b$, is balanced by the $\beta$ effect. Reid finds, if we neglect the effect of entry angle,

$$b = 2\, v\beta \tag{1}$$

where $v$ is an average velocity in the upper layer.

We suggest that the observed phase delay represents the simple fact that, when the speed of the flow changes, Eq. (1) is unbalanced, and the Loop Current position changes as a result of vorticity constraints. It is not clear whether Eq. (1) is *ever* balanced.

The path length of a large intrusion of the Loop Current (Fig. 1) is over 1000 km long, and represents ~1.5 months of transport of the Florida Current. Thus, even if the outflow between Key West and Cuba were *completely closed,* it would take ~1.5 months for the Loop Current to develop a large meander.

### 6. Forcing of longshore flow

As the southerly-going part of the Loop Current flows past the outer edge of the continental shelf, there is presumably an exchange of momentum between the Loop Current and the shelf water, through eddy-like motions at the edge of the shelf, as found inside the Florida Current (e.g., Lee and Mayer, 1977). Niller (1976) postulated such eddy motions on the basis of the current meter records (e.g., his Fig. 25). High resolution satellite IR images in the last few years frequently show such eddy motions with startling clarity. The important terms in the longshore momentum equation (taken to be the $y$ direction; $x$ positive to the east, $y$ positive north) would seem to be

$$v_t + vv_y + \overline{u'v'_x} + fu = -\, 1/\rho\, p_y \tag{2}$$

We estimate the magnitude of the terms by using the scaling on the shelf, $v \sim 10$ cm/sec; horizontal scales in $y \sim 300$ km (half the distance from Dry Tortugas to the sharp bend in the coastline); in $x \sim 150$ km (the width of the shelf). A typical value of

$\overline{u'v'}$ is $\sim -50\ cm^2/sec^2$ (Schmitz, 1982), although larger values are seen in the confined sections off Miami (Brooks and Niiler, 1977). Niiler (1976) has shown (e.g., his Fig. 11) that at some (but not all) of the upper current meters the $u$, $v$ correlations are negative at subinertial frequencies. Koblinsky and Niiler (1980) show in their Figure 3 that the eddy fluctuations, such as at Mooring 31, at 53 and 144 m; and Mooring 32, at depths of 106 m (in 150 m of water) have strongly negative $u$, $v$ correlations.

The Reynolds-stress term in (2), therefore, has a magnitude of order $3 \times 10^{-6}$ c.g.s. The local time derivative has equal magnitude for periods of ~4 months, so that for longer periods the forcing from the $\overline{u'v'_x}$ term is clearly large enough to accelerate a flow along the shelf. Presumably the flow field develops until some other term becomes important. The downstream acceleration term, for $v \sim 10$ cm/sec, has the same magnitude.

Suggestive evidence supporting the notion that the Loop Current drives currents on the outer region of the shelf is found in current meter data compiled by Koblinsky and Niiler (1980) and Niiler (1976). They find that the mean flow is southward during the winters of 1973–1974 and 1974–1975 for depths of 40 to 100 m on the outer shelf.

Niiler (1976) reports, at a depth of 39 m at a mooring in 105 m depth, a mean flow to the south of 8.6 cm/sec, (std. dev. 14.3) for a record of 8 months, with sustained speeds over 20 cm/sec for as long as a month, and as large as 10 cm/sec for periods as long as 3 months. At 69 m depth (same mooring) the mean southerly component was only 1.6 cm/sec (std. dev. 12). Koblinsky and Niiler show several moorings that have monthly mean speeds to the south, at depths near 50 m, as large as 10 to 12 cm/sec. During both of these periods the Loop Current had extended well north of the current meter moorings. Niiler found that these motions were incoherent with the wind.

A change in coastal sea level of 5 cm is induced by a velocity of 10 cm/sec at the outer edge of the shelf, if it decays to zero linearly toward the coast. The velocities observed by Niiler are *consistent* with the sea-level departures observed and the sketch of Figure 7. The very low frequency (periods longer than 20 months) signals at the coast are well resolved and reliably above the noise level. Present current-meter data are too sparse to allow meaningful calculations of coherence.

Molinari and Mayer (1982) report on current-meter observations just beyond the edge of the shelf at the latitude of Tampa. During the duration of their mooring, however, the Loop Current remained well south of the mooring position, except for about the last few months of data at the uppermost current meter (150 m). When the Loop Current was nearby, the observed flow was indeed to the southeast for the last 94 days of data (see their Fig. 2) even when the Loop Current was over 200 km away; the flow was approximately parallel to the coastline, and seems *consistent* with the idea of forcing by the Loop Current.

## 7. Discussion

It seems likely that the annual fluctuations in the Loop Current are forced by the annual cycle of winds. The annual variation in the flow of the Florida Current is well known (e.g. Fuglister, 1951; Niiler and Richardson, 1973). The idea that the Loop Current varies in response to wind forcing is hardly new (see e.g., Cochrane, 1965). The fluctuations at periods near 30 months may also be driven by atmospheric forcing. Krishnamurti *et al.* (1982) have shown that at periods of ~30–50 months, large-scale waves in the atmosphere over the North Atlantic are coherent over the full width of the ocean. The curl one deduces is coherent from latitudes of ~15N to ~36N. At these frequencies, the ocean will respond by time variations in the transport of the Gulf-Stream system. Thus, the idea seems *plausible* that variations in the Loop Current position, at the longest periods may also be wind forced.

The wind curl is the appropriate variable, but the parameter conveniently available to us is wind strength. The north-south component of wind was found to be coherent with the Loop Current positions, at a confidence limit above 90%, for periods of 24 months and longer. Although it is suggestive, further study of this forcing is beyond the scope of the present paper.

The annual and the 30-month variations may be expected to have interactions. Their beat frequencies are near 20 and 8.6 months. Some power is seen at the higher of these in both sea level and the Loop Current position. The fluctuations of the Loop Current near 20 months are coherent with Key West sea levels.

The Loop Current signal near 30 months should drift in and out of phase with the annual signal approximately every 5 years. A plot of the "intermediate" frequency content of the Loop Current signal—periods shorter than 11 months but longer than ~8 months—reveals a clearly modulated amplitude envelope, having essentially zero amplitude in ~January 1971, and a maximum—2.5 degrees latitude—in late 1973, diminishing again by 1976. A similar effect is seen in the previous 5 years, with the maximum in late 1969, although the higher-frequencies are poorly resolved in the earlier part of the record.

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