Deep flows in the Yucatan Channel and their relation to changes in the Loop Current extension

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[1] The first attempt to establish a relation between the Loop Current extension and deep flows in Yucatan Channel was made by Maul et al. [1985]; it was unsuccessful, probably because of the low spatial resolution of their observations. From September 8, 1999, to June 17, 2000, eight moorings with acoustic Doppler current profilers, current meters, and thermometers were deployed across the Yucatan Channel. The data from these arrays were used to compute time series of the transports below the level of the deepest isotherm observed in the Florida Straits, as required by a simple box model that restricts deep exchanges with the Gulf of Mexico to the Yucatan Channel. The surface extension of the Loop Current was inferred from 3 day advanced very high resolution radiometer imagery from October to May, when temperature gradients were sufficient to map the warm water unambiguously. The deep transports appear at first unrelated to the rate of change of the Loop Current extension, but filtering the series with a 20 day running mean increases the correlation between the low-pass series to 0.62, and up to 0.83 with a lag of 8.5 days, with Loop Current changes leading the deep flows. The cumulative deep transport, a quantity that favors lower frequencies, is very well related (correlations >0.9) to the surface extension of the Loop Current, also with a lag of about a week. These lags are not statistically significant but suggest a timescale for internal adjustment processes in the Gulf of Mexico. The empirical orthogonal function of the current best related to the area extension of the Loop Current represents a unidirectional flow across the entire deep section, flowing either toward or from the Gulf of Mexico, and includes a strong expression of the Yucatan Undercurrent.

INDEX TERMS: 4243 Oceanography: General: Marginal and semienclosed seas; 4520 Oceanography: Physical: Eddies and mesoscale processes; 4576 Oceanography: Physical: Western boundary currents; KEYWORDS: Yucatan Channel, Loop Current, deep flows


1. Introduction

[2] The Gulf of Mexico is a semienclosed sea with connections to the Caribbean Sea through the Yucatan Channel and to the Atlantic Ocean through the Florida Straits. The total mean transport flowing from the Caribbean into the Gulf of Mexico through the Yucatan Channel is close to 24 Sv, with RMS fluctuations of 4.6 Sv [Ochoa et al., 2001; Sheinbaum et al., 2002]. The Yucatan Current, which accounts for most of this transport, passes through the Yucatan Channel, where it becomes the Loop Current. This warm surface current shows great variability, either crossing directly toward the Florida Straits, or forming large loops inside the Gulf of Mexico, often followed by the shedding of large anticyclonic eddies. The dynamic reasons for the variations in the path of the current and for the eventual shedding of eddies are poorly understood. Nonetheless, some hypothesis have been explored using mass conservation. Maul [1977] suggested that changes in the Loop Current volume needed to be compensated by deep flows which, because of the large difference between the sill depth at the Yucatan Channel (2040 m) and at the Florida Straits (730 m at its shallowest point, between Miami and Bimini), may only occur at Yucatan. Maul et al. [1985] examined their idea by comparing observations made over a 3 year period with a current meter placed at the bottom of the Yucatan Channel, to the surface area of the Loop Current inferred from satellite infrared observations, but found no relation between the two data sets. Maul and Vukovich [1993] compared the volume transports in the Florida Straits and the Loop Current extension, but again found little correlation. The purpose of this paper is to show the validity of Maul’s hypothesis by using a simple conceptual model based on his idea in conjunction with recent

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flow observations in the Yucatan Channel, and to explore
the structure of the deep currents in the channel that are
related to the fluctuations of the Loop Current. The paper
is organized as follows: section 2 describes the conceptual
model based simply on mass (volume) conservation, section
3 shows a description of the data used, section 4 presents
the results, and section 5 summarizes our conclusions.

2. Box Model

[3] Supposing incompressibility in the mass conservation
law, the equation for the balance of volume in the Gulf of
Mexico may be written as

\[
d\frac{V_{\text{Gulf}}}{dt} = T_Y + T_F + R + (P - E),
\]

where \( V_{\text{Gulf}} \) is the total volume of water in the Gulf of
Mexico, \( T_Y \) is the volume transport across Yucatan Channel,
\( T_F \) is the volume transport across the Florida Straits, \( R \) is the
runoff and \( P - E \) is the volume transport due to precipitation
minus evaporation. Estimates of \( R + P - E \) made by Etter
[1983] show that these terms are very small, on the order of
0.1 percent of \( T_Y \) and \( T_F \). The volume rate of change of the
Gulf of Mexico may be estimated through altimetry measurements
available on the Web; the data show that \( dV_{\text{Gulf}}/dt \) is also a small term, less than one percent of the
transports through the Yucatan Channel and Florida Straits.

[4] Thus, two large terms in equation (1) (\( T_Y \) and \( T_F \))
almost balance out, showing that the Loop Current is indeed a
throughflow. The difference between the sill depths at the
Yucatan Channel and the Florida Straits suggests the use of
a two-layer model, with the lower layer extending from the
bottom of the Gulf of Mexico to the level of the deepest
isotherm found in the Florida Straits, and the upper layer
from that isotherm to the surface (Figure 1). Strictly speak-
ing, \( T_F \) should correspond to the transport across the Key
West to Havana section, where all the contribution to the
Florida Current originates from the Yucatan Channel and the
sill depth is close to 900 m, but the deepest connection with the Atlantic Ocean at the Miami-Bimini section, is
shallower than that (730 m) and the minimum temperature
observed there is about 6°C [Schmitz and Richardson,
1991]. In view of this, equation (1) can be approximated as

\[
T_Y^\text{II} + T_Y^\text{I} + T_F \approx 0,
\]

where \( T_Y^\text{II} \) and \( T_Y^\text{I} \) are the transports through the upper and
lower layers in the Yucatan Channel. If we now assume that the
Loop Current exists exclusively in the upper layer, as a
ribbon that connects the Yucatan Channel to the entire width
of the Florida Straits, its volume budget becomes

\[
d\frac{V_{\text{Loop}}}{dt} = T_Y^\text{I} + T_F,
\]

where \( V_{\text{Loop}} \) is the Loop Current volume. Combining
equations 2 and 3 it follows that

\[
d\frac{V_{\text{Loop}}}{dt} = -T_Y^\text{I}.
\]

Thus, the rate of change in the total volume of water included
in the Loop Current should be equal in magnitude to the deep
transports in the Yucatan Channel, which is Maul’s idea. The

model includes the following assumptions: 1) No exchange
of water from the deep layer occurs at Florida Straits, 2)
Mass exchanges occur neither across the layer’s interface,
nor across the lateral boundaries of the Loop Current, 3) The
total volume of water in the Gulf of Mexico remains
constant, and 4) The volume of surface waters that do not
belong to the Loop Current proper remains constant.

3. Data

[5] Eight moorings with acoustic Doppler current prof-
ilers (ADCPs), current meters and thermometers were
deployed across the entire Yucatan Channel from September
8, 1999, to June 17, 2000, in an array that allows a
statistically satisfying determination of the exchange
between the Caribbean Sea and the Gulf of Mexico. The
location of the moorings, the distribution of the sensors
across the section, and the method for calculating the
transports are detailed by Sheinbaum et al. [2002]. The
data were low-pass filtered to remove tidal frequencies and
objectively mapped over a grid of 106 depths by 39
longitudes at hourly values. These data were then used to
compute time series of transports below the 6°C isotherm,
the lowest temperature typically observed in the Florida
Straits and the upper limit of the model’s lower layer.

[6] The surface extension of the Loop Current was inferred from an uninterrupted series of 3 day averaged
advanced very high resolution radiometer (AVHRR) images
spanning from October 1999 to May 2000, using graphic
software to manually define the boundaries of the current,
and integrating to estimate the areas. The images where
obtained from the Johns Hopkins University web page
http://fermi.jhuapl.edu/). Estimations during the summer
were impossible because of insufficient temperature contrast
between the current and the remaining Gulf of Mexico
surface waters. In most images only the external border
could be defined (Figure 2a); using 12 images on which
both the external and the internal borders were visible
(Figure 2b), we extracted a simple proportion between the
total area contained within the external border and the ‘real’
area of the current. To reduce subjectivity, two sets of
estimations were made by different persons; the final series
of Loop Current area estimates is the average of both. It
should be mentioned that an eddy shedding event occurred
around 4 October 1999, which was detected with Lagrangian drifters released at that time, but appears to be the only event of this sort during the measurement period.

4. Results

[7] To estimate the volume of the current, we assume the area is proportional to the volume (i.e., \( V_{\text{Loop}}(t) = H A_{\text{Loop}}(t) \), where \( H \), the depth of the Loop Current, is a constant). A linear regression following equation (4) is then given by

\[
H \frac{dA_{\text{Loop}}}{dt} \approx -T'_1 + \epsilon_1,
\]

where the residual, \( \epsilon_1 \), absorbs the lack of exact proportionality between areas and volumes, errors in the estimation of areas and transports, and the approximations made in the model. The size of \( \epsilon_1 \) then depends on how well correlated the two time series are.

[8] This expression, being a relation of derivatives, favors the high frequency variability of both time series. The correlation between the unsmoothed series of deep transport and Loop Current area changes is null; only when filtered, for example, with a running mean of 20 days, does the similarity between the series become evident. The low-passed series shown in Figure 3 suggest that the correlation between them is owed not only to the lowest frequencies but also to periods of approximately 40 days. The correlation coefficient at lag zero is 0.62 for the original series, and 0.31 for those detrended; their statistical significance is discussed below.

[9] We can also integrate equation (5), thus favoring low frequencies. The linear regression may then be written as follows:

\[
A_{\text{Loop}} \approx A_0 - \frac{1}{H} \int_{t_0}^{t} T'_1(t')dt' + \epsilon_2,
\]

where \( A_0 \) is a reference Loop Current area, \( \epsilon_2 \) is the residual of this operation, and the remaining variables have been defined above. The correlation coefficient between these two series, the area extension of the Loop Current and minus the cumulative deep transports (i.e. \( A_{\text{Loop}} \) and \( \int_{t_0}^{t} -T'_1(t')dt' \)), is astonishingly high, 0.94 for the series with the trend, and 0.89 without. Both series again show fluctuations of approximately 40 days (Figure 4). Oscillations with similar period were found by Maul et al. [1985] in their current meter data, placed at the bottom of the Yucatan Channel, but we do not yet know what the origin and significance of these 40 day fluctuations might be.

[10] The two sets of series have maximum correlation at nonzero lags. For the series with the trend corresponding to equation (5) (see Figure 3a), the maximum correlation (0.83) occurs with a lag of 8.6 days, while in the integral case of equation (6) (shown in Figure 4a) the maximum correlation is 0.95 at a lag of 7 days. In both cases changes in the surface expression of the current lead the compensation by the deep flows. But the smoothness of the time series yields an insufficient number of equivalent degrees of freedom (15 and 9), computed using the formulas of Priestley [1989] and Richman et al. [1977], which implies that, although correlations are significant, the intervals at 95% confidence are too large (0.07 < 0.62 < 0.88 for the low-passed series corresponding to equation (5) and 0.84 < 0.94 < 0.98 for equation (6)) for the lags to be statistically significant. The conceptual model excludes lags between the series, as it ignores the changes in the volume of the Gulf of Mexico implied by them.

[11] Another caveat of the model is that the equivalent depths of the Loop Current, found by the linear regression, are far smaller than the mean depth of the 6°C isotherm: the maximum depth obtained with the linear regression is 261 m while the mean depth of that isotherm in the Yucatan Channel is 900 m. This nominal underestimation of deep flows may imply that compensation of the imbalance produced by the changes of the Loop Current extension is not only accounted for by deep flows in the Channel but also by surface waters external to the Loop Current proper, or that we have overestimated the current’s surface extension. Perhaps the most serious shortcoming of the model.

**Figure 2.** (a) An example of the calculation of the areal extension of the Loop Current when only the external border was visible. (b) One of the 12 images for which the inner border was visible as well.
arises with the detachment of eddies from the Loop Current; if we allow these, the model of section 2 collapses because it assumes no exchange between the different waters in the system, and thus implies an accumulation of Loop Current water inside the Gulf of Mexico.

In order to keep the relation between the Loop Current areas and the deep transports in Yucatan Channel one could also consider mixing between surface waters outside the Loop Current and the Loop Current itself, maintaining the volume of these Gulf of Mexico surface waters \( GM_{sw} \) constant. This means that if an eddy detaches from the Loop Current, we assume that the water from that eddy becomes part of the surface waters of the Gulf of Mexico and, if we insist on maintaining the \( GM_{sw} \) volume constant, an equivalent amount of these waters must simultaneously leave the Gulf. To clarify this idea let us reformulate the previous model. For simplicity we assume that the outflow of these \( GM_{sw} \) takes place only in Florida, so \( T_F = T_F^{loop} + T_F^{GM} \). The changes in the Loop Current volume are given by

\[
\frac{dV_{Loop}}{dt} = T_F^{loop} + T_F^{GM} - \delta T.
\]  

where \( \delta T \) represents the waters that built up the eddy. The changes in the \( GM_{sw} \) water volume are

\[
\frac{dV_{GM}}{dt} = T_F^{GM} + \delta T = 0.
\]  

This means that either \( T_F^{GM} \) and \( \delta T \) are both zero (when there is no eddy shedding), or that they cancel out. This is a strong supposition, which states that at the moment an eddy detaches a large amount of \( GM_{sw} \) exits the Gulf. Although the outflow of these waters could take place both at Yucatan and Florida, for simplicity we are considering that this takes place only off Florida.

On the other hand, changes in the lower layer water volume will be given by deep transports like in the previous model. Since the total Gulf of Mexico water volume remains constant, equation (4) holds unchanged:

\[
\frac{dV_{Loop}}{dt} = -T_V^{GM} - \delta T = -T_V^{GM}.
\]  

which means that Loop Current volume changes are still compensated by deep flows in the Yucatan Channel. The
unrealistic requirement of the exit of the waters simultaneously with the eddy detachment, set in equation (8), was done to maintain equation (4) artificially, as an ad hoc remedy. The relaxation of such requirement, leaving only the left equality in equations (8) and (9), allows effects like the suggested delay in the series of Figures 3 and 4, but includes terms that are difficult to measure, specifically the distribution in the Florida transport, $T_F$, of $T_{Loop}^F$ and $T_{GM}^F$.

[14] Given the importance and magnitude of the deep flows we observe as a response to Loop Current incursions, it is relevant to examine the structure of the exchange beneath the $6^\circ$C isotherm in the Yucatan Channel, the level we have taken as upper limit for the lower layer. Twice-daily maps of the detided along-channel velocity (not shown) indicate that most of the time, the exchange has a three-band cross-channel configuration, with flow near the edges being southward toward the Caribbean, and currents near the center of the Channel flowing into the Gulf of Mexico. Nonetheless, during the most intense southerly events, the flow is toward the Caribbean Sea over the entire deep section. This is synthesized by the Empirical Orthogonal Functions of the detided along-channel velocity series (Figure 5), of which the first two modes contain 63.6 percent of the total variance of the flow. Both these modes are dominated by spatial structures near the edges of the channel; mode 1 (40% of the variance) consists of a three-banded structure with flow in the center opposing that near the edges; mode 2 (23.6% of the variance) consists predominantly of a jet that hugs the Yucatan slope beneath the Yucatan Current, possibly a signature of the Yucatan Undercurrent, and of a slight intensification near Cuba. The temporal evolution of mode 1 (Figure 5, panel 3) indicates that the flow should be directed to the north in the center of the channel and to the south near its edges most of the time, since the series is mostly positive. Only once does the flow reverse, in November 1999, a time when the most intense southerly flow was seen to occur throughout the section. The correlation of the temporal evolution of mode 1 with the areal extension of the Loop Current is small, and nondifferent from zero within the 95% confidence interval.

[15] Mode 2 fluctuations are of somewhat higher frequency, with various southerly events dominating the series. In particular, the Yucatan Undercurrent is seen to be most intense to the south also during November 1999, coinciding with the main southerly event of mode 1. The cumulative temporal series of this mode is highly correlated (0.73 ≤
0.91 ≤ 0.98; 95% significance) with the areal extension of the Loop Current, suggesting a close relation between the Yucatan and Loop Currents, the Yucatan Undercurrent, and the flow toward the Caribbean Sea within the entire deep section.

5. Conclusions

[16] The hypothesis of Maul [1977], which stated that the extension of the Loop Current and the deep transports in the Yucatan Channel should be related, was tested with a high resolution array of observations and verified to be true for the period of our measurements. In particular, we find that mode 2 of the along-channel velocity, which explains 23.6 percent of the variance and includes a strong signature of the Yucatan Undercurrent, is best related to the Loop Current oscillations. Previous authors may have failed to verify this idea because of poor spatial resolution of their data or an unfortunate location of their instruments. We tested this idea by comparing the output of our instrument closest to the location of that of Maul et al. [1985], near the bottom in a region where both modes are weak. Both instruments possess similar kinematic characteristics, but fail to properly predict the transports of the lower layer. Oscillations with periods of around 40 days seem to be a common feature in the deep flows in the Yucatan Channel and are also expressed in the fluctuations of the Loop Current area, but their origin remains unclear. In addition, the lags between series, although not significant statistically, might be an indication of a time scale for internal adjustment processes in the Gulf of Mexico. A simple calculation based on a density profile inside the Gulf of Mexico shows that the phase velocity of a first baroclinic mode Kelvin wave takes about a week to travel around the Gulf. The high correlations were found for a measurement period that does not include an eddy-shedding event. In order to maintain the validity of equation (4) in the event of eddy detachments, an alternative model suggests that there should be a massive outflow of \( GM_{sw} \) when this kind of events occur. This supposition seems highly restrictive since we are unaware of a dynamical reason to justify such behavior. The strong relationship between deep transports and the Loop Current
extension is valid for the measurement period, but the mechanisms by which this relation could extend for longer periods remains to be found.

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