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A Loop Current-Induced Jet Along the Edge of the West Florida Shelf

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Abstract. The pressure imposed upon the West Florida Shelf by the Gulf of Mexico Loop Current is found to give rise to a southward flowing jet along the shelf edge. The pressure-induced jet is simulated by a general circulation model of the Gulf. However, the physics causing formation of the jet are well represented by a simple continental shelf model incorporating an idealized geometry for the West Florida Shelf. The pressure response over the shelf, in an analogy to conductive heat transfer in a rod, is limited by the "insulating" effect of the steep topography of the West Florida Escarpment, which hinders the onshore spreading of the pressure influence. The shelf-edge jet is apparent in the trajectories of satellite-tracked surface drifters deployed from February 1996 through March 1997. Evidence for the requisite pressure distribution over the escarpment is provided by measurements of sea level from the satellite altimeter aboard the TOPEX/POSEIDON satellite.

1. Introduction

The circulation of the Gulf of Mexico is dominated by the Loop Current (LC), which enters the Gulf through the Yucatan Straits and exits through the Straits of Florida after looping anticyclonically through the southeastern Gulf [*Leipper*, 1970]. Irregular deep northward penetrations of the LC into the eastern Gulf occur with nearly annual frequency and are associated with the shedding of large anticyclonic eddies that propagate to the west after separation from the LC. Following an eddy shedding, the LC often retreats to the south, hugging the northwest coast of Cuba.

It is believed that the LC entrains West Florida Shelf (WFS) water as it flows along the West Florida Escarpment (WFE) and South Florida Slope [*Wennekens*, 1959]. However, the low-frequency southward flow inferred from coastal sea-surface elevation over the WFS does not reach its maximum strength at the time when the LC has fully penetrated into the Gulf and the LC front is closest to the WFS [*Sturges and Evans*, 1983].

A numerical simulation of the Gulf of Mexico with realistic bottom topography and circulation driven solely by the LC inflow shows that the southward flow on the WFS varies out of phase with the LC penetration [Hsueh et al., submitted]. From these model results, it appears that the southward flow on the WFS at nearly annual frequencies is caused by the north-to-south pressure drop imposed on the shelf by the LC. When LC penetration is small, the pressure drop is accounted for by the Bernoulli effect; the LC quickens as it is constricted by the presence of the WFS. When LC penetration is greater a meander develops which again creates a low pressure region on the southern corner of the shelf [*Hetland*, 1999].

At these low frequencies, the extent of influence of the imposed pressure is inversely proportional to the slope of the sea bottom [*Chapman and Brink*, 1987]. Thus, the steep topography of the WFE "insulates" the WFS from the influence of the LC pressure and turns the along-break north-to-south pressure drop into a sharp drop in pressure onshore, giving rise to a focussed southward flow along the shelf edge and leaving the flow weak over the rest of the shelf [*Csanady and Shaw*, 1983].

The exception occurs when the pressure drop is imposed at the southern extent of the WFS, which happens when the LC is in its southernmost position skirting Cuba. In this case, the imposed pressure drop conducts northward along depth contours and effects a broad southward flow over the WFS. The "insulating" effect of the WFE and the "conducting" effect of the isobaths act to produce low-frequency southward flow on the WFS, out of phase with the northward penetration of the LC. An analogy with heat conduction in a rod elucidates the physical mechanisms controlling the shelf circulation, mechanisms that are supported by direct observational evidence.

2. Theory

The "insulating" effect of steep topography on the low-frequency influence of downcoast pressure imposed at a point along the shelf edge is analogous to the conduction of heat along a rod [*Peng*, 1976; *Csanady*, 1978]. The alongshore distance in the direction of topographic wave propagation corresponds to time, and the onshore extent of pressure corresponds to the distance reached by conducted heat along the rod. The application of this analogy to the WFS requires an extension to account for the varying depth of the WFS and the narrowing of the shelf north of Key West.

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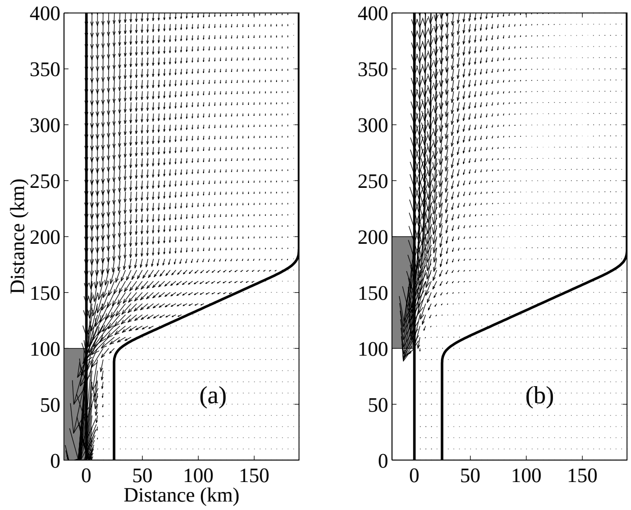

Figure 1. Current velocities calculated numerically from equation 1 over a continental shelf with a shelf-similar topography. (a) is for the case where a linear north-south pressure step-down (shaded stretch) is imposed along the edge of the narrow section of the shelf. (b) is for the case where the north-south pressure step-down is imposed along the shelf break just north of the narrow section of the shelf. The shelf break is represented by the heavy straight line, and the coastline is represented by the curve on the right. The depth distribution across the shelf is shown in (c). The imposed pressure north of the step-down is unity and that south of the step-down and along the southern end of the shelf is zero.

One approach is to assume a shelf-similar cross-shelf topography (The assumption of shelf-similar topography restricts the consideration to a particular class of shelf geometry for which the spread of imposed pressure is again analogous to heat conduction. In general, a given isobath may not always be found at different along shore points at a distance from the shelf break that is a constant fraction of the local shelf width.) bounded by a straight shelf-break, where the shelf width varies along-shelf and linearly scales the cross-shelf topographic profile [*Hsueh*, 1980]. That is, $h = h(x)$, where $x = x^*/b(y)$ is the shelf-similar cross-shelf coordinate, $b(y)$ is the shelf width, x^* is the actual cross-shelf distance (to the east) measured from the shelf break, and y is the distance along the straight shelf-break (to the north). With linear bottom friction included in the along-shelf momentum equation, the barotropic pressure over the shelf is given by an equation with the form of the partial differential heat equation:

$$\frac{\partial \zeta}{\partial y} = \frac{r}{\alpha f b} \frac{\partial^2 \zeta}{\partial x^2} \quad (1)$$

subject to the boundary conditions:

$$\zeta(x, 0) = k(x) \quad (2)$$

$$\zeta(0, y) = g(y) \quad (3)$$

$$\frac{\partial \zeta}{\partial x}(1, y) = 0 \quad (4)$$

where, ζ is pressure in cm of water, r, a bottom friction coefficient, f, a constant Coriolis parameter, and $\alpha = \alpha(x)$, the bottom slope. The analogy to heat conduction is clear.

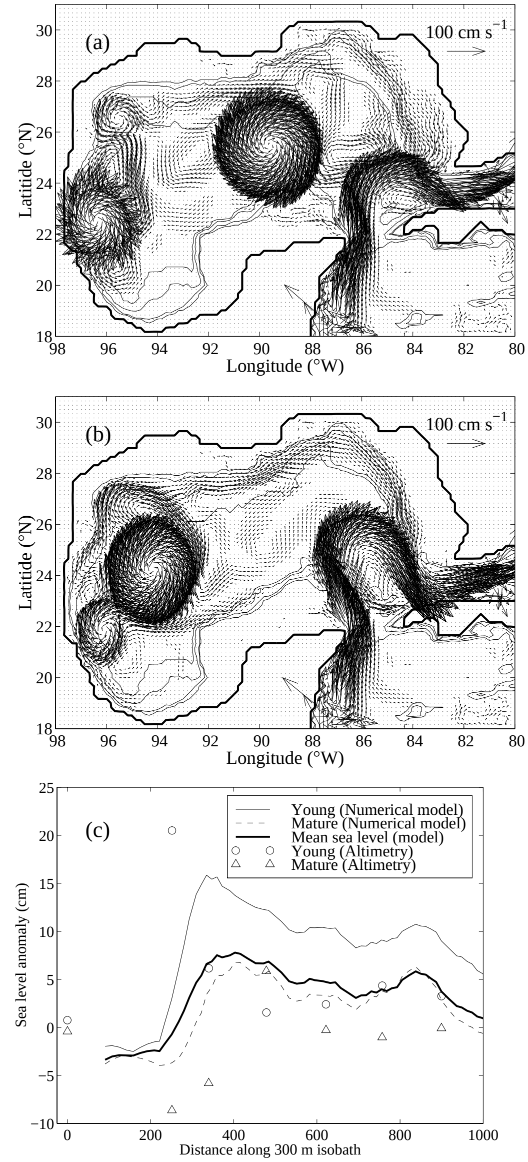

Figure 2. Results from a numerical model of the Gulf of Mexico circulation driven by a volume transport of 30 Sv (1 Sv $\equiv 10^6$ m s^{-1}) imposed at the inflow (Caribbean Sea) and outflow (Straits of Florida) boundaries. (a) and (b) show current velocities greater than 5 cm s^{-1} at 5 m depth. (a) represents a snapshot of the circulation when the Loop Current is "young" in its eddy-shedding cycle. (b) represents a snapshot of the circulation when the Loop Current "mature." Dynamic pressure, in centimeters of water, along the 300 m isobath on the West Florida Shelf corresponding to each of the snapshots is shown in (c). The origin of the abscissa coincides with the easternmost shaded dot in Plate 1. The time-average of dynamic pressure over three eddy-shedding cycles is given by the heavy curve. The mean sea-surface height anomaly from the TOPEX/POSEIDON altimetry at the seven shaded dots for the two time windows shown in Plate 1 are indicated by circles (triangles) for the time when the Loop Current is "young" ("mature").

The onshore spread of an imposed pressure is less with a locally wider shelf and steeper topography, since the diffusion coefficient is inversely proportional to the shelf width and slope.

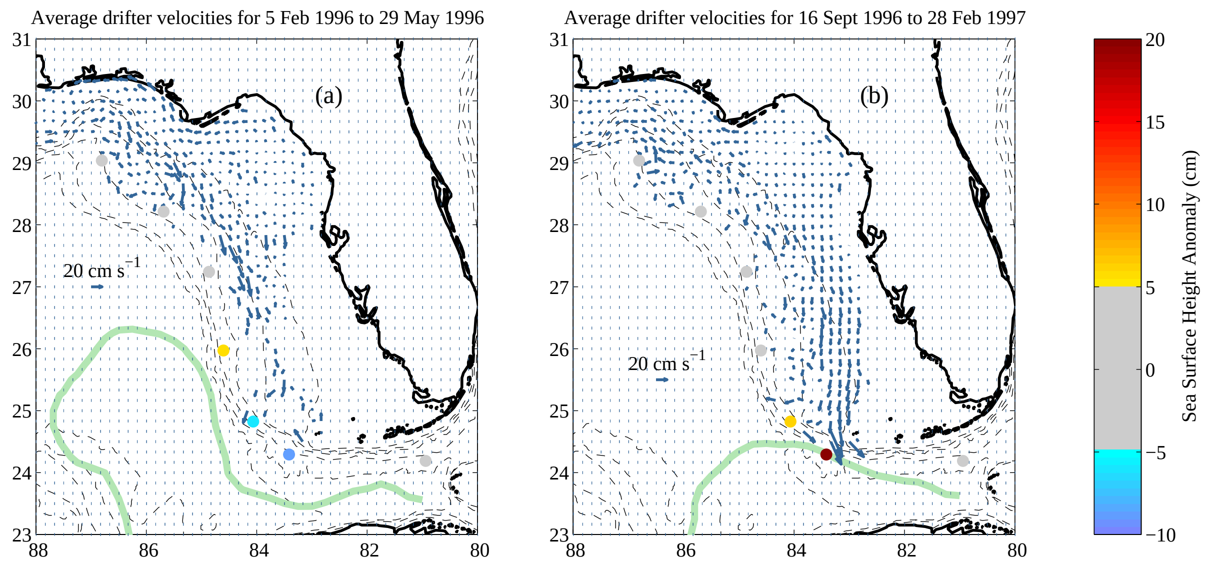

Plate 1. Averages of $\frac{1}{6}^{\circ}$ square bin-averaged current velocities calculated from the distance traveled by surface drifters between successive position fixes. (a) shows, in the northeastern Gulf of Mexico, the average for 5 February to 29 May, 1996 when the Loop Current is “mature.” (b) shows the same for 16 September, 1996 to 28 February, 1997 when the Loop Current is “young.” The shaded dots mark the positions where the sea-surface height anomaly is available from the TOPEX/POSEIDON altimeter measurements. For each time period the anomaly is denoted according to the color bar on the right. The light green ribbon marks the mean edge of the Loop Current. Dashed curves represent isobaths (50, 100, 200, 500, 1000, and 2000 m).

The “heat” equation can be solved numerically for a shelf/slope configuration qualitatively like the WFE and WFS. Figures 1a and 1b present, the flow field given by the numerical solutions for two cases of pressure forcing. In both cases, the pressure forcing is specified in the form of a north-to-south decrease from unity to zero in a 100 km segment of the shelf break. (The shelf topography is shown in Figure 1c.) In the first case (Figure 1a), the pressure decrease is specified along the narrow shelf edge at the southernmost end of the shelf. In the second case (Figure 1b, the 100 km segment of decreased pressure is moved 100 km to the north. In both cases, the computed velocity is southward and reaches a maximum at the shelf break. When the pressure drop is specified at the southernmost position, however, there is increased “conduction” of the pressure (due to the narrowness of the shelf and the presence of diverging isobaths) and the southward flow is found all the way to the coast, whereas hardly any nearshore flow is found when the pressure drop is imposed to the north where the shelf is much broader.

3. General Circulation Model

The shelf-edge jet is found in a general circulation model simulation of the Gulf of Mexico driven with an inflow-outflow combination that reproduces the LC [Hsueh et al., submitted]. Two snapshots of the modeled surface velocity field show strong currents along the WFS edge (Figures 2a and 2b), even though the LC is in remarkably different positions. When the LC is nearly fully grown or “mature” (Figure 2b), the shelf-edge jet (indicated by velocity greater than 10 cm s^{-1}) is sharply focussed and there is little flow near the coast. When the LC has retreated to the southern edge of the shelf after shedding an eddy and is considered “young” (Figure 2a), the jet diffuses onshore, particularly along the southern extent of the WFS and some flow is found all along the coast. The dynamic pressure along the 300 m isobath on the WFS (Figure 2c) for both cases shows a north-to-south stepwise decrease qualitatively compatible with the theory outlined above.

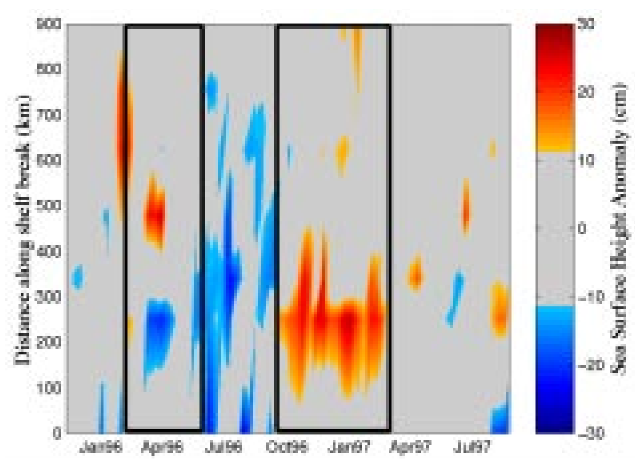

Plate 2. TOPEX/POSEIDON altimeter-sensed sea-surface height anomaly along a belt between the positions of the 200 m and 1000 m isobaths along the West Florida Shelf edge. The ordinate is distance in kilometers along the shelf in the northwest direction starting from the easternmost shaded dot in Plate 1. The abscissa is time. The anomaly is interpolated between the dots in Plate 1 and mapped in color according to the bar on the right. The anomaly map in the two time-windows in Plate 1 are framed with heavy black lines.

4. Observational Evidence

Satellite-tracked surface drifters deployed during February 1996 - March 1997 provide observational evidence for the shelf-edge jet. The averaged velocity fields derived from drifters tracked during February 5 - May 29, 1996 (Plate 1a) and September 16, 1996 - February 28, 1997 (Plate 1b) show current velocities greater than 10 cm s^{-1} at the shelf edge. The mean edge of the LC (light green ribbon) determined from satellite altimetry (The mean position of the LC over each period was determined from a sea-surface height anomaly map based on all TOPEX/POSEIDON and ERS-1 and 2 data collected over the time interval, which had been added to a model mean sea surface to estimate the total sea-surface height field. The 17 cm contour from these time averaged maps showed the mean LC position. The 17 cm contour corresponds approximately to the 200 m depth of the isotherm, which has historically been used to track the LC boundary.) shows that the LC is in "mature" and "young" phases during these respective time periods. Consistent with the theoretical and modeling results, there is a shelf-edge jet associated with these LC paths and the jet is more diffused when the LC is "young". Also, the meander in the LC front creating a low pressure on the southwest corner of the WFS is apparent.

Evidence for the required pressure distribution driving the shelf-edge jet is found in satellite altimeter measurements of sea-surface height (SSH), which is an analog for dynamic pressure in the theoretical and numerical models. Observations of SSH anomalies along TOPEX/POSEIDON ground tracks over the WFS between the 200 and 1000 m isobaths (seven shaded dots in Plate 1) show a stepwise decrease in the SSH at the 100 km point (second dot) along the slope for the "young" LC configuration. This north-to-south step-decrease moves to the north when the LC is in the "mature" phase. The average SSH anomaly for each phase compares qualitatively well with the dynamic pressure found in the two corresponding snapshots of the numerical simulation (Figure 2c). The signatures in SSH corresponding to both phases of the LC penetration persist along the slope for extended time periods (the SSH anomaly is presented in Plate 2). Thus, the requisite pressure distribution for the shelf-edge jet is observed, supporting the hypothesis that the jet is pressure-induced.

There is also observational evidence for the shelf break jet in historical hydrographic data (not presented for brevity). A comparison of observational and numerical hydrographic cross-sections is found in *Hetland* [1999].

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