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A Loop Current experiment: Field and remote measurements

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ABSTRACT

An overview of a new comprehensive observational study of the Loop Current (LC) in the eastern Gulf of Mexico that encompassed full-depth and near-bottom moorings, pressure-equipped inverted echo sounders (PIES) and remote sensing is presented. The study array was designed to encompass the LC from the Campeche Bank to the west Florida escarpment. This overview centers about principal findings as they pertain to mesoscale dynamics. Two companion papers provide in-depth analyses. Three LC anticyclonic eddy separation events were observed with good 3D spatial coverage over the 2½ year extent of the field study; the three separations exhibited similar processes after the LC had extended into the eastern Gulf. Large scale (~300 km wavelength, 40–60 day periods) southward propagating meanders developed on the eastern side of the LC over deep (~3000 m) water that were the result of baroclinic instability between the upper layer meandering jet and lower layer cyclones and anticyclones. The lower layer was only highly energetic during relatively short (~2–3 months) intervals just prior to or during eddy detachments because of baroclinic instability. The steepening of the meanders lead to a pinch-off of LC eddies. The deep lower-layer eddies, constrained by the closed topography of the southeastern Gulf, propagated westward across the detachment zone and appear to assist in achieving separation. Small scale (~50–100 km, periods ~10 days) frontal eddies, observed on the western side of the LC along the Campeche Bank slope, decay over the deep water of the northern part of an extended LC, and have little influence on lower layer eddies, the east side meanders and the eddy detachment processes.

1. Introduction

The Loop Current (LC) in the eastern Gulf of Mexico is part of the semi-permanent anticyclonic gyre of the North Atlantic Ocean (Candela et al., 2003; Schmitz et al., 2005). Knowledge of the LC behavior is based essentially on hydrographic and remote sensing observations, and numerical models results. Current and temperature measurements under the LC are scarce but are very important to decipher its dynamics and predict future LC states. Still, about 60 years after its first mention in the scientific literature, we are struggling to understand the processes controlling the LC behavior inside the Gulf of Mexico.

This potent flow, as its name indicates, forms an anticyclonic loop inside the Gulf of Mexico (Austin, 1955) that is confined over the deep waters of the eastern Gulf, bounded to the north by the continental slope of the northeast Gulf, and to the east by the Florida Escarpment. It enters the Gulf through the Yucatan Channel as a near surface jet about 200 km wide, about

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800–1000 m deep, surface speeds of 1.5 $\mathrm{m\,s^{-1}}$ and carrying on average 30 Sv (22–30 Sv; Athie et al., 2015; Rousset and Beal, 2010; Sheinbaum et al., 2002) (1 Sv = 10^6 $\mathrm{m^3\,s^{-1}}$). Inside the Gulf the LC oscillates between two extreme states: a port-to-port retracted configuration where the LC exits the Gulf very fast by turning immediately from Yucatan to the Florida Straits. The second configuration is a northern intrusion reaching on average to 27.47° N and is the prevalent state.

Before the early 1980s, most observational studies of the LC were done by ship surveys, e.g., Austin (1955), Cochrane (1972) or Nowlin (1972). These initial studies revealed the LC intrusion, the eddy separation, and frontal eddies. Because of cruise limitations, these observations were severely aliased. On the basis of these data an annual cycle paradigm for the LC intrusion (e.g., Molinari et al. (1978) and references therein) and its dependence on inflows at Yucatan (e.g., Molinari et al., 1978) were proposed. In the 1980s, ocean observing with remote infrared and altimetry sensing satellites and moorings became available and the number of studies about the LC increased, e.g. Vukovich (1988), Maul (1977), Molinari (1980), Molinari and Morrison (1988), and Hamilton (1990). Weak sea surface temperature gradients in summer, along with cloud cover, made LC and LC eddy fronts difficult to track in satellite imagery, resulting in aliasing. Satellite altimetry was in its infancy so it was limited as well. It was during this decade that the first water column current measurements became available and it was hypothesized that the LC was a source of topographic Rossby waves (TRW) in the deep Gulf (Hamilton, 1990). In the two subsequent decades, measurement after measurement in the deep Gulf, showed that observations could be explained by TRW's generated either by the LC incursion or eddies along the LC front (Hamilton, 2009; Oey and Lee, 2002). During this period deep water currents of 0.9 $\mathrm{m\,s^{-1}}$ 100 m above the bottom in depths of over 2000 m near the Sigsbee escarpment were discovered (Hamilton and Lugo-Fernández, 2001). The strong connection between the LC and Gulf of Mexico dynamics lead to the implementation of the first comprehensive mooring observing system for the Yucatan Channel (Sheinbaum et al., 2002). Also, this period saw renewed interest in the hypothesis that cyclonic LC frontal eddies were involved in the separation of LC anticyclones (Cochrane, 1972; Fratantoni et al., 1998; Schmitz, 2005). Concurrently, numerical models results suggested that baroclinic and barotropic instabilities were involved in the separation of eddies (Hurlburt and Thompson, 1980; Chérubin et al., 2006).

The "gestation and birth" of a LC warm ring is a complicated and protracted process that is well documented but the dynamical processes involved remain uncertain. The retracted LC begins its northward intrusion at 0.02 $\mathrm{m\,s^{-1}}$ into the Gulf, reaching on average to 27.47° N or ~190 km, and a maximum of 28°N in ~200 days. Proposed reasons driving the intrusion are a flow imbalance between Yucatan Channel and Florida Straits (Nof and Pichevin, 2001; Bunge et al., 2002), vorticity and its flux (Reid, 1972; Candela et al., 2003; Oey, 2004), bottom form drag (Lin et al., 2009), or deep flows through the Yucatan Channel (Hurlburt and Thompson, 1980). During its intrusion, the LC balloons out and often leans toward the northwest that is accounted for by the Pichevin and Nof (1997) momentum paradox (discussed below; see also Reid (1972)). During the extension, sometimes a large anticyclone detaches from the LC, indicated by breaks of sea surface height contours that may last days to weeks, followed by the reattachment of the eddy to the LC, thus allowing the LC to increase in length and area. Upon reaching its maximum northward intrusion, the LC stops growing, retracts a little and undergoes one or several detachments and reattachments, leading to an eventual separation (Lugo-Fernández et al., in this issue). While the exact reasons for stopping its northward intrusion are, again, unknown, it seems reasonable that the closed geometry of the Gulf is a major contributor, or a major cyclone near the northern slope is responsible (Zavala-Hidalgo et al., 2002). Then, for reasons also unknown, eddies separate completely and behave like isolated vortices. The region of separation appears to be between 25° to 26° N and 87° to 88° W (Hamilton et al., 2011; Kantha et al., 2005). The interval between final separations (eddy shedding period) is 14–559 days. The newly separated eddy (200–400 km in diameter; and ~1000 m in vertical extent) propagates mainly southwestward inside the Gulf under the β-effect at 2–5 $\mathrm{km\,day^{-1}}$. Once the eddy separates, the LC retracts to a new southern position, resets and starts a new cycle. Upon reaching the west continental slope waters off Mexico and Texas, eddies dissipate by friction, radiating TRWs, expulsing water, merging with other eddies or a combination of several of these processes (e.g., Vukovich and Waddell, 1991).

Numerical model results suggest that baroclinic or barotropic instabilities are involved in the separation process (Hurlburt and Thomson, 1980; Chérubin et al., 2006). Pichevin and Nof (1997) suggested the momentum imbalance paradox for explaining eddy separation. The paradox arises because most of the Yucatan inflow goes north, but a outflow by the Florida Straits induces a recoil momentum to the west that's unbalanced; a way to balance this momentum is by having eddies separate from the northern branch so their eastward recoil momentum balances the outflow momentum. Others speculate that frontal perturbations of cyclonic vorticity traveling along the LC periphery sever it and cause detachments (Cochrane, 1972; Fratantoni et al., 1998; Schmitz, 2005), often followed by a separation as the eddy drifts to the west under the β-effect. LC frontal eddies and LC eddy detachments have also been linked to eddies or perturbations coming from the Caribbean (Athie et al., 2012) or the eastern U.S. coast (Sturges et al., 2010).

The LC is, therefore, of major importance to the circulation in the Gulf of Mexico both as direct and indirect generator of surface-layer eddies, and as a source of deep lower-layer flows. In order to advance understanding of the LC role in the Gulf, the U.S. Bureau of Ocean Energy Management (BOEM) funded two studies in U.S. and Mexican waters, to deploy a comprehensive array of instruments in the eastern Gulf, supplemented by remote sensing observations and numerical modeling. The resulting 2–2.5 year-long observational database is used to study LC variability, LC eddy separation, and the controlling dynamics from the basin scale to the small LC frontal eddy (LCFE) scales. Until this study, the LC had surprisingly few in situ observations commensurate with the time scales of the LC eddy-separation cycle. Much of what is known has come from remote sensing studies of surface layer variability (Leben, 2005; Leben and Born, 1993; Vukovich, 1988; Vukovich et al., 1979), and numerical modeling studies (Oey et al., 2005).

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