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Loop Current Eddy formation and baroclinic instability

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ABSTRACT

The formation of three Loop Current Eddies, Ekman, Franklin, and Hadal, during the period April 2009 through November 2011 was observed by an array of moored current meters and bottom mounted pressure equipped inverted echo sounders. The array design, areal extent nominally 89° W to 85° W, 25° N to 27° N with 30–50 km mesoscale resolution, permits quantitative mapping of the regional circulation at all depths. During Loop Current Eddy detachment and formation events, a marked increase in deep eddy kinetic energy occurs coincident with the growth of a large-scale meander along the northern and eastern parts of the Loop Current. Deep eddies develop in a pattern where the deep fields were offset and leading upper meanders consistent with developing baroclinic instability. The interaction between the upper and deep fields is quantified by evaluating the mean eddy potential energy budget. Largest down-gradient heat fluxes are found along the eastern side of the Loop Current. Where strong, the horizontal down-gradient eddy heat flux (baroclinic conversion rate) nearly balances the vertical down-gradient eddy heat flux indicating that eddies extract available potential energy from the mean field and convert eddy potential energy to eddy kinetic energy.

1. Introduction

The Loop Current (LC) dominates the circulation in the Gulf of Mexico. As part of the North Atlantic western boundary current system, it enters the Gulf through the Yucatan Channel and exits through the Straits of Florida. While the shortest circuit within Gulf is a port-to-port mode along the northern Cuban coast, the LC can penetrate the Gulf as far north as 28° N and as far west as 93° W, expanding in area by a factor of 4 from the port-to-port mode during its northward advancement (Leben, 2005). Its influence extends to the far western Gulf due to the formation of large anticyclonic rings known as Loop Current Eddies (LCE). On an irregular time interval a LCE pinches off from the LC and migrates westward in the Gulf, the time interval between separations can be as rapid as a few weeks or as long as 18 months (Vukovich and Maul, 1985; Sturges and Leben, 2000; Leben, 2005). The LCE separation process is not readily predictable, although an empirical linkage between retreat latitude and subsequent separation time has been found (Leben, 2005; Alvera-Azcárate et al., 2009). Complex and multi-scale circulation is associated with the LCE formation (Sturges and Leben, 2000). The separation cycle often exhibits a series of detachments and reattachments before the final separation (see, for example, the LCE Franklin formation discussed in Liu et al. (2011)). Frontal eddies and meanders along the periphery of the LC are present during separation (Cochrane,

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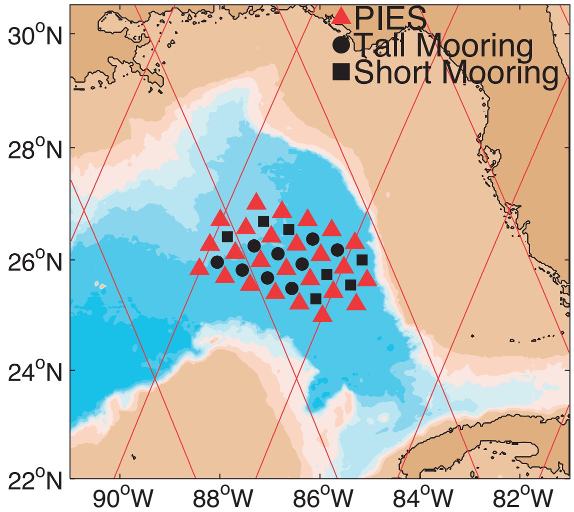

Fig. 1. Dynamics of the Loop Current Array consisted of 25 pressure inverted echo sounders, PIES, (red triangle), 9 tall moorings (black circles) and 7 short moorings (black squares). Bathymetry contoured every 1000 m depth, deepest topography denoted by the darkest blue hues. Jason-2 altimetry tracks shown in red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

1972; Vukovich and Maul, 1985; Fratantoni et al., 1998; Zavala-Hidalgo et al., 2003). The LC's influence extends beyond the depth of its surface-intensified core. Through interaction with topography and LCE generation, the LC provides the primary forcing of deep circulation. It has been hypothesized that deep energy generated beneath the LC during LCE separation radiates away from its source to the Gulf's boundary either as linear waves or eddies (Hamilton, 2009). At the boundary, steep escarpments act to focus this deep energy into narrow swift boundary currents (Oey and Lee, 2002; Oey, 2008).

Although qualitative analysis of surface fields has led to a classification of separation modes based upon the juxtaposition of cyclonic eddies and LC position within the Gulf (Schmitz, 2005), to date no theoretical framework fully explains LCE formation. Pichevin and Nof (1997) and Nof and Pichevin (2001) show that in order to conserve momentum, an anticyclonic eddy forms as the northward flowing LC turns eastward and realistic numerical models have demonstrated this process (Chérubin et al., 2005; Chang and Oey, 2011). Numerical studies highlight the role of instability and LC-topographic interactions in LCE formation e.g. Hurlburt and Thompson (1980), Hurlburt (1986), Welsh and Inoue (2000), Oey (2008), Chérubin et al. (2006), Le Hénaff et al. (2012). Essential in these studies are the feedbacks between upper and deep circulation. Hurlburt (1986) and Oey (2008) suggested that the region north of Campeche Bank is an important area for generation of deep eddies. Large mean-to-eddy energy conversion rates appear along the western edge of the Loop Current as the current moves off the relatively shallow western slope of the Yucatan Channel into the deep topography of the Gulf. Eddies propagate upstream along the Loop Current, grow in strength off the west Florida Slope and participate in the LC's necking-down that precedes LCE separation (Oey, 2008). In the Gulf of Mexico literature "necking-down" is often used to describe the spatial configuration where one or more adjacent LC cyclones appear to pinch together the sides of an extended LC below a developing LCE giving the LC a neck-like feature, e.g. Schmitz (2005). Chérubin et al. (2005) showed that a baroclinically unstable vortex generates a vigorous deep eddy field whose interaction with the LC becomes increasingly complex when realistic Gulf topography is included. More recently, the simulations in Le Hénaff et al. (2012) show that as frontal cyclones propagate over the Mississippi Fan, a coupled upper-deep cyclone pair develops that ultimately facilitates the LCE shedding process. Several studies have suggested linkage between the passage of cyclonic eddies from the Caribbean through Yucatan Channel to subsequent LCE separation (Oey et al., 2003; Oey, 2004; Athié et al., 2012; Huang et al., 2013).

To address the need for full-water column observations during the full eddy shedding cycle in order to improve the dynamical understanding of how the LC interacts with and drives deep circulation, an array of twenty-five inverted echo sounders with pressure gauges (PIES), nine full-depth moorings and seven near-bottom moorings was deployed April 2009 and recovered in October–November 2011 as part of the Dynamics of the Loop Current in US Waters Study (Fig. 1). Three LCEs formed during the 30-month deployment, Ekman, Franklin, and Hadal (Fig. 2). The array spanned 89° W to 85° W, 25° N to 27° N with 30–50 km mesoscale resolution. This permits quantitative mapping of the regional circulation during the LCE separation events. Hamilton et al. (2016), this volume, provides a review of the experiment and Hamilton et al. (2014) gives a detailed description of the field operations and data processing.

We note that the *Deepwater Horizon* oil-spill event occurred in spring-summer 2010 and coincided in time with Eddy Franklin's formation. (The *Deepwater Horizon* platform, 88.39° N, 28.74° N, was located well to the north, ~230 km from the northwesternmost edge of the array discussed in this work.) Considerable efforts were made during that time period to rapidly acquire and analyze oceanographic observations as well to focus and improve modeling studies. A thorough review of the subsequent literature is beyond the scope of this study, as a starting point, the reader is referred to the dedicated