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Three-dimensional model-observation comparison in the Loop Current region

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ABSTRACT

Accurate high-resolution ocean models are required for hurricane and oil spill pathway predictions, and to enhance the dynamical understanding of circulation dynamics. Output from the 1/25° data-assimilating Gulf of Mexico HYbrid Coordinate Ocean Model (HYCOM31.0) is compared to daily full water column observations from a moored array, with a focus on Loop Current path variability and upper-deep layer coupling during eddy separation. Array-mean correlation was 0.93 for sea surface height, and 0.93, 0.63, and 0.75 in the thermocline for temperature, zonal, and meridional velocity, respectively. Peaks in modeled eddy kinetic energy were consistent with observations during Loop Current eddy separation, but with modeled deep eddy kinetic energy at half the observed amplitude. Modeled and observed LC meander phase speeds agreed within 8% and 2% of each other within the 100 – 40 and 40 – 20 day bands, respectively. The model reproduced observed patterns indicative of baroclinic instability, that is, a vertical offset with deep stream function leading upper stream function in the along-stream direction. While modeled deep eddies differed slightly spatially and temporally, the joint development of an upper-ocean meander along the eastern side of the LC and the successive propagation of upper-deep cyclone/anticylone pairs that preceded separation were contained within the model solution. Overall, model-observation comparison indicated that HYCOM31.0 could provide insight into processes within the 100 – 20 day band, offering a larger spatial and temporal window than observational arrays.

1. Introduction

As part of the North Atlantic subtropical western boundary current system, the Loop Current (LC) enters the Gulf of Mexico (GOM) from the Caribbean Sea as the continuation of the Yucatán Current (YC), circulates anticyclonically within the Gulf forming a large loop, exits through the Florida Straits, and becomes the Florida Current after turning north along the eastern side of Florida. On irregular intervals, between 3 and 17 months, a large (200 – 400 km diameter) anticyclonic eddy, a LC eddy (LCE), separates from the LC (Sturges and Leben, 2000; Dukhovskoy et al., 2015). The separation process, shown schematically in Fig. 1, begins with the northward intrusion of the LC into the GOM, followed by the necking down of the LC and eventual pinching-off of a LCE. After separation, the LC retreats southward to the so-called port-to-port mode while the newly shed LCE propagates westward across the Gulf.

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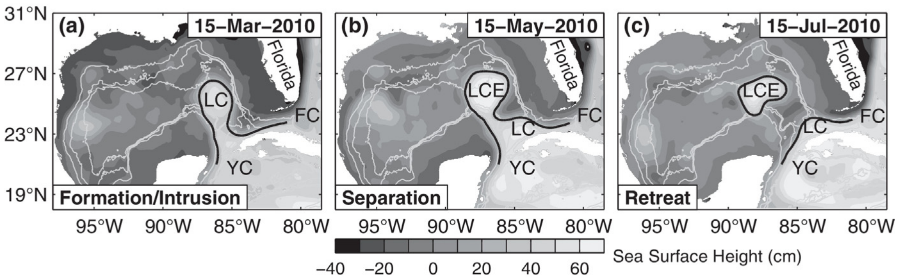

Fig. 1. Maps of sea surface height depicting the three-stage Loop Current eddy cycle: (a) northward intrusion/growth of the Loop Current (LC), (b) pinch-off of the anticyclonic ring, and (c) final separation and subsequent westward propagation of the eddy, and retreat of the LC to port-to-port mode. FC is Florida Current. YC is Yucatan Current. Sea surface height from the 1/25° Gulf of Mexico Hybrid Coordinate Ocean Model, GOMl0.04 expt_31.0.

There is a strong need for predictive skill for LCE separation. For example, strong currents associated with the LC and LCEs, as well as the strong deep currents generated during LCE separation, are hazardous to deep-water oil drilling operations. The warm cores of LCEs are also known to modify the intensity of passing hurricanes (e.g. Cione and Uhlhorn, 2003; Yablonsky and Ginis, 2012; Lin et al., 2008). Deep circulation, especially along the steep escarpments of the Gulf's continental slope play an important role in the rapid dispersal of contaminants (e.g. Paris et al., 2012; Nguyen et al., 2015).

Efforts have been made to predict and model LCE separation. Using an idealized vorticity model, Lugo-Fernández and Leben (2010) confirmed a linear relationship between the latitude of LC retreat and the length of time between LCE separations, a trend previously seen in satellite altimetry (Leben, 2005). Maul (1977) hypothesized a linkage between the rate of change of LC volume and deep transport through the Yucatán Channel. This idea is supported by 7.5 months of YC mooring observations (Bunge et al., 2002) and the recent analysis of a 54-year free-running 1/25° model (Nedbor-Gross et al., 2014). Chang and Oey (2011), on the other hand, suggest that mass exchange between the eastern and western basins, as well as exchange between the LC and deeper waters, play a significant role in the separation process. Evidence has been found for both seasonal (Leben et al., 2012; Chang and Oey, 2012) and inter-annual (Lugo-Fernández, 2007) trends in the length of the eddy separation period. Recent modeling studies suggest that seasonality in the trade winds may affect LCE separation (e.g. Chang and Oey, 2013; Xu et al., 2013). Using an artificial neural network approach, Zeng et al. (2015) achieved reliable LCE shedding forecasts of up to four weeks in SSH. Numerical studies also point to the importance of instability processes, the coupling between upper and deep circulation, and the generation of bursts of strong deep eddies during LCE separation. Examining instabilities exhibited in upper and deep pressure fields of a two-layer model, Hurlburt and Thompson (1980, 1982) found deep circulation driven by mixed baroclinic and barotropic instabilities. During LCE separation and detachment events, deep circulation is dominated by a field of intense deep eddies that propagate and couple with vortices of the upper-ocean LC (Sturges et al., 1993; Chérubin et al., 2005). Baroclinic instabilities near Campeche Bank and the West Florida Shelf have also been identified as a possible mechanism for the generation of deep eddies that facilitate LCE detachment (Chérubin et al., 2005; Oey, 2008). Finally, Le Hénaff et al. (2012) suggest that deep eddies spin up as the LC moves off the Mississippi Fan. How well numerical models predict or simulate deep currents is not well documented owing to sparse observations of circulation below the surface and in particular below the thermocline.

In 2009, a comprehensive field study "Observations and Dynamics of the Loop Current" (DynLoop) was undertaken. Funded by the Bureau of Ocean Energy Management (BOEM), DynLoop aimed to investigate LC circulation dynamics, eddy-shedding mechanisms, and forcing of deep flow. The study utilized an *in situ* mapping array centered in the LC (Fig. 2) that included nine full water column (tall) moorings, seven near-bottom moorings, and 25 pressure sensing inverted echo sounders (PIES). The array provides a unique dataset for studying the LCE cycle: it was centered in the region of LCE formation/separation and during its 30-month deployment observed four LCE events with daily measurements throughout the water column at mesoscale resolution. The dataset from this study provides critical deep-velocity information required for a comprehensive 3D model-data comparison. Hamilton et al. (2016) provides a review of the study.

Through advances in modeling, advanced assimilation techniques, and increased computational power, modern predictive ocean models reproduce surface currents to a high degree of accuracy. One example is the HYbrid Coordinate Ocean Model (HYCOM). Because of the demonstrated application of global- and basin-scale real time ocean predictions, the US Navy has transitioned HYCOM into operational use at the Naval Oceanographic Office (NAVOCEANO; Chassignet et al., 2009; Cummings and Smedstad, 2013; Metzger et al., 2014). The high-resolution 1/25° regional-scale data-assimilative GOM HYCOM has undergone a number of improvements; the current version (at the time of writing), GOMl0.04 expt_31.0 (hereafter HYCOM31.0) is one of the highest resolution and most advanced data-assimilative numerical models available for studies and predictions of GOM circulation. HYCOM31.0 assimilates predominately surface measurements from remotely sensed satellite altimetry and temperature, as well as temperature and salinity profiles, but does not incorporate deep (> 2000 meters) observations. Previous validation of HYCOM includes comparison to other models, satellite SST, SSS (salinity), SSH, and ocean color (Chassignet et al., 2005, 2007, 2009), to satellite-tracked surface drifters (Liu and Weisberg, 2011; Liu et al., 2014), and to airborne profiles of near-surface temperature and 20 °C isotherm depth (Shay et al., 2011). Scott et al. (2010) did compare global HYCOM ocean forecasting systems to a global current meter record dataset that included