On the Formation and Interaction of Cyclonic Eddies with the Loop Current Using NCOM and a Suite of Observations

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Abstract – **The life cycle of cyclonic eddies associated with the Loop Current (LC) evolution is studied using the Navy Coastal Ocean Model, Topex/Poseidon altimetry, and AVHRR images. It is shown that the formation of the cyclones in the western side of the LC is related to its dynamics, with their time of generation in the last stage of the anticyclone shedding from the LC. It is shown that the longest period registered between eddy shedding, between February 1998 and August 1999, is associated with the presence of a large cyclone that remains north of the LC during several months. Using numerical simulations, it is shown that large cyclones develop sporadically in the region and that they block the northward penetration of the LC. The LC is shifted to the east and leaks mass, momentum, and energy through a jet and small anticyclones moving along the slope of the West Florida Shelf, east of the cyclone. The process causes an enlargement of the period between eddy shedding.**

I. INTRODUCTION

The Loop Current (LC) runs into the Gulf of Mexico (GoM) from the Caribbean Sea, penetrates northward, then turns eastward and leaves the GoM through the Southern Straits of Florida (Fig. 1). It transports around 30 Sv [1] and its major characteristic is that sheds big anticyclonic eddies of around 300 km diameter [2]. The anticyclones are generated every 3 to 15 months, with a mean at 9.5 months and a frequency distribution with peaks at 6 and 11 months [3]. They move to the western GoM where they dissipate. In a numerical study using a constant inflow at the Yucatan Strait on a β-plane, Hurlburt and Thompson [4] showed that the LC sheds eddies. This was against the prevailing idea at that time that a decrease in the inflow causes the separation of the eddy. On a diagram of Reynolds number (Re) vs β-Rossby number (R_B), Hurlburt and Thompson [5] showed that there is eddy shedding when Re is relatively large and R_B is low. Pichevin and Nof [6] showed that, in order to conserve momentum, the LC has to pinch off the anticyclones and they have to move to the west to compensate the momentum of the current going eastward through the southern Florida Strait.

In addition, linked to the LC dynamics, relatively small cyclones have been observed. Classified by their location, movement, and size there are three kinds of cyclones linked to the LC. Moving along the edge of the LC are the Loop Current Frontal Eddies (LCFEs) that are commonly observed north of 27°N [7, 8, 9, 10]. These eddies are generated along the edge of the LC and move along its edge in a typical period of several weeks. When the eddies reach the Dry Tortugas region they remain there until the next LCFE "push" them and are advected by the LC through the Southern Straits of Florida. While eddies remain near Dry Tortugas they are named Dry Tortugas eddies [9, 11]. In the western side of the LC, at the last stage of the separation of the big anticyclones from the LC, cyclones are formed, which are named Campeche Bank cyclones. These cyclones remain for several weeks between the Campeche Bank shelf, the recently retracted LC, and the new anticyclone [12].

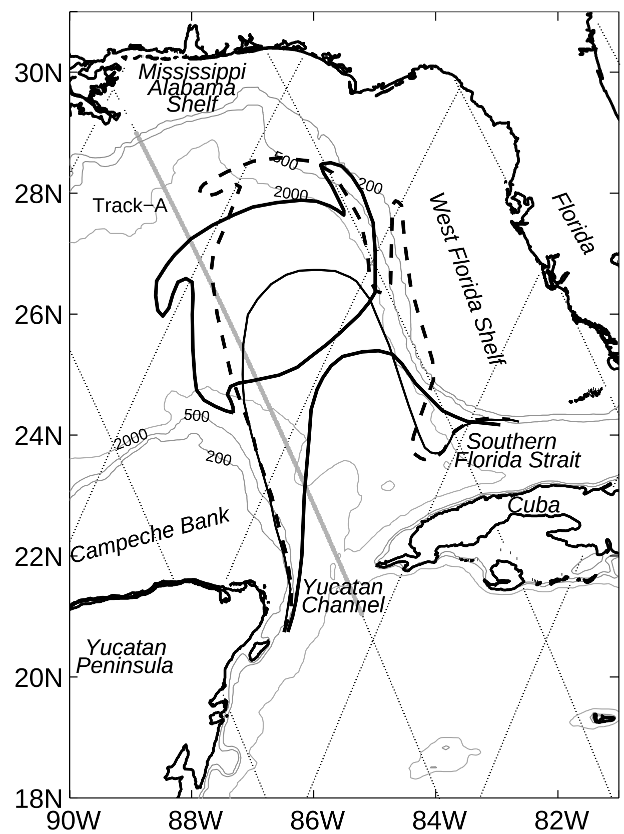

Fig. 1. Schematic evolution of the Loop Current: early stage with thin line, mature stage with dashed line, and after the shedding of an anticyclone with thick line. The TOPEX/Poseidon tracks over the region are shown. The location of Track-A from 21°N to 29°N is highlighted with a thick line.

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In this study we show that in some cases the cyclones, mainly a Campeche Bank cyclone and a Tortugas cyclone, merge forming a relatively big cyclone that blocks the northward penetration of the LC. In order to balance the momentum, the LC leaks a jet and small anticyclones in a narrow region between the big cyclone and the shelf break of the West Florida Shelf (WFS). As a result of these processes the eddy-shedding period becomes larger.

II. RESULTS AND DISCUSSION

A. Observations

The analysis of eddy shedding from the LC for the period 1973 to 1999 [3] show that the largest period between shedding was 17 months, from March 1998 to August 1999. During that period, also a big cyclone remains north of the LC for several months. From the analysis of sea surface temperature images it can be identified that during the last stage of the separation of the February 1998 anticyclone, the edge of the LC develops a meander, separating the edge of the Loop Current from the Campeche Bank slope (Fig. 2). The meander grew since the beginning of January to the end of February, penetrating to the east and developing a Campeche Bank cyclone. When the anticyclone separates from the LC, a cyclone from the eastern side of the LC merges with the one generated in the west forming a bigger cyclone, with the strongest sea surface height (SSH) signal of the Topex/Poseidon (TP) period [13] (Fig. 3).

The merged cyclone remained north of the LC from March to the end of November, which is the largest time for one of these cyclones during the TP history. Due to the location of the TP tracks (see Fig. 1), the zonal extension of the cyclone cannot be identified solely with these data. A product that combines TP and ERS altimeter data show that the big cyclone had a diameter of around 200 km [14] (Fig. 4). Two outstanding characteristics in the 1998 event were the very strong Campeche Bank cyclone and the merging, several weeks later in June, of an independent cyclone that was in the northeast of the Gulf.

B. Model results

Model data from a simulation of the Gulf of Mexico using the Navy Coastal Ocean Model [15] are analyzed. The simulation includes the whole GoM and the western Caribbean Sea from 98.15°W to 80.60°W, and from 15.55°N to 31.50°N, in a 1/20-degree grid, 20 sigma layers uniformly distributed in the upper 100 meters, and 20 z-level layers. Model results show that the formation of these relatively big cyclones happens sporadically. They are formed when a Tortugas eddy, a Campeche Bank eddy, and other cyclones merge in the region. The simulations performed are not long enough to conclude if there is any periodicity on the occurrence of these events.

Like in observations, in model simulations happen that when a big cyclone remains in the region, the time between the shedding of big anticyclones is larger. The presence of the cyclone blocks the penetration to the north of the LC delaying the shedding of the anticyclone. Model results also show that a jet and small anticyclones are ejected in the eastern side (Fig. 5). They move northward between the cyclone and the slope of the WFS. The LC leaks mass, momentum, and energy in this process, which delays the eddy pinch off. A careful analysis of TP data show that there are positive anomalies moving along the slope during the period between big anticyclones shedding in 1998-1999.

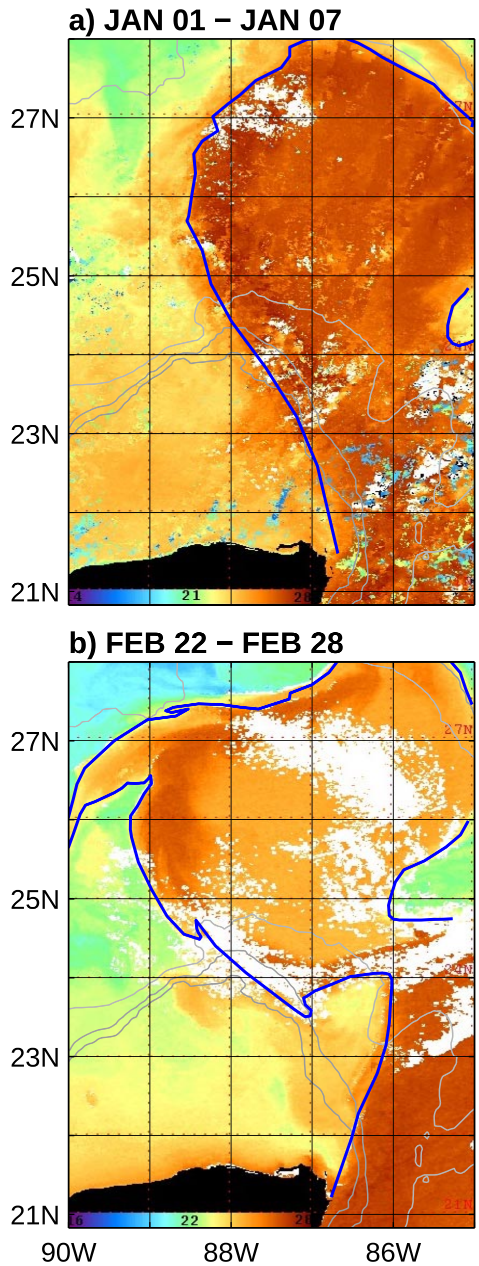

Fig. 2. Evolution of the Loop Current during the formation of a Campeche Bank cyclone from AVHRR sea surface temperature images. Images are from 10-day composites.

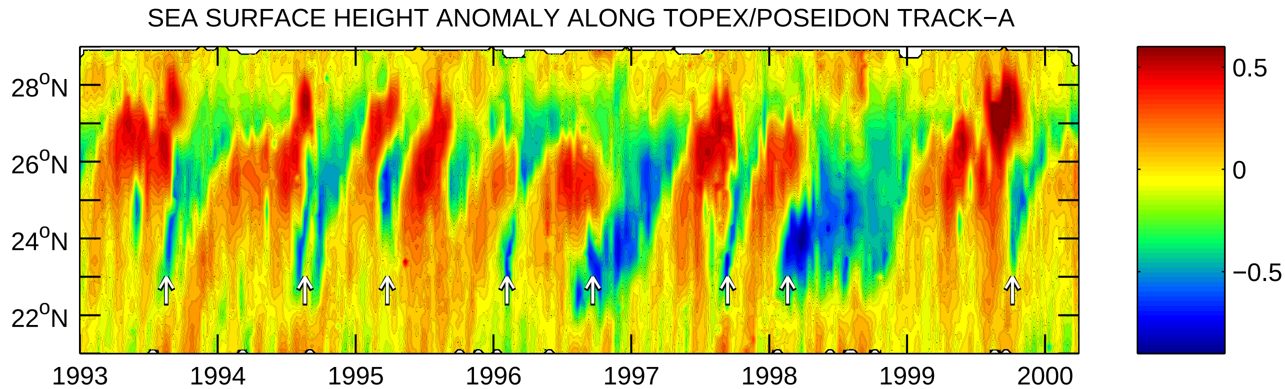

Fig. 3. Sea surface height anomaly along Track-A in meters for the period January 1993 to March 2000. The arrows indicate the periods when the Campeche Bank cyclones can be clearly identified.

The question on how the presence of the blocking cyclone is related with the time between the shedding of big anticyclones can be answered based on the leaking of momentum and mass along the slope of the WFS. Pichevin and Nof [6] have shown that the eddy shedding is a consequence of the momentum conservation principle because the turning to the east of the LC is balanced by the generation of eddies moving to the west. Therefore, by leaking momentum the shedding frequency decreases. An alternative way of measuring the evolution of the LC is by means of the momentum flux including the contribution of the small eddies. In this case, the generation of small anticyclones and the enhancement of the jet are the cause of the longer period between LC eddy pinch off. This is only one of the processes that may modify the periodicity of the LC eddy shedding.

C. Discussion

The jet is developed by an along slope pressure gradient. Analyzing this jet, Hetland et al., [16] showed that the interaction of the LC with the wall generates the jet. Here, it is shown that the cyclone enhances the jet. The mechanism is as follows: In the absence of a blocking cyclone, the LC penetrates to the north with a component to the west. The component to the west reduces the interaction of the LC with the WFS slope, therefore the jet get weaker or vanishes. In addition, often there is a Tortugas eddy between the LC and the WFS that reduces or avoids the interaction of the LC with the slope. This scenario is the more frequently observed. An alternative scenario is when the cyclone blocks the northward penetration of the LC, then it shifts to the east, interacting with the slope, developing a jet and ejecting small anticyclones. After the shedding of a big anticyclone is common that a cyclone remains northwest of the LC but frequently, after few weeks, those cyclones move to the north or along the LC edge into the Dry Tortugas region. It is in the cases that the cyclone remains for a longer period north of the LC when the blocking process develops. Model results and observations suggest that the size of the cyclone is one variable that contributes to determine the time that the cyclone remains in the region, but model results clearly show that the interaction of the cyclone with other eddies and the LC is also important.

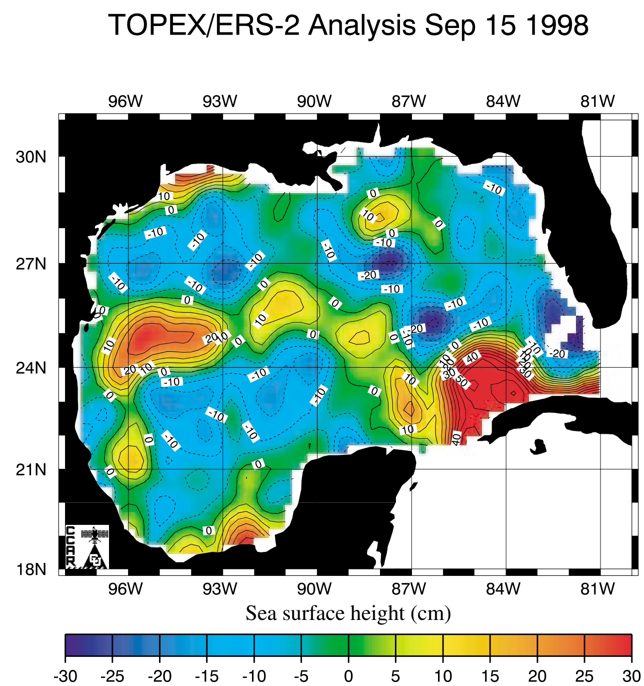

Fig. 4. Sea surface height in September 1998 from a compose using TOPEX/Poseidon and ERS data. The figure was obtained from the public web site of Colorado Center for Astrodynamics Research http://www-ccar.colorado.edu /~realtime/gom-real-time_ssh.

III. CONCLUSIONS

These results help to understand the eddy shedding dynamics of the Loop Current. The largest time between the shedding of LC anticyclones in 1998 is characterized also by the presence of a large cyclone north of the LC. The cyclone blocks the northward penetration of the LC, which shifts to the east and leaks mass, momentum, and energy through a jet and small anticyclones moving along the slope of the WFS, east of the cyclone.

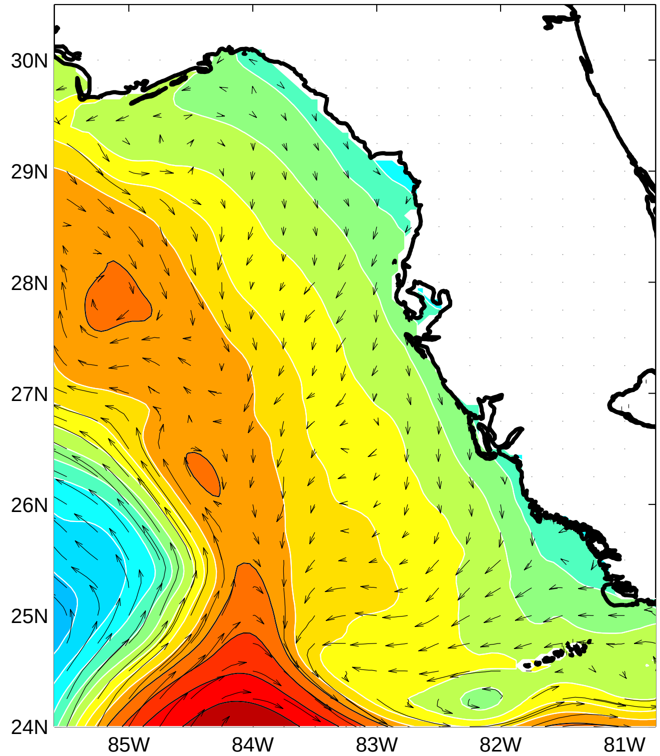

Fig. 5. Sea level and surface velocities from a model simulation. Small anticyclones that are ejected from the Loop Current are associated with high values of sea level. Contours every 0.05 meters, positive contour lines are black and negative are white.

Model simulations show the sporadic formation of big cyclones that remain north of the LC blocking its penetration to the north. When this happens, the time between pinch off of big anticyclones is larger. In addition, the LC expels small anticyclones that move along the shelf break, between the big cyclone and the shelf break of the West Florida Shelf. The momentum flux associated to the jet and the small anticyclones explains the delay in the pinch off, accordingly to Pichevin and Nof [6]. TP-SSH data also show the generation of these jets when a large cyclone was present during 1998.

The evolution of the Loop Current after the pinch off of an anticyclone can be divided in two scenarios. One in which the cyclones in the region after the eddy-shedding remain for few weeks and are removed when the LC penetrates to the north, and the other in which a big cyclone remains longer blocking the northward penetration of the LC. In the first scenario, soon after the pinch off, the LC has a westward movement, Tortugas eddies are formed, and the interaction of the LC with the shelf is weak or null. In the second scenario, the LC shifts to the east, Tortugas eddies are smaller or non-existent, the interaction of the LC with the WFS slope is stronger, a jet is formed along the slope, and small anticyclones are expelled.

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