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On the Loop Current eddy shedding variability

J. ZAVALA-HIDALGO
Centro de Ciencias de la Atmósfera, Universidad Nacional Autónoma de México,
Circuito Exterior, Ciudad Universitaria, México D. F., 04510, México
Corresponding autor: J. Zavala; e-mail: jzavala@atmosfera.unam.mx

S. L. MOREY, J. J. O'BRIEN, L. ZAMUDIO
Center for Ocean-Atmospheric Prediction Studies,
The Florida State University, USA

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RESUMEN

El análisis de observaciones de la penetración hacia el norte de la Corriente del Lazo (CL) y de su área a partir de imágenes satelitales de temperatura superficial del mar, de anomalías de la altura de la superficie del mar del satélite Topex/Poseidon (TP) y de resultados de simulaciones numéricas, muestra que cuando un remolino ciclónico relativamente grande permanece al norte de la CL, el tiempo transcurrido entre el desprendimiento de dos remolinos consecutivos puede incrementarse. Se muestra que la interacción entre la CL y el ciclón produce que la corriente pierda masa y se desplace hacia el escarpe de la plataforma occidental de Florida, donde la masa es también redistribuida debido a la generación de un gradiente de presión y un jet a lo largo del quiebre de la plataforma. Este proceso retrasa la penetración hacia el norte de la CL y el crecimiento de su área, incrementando el tiempo entre el desprendimiento de remolinos. Esto sucedió en 1998, cuando ocurrió el período más largo registrado entre el desprendimiento de remolinos desde 1973, y el ciclón más grande del período de TP estuvo al norte de la CL.

ABSTRACT

Analysis of observations of the Loop Current (LC) northward penetration and LC area, from satellite sea surface temperature, Topex/Poseidon (TP) sea surface height anomaly, and results from numerical simulations shows that when a relatively large cyclone remains north of the LC, the shedding period between two consecutive eddies may increase. It is shown that the interaction between the LC and the cyclone produces leakage of mass from the current and pushes the LC towards the West Florida Shelf escarpment, where mass

is also redistributed due to the generation of a pressure gradient and a jet along the shelf edge. This process delays the northward penetration of the LC and the enlargement of its area, increasing the time between eddy shedding. This happened in 1998, when the largest registered period between eddy shedding since 1973 occurred, and the largest cyclone of the TP era was north of the LC.

Key words: Loop Current, Gulf of México

1. Introduction

The importance of the Loop Current (LC) on the Gulf of México thermodynamics and circulation has been recognized for decades. This current transports around 23 Sv (1 Sv = 10^6 m^3s^{-1}) (Ochoa *et al.*, 2001; Sheinbaum, *et al.*, 2002) and is the main branch feeding the Gulf Stream. It sheds large anticyclonic eddies, known as Loop Current eddies (LCEs), of more than 250 km in diameter and around 800 m in depth, which live for more than a year and move towards the western Gulf where they decay. The LCEs are generated apperiodically with an average shedding time of 9.5 months and range from 3 to 21 months (Fig. 1). The largest period between shedding since 1973 (Sturges and Leben, 2000; Sturges, personal communication) was observed between February 1998 and December 1999. The moment of a LCE separation cannot be determined precisely because the process begins with a closed circulation in the center of the meander while there is still a non-closed circulation at the edge of the current. Often, after an eddy has separated, it reattaches to the LC (Sturges *et al.*, 1993; Sturges and Leben, 2000). Therefore, the separation process may take several days to few weeks.

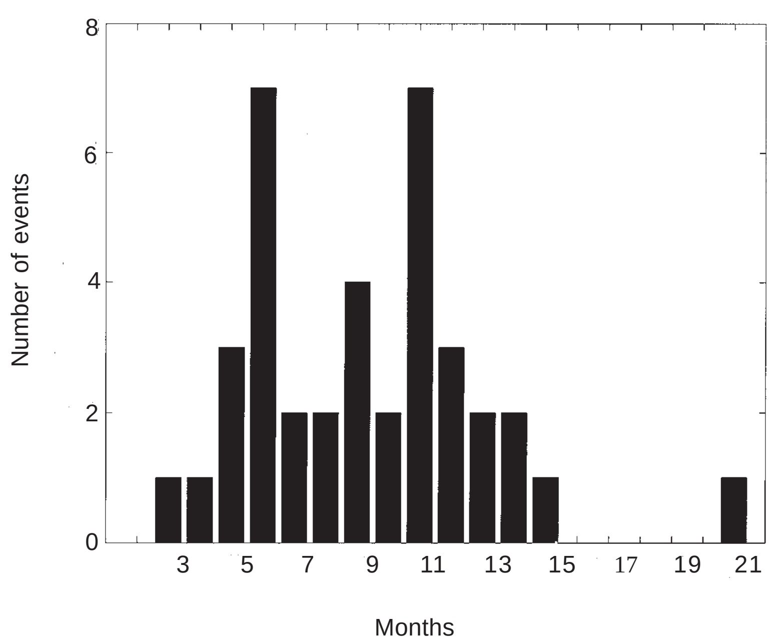

Fig. 1. Distribution of elapsed time between consecutive Loop Current eddy shedding events for July 1973-December 2003. Data from Sturges and Leben (2000) and Sturges, personal communication.

Cyclones have also been observed in the Gulf of México and there is evidence that during the separation of the LCEs, they play a role in the LC hanging, that is, forming a bulge with a constricted neck (Cochrane, 1972; Zavala-Hidalgo *et al*., 2003; Schmitz, in press). Cyclones, like anticyclones, move from the eastern to the northwestern Gulf (Hamilton, 1992). Zavala-Hidalgo *et al*. (2002) suggest that large cyclones may block the LC northward penetration but the mechanism was not specified. In this manuscript it is shown that, when large cyclones are stationary north of the LC, the current leaks water mass along with its dynamical properties. The leaking process may feed the cyclone and/or generate a jet along the West Florida Shelf (WFS) slope and small anticyclonic features. These processes are identified using independent observations and results from numerical simulations with emphasis on the presence of a large long-lived cyclone in the northeastern Gulf during 1998.

2. Observations

The LC has an aperiodic behavior; it penetrates northward, increasing its area, in a process that takes several months until a LCE separates and the LC suddenly losses its core and retreats. Sometimes a LCE reattaches to the LC inducing an abrupt recovery of its northward penetration (Fig. 2). The current typically retreats to a latitude near to 24° 30’ N or 25° 30´ N, which is consistent with the identification of two major regions where the LC neck is constricted (Schmitz, in press). Pichevin and Nof (1997) explained the cycle of the LC as a consequence of its momentum balance by requiring the expulsion of LCEs.

Occasionally, after the shedding of a large eddy, the LC northward penetration and its area remain relatively stagnant, delaying its evolution and the shedding of the next eddy. This happened from March to November 1998 when the largest and longest-lived cyclone of the Topex/Poseidon (TP) era remained north of the LC (Fig. 3), whose northward penetration remained south of 25° 30´ N, with some northward penetration in August 1998. During October, the LC retreated without shedding a large eddy. TP sea surface height (SSH) altimetry data suggest that by November 1998 the cyclone moved northwestward and was identifiable in the central Gulf in March-April 1999, 15 months after its formation east of the Campeche Bank (Zavala-Hidalgo *et al*., 2003). All LCEs are identifiable in the along-track SSH anomaly data while they move across the central Gulf. In these data one can see a relatively small LCE that crossed the central Gulf around September 1995 (Figs. 2, 3), which was registered by Nowlin *et al.* (2001). Altimetry data also show that during August-September positive SSH anomalies were observed along the slope of the WFS and the Mississippi-Alabama-Florida Shelf, which seem to be generated as a consequence of the leaking of the LC.

3. Numerical simulation

To illustrate the interaction of the LC with large cyclones, a case study was chosen from a high resolution numerical simulation of the Gulf of México, without data assimilation, using the Navy Coastal Ocean Model (Morey *et al.*, 2003). During the studied period a large cyclone was located north of the LC. Beginning on model day 2070, particles were seeded along the LC and across the

Yucatán Channel with a constant particle density, so that each particle may be representative of a similar volume of water. The particles were freely advected in the model horizontal velocity field between 95 and 100 m deep, in order to avoid Ekman transport contamination, as was also done for the model upper layer with a similar outcome. Results show that many particles separate from the LC and feed the cyclone (Fig. 4a, b) or move along the WFS slope (Fig. 4c, d). The mass transferred from the LC into the cyclone may contribute to the longevity of the cyclones that remain north of the LC, such as the one formed in 1998. Many of the particles that leave the LC and are captured by the cyclone are those on small cyclonic shingles that move along the edge of the LC. On the other hand, the leakage along the shelf edge is most favorable when the LC edge moves towards the shelf slope developing positive SSH anomalies in the region and a pressure gradient along the slope, a process described by Hetland *et al.* (1999). These results agree with Toner *et al.* (2003) who found entrainment into the 1998 cyclone in a study using SeaWiFS ocean color satellite images and a numerical model with data assimilation.

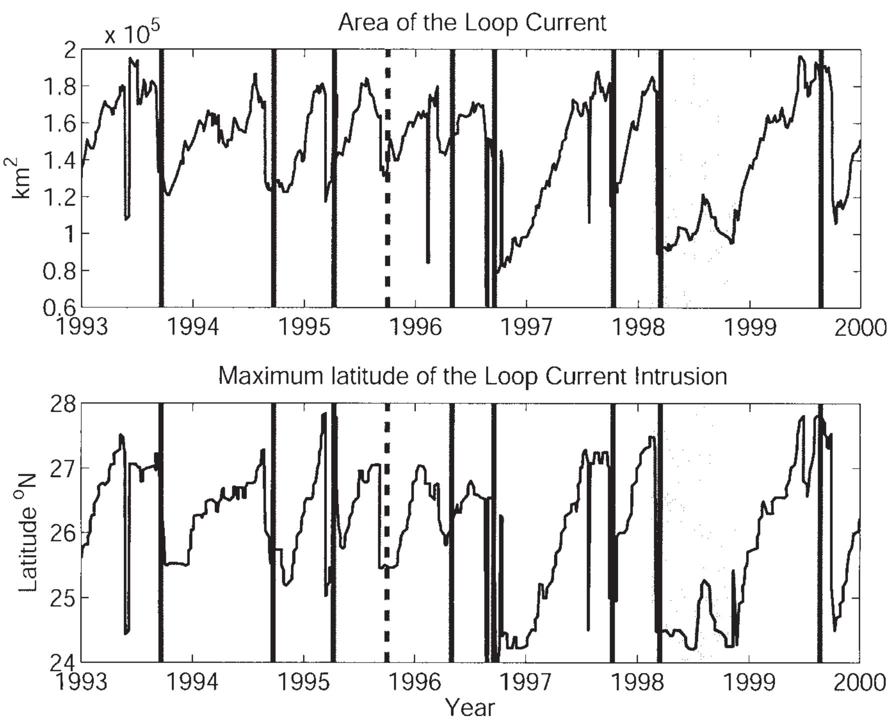

Fig. 2. (Top) Loop Current area, and (Bottom) Loop Current northward penetration. Shaded areas indicate the period when a large cyclone was north to the Loop Current. Thick lines indicate the moment of separation of Loop Current eddies following Sturges and Leben (2000), and the segmented line indicates the separation of an eddy not reported in Sturges and Leben (2000) but registered by Nowlin *et al*. (2001). The figure is adapted from Nowlin *et al*. (2001).

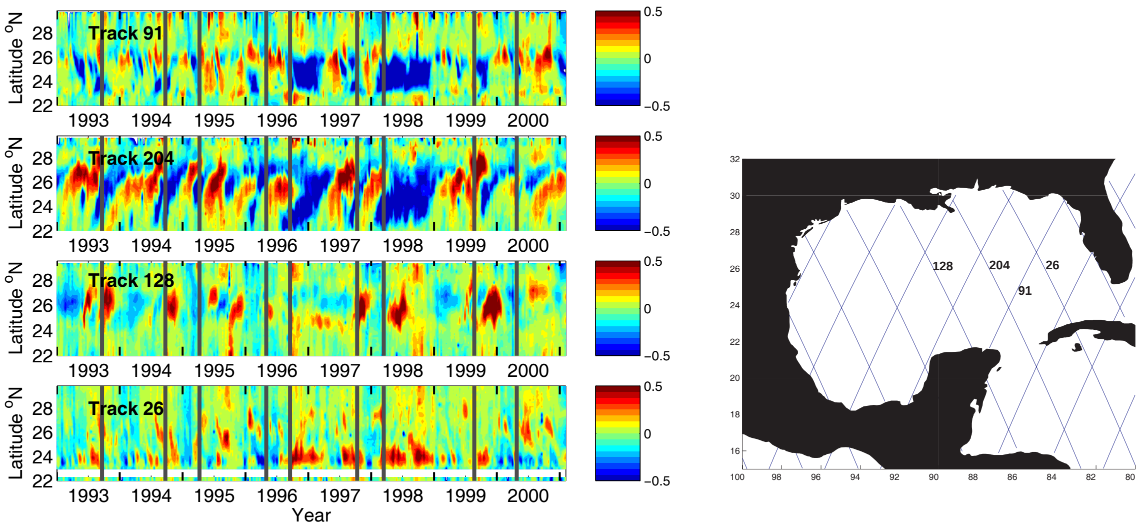

Fig. 3. Sea surface height anomaly along Topex/Poseidon tracks. Thick lines indicate the moment of separation of Loop Current eddies following Sturges and Leben (2000) and Sturges (personal communication). The track locations are indicated in the map.

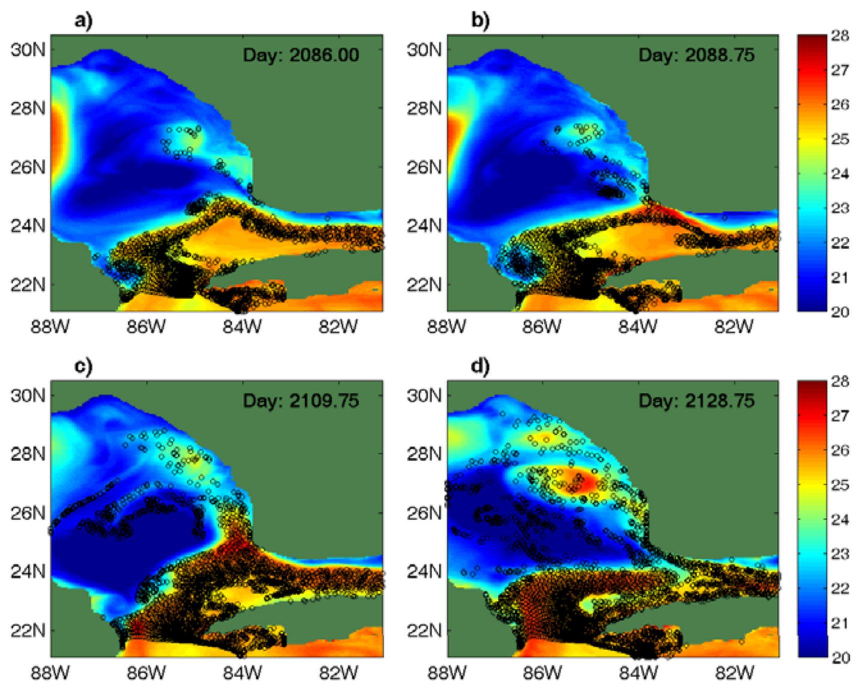

Fig. 4. Synoptic maps of 95-1000 m layer-averaged temperature and particle locations from a Gulf of México numerical simulation using the Navy Coastal Ocean Model. Colors represent temperature in Celsius and black dots represent particles seeded in the Yucatán Channel with a uniform particle density.

4. Discussion

A proposed mechanism by which a large cyclone blocks the LC northward penetration is the following: the LC leaks mass from its cyclonic side, which is captured by the large cyclone; in particular, it captures the small shingles coming along the edge of the Yucatán Current. In addition, the cyclone pushes the LC towards the WFS escarpment, increasing the SSH next to the slope, creating a pressure gradient along the shelf break and a leakage in a northward flowing jet along the slope. The jet eventually forms small anticyclones along the slope. During August-September 1998, a footprint of this process is on the TP SSH along track data (Fig. 3).

The hypothesis that the presence of a large cyclone located north of the LC delays the formation of large LCEs is based on the notion that the LC is more likely to shed a large LCE when its surface extension and northward penetration are large. This statement is based on observations of the LC evolution, model results with simplified dynamics (Hurlburt and Thompson, 1980; Hurlburt, 1986), and idealized analytical models (Pichevin and Nof, 1997). These results do not imply that these processes are the only ones that control the aperiodic evolution of the LC and the LCE shedding. Other contributions may be the vorticity flux through the Yucatán Channel (Candela *et al*., 2002, 2003; Oey *et al*., 2004), Caribbean eddies (Oey *et al*., 2003), and the constriction of the current by cyclones (Cochrane, 1972; Hurlburt, 1986; Zavala-Hidalgo, *et al*., 2003; Schmitz, 2005). The formation of the cyclones and its evolution is strongly associated with the LC itself, which suggest that the system might have some memory and feedback mechanisms that may be investigated.

5. Conclusions

Altimetry observations, numerical simulation results, and LC northward penetration and areal extension analysis show that the LC leaks mass and dynamic properties associated with the water mass, even when no large anticyclonic eddies are shed. Alternative leaking processes are the transfer of mass into a large cyclone, which happens when there is one north of the LC, and the leaking of mass along the slope forming a filament and small anticyclones when the LC interacts with the WFS escarpment. The latter process is also favored by the presence of a large cyclone next to the LC (Fig. 4). These results suggest that the leaking processes delay the northward penetration and area growth of the LC and increase the time between consecutive LCEs shedding. During 1998, positive SSH anomalies were observed along the slope of the WFS and the Mississippi-Alabama-North Florida Shelf (Fig. 3). The anomalies were on the slope area after a slight retreat of the LC and a reduction of its area, which supports the hypothesis that there was mass leaking along this region.

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