International Journal of Remote Sensing, 2013
Vol. 34, No. 14, 5042–5053, http://dx.doi.org/10.1080/01431161.2013.787504

Loop Current excursions and ring detachments during 1993–2009

David Lindo-Atichati[a,b,c]*, Francis Bringas[b], and Gustavo Goni[b]

[a] *Cooperative Institute for Marine and Atmospheric Studies, University of Miami, Miami, FL 33149, USA;* [b] *Atlantic Oceanographic and Meteorological Laboratory, National Oceanic and Atmospheric Administration, Miami, FL 33149, USA;* [c] *Facultad de Ciencias del Mar, Universidad de Las Palmas de Gran Canaria, 35017 Las Palmas de Gran Canaria, Spain*

(*Received 24 July 2012; accepted 15 March 2013*)

Linkages between the variability of Loop Current (LC) surface dynamics, LC ring detachments, and the mean sea height anomaly in the Gulf of Mexico (GOM) are explored using a new methodology that locates the LC fronts and detects the shedding of LC rings. Based on satellite altimetry observations and dynamic height gradient, this methodology allows the determination of the dynamic structure in the region from 1993 to 2009. Northward penetration of the LC was found to be seasonal, with a tendency to increase during the spring and peaking in summer. Whereas northward oscillations exhibit ranges of 4 degrees of latitude, the range of westward oscillations is 6 degrees of longitude. Using the newly developed methodology, 28 LC rings are identified and described during 1993–2009. Starting in 2003, the LC is located more to the north on average, and the average number of LC rings formed per year increases. Since 2003, a significant increase in sea height residuals in the GOM has been observed, exhibiting a linear trend of 2.78 ± 0.26 cm/decade for the period 1993–2009. It is hypothesized here that the increase observed in sea height residuals is linked to the increase in mesoscale activity (LC northward intrusions and number of rings shed) obtained from satellite altimetry observations. Results shown here complement previous observational studies in the region, cover a longer time span, and define objectively the locations of the LC front and the shedding of the rings.

1. Introduction

The mesoscale upper ocean circulation in the Gulf of Mexico (GOM) is characterized by fluctuations of the Loop Current (LC), which irregularly sheds anticyclonic rings that travel in a southwest direction into the GOM. The LC forms an intense anticyclonic flow, which expands northwestward in accordance with Rossby wave dynamics (Hurlburt and Thompson 1980) and can extend northward into the GOM to 28° N, in the vicinity of the shelf break of the West Florida Shelf (WFS) at about 250 km off Mobile Point (Molinari and Mayer 1982). Although northern intrusions of the LC tend to be more frequent in the spring, they may occur in any season with periods varying from 6 to 17 months and an average period of 10 to 11 months (Maul and Vukovich 1993). The large, warm-core anticyclonic rings generally propagate westward at mean translation speeds of approximately 4 km day^{-1} with a standard deviation of 3 km day^{-1} and have mean lifetimes of days to around a year (Vukovich 2007). These rings have radii of about 150 km, may reach depths of

*Corresponding author. Email: dlindo@rsmas.miami.edu

800 m (Oey, Ezer, and Lee 2005), and are generated irregularly but not chaotically (Lugo-Fernandez 2007), with an average shedding period of 11 months and a standard deviation of 4 months (Vukovich 2007). Whereas the frequency of LC ring shedding has been studied by many authors, the mechanism for eddy detachment remains unknown. However, it has been proposed that when the LC grows, the westward Rossby wave speed (which is proportional to βR^2, where β is the meridional variation of the Coriolis force and R is the Rossby radius based on the matured deep Loop) overcomes the growth rate. As a result, the LC becomes an unstable configuration and usually sheds a ring (Nof 2005).

An accurate knowledge of the position and dynamics of main mesoscale ocean features, the LC rings and LC fronts, is critical for a variety of applications: for understanding the environmental conditions that influence the habitat of marine fish larvae (Bakun 2006; Lindo-Atichati et al. 2012); for use in oil spill response; for navigation; for search and rescue operations; for forecasting hurricane intensity (Shay 2010); or for understanding red tide occurrences (Olascoaga 2010).

Satellite altimetry has allowed the monitoring of mesoscale features over the World Ocean since 1993. Altimetry data have helped to better understand the upper ocean dynamics and vertical thermal structure at a spatial and temporal resolution that resolves many ocean mesoscale features and fronts (Le Traon and Dibarboure 1999). Although studies using thermal satellite imagery in the GOM continue to be invaluable due to the excellent spatial resolution of satellite infrared data (starting at 1 km), they may be limited to winter months due to the lack of thermal contrast. Clouds often obscure thermal satellite imagery, making it difficult to locate and track dynamic mesoscale features. For these reasons, satellite altimetry fields, obtained from two or three satellites, are used herein to monitor the mesoscale features in the GOM from January 1993 to December 2009.

The objectives of this article are (1) to monitor and describe the spatial and temporal variability of LC intrusions (northward and westward), LC retreats (southward), and ring detachments, and (2) to infer a possible link between this variability and changes in the upper ocean thermal structure in the GOM. In order to do that, satellite altimetry observations are used in this work to determine the dynamic structure in the region. The temporal and spatial variability of the main mesoscale features in the GOM are addressed here in terms of the northward and westward intrusion of the LC, and by using a characterization of ring-shedding events. The significance of this work lies in (1) the development of a new methodology to objectively define the locations of the LC front and rings, (2) the description of the variability of the LC excursions and ring detachments, and (3) shedding some light on observed linkages between mesoscale activity and the variability in the sea height anomaly in the region.

This article is organized as follows. Section 2 describes the data and methods used in this work. Section 3 presents results and analysis of the variability of the LC and anticyclonic rings in the GOM. Finally, Section 4 summarizes the main findings of this work.

2. Data and methodology

The altimetry data used here are the optimally interpolated gridded sea height anomaly (SHA) fields produced by Archiving, Validation and Interpretation of Satellite Oceanographic (AVISO) data according to an improved objective analysis method (Le Traon, Nadal, and Ducet 1998). These fields have a spatial resolution of 0.25 degrees and temporal resolution of 1 week. The AVISO SHA fields are anomalies computed with respect to the 1993–1999 mean from direct altimetry observations (Rio and Hernandez

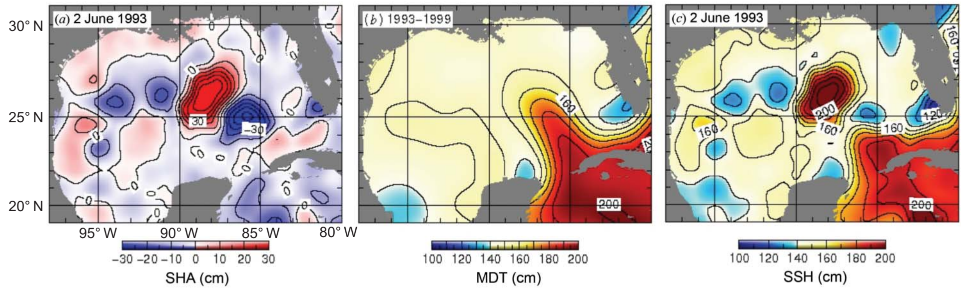

Figure 1. Example of general circulation through the Gulf of Mexico from satellite altimetry fields on 2 June 1993. Fields illustrate the LC and rings shed in terms of (*a*) sea height anomaly (SHA) and (*c*) sea surface height (SSH). SSH fields are obtained by adding (*b*) mean dynamic topography (MDT) to (*a*) SHA fields.

2004). Numerical modelling studies have determined that SHA fields from two independent altimeters are needed to properly position mesoscale features and fronts (Le Traon and Dibarboure 1999), such as those investigated in this work. The altimetric observations used here correspond to T/P, ERS-1/2, GFO, Jason-1, Envisat, and Jason-2 satellites throughout the period January 1993 to December 2009.

The investigation of the dynamics of mesoscale features in the GOM is performed using sea surface height (SSH) fields obtained by adding SHA data to a mean dynamic topography (MDT) of the ocean (Figure 1):

$$\mathrm{SSH} = \mathrm{SHA} + \mathrm{MDT}, \tag{1}$$

where SSH, SHA, and MDT are measured in centimetres.

The LC and ring field are characterized by their anticyclonic motion and SSH values that are larger than those of their surrounding waters (Figure 1(*c*)). Selected contours of constant SSH values are used here to objectively define the locations of the LC front and shedding of the rings.

2.1. LC fronts

The location of the LC front is determined here from the region of maximum horizontal gradient of SSH. Specifically, the northernmost and westernmost locations of the LC are detected from the maximum latitude and longitude of the SSH contours corresponding to the location of the maximum gradient of SSH (Figure 2). The methodology used herein to locate the LC front and its northernmost and westernmost locations consists of the following steps, which are based on a method previously developed to investigate the link between GOM mesoscale features and larval fish distribution (Lindo-Atichati et al. 2012).

(1) The absolute value of the SSH gradient is computed using zonal and meridional derivatives of the SSH field.
(2) The SSH gradient is mapped over the corresponding SSH contour map.
(3) The value of SSH contours corresponding to the location of maximum SSH gradient defines the LC front. To avoid confusion between the LC front and the boundary of a ring, which may also have maximum SSH gradients, the selected SSH contours belonging to a location of maximum SSH gradient must describe an open path.

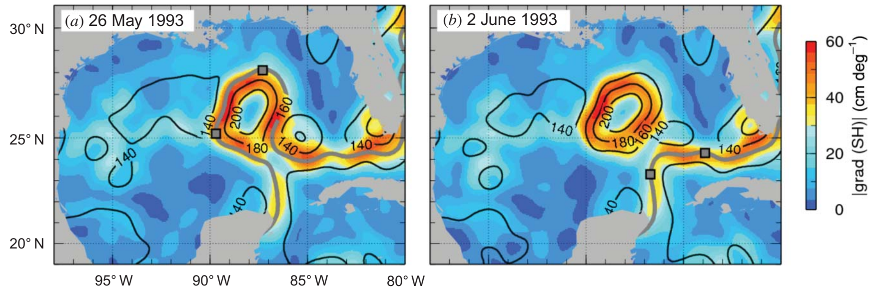

Figure 2. Fields of altimetry-derived SSH gradient in the GOM with contours of SSH (in cm, black lines) superimposed, for (*a*) 26 May 1993 and (*b*) 2 June 1993. Fields illustrate (*a*) the location of the LC front and (*b*) the detection of an LC ring and the LC front. The northernmost and westernmost locations of the LC are tagged with a square in both panels.

(4) The northernmost latitude of these selected contours defines the LC northernmost location.
(5) The westernmost longitude of these selected contours defines the LC westernmost location.

For example, for the GOM conditions on 26 May 1993 (Figure 2(*a*)), the LC northernmost location is 28° N (upper grey square) and the LC westernmost location is 89.75° W (left grey square).

2.2. LC ring shedding

The LC ring-shedding events are also partially detected using the methodology described in Section 2.1. In addition, an LC ring is considered here to be separated from the LC at the surface when the following two conditions are satisfied: (1) when all SSH contours belonging to the region of higher values of SSH gradient exhibit a closed path (Figure 2(*b*)), and (2) when this condition lasts for a period longer than 4 weeks, which is the observed maximum period of time for an LC ring to reattach. The life span of a ring is determined here as the period of time from when the ring is shed until the values of the enclosed dynamic height contours decrease to reach maximum SSH of only 10 cm larger than the mean SSH of surrounding waters – typically between 160 and 140 cm. This value was chosen because it represents the mean standard deviation of SSH of waters west of 90° W.

The results obtained here are compared with those obtained in previous works on LC northward penetration (Zavala-Hidalgo et al. 2006) and ring separation (Sturges and Leben 2000; Alvera-Azcárate, Barth, and Weisberg 2008; Lugo-Fernández and Leben 2010). The fact that rings identified and LC excursions studied in this work are in agreement with the findings of previous studies confirms the consistency of the novel methodology used here, and also supplements results obtained in previous studies. The results shown here are more complete in the sense that they detected more rings than the most recently updated work on the compilation of ring-separation events (Lugo-Fernández and Leben 2010), covered a longer time span, and also helped in defining objectively the locations of the LC front and the shedding of rings.

3. Results and discussion

3.1. Northern and western LC excursions

Weekly time series of the northernmost and westernmost position of the LC during the period November 1992 to December 2009 are presented in Figure 3. These signals are filtered using a Butterworth filter (black lines in Figure 3), which is designed with order 6 and angular cut-off frequency $1/7$ rad s^{-1}, which means that the boundary in the filter response is 7 weeks and the maximum filter slope is 20 degrees $week^{-1}$.

The northernmost location of the LC varies between 24.0° N and 28.5° N, with a mean value (mean ± SD) of (26.5 ± 1)° N and marked seasonal variability (Figure 3(*a*)). The amplitude of the oscillations exhibits maximum values, with meridional motion of 4.0 and 2.5 degrees of latitude for 1993–2003 and 2004–2009, respectively.

Monthly mean values of the LC northward excursions between 1993 and 2009 indicate that the location of the LC in summer (July to August) is significantly more to the north than in the fall season, with winter and spring having values closer to the mean (Figure 4(*a*)). Similar results are found in previous studies; data from 47 cruises in the eastern GOM and monthly fields of temperature at 200 m from 1970 to 1976 have shown that on average, the penetration of the LC into the GOM increases during the winter and spring, reaching a maximum in the early summer (Behringer, Molinari, and Festa 1977). The northward penetration of the LC also exhibits year-to-year variability (Figure 4(*b*)), showing a mean maximum value of 27.5° N and 25.0° N in the annual northernmost location in 2005 and 1998, respectively, and an interannual mean of around 26.3° N. Between 1993 and 2002, the annual mean location of the LC northward penetration was generally to the south of the annual mean location (26.3° N). On the other hand, the annual mean location during 2003–2009 was usually to the north of the mean location, except for 2008 (Figure 4(*b*)). The annual mean location over 1993–1996 (26.2° N) was averaged with that of 1997–2002

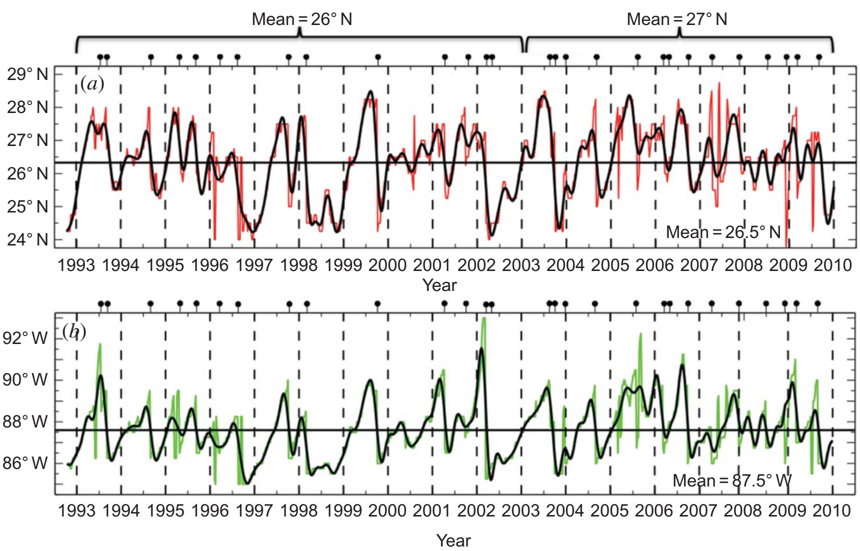

Figure 3. Time series of (*a*) LC northward penetration (red line) and (*b*) LC westward penetration (green line), from November 1992 to December 2009. Black circles indicate the time of separation of LC rings. The signal was filtered using a Butterworth filter of order 6 and cut-off frequency $1/7$ rad s^{-1} (black line).

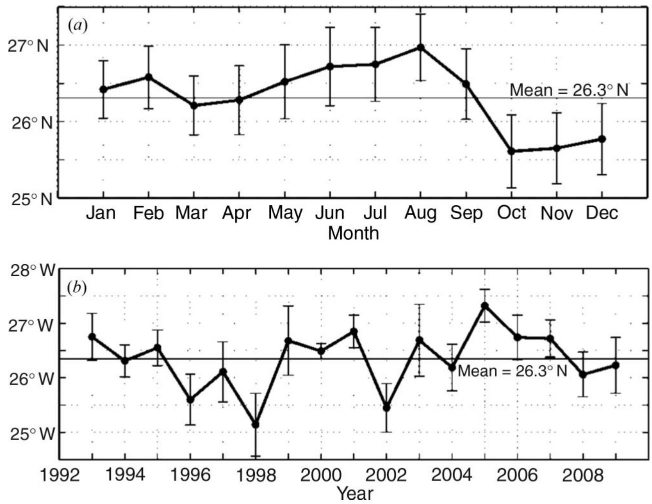

Figure 4. (*a*) Monthly mean location of the LC northward penetration and (*b*) annual mean location of the LC northward penetration. Error bars indicate one standard deviation over the 17 years of data analysed, from January 1993 to December 2009.

(26° N), since both show lower values than the interannual mean LC location. The link between northward excursions and ring formation will be discussed in Section 3.2.

The LC westernmost location oscillates between 91° W and 85° W, with a mean value (mean ± SD) of (87.5 ± 1.0)° W and pronounced seasonal variability (Figure 3(*b*)). The amplitude of the oscillations exhibits maximum values with zonal motion of approximately 6 and 4 degrees of longitude for 1993–2003 and 2004–2009, respectively. No previous studies have reported on the spatial and temporal variability of western LC excursions.

3.2. Ring-shedding events

The location, lifetime, shape, size, kinetic energy, and available potential energy of LC rings can be characterized by undertaking a ring census similar to those carried out in other regions that used observations of infrared imagery (Brown et al. 1986) or a combination of climatological data, *in situ* data, and satellite altimetry (Goni and Johns 2001). Following the methodology described in Section 2, all LC ring-shedding events between November 1992 and December 2009 (black circles in Figures 3(*a*) and (*b*)) are identified and described (Table 1).

A total of 28 rings are identified as having been shed from the LC between November 1992 and December 2009 (Table 1 and Figure 5). The average annual number of rings formed is 1.5, with a standard deviation of 0.7. An increase in annual ring formation is detected beginning in 2003. While from 1993 to 2002 an average annual number of rings of 1.4 was observed, from 2003 this figure rose to 2.0. The average annual number of rings formed during 1993–1996 (1.7) and 1997–2002 (1.2) is lower than for 2003–2009 (2.0). Fourteen out of the 28 rings identified here were shed in the 3 month period from July to September, which is in agreement with the seasonality in the timing of ring shedding suggested in a previous work that monitored ring-detachment events from October 1993 to February 2006 using satellite altimetry observations and a visual methodology for ring determination (Alvera-Azcárate, Barth, and Weisberg 2008). September and August, which

Table 1. Compilation of ring-separation events, including dates of LC ring detachment, inter-detachment periods, dates of extreme LC intrusions (northward or westward), dates of extreme LC retreats (southward), and description of such extreme excursions (intrusions or retreats). Rings were identified using estimates of the gradient of SSH derived from satellite altimetry observations, from January 1993 to December 2009, using the methodology described in Section 2.

Ring	Date	Life span	Extreme LC	Extreme LC retreat	Description
			7 to 14 July		LC intrudes to 92° W
1-93	21 July 1993	5			
2-93	8 September 1993	5			
3-94	31 August 1994	6			
4-95	26 April 1995	5			
5-95	13 September 1995	5			
6-96	20 March 1996	7			
7-96	21 August 1996	9			
				4 to 25 December	LC retreats to 24° N
8-97	24 September 1997	10			
9-98	4 March 1998	11			
			23 June to 22 September		LC intrudes to 28° N
10-99	29 September 1999	12			
11-01	11 April 2001	7			
12-01	21 September 2001	7			
			20 February to 6 March		LC intrudes to 93° W
13-02	13 March 2002	1			
14-02	17 April 2002	11		3 to 17 April	LC retreats to 24° N
			7 May to 13 August		LC intrudes to 28° N
15-03	20 August 2003	4			
16-03	24 September 2003	10			
17-03	24 December 2003	8			
18-04	1 September 2004	11			
			13 April to 29 June		LC intrudes to 28° N
19-05	3 August 2005	9			
20-06	8 March 2006	2			
21-06	19 April 2006	5			
			9 to 23 August		LC intrudes to 91° W
22-06	27 September 2006	12			
23-07	11 April 2007	4			
24-07	14 November 2007	6			
25-08	2 July 2008	8			
26-08	3 December 2008	2			
			11 to 25 February		LC intrudes to 91° W
27-09	4 March 2009	8			
28-09	2 September 2009	7			

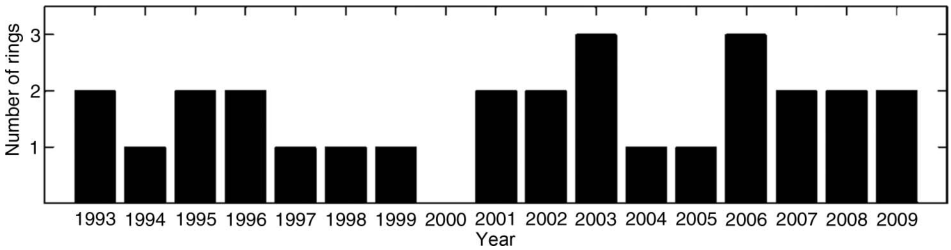

Figure 5. Number of LC rings shed during each year, from January 1993 to December 2009, as obtained according to the methodology described in Section 2.

are the months seeing most LC intrusions to the north, are also the months exhibiting more ring-separation events. There were no ring-separation events identified during the months of January, May, and June from November 1992 to December 2009. The average period between consecutive LC ring detachments is approximately 9 months for 1993–2003 with a standard deviation of 6 months, which also is in agreement with the 8.2 month period suggested by other authors (Alvera-Azcárate, Barth, and Weisberg 2008). The average period between consecutive LC ring detachments, and its variability, declined between 2004 and 2009, exhibiting average periods between consecutive shedding of 6 months with a standard deviation of 1 month. This observed seasonal preference for the LC to shed rings has recently been described as a combination of seasonal winds in the Caribbean Sea and the GOM (Chang and Oey 2012).

If results from the present ring census are compared to previous relevant work in the GOM region (Sturges and Leben 2000; Leben 2005; Alvera-Azcárate, Barth, and Weisberg 2008; Lugo-Fernández and Leben 2010), some similarities are found in the main results discussed above. The present census shows 10 ring-separation events between 1993 and 1999, the same LC ring detachments as reported by a previous work (Sturges and Leben 2000). When results from November 1992 to March 2006 are compared to results from a recent work on the compilation of ring-separation events (Alvera-Azcárate, Barth, and Weisberg 2008), the present census shows 20 events as opposed to the 21 reported by that study. Specifically, this difference is due to the fact that the ring shed on 24 September 2003 was not detected by previous authors, and those shed on 1 September 1999 and 10 May 2000 were detected neither by our team nor other teams (Leben 2005; Lugo-Fernández and Leben 2010). The main reason for this discrepancy may be differences in criteria used to determine ring-shedding events. The ring reportedly shed on 1 September 1999 (Alvera-Azcárate, Barth, and Weisberg 2008) had a lifetime inferior of under one month and did not satisfy the second condition imposed in our method – the detection of rings lasting longer than 4 weeks, the observed maximum period of time for an LC ring to reattach. This ring was not reported by other studies either (Leben 2005; Lugo-Fernández and Leben 2010), and possibly was not totally detached. The ring reportedly shed on 10 May 2000 (Alvera-Azcárate, Barth, and Weisberg 2008) did not satisfy the first condition of our method – SSH contours belonging to the region of higher values of SSH gradient must describe a closed path. This ring was not reported by some other studies either (Leben 2005; Lugo-Fernández and Leben 2010), since it did not satisfy the objective criteria of breaking of the 17 cm contour (Leben 2005). Results from July 1993 to March 2009 were compared to results from a more updated work on the compilation of ring-separation events (Lugo-Fernández and Leben 2010). From July 1993 to March 2009, the present census shows 27 ring-separation events while 26 such events were reported by previous work over the same period. This discrepancy is due to the fact that these authors did not report the ring shed on 24 September 2003, likely because the 17 cm contour criterion alone – without using the information provided by SSH gradient – was not sufficient to define the ring as being detached.

When LC excursions are linked to ring-formation events, it is observed that in 70% of the cases, the separation of the LC rings (circles in Figure 3(*a*)) occurs when the northernmost location exceeds 27° N (approximately 1° N of its mean location), with separation events happening at a frequency ranging from 2 to 18 months. Conversely, when the LC is located to the south for long periods of time, few or no rings are detached (Alvera-Azcárate, Barth, and Weisberg 2008), which was also observed in 1997, 1998, and 2002 (Figure 3(*a*)). From 1993 to 2005, the mean retreat latitude was 26.2° N and the mean separation period was 8 months. From 2005 to 2009, the mean retreat latitude increased to 26.7° N and the mean separation period decreased to 5 months. A correlation between the retreat latitude of the LC and the ring-separation period was reported by a previous study (Leben 2005), and this is still valid in our observations. The maximum number of ring sheddings detected is for 2003: three rings were shed after extreme northward intrusion of the LC to 28° N during the spring and summer months and after a long period of 17 months with no shedding (Figures 3(*a*) and 5).

3.3. Sea height residuals and upper ocean thermal structure

Sea surface height anomalies are strongly related to the internal thermal structure of the ocean. A higher SSH than normal corresponds to a deep layer of very warm water. Depending on many factors, such as the vertical stratification and the dynamic processes involved, the relationship between selected isotherms (such as the depth of the 20°C isotherm, which usually lies within the thermocline waters in most tropical regions) and the SSH can be readily estimated from altimeter-derived SHA, in combination with *in situ* and climatological hydrographical observations. In general, variations in the depth of the main thermocline can be associated with variations in the SHA field (Willis, Roemmich, and Cornuelle 2004). Given the strong relationship that exists between SHA and the thermal structure of the ocean, it is hypothesized from our results that the observed increase in mean SHA in the GOM from 1992 to 2009, especially marked starting in 2000, is linked to increased mesoscale activity in the region shown in this work through variations in the thermal structure of the GOM. We shed some light here on this hypothesis, which may become a topic for future studies.

Our results regarding the northern LC excursions and the marked increase in ring formation beginning in 2003 are reflected in an increase in monthly sea height residuals (SHRs) over the entire GOM, estimated as the difference between the mean sea height anomaly for each specific month and that for the same month since November 1992. These residuals are estimated as the difference between mean SHAs for each specific month and that for the same month since November 1992. A positive linear trend in the monthly SHR is found (Figure 6), where SHR exhibits an increase of 2.8 ± 0.3 cm decade^{-1} from November 1992 to December 2009, which is statistically significant ($r = 0.6$, p-value < 0.0001). In addition to this, 80% of negative SHR and 20% of positive SHR values are observed between December 1992 and December 1999, and conversely 15% of negative SHR and 85% of positive SHR values are observed between January 2000 and December 2009. It is suggested here that higher mean SHA values for the GOM starting in 2000 may be related to the increase in mean LC northward intrusions and the increase in number of rings shed

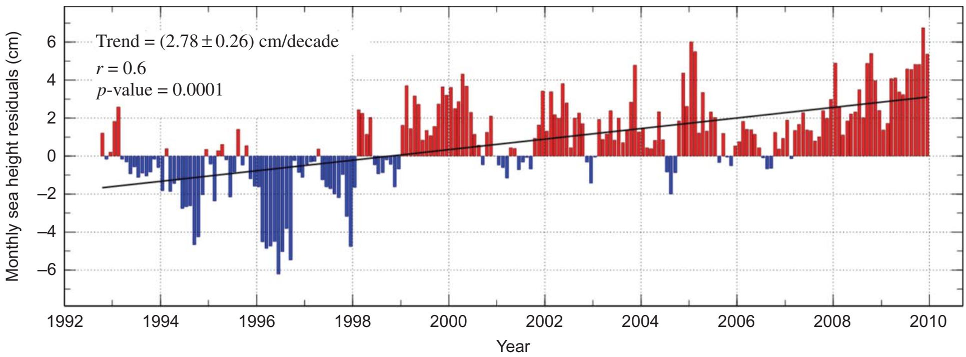

Figure 6. Monthly sea height residuals (SHR), estimated as the difference between the mean SHA for each specific month and the mean SHA value for that same month since November 1992. The black line indicates a mean SHR increase of 2.78 cm per decade over the 17 years of data analysed.

starting in 2003 (Section 3.2). The analysis provided here is carried out for long, interannual time scales and therefore does not apply to individual year comparisons. The amplitude of the meridional excursions of the LC decreased from mean meridional motion of 4.0 degrees of latitude for 1993–2003 to 2.5 degrees for 2004–2009 (Section 3.1). This shorter amplitude of meridional excursions of the LC, together with an LC generally more to the north starting in 2003, may also be partially associated with the higher mean SHA values found for the GOM for 2000–2009.

4. Conclusions

Satellite altimetry fields were used to identify mesoscale features in the GOM for the period 1993–2009. The key findings from this work are that (1) starting in 2003, the LC was located more to the north (Figures 3 and 4(*b*)) and (2) there was an increase in the average number of rings shed from the LC (Figure 5). Consequently, beginning in 2003, the mean location of the LC northward penetration was 27° N, or 1.5 degrees of latitude above the interannual mean, and approximately 2.0 rings were formed per year. In contrast, for 1993–2002, only 1.4 rings were formed per year. The range of meridional oscillations of the LC exhibits maximum values with meridional motion of 4.0 degrees of latitude for 1993–2003 and 2.5 for 2004–2009. The range of zonal oscillations of the LC exhibits maximum values with zonal motion of approximately 6.0 degrees of longitude for 1993–2003, and 4.0 degrees for 2004–2009. The higher mesoscale activity observed for 2003–2009 may have a measurable impact on mean SHA in the GOM, showing positive SHR for 2000–2009. On the other hand, LC northward penetration appears to be mostly seasonal (Figure 4(*a*)), with maximum values of 0.8 degrees of latitude above the annual mean during June, July, and August, in accord with previous studies (Behringer, Molinari, and Festa 1977; Blumberg and Mellor 1985; Maul and Vukovich 1993). However, the mean northward penetration of the LC is highly variable from year to year (Figure 4(*b*)).

This work also identified LC rings using a similar method to that developed here to identify LC fronts. Half of the rings identified here were shed in the 3 month period from July to September. September and August are the months exhibiting the most ring-separation events (7 and 4, respectively).

Monthly sea height residuals – estimated as the difference between the mean sea height anomaly for each specific month and that for the same month since November

1992 – exhibit a significant linear trend of 2.78 ± 0.26 cm per decade for 1993–2009. It is hypothesized here that the increase in sea height anomaly residuals might be linked to the observed increase in mesoscale activity in the region for the same period, although this significant positive trend could be part of a longer-period signal. The increase in the sea height anomaly residuals could also be partly related to the phenomenon of hysteresis. Evidence of possible links between increase in sea height anomaly residuals and increase in mesoscale activity in the GOM are presented in this work. However, more studies will be needed, in particular involving numerical modelling, to confirm these results.

This study provides updated statistics on LC and ring variability (position and number) using a newly developed methodology. By covering a greater time span and defining objectively the locations of the LC front and the shedding of rings, the results discussed here complement previous studies that report ring detachments and LC excursions in the GOM. In addition, this work also highlights the importance of multimission, eddy-permitting, satellite altimetry observations.

Acknowledgements

The altimeter products were produced by Ssalto/Duacs (Segment sol multimissions d'Altimétrie, d'Orbitographie et de localisation précise/Developing Use of Altimetry for Climate Studies) and distributed by AVISO, with support from Centre National d'Etudes Spatiales (CNES). The authors are grateful to P. Sangra and A. Lugo-Fernandez, and to Elizabeth Johns and Sang-Ki Lee from the NOAA/Atlantic Oceanographic and Meteorological Laboratory (AOML) for providing suggestions and comments that have improved the article. This work was supported by NOAA/AOML.

References

Alvera-Azcárate, A., A. Barth, and R. H. Weisberg. 2008. "The Surface Circulation of the Caribbean Sea and the Gulf of Mexico as Inferred from Satellite Altimetry." *Journal of Physical Oceanography* 39: 640–657.

Bakun, A. 2006. "Fronts and Eddies as Key Structures in Habitat of Marine Fish Larvae: Opportunity, Adaptive Response and Competitive Advantage." *Scientia Marina* 70: 105–122.

Behringer, D. W., R. L. Molinari, and J. F. Festa. 1977. "The Variability of Anticyclonic Current Patterns in the Gulf of Mexico." *Journal of Geophysical Research* 82: 5469–5476.

Blumberg, A. F., and G. L. Mellor. 1985. "A Simulation of the Circulation in the Gulf of Mexico." *Israel Journal of Earth Sciences* 34: 122–144.

Brown, O. B., P. C. Cornillon, S. R. Emmerson, and H. M. Carle. 1986. "Gulf Stream Warm Rings: A Statistical Study of Their Behaviour." *Deep-Sea Research* 33: 1459–1473.

Chang, Y.-L., and L.-Y. Oey. 2012. "Why Does the Loop Current Tend to Shed More Eddies in Summer and Winter?" *Geophysical Research Letters* 39: L05605. doi:10.1029/2011GL050773.

Goni, G. J., and W. E. Johns. 2001. "A Census of North Brazil Current Rings Observed from T/P Altimetry: 1992–1998." *Geophysical Research Letters* 28: 1–4.

Hurlburt, H. E., and J. D. Thompson. 1980. "A Numerical Study of Loop Current Intrusions and Eddy Shedding." *Journal of Physical Oceanography* 10: 1611–1651.

Le Traon, P. Y., and G. Dibarboure. 1999. "Mesoscale Mapping Capabilities from Multiple-Satellite Altimeter Missions." *Journal of Atmospheric and Oceanic Technology* 16: 1208–1223.

Le Traon, P. Y., F. Nadal, and N. Ducet. 1998. "An Improved Mapping Method of Multi-Satellite Altimeter Data." *Journal of Atmospheric and Oceanic Technology* 15: 522–534.

Leben, R. R. 2005. "Altimeter-Derived Loop Current Metrics. Circulation of the Gulf of Mexico: Observations and Models." In *Circulation in the Gulf of Mexico: Observations and Models*, edited by W. Sturges and A. Lugo-Fernandez, 181–202. Washington, DC: American Geophysical Union.

Lindo-Atichati, D., F. Bringas, G. Goni, B. Muhling, F. E. Muller-Karger, and S. Habtes. 2012. "Varying Mesoscale Structures Influence Larval Fish Distribution in the Northern Gulf of Mexico." *Marine, Ecology, Progress, Series* 463: 245–257.

Lugo-Fernández, A. 2007. "Is the Loop Current a Chaotic Oscillator?" *Journal of Physical Oceanography* 37: 1455–1469.
Lugo-Fernández, A., and R. Leben. 2010. "On the Linear Relationship Between Loop Current Retreat Latitude and Eddy Separation Period." *Journal of Physical Oceanography* 40: 2778–2784.
Maul, G. A., and F. M. Vukovich. 1993. "The Relationship Between Variations in the Gulf of Mexico Loop Current and Straits of Florida Volume Transport." *Journal of Physical Oceanography* 23: 785–796.
Molinari, R. L., and D. A. Mayer. 1982. "Current Meter Observations on the Continental Slope at Two Sites in the Eastern Gulf of Mexico." *Journal of Physical Oceanography* 12: 1480–1492.
Nof, D. 2005. "The Momentum Imbalance Paradox Revisited." *Journal of Physical Oceanography* 35: 1928–1939.
Oey, L.-Y., T. Ezer, and H. C. Lee. 2005. "Loop Current, Rings and Related Circulation in the Gulf of Mexico: A Review of Numerical Models and Future Challenges." In *Circulation in the Gulf of Mexico: Observations and Models*, edited by W. Sturges and A. Lugo-Fernandez, 31–56. Washington, DC: American Geophysical Union.
Olascoaga, M. J. 2010. "Isolation on the West Florida Shelf with Implication for Red Tides and Pollutant Dispersal in the Gulf of Mexico." *Nonlinear Processes in Geophysics* 17: 685–696.
Rio, M.-H., and F. Hernandez. 2004. "A Mean Dynamic Topography Computed over the World Ocean from Altimetry, in situ Measurements, and a Geoid Model." *Journal of Geophysical Research* 109: C12032. doi:10.1029/2003JC002226.
Shay, L. K. 2010. "Air-Sea Interactions in Tropical Cyclones (Chapter 3)." In *Global Perspectives of Tropical Cyclones*, edited by J. C. Chan and J. D. Kepert, 93–132. London: World Scientific Publishing Company: Earth System Science Publication Series.
Sturges, W., and R. Leben. 2000. "Frequency of Ring Separations from the Loop Current in the Gulf of Mexico: A Revised Estimate." *Journal of Physical Oceanography* 30: 1814–1819.
Vukovich, F. M. 2007. "Climatology of Ocean Features in the Gulf of Mexico Using Satellite Remote Sensing Data." *Journal of Physical Oceanography* 37: 689–707.
Willis, J. K., D. Roemmich, and B. Cornuelle. 2004. "Interannual Variability in Upper Ocean Heat Content, Temperature, and Thermosteric Expansion on Global Scales." *Journal of Geophysical Research* 109: C12036. doi:10.1029/2003JC002260.
Zavala-Hidalgo, J., S. L. Morey, J. J. O'brien, and L. Zamudio. 2006. "On the Loop Current Eddy Shedding Variability." *Atmosfera* 19: 41–48.