C3.4 INFLUENCE OF LOOP CURRENT OCEAN HEAT CONTENT ON HURRICANES KATRINA, RITA, AND WILMA

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1. INTRODUCTION

Ocean heat content (OHC) relative to the 26°C isotherm plays an important role during sudden hurricane intensification when atmospheric conditions are favorable [*Shay et al.*, 2000; *Shay*, 2006]. In the Gulf of Mexico, the Loop Current is a heat conveyor that builds a heat reservoir spanning 200-300 kilometers in diameter and 80-150 meters in depth. The reservoir takes the form of a ring (warm core ring, WCR) and separates from the Loop Current transporting heat into the Gulf interior (Figure 1). The Loop Current (LC) is strongly variable in time with recurrent ring shedding events at peak periods from 6 to 11 months [*Sturges and Leben*, 2000].

Recent theoretical developments and realistic numerical simulations suggest that the LC cycle can be explained in terms of the momentum imbalance paradox theory [*Pichevin and Nof*, 1997; *Nof and Pichevin*, 2001; *Nof*, 2005], which predicts that, in the β–plane, when a northward-propagating anomalous density current (the Yucatan Current) flows into an open basin (the Gulf of Mexico) with a coast on its right (Cuba) the outflow balloons near its source forming an anticyclonic bulge (LC) because the outflow cannot balance the along-shelf momentum flux after turning eastward. Thus the ballooning of the current (ring formation) is a necessary condition to satisfy the balance of momentum flux along the northern coast of Cuba.

The momentum imbalance paradox mechanism can be divided in two steps. The first step is the ballooning of the current, when 66% of the outflow mass flux goes into the bulge and the remaining 33% goes into the downstream current. The second step is the separation of the ring by the β and/or topographic effects [*Nof*, 2005; *Chérubin et al.*, 2005], when 80% of the inflow goes into the downstream current and 20% into an incipient new ring [*Nof and Pichevin*, 2001]. This theoretical approach predicts a mass partition that has been observed during ring shedding in a realistic simulation of the North Atlantic, which includes the Gulf of Mexico [*Chérubin et al.*, 2005]. The mass partition has a profound impact on the oceanic heat content within the Gulf, since up to 66% of the warm water coming from the Caribbean may enter the Loop Current bulge during about 100 ring-growth days before ring shedding events [*Nof and Pichevin*, 2001].

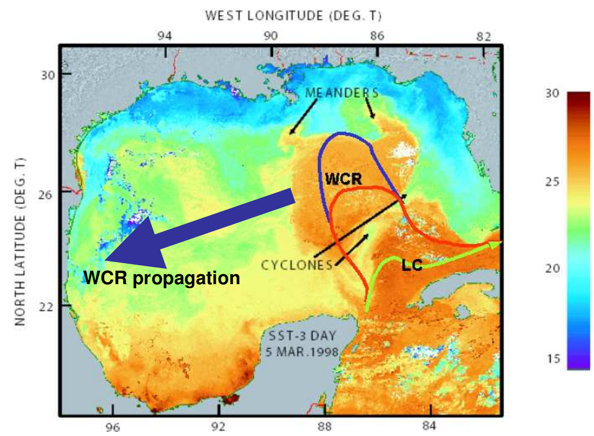

Figure 1: The Loop Current cycle consists of an extensive northwestward intrusion (blue) followed by the shedding of a mesoscale anticyclonic warm core ring (WCR), and the return to the so called port-to-port configuration (green). The approximated mean current position is in red [Adapted from Schmitz, 2002].

Satellite-based radar altimetry measurements showed that prior to Katrina, the LC reached its maximum northward penetration, and a mature WCR was about to separate from the parent current. The WCR detached on September 20-27, the time span when Rita passed on the shedding region. Finally, the Loop Current was retracting to a port-to-port position when Wilma passed over the current. Katrina, Rita, and Wilma rapidly intensified to major hurricanes on LC

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waters with high oceanic heat content (category 5, 5, and 3 respectively), even under unfavorable atmospheric conditions (Wilma on her way to South Florida after leaving the Peninsula of Yucatan).

Given the importance of the warm waters in the LC system on rapid hurricane intensification, measurements acquired from the deployment of airborne probes in the LC complex are used together with satellite-based measurements to describe the separation of a LC ring simultaneous to the passage of Katrina, Rita, and Wilma, and to discuss the effects of the ring separation on oceanic heat content in the eastern Gulf of Mexico and its implication on intensity changes in these record-breaking hurricanes.

It is shown that the ballooning of the LC –ring genesis process– built a large reservoir of oceanic heat that was available during the passage of Katrina, Rita, and Wilma. Shear-induced mixing in the deep layers does not significantly cool the upper ocean, and horizontal advection of thermal structure play an important role in replenishing the heat of the upper ocean. The development of cold-core rings (CCR) along the LC rim during ring separation affected Rita intensity, since she encountered one CCR prior to landfall, which was juxtaposed with an eyewall replacement cycle that contributed to her weakening from category five to three. Therefore, understanding the LC cycle is an important part for hurricanes entering the Gulf of Mexico during the summer months and for hurricane intensity forecasting (*Mainelli et al.*, 2006).

2. THE LOOP CURRENT CYCLE AND OHC VARIABILITY IN THE GULF OF MEXICO

The LC cycle suggests a tendency of the area-averaged thickness of the layer with waters warmer than 26°C in the eastern Gulf of Mexico (93-81°W, 22-28.5°N) (Figure 2a). The depth of the 26°C isotherm is inferred from surface height anomaly from radar altimetry as in *Shay et al.* [2000]. By yearday 80 the LC starts to balloon as warmer subtropical water from the Caribbean Sea is entrained into the incipient WCR; the thickness of the layer warmer than 26°C grows gradually and by yearday 200 the ring has matured and is about to separate (step 1 of the momentum imbalance paradox mechanism). Hurricane-induced cooling due to the passage of Katrina and Rita is negligible since the large-scale tendency is for the LC to deepen as the shedding is in progress. Using gridded profiles from airborne profilers, *Uhlhorn and Shay* [2004], and *Shay* [2006] reported less negative feedback in the LC during the passage of Isidore and Lili (2002) since advection of deep, warm thermal gradients by the current of ~1.5 m s^{-1} caused minimal SST decreases and OHC losses.

The maximum layer thickness warmer than 26°C (day 270, Figure 2a) represents the culmination of the ring separation sequence and marks the beginning of the LC retraction. Wilma encounters the LC as the thickness of the >26°C layer is fluctuating since the warmer water is advected mostly to the Florida Straits rather than being incorporated into a new bulge (step 2 of the momentum imbalance paradox mechanism).

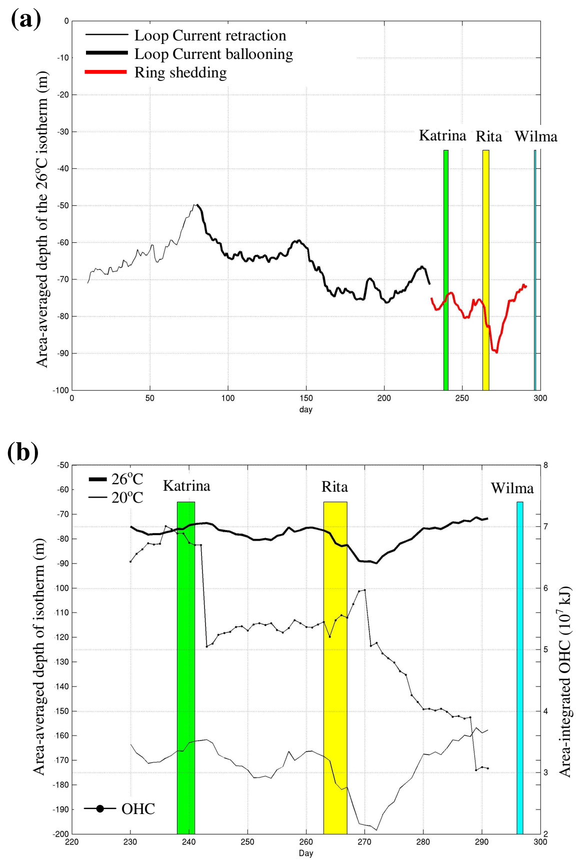

Figure 2: The Loop Current cycle from radar altimetry. (a) Area-averaged depth of the 26°C isotherm (93-81°W, 22-28.5°N) as inferred from surface height anomaly from radar-altimetry in combination with a two-layer model and a seasonal climatology [*Shay et al.*, 2000]. (b) Same as (a) but including area-integrated OHC and area-averaged depth of the 20°C isotherm for the ring shedding days.

Figure 2b shows a significant increase in OHC during the culmination of the ring separation sequence and, from that point, the OHC decreases as the thickness of the layer >26°C due to the LC retraction towards the Yucatan Straits. The amplitude of the fluctuation in the 20°C isotherm is larger than that of the 26°C isotherm. Since the two layers return to a layer thickness comparable to that before the ring separation, the plot suggest that more available potential energy was released on the 20°C isotherm, which supports the hypothesis of bottom-intensified baroclinic instabilities during shedding events [*Chérubin et al.*, 2005].

3. IMPACT OF THE RING SHEDDING ON STORM INTENSITY

Chérubin et al. [2005] showed that the development of cyclones in the periphery of the LC are the result of the growth of a vortex rim instability due to the sudden and rapid deepening of the active layer underneath the LC during shedding events. They argued that the cyclones contribute to the separation of the WCR from the parent current by enhancing the westward drift of the ring. The remote control mechanism of the separation process, however, remains the β effect [*Hurlburt and Thompson*, 1980; *Chérubin et al.*, 2005; *Nof*, 2005].

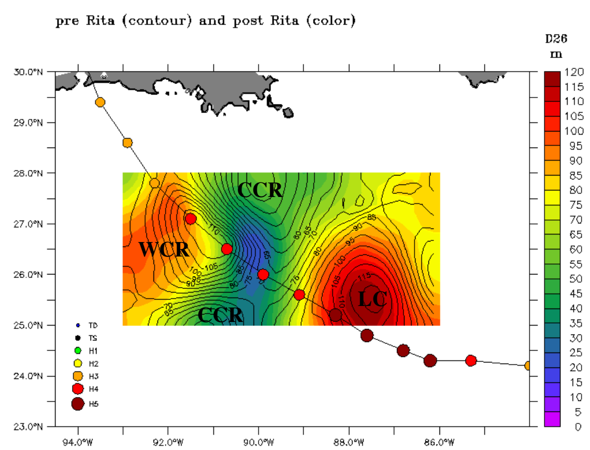

Figure 3. Pre-storm (contours) and post-storm (color) 26°C isotherm depth calculated from data acquired by deploying airborne expendable current, temperature and salinity profilers in LC and WCR waters. The line with circles is the Rita best track.

As shown in Figure 3, objectively analyzed [*Mariano and Brown,* 1992] 26°C isotherm depth calculated from data collected by deploying airborne expendable current, temperature and salinity profilers in LC and WCR waters before and after Rita [*Shay*, 2006]. Before Rita (15 Sep), two cyclones (CCR) are observed between the LC and the WCR. Eleven days later (26 Sep), one of the CCR enhanced the westward propagation of the WCR, which was displaced by about 120 km to the west (~12 km d^{-1} or more than double the β-driven westward propagation speed). Figure 3 also illustrates the change in hurricane intensity as Rita moved on warm/cold ocean features that resulted from the ring separation sequence. Rita attained category 5 status over the warmer waters of the LC, then her intensity decreased to category 3 as the storm encountered one of the CCR developed along the LC periphery during the shedding.

Regression analysis (not shown) between *in situ* measurements and altimeter fields revealed slopes close to 1 and correlation coefficients in the rank of 0.88-0.94, suggesting satellite-derived isotherm depths and OHC fields were accurate.

4. CONCLUDING REMARKS

Satellite-based and *in situ* measurements support the hypothesis that the LC complex played an important role on the rapid deepening of Katrina, Rita, and Wilma as the storms passed over the Gulf of Mexico and northwest Caribbean Sea. Wilma deserves a special mention, since she re-intensified from category 1 to category 3 storm over the LC even when the OHC in the region was depleting and the conditions in the atmosphere were unfavorable.

The large values of OHC (>100 kJ cm^{-2}) in the Gulf of Mexico is predominantly determined by the Loop Current cycle. Maximum in OHC occur during WCR shedding, while minimum levels are attained when the current returns to port-to-port position. Even at minimum levels in OHC the Loop Current can fuel up to five consecutive hurricanes. In contrast, the cold cyclones that develop along the Loop Current rim during ring shedding enhance locally the hurricane negative feedback. Therefore, understanding the Loop Current cycle is crucial to better forecast changes in hurricane intensity in the Gulf of Mexico.

Hurricane-induced cooling during the passage of Katrina, Rita, and Wilma was cancelled by the large-scale tendency for the Loop Current system to attain momentum flux balance, which is characterized by the deepening of isotherms as the ring formation/shedding is in progress. Thus, positive (or less negative) feedback is expected in the Loop Current during the passage of tropical cyclones since advection of deep, warm thermal gradients by a strong current causes minimal SST decreases and OHC losses.

Satellite-based measurements support the premise of the ballooning mechanism predicted by the momentum imbalance paradox theory to explain the Loop Current cycle. The amplitude of the perturbations in the 20 and 26°C isotherms suggest bottom-intensified baroclinic instability during the separation sequence, as simulated in numerical models of the Gulf of Mexico. Moreover, it was observed that the intrusion of a cold cyclone between the LC and the WCR enhanced the separation sequence with a displacement speed more than double the β-driven westward propagation speed of the WCR.

Given the effects that the LC system had on the record-breaking 2005 storms in the Gulf of Mexico, the numerical weather prediction models must be able to simulate properly the Loop Current cycle, including area and depth spanning, ring formation and shedding, and instabilities triggered during the ring separation sequence. This will have important consequences in coupled operational at the national centers.

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