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^{o}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 (LC) 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 LC transporting heat into the Gulf interior. The 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 OHC within the Gulf, since up to 66% of the warm water coming from the Caribbean may enter the LC bulge during about 100 ring-growth days before ring shedding events [*Nof and Pichevin*, 2001].

Satellite-based radar altimeter measurements suggest 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 20-27 September, the time span when Rita passed on the shedding region. Finally, the LC 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 waters with high OHC (category 5, 5, and 3 respectively), even under unfavorable atmospheric conditions (Wilma on her way to South Florida after leaving the Peninsula of Yucatan).

In this seminar, measurements acquired from the deployment of airborne ocean 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 OHC 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 ocean heat that was available during the passage of Katrina, Rita, and Wilma. Shear-induced mixing in the deep layers did not significantly cool the upper ocean, and horizontal advection of thermal structure played 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, as 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.

2. The LC cycle and OHC variability

The LC cycle indicates a tendency of the area-averaged thickness of the layer with waters warmer than 26^{o}C in the eastern Gulf of Mexico (93-81^{o}W, 22-28.5^{o}N) (Figure 1). The 26^{o}C isotherm depth is inferred from surface height anomaly from radar altimetry as in *Shay et al.* [2000]. By YearDay (YD) 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^{o}C grows gradually and by YD 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 because the large-scale tendency is for the LC to deepen as the shedding is in progress. The maximum layer thickness warmer than 26^{o}C (YD 270) 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^{o}C layer is fluctuating because 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). 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.

3. Impact of WCR shedding on storm intensity

As shown in Figure 2, objectively analyzed 26^{o}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 ($\sim$12 km d^{-1} or more than double the β-driven westward propagation speed). Notice 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.

4. Concluding remarks

In situ and satellite-based 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 eastern Gulf of Mexico. The large values of OHC (100 kJ cm^{-2}) in the LC complex were determined by the formation and shedding of a WCR. Moreover, during the passages of the three storms, hurricane-induced cooling was canceled by the large-scale tendency for the LC to attain momentum flux balance, which was characterized by the deepening of isotherms as the WCR formation/shedding was in progress. Thus, positive (or less negative) feedback is expected in the LC complex during the passage of tropical cyclones as advection of deep, warm thermal gradients by a strong current causes minimal SST decreases and OHC losses. In contrast, the cold cyclones that developed along the LC rim during ring shedding enhanced locally the hurricane negative feedback. Therefore, understanding the LC cycle is crucial to better forecast changes in hurricane intensity in the Gulf of Mexico. In particular, the numerical weather prediction models must be able to incorporate and 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 models at the national centers.

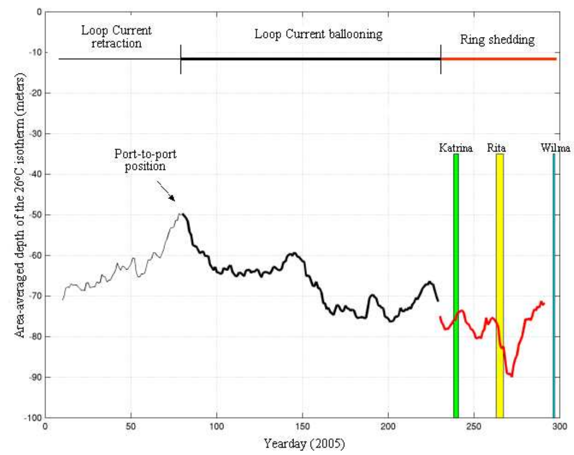

Figure 1: Area-averaged depth of the 26^{o}C isotherm (93-81^{o}W, 22-28.5^{o}N) as inferred from surface height anomaly from radar-altimetry as in *Shay et al.* [2000].

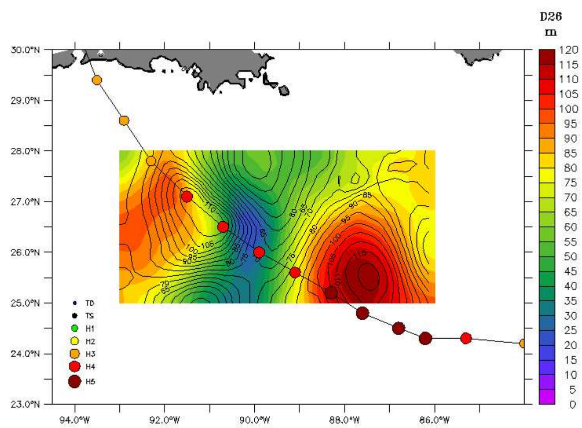

Figure 2: Pre-storm (contours) and post-storm (color) 26^{o}C isotherm depth calculated from data acquired by deploying airborne expendable current, temperature and salinity profilers in LC and WCR waters. The line with circles is the Rita best track.

References

Chérubin, L.M., W. Sturges, and E.P. Chassignet (2005), Deep flow variability in the vicinity of the Yucatan Straits from a high-resolution numerical simulation, *J. Geophys. Res., 110*, C04009, doi:10.1029/2004JC002280.

Nof, D. (2005), The momentum imbalance paradox revisited, *J. Phys. Oceanogr., 35*, 1928-1939.

Nof, D., and T. Pichevin (2001), The ballooning of outflows, *J. Phys. Oceanogr., 31*, 3045-3058.

Pichevin, T., and D. Nof (1997), The momentum imbalance paradox, *Tellus, Ser. A, 49*, 298-319.

Shay, L. K., G. J. Goni, and P. G. Black (2000), Effects of a warm oceanic feature on hurricane Opal, *Mon. Wea. Rev., 128*, 1366-1383.

Shay, L. K. (2006), Positive feedback regimes during tropical cyclone passage, *14th Conference on Sea-Air Interactions*, AMS Annual Meeting, 30 Jan-3 Feb, Atlanta, GA.

Sturges, W., and R. Leben (2000), Frequency of ring separations from the Loop current in the Gulf of Mexico: A revised estimate, *J. Phys. Oceanogr., 30(7)*, 1814-1819.