3C.3 LOOP CURRENT INTERACTIONS DURING HURRICANES ISIDORE AND LILI

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1. INTRODUCTION

Coupled oceanic and atmospheric models to accurately predict hurricane intensity and structure change will eventually be used to issue forecasts to the public who increasingly rely on the most advanced weather forecasting systems to prepare for landfall. Early ocean-atmosphere studies have emphasized the negative feedback between tropical cyclones and the ocean due to the cold wake and ocean mixed layer (OML) deepening and cooling beginning in back of the eye (Price 1981; Shay 2001).

Recent cases of hurricane passage (Bret, Opal, Isidore, Lili, Katrina, Rita and Wilma) underscore sudden and unexpected intensification often occurs within 24 to 48 hours of landfall as storms move over deep, warm layers associated with the Loop Current (LC) and warm core ring (WCR) field in the western Atlantic Ocean and Gulf of Mexico. Based on deliberations by the Prospectus Development Team who were tasked by the lead scientist of the United States Weather Research Program for NOAA and NSF, understanding and predicting intensity change will require knowledge of: tropospheric interactions, inner-core dynamics, and ocean circulation which controls the oceanic heat content (OHC) (Marks et al., 1998).

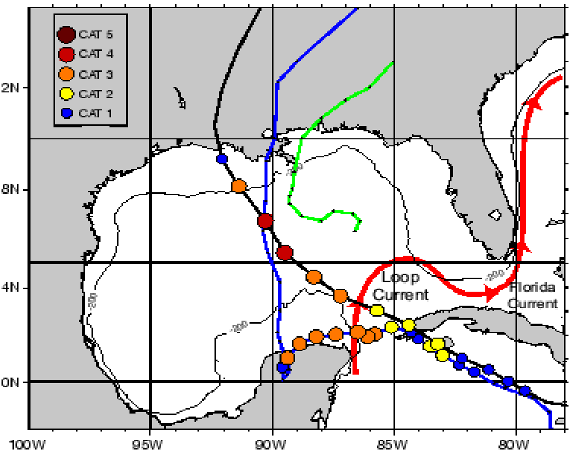

Figure 1: a) Cartoon of the LC relative to the tracks of TS Hanna (green), Hurricanes Isidore (blue), and Lili (black) in Sept-Oct 02 with intensities in legend.

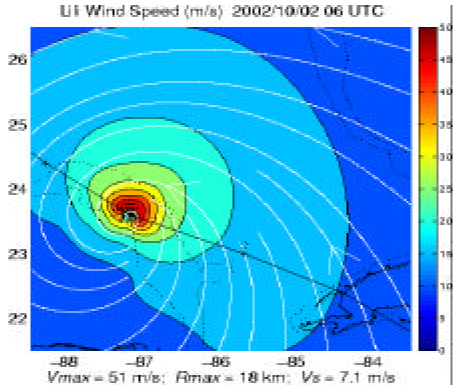

Figure 2: Hurricane Lili wind fields based on observed surface winds (m s^{-1} color) and streamlines (white arrows) 02 Oct 2002 with R_{max}, V_{max} and translation speeds (V_S).

Life cycles of TCs Hanna, Isidore and Lili in Sept and Oct 2002 in the northwestern Caribbean Sea and Gulf of Mexico (GOM) revealed inherent uncertainties in predicting intensity changes (Fig. 1). Hanna was a strong tropical storm that induced SST cooling of $\sim 1^{o}$C and an OHC loss of 10 kJ cm^{-2} in the north central GOM over Gulf Common Water (GCW) . Isidore and Lili (Figure 2) felt the deeper, warmer reservoirs (*less negative feedback*) associated with the LC that results from strong northward transport of more than 30 Sv through the Yucatan Straits. Upper ocean heat and mass budgets are determined by entrainment mixing due to ocean current shear instability across the ocean mixed layer (OML) base (~75%), surface fluxes (5 to 20%), and horizontal advection by ocean currents (5 to 10%) (Jacob et al., 2000; Jacob and Shay 2003). Wind-driven upwelling processes along the track modulate shear-induced ocean mixing by upwelling more stable water (larger buoyancy frequency) from the thermocline closer to the surface.

As part of an NSF/NOAA sponsored Hurricane Air-Sea Interaction Experiment, ocean and atmosphere conditions were concurrently mapped using a series of Airborne eXpendable Current Profilers (AXCP), Airborne eXpendable Conductivity Temperature and Depth (AXCTD) profilers and Airborne eXpendable

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Bathythermographs (AXBT) deployed from NOAA research aircraft as Isidore and Lili moved over the Gulf of Mexico in Sep and Oct 2002 (Shay and Uhlhorn 2006). Measurements were acquired prior, during and subsequent to storm passage. Success rates exceeded 80%, including salinity and temperature profiles from AXCTDs. In addition, the hurricane boundary layer was observed using Global Positioning System (GPS) Sondes. Surface winds were measured with the Stepped Frequency Microwave Radiometer (Uhlhorn and Black 2003).

2. ISIDORE AND LILI

As shown in Figure 1, Isidore moved off the tip of Cuba and across the Yucatan Straits (R_{max}~18 km) and intensified to a strong Category-3 storm prior to landfall on the Yucatan Peninsula. As Isidore moved relatively slow (~4 m s^{-1}) across the straits, wind-driven currents should have resulted in a net upwelling of isotherms due to net current divergence from the track. However, northward advection of the thermal gradients (i.e. OHC) by the LC caused minimal SST and OHC loss in the domain. As the storm encountered the Yucatan shelf, dramatic cooling was observed of several degrees (not shown). Here, shelf waters are maintained by the trade-wind regime that keeps the seasonal thermocline close to the surface. Any impulsive force associated with even a weak storm, can significantly induce upwelling due to offshore wind-driven transport. After landfalling on the peninsula, Tropical Storm Isidore moved across the Gulf of Mexico to form a broad, cool wake with SSTs of 28^{o}C compared to pre-storm SST of about 29.5^{o}C.

After forming in the northwest Caribbean Sea from a tropical wave, Lili was upgraded to a hurricane on 30 Sept. Lili tracked northwest (Figure 1) and moved over the western tip of Cuba and over the southern Gulf of Mexico where deep, warm layers associated with the LC as she rapidly intensified from a category 2 to a category 4 hurricane (V_{max}~62 m s^{-1}) as suggested by Figure 2. Thermal energy in the LC was replenished by this time since the advective time scale (L/U: L is cross-stream width and U is the OML current) is about a day. Cooling in this regime was less than 1^{o}C due to the advection of thermal gradients by the oceanic currents through the Yucatan Straits. Lili's rapid deepening and filling was not well predicted in any forecasts. Even at these levels of intensity, the ocean response indicated minimal SST decrease of less than 1^{o}C and OHC loss of about 15 kJ cm^{-2} (Fig. 3).

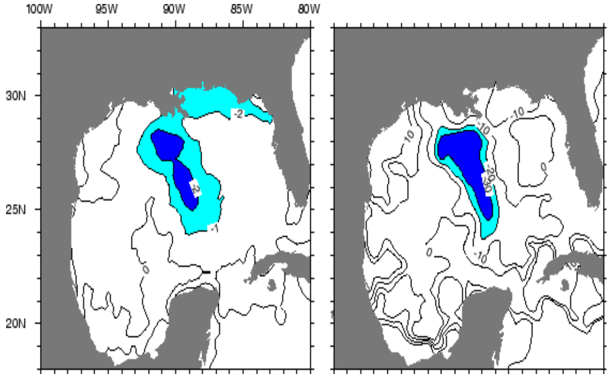

Figure 3: a) SST (^{o}C) and b) OHC (kJ cm^{-2}) differences derived from satellite sensors including radar altimeter based on pre and post-Lili periods. Shaded areas depict SST cooling >1^{o}C and OHC changes >20 kJ cm^{-2} .

Horizontal advection balanced upwelling and shear-induced mixing events associated with forced near-inertial motions resulting in more positive (less negative) feedback to the atmosphere. As Lili moved northwest of the LC, the upper ocean cooled by more than 2^{o}C with a net OHC loss of 30 kJ cm^{-2} (twice the Leipper and Volgenau (1972) estimate required to sustain a hurricane) due to shear-induced mixing across the base of a thinning ocean mixed layer. In addition to this negative feedback induced by the wind-induced mixing, Lili weakened prior to a category 1 storm due to dry air entrainment observed by GPS sondes and she interacted with a broad wake of cooling induced by Hanna and Isidore.

3. PROFILES

Current and temperature profiles from the **B'-B** transect along 1.5 R_{max} is shown in Fig. 4 in the wake of Lili. Current profiles along the northern part of transect indicate an anticyclonic rotation of the current profiles suggestive of vertical energy propagation out of the wind-forced OML (Leaman and Sanford 1975). Rapid rotation of the current vector gives rise to strong current shears that lower the Richardson numbers to below criticality and forces the upper ocean to mix and OML to deepen. In the center of the **B'-B** transect, OML currents approach 1 m s^{-1} flowing towards the east. Warm thermal structure is relatively deep approaching 100 m towards point **B**. This energetic current structure is associated with the LC, and in its core, there are energetic currents at depth owing to the geostrophic nature of the current. At point **B**, the layer is the deepest with currents of about 50 cm s^{-1}.

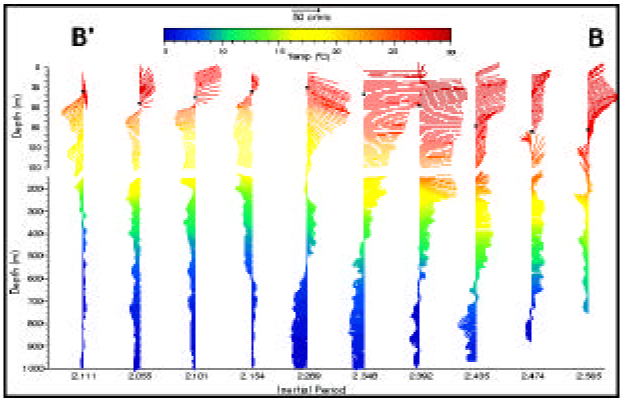

Figure 4: Post-Lili transect (see Figure 3c. **B'-B**) of the current (cm s^{-1}) and temperature structure (color) in the upper 100 m (top panel) and ocean structure between 100-1000 m (lower panel).

4. LOOP CURRENT RESPONSE

4.1 SSTs

Using measurement grids, temperature, current, and salinity profiles have been objectively analyzed. As shown in Fig. 5, pre and post sea surface temperatures suggest little cooling in the LC core. As noted above horizontal heat advection by the LC over time scales of days will certainly be replenished by the 0.8 to 1 m s^{-1} currents through the Yucatan Straits from the warm subtropical water in the northwest Caribbean Sea. By contrast, along the northern part of the measurement domain, the temperatures cooled by more than 2°C .

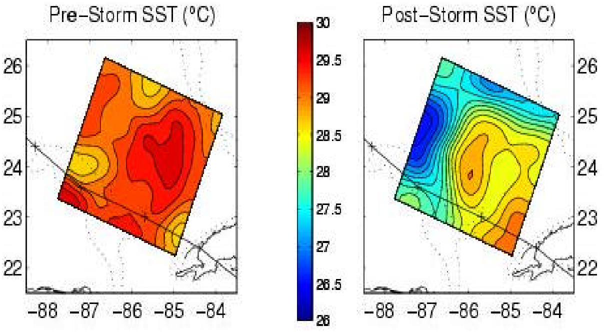

Figure 5: Pre and post Lili SSTs (°C) based airborne profilers relative to Lili's track (blue line).

4.2 26°C Isotherm Depths

Isotherm depths of the 26°C water are shown in Fig. 6 for the pre and post-Lili conditions. Isotherm depths exceeded 150 m in the LC suggesting a significant amount of OHC, consistent with the satellite-derived estimates (not shown). In the NW Caribbean Sea, the 26°C isotherm depths approach 175 m. Isotherm depths in the northwest section of the grid are less than 50 m in the pre-storm, and decrease to less than 40 m along the Lili's track due to upwelling of the isotherms and the transport away from the track. Large horizontal differences set up a pressure gradient to drive the energetic LC.

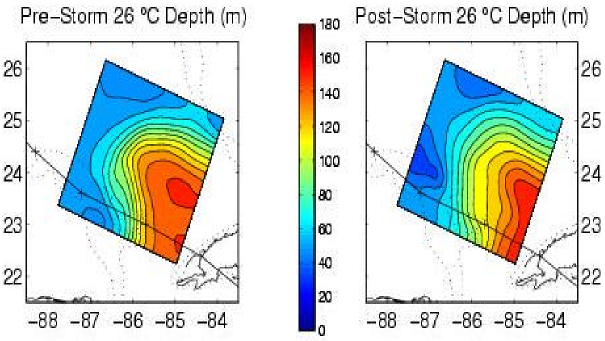

Figure 6: a) Pre- and Post-Lili depth of the 26°C isotherms (m) relative to Lili's track.

4.3 *OHC Variations*

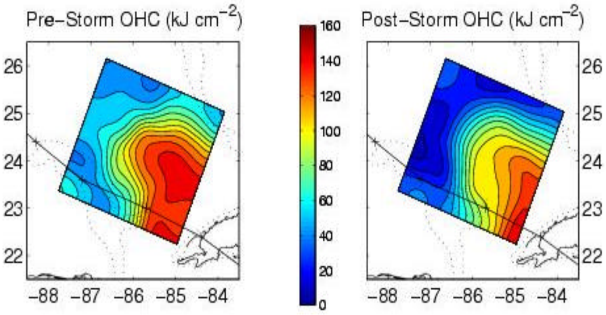

Figure 7: Pre (left) and post (right)–Lili OHC distribution from the in situ profilers (kJ cm^{-2}).

Isotherm depths decreased by ~20 m in the LC whereas the differences were much larger in the GCW along the northern boundary. Isotherm depths support relatively high values of OHC as suggested by Fig. 7 in pre and post-Lili measurements. OHC values exceeded 150 kJ cm^{-2} since OHC scales approximately as 1 kJ cm^{-2} m^{-1}. In the GCW, the OHC values after Lili decreased by more than 30 kJ cm^{-2} compared to about 15 to 20 kJ cm^{-2} in the LC regime. As the advective time scale ~30 h, and the post-Lili survey was conducted two days after the storm, it is possible that the OHC loss may have been more than this value. The point is that the upper ocean's heat is replenished quickly after hurricane passage in these strong current systems compared to the water mass outside of the frontal boundaries as observed during Opal's passage over a WCR (Shay et al. 2000). Normalized pre and post-Lili OHC fields indicate values of about one (~16.7 kJ cm^{-2}). Along the northwest boundary, normalized OHC loss approaches a factor of 2.

5. SUMMARY

Pre-existing ocean current structure advects deep, warm thermal layers, which limits cooling induced by these physical processes (e.g. *less negative feedback*) as more turbulent-induced mixing is required to cool and deepen the OML. Energetic oceanic current features, which are part of the gyre circulation in the Atlantic Ocean Basin, are characterized as deep, warm thermal regimes with OHC values exceeding 100 kJ cm^{-2}. For intensity forecasting, inclusion of pre-storm OHC in SHIPS has already shown a reduction of 5 to 15% in intensity errors (DeMaria et al. 2005; Mainelli et al. 2006).

The extent of cooling in the cold wake is a function of vertical current shears (known as entrainment heat flux) that reduce the Richardson numbers to below criticality and subsequently cools and deepens the OML through vigorous mixing. The key finding emerging from our research is the OHC is a more effective measure of the ocean's influence on storm intensity than just SST as recently shown during the passage of hurricanes Katrina, Rita and Wilma. Pre-storm ocean structure must be accurately accounted for in the models with realistic ocean mixing parameterization schemes based on measurement. By contrast, thin OML deepen and cool quickly through shear instability (Price 1981; Shay 2001; Jacob *et al*. 2000) and induce negative feedback to the atmosphere. In regimes of deep OML, there is significantly reduced negative (or positive) feedback, as the upper ocean does not significantly cool.

To further our understanding of these feedback regimes, empirical, analytical, and numerical approaches are required to examine complex air-sea processes and storm intensity changes. In situ data (D'Asaro 2003; Uhlhorn and Shay 2004) are needed to not only improve satellite algorithms and retrievals but to get the basic state in the ocean models such as HYCOM.

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