10.7 POSITIVE FEEDBACK REGIMES DURING TROPICAL CYCLONE PASSAGE

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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 beginning in back of the eye (Chang and Anthes 1978; Price 1981; Shay *et al*. 1992).

The extent of this 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 oceanic mixed layer (OML) through vigorous mixing. Notwithstanding, early studies did not consider the relative importance of deep, warm OML associated with Caribbean Current, Loop Current, Florida Current, Gulf Stream and the warm eddy field. Since pre-existing ocean current structure advects deep, warm thermal layers, cooling induced by these physical processes (Fig.~1) is considerably less (e.g. *less negative feedback*) as more turbulent-induced mixing is required to cool and deepen the OML. Central to the atmospheric response is the amount of heat in the OML or ocean heat content (OHC) relative to the depth of the 26^{o}C isotherm (Leipper and Volgenau 1972). These energetic oceanic current features, which are part of the gyre circulation in the Atlantic Ocean Basin, are characterized as deep, warm thermal regimes (high OHC). In a broader context, quantifying the effects of forced oceanic currents and their shears on the OHC distribution is central to forecasting intensity and structure change using the Statistical Hurricane Intensity Prediction Scheme (DeMaria *et al*. 2005).

In this note, *in situ* oceanic current, temperature and salinity measurements from Airborne eXpendable Current Profilers (AXCP), Airborne eXpendable Conductivity Temperature and Depth (AXCTDs) profilers and Airborne eXpendable Bathythermographs deployed during a joint NSF/NOAA experiment from several aircraft flights in hurricanes Isidore and Lili (2002) are used to demonstrate the lack of strong oceanic response across the Yucatan Straits and Loop Current. These *in situ* measurements are complemented by satellite-based radar altimeter measurements of the surface height anomaly (SHA) field from NASA TOPEX, Jason-1 and the NOAA Geosat Follow-on- Mission (GFO) (Cheney *et al.* 1994) and sea surface temperatures (SST) cast within a two-layer model and a seasonal climatology to estimate isotherm depths and OHC (Shay *et al.* 2000; Mainelli-Huber 2000). These analyses are extended to recent storms in the Northwest Caribbean Sea and Gulf of Mexico including hurricanes Ivan (2004), Katrina, Rita, and Wilma (2005) as these storms intensified after encountering warm subtropical water transported by the warm Caribbean Current and Loop Current during favorable atmospheric conditions.

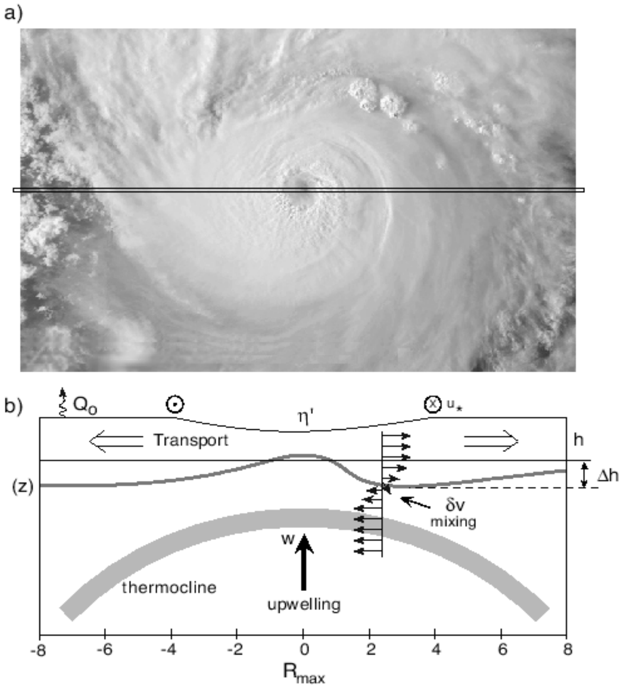

Figure 1: a) Hurricane image and b) a cartoon showing physical processes forced by hurricane winds.

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2. OHC VARIABILITY

An example of significant OHC variability is the western Atlantic Ocean that includes the northwestern Caribbean Sea, Gulf of Mexico, and western Atlantic Ocean basins. Once a storm enters the Caribbean Sea and Gulf of Mexico basins, hurricanes will inevitably landfall along either the coast or the Caribbean Islands (Marks *et al.* 1998). As shown in Fig. 2, the upper ocean's northward flow through the Yucatan Straits forces an annual variation in the Loop Current (Leipper and Volgenau 1972; Maul 1977). Annually, the average transport is ~30 Sv (where 1 Sv=10^6 m^3 s^{-1}) through the straits (Leipper 1970). The forced anticyclonically rotating Loop Current has maximum flows of 1 to 1.5 m s^{-1} and intrudes ~500 km northward into the Gulf of Mexico, transporting warm subtropical water with a markedly different temperature and salinity relationship compared to the background Gulf of Mexico common water (Shay *et al.* 1998). For example, the averaged 20^{o}C and 26^{o}C isotherm depths occur at 250 m and 125 m in the subtropical water compared to 100 m and 50 m, respectively for the Gulf common water. Thus, warmer subtropical waters extend several hundred meters deeper thereby increasing its OHC and hurricane heat potential (Leipper and Volgenau 1972). As the Loop Current feature intrudes further north, warm core rings (WCR) or eddies having diameters of 100 to 200 km pinch off at 11 to 14 month intervals. These features propagate westward at speeds of 3 to 5 km d^{-1} over a 9 to 12-month period, dissipating along the shelf break off Texas and Mexico (Elliot 1982).

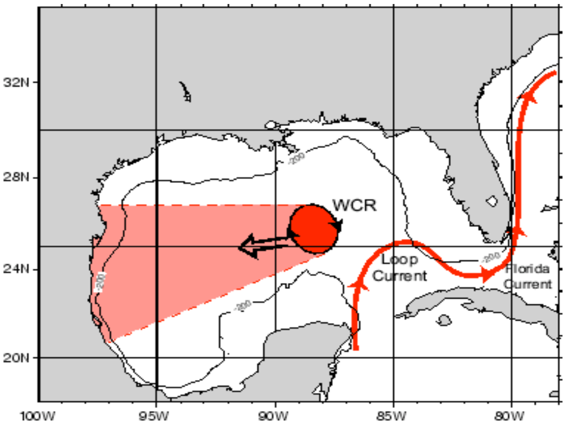

Figure 2: Cartoon of the Gulf of Mexico showing the mean boundaries of the Loop Current and the warm core rings/eddies (WCR) as they propagate westward.

The anticyclonic circulation around the Loop Current flows through the Florida Straits between United States and Cuba forming the Florida Current. This deep, warm ribbon of high OHC water combines with the Antilles Current north of the Caribbean Islands then follows the eastern seaboard to form the core of the Gulf Stream. In the presence of these major currents, the 26^{o}C isotherm depth is deeper as warm subtropical water is transported from the tropics to higher latitudes as part of the gyre circulation. Central to the storm intensity issue is that since the warm water extends to depths often exceeding 120 m, they represent heat reservoirs to fuel tropical and extratropical storms as observed during Opal (1995) (Shay *et al.* 2000). In these regimes, more heat is available for the storm through enhanced air-sea fluxes that may exceed 2 KW m^{-2} (Hong *et al.* 2000; Shay *et al.* 2000) compared to the surrounding water mass where there is considerably mixing and upwelling. This warmer thermal structure is distributed through the OML through the top of the thermocline (i.e. depth of the 26^{o}C), and represents a more effective means of assessing oceanic regimes where intensity increases are more likely to occur.

As shown in Fig..~3, the integrated OHC and 26^{o}C isotherm depth estimates based on the thermal and haline profiles are objectively analyzed based on temporal and spatial scales as determined from the hurricane Gilbert data set (Shay *et al.* 1992). As the depth of the 26^{o}C isotherm depicts the top of the thermocline, subtropical water is distributed over deep layers (~130 m deep) compared to ~40 m in the Gulf common water. Given these differing depths, observed OHC estimates of 130 KJ cm^{-2} in the Loop Current and WCR are about three times larger than those in the Gulf Common water. Interestingly, the OHC estimates suggest a value of ~1 KJ cm^{-2} m^{-1} in the Loop Current/WCR complex. These anomalously large OHC values represent a significant heat reservoir for storms to tap as they move from the NW Caribbean Sea into the Gulf of Mexico. This observed WCR separated from the Loop Current over a two-month period as suggested by the Oct 1999 measurements (not shown).

Satellite altimetry data has proven to be a useful tool to study of isotherm depths and to estimate the OHC variability (Shay *et al.* 2000; Mainelli-Huber 2000), and is now a key input parameter to the SHIPS for forecasting hurricane intensity (DeMaria *et al.* 2005). Unlike AVHRR imagery, altimeter data are unaffected by cloud obscuration and can provide information on the vertical ocean structure if complemented by historical hydrographic data. Given the slow translational speeds of mesoscale ocean features (a few km per day), the SHA data from the altimeter detects and locates warm mesoscale features, usually identified as positive SHA values. The TOPEX/Jason-1 altimeter measures the sea level beneath its ground track at 7 km intervals every 9.9 days where adjacent tracks are separated by about 3° (300 km) in longitude. By contrast, the repeat cycle for ERS-2 is 35 days, but with much higher horizontal resolution as adjacent tracks are less than 100 km apart. The GFO altimeter has a 17-d repeat cycle. The SHA data are corrected for solid and ocean tides, wet and dry tropospheric effects, ionospheric processes, electro-magnetic bias and inverse barometric corrections. The SHA fields from these platforms represent sea level heights at each satellite along-track location referenced to the mean sea level heights based on several years of measurements. The 7 km-along track SHA are then smoothed using a 30-km running mean filter.

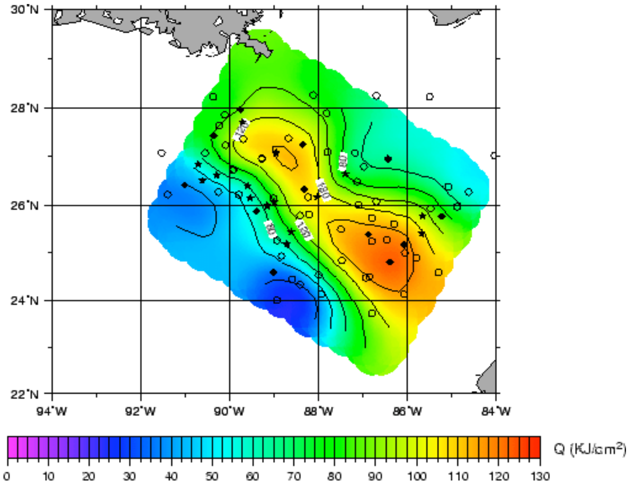

Figure 3: OHC (color: KJ cm^{-2}) and 26°C isotherm depth (contour: m) based on AXCPs (star), AXCTDs (diamond), and AXBTs (circle) deployed in the eastern Gulf of Mexico in Aug 99 from a NOAA flight (from Shay 2001).

SHA fields from at least two radar altimeters are combined using a parameter matrix scheme to objectively map the field (Mariano and Brown 1992). This approach minimizes mapping errors provided the SHA data are of sufficient quality. These analyzed altimeter-derived SHA data calibrated by hydrographic data (temperature and salinity climatology) are then used as a proxy to monitor the upper layer thickness or the depth of the 20°C isotherm based on a two-layer model approximation. Mean upper layer thickness along with historical temperature and salinity profiles are used to monitor the upper layer OHC relative to the depth of the 26°C isotherm (Shay *et al.* 2000). This value is chosen since it represents a threshold temperature suggested for cyclogenesis by Palmen (1948). Comparisons to pre-event *in situ* data have revealed regression slopes of 0.88 to 0.95 with a cold bias of 10 to 15 KJ cm^{-2} in satellite estimates.

3. HURRICANES ISIDORE AND LILI

As part of a NSF/NOAA sponsored Hurricane Air-Sea Interaction Experiment, dual aircraft experiments concurrently mapped ocean-atmosphere fields using expendable profilers oceanic and atmospheric deployed from NOAA research aircraft as Isidore and Lili moved into the Gulf of Mexico in Sep and Oct 2002 (Uhlhorn and Shay 2004). Grids of AXCPs, AXCTDs and AXBTs were deployed during prior, during and subsequent to storm passage. Success rates exceeded 80%, including the deployment of the AXCTDs, which provide conductivity (salinity) and temperature profiles to 1000 m. AXCTDs provide salinity with accuracies of about 0.05 psu and resolution of 0.03 psu to 1000 m over 1-m scales.

The passages of hurricane Isidore and Lili in Sept and Oct 2002 in the NW Caribbean Sea and Gulf of Mexico underscored uncertainties in accurately predicting hurricane intensity changes. Lili formed in the same area as Isidore about a week before. While Isidore moved off the tip of Cuba and across the Yucatan Straits landfalling as a cat-3 storm on the Yucatan Peninsula, Lili moved over the southern Gulf of Mexico where deep, warm layers associated with the Loop Current provided additional heat as she strengthened to a category 4 hurricane while atmospheric shear was relatively weak and the anticyclonic circulation over the storm provided good outflow.

Both Isidore and Lili felt these deeper, warmer reservoirs (*positive, less negative feedback*) associated with the Loop Current through the Yucatan Straits. As Isidore moved slowly (< 3 m s^{-1}), wind-driven currents should have resulted in upwelling of isotherms due to net current divergence from the track (see Fig. 1). However, advection of the deep, warm thermal gradients by the Loop Current of 1.5 m s^{-1} caused minimal SST decreases and OHC losses. As the storm moved over the Yucatan shelf, fairly dramatic cooling was observed of more than several degrees (not shown) in the OML. Here, the shelf water is maintained by trade wind regime where the seasonal thermocline is close to the ocean surface. Thus, impulsive forcing events will significantly cool the shelf due to net offshore transport and upwelling of colder water. After landfalling on the Yucatan Peninsula, Tropical Storm Isidore moved across the Gulf of Mexico to force a broad, cool wake with SSTs of 28°C compared to pre-storm SST of about 29.5°C as observed at an NDBC buoy (White and Shay 2005).

Lili initially tracked across the Yucatan Straits as a cat-2 storm after emerging off the Cuban coast. Even at these levels of intensity, the ocean response was minimal with an SST decrease of less than 1°C and an OHC loss of 6-8 KJ cm^{-2} (Fig. 4) in the Loop Current regime. Lili subsequently began to intensify over the open water, and on 2 Oct, she became a cat-4 storm with surface winds approaching 60 m s^{-1} as observed at an NDBC buoy in the central Gulf of Mexico (White and Shay 2005). Advection of thermal gradients counterbalanced shear-induced mixing events associated with forced near-inertial motions and upwelling processes, which resulted in more *positive feedback* to the atmosphere. As Lili accelerated towards northwest of the Loop Current over the Gulf common water, the ocean cooled by more than 2°C with an OHC loss of 30 KJ cm^{-2} due to shear-induced mixing across the base of a thin OML. By landfall on 3 Oct, Lili was downgraded to a category one status due in part to and entrainment of cooler, drier air as suggested by GPS sondes as well as interacting with a broad wake of cooling induced by tropical storms Hanna and Isidore.

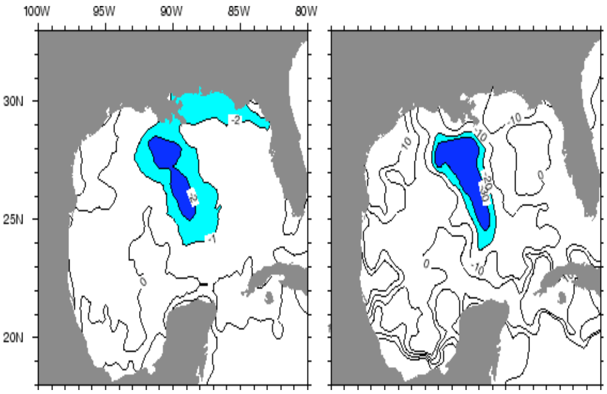

Figure 4: a) SST (°C) and b) OHC (KJ cm^{-2}) differences derived from satellite sensors including radar altimeter based on pre and post-Lili periods. Shaded areas depict SST cooling >1°C and OHC changes >20 KJ cm^{-2}.

These large SST changes and OHC losses were associated with wind-induced current shears in the Gulf common water (Fig. 5). That is, the current reversed direction beneath the OML leading to strong current shears (Uhlhorn and Shay 2004). The observed anticyclonic rotation of current vectors with depth in the upper ocean is indicative of strong near-inertial motions and vertical energy propagation from the wind-mixed OML into the thermocline. These strong near-inertial shears lower the Richardson number to below criticality, and induce mixing between the thin OML and the top of the thermocline (Price 1981; Jacob and Shay 2003). These are regimes of *negative feedback* to the hurricane that may induce storm weakening by decreasing the air-sea fluxes of heat and moisture (Chang and Anthes 1978).

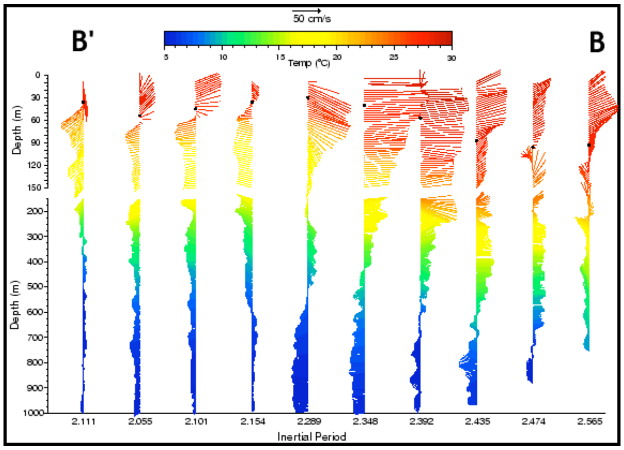

Figure 5: Current (vector: cm s^{-1}) and temperature (color: °C) section at 1.5 R_{max} from Lili's track after about 2 inertial periods (~27.5 h) following passage on 4 Oct 2002. Notice the enhanced current shears at **B'** in the Gulf Common water compared to the Loop Current at **B** (warmer temperatures go to greater depths) where a current towards the east and north are positive.

4. RECENT GULF OF MEXICO HURRICANES

Hurricanes Ivan (04), Katrina, Rita and Wilma (05) exemplified this positive feedback between the ocean and atmosphere where these storms reached category 5 status over deep warm layers in the NW Caribbean Sea, and Gulf of Mexico.

Ivan (2-24 Sept 2004) was a classical hurricane of Cape Verde origin that reached cat-5 strength on three separate occasions (Stewart 2004). As Ivan moved over the NW Caribbean Sea with an R_{max} of ~36 km, high OHC water (>150 KJ cm^{-2}) plus tropospheric outflow enhanced by upper atmospheric flow ahead of an approaching trough helped Ivan maintain cat-5 strength over 24-30 h (about one inertial period). During Ivan's passage, the net change in post-storm SST and OHC was less than 1°C and 10 KJ cm^{-2} in the NW Caribbean Sea. Convection based on satellite imagery (not shown) showed well-developed storm structure and eyewall in the NW Caribbean Sea under favorable atmospheric conditions. Upon entering the Gulf of Mexico on 14 Sept as a cat-5 storm, Ivan turned NNW and then northward as the high OHC of the Loop Current maintained its intensity. Ivan subsequently weakened to a category 3 storm due to a combination of lower OHC north of Loop Current (i.e. Gulf common water), vertical shear in the atmosphere associated with an upper-level trough, and drawing dry air into its circulation. Within 12-24 hours of landfall, Ivan encountered a warm core eddy shed by the Loop Current earlier that provided positive feedback. After passing the warm eddy where surface pressures decreased by ~10 mb during a brief encounter, cooler shelf water induced by hurricane Frances about 2 weeks earlier along with increasing atmospheric shear opposed intensification. In addition, the eye increased to about $R_{max\sim}$ ~ 80 km as part of replacement cycle just prior to landfall near the Alabama-Florida border. Ivan was a clear example of the impact of alternating positive and negative feedbacks from the ocean and atmosphere on hurricane intensity, as was the case for hurricane Opal (Marks *et al.* 1998).

Similar to the explosive nature of hurricane Opal (1995), hurricanes Katrina (23-29 Aug 2005), Rita (18-24 Sept 2005), and Wilma (15-25 Oct 2005) all rapidly deepened from tropical storm to cat-5 status in less than 24 hours. For the first time in the Atlantic Ocean basin, three cat-5 storms occurred within the same year. The lowest central pressures were 896 mb, 892 mb, and 882 mb for Katrina, Rita and Wilma, respectively. Up until this summer, hurricane Gilbert held the record of 888 mb in the NW Caribbean for the lowest surface pressure in the Atlantic basin (Shay *et al.* 1992). Wilma shattered that record by dropping about ~70 mb over 8-h time window at 17.1^{o}N and 82.3^{o}W. That is, the rapid deepening index, which is typically 2 to 3 mb per hour over several hours, was 8 to 9 mb per hour or almost three times larger than the average rate of rapid deepening. In all three of these storms, low surface pressures (and their gradients) supported surface winds of 75-85 m s^{-1}.

As shown in Fig. ~6, Katrina deepened to a cat-5 storm over a warm eddy that was being shed by the Loop Current. Notice the one-to-one correlation between the hurricane intensity and OHC variations in the Gulf of Mexico compared to the SST. This eddy shedding process often takes several weeks to a few months due to instability process in the horizontal current field (Hurlburt and Thompson 1982). As strong winds cross the large OHC gradients, there is a fairly significant increase in the surface fluxes. For example, in numerical simulations during Opal's passage, Hong *et al.* (2000) found surface fluxes exceeding 2 KW m^{-2}. This is a factor of two larger than is commonly used in oceanic response models. A similar value was found by differencing pre- and post-OHC based on satellite-altimeter derived estimates. Clearly, the storm started to feel the Loop Current field upon emerging into the Gulf of Mexico. Note the areas where two warm ocean features (OHC >80 KJ cm^{-2}) were located in the Gulf of Mexico. This is about five times the threshold of 16 KJ cm^{-2} suggested by Leipper and Volgenau (1972) required to sustain a hurricane.

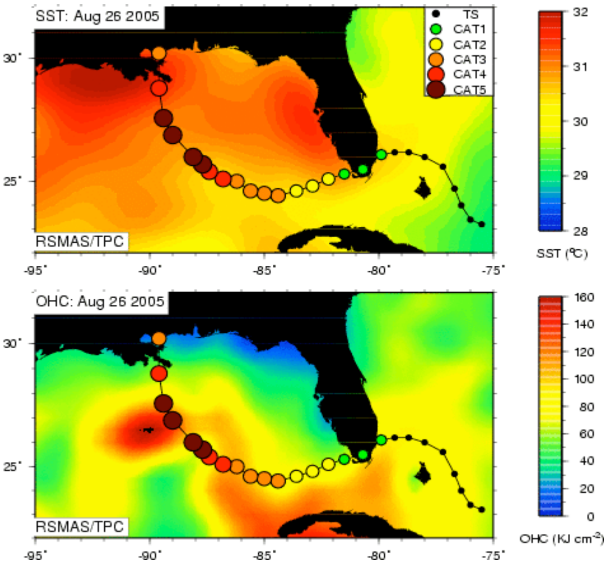

Figure 6: Pre-storm SST (^{o}C: upper panel) from TMI and OHC (KJ cm^{-2}: lower panel) based on a hurricane season climatology relative to the track of hurricane Katrina and her intensity as per the legend.

Closer examination of the warm eddy is shown in Fig.~7 where a Jason-1 and a GFO altimeter tracks went over the warm oceanic feature a few days prior to Katrina's passage. The SHA deflection ranged from 50 to 70 cm, which is higher than Loop Current warm eddy surface signatures in the Gulf of Mexico of 35 to 50 cm. This warm eddy variability was subsequently sampled after few days after Katrina's landfall by deploying AXCTDs, AXCPs, and AXBTs over a grid in a warm eddy frame of reference from NOAA WP-3D research aircraft (not shown). The sample strategy also included a Loop Current transect. Preliminary estimates of 26^{o}C isotherm depths from the profiles were in the 90-110 m range, consistent with those derived from radar altimetry. These profiler data are now being post-processed for more detailed analysis and comparison to satellite-derived fields. Unknown at the survey time, Rita's future track would encounter the Loop Current and clip the NE part of the warm eddy a few weeks later, deepening to 898 mb along the western flank of the Loop Current. Essentially, Rita's track was very similar to Katrina's except that Rita entered the Gulf of Mexico through the Florida Straits. A second warm eddy was subsequently shed by the Loop Current where Rita crossed it's path. Cyclones along the periphery of the Loop Current are a precursor to shedding events.

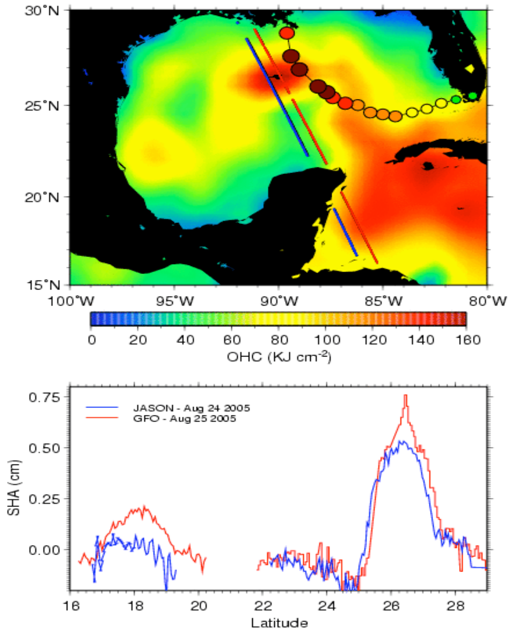

Figure 7: OHC (color: KJ cm^{-2}) relative to the track of hurricane Katrina as per the legend in Fig. 6 (upper panel) and altimeter tracks (lower panel) that cut through the warm eddy from Jason-1 (blue) on 24 Aug and GFO (red) on 25 Aug 2005 before Katrina.

Prior to Wilma, the OHC exceeded values 100 KJ cm^{-2} with deep warm layers in the NW Caribbean Sea. On 19 Oct, Wilma explosively intensified as the surface pressure decreased to 882 mb-the lowest on record in the Atlantic Ocean basin. Wilma then moved over the slowly moved over the Yucatan Peninsula and weakened from a cat-5 storm to a cat-1 storm. As the storm re-emerged off the landmass, she began to intensify upon interacting with the Loop Current under less atmospheric favorable atmospheric conditions. Upon completion of an eyewall cycle, the storm intensified to a cat-3 just prior to landfall in south Florida. Here the point is that although the storm occurred in mid-October, she still felt the large OHC values of more than 80 KJ cm^{-2}.

For these reasons, oceanic and coupled models must have realistic ocean conditions to correctly simulate the response, and forecast intensity. Jacob and Shay (2003) has showed that ocean models must be properly initialized with realistic ocean conditions, which is central to the atmospheric feedback. In addition, the choice of the mixing scheme (largely through shear) is not only central to how the ocean mixed layer cools and deepens, but also affects the available heat to the storm via surface fluxes. By contrast, negative feedback occurs for a storm moving over regions of thin OML (i.e. shallow thermocline) where shear-induced mixing events cool the deepening layer at 1 to 2 radii of maximum winds in the storm's right-rear quadrant (Shay *et al*. 1998; Jacob *et al*. 2000).

5. CONCLUDING REMARKS

Satellite and *in situ* data supports the premise that when neutral or favorable atmospheric conditions (weak shear and good outflow) are juxtaposed with high levels of OHC, significant and in some cases explosive deepening in hurricanes are possible (Lili, Ivan, Katrina, Rita, and Wilma). Even for weak storms encountering the Loop Current, Hurricane Gordon and Tropical Storm Helene (2000) intensified despite unfavorable atmospheric conditions. Thus, deeper heat reservoirs provide heat and moisture to the hurricane regardless of whether the atmospheric conditions are favorable or unfavorable. More recently, as Wilma moved off the Yucatan Peninsula as a weakened cat-1 storm, she accelerated towards the northeast over the Loop Current where OHC exceeded 80 KJ cm^{-2}, and still intensified to cat-3 after an eyewall cycle was completed.

The key finding emerging from our research is the integrated thermal structure (OHC) is a more effective measure of the ocean's influence on storm intensity than just SST. In this context, upper ocean structure must be accurately accounted for in the models with realistic ocean mixing parameterization schemes based on measurements. Thin OML deepen and cool quickly through shear instability (Price 1981; Shay *et al.* 1992; 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 cool. For example, the upper ocean (SST) cooled by less than 1°C in the WCR during Opal's passage as observed at a NOAA data buoy similar to Isidore's and Lili's passage over the Loop Current as measured by *in situ* and satellite sensors.

Implicit in satellite algorithms is the acquisition of high-quality ocean structure measurements before, during and after hurricane passage. These data, including float data, (D'Asaro 2003; Uhlhorn and Shay 2004) are needed to refine the algorithms to estimate OHC. Three dimensional snapshots of the atmospheric and oceanic structure are not only important for the evaluation of remotely sensed signatures from radar altimetry (Shay *et al.* 2000), but are crucial in evaluating oceanic and coupled model simulations. An important ingredient in these coupled models is the parameterization of air-sea fluxes where little is known about these fluxes in high wind conditions.

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