P1.26 ROLE OF WARM OCEAN FEATURES ON INTENSITY CHANGE: HURRICANE OPAL

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1. INTRODUCTION

Recent cases have demonstrated that sudden unexpected intensification in tropical cyclones often occurs within 24 to 48 hours of striking the coast over oceanic regimes such as the Gulf Stream, Florida Current, Loop Current or warm core eddies (WCE) in the western North Atlantic Ocean and Gulf of Mexico. Based on deliberations from the Prospectus Development Team 5 (PDT5), who were tasked by the lead scientist of the United States Weather Research Program for NOAA and NSF, understanding and predicting intensity change requires the knowledge of: tropospheric interactions (troughs and ridges); internal core dynamics; and upper oceanic circulation which control the Oceanic Planetary Boundary Layer's (OPBL) heat content (Marks and Shay 1997).

Sea surface temperatures (SSTs) remain a necessary, but insufficient condition on the ocean's influence on the tropical cyclone pressure and wind variations. For this reason, temperatures distributed over the OPBL represents a more effective means of assessing oceanic regimes where intensification is likely to occur. In the presence of warm, energetic baroclinic features such as the Florida Current, Gulf Stream and WCE, the OPBL and depth of the 26°C isotherm are deeper due to warm water transport from the tropics to the higher latitudes as part of the subtropical gyre circulation. These intense current regimes border the coastlines along the United States Eastern Seaboard and Gulf of Mexico states thereby providing additional heat for tropical cyclones. Quantifying the effects of these oceanic features on changes in the surface pressure and wind field during tropical cyclone passage has far-reaching consequences for not only the research and forecasting communities, but also for the public who rely on the most advanced forecasting systems to prepare for landfall. Given the unprecedented activity in the Atlantic Ocean Basin in 1995 and 1996, the relevance of the warm upper ocean processes on the Atmospheric Planetary Boundary Layer (APBL) has to be assessed with respect to intensity to advance the state of forecasting of these events. The approach described herein focuses on the role of the upper ocean circulation in altering the tropical cyclone wind fields during hurricane Opal.

2. HURRICANE OPAL

As shown in Fig. 1a., the passage of hurricane Opal in 1995 in the Gulf of Mexico underscored the inherent uncertainties in predicting wind-field changes of tropical cyclones (Marks and Shay 1997). Sudden unexpected intensification occurred within 24 hours of striking the coast while residents were sleeping, which severely decreased the effective lead time for coastal evacuation procedures. During this deepening phase from 965 hPA to 916 hPa over 14 hours, hurricane Opal moved over a warm core eddy detected by the altimeter onboard the NASA oceanographic TOPography EXperiment (TOPEX) mission. The corresponding winds increased from 110 to over 130 mph, equating to a 45% increase of the surface wind stress, which is an indicator of intensity change. What complicated this particular problem was that when forecasters observed the SST distribution in the Gulf of Mexico from satellite-based AVHRR measurements, there were no apparent signs of a warm core eddy as AVHRR-derived SSTs exceeding 29°C were uniformly distributed over the Gulf of Mexico. This situation was due to strong solar heating that occurs during the summer months in the Gulf of Mexico (Shay *et al.* 1992).

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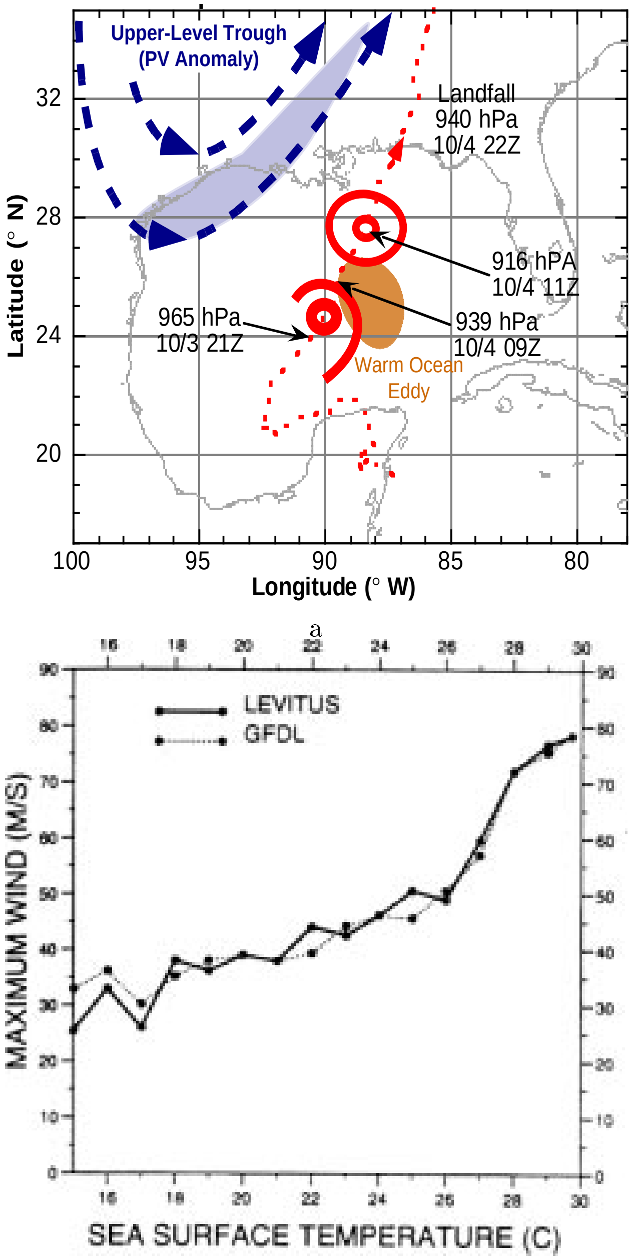

a

b

Figure 1: a) Position of upper-level trough and location of Loop Current warm core eddy based upon TOPEX altimetry data relative to the position of hurricane Opal's track in the Gulf of Mexico from 28 September to 5 October 1995 (from Marks and Shay 1997). b) Maximum storm intensity for each 1°C group for 1962-1988 sample with Levitus climatological SST and GFDL monthly SST analyses (from DeMaria and Kaplan 1994). Note the sharp rise in maximum winds beyond 26° C.

3. SCIENCE HYPOTHESIS

Palmen (1948) originally noted that warm, pre-existing SSTs in excess of 26°C were a necessary, yet insufficient condition for cyclogenesis. Once the tropical cyclone develops and translates over the tropical oceans, statistical models suggest that climatological SSTs (actually OPBL temperatures) describe a large fraction of the variance (40 to 70%) associated with wind speed increases as shown in Figure 1b (DeMaria and Kaplan 1994). However, these models neither account for the layer depths where temperatures exceed the 26°C threshold temperatures nor advective tendencies by basic-state oceanic currents. In energetic current regimes, velocities range from 1 to 2 m s^{-1} and advect deep, warm upper ocean layers that represent reservoirs of high-heat content water that provide enhanced surface heat fluxes during tropical cyclone passage.

To address this issue, the working **hypothesis** is that as a tropical cyclone moves over these warm current regimes (*i.e.* Loop Current, Gulf Stream, warm core eddies) the *time available for vertical mixing* ($\frac{L}{U_h}$, where U_h is the storm speed and L represents the curl of the near-surface wind stress or approximately $\pm 2R_{max}$) is short compared to the storm period (f^{-1}-inertial time scale) (Greatbatch, 1983). Accordingly, a source of warm upper ocean water advected by a current such as the Gulf Stream, Florida Current or the Loop Current provides a nearly continuous source of heat and moisture for a moderate to fast-moving (4 to 10 m s^{-1}) tropical cyclone along its lower boundary. This effect may have led to significant increases in the surface wind field that devastated coastal communities during hurricanes Andrew in 1992 and Opal in 1995.

4. ALTIMETRY AND SST DATA

Satellite altimetry data, provided by NASA JPL, has been proven to be a useful tool to study eddy dynamics since it acquires continuous global coverage of surface height anaomaly (SHA). Unlike AVHRR imagery, altimeter data is unaffected by cloud obscuration and can provide information on the vertical ocean structure if complemented by historical hydrographic data. Given the relatively slow-time scale of mesoscale ocean features of a few km d^{-1}, altimetry measurements provide the surface data for the detection and location of warm mesoscale features, identified as positive SHA values. In addition to observed SST cooling patterns induced by tropical cyclones (Black 1983; Shay *et al.* 1992), recent studies have shown that the tropical cyclone wind field also causes a surface depression that can also be extracted from the SHA field (Shay and Chang 1997).

Altimeter-derived SHA field during Sept 95 indicated the presence of warm ocean features in the Gulf of Mexico prior to the passage of Opal in 1995 (Fig. 2a). The SST exceeded 29°C over the basin except along the northern periphery where shelf waters had temperatures about 2°C cooler (Fig. 2b). Notice that Opal's path was located just to the left of the warm core eddy where winds increased by 20 to 25 mph (Fig. 2c). Objectively-analyzed SST composites indicated a 2 to 3°C cooling along the track. Since prestorm SSTs exceeding 29°C were distributed over the Gulf of Mexico basin, this cooling was induced by the upper ocean mixing processes and the loss of heat to the atmosphere (Fig. 2d). The cooling in the vicinity of the WCE was between 1 to 2°C due to the deeper, warm layers of the oceanic feature as suggested by the SHA of 30 to 40 cm elevation, consistent with hydrostatic dynamics.

5. UPPER LAYER THICKNESS

Altimetry data calibrated by hydrographic data (*i.e.* T/S relationships) allows the SHA to be used as a proxy to monitor the upper layer thickness (Goni *et al.* 1996; Garzoli *et al.* 1997) and upper ocean heat content. Based on a two-layer model, relationships between surface elevation and density structure are described in detail in Goni *et al.* (1996), and will be used here to establish a data base for SHA, upper layer thickness, and heat content. Central to these calculations is the depth of the 26°C isotherm, which ranges between 80 to 120 m in warm core eddies. This represents a fairly substantial heat contribution since it is proportional to the product of temperature differences relative to the 26°C water.

If the vertical ocean structure is described by the two-layer approximation, the upper layer thickness, h_1, is estimated from altimeter-derived SHA field, provided that the mean upper layer thickness and reduced gravity fields are known (Goni *et al.*, 1996) :

$$h_1(x,y,t) = \overline{h}_1(x,y) + \frac{g'(x,y)}{g}\eta'(x,y,t), \qquad (1)$$

where $\overline{h}_1(x,y)$ is the mean upper layer thickness, $g' = \epsilon g$ is the reduced gravity, g is the acceleration of gravity and η' is the SHA field from TOPEX imagery. Note that the second term on the right side of the equation is the perturbation upper layer thickness. The reduced gravity field can be obtained from hydrographic data using the expression

$$\epsilon(x,y) = \frac{(\rho_2 - \rho_1)}{\rho_2}, \qquad (2)$$

where ρ_2 and ρ_1 are the densities of the upper and lower layer, respectively. Although the vertical temperature gradient may differ throughout the Gulf, upper layer thickness is assumed here to extend from the surface to the depth of the 20°C isotherm (Fig. 3). Given the variability in the temperature and salinity data from hydrographic measurements, the choice of the depth of the 20°C isotherm was appropriate for the two-layer approach. Mean upper layer thickness, derived from $O(10^4)$ historical hydrographic observations, were available for the Gulf of Mexico. The deeper layer thicknesses were aligned with meridional axes along 84°W, due to the warmer waters of the Loop Current, which periodically intrudes into the Gulf of Mexico at intervals of 12 to 14 months. During the time of maximum penetration, which is about 500 km northward of the Yucatan Straits, WCE spin off from this mean current. These eddies have horizontal scales of about 200 km, and propagate west to southwest at rates of 3 to 5 km d^{-1} (Shay *et al.* 1997).

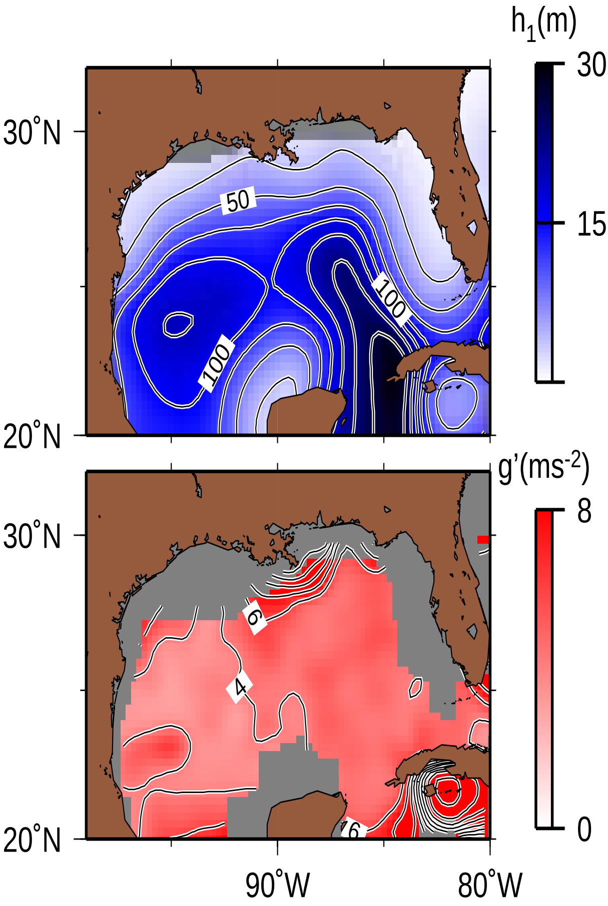

Figure 3: Mean upper layer thickness (upper panel) in m and the reduced gravity (lower panel) in m s^{-2} in the Gulf of Mexico relative to the depth of the 20°C isotherm.

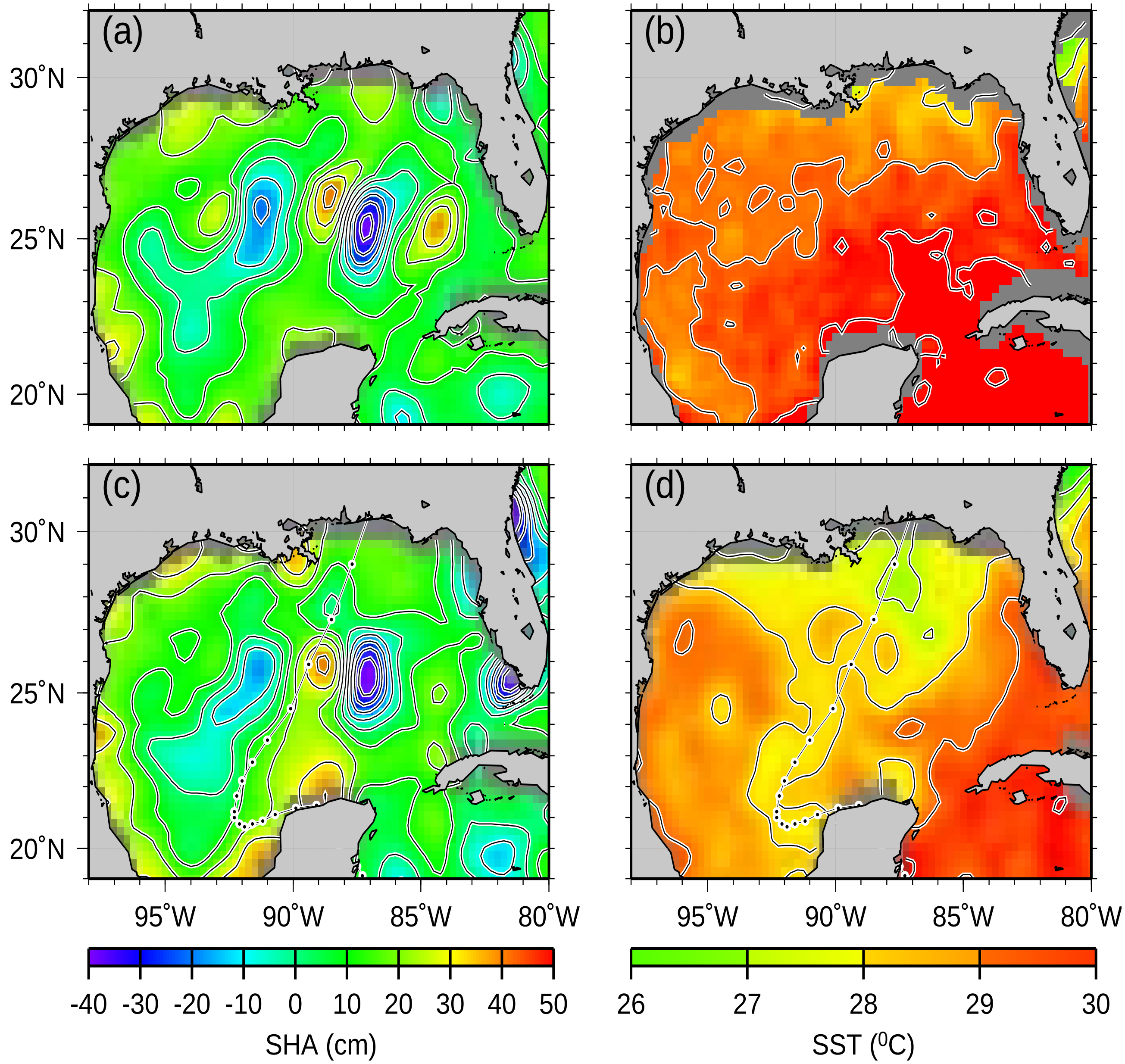

Figure 2: a) Pre-storm altimeter-derived SHA map for cycle 111 (18 Sep-27 Sep 95) showing positive height anomalies above 40 cm height corresponding to the warm eddy located on the right side of Opal's track. b) Pre-storm objectively-analyzed AVHRR SST composited from 27 to 28 Sept images. c) Post-storm altimeter-derived SHA map for cycle 112 (28 Sep-8 Oct 95) showing positive anomalies above 20 cm height corresponding to the warm eddy located on the right side of Opal's track. d) Post-storm objectively-analyzed AVHRR SST composited from 4 to 5 Oct 95 showing the ocean cooling pattern induced by Opal's winds along the track (SST images courtesy of Mariano and Ryan, RSMAS Remote Sensing Group).

Hydrographic observations were used to compute the densities of the upper (surface) and lower layers (> 200 m). As shown in Fig. 3, the field of reduced gravity in the Gulf of Mexico indicated regions where stronger stratification occurs, for example off the Mississippi River Delta where fresher water mixes with the ambient, saltier shelf water. The higher reduced gravities between the upper and lower layers represented a more stably stratified regime. TOPEX-derived sea height anomaly (SHA) for cycle 112 (Sept 28 - Oct 8) indicated three areas of SHA where the largest SHA was centered at 26°N and 87°W. For this reason, the mean field was added to these anomalies to understand the actual sea height and upper layer thickness as per (1). As shown in Fig. 4, the upper layer thickness (h_1(x,y,t)) for this same period was computed using the derived fields for mean upper layer thickness, reduced gravity and sea height anomaly (η') fields. This approach delineated two anticyclonic-rotating rings between 25 and 26°N.

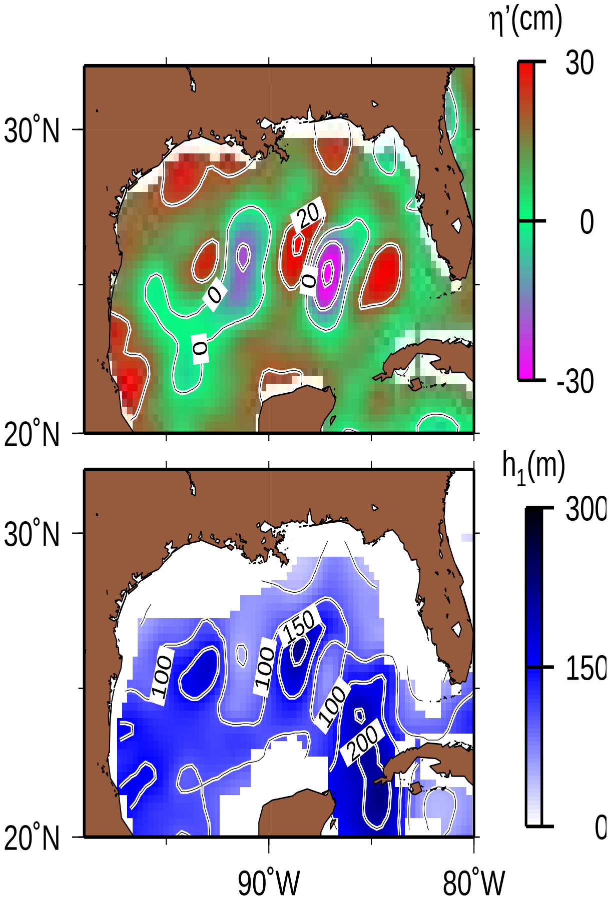

Figure 4: Surface height anomaly field (η' in cm) after the passage of Opal (upper panel) and the upper layer thickness ($h_1(x, y, t)$ in m) (lower panel). Notice that the upper layer thickness exceeds 200 m in the WCE.

A linear fit between the hydrographic data in the region revealed the relationship between the depths of the 20°C and 26°C isotherms

$$h_{20} = 1.93 h_{26} - 1.17, \qquad (3)$$

where h_{20} and h_{26} represent the depths of the respective isotherms. Note that the h_{20} is nearly twice the depth of the 26°C isotherm. The fits, based on 6461 profiles, were correlated at a level of 0.77 over most of the Gulf of Mexico except for the Bay of Campeche where considerable variability occurs in the temperature and salinity field. This procedure allowed a conversion of the upper layer thickness field relative to h_{20} based on the two-layer model to maps of the h_{26}, which are more relevant to the computation of hurricane heat potential according to arguments raised by Leipper and Volgenau (1972).

6. UPPER OCEAN HEAT CONTENT

A common perception of air-sea coupling in tropical cyclones is that SST represents the only important oceanic parameter for the development and maintenance of tropical cyclones (Palmen, 1948). SSTs represent only the temperature of a thin layer of less than a few centimeters thick that mixes with the underlying OPBL as the winds increase beyond 5 m s^{-1}. Winds of this magnitude extend well out in front of the storm (250 to 300 km) and erode this thin layer over time scale of tens of minutes. Even if the thickness of this layer is 5 m, it cools due to vertical mixing processes within an hour after the onset of 5 to 10 m s^{-1} winds based on Kraus and Turner (1967) physics. As winds increase to gale force, the tropical cyclone structure removes heat from the OPBL, not from the thin SST layer that has already been mixed. This implies that the underlying oceanic structure has far more importance to the heat and moisture fluxes feeding the storm than just SST as suggested in previous studies (Elsberry *et al.*, 1976; Black 1983; Shay *et al.*, 1992).

The depth over which temperatures exceed 26°C represents a heat potential for the storm's maintenance and development as shown in Fig. 1b (DeMaria and Kaplan 1994). In warm baroclinic structures, the 26°C water is distributed over deep layers ranging from 80 to 120 deep. The upper ocean's heat content is

$$Q = \rho c_p \Delta T \Delta z, \qquad (4)$$

where ρ is the oceanic density, c_p is specific heat at constant pressure taken as 1 gm cm^{-3}, ΔT is the temperature difference relative to 26°C distributed over a depth interval Δz (Leipper and Volgenau 1972).

As per (4), the SST was set to the observed AVHRR-derived SST (in Fig. 2) less 0.5°C, which is a bias that was found between mixed layer and skin temperatures observed from **A**irbornae e**X**pendable **C**urrent **P**rofilers and AVHRR in hurricane Gilbert (Shay *et al.* 1992). Note that the prestorm SSTs derived from the AVHRR were about 29°C. This adjusted surface layer temperature was assumed to linearly decrease over the upper layer relative to h_{26}-the depth of the 26°C isotherm. A further refinement to this crude approximation involves using the hydrographic measurements and a series of fits relative to h_{20} in resolving the vertical structure at 0.5°C increments similar to the calculations in (3).

The heat content prior to the passage of Opal ranged between 40 to 45 $\times 10^3$ cal cm^{-2} within the WCE (Fig. 5). Within the Loop Current, estimates of heat content were as large as 50 $\times 10^3$ cal cm^{-2}, consistent with estimates of Leipper and Volgenau (1972). Given that Opal encountered the WCE between 2100 GMT 3 Oct to 1100 GMT 4 Oct, the heat content relative to 26°C changed to a relative maximum of 20 to 25 x 10^3 cal cm^{-2}. The heat content change of 15 to 20 x 10^3 cal cm^{-2} occurred over approximate scales of 200 to 250 km. Given that this heat content change occurred over a period of 14 h, the heat loss rate is estimated to be from 25 to 35 x 10^3 cal cm^{-2} d^{-1}, which is well above the 4 x 10^3 cal cm^{-2} d^{-1} threshold estimate of heat content to sustain a tropical cyclone suggested by Leipper and Volgenau (1972). The ratio of this net difference to this threshold value was a factor of five to eight times larger. Thus, it is likely that the WCE played an important role in the intensification phase of Opal. Along the shelf in the Northern Gulf of Mexico, the prestorm oceanic heat content was less than 5 x 10^3 cal cm^{-2}, which may be one possible explanation of why Opal decreased in intensity prior to landfall.

The total observed heat loss here probably was not all released to the atmosphere by air-sea fluxes. Entrainment mixing at the base of the OPBL generally accounts for 75 to 90% of the cooling based on observational (Black 1983, Shay *et al.* 1992, Jacob *et al.* 1996) and theoretical and numerical results (Greatbatch 1983; Price 1981). Since Opal moved about 5 to 6 m s^{-1}, the *time available for vertical mixing* ($\approx$ 5 h) was short compared to the local inertial period ($\approx$ 27 h). Since *in situ* measurements were not acquired from AXCPs, it is difficult to assess the shear-induced mixing effect as in previous hurricanes (Sanford *et al.* 1987; Shay *et al.* 1992). These measurements would have provided ocean velocity and temperature structural variations to assess entrainment heat fluxes induced by near-inertial current shear as well as advective tendencies. Horizontal advection by geostrophic currents may have also played a role in the OPBL heat balance by redistributing the properties (Elsberry *et al.* 1976; Jacob *et al.* 1996). During the passage of Gilbert, Jacob *et al.* (1996) found that 10 to 15% of the heat budget in a WCE was associated with geostrophic advection. The satellite-based estimates from Opal were for a few days prior and after the storm, where advection may not have played a significant role with respect to the heat budget, compared to the Leipper and Volgenau measurements over three to four weeks. It is unclear as to how much of this observed heat escaped to the atmosphere through the air-sea interface by latent and sensible heat flux, however, the higher heat content water was available for hurricane Opal when the observed surface wind and stress field increased. Thus, SSTs may not necessarily represent the potential for a hurricane to reach its maximum intensity suggested by Fig. 1b (DeMaria and Kaplan 1984).

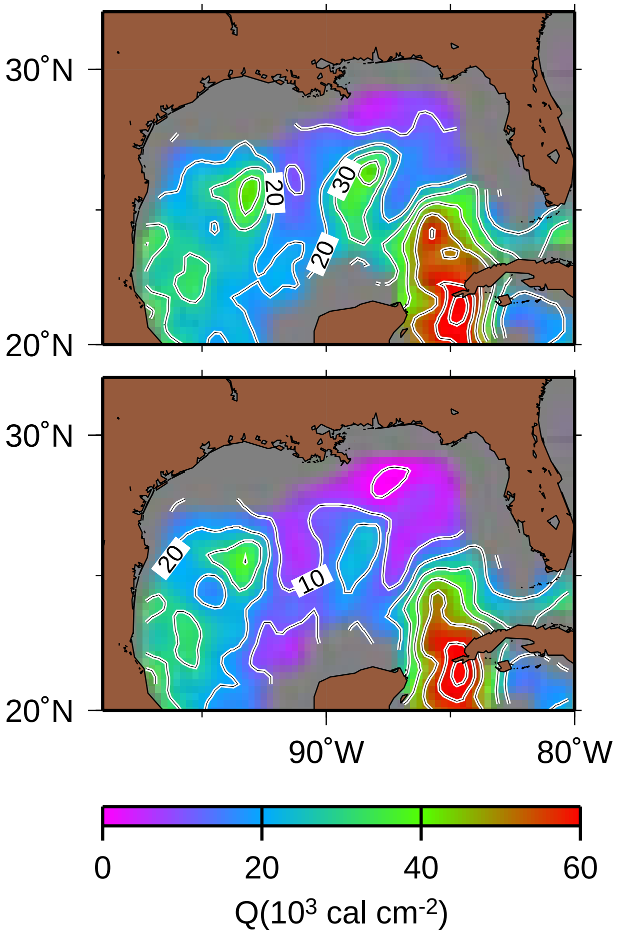

Figure 5: Heat content (Q) before the storm (upper panel) and after the storm (lower panel) $\times 10^3$ cal cm^{-2} relative to the depth of the 26°C isotherm.

The relevant horizontal scale associated with the positive vorticity core of the tropical cyclone is approximately ± $2R_{max}$. In the Opal case the initial R_{max} was about 30 km, whereas in the area of maximum deepening the eye contracted to 15 km due in part to the internal core dynamics. The core of the vorticity maximum decreased from 120 km to 60 km, which was smaller than the size of the WCE. While the tropical cyclone removes heat from the ocean over broad scales, however, as the core of the storms encounter these deeper reserviors of high-heat content water, a substantial increase in the heat fluxes is likely to occur over these scales. Previous studies have shown that strong winds blowing over temperature gradients significantly influence the air-sea fluxes that lower pressures via latent heat release.

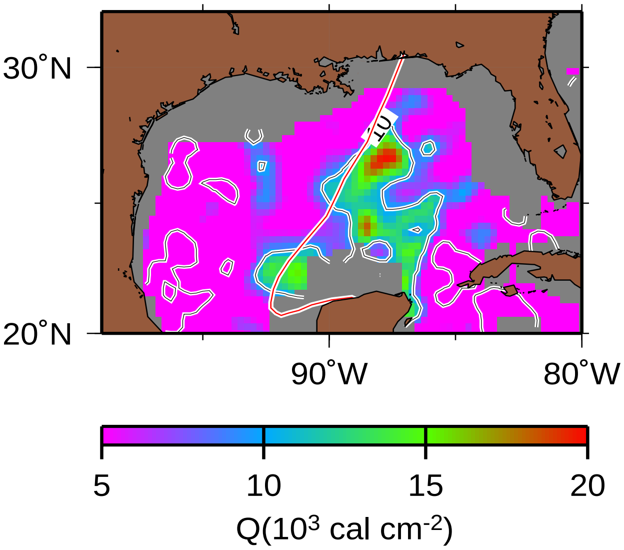

Figure 6: The change in heat content (ΔQ) x 10^3 cal cm^{-2} found by differencing the prestorm and poststorm heat content relative to the track of Opal.

7. SUMMARY

Satellite-based remote sensing using surface topography provides significantly more information about the underlying ocean structure when combined with historical and *in situ* measurements (*i.e.* AXCPs). Given an *RMS* error of a few cm for the NASA TOPEX altimeter, these structures include warm and cold rings, boundary currents and fronts all of which manifest themselves as free surface elevation. Goni *et al.* (1996) demonstrated that the altimeter data was useful in determining regimes rich in mesoscale variability such as rings off the Agulhas retroflection area off South Africa. Time series of continuous spatial measurements provides the data to trace the paths of eddies, upper layer thicknesses and the baroclinic and barotropic transports when combined with historical hydrographic measurements within the context of a two-layer model.

Extraction of the heat content is a straightforward extension of hydrostatic equilibrium in that warm features will be elevated (SHA > 0) and cold features will be depressed (SHA < 0). The two-layer model was based on a 20°C isotherm depth which separates the lower from the upper layer. Hurricane heat potential relative to the depth of the 26°C isotherm was estimated by first fitting hydrographic data to the 20°C isotherm depth, and by using the AVHRR-derived SST less a known bias from measurements (Shay *et al.* 1992). The heat content decreased by more than a factor of two, and based upon this difference and the approximate time of encounter of 14 h, the rate of 25 to 35 x 10^{-3} cal cm^{-2} d^{-1} was a factor of six to eight times larger than the Leipper and Volgenau (1972) threshold estimate. Some caution has to be applied to this threshold given that upper ocean processes such as advection and vertical shear were not explicitly included in their approach.

The key science issue is how much of the heat potential loss found prior to and subsequent to Opal was due to enhanced air-sea exchange, entrainment mixing at the base of the OPBL through shear-instabilities, and horizontal advection. The *time available for vertical mixing* was short compared to the local inertial period (Greatbatch 1983). Thus, the entrainment heat flux may have not approached the limits found under quiescent conditions where mixed layers were shallower. Considerably more near-inertial shear is required in warmer, deeper WCE to lower the bulk Richardson number to below criticality. Such strong shear-induced mixing events do not occur at depths of O(100 m). Slow moving or stationary storms may actually induce upwelling of the isotherms and alter the structure of WCE such as in the hurricane Anita case (Black 1983). Jacob *et al.* (1996) has documented the importance of horizontal advection in the mixed layer heat balance in a WCE during the passage of Gilbert. The WCE did not cool significantly suggesting that addtional heat was available for the atmosphere. Thus, in the present case, it is a real possiblity that a large fraction of the heat lost may have been due to the enhanced air-sea exchange process. These unresolved processes, and the lack of concurrent oceanic measurements raise new questions about the role of the upper ocean in intensity changes in the tropical storms.

Remotely-sensed observations from NASA TOPEX and AVHRR set the background conditions by detecting warm oceanic features and provide spatial context for oceanic and atmospheric observations acquired during NOAA HRD research flights. Pre- and post-storm SHA and SST observations will establish a data base to determine relationships between these oceanic data and tropical cyclone observations where intensification is likely to occur over warm oceanic features. Locations of these areas of variability where warm SHA dominate the circulation, and SHA maps derived from TOPEX will be made available on a RSMAS web site for both forecasters at NHC as well as experimentalists at HRD to access for their operational forecasting. Aircraft and buoy technology has emerged to the point where the air-sea interactions during these extreme events can be quantified with movable observing strategies that complements NOAA HRD research missions. These measurements will allow coupled models to be tested to exploit deficiencies in parameterizations, to advance new ideas, and to isolate physical processes involved in the air-sea interactions. The program sets the stage aimed at improving the understanding and forecasting of intensity change associated in tropical cyclones as discussed in Marks and Shay (1997).

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