1.3 HURRICANE HEAT POTENTIAL ESTIMATES FROM SATELLITE RADAR ALTIMETER MEASUREMENTS

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1. BACKGROUND

Tropical cyclone intensity forecasting has little skill in predicting storm strength particularly for rapid deepening storms (Elsberry *et al.* 1992). Based on deliberations from the Prospectus Development Team 5 (PDT5), tasked by the lead scientist of the United States Weather Research Program (USWRP) for NOAA and NSF (Marks *et al.* 1998), understanding and predicting intensity change requires the knowledge of: tropospheric interactions (troughs and ridges); internal core dynamics; and upper oceanic circulation which controls the upper ocean's heat potential.

Central to the upper ocean's effect on hurricane intensity is understanding the thermodynamics of the ocean mixed layer (OML) and the dynamical processes that modulate it such as the current field. An important example of this effect is the Gulf of Mexico basin since once a storm enters the semi-enclosed basin, it will make landfall along either the Mexican or United States coasts. The upper ocean's flow through the Yucatan Straits forces an annual variation in the Loop Current (Leipper and Volgenau 1972) (Fig. 1). This 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 and transports subtropical water with a markedly different temperature and salinity relationship compared to the background Gulf of Mexico water. Since the depth of the 20°C isotherm occurs at 250 to 300 m in the subtropical water compared to 100 m for the Gulf common water, warmer subtropical waters extend several hundred meters deeper thereby increasing its heat potential. As this feature intrudes further north, warm core rings (WCR) having diameters of 100 to 200 km pinch off at 11 to 14 month intervals. Rings 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. 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 heat potential water then follows the eastern seaboard, and as it separates from the coast off North Carolina, it forms the core of the Gulf Stream. Central to the storm intensity issue is that since the warm water extends to depths exceeding 100 m, they represent heat reservoirs to fuel tropical and extratropical storms.

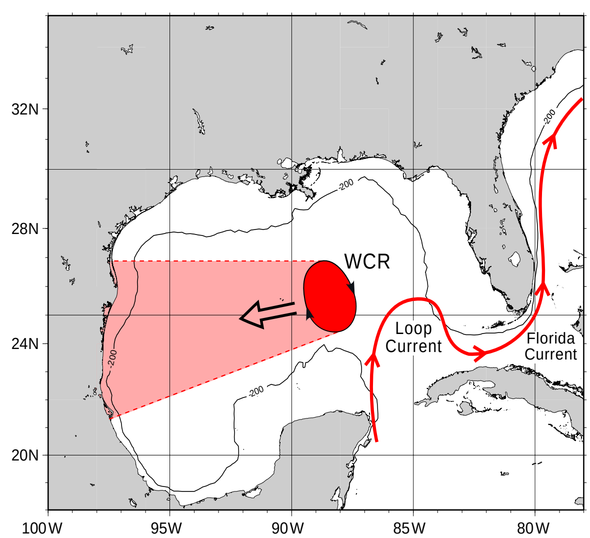

Figure 1: Cartoon of the Gulf of Mexico showing the mean boundaries of the Loop Current and the warm core rings (WCR) as they propagate westward.

Within this broader oceanographic context, the passage of hurricane Opal in 1995 in the Gulf of Mexico underscored inherent uncertainties in predicting sudden (and dramatic) wind-field changes. During hurricane Opal's intense deepening phase on 3 Oct 1995, surface winds increased from 35 m s^{-1} to more than 60 m s^{-1}. Vertical wind shear in the upper atmosphere was relatively weak; and, the cyclonic spin-up of Opal was maximized due to the approaching trough from

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the northwest (Bosart *et al.* 2000). Atmospheric conditions were favorable for this intense deepening cycle starting late on 3 Oct. In this area of Opal's rapid deepening, the SST distribution in the Gulf of Mexico showed no apparent signs of any warm ocean feature as uniformly distributed SSTs exceeded 29°C. However, images from the NASA oceanographic TOPography EXperiment (TOPEX) mission and post-storm Advanced Very High Resolution Radiometer (AVHRR)-derived sea surface temperatures (SST) suggested that during this time Opal passed over a WCR (Shay *et al.* 2000; Hong *et al.* 2000). This rapid intensification ended on 4 Oct as Opal exited this WCR, and it encountered less favorable atmospheric conditions. This was fortunate for the Florida Panhandle residents as even a weakened Opal inflicted severe damage to the coastal community. Notwithstanding, the community learned a valuable lesson concerning rapid deepening. That is, oceanic heat potential associated with warm ocean features played a significant role in the rapid intensification of storms during neutral or favorable atmospheric conditions. This is important for the public who rely on advancements in intensity forecasts for evacuation purposes.

In this note, SSTs and oceanic heat potential are described and cast within a simple OML model. Upper ocean measurements, acquired during the 1999 and 2000 hurricane field program from NOAA WP-3D aircraft (listed in Table 1), are used to estimate oceanic heat potential in the Gulf of Mexico. The approach of estimating heat potential from satellite radar altimetry algorithms is described using the Gulf of Mexico as a test bed. This is followed by two recent storms where rapid intensification occurred relative to warm ocean features such as the Loop Current/WCR Complex. Recommendations for future research efforts are summarized in concluding remarks.

2. SST VERSUS HEAT POTENTIAL

Palmen (1948) noted that warm, pre-existing SSTs in excess of 26°C were a necessary, but insufficient condition for cyclogenesis. Once the tropical cyclone (TC) develops and translates over the tropical oceans, statistical models suggest that climatological SSTs (OML temperatures) describe a large fraction of the variance (40 to 70%) associated with wind speed increases (DeMaria and Kaplan 1994). However, these models neither account for layer depths where temperatures exceed the 26°C temperatures nor advective tendencies by basic-state oceanic currents.

A common perception of air-sea coupling in TCs is that SST represents the only important oceanic parameter for their maintenance (Palmen 1948). To illustrate that OML temperatures are important, a highly idealized case is considered where the surface buoyancy

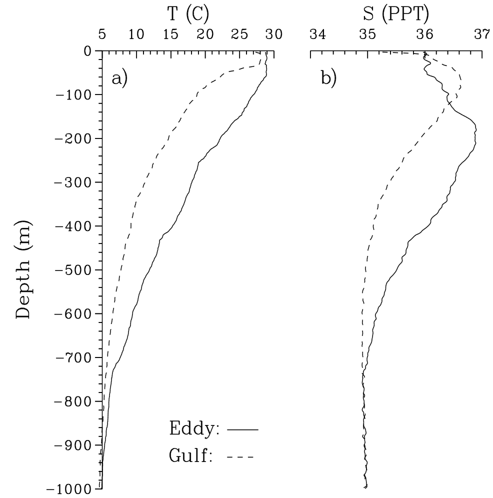

Figure 2: a) Temperature, and b) salinity profiles from two AXCTDs in the WCE/WCR (solid) and Gulf water (dash) deployed from the NOAA WP-3D.

flux is set to zero in a 1-dimensional, deepening mixed layer based upon Kraus and Turner (1967) given by:

$$\frac{dh}{dt} = \frac{1}{\Delta T}\left\{\frac{2}{\alpha g h}\left(\frac{\rho_a c_d}{\rho_o}\right)^{\frac{3}{2}} W^3\right\}, \qquad (1)$$

where h is the OML depth, ΔT is the temperature difference between an AVHRR-derived SST and the underlying OML temperature of 0.6°C (Shay *et al.* 1992), α is the thermal expansion coefficient (2.5 x 10^{-4} $^\circ C^{-1}$), g is the acceleration of gravity (9.81 m s^{-2}), ρ_o is the water density (1.026 x 10^3 kg m^{-3}), ρ_a is the air density (1.2 kg m^{-3}), c_d is the bulk aerodynamic drag coefficient (1.3 x 10^{-3}), and W is the wind speed at 10 m.

This simple model is solved for the time required for nominal wind speeds of 4 to 10 m s^{-1} to erode thin SST layers of thicknesses 0.5 m, 1 m, and 3 m that usually overlie an OML. For a ΔT of 0.6°C, the time required to erode the thin layer from an AVHRR-derived SST ($\approx$ mm thick) is a fraction of an hour even for a 4 m s^{-1} wind speed. If the 3 m depth is chosen for the same wind condition, the time required to vertically mix it is 15 h. As the winds increase, however, the required time to erode even a 3 m layer decreases substantially from 2.7 h for a 7 m s^{-1} wind speed to less than an hour for a 10 m s^{-1} surface wind speed. As winds increase to gale force ($>$ 17 m s^{-1}), the TC removes heat from the OML. The implication here is that the underlying oceanic structure has far more importance to the heat and moisture fluxes feeding the storm than just SST as observed in the hurricane Opal case (Shay

Date	AXBTs	AXCPs	AXCTDs
03 Aug 1999	46(3)	2(0)	2(1)
06 Aug 1999	18(0)	18(3)	16(2)
02 Oct 1999	14(0)	8(0)	8(1)
04 Oct 1999	8(2)	6(1)	5(1)
Success Rate	**94%**	**88%**	**84%**
10 Aug 2000	36(5)	1(0)	3(0)
13 Sept 2000	20(3)	16(3)	15(1)
21 Sept 2000	45(4)	0(0)	0(1)
01 Oct 2000	37(4)	9(2)	4(2)
Success Rate	**88%**	**81%**	**86%**

Table 1: Deployed probes during the 99 and 00 hurricane seasons. Numbers in parentheses indicate probe failures.

et al. 2000). Since the degree of upper ocean cooling is also a function of the OML depth, the regions of deep warm layers (i.e. WCR) thus provide more heat to the storm than regions of shallow OMLs (i.e. Gulf Common water).

3. RECENT IN SITU MEASUREMENTS

Research flights over the Loop Current in the eastern Gulf of Mexico were conducted on the NOAA WP-3D research aircraft over the past two seasons (Table 1). Grids of Airborne eXpendable Current Profilers (AXCPs), Airborne eXpendable Conductivity Temperature and Depth (AXCTDs) profilers and Airborne eXpendable Bathythermographs (AXBTs) were deployed during quiescent atmospheric conditions. As listed in Table 1, success rates exceeded 80%, including the deployment of the new AXCTDs, which provide conductivity (salinity) and temperature profiles to 1000 m. The AXCTDs provide salinity (via conductivity ratios) with accuracies of about 0.05 ppt and resolution of ±0.03 ppt to 1000 m over vertical scales of 1 m.

As shown in Fig. 2, thermal structure profiles from the Gulf of Mexico indicated that the depth of the 20 and 26°C isotherms of the warm, subtropical water were located at 260 and 130 m, respectively or nearly twice that of Gulf Common water. In the WCR, salinity changed by 1 ppt over 200 m compared to the salinity change by 0.6 ppt over 60 m in the Gulf water. This salinity gradient, coupled with stronger thermal gradients caused the buoyancy frequency to be 12 to 15 cph in the Gulf Common water compared to 6 to 8 cph in the WCR water (not shown). In this regime, salinity is important to the upper ocean mixing and has similar characteristics to those observed in the western Pacific Ocean warm pool (Lukas and Lindstrom 1991).

Given the depth of warm ocean features, these deeper profilers are useful in determining the horizontal structure of heat potential and geostrophically balanced current fields (steady-state). Based on representative velocity (V) and length (L) scales, the advective time scale ($\frac{L}{V}$) is about 1.5 days in this oceanic regime. As shown in Fig. 3, the integrated oceanic heat potential estimates were objectively analyzed using temporal and spatial scales based on the hurricane Gilbert data set (Shay *et al.* 1992). As the depth of the 26°C isotherm depicts the top of the cooler thermocline water, subtropical water is distributed over deep layers (≈ 130 m deep) compared to 35 to 40 m in the Gulf Common water. Given these differing depths, observed heat potential estimates of 130 KJ cm^{-2} in the Loop Current and WCR were well above those values in the Gulf Common water. Interestingly, the integrated heat potential estimates suggest a value of 1 KJ cm^{-2} m^{-1} at least in the Loop Current/WCR complex. These anomalously large values for heat potential represent a significant heat reservior for storms to tap. Note that the WCR separated from the Loop Current over a two-month period as suggested by the Oct 1999 observations.

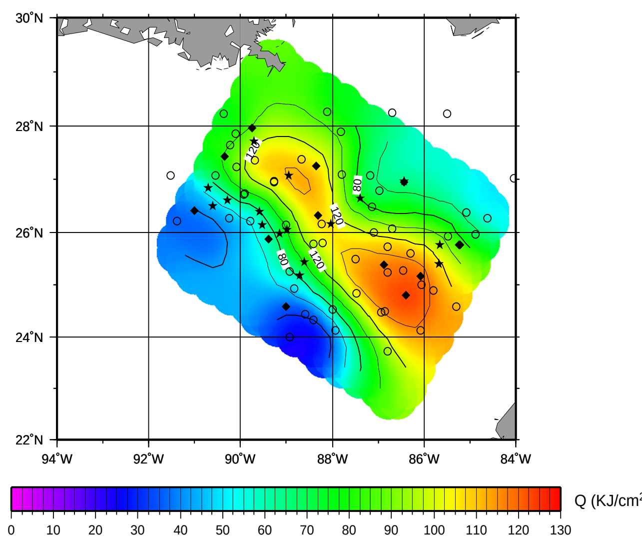

Figure 3: Ocean heat potential (color) and isotherm depth of the 26°C water (contour: m) based on AXCPs (star), AXCTDs (diamond), and AXBTs (circle) deployed in the eastern Gulf of Mexico in Aug 99 from a NOAA WP-3D flight.

4. RADAR ALTIMETRIC ESTIMATES OF HEAT POTENTIAL

Satellite altimetry data has proven to be a useful tool to study ring/eddy dynamics by acquiring continuous global coverage of surface height anomaly (SHA) fields (Goni *et al.* 1997). 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 relatively slow translational speeds of mesoscale ocean features ($\approx$ a few km d^{-1}), the SHA data from the altimeter detects and locates warm mesoscale features, usually identified as positive SHA values. The data used in this study are derived from TOPEX/Poseidon and ERS-2 radar altimeters (Cheney *et al.* 1994). The TOPEX altimeter measures the sea level beneath its groundtrack 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 resulting 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 represent sea level heights at each satellite alongtrack location referenced to the mean sea level heights based on several years of measurements. The 7 km-alongtrack SHA are then smoothed using a 30 km running mean filter.

As shown in Fig. 4a,b, comparison of TOPEX and blended TOPEX/ERS-2 SHA fields have differing characteristics based on their ground tracks noted above. These ground tracks have consequences on resolving the mesoscale eddy field in the Gulf of Mexico where ring diameters are O(200 km). Using the parameter matrix scheme of Mariano and Brown (1992), and the parameters from the hurricane Gilbert data set (Shay *et al.* 1992), the SHA fields from TOPEX and blended (TOPEX/ERS-2) data set were objectively analyzed. This analysis technique consists of decomposing a scalar observation into a large-scale or trend field, natural field variability on the mesoscale or synoptic time scale and the combined effects of unresolved scales (i.e. subgrid-scale noise). The trend is calculated using a least-square plane fit to the data variable. Final field estimates are the sum of the trend field and a mapped deviation field. In Figs. 4c,d, the blended fields have higher resolution and smaller mapping errors than TOPEX only 0.8 (12 cm), due to the large diamonds between the ascending and decending tracks of 300 km. Understanding and mapping measurement uncertainties is an important step in the improvement for estimating heat potential from satellite data.

These analyzed altimeter-derived SHA data calibrated by hydrographic data (i.e. temperature and salinity climatology) are then used as a proxy to monitor the upper layer thickness based on a two-layer model approximation (Goni *et al.* 1997). Mean upper layer thickness along with historical temperature and salinity profiles are used here to monitor the upper layer heat potential 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 hurricane genesis by Palmen (1948). Presumably, surface fluxes would be small below this value.

If the vertical ocean structure is approximated by a two-layer fluid, the upper layer thickness (h_1) can be estimated from the altimeter-derived SHA (η') field, provided that the mean upper layer thickness ($\overline{h}_1$) and reduced gravity (g') fields are known to a first-order from historical measurements based upon the expression:

$$h_1(x, y, t) = \overline{h}_1(x, y) + \frac{g}{g'(x, y)}\,\eta'(x, y, t), \qquad (2)$$

where $g' = \epsilon g$, g is the acceleration of gravity, and:

$$\epsilon(x, y) = \frac{\rho_2(x, y) - \rho_1(x, y)}{\rho_2(x, y)}, \qquad (3)$$

where $\rho_1(x, y)$ and $\rho_2(x, y)$ represent upper and lower layer densities, respectively. The upper layer thickness is defined from the sea surface to the depth of the 20°C isotherm. Early studies of the vertical structure of rings in the Gulf of Mexico show that the largest vertical temperature gradients are located between 15 and 21°C. Based upon temperature and salinity variability from hydrographic measurements, the choice of the 20°C isotherm depth is appropriate for the assumed two-layer ocean in this analysis. That is, the 20°C isotherm separates two layers of differing densities in and outside the WCR (see Fig. 4 in Shay *et al.* (1998)). However, in this two-layer approximation (Goni *et al.* 1997), the density is considered constant in the upper layer defined by the depth of the 20°C isotherm.

Climatology based upon Levitus (1984) is used to estimate both reduced gravity (g') and mean upper layer thicknesses ($\overline{h}_1$). Central to this question is the determination of an appropriate climatology of the upper layer thicknesses representing the depths of the 20°C and 26°C isotherms. Shay *et al.* (2000) used an annual climatology (Fig. 5) for the depth of the 26°C isotherm. These estimates oversmooth the penetration of the Loop Current into the Gulf of Mexico compared to a hurricane seasonal climatology (Fig. 6). Mainelli-Huber (2000) found improved agreements with in situ data with a hurricane (six-month average) climatology particularly during periods when the Loop Current was located well into the Gulf of Mexico. Deeper layer thicknesses exceeding 100 m are aligned with the axis of the Loop Current along 84°W. Generally, reduced gravities (not shown) range from 2 to 6 x10^{-2} m s^{-2}, suggestive of a stratified ocean. Larger values of reduced gravities are associated with the core of the

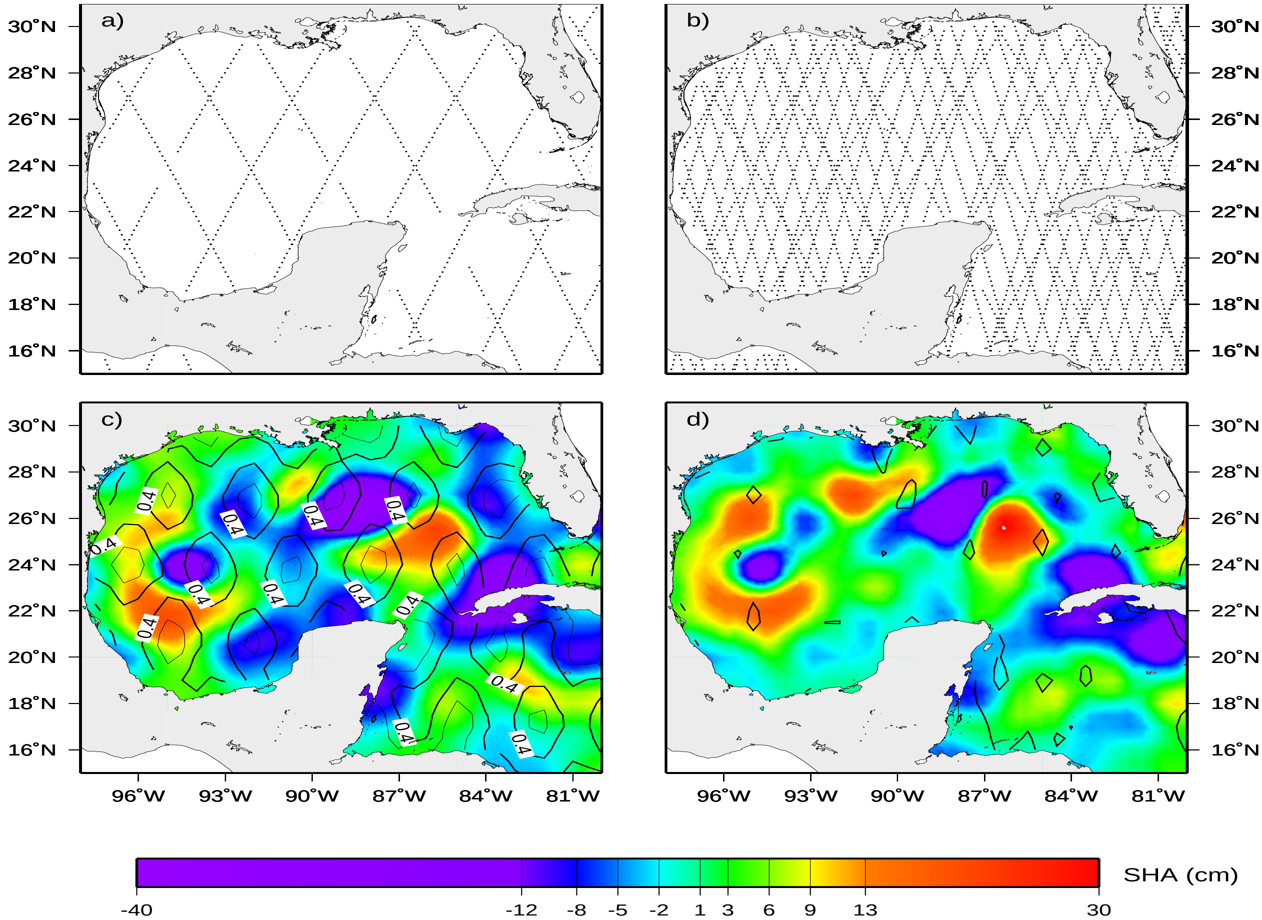

Figure 4: a) TOPEX and b) blended TOPEX/ERS-2 ground tracks in the Gulf of Mexico, objectively analyzed SHA fields (cm) and mapping errors for c) TOPEX and d) blended fields. A mapping error of 0.4 (darker contours) equates to a SHA error of 8 cm, 0.8 (lighter contours) represent 12 cm.

Loop Current, and the fresher water influx from the Mississippi River Delta along the shelf in the northern part of the basin. As indicated by Fig.2, the maximum upper layer thickness for the 20°C isotherm depth in the Loop Current exceeds 250 m north of the Yucatan Straits.

Hydrographic data from the Gulf of Mexico were used to determine an empirical relationship between the depth of the upper layer thicknesses (i.e. depth of the 20°C isotherm) and the depth of the 26°C isotherm (referred to as H), which is more relevant for hurricanes (Palmen 1948, DeMaria and Kaplan 1994). As a first approximation, a linear regression is made between H and h_1, yielding a relationship where the upper layer thickness is approximately twice the depth of the 26°C isotherm:

$$H(x, y, t) \; = \; 0.48 \; h_1(x, y, t) - 5. \qquad (4)$$

This linear regression is correlated at a level of 0.77 over most of the Gulf of Mexico. A large fraction ($\approx$ 98%) of the data is within one standard deviation from the regression line. This procedure allows the conversion of the upper layer thickness field relative to h_1 based on the two-layer model to maps of H. Note that the relative ratios of these two isotherms do not necessarily agree with this empirical relationship outside of the Gulf of Mexico (Mainelli-Huber 2000).

The depth to which the temperature exceeds 26°C is proportional to the *hurricane heat potential* (Leipper and Volgenau 1972). This definition is arbitrary in the sense that the average air temperature is typically 24 to 26°C. In warm baroclinic structures, the 26°C water is distributed over deep layers ranging from 80 to 120 m deep (see Fig. 3). The heat potential of the upper layer relative to the depth of the 26°C isotherm:

$$Q(x, y, t) = \rho c_p \Delta T(x, y, t) \Delta z(x, y, t), \qquad (5)$$

where ρ is the average oceanic density taken as 1.026 g cm^{-3}, c_p is the specific heat at constant pressure taken as 1 cal gm^{-1} °C^{-1}, and ΔT is the difference between

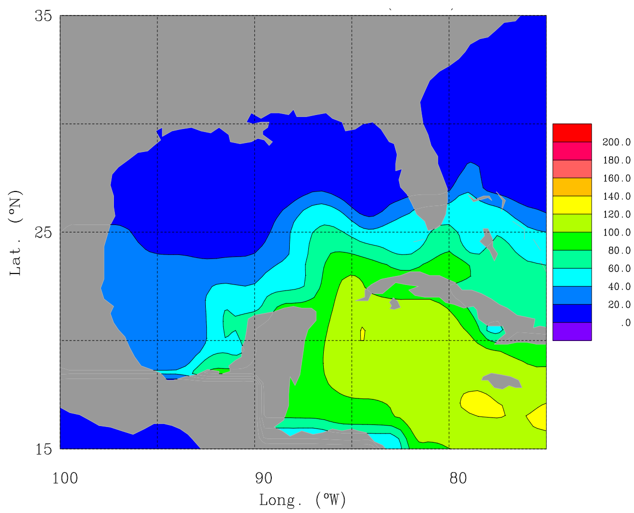

Figure 5: a) Annual climatology of the depth of the 26°C isotherm in the Gulf of Mexico (Mainelli-Huber 2000).

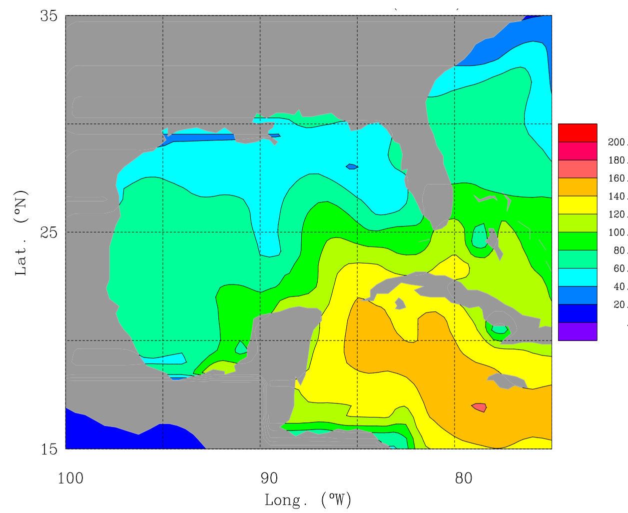

Figure 6: a) Hurricane season climatology of the depth of the 26°C isotherm in the Gulf of Mexico (Mainelli-Huber 2000).

the SST and 26°C summed over a depth interval Δz. If vertical structural measurements are available at a given depth interval, the heat potential expression is easily solved by vertical integration. However, *in situ* thermal and momentum structure observations are not always available, and in the summer months one of the setbacks is the spatially uniform SSTs above 29°C with little thermal contrast in the Gulf of Mexico (see Fig. 6 of Shay *et al.* 2000). From a bulk perspective, if Δz is taken as H, the depth of the 26°C isotherm, then (5) becomes:

$$Q(x, y, t) = A_1 \rho c_p \nabla_z T(x, y) H^2(x, y, t), \qquad (6)$$

where $\nabla_z T$ is the mean vertical temperature gradient between the surface and the 26°C isotherm obtained from AVHRR-derived SSTs and historical hydrographic data. Based on regression analyses, we have found a slope (A_1) of 0.8 to 0.85 between the satellite derived and the integrated thermal structure from the aircraft profiles (see Table 1). By multipling the expression by the regression slope (0.83) the gradient and integral methods begin to converge towards a realistic value of heat potential. Our approach is also being applied to available Lagrangian float data (T,S) in the western Atlantic Ocean basin to continue to refine this estimate through regression analyses.

5. STORM INTERACTIONS

Similar to the explosive nature of hurricane Opal, hurricanes Bret (August 1999) and Keith (October 2000) rapidly deepened from tropical storm status to category 4 storms in less than 24 hours. As shown in Fig. 7, Bret deepened to a category 4 storm over an area where two warm ocean features (heat potential > 80 KJ cm^{-2}) were located in the western Gulf of Mexico (Goni *et al.* 2000). By differencing pre and post-storm heat content data derived from the TOPEX-derived surface height anomaly field (SHA), normalized heat potential by the threshold value of 16.7 KJ cm^{-2} (Leipper and Volgenau 1972), changed by a factor of about 4 in this region. Thermal profiles from AXBTs also showed that 29°C water extended to 50 m depths. Hurricane Keith rapidly intensified from tropical storm to a category 4 storm in the northwestern Caribbean Sea where the heat potential exceeded 120 KJ cm^{-2} (Fig. 7b). These rapid-intensifiers occurred under favorable atmospheric conditions juxtaposed with high heat potential regimes. For ten storms over the past three hurricane seasons, Mainelli-Huber (2000) found maximum cross correlations between wind speed and heat potential changes ranging between 0.7 to 0.9. These heat potential changes (3 to 4 times the threshold) lead the wind speed by 12 to 18 h. Thus, mapping the heat potential is important even for slowly developing storms.

For this reason, oceanic and coupled models must have realistic ocean conditions to correctly simulate the response, and eventually forecast intensity. Jacob (2000) has showed that the choice of the entrainment mixing scheme 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 ocean mixed layers (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). Understanding the impact of oceanic

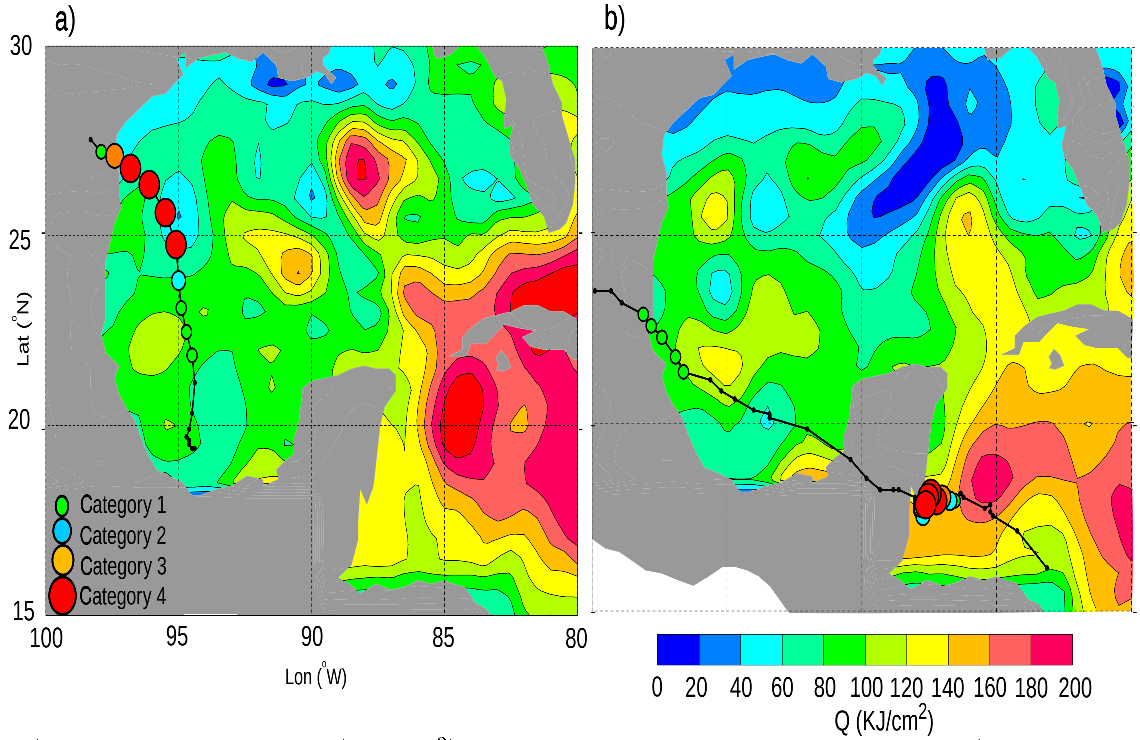

Figure 7: a) Heat potential estimates (KJ cm^{-2}) based on a hurricane climatology and the SHA field ftom TOPEX radar altimetry prior to hurricanes a) Bret (1999) and b) Keith (2000) relative to the track and intensity (legend in upper left of panel a). Notice that in panel a, WCR is just beginning to spin off the Loop Current at 28°N in the Gulf of Mexico in Aug 1999 (Images courtesy of M. Mainelli of TPC).

feedback is crucial to accurately forecasting storm intensity change. In this context, the OML structure and thermocline depth (including current and current shear) is fundamentally important to both feedback regimes as these processes modulate the amount of heat available to the storm.

6. CONCLUDING REMARKS

Observational (satellite and *in situ*) evidence supports the premise that when neutral or favorable atmospheric conditions (weak shear) are juxtaposed with high levels of oceanic heat potential, explosive deepening in hurricanes may occur as observed in recent hurricanes (Opal, Bret, and Keith). Even for weak storms encountering the Loop Current or WCRs, intensification was observed in Hurricane Gordon and Tropical Storm Helene (2000) despite unfavorable atmospheric conditions.

The key finding emerging from our research is the integrated thermal structure (heat potential) is a more effective measure of the ocean's influence on storm intensity than just SST. That is, the upper ocean structure must be accurately accounted for in the models with realistic ocean mixing parameterization schemes based on observations. Thin OML deepen and cool very quickly and may cause negative feedback to the atmosphere to occur. In regimes of deep OML, there is reduced negative feedback as the layer does not significantly cool and deepen. 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 (Shay *et al.* 2000).

Implicit in these satellite algorithms is the acquisition of high-quality ocean structure measurements before, during and after hurricane passage. These data, including lagrangian float data, are needed to refine the algorithms to estimate heat potential. 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; Mainelli-Huber 2000), but they are crucial in evaluating oceanic and coupled model simulations. An important ingredient in these coupled models is the parameterization of air-sea fluxes. Little is known about these fluxes in high wind conditions. Thus, to examine the physics of these processes, and to improve model parameteriztions, coupled observations are needed for rigorous, detailed comparisons to model generated fields. The TC community has now entered a **new era of hurricane intensity forecasting** where observed and modeled fields must be examined carefully to undertand these processes that contribute to intensity (Marks *et al.* 1998).

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