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Mid-Year 2 Report: Eastern Pacific Ocean Heat Content Estimates For SHIPS Forecasts

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1. Introduction: Over the past ten months of the grant, the effort has focused on processing data and synthesizing data sets discussed in Section I of the grant and building a realistic climatology. The approach includes satellite data, XBT data (including moored data in the EPAC such as TAO arrays), and exploring climatologies such as the US Navy's Generalized Digital Environmental Model (GDEM) in building a suitable hurricane season climatology for EPAC.

2. Altimetry: TOPEX/ Poseidon (T/P) and Jason-1 altimeter measures the sea level every 9.9 days along repeat ground-track spaced 3^{o} longitudinally at the Equator. ERS-2 mission and Geosat Follow-On-Missions (GFO) have repeat tracks of 35 and 17 days, respectively. The availability of a merged SSH data is shown in Figure 1 for a merged product (http://www.jason.oceanobs.com/html/donees/produits/satellites_{uk}.html) for an altimetry product available 1992-2005 from AVISO. Weekly SSHs track eddies from Aug through Oct 2001 using the product during the EPIC field program (Fig 1). By the time the eddy reaches the center of the EPIC domain, it starts to spin down in strength. The ring pathway, tracked over a three-month period based successive images, suggests that the warm features move at 13 to 15 cm s^{-1} towards the west southwest and have OHC heat content values of more than 50 kJ cm^{-2} (Fig.2).

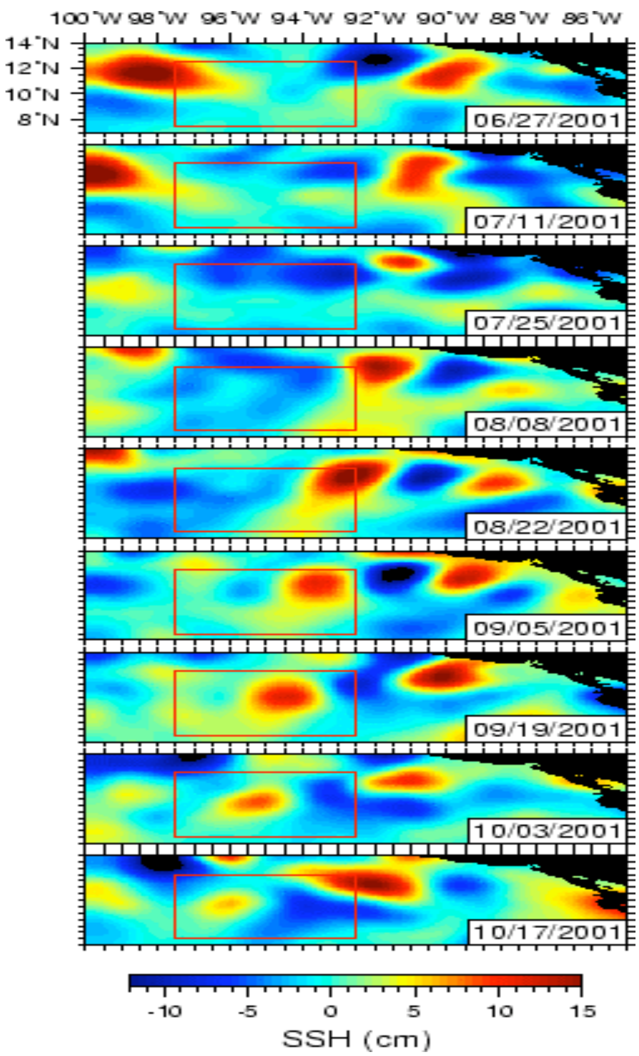

Fig 1: SSH field (cm) in the EPAC relative to the EPIC domain in summer 2001.

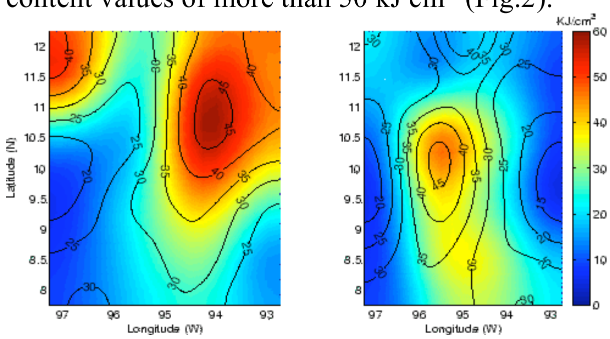

Fig 2: OHC (kJ cm^{-2}) from *in situ* profiles during EPIC in Sept (left) and Oct (right).

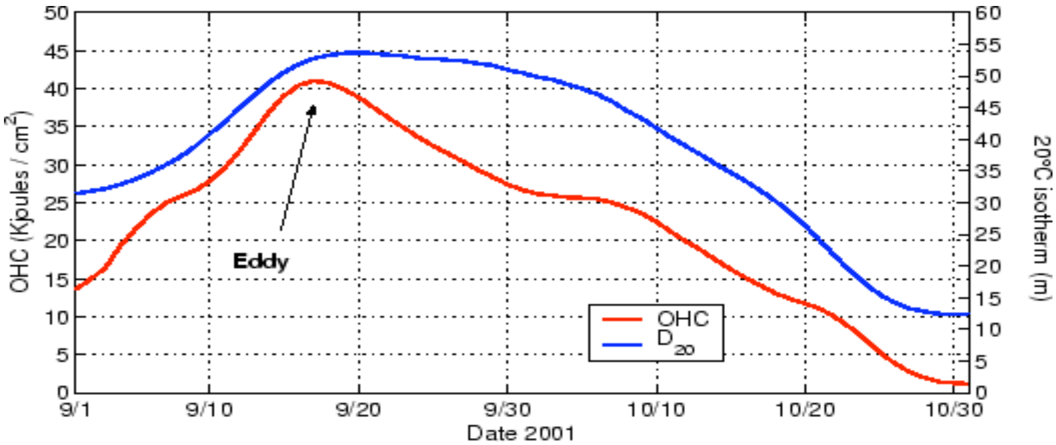

Fig 3: OHC (kJ cm^{-2}) and Depth of the 20ºC isotherm (m) determined from the TAO mooring at 10ºN95ºW during Sept and Oct of 2001 during the EPIC field program**.**

3. Mooring Data: Time series of thermal structure measurements from TAO moorings in the EPAC deployed as part of the long-term monitoring by PMEL have been processed. As shown in Figure 3, here is an example of depressed thermocline (i.e. 20ºC isotherm depth) that occurs during the passage of a warm core eddy at 10ºN and 95ºW. At this position, the OHC values exceeded 40 kJ cm^{-2} as the eddy began to spin down and weaken, consistent with Figures 1 and 2. The TAO time series from May through October will be used below to ground truth the remotely sensed OHC values.

4. Revised Empirical Model: Based on our analysis, it became clear that the approach in the Atlantic Ocean basin needed to be revised for application in the EPAC. The rational is that the stratification is much stronger in the EPAC where the stratification or buoyancy frequency (i.e. the vertical derivative of the density structure) has a maximum (N_{max}) value of 24 cycles per hour (cph) compared to values of 6 to 12 cph in the Atlantic basin (Figure 4 right panel). Moreover, the vertical salinity changes (not shown) at the base of the oceanic mixed layer (h) contribute to these changes. Salinities in the EPAC tend to be less than in the Gulf of Mexico due to the ITCZ where excess rainfall reduces the mixed layer salinities compared to the Gulf of Mexico. However, the shoaling thermocline that sets this large value of N, which ironically is close to the depth of the 26ºC isotherm.

As the algorithm represents the area underneath the curve (Fig. 4 gray area), the OHC in the oceanic mixed layer (h) relative to the remotely sensed SST from TRMM microwave imager (TMI) is proportional to the product *[(SST-26ºC) x h]* plus the contribution underneath the layer from h to the depth of the 26ºC isotherm using the SST given by $0.5\ [H_{26} - h][SST - 26^{o}C]$. The total OHC is the addition of the mixed layer contribution plus the contribution from the layer depth to the isotherm depth. There are a few caveats associated with this empirical. First, the

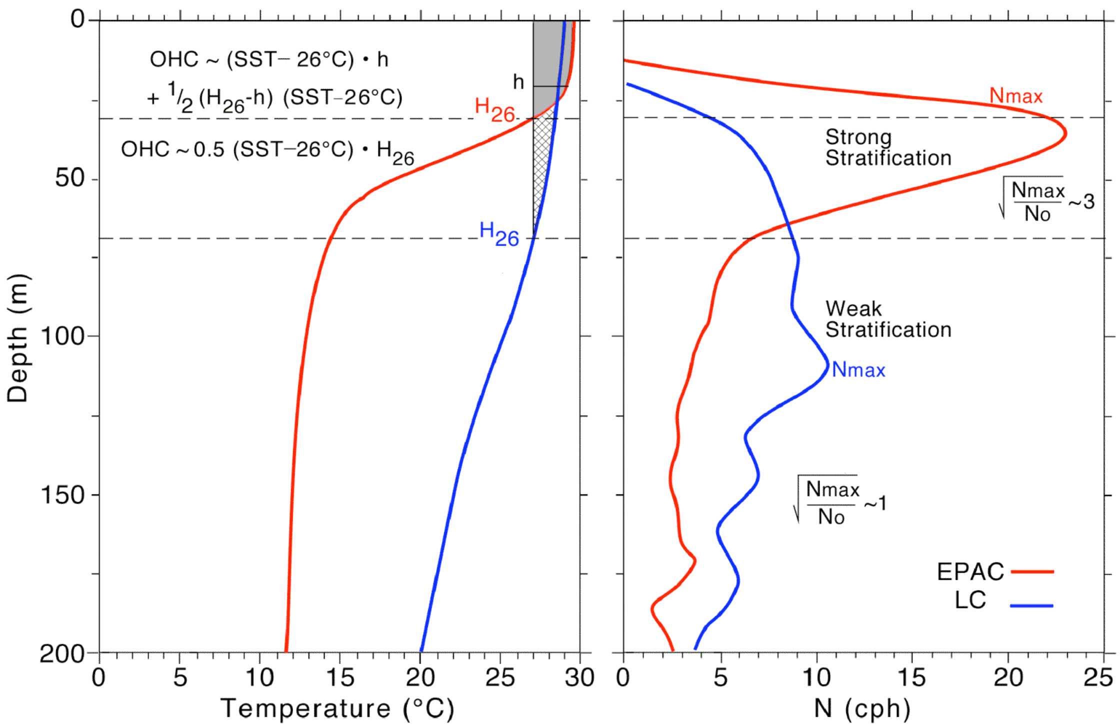

Figure 4: Carton of the revised empirical approach for the EPAC based on two AXCTD profiles shown in red curves (shaded area) compared to the approach used in the Atlantic Ocean basin shown in blue curves (hatched area) in the temperature (left panel:°C) and the corresponding N profiles (right panel: cph) that reflects strong stratification (EPAC-red) and weak stratification (Loop Current-blue), h is the ocean mixed layer depth and H_{26} represents the 26°C isotherm depth. Notice the ratios of the maximum buoyancy frequency (N_{max}) to the reference buoyancy frequency (N_o). Notice the square root of this ratio is a factor of two to three times greater in the EPAC than in the LC.

seasonal climatological mixed layer has its own density that sits on top of a two-layer fluid. Second, the mixed layer depth is time invariant since we do not have surface heat fluxes, wind stress or current shear at the base of h to determine the evolution the oceanic mixed layer. Variations in the SHA anomaly field have maximum impact in the seasonal thermocline (i.e. 20°C isotherm depth) and have a minimum impact at h. This approach must be equally tested in the Atlantic Ocean basin to assess whether there is an improvement in the OHC estimates. Previous comparisons based on seasonal climatology, however, have indicated good agreement between satellite-inferred and observed OHC estimates in the Gulf of Mexico given its weaker thermal structure compared to the EPAC.

5. GDEM (V3 versus 2.1): We are comparing results for these two climatologies over monthly and seasonal time scales. One issue that has recently arisen is determining the oceanic mixed layer depth as shown in Figure 5. For example, the ocean mixed layer (h) by definition is well mixed in properties such as temperature and salinity. Close inspection of the salinity profiles for Sept reveal significant differences between salinity in the upper 10 to 15 m of the water column. That is, the salinity structure in **V2.1** reveals no constant salinity in this near-surface layer, by contrast, the salinity is relatively constant in the layer from 15 m to the surface. These vertical changes alter the density structure. In addition, h decreases from a maximum in May of 30 to 40 m to a minimum of about 10 m in October. *This result points to the importance of perhaps using a monthly climatology for the OHC estimation.*

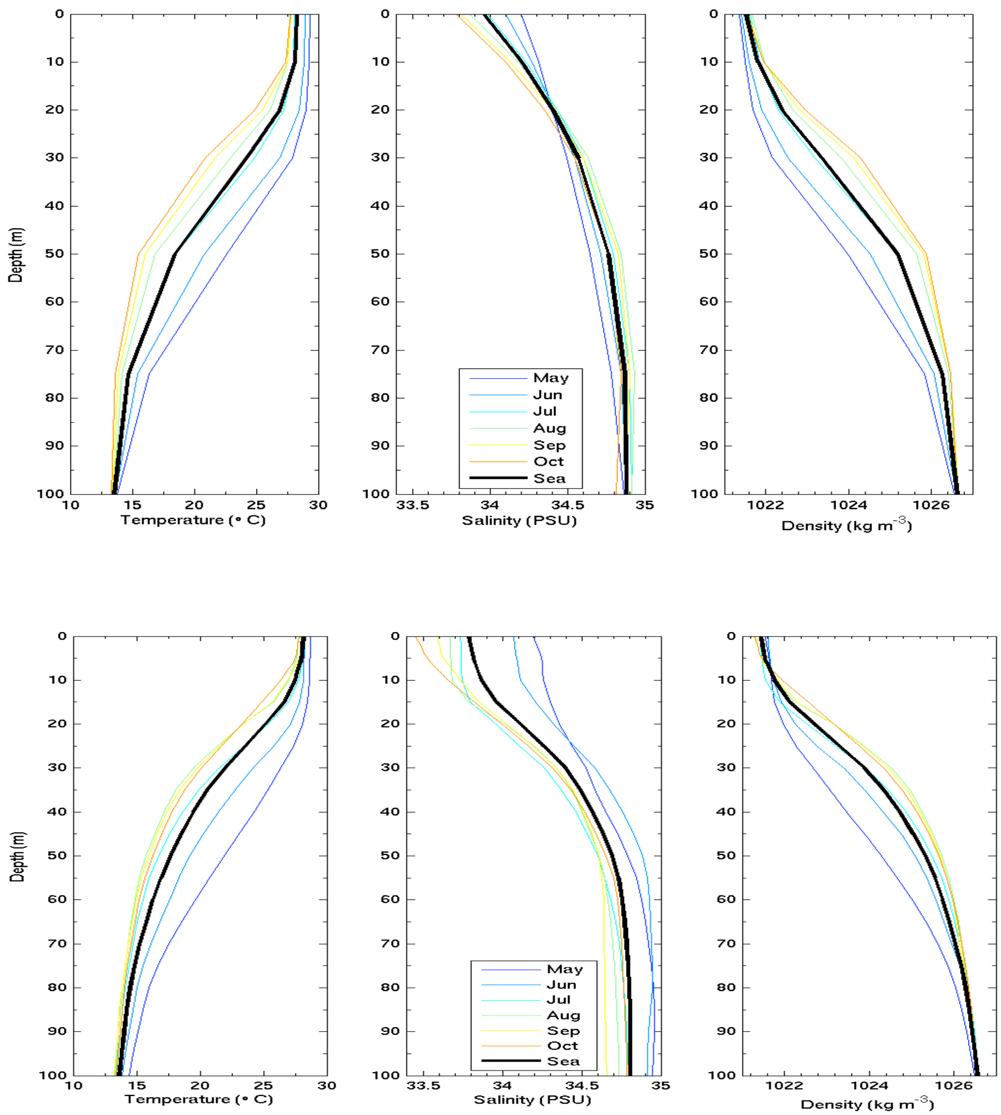

Figure 5: Monthly temperature (left), salinity (center) and density (right) profiles from GDEM V2.1 (upper) and GDEM V3 (lower) at 10ºN and 95ºW in the upper 100 m from May to October

(also constant in an ocean mixed layer). Over the season from May to October at 10ºN and 95ºW, climatologies suggest a shallowing of the surface mixed layer to about 10 m. This layer shallowing is inconsistent with the EPIC data that suggests that the ocean mixed layer is about 20 to 25 m deep in the warm pool. <u>In terms of the above a model in Figure 4, this results in an underestimate of the OHC.</u>

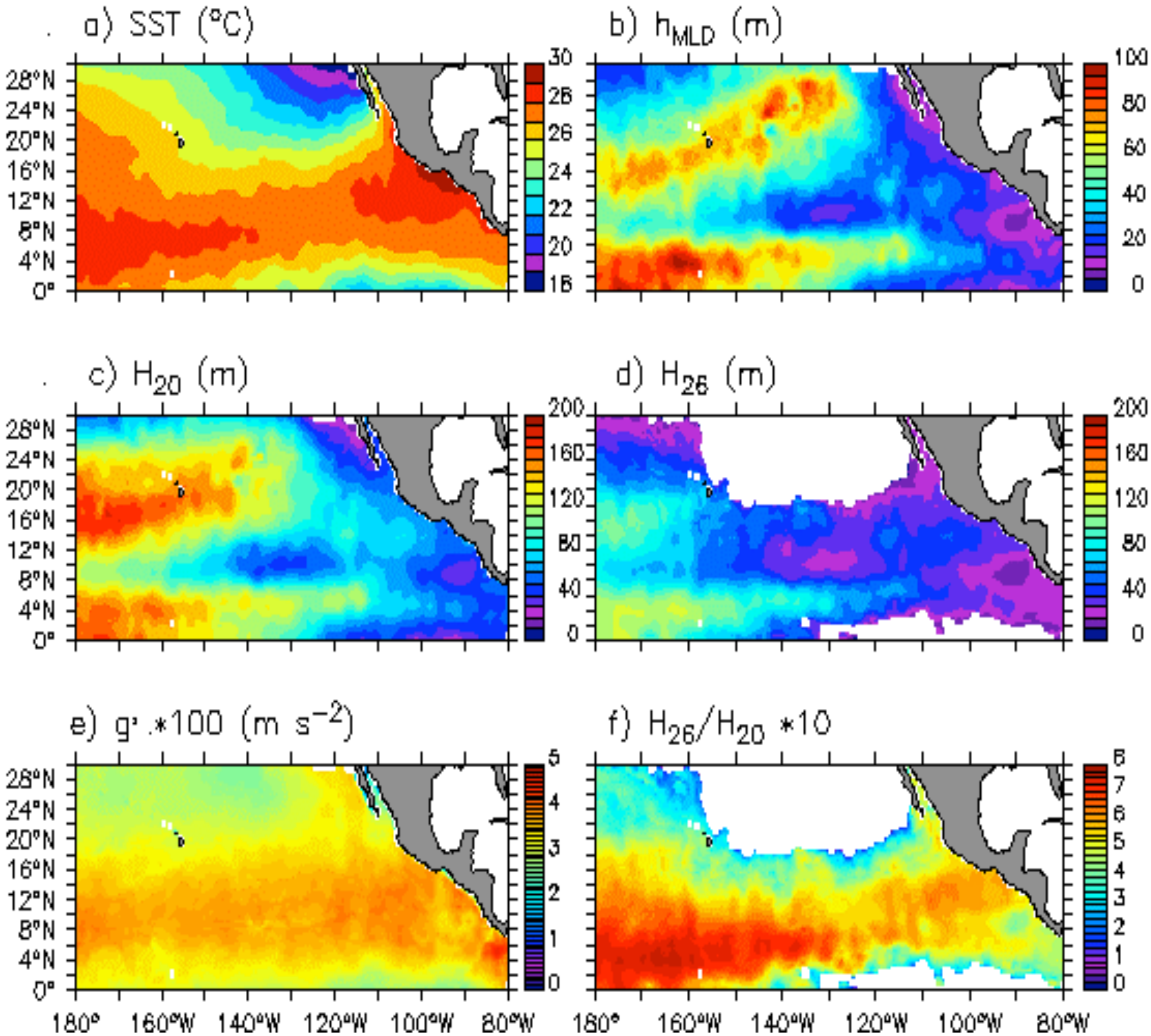

Figure 6: Hurricane seasonal climatology values for a) SST (ºC), b) h (m), c) H_{20} (m) , d) H_{26} (m), e) g' (x 10^2 m s^{-2}) and f) $H_{26}\, H_{20}^{-1}$ (x 10) from GDEM V 3 for use with the empirical approach outlined in Figure 4.

Accordingly, this approach will use the latest version of the GDEM **V3** climatology is being used for this grant and the analysis contained herein. This is the same version used for the Atlantic Ocean basin to ensure consistency between the two basins. Climatologically, the SSTs exceed 28ºC in the EPAC as shown in Fig. 6a. The spatial variations in the surface mixed layer depth are shown in Figure 6b based on an average from May through October. Notice how the oceanic mixed layer depth shoals towards the east where mean values range between 15 to 20 m as compared to h of more than 80 m west of 120ºW. These spatial changes in h are now reflected in the approach.

As shown in Figure 6c,d, the seasonal mean depths of the 20º and 26ºC isotherms are based on an average over a hurricane season using GDEM profiles at 0.5º resolution in the EPAC. Notice the general shoaling of the isotherm depths from west to east forces tighter vertical gradients in the warm pool's upper ocean thermal structure (and shallower ocean mixed layer depths). Generally, the 20ºC isotherm depths range from 30 to 50 m compared to more than 100 m west of 140ºW. The corresponding 26ºC mean isotherm depth ranges between 15 to 25 m in the warm pool (12ºN, 95ºW) and north of 20ºN, the 26ºC isotherm shoals to the surface. This surface shoaling, known as ventilating of the 26ºC isotherm, implies that once a TC reaches that area, they will begin to lose their oceanic heat source and presumably begin to weaken. A second aspect of this area is that the buoyancy frequencies at the base of the ocean mixed layer exceed 20 cph as suggested in Figure 4.

As per the model, reduced gravity (g') distribution (density difference between upper and lower layer multiplied by the acceleration of gravity) and the ratio between the 26ºC and 20ºC isotherm depths are shown in Fig. 6e,f. East of 120ºW, reduced gravities are about 5 x 10^{-2} m s^{-2}, which is indicative of the strong stratification of the EPAC. West of this longitude, g' decreases to about 3.5 x 10^{-2} m s^{-2} whereas towards the northern part of the domain, reduced gravities decrease to about 2 x 10^{-2} m s^{-2}. For example, in the area of hurricane Norbert experiment (84), the observed buoyancy frequency was 11 cycles per hour (cph) compared to more than 20 cph in the warm pool. Such spatial variations have a pronounced impact on cooling and the cold wake or trail left behind by the hurricane. In general, the strong stratification in the warm pool often precludes a strong internal wave wake left behind by hurricanes. During hurricane Juliette in 2001 (not shown), the cold wake of SSTs exceeding 4ºC only began towards the north and west of the warm pool.

6. OHC: As shown in Figure 7, the OHC is estimated using **GDEM V3** climatology from Figure 6 using the surface height anomaly (SHA) and TMI-derived Sea-Surface Temperature (SST) fields for mid-September 2001. The approach uses SHA from T/P, GFO, and ERS-2 altimetry data (not blended AVISO in Figure 1) where repeat tracks are 9.9, 17 and 35 days for T/P, respectively. These fields are blended and objectively analyzed to a 0.5º grid from the coast to 180ºW and from the equator to 30ºN and are then combined to estimate isotherm depths and OHC. As shown in Fig. 6a, the warm SSTs exceeded 27.5ºC north of the equatorial cold tongue and extended longitudinally from the coast to 180ºW. Cooler SSTs are observed north of 20ºN,

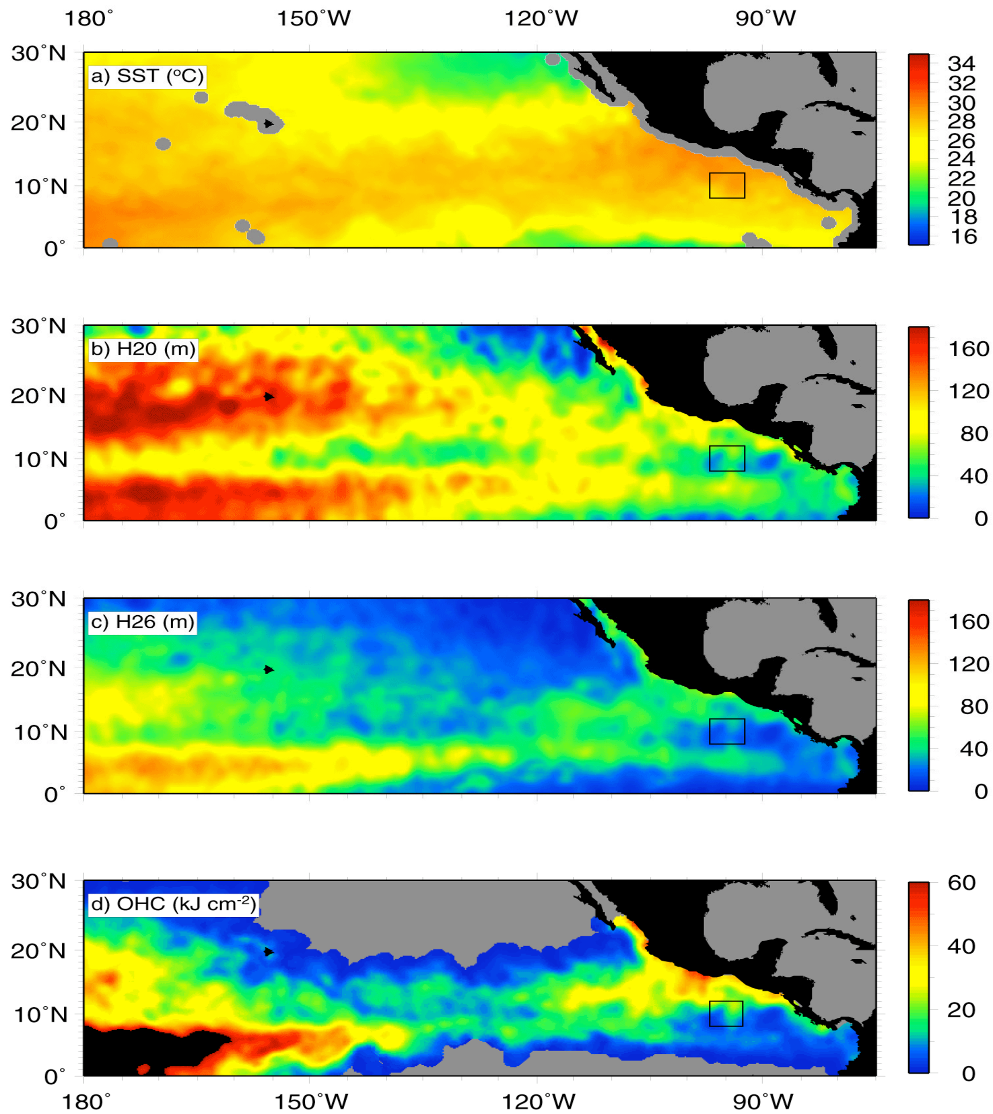

Figure 7: a) TMI-derived SST (ºC) , b) H_{20} (m), c) H_{26} (m), and d) OHC (kJ cm^{-2}) in the EPAC for 15 Sept 2001 during the EPIC field program as depicted by the black box centered at 10ºN and 95ºW.

and decrease to below 26ºC at about 24ºN. The mean 20ºC isotherm depths suggest a general shoaling from west to east to a relative minimum of about 40 m in the EPIC domain. Notice the general shape of this minimum that apparently was affected by a warmer feature between the two cold cells (Fig. 7b). This may be a manifestation of the Costa Rica Dome, which is a semi-permanent feature of the EPAC due to the cyclonic mean wind stress curl. The 26ºC isotherm depths also show a similar pattern except that the relative minimum is about 20 to 25 m. Finally, the resultant OHC distribution shows values of ~50 kJ cm^{-2} at ~14ºN and 95ºW. As suggested by Figure 2, a key issue is the OHC distribution within the EPIC domain should have a similar value but is actually 10 to 15 kJ cm^{-2} less than observed However, satellite-derived OHC and isotherm depths have a similar pattern to those observed, but are underestimated.

7. Choice of SST: The surface boundary condition is central to these satellite retrievals. As shown in Figure 8, the SSTs from Reynolds, TMI and TAO mooring data are compared using regression techniques. For example, TAO mooring derived data suggest warmer SSTs than those derived from Reynolds analysis (slope of the least squares fit is 0.63) with RMS differences of

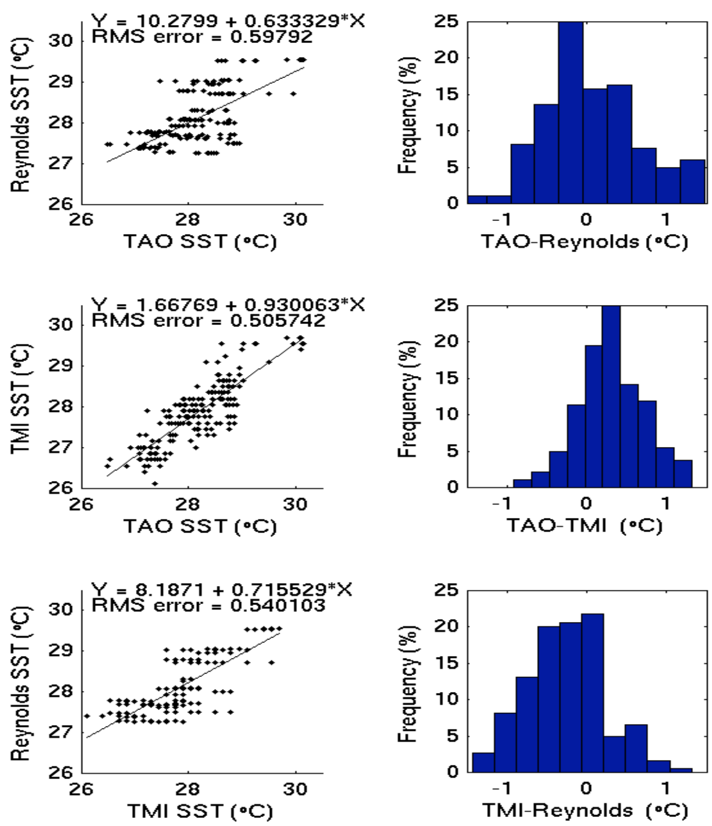

Figure 8: Regression analysis (left panel) and histograms of differences in SST (°C) measurements (right panel) between TMI, Reynolds, and the TAO 1-m mooring data at 10°N, 95°W from May through Oct 2001. The regression line (including the linear equation) and RMS differences are given for each analysis.

about 0.6°C. A better comparison is the TAO versus the TMI data where RMS differences are 0.5°C. Note that is this comparison, the slope of the curve is 0.93-indicative of a better fit with a bias of 1.7°C. Finally, the Reynolds analysis is compared to the TMI SSTs. The RMS differences are 0.54°C and the slope of the regression curve is 0.71 with a very small bias. In general, Reynolds-derived SSTs tend to be higher than the TMI SST. Notwithstanding, the point here is that not all SST products are equal, and when it represents the surface boundary condition, care must be afforded to the most appropriate choice of the data stream for OHC estimation for input into SHIPS.

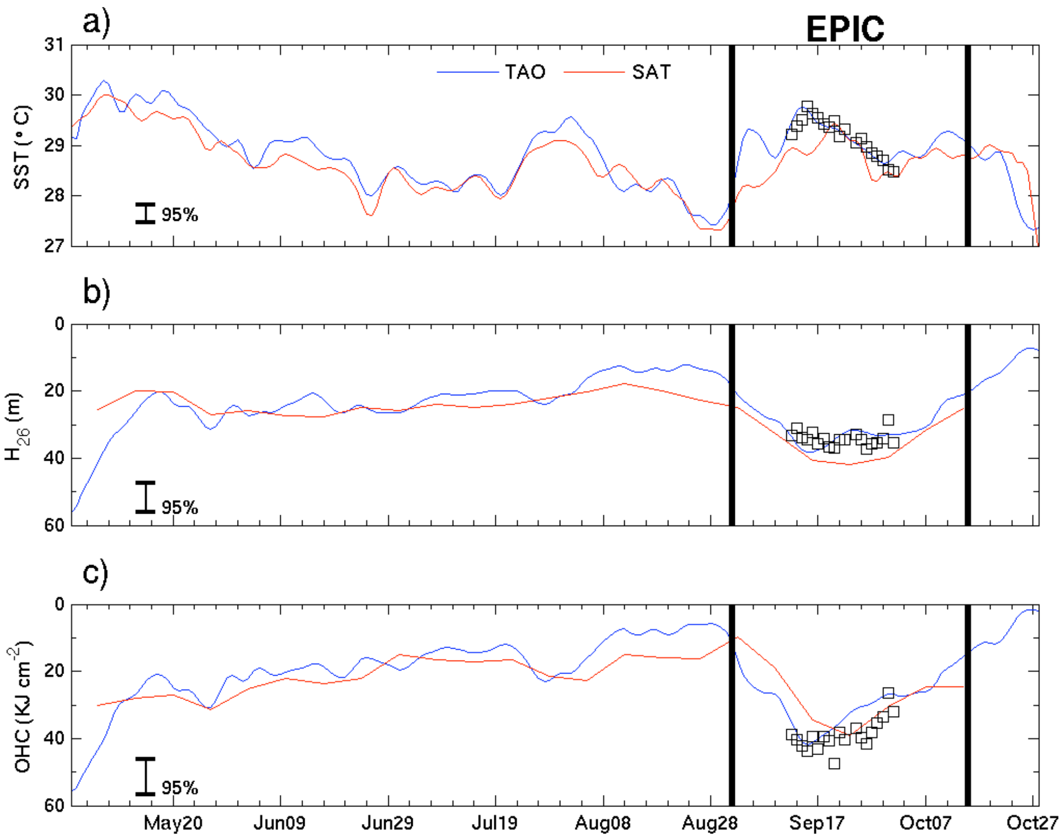

Figure 9: Time series comparisons of a) SST (ºC) , b) H_{26} (m) and c) OHC (kJ cm^{-2}) from TAO mooring at 10ºN, 95ºW (blue), satellite-derived (red) based on GDEM **V3**, and CTD profiles (boxes) from the *R/V Ron Brown* acquired at the TAO mooring during EPIC experiment from 1 Sept to 15 Oct 2001. The 95% confidence interval is based on the *student-t test* for comparing two sets of mean quantities.

8. Comparison to Observations: As shown in Figure 9, observed SSTs, 26ºC isotherm depth and OHC values from the TAO mooring at 10ºN and 95ºW (as well as CTD profiles from *R/V Ron Brown)* are compared to satellite-derived fields based on the AVISO images in Figure 1 that use the TMI and the GDEM **V3** climatology. SSTs from 1-m depth on the TAO mooring are in good agreement with those from the satellite derived SSTs over the time series. Here, the approximate 0.5ºC differences are attributed to the fact that the TMI sensor sees only skin temperature whereas the TAO data represent a more bulk measurement in the upper part of the surface mixed layer. However, the depth of the 20ºC isotherm suggests about a 15 m difference between observed and satellite inferred. The TAO mooring data suggests shallower isotherm 20ºC isotherm depth compared to the satellite-derived isotherm depth. Since the TAO mooring data are acquired at discrete depths of 20, 40 and 60 m, the comparison to the CTD profiles to the

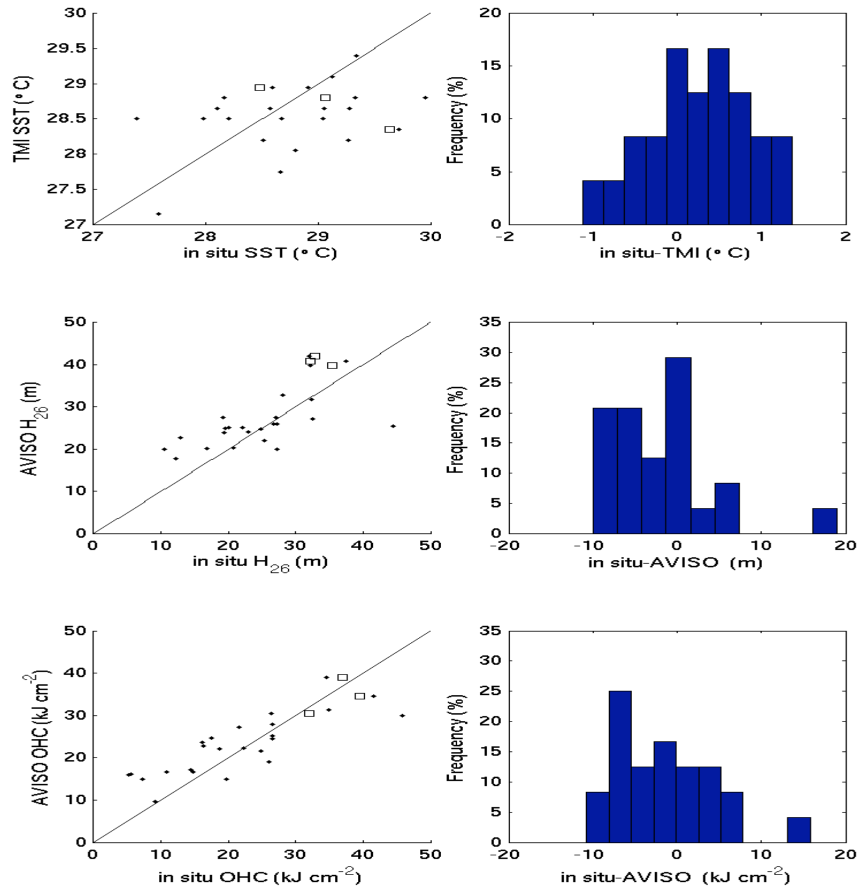

Figure 10: Scatter of *in situ* data versus satellite derived (left panels) and histograms of their differences (right panels) for a) SST (ºC) , b) H_{26} (m) and c) OHC (kJ cm^{-2}) in Figure 9. Solid line is optimal fit. Squares represent measurements from the *R/V Ron Brown*.

R/V Ron Brown indicate that the derived depth from the TAO moorings may actually be a bit deeper. As shown in Fig. 9b, however, the satellite inferred 26ºC isotherm depth shows a much higher correlation to this observed isotherm depth. Note that as the eddy passes the mooring, in mid-September, both isotherm depths reflect a deeper warmer layer. The corresponding OHC (Fig. 9c), derived from the satellite data, range in values of 20 to 30 kJ cm^{-2} prior to eddy passage. As the eddy passes over the mooring, it increases to about 40 kJ cm^{-2} where the TAO mooring suggests a larger value of 43 kJ cm^{-2} compared to 38 kJ cm^{-2}. The corresponding regression analysis is consistent with these time series comparisons for isotherm depth and OHC variations. (Figure 10). We are currently working on the daily comparisons from our blended fields and comparing them to the TAO mooring, *R/V Ron Brown* CTDs and aircraft profiles data

9. Summary: Over the seventeen months of the grant, we have made progress on developing the climatology for the EPAC using **GDEM V3** (and comparing them to **V2.1**). Presently, we are continuing to make detailed comparisons to observed profiles as well as estimates of the isotherm depths and OHC fields from the EPIC experiment and time series from the TAO moorings (10ºN). These comparisons include data will also include TAO mooring data at other locations (i.e. 110ºW) and the XBT transects. Following the approach above, the statistics will be improved with more data from differing platforms. It is a possibility that we may have to use a monthly climatology. For these reasons, we will push back the delivery of the climatology and empirical model. We simply did not anticipate this at the beginning of the project that had a six-month delay in its start date. It is our intent to bring this applied research project to closure as soon as possible by meeting Objectives I and II as part of this NOAA Joint Hurricane Testbed grant.

10. Revised Timeline: We are following the revised timeline and delivery schedule:

A. August 06: From latest GDEM,

1. Isotherm Depths/Reduced Gravities
2. SHA and Upper Layer Thickness
3. OHC Estimation
4. **Comparison to In situ measurements (In Progress)**

B: April 07: Seasonal Climatology (to TPC) as per Section II of proposal

C: May-Oct 07: Monitoring and Daily Estimates for SHIPS