I. Introduction

A new Systematically merged Pacific Ocean Regional Temperature and Salinity (SPORTS) climatology was created to help estimate ocean heat content (OHC) for tropical cyclone (TC) intensity forecasting and other applications. A technique similar to the creation of the Systematically Merged Atlantic Regional Temperature and Salinity (SMARTS) climatology was used to blend temperature and salinity fields from the Generalized Digital Environment Model (GDEM) and World Ocean Atlas 2001 (WOA) at a 1/4° resolution (Meyers, 2011; Meyers et al., 2014). The appropriate weighting for the blending of these two climatologies was estimated by minimizing the residual covariances across the basin and accounting for drift velocities associated with eddy variability using a series of 3-year sea surface height anomalies (SSHA) tracks to insure continuity between the periods of differing altimeters. In addition to producing daily estimates of the 20°C (D20) and 26°C (D26) isotherm depths (and their mean ratios), mixed layer depth (MLD), reduced gravities, and OHC, the SSHA surface height anomalies product includes mapping errors given the differing repeat tracks from the altimeters and sensor uncertainties. This is especially important across the eddy-rich regime in the western Pacific Ocean.

Using SPORTS in concert with satellite-derived sea-surface temperature (SST) and SSHA fields from radar altimetry, daily OHC has been estimated from 2000 to 2011 using a two-layer model approach. Argo-floats, expendable probes from ships and aircraft, long-term moorings from the TAO array, and drifters provide approximately 267,540 quality controlled in-situ thermal profiles to assess uncertainty in estimates from SPORTS. This carefully constructed climatology creates an accurate estimation of OHC from satellite based measurements, which can then be used in tropical cyclone intensity forecasts in the North Pacific Ocean basin and building realistic ocean products for subsequent analyses.

II. Motivation and Background

Tropical cyclones are incredible forces of nature that have a profound impact on humanity. The ability to accurately predict these storms has always been important for the safety of lives and property. The ocean plays a significant role in forecasting the intensity of a tropical cyclone, providing a source of heat to power the storm. The upper ocean responds to a tropical cyclone in three ways: (i) latent and sensible heat loss through the air-sea interface (ii) upwelling of cooler thermocline through Ekman pumping induced by wind-driven currents from the storm and (iii) turbulent entrainment of cooler thermocline waters through wind stirring in the mixed layer or vertical shear instability from the wind-driven currents above and below the base of the mixed layer. (Jaimes and Shay, 2009). OHC has a strong impact on the first two ocean responses. Leipper and Volgenau (1972) quantify ocean heat content as the thermal energy available in the upper ocean

$$OHC = \int_{D26}^{Sfc} c_p \rho (T - 26°C) dz \quad \text{....(1)}$$

where c_p is the specific heat of seawater, ϱ is density of seawater, and T is the temperature at depth. The 26° isotherm was used because of results found by Palmen (1948), finding that a minimum sea surface temperature of 26°C was important for tropical cyclone formation. High values of OHC provide an abundant source of thermal energy available for a tropical storm through heat fluxes and also dampen the amount of sea surface temperature (SST) cooling due to upwelling and loss of heat to the storm.

Several case studies have shown the importance of OHC in tropical cyclone intensification. Shay et al. (2000) studied Hurricane Opal as it passed over a warm core ring (WCR) in the Gulf of Mexico in October of 1995. Hurricane Opal traversed over a warm core ring with OHC values over 100 kJ/cm^2, allowing the storm to rapidly intensify from a category one storm to a category four storm over an approximate 14-hour period. A coupled ocean-atmosphere model showed that Hurricane Opal would not have reached such intensity without the presence of the warm core ring (Hong et al., 2000). Similarly, Hurricane Katrina and Rita in 2005 experienced rapid intensification over areas of high OHC (Jaimes and Shay, 2009).

Mainelli (2000) proved the value of OHC in hurricane intensity forecast by using OHC as a forecast variable in the Statistical Hurricane Intensity Prediction Scheme (SHIPS; DeMaria et al. 2005). The intensity forecast improved by 5-6 % for category five storms and by 22% in the case of Hurricane Ivan (2004).

The strength of the thermocline also has an impact on tropical cyclone intensification (Shay and Brewster, 2010). A strong thermocline, as seen in the eastern tropical Pacific Ocean, will inhibit mixing of cooler waters at the thermocline, allowing for lower OHC values necessary for rapid intensification of TCs over that area.

The following sections describe a method for calculating OHC for the Northern Pacific Ocean basin. Section III outlines the methodology, section IV details the results and section V provides the conclusions.

III. Methodology

The GDEM and WOA climatologies provided the necessary 4-dimensional oceanic data set for implementation of the empirical two-layer model used to derive ocean thermal profiles. A piecewise cubic Hermite scheme interpolated temperature and salinity profiles from the 2 climatologies to a 2-mresolution and identified the approximate depths of the 20 and 26°C isotherms. The MLD was then found by determining the depth at which the profile temperature deviated from the SST by 0.5°C. To take the climatologies from monthly to daily climatology, a 15-day running mean was applied. This technique also allowed for smoothing between monthly transitions. The daily climatology provided the background ocean thermal profile needed in the two-layer reduced gravity model.

Satellite SSHA and SST were used in the two-layer model to create daily estimates of OHC. The SSHA fields were created using Mariano and Brown's (1992) objective analysis (OA) scheme on satellite altimetry track data. Two or more satellites were active at all times to resolve mesoscale features from the altimetry data (Rosmorduc, 2003). Drift velocities used the OA were calculated from three years (2002-2004) of SSHA data to make the final SSHA field as accurate as possible.

The two-layer reduced gravity model depends on a density difference between the upper and lower layers. Reduced gravity here is defined as g':

$$g' = \frac{g(\rho_2 - \rho_1)}{\rho_2} \quad \ldots(2)$$

where g is the acceleration due to gravity (9.81 m s^{-2}), ϱ_2 is the density in the lowers layer and ϱ_1 is the density in the upper layer (O'Brein and Reid, 1967; Kundu, 1990; Goni et al., 1996). Density was calculated from the climatological temperature profiles. An arithmetic mean was used to estimate the density in the upper and lower layers. The 20°C degree isotherm was used as the interface between the density two layers since this isotherm is typically found within the thermocline. The depth of 20° isotherm (D_{20}) is given by

$$D_{20} = \overline{D_{20}} + \frac{g}{g'}\eta' \quad \ldots(3)$$

where $\overline{D_{20}}$ is the SPORTS climatological value of the depth of the 20° isotherm and η' is the satellite SSHA. Changes in SSHA are reflected on the interface in this model. Positive SSHA correlate with a deeper interface depth and negative SSHA correlate with a shallower interface depth. The SSHA is updated daily, therefore the D_{20} is also updated daily through the equation above. The model assumes uniform stretching and shrinking in the upper water column. Therefore, MLD and D_{26} can be estimated in a straightforward manner using ratios after we know the depth of the 20° isotherm

$$D_{26} = \frac{\overline{D_{26}}}{\overline{D_{20}}} D_{20} \quad \ldots(4)$$

$$MLD = \frac{\overline{MLD}}{\overline{D_{20}}} D_{20} \quad \ldots(5)$$

where $\overline{D_{26}}$ and $\overline{MLD}$ are the SPORTS climatological value of the depth of the 26° C isotherm and mixed layer depth respectively. An adjusted value of MLD was used over the climatological value as the adjusted value proved to be closer to reality (Meyers, 2011). These calculations were made at each grid point at a quarter degree resolution.

Assuming a homogeneous mixed layer with respect to temperature from satellite derived SST and a constant temperature gradient below the base of the mixed layer, OHC was calculated using the following adjusted equation (1).

$$OHC = \frac{1}{2}\rho_1 c_P (D26 + MLD)(SST - 26°C) \quad \ldots(6)$$

The two-layer model was used to calculate values of D20, D26, MLD, and OHC separately using the GDEM and WOA as background climatology. In-situ values of D20, D26, MLD, and OHC were then compared to these satellite estimations of the values at the nearest grid point over a twelve-year period (2000-2011). Only satellite estimations with OA error values less than 0.5 were used to ensure quality results. Figure 1 shows the coverage of the 267,540 quality controlled in-situ profiles used in the analysis.

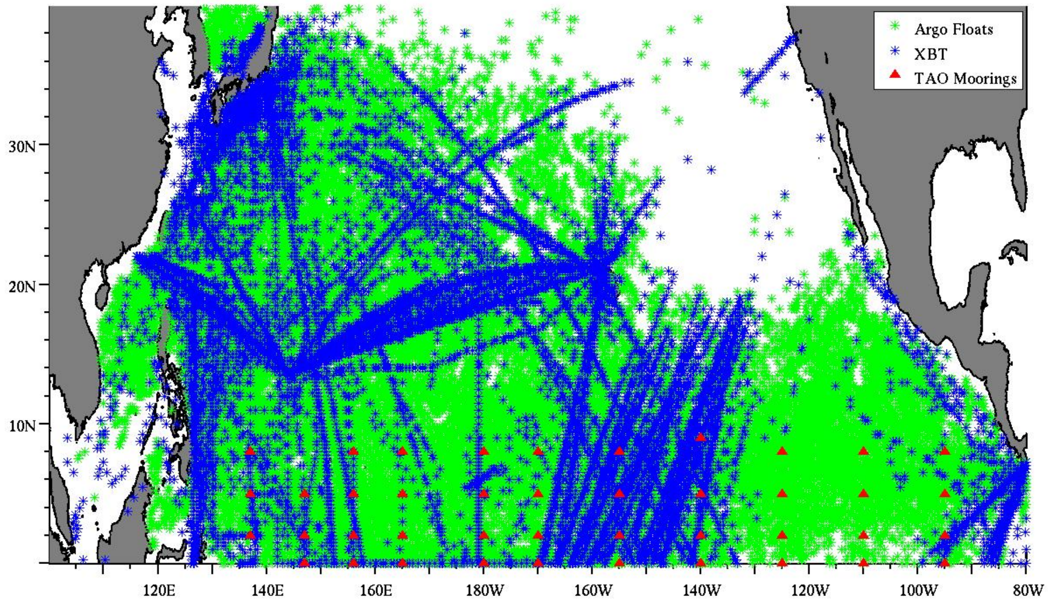

Figure 1. Position of in-situ profiles from 2000-2011. Green indicates argo profiles, blue denotes XBTs, and red triangles are TAO mooring locations.

A statistical analysis was used to determine the accuracy of the two different climatologies. The root mean squared deviations (RMSD), which measure the difference between observation and satellite obtained values, provided an estimator for accuracy.

$$RMSD = \sqrt{\frac{\sum_{i=1}^{n}(x'_i - x_i)^2}{n}} \quad \ldots(7)$$

The prime indicates the estimated value of n observations.

IV. Results

To help include spatially variability, the Northern Pacific Ocean basin was broken down into a regional analysis to determine the regional accuracy of the GDEM and WOA climatologies. The basin was divided into 5°x5° boxes, allowing for optical number of in-situ observations per box, to determine the RMSD of each climatology. The edges of each box were then weighted with a 2° linear transition zone to smooth abrupt changes across the borders. Note that the 2° buffer zone was larger than the Rossby radius of deformation to avoid possible distortion of features as they moved between boxes. The seasonally oceanic changes were accounted for by determining weights for two time periods, tropical cyclone season (May 1 – November 30) and off-season (December 1 – April 30).

RMSD values were calculated for each 5°x5° box during the tropical cyclone season and off-season for both GDEM and WOA to help determine the weight of each climatolgoy. If a box contained less than 50 in-situ observations, the climatologies were weighted equally. These weights helped determine the final value that made up the SPORTS climatology.

$$x_{SPORTS} = \frac{x_{GDEM} RMSD_{WOA}^2 + x_{WOA} RMSD_{GDEM}^2}{RMSD_{GDEM}^2 + RMSD_{WOA}^2} \quad \ldots(8)$$

Figure 2 shows the results from the RSMD weighting analysis for typhoon and off-season.

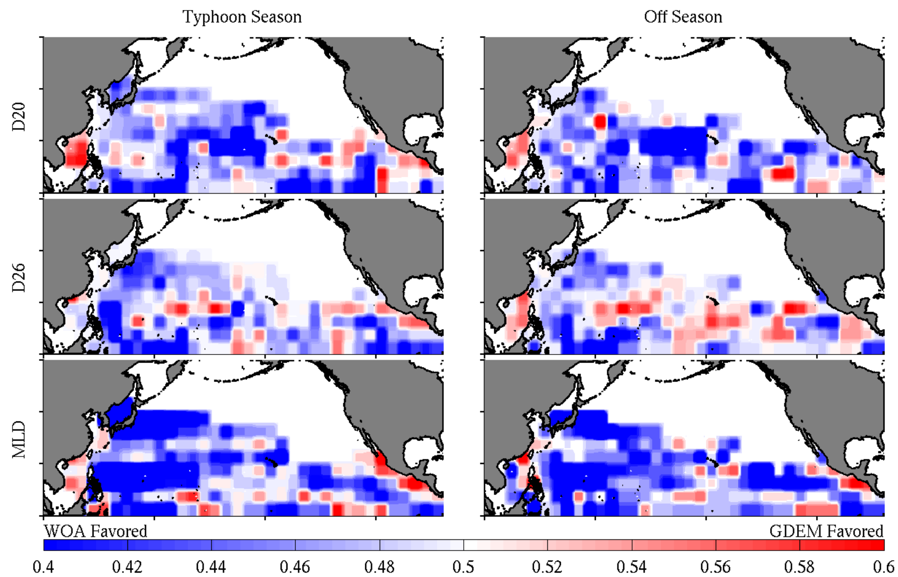

Figure 2. Weighting maps derived from RMSD analysis for climatological D_{20}, D_{26}, and MLD for Typhoon season and Off season. The bluer squares favor WOA climatology and the redder squares favor the GDEM climatology.

The SPORTS climatology was then used in the two-layer model to calculate D20, D26, MLD and OHC over a 12-year period (2000-2011). The 12-year in-situ dataset was used to evaluate the accuracy of SPORTS, as seen in Figure 3, through a regression analysis.

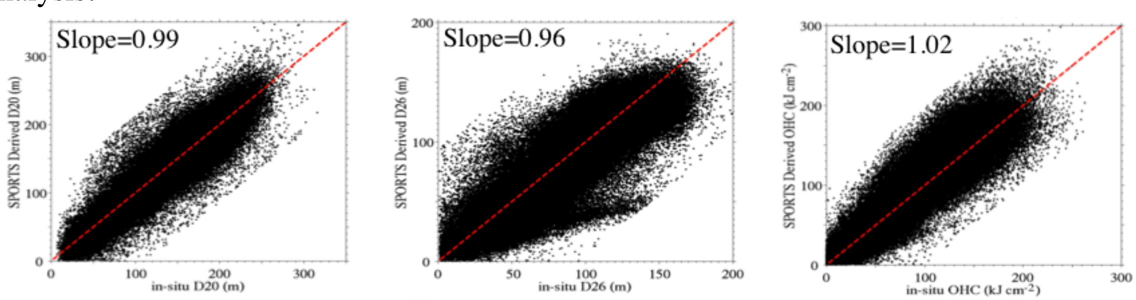

Figure 3. The scatter plots of SPORTS derived variables against in-situ variable. The red dashed line represents the 1:1 line.

The regressions showed that the SPORTS variables (D20, D26, and OHC) were highly correlated with the in-situ variables over the 12-year period. The anomalous signal present in the D26 regression corresponds with the El Niño.

V. Conclusions

The SPORTS climatology was created as a blend of the GDEM and WOA climatogolies to help estimate OHC. A reduced gravity two-layer model was used in concert with the newly created SPORTS climatology and satellite SSHA and SST to estimate OHC. Drift velocities used in the OA of the SSHA field helped to ensure better accuracy. A 12-year quality controlled in-situ dataset with approximately 267,540 points was used to create the weights for the SPORTS climatology and to evaluate the SPORTS calculated OHC. A regression analysis between the in-situ and SPORTS calculated variables proved that the carefully constructed SPORTS climatology provided an accurate method of OHC calculation.

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