Comparison of Satellite-Based Ocean Heat Content Estimates with Argo Measurements

Brian Young*

Indiana University-Purdue University Indianapolis, Indianapolis, IN 46229

Department of Physics undergraduate

Mentor: Paolo de Matthaeis†

UMBC/GEST NASA Goddard Space Flight Center,

Hydrospheric and Biospheric Sciences Laboratory,

Instrumentation Sciences Branch / Code 614.6, Greenbelt, MD 20771

Mentor: Daniel Jacob‡

UMBC/GEST NASA Goddard Space Flight Center,

Ocean Sciences Branch / Code 614.2,

Greenbelt, MD 20771

Abstract

The role of the ocean's vertical structure in determining the heatcontent of the North Atlantic Ocean is examined. Satellite observationsof Sea Surface Temperature (SST) and Sea Surface Height Anomalies(SSHA) are combined with long-term climatological data on the verticalstructure and salinity of the ocean to estimate oceanic heat content inthe region from between 10°N to 45°N and from 50°W to 85°W during the2004-2007 hurricane seasons. By comparing the satellite estimates to in situArgo measured heat content from 2004 to 2006, an empirical method forcorrecting the satellite estimates is developed. This empirical approach isvalidated using data from 2007.

*Electronic address: `brayoung@iupui.edu`

†Electronic address: `paolo.dematthaeis@nasa.gov`

‡Electronic address: `samuelraj.d.jacob@nasa.gov`

I. INTRODUCTION

Tropical cyclones that develop in the Atlantic tropical and subtropical waters are called, "hurricanes." Hurricanes occur primarily during the months of June to November when the waters are warm due to heating from the sun during the summer months. Because of the significant risk and destructive force tropical cyclones can bring with them, observations in this area of the ocean have continued to become more numerous, and now these weather systems can be detected before significant development and far in advance of any landfall.

Despite the many resources that are devoted to forecasting hurricanes, forecasts of storm intensity can often be inaccurate. One recent notable case is the unexpected rapid intensification of Hurricane Wilma in 2005[1] which underwent an incredible pressure drop from 981 millibars to 882 millibars in only 24 hours–an event unprecedented for an Atlantic tropical cyclone[2]. It is well known that hurricanes need sea surface temperatures (SST) to be above 26°C for their development and maintenance, but oceanic heat content plays a much larger role in predicting rapid intensification, similar to as seen in Hurricane Wilma.

Deep oceanic currents in the Atlantic Ocean have been extensively documented and studied, and these currents are well understood; warm waters from the Caribbean Sea move poleward in a deep layer through such currents as the Gulf Stream, the Florida Current, and the Loop Current. The Caribbean waters in this deep layer have a much different temperature and salinity profile than the surrounding waters native to the Gulf of Mexico. As the deep, warm layers move poleward, they are transported in the form of warm core rings shed by the Loop Current into regions with warm, shallow layers of water. When a hurricane moves over the ocean, the winds induce severe vertical mixing of the sea water below. Although the SST might be warm enough to sustain tropical development, the vertical mixing of the sea water will cause the water to cool, enough so to inhibit further development of the hurricane; this is especially true if the hurricane is slow moving. Areas with deep warm layers, however, will retain their warm temperature for longer as vertical mixing will not cause the sea surface to cool as much. These areas of higher heat content are more capable of supporting the intensification of tropical cyclones than the surrounding waters. More specifically, rapid intensification of a hurricane is likely to occur if the oceanic heat content below it is greater than 600 $MJ \cdot m^{-2}$.

There still remains, however, a lack of data in the tropical Atlantic area. One of the

best resources for obtaining accurate oceanic measurements in this area – Argo floats, which take physical measurements of the ocean at varying depths – is only deployed in relatively small numbers; of the over 3330 currently-deployed Argo floats, less than 100 floats are in the region of the Atlantic ocean between 10řN to 45řN and 50řW to 85řW covering more than 12 million square kilometers. Deploying additional Argo floats is costly, however, and thusly a satellite-based method of calculating oceanic heat content is generally preferred.

The purpose of this research is to examine a current model used to estimate oceanic heat content from satellite observations, and compare these estimates to values derived using in situ measurements from Argo floats.

II. INSTRUMENTS AND MEASUREMENTS

A. Argo floats

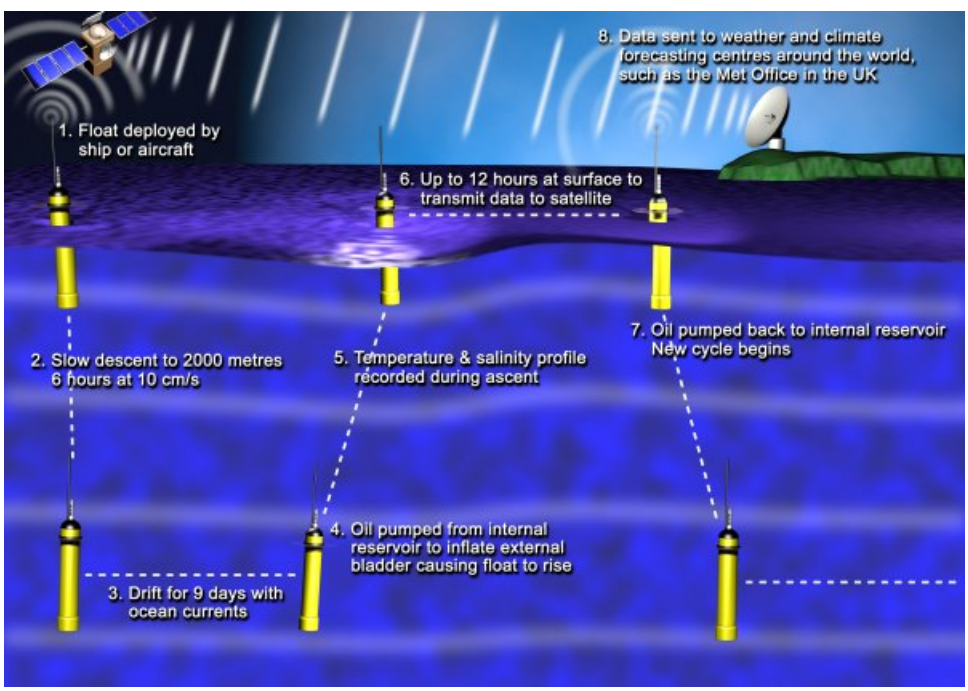

Figure 1: One Argo float cycle[3]

Argo is a worldwide network of over 3000 robotic float probes that take in situ measurements of conductivity and temperature at various depths in the ocean from which salinity and density can also be calculated. The typical operating cycle of an Argo float (Figure 1)

begins with the deployment of the instrument. After deployment, the float slowly descends to a depth of up to 2 km. The probe drifts at this depth for 9 days with the ocean currents, after which it rises to the surface while constantly taking in situ conductivity and temperature measurements. The float remains at the surface for up to 12 hours to transmit the data to a satellite, after which it begins sinking and repeats the process. The entire cycle takes 10 days, designed to match the cycle of the Topex/Poseidon and Jason 1 satellites; this was done in order to improve redundancy data measurements in order to ensure mutual accuracy between the in situ measurements and the satellite observations.

B. Satellite Data

The Advanced Very High Resolution Radiometer (AVHRR) satellite measures Sea Surface Temperatures (SST) using an array of small sensors that measure the reflectance of Earth in five visible and infrared channels at a spatial resolution of about 1 km[4]. There are two of these polar-orbiting satellites, maintained by NOAA, in orbit at all times. One satellite crosses the equator in the morning and one in the evening, providing twice-daily coverage of the entire globe and ensuring that data from any region is no more than 6 hours old.

The Poseidon-2 instrument aboard the Jason-1 satellite provides the data for Sea Surface Height Anomalies (SSHA). Jason-1 is the successor to the TOPEX/Poseidon mission, a joint mission between NASA and French space agency CNES (Centre National d'Etudes Spatiales), which measured ocean surface topography from 1992 to 2005. Poseidon-2 is a radar altimeter that uses the C band and Ku band portions of the electromagnetic spectrum to measure the sea surface height to within an accuracy of 3.3 cm. When launched in 2001, it was originally put in a nearly identical orbit with TOPEX/Poseidon to allow for cross-calibration, after which the older satellite was moved to an orbit midway between each Jason-1 ground track. In 2008, Jason-2 was launched carrying the Poseidon-3 radar altimeter which, compared to Poseidon-2, will provide better accuracy, reduced instrumental noise, and better tracking over land and ice in its measurements. Jason-1 has been moved to an orbit in tandem with Jason-2 on the opposite side of Earth[5], allowing for more detailed observations of SSHA to be made. All three satellites have a cycle time of 10 days.

C. Climatological Data

The World Ocean Circulation Experiment (WOCE) was carried out from 1990 to 1997. The data collected from WOCE remains the most comprehensive data set ever collected from the global ocean to date[6]. Data used in this research includes density measurements at varying depths and measurements of the 20°C and 26°C isotherms; this data is part of the WOCE Global Hydrographic Climatology (WGHC) data set[7].

III. METHODS AND CALCULATIONS

A. Defining Oceanic Heat Content

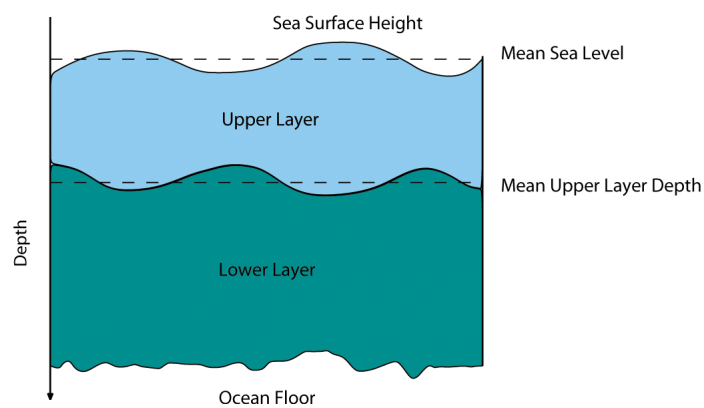

Figure 2: Two-layer ocean model

Because ocean temperature beyond the surface cannot be easily observed by satellites, a two-layer model is used to estimate heat content. The area above the 20°C thermocline is defined as the oceanic upper layer, and the depth of this upper layer is defined as d_{20}. The heat content of the ocean is defined as:

$$Q = c_p \int_0^{d_{26}} \rho(z) \left[T(z) - T_0\right] \, dz, \tag{1}$$

where c_p is the specific heat constant of the ocean water, and $\rho(z)$ and $T(z)$ are functions of density and temperature, respectively, with respect to depth z. Because hurricanes form only with SSTs above 26°C, this research only uses those temperatures that are above 26°C.

Thusly, Equation (2) is integrated from the surface (0) to the depth of the 26°C isotherm (d_{26}), and T_0, then, is equal to 26°C.

If the complete profile of temperature and density is known (as is the case in the Argo float datasets), the integral in Equation (1) can be computed by using the trapezoidal rule, such that

$$Q \cong c_p \sum_{k=1}^{M} \rho_k \left(T_k - T_0\right)\left(z_k - z_{k-1}\right) = Q_{cont} \tag{2}$$

where ρ_k and T_k are the density and temperature at depth z_k, respectively, with $k = 1 \ldots M$, where M is the number of measurements, and z_0 at depth 0. This estimation in Equation (2) is defined as the continuous-profile heat content of the upper layer, Q_{cont}.

If only the SST is known, the vertical structure of the ocean is approximated as having only two homogenous layers – the previously defined upper and lower layers – with constant temperature and density. The upper layer extends from the sea surface to the depth of the 26°C isotherm, d_{26}. The lower layer extends to the ocean floor and is colder. Using this two-layer model, the integral from Equation (1) is approximated by

$$Q \cong \frac{1}{2}\, c_p\, \rho_0 \left(T_{surf} - T_0\right) d_{26} = Q_{2lyr} \tag{3}$$

where ρ_0 is the average density of the ocean water and T_{surf} is the SST.

B. Estimating Oceanic Heat Content

To estimate heat content via satellite, several variables must be used. Firstly, the SST and SSHA must be observed and measured by the AVHRR and the Jason satellites. Secondly, the average depth of the 20°C isotherm (d_{20}) and a value, epsilon (ε), must be retrieved from the WGHC data. As seen in Figure 2, in a two-layer model, for every area where the sea surface height is raised there is a compensation for that rise with a dip in the d_{20} isotherm. Epsilon (ε) is a factor that is used to calculate that dip in the depth of the d_{20} layer from the SSHA. Satellite-observed d_{20} can be estimated by the relationship:

$$d_{20} = d_{20}^{WGHC} + \varepsilon\, SSHA \tag{4}$$

Then, byusing linear regression, a linear relationship between d_{26} and. d_{20} can be found.

$$d_{26} = \alpha\, d_{20} + \beta \tag{5}$$

In the Gulf of Mexico, this linear relationship was estimated to be[8]:

$$d_{26} = 0.48\, d_{20} - 5 \tag{6}$$

Lastly, heat content, Q, is calculated as in Equation (3)

IV. RESULTS

The oceanic heat content of the North Atlantic Ocean was estimated by Equation (3), yielding results that underestimate the Argo-measured heat content values (Figure 3).

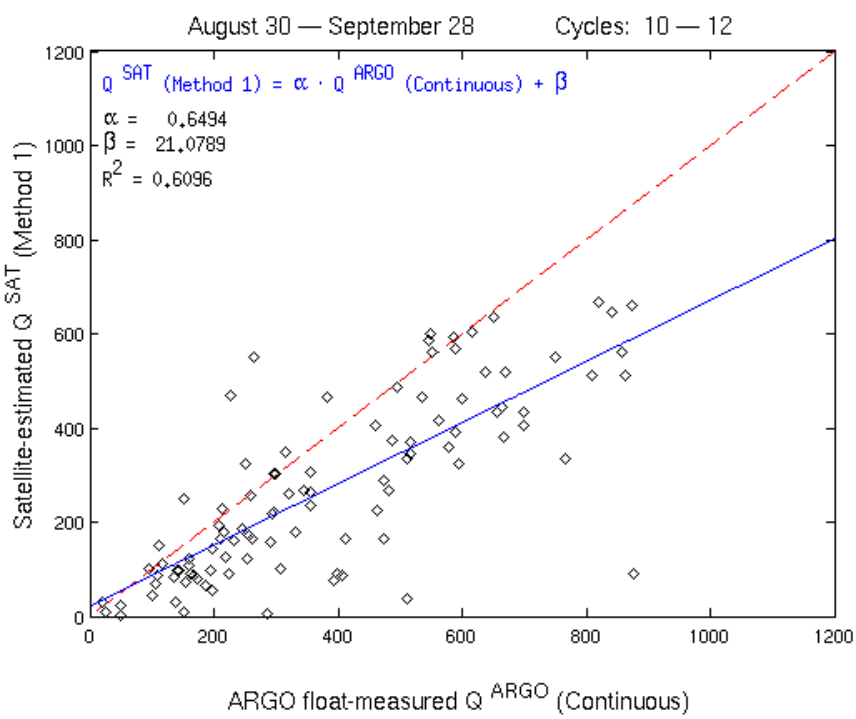

Figure 3: Estimated heat content (Q^{SAT}) vs. measured heat content (Q^{ARGO})
Estimated heat content is underestimating the measured heat content

Because oceanic heat content Q is directly proportional to d_{26}, an underestimated heat content value will likely also mean an underestimated d_{26} value. This assumption is shown to be true in Figure 4.

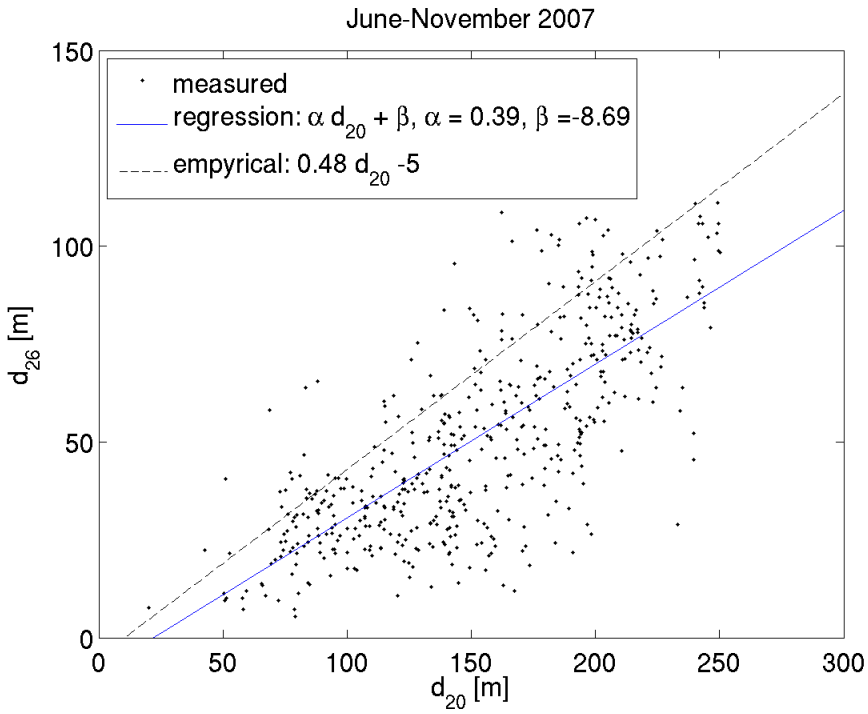

Figure 4: Argo-measured d_{26}vs d_{20}in the North Atlantic Ocean

Currently-used relationship is $0.48\,d_{20}-5$, but this figure shows that in the North Atlantic, $0.39\,d_{20}-8.69$ is more accurate

In Figure 4, Argo measurements of d_{26} and d_{20} from 2004 - 2006 are compared and yield a slope that is less than the commonly accepted value from Equation (6). This is important because it shows that while the relationship in Equation (6) may be accurate in the Gulf of Mexico where it was observed, it does not appear to be accurate in the North Atlantic Ocean. Using the values for d_{26} found by linear regression using Equation (5), the estimated oceanic heat content for each month, month-by-month, from 2004-2006 is compared to the Argo-measured heat content. Linear regression is then used to estimate a relationship between the estimated and the measured oceanic heat content values (Figure 5). For instance, one might compare satellite-estimated heat content vs. Argo-measured heat content (Q^{SAT} vs. Q^{meas}) in June from 2004-2006, in July from 2004 - 2006, in August from 2004 - 2006 and so forth, and then find Q^{SAT} as a function of Q^{meas}:

$$Q^{SAT} = \gamma\, Q^{meas} + \delta \tag{7}$$

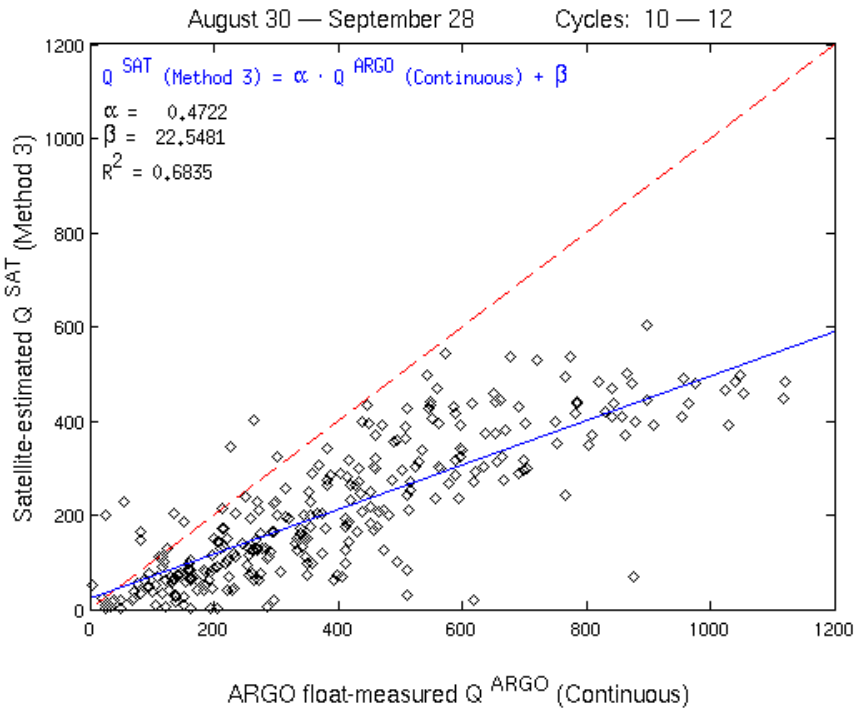

Figure 5: Satellite-estimated heat content vs. Argo-measured heat content.

The satellite-estimated heat content was calculated using regression statistics found by comparing d_{26} vs. d_{20} for years 2004-2006

Then, the heat content values estimated for 2007 using Equation (5) (which are an underestimate of the Argo-measured values) are corrected by using the following expression:

$$\widetilde{Q}^{SAT} = \frac{Q^{SAT} - \delta}{\gamma} \tag{8}$$

Finally, by comparing the corrected heat content for 2007 with the Argo-measured values, it is clear that the satellite estimates are much improved (Figure 6). Specifically, though at the beginning and end of the hurricane season the error bars are relatively large, as the ocean warms during the summer months–during the peak of the hurricane season–the estimates are much more accurate and precise.

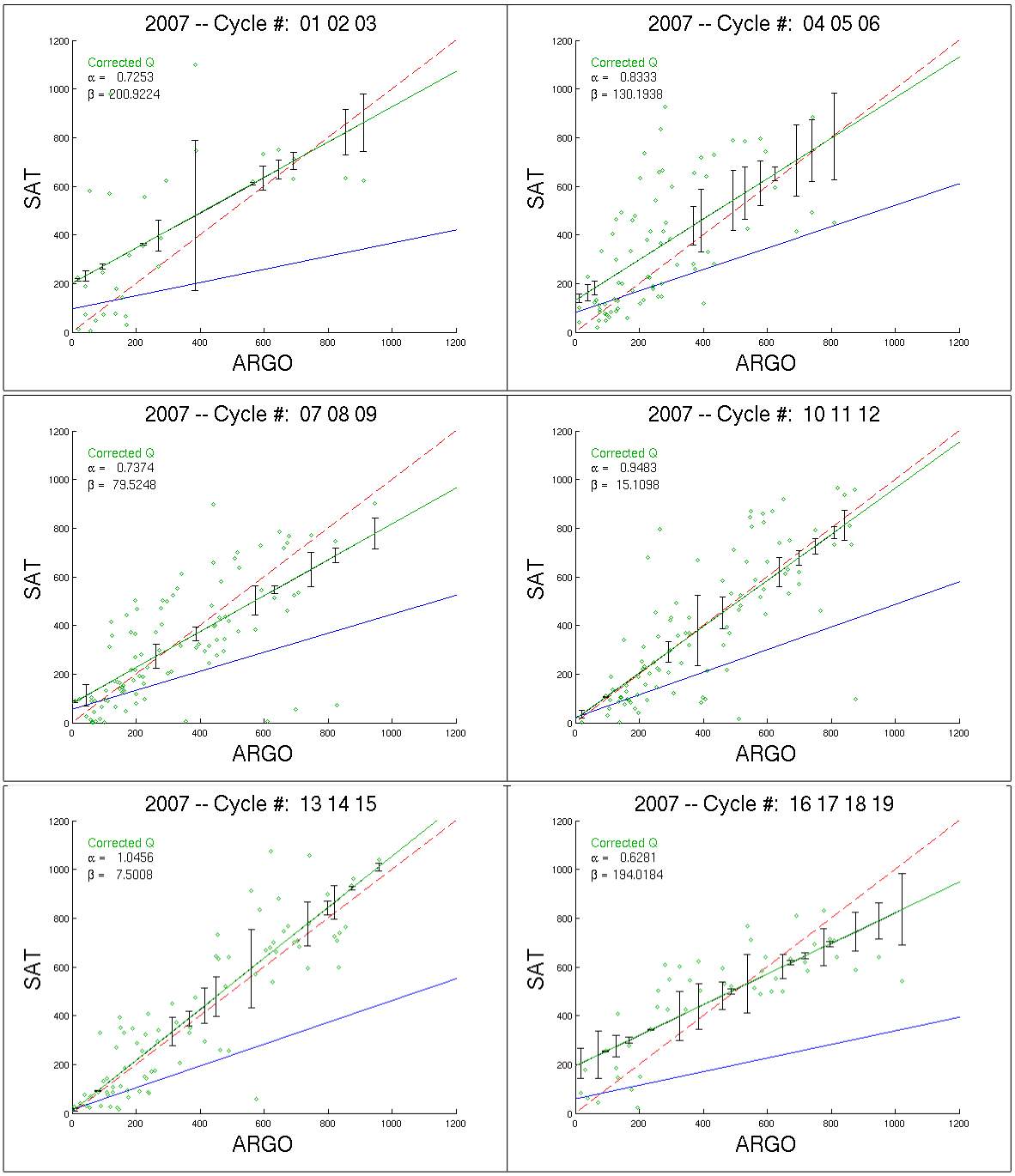

Figure 6: Corrected heat content estimates vs. Argo-measured heat content values

The green bar with error bars shows corrected $\widetilde{Q}^{SAT}$ vs. Q^{meas} heat content values

The blue bar shows uncorrected Q^{SAT} vs Q^{meas} heat content estimates

Each satellite cycle is 10 days in length, with cycle 01 defined as beginning at the beginning of hurricane season (June 01) and cycle 19 ending at the end of hurricane season (November 30). Therefore, each group of three cycles is approximately one month.

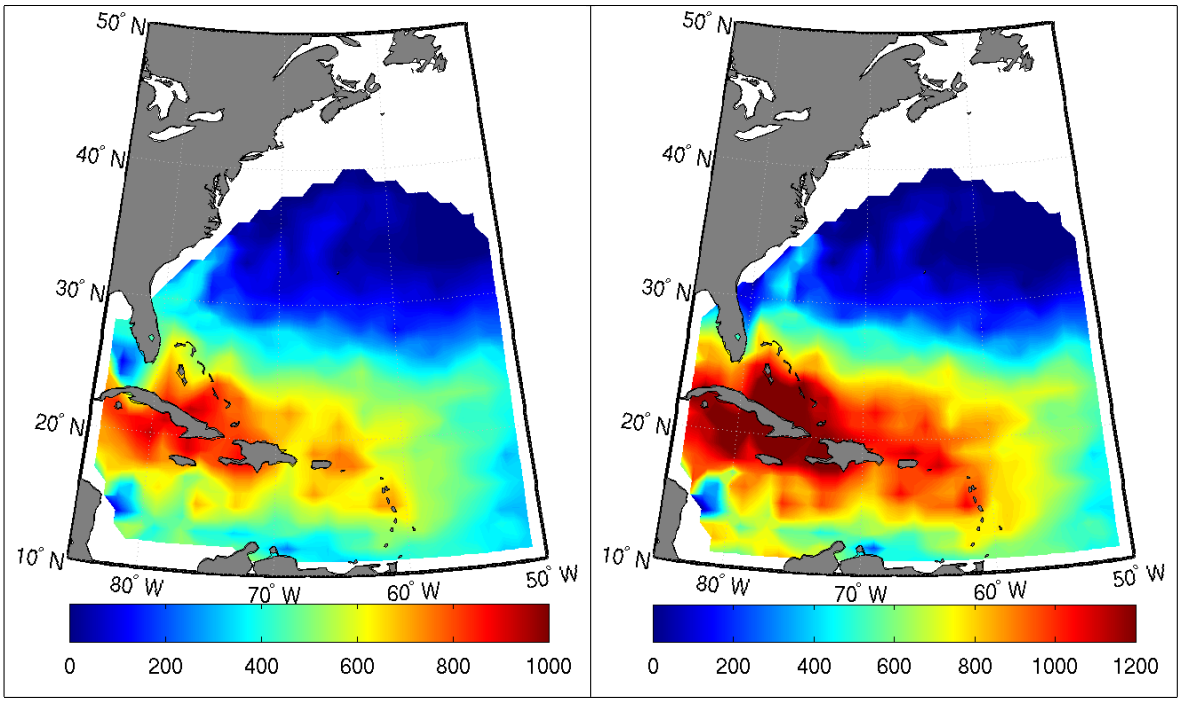

Figure 7: Comparison of heat content estimate contour maps in late September

On the left is before correction, on the right is after correction

The units of measurement are in megajoules per meter squared

V. CONCLUSIONS

Conclusions drawn from this research are that firstly, the current estimates of heat content in the North Atlantic Ocean are underestimating the Argo float-measured heat content (Figure 3).

Secondly, the accepted relationship between d_{26} and d_{20} in Equation (4) was estimated in the Gulf of Mexico[8]. This research shows that this relationship is not accurate in the Atlantic ocean, and that more accurate results can be estimated by linear regression. By comparing satellite-estimated d_{26} to Argo-measured d_{26} from all years, a more accurate relationship for the North Atlantic Ocean can be found (Equation 5).

Lastly, after estimating the per-month average heat content from 2004 - 2006 by Equation (3), estimated heat content is compared to measured heat content, and a linear relationship is found (Equation 7). By using this relationship to correct the heat content estimates for 2007 (Equation 8), the estimates for 2007 are greatly improved (Figure 6). In particular, these corrected heat content estimates compare very well with the Argo measurements during the

peak of hurricane season (August and September).

.

Acknowledgments

I wish to thank Valerie Casasanto and NASA Goddard Space Flight Center/University of Maryland, Baltimore County's GEST Summer Internship in in Earth Sciences program, as well as my mentors, Dr. Paolo de Matthaeis and Dr. Daniel Jacob. Additionally, I'd like to acknowledge the friendly Chinese and Taiwanese employees whom I ate lunch with most every day on the second floor at GSFC.

---

[1] National Hurricane Center, *Hurricane Wilma Discussion* 1-48. (2005, October 15-25). (Retrieved July 23, 2009),
<http://www.nhc.noaa.gov/archive/2005/WILMA.shtml>

[2] National Hurricane Center (USA), *Tropical Cyclone Report – Hurricane Wilma.* (2006, January 12). (Retrieved July 23, 2009),
<http://www.nhc.noaa.gov/pdf/TCR-AL252005_Wilma.pdf>

[3] Met Office (UK), *Met Office: Argo.* (n.d.) (Retrieved July 27, 2009),
<http://www.metoffice.gov.uk/research/ocean/argo/>

[4] National Atlas (USA), *What is AVHRR?.* (September 22, 2008). (Retrieved on July 27, 2009),
<http://rnp782.er.usgs.gov/atlas2/articles/mapping/a_avhrr.html>

[5] Aviso (France), *Jason-1.* (n.d.). (Retrieved on July 27, 2009),
<http://www.aviso.oceanobs.com/en/missions/current-missions/jason-1/>

[6] National Oceanography Centre (UK), *The World Ocean Circulation Experiment (WOCE) 1990–2002.* (n.d.). (Retrieved July 27, 2009),
<http://www.noc.soton.ac.uk/OTHERS/woceipo/ipo.html>

[7] Federal Maritime and Hydrographic Agency (Germany), *Global Climatology and Atlantic Ocean Atlas.* (n.d.). (Retrieved July 27, 2009),
<http://www.bsh.de/en/Marine_data/Observations/Climate/WOCE-AIMS/WGHC/>

[8] Shay, L., Goni, G., & Black, P. (2000). Effects of a Warm Oceanic Feature on Hurricane Opal. *Monthly Weather Revew*, 128, 1375