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LONG-TERM TREND IN THE OCEANIC HEAT STORAGE OF THE SOUTH ATLANTIC ESTIMATED FROM ALTIMETER AND PIRATA DATA

Olga T. Sato and Paulo S. Polito
Oceanographic Institute, University of São Paulo, São Paulo, SP, Brazil

1. INTRODUCTION

An accurate estimation of the oceanic heat storage (HS) is important to determine the global heat fluxes. The temporal rate of change of the heat storage (HSR) is balanced by the difference between the horizontal divergence of advective oceanic heat transport and the net air-sea interface flux. In a time scale of days, these environmental variables are essential to provide a lower boundary condition to weather prediction models. In a time scale of years the HS and HSR can be used for comparison with *in situ* estimates and for comparison and tuning of numerical models of ocean circulation. In a decadal time scale, changes in HS can reveal climatic tendencies and patterns. In addition, HS variability can be correlated to chemical and biological processes variability, stressing the interdisciplinary potential of this line of research.

Of particular interest is the comparison between satellite estimates and those derived from *in situ* measurements. Correlations greater than 60% between HS estimated based on XBT and TOPEX/Poseidon (T/P) altimeter data are reported over the northern hemisphere by White and Tai (1995). Good agreement between heat storage estimates based on XBT and T/P were also reported by Wang and Koblinsky (1997) over the North Atlantic away from the western boundary and subtropical recirculation regions. Chambers et al. (1997) showed that the inter–annual HSR variability based on T/P and those from TAO measurements agree within 5 to 10 $W.m^{-2}$. Polito et al. (2000) compared HS and HSR anomalies derived from the T/P altimeter data with local measurements of HS and HSR. The comparison

Corresponding author address: Olga T. Sato, University of São Paulo (IOUSP), DOF, São Paulo, 05508-120; e-mail: olga@io.usp.br.

was made at four oceanographic sites: TOGA/TAO in the equatorial Pacific, HOT/Aloha in the tropical North Pacific near Hawaii, CalCOFI in the mid-latitudes of the northeastern Pacific near California and, Hydrostation "S" in the mid-latitudes of the North Atlantic near Bermuda. In the four cases for both HS and HSR the correlations were relatively high (67% to 89%) and the rms differences were comparable to the precision of the measurements.

The focus of this study is to expand the results of Polito et al. (2000) with the presentation and analysis of long–term trend observations of HS variability in the Atlantic. In the following section we addresse how the HS is estimated, followed by a brief description of the in situ and the altimeter data, and the filtering procedure. Section 5 shows evidences of seasonality, Rossby, Kelvin , and instability waves in zonal-temporal and meridional-temporal diagrams of the sea surface height anomaly components at several locations. Section 6 summarizes the results and presents the main conclusions of this study.

2. THE HEAT STORAGE

Typically, the oceanic heat storage is estimated by vertically integrating the *in situ* measured temperature profiles as:

$$HS = \int_0^h T dz, \qquad (1)$$

where *h* is a depth (*z*), in our study it is defined as below the main thermocline, and T is the temperature. The heat storage anomaly can be estimated by subtracting a long–term mean value from the total.

The sea surface height anomaly (η) is obtained from altimeter measurements contains a variety of signals associated with many dynamical and thermodynamical processes. In terms of HS, measurements of η are of interest because they reflect the local expansion of the water column due to changes in the vertical density profile. These changes are dominated by relatively large changes in temperature compared to changes in salinity. The observed η can be used to estimate the heat storage anomaly (HS') according to the linear relation derived by Chambers et al. (1997):

$$HS' = \frac{\rho C_p \eta}{\alpha} \qquad (2)$$

where ρ is the density of seawater, C_p is the specific heat at constant pressure, and HS' is expressed in J m^{-2}.

In this study the effects of the haline contraction of the water column on the sea surface height anomaly are neglected. The available global estimates of salinity profiles based on *in situ* oceanographic data are climatological. Sato et al. (2000) have shown that a haline correction of the sea surface height based on climatological salinity data did not improve their HS measurements compared to local estimates.

It is assumed that the bulk of the oceanic heat storage variability in time scales on the order of years to months is due to processes occurring in the layer above the main thermocline. These inherently baroclinic processes dominate the sea surface height anomaly field (*e.g.* the seasonal thermosteric signal, baroclinic Rossby waves and tropical instability waves). Any dynamical process that changes the sea surface height without changing the integrated temperature profile introduces an error in the HS estimates (*e.g.* the barotropic response to changes in atmospheric pressure, changes in salinity, barotropic Rossby waves and tides).

In the following sections we describe some details of the *in situ* and satellite data used on this study to estimate the heat storage anomaly.

3. THE PIRATA ARRAY

The Pilot Research Moored Array in the Tropical Atlantic (PIRATA) is a multi–nation cooperation program to study the atmosphere and ocean interaction processes in the tropical Atlantic region, Servain et al. (1998). The purpose of PIRATA is to study ocean-atmosphere interactions in the tropical Atlantic that are relevant to regional climate variability on seasonal, inter–annual and longer time scales. The program is maintained by research institutions from the United States, France, and Brazil.

The PIRATA array consists of 13 moored buoys that transmit daily averaged measurements of several oceanic and atmosphere variables, such as the ocean temperature and salinity profiles, air temperature, wind speed and direction, solar radiation, precipitation, etc. These parameters are measured every 10 min, and stored locally. However, for energy saving issues, they are averaged and transmitted only once a day. All the time series started between 1997 and 2000, and there are data gaps usually caused by instrument problems or failure along the time.

From the original 13 stations allocated at the PIRATA array, only 10 of them are currently transmitting data and have a time series long enough to perform the validation. Therefore, the stations located at 2º N 10º W, 2º S 10º W, and 5º S 10º W were excluded from the analysis.

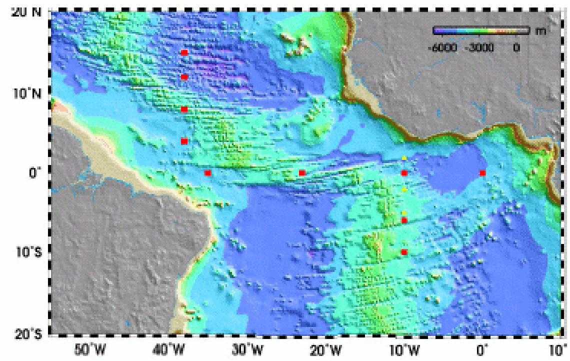

Figure 1: Location of the moored buoys of the PIRATA array. Red squares show the buoys currently working. The colors in the background indicate the topography. Source: http://goos.io.usp.br.

The PIRATA moored buoys are the only stations to produce time series of oceanic variables simultaneously with the passage of TOPEX/Poseidon and Jason satellite altimeters. Because of the near real–time measurements of oceanic variables, the region covered by the PIRATA array has a unique characteristic for the study of climate related variables such as heat storage, surface heat flux balance. The region also call for special attention related to inter–hemispheric exchange, the tropical Atlantic is important in the determination of high and meso–scale variability observed in the regional climate of the northeast Brazil.

4. THE ALTIMETER DATA

The sea surface height anomaly is obtained from the data distributed by the Jet Propulsion Laboratory Physical Oceanography Distributed Active Archive Center (JPL/PODAAC) for the World Ocean Circulation Experiment conference (WOCE global data, version 1.1, 1998). The satellite data are obtained from the TOPEX/Poseidon and Jason 1 (TJ) combined altimeters measurements. The anomaly is calculated with respect to a 12-year average (1993-2005) and spans from January 1993 to January 2005 with a resolution of approximately 10 days. The standard corrections are applied according to the documentation distributed with the data.

The sea height anomaly (□) is used to estimate the heat storage (HS') according to equation 2. Mean values of □ and C_p, averaged from the surface to a depth *h* below the main thermocline, are calculated from climatological maps of the World Ocean Database 2002 (WOA01) (Conkright et al., 2001) for a $1^o \times 1^o$ grid. □ is considered constant at each grid point and it is estimated by vertically averaging between the surface and the depth *h* the climatological a profile weighted by layer thickness and by temperature anomaly.

The objective of this study is the analysis of HS' estimates, with particular attention to some of its spectral components. The decomposition is intended to separate the original signal into additive components that are associated with baroclinic processes whose dynamics are known to a significant extent.

The filtering procedure is based on finite impulse response (FIR) filters applied in two dimensions (zonal and temporal), (Polito and Liu, 2003). The filter separates the original (□) signal in the following components Polito et al. (2000):

$$\begin{aligned} \eta &= \eta_t + \eta_{24} + \eta_{12} + \eta_6 + \eta_3 + \eta_1 \\ &+ \eta_{K1} + \eta_{K3} + \eta_{K6} + \eta_E + \eta_r . \end{aligned} \quad (3)$$

The subscript *t* refers to the portion of the sea height anomaly signal which is characteristically basin-wide and non-propagating. This component corresponds to thermal variations in the water column mostly due to the seasonal heating and cooling and the local net effects of the advection of heat by the large-scale circulation. Subscripts 24, 12, 6, 3 and 1 refer to spectral bands of the westward propagating first-mode baroclinic Rossby waves (including the equatorial) and tropical instability waves with periods centered at approximately 24, 12, 6, 3 and 1.5 months. The subscript *K* refers to equatorial Kelvin waves of 1, 3 and 6 months bands, *E* to generic meso-scale eddy signals, and *r* to the residual small-scale signal. Our analysis concentrates on the large–scale features therefore, we grouped the all the wave components into one major contribution,

$$\eta = \eta_t + \eta_w + \eta_E + \eta_r . \quad (4)$$

The objective of this study is to investigate the long–term trend in the heat storage anomaly in the South Atlantic. To validate the use of the altimeter based estimations, the heat storage from satellites are compared to the values estimated from the *in situ* PIRATA data. The analysis of the long–term trends in the heat storage anomaly time series from the altimeters are based on the variability of the seasonal and basin–scale components.

5. RESULTS

The heat storage is estimated at the PIRATA array by integrating the temperature profile as described on equation 1. The temperature profiles on the moored buoys are measured at the surface, 20, 40, 60, 80, 100, 120, 140, 180, 300, 500 m of depth. Most of the anomaly signal captured by the altimeter are due to variations in the ocean's upper layer, basically above the main thermocline. After some tests, we chose 300 m as the depth of integration, which showed a better agreement with the dynamics captured by the altimeter data. To estimate the heat storage anomaly, the long–term mean HS estimated from the time series with an entire number of years was subtracted from the total HS.

The heat storage anomaly from the altimeters data are estimated using the relationship defined in equation 2. The constants □, C_p and □ are estimated from the climatological temperature and salinity data, Conkright et al. (2002). These parameters are depth averaged between the surface and 300 m, the depth of integration for the *in situ* heat storage.

The heat storage anomaly derived from both satellite and moored buoy data were compared in terms of correlation and rms difference, Figure 2. At the studied locations the HS correlations range from 56% to 86%, and the rms differences range between 0.37 and 0.47 x 10^9 J.m^{-2}.

Figure 2 shows the comparison of the heat storage anomaly estimated from both data sources. The altimeter based heat storage corresponds to the total (original) signal measured, i.e., HS based on □. The most striking feature is that the satellite based HS time series is capable of reproducing the annual cycle and amplitude of the *in situ* estimated HS. The best correlations found at the equator with values between 73% and 92%. The rms differences in these stations vary between 0.39 to 0.6 x 10^9 J.m^{-2}. Better correlations are usually found where the large scale processes dominates over the other dynamical components such as the waves and meso–scale eddies.

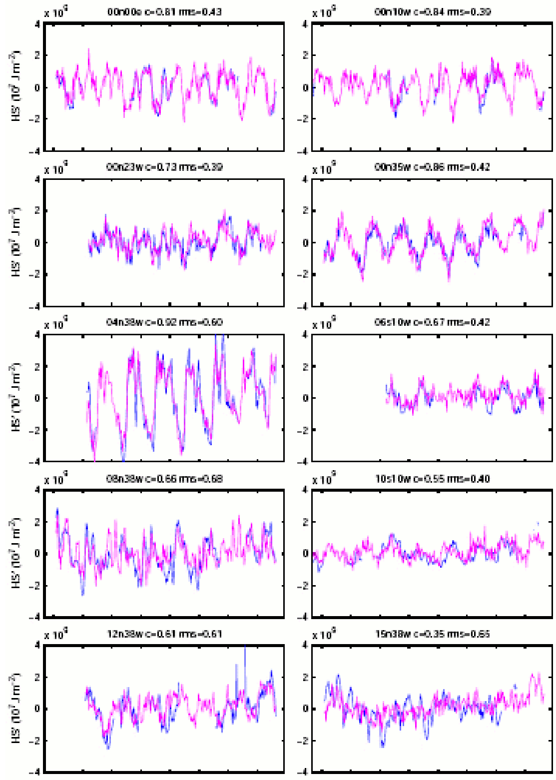

Figure 2: Total heat storage anomaly from TJ (magenta) and PIRATA *in situ* data.

The *in situ* and satellite HS are more correlated and show smaller rms differences at the buoys over the equator and at the southern part of the array. The region located at the western Atlantic are strongly driven by salinity fluctuations due to seasonal changes in river discharge, evaporation and precipitation cycle linked to the migration of the Intertropical Convergence Zone (Foltz et al., 2004). This explains the lower correlations found at the buoys over the longitude of 35°W. Our main assumption on the HS estimation from satellite data is that the sea surface height anomalies are driven by temperature. Although the correlations at this region are not insignificant, sea surface height anomaly due to local salinity changes may play an important role.

The heat storage anomaly from satellite data has been validated over several regions of the global oceans (Polito et al, 2000, Sato et al., 2000). The correlations between the *in situ* and satellite data are generally high (above 75%). For the Atlantic ocean, even using the PIRATA time series which has a considerable large data gaps compared to data from TOGA/TAO for instance, we also obtained significantly good results. This motivates us to use the altimeter data to investigate the spatial and temporal variability of HS anomaly over the Atlantic ocean.

Figure 2 shows that the HS anomaly time series is a combination of several modes of variability. The most prominent signal is the fluctuation due to the annual cycle. The filtering process allowed us to break up the original signal of the heat storage anomaly from satellite data into several components.

The amplitude of the non–propagating seasonal and basin–scale (HS_t) component of the heat storage anomaly is estimated from the satellite data. Figure 3 shows the spatial variability of the amplitude of seasonal cycle in the Atlantic. Low amplitudes are found in the tropical regions, near the center of the gyres. The interaction of the regional circulation due to the discharge of Amazon river in the western equatorial region combined with the presence of the Intertropical Convergence Zone, contribute to the fluctuations in the amplitude of the heat storage anomaly.

The largest amplitudes of the HS component are found at higher latitudes of the South Atlantic and in the western boundary of the North Atlantic ocean. Higher amplitudes are found particularly in the regions of the convergence between the Malvinas and Brazil currents. The zonally average of the amplitude of the HS_t shows an amplitude larger 1.5 x 10^9 J.m^{-2} south of 50^{o}S, while as in the tropical region the average values is around 0.5 x 10^9 J.m^{-2}, Figure 4. This figure shows the asymmetry between the hemispheres, with much higher amplitudes found at the high latitudes of the South Atlantic.

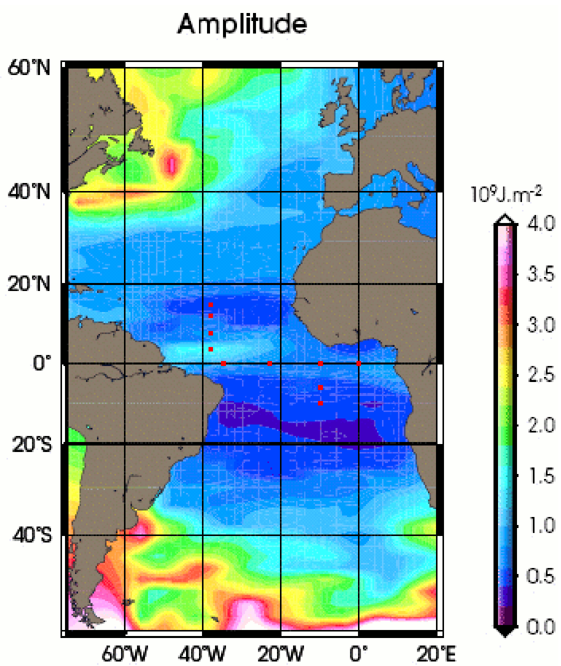

Figure 3: Amplitude of the annual cycle of the seasonal and basin-scale component of the heat storage anomaly from the altimeters. The red squares mark the location of the PIRATA array.

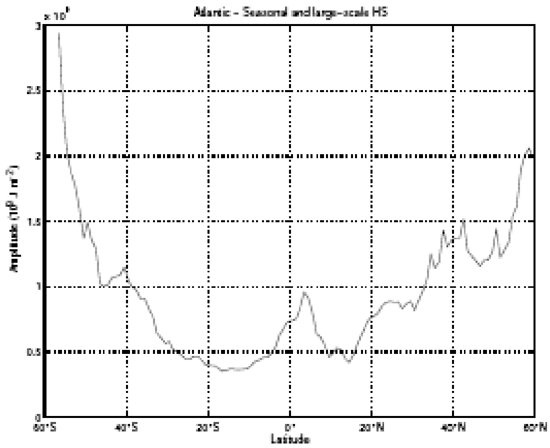

Figure 4: Zonally averaged of the amplitude of the seasonal and basin–scale (HS_t) component of the heat storage anomaly from the altimeter data.

The time series from both, PIRATA and satellite data, in Figure 2, show a increasing long–term trend in the heat storage anomaly. To investigate the significance of the decadal scale trend, a straight line was least square fit to the whole HS_t time series at each grid point of the satellite data. The angular coefficient of the linear fit is the long–term trend in the heat storage anomaly estimates. Figure 5 shows the distribution of the slope for the whole Atlantic basin.

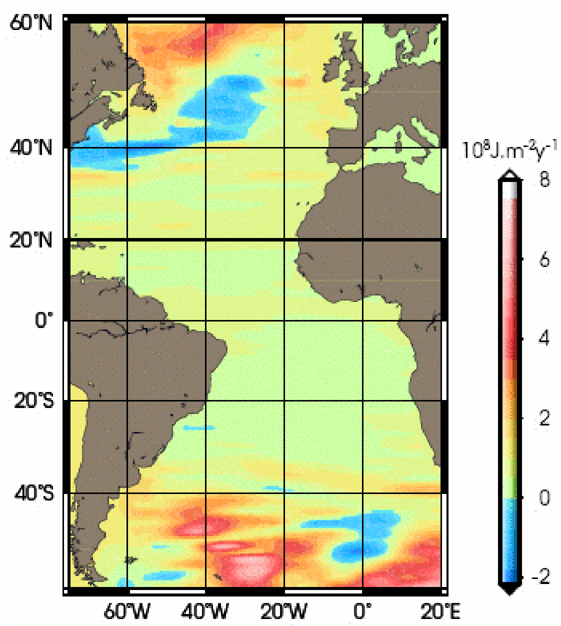

Figure 5: Slope of the straight line least square fit to the 12–year long HS time series from TJ for the Atlantic.

Mostly in the area between 35º of latitude, there is a slight increase in the heat storage anomaly over the past 12 years. The most striking features in Figure 5 are the significant increase in the seasonal and basin–scale heat storage at high latitudes, especially south of 40ºS, and a decrease in the North Atlantic and around in the southern ocean. A zonal mean of these slopes, Figure 6, show that in general the Atlantic ocean has a increasing decadal trend over the past decade.

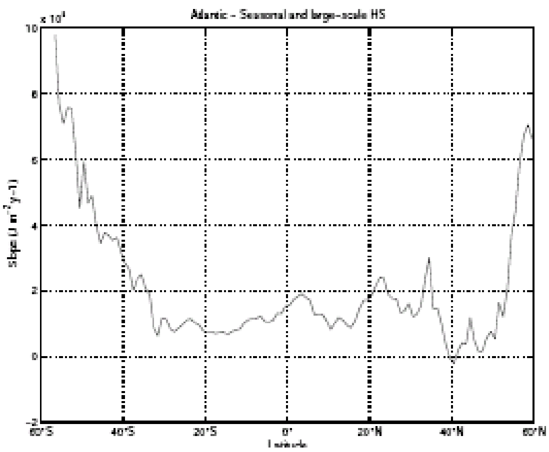

Figure 6: Zonally averaged slope of the long–term trend in the seasonal and basin–scale components of heat storage anomaly.

These results show that the ocean's capacity of storing heat has been continuously increasing in the last decade. Although there are regions showing a decreasing trend, they are not relatively large to compensate the overall increasing tendency in the Atlantic. One concerning issue of these results are a decrease of the rate of deep water formation associated with the regions of increasing heat storage trend. If this trend is not somehow compensated by a decrease in the ocean's interior transport or by increasing the ocean heat exchanged at the surface, this could have a significant impact on climate change.

6. CONCLUSION

The objective of this study was to validate the heat storage anomaly estimated from altimeter data in the Atlantic ocean. This validation was done by comparing satellite based with *in situ* estimated heat storage anomaly. The base for the *in situ* data is the PIRATA moored buoy array in the tropical Atlantic. This system currently maintains a set of 10 stations with measurements of temperature profiles up to 500 m since 1997. Concurrently with the *in situ* stations, we used the combination of two altimeter data, TOPEX/Poseidon and Jason 1, which together cover the whole surface of the earth in approximately 10 days.

The sea surface height measured by the altimeter allows us to estimate the oceanic heat content. Its variability is dominated by variations in the density of the ocean, that is, mostly because of changes in the temperature field, and in lesser degree, due to changes in the salinity changes. Therefore, because of the dominance of the temperature field, the altimeter data provide with an excellent way to estimate the oceanic heat storage.

The correlation between the satellite and *in situ* based heat storage was very good when the seasonal and basin–scale variability are the dominant components. At the stations closer to the equator the correlations found are between 73% and 92%. The worst correlation found was the buoy located at 15ºN 38ºW, 35%. The stations along 38ºW were thoroughly studied by Foltz et al. (2004). This region is strongly influenced by the Amazon river discharge and the precipitation and evaporation cycle promoted by the migration of the

Intertropical Convergence Zone nearby. In this region, our assumption that the heat storage is tied to the temperature field is weakened by the local dynamics. Nevertheless, even in this region, the correlations found are not insignificant and the satellite based estimation of the heat storage is still a reliable tool to investigate the variability in space and time over the Atlantic.

The total heat storage estimated by the altimeter are decomposed into several components dynamical components. The filtering used is a finite impulse response (FIR) filters applied in 2D.

The amplitude of the large–scale component is much higher at the higher latitudes of South Atlantic and in the western boundary of the North Atlantic. Higher values are also found in the region of the Brazil and Malvinas currents. Evidences of low frequency trend in the 12–year long time series made us examine the dependence of these trends throughout the basin. A straight line was least square fit to the seasonal and basin–scale component of the heat storage anomaly (HS_t) time series at each grid point over the Atlantic. The slope of this line determined by linear regression shows the decadal trend of HS_t . The interesting result is that the whole basin presents an increasing trend over the period. Statistically significant values of HS_t were found at high latitudes of the Atlantic, and some small regions showed a slight decrease. The observations of the long–term trends in heat storage anomaly show important results that could have meaningful implications in world climate.

Our results show that the oceanic heat storage is an important element on the heat budget analysis. In theory, the heat balance in the ocean is defined as $Q = \nabla_H F_o + \frac{\partial HS}{\partial t}$, where Q is the net flux at the ocean–atmosphere interface, $\nabla_H F_o$ is the horizontal divergence of the oceanic heat flux, i.e, the heat advected horizontally by the ocean currents, and $\frac{\partial HS}{\partial t}$ is the rate of change of the heat storage. It was a usual assumption to neglect the changes in the heat storage term, as long–term changes in the temperature of the ocean were considered negligible. From the long–term trend analysis on the Atlantic we conclude that the heat storage changes are important to establish the correct heat balance between the ocean interior and its interface with the atmosphere.

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