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Influence of salinity in the heat storage anomaly estimated from Argo and altimeter data in the tropical and South Atlantic

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Abstract. The monitoring of the oceanic heat storage is a task that can be carried out by the use of satellite altimeter data. Since variability in sea surface height is mostly due to the expansion and contraction of the water column it can be correlated with variations in the heat and salt content. Therefore, estimation of heat storage from space would require corrections for the haline effect. To investigate the importance of salinity effects on heat storage anomaly over the tropical and South Atlantic ocean we compare the estimates using in situ data. Over 22,000 temperature and salinity (TS) profiles were obtained from Argo vertical profilers drifters to examine the influence of salinity variability in the estimation of heat storage from altimeters. Mean climatological TS values are provided by the World Ocean Database 2001. The anomalies from in situ data are estimated relative to these means from climatology.

The sea surface height anomaly due to haline effects are prominent in two regions near: near the Brazil and Malvinas currents confluence zone at 40°S, and around this same latitute on the eastern side of the basin, possibly brought by the Agulhas currents. The South Atlantic presents a slight positive anomaly in sea surface height. The correlations in the heat storage anomaly between the Argo in situ and altimeter data are generally good throughout the Atlantic. The largest discrepancies are found near the a Plata river region, as expected, and in the eastern North Atlantic. The latter could be related to subsurface flow of salty waters from the Mediterranean Sea. The use of in situ measurements of subsurface salinity to correct the heat storage from satellite is an important addition to observe and understand the ocean dynamics.

Palvras-Chaves: satellite oceanography, salinity, ocean–atmosphere interaction, climate variability, heat flux

1. Introduction

Changes in the oceanic heat storage (HS) reveal important evidences of climate variability on the ocean heat fluxes. The oceanic heat budget is a balance of heat storage (HS) rate, heat flux at the air–sea interface, and horizontal divergence of oceanic heat flux. Specifically, long-term variations in the oceanic heat storage is a powerful indicator of climate change as HS represents a balance between the net energy input into the ocean through the surface and the poleward heat fluxes by the ocean currents. Historically, HS has been estimated by integrating the temperature profiles from hydrographic cruises or buoy data. Therefore, the knowledge of its variability is limited by data availability. The use of satellite altimeter data opened up new possibilities to continuously monitor the oceanic HS in a global scale with unprecedented resolution in both space and time. Oceanic heat storage anomalies are estimated from sea surface height anomalies measured from the altimeters TOPEX/Poseidon and Jason 1 (TJ). To characterize and validate the use of the altimeter based HS in the Atlantic, we used the data from the Argo project.

HS has been derived from altimeter data through the relation between thermosteric variations in the upper layer and variations in the sea surface height (White and Tai (1995), Chambers et al. (1997), Wang and Koblinsky (1997), Polito et al. (2000). The comparison between in situ and satellite derived HS shows discrepancies that can be related to haline effects. These effects are relatively strong in coastal regions, decreasing toward the open ocean (Tabata et al., 1986). Sato et al. (2000) using data from three locations showed that a haline height correction significantly improves the satellite derived HS and that this correction should be based on in situ rather than climatological estimates. In this study we intend to expand their methodology for the tropical and South Atlantic ocean using a expanding collection of temperature and salinity measurements from the Argo project.

To quantify the salinity variability is an important point to understand the global climate change. It has been suggested that the thermohaline circulation in the North Atlantic could be weakened due to an increase in fresh water in the northern North Atlantic. Salinity changes play a role in sea level change due to the addition or removal of fresh water and due to the haline contraction factor in sea level (density) calculations. Many studies have focused in the study of surface salinity variability limited to regional circulation or short periods of time. In the past decade, the establishment of moored array such as the Pilot Research Moored Array in the Tropical Atlantic (PIRATA) allow us to continuously monitor the variability of ocean parameters at surface and subsurface layers. Initiatives such as the Argo drifter profilers represent an unprecedented view of the ocean interior. The combination of salinity measurements over almost a half decade in the Atlantic ocean in combination with altimeter based heat storage we will be able to improve our knowledge of the relations between the salinity and temperature structure and their variability at the surface and subsurface layers of the oceans.

2. Method

The HS of an observed temperature profile is

$$HS = \rho C_p \int_{-h}^{0} T(z) dz, \tag{1}$$

where ρ is the density of seawater, C_p is the specific heat at constant pressure, $T(z)$ is the temperature profile, and h is the depth to which the temperature is integrated. HS is expressed in units of J m^{-2}.

The heat storage anomaly (HS$'$) is estimated from the filtered height anomaly (η) according to the linear relation (Chambers et al. (1997):

$$HS' = \frac{\rho C_p}{\alpha} (\eta + \eta_h), \tag{2}$$

where α is the thermal expansion coefficient and η_h the height correction for the haline effect.

The product $\rho C_p(x, y, t)$, a function of longitude, latitude and time, is derived from climatological maps of the World Ocean Atlas 2001 (WOA01) (Conkright et al. (2002) for a 1°×1° grid and is averaged from the surface to a depth h. $\alpha(x, y, t)$ is estimated by averaging from the surface to a depth h the climatological α profile weighted by layer thickness and temperature anomaly.

$\eta_h(x, y, t)$ is estimated by the integral of the product of the climatological haline contraction coefficient, β, and the salinity anomaly (residual after subtracting the annual mean) profiles from the surface to a depth h

$$\eta_h = \int_{-h}^{0} \beta \Delta S dz. \tag{3}$$

The original TOPEX/Poseidon and Jason 1 (T/J) sea surface height anomaly (η_o) is decomposed using 2D finite impulse response filters (Polito and Liu (2003). This method uses previous knowledge of the spectral composition of the signal (approximate period and wavelength) to separate it into additive components:

$$\eta_o = \eta_t + \eta_w + \eta_r = \eta + \eta_r. \tag{4}$$

η_t is the basin–wide variability, mostly due to seasonality and advection. η_w is the meso to large–scale propagating signal composed mainly of baroclinic Rossby, Kelvin and instability waves. η_r is the small to meso–scale non–propagating eddy variability.

3. Data

The *in situ* data are obtained from the Argo project site (http://argo.jcommops.org). The objectives of the Argo project is to launch a total of 3000 floats up to 2006 over the whole oceans and operationalize a network of data distribution. The Argo floats are design to stay in the water for a number of years continuously performing measurements cycles. Each cycle lasts about 10 days and can be divided into 4 phases: i) descent from surface to 2000 dbar; ii) subsurface drift of 10 days; iii) ascending profile with measurements of pressure, temperature, and salinity; and iv) a surface drift with data transmission to a communication satellite. Data from Argo floats are transmitted from the float, passed through processing and automatic quality control procedures as quickly as possible after the float begins reporting at the surface. The target is to issue the data to the Global Telecommunication System (GTS) and Global Data servers within 24 hours of surfacing, or as quickly thereafter as possible. These are called real-time data.

For this study, stations from the period between 01/01/1998 to 01/31/2006 were retrieved from the Argo data base for the Atlantic ocean between 20 °N and 60 °S. Over 22,000 profiles of temperature and salinity were selected. The spatial distribution of profiles are not uniform in the Atlantic. Most of them are located in near the equatorial region, Figure 1.

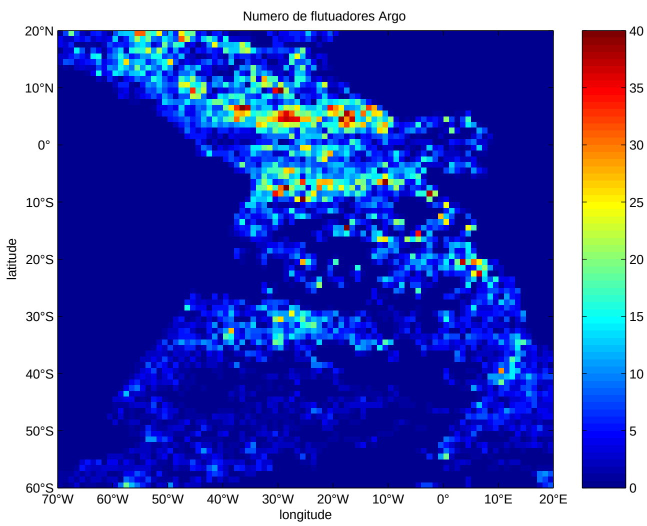

Figura 1. Spatial distribution of the Argo profiles for the tropical and South Atlantic ocean averaged in $1^{\circ}\times1^{\circ}$ bin.

The general procedure consists of linearly interpolating individual temperature and salinity profiles in the vertical at standard depths levels. Stations with gaps larger than one standard depth were discarded. Missing surface data (above 5 m) were extrapolated by repeating the first measured value upward assuming that the data were within the mixed layer. Missing data in the deepest part of the profile (below the main thermocline) were extrapolated using the local mean gradient.

The mean temperature and salinity fields from Argo data are compared to climatological values from the World Ocean Database, (Conkright et al., 2002). The constants ρ, C_p and α are also estimated from the climatological temperature and salinity data.

The mean surface salinity field measured by the *in situ* Argo floats represents very closely the long term mean from the climatological data. The mean values from Argo represent an average of few years compared to the climatological data. The stations in the North Atlantic were taken since 1998, however the floats started to be deployed in the South Atlantic ocean only after 2002. The difference in sea surface salinity are generally small (< 0.1) within the subtropical gyre. The largest differences occur near the coastal areas especially closer to regions of river discharge: Amazon plumes in the western equatorial, La Plata in the southwestern region and the Niger in the Gulf of Guinea in the coast of Africa.

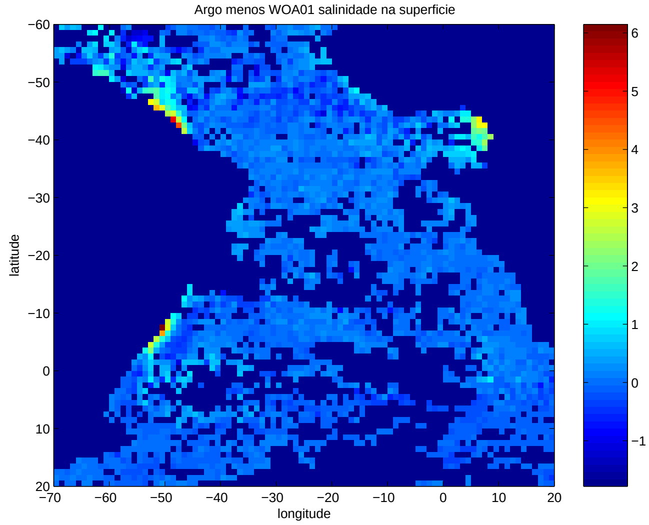

Figura 2. Sea surface salinity difference between Argo and WOA01 climatological data for the tropical and South Atlantic ocean averaged in 1×1 ° bins.

The integral in Equation 1 is calculated to a depth h below the main thermocline. For the study region we chose the depth of 500 m. The T/P HS′ comes from Equation 2.

4. Results

The comparison of results is based on the correlation between the *in situ* Argo and TJ HS′ for the Atlantic. Normally, the correlations should be computed between two corresponding time series. In the case of lagrangian Argo floats, there is no time series, but just a collection of data from independent realizations of a number of floats. Therefore, to be able to perform any statistical test and comparison with the altimeter data we grouped the data into small square bins of 1 °× 1 ° and estimate the correlations within each bin. Better correlations are function of number of floats in each bin.

As a illustration we show Figure 3 with all points within the latitudinal band between 5 °N and 6 °N. This region was chosen because of the high density of data, 774 points. A three point moving average was used to remove the higher frequencies. This figure helps to visualize the correlation between the two independently estimated heat storage.

The correlations of the heat storage from *in situ* and satellite data at each 1 °× 1 ° are surprisingly good in large areas of the basin, Figure 4. In the tropical North Atlantic we found lower correlations in the eastern portion of the basin. We speculate that these discrepancies could be related to the salty flux from the Mediterranean Sea through the lower layers. Pour correlations are also found near the La Plata region in the western South Atlantic. The results in the North Atlantic and near the equatorial band tend to be more reliable due to the data availability.

We could relate that discrepancies in the heat storage between the two sources of data are due to variations in the salinity anomaly. The sea surface height measured from the satellite altimeter data is a result of steric (or density) changes in the water column. Therefore, both fluctuations in the temperature and salinity fields contribute to the establishment of the observed sea height and to the oceanic heat stored locally in the water column. Generally, the temperature is the dominant term in determining the density of the water, however there are regional circulations that will depend on the salinity as well. These regions are usually near the coastal areas under

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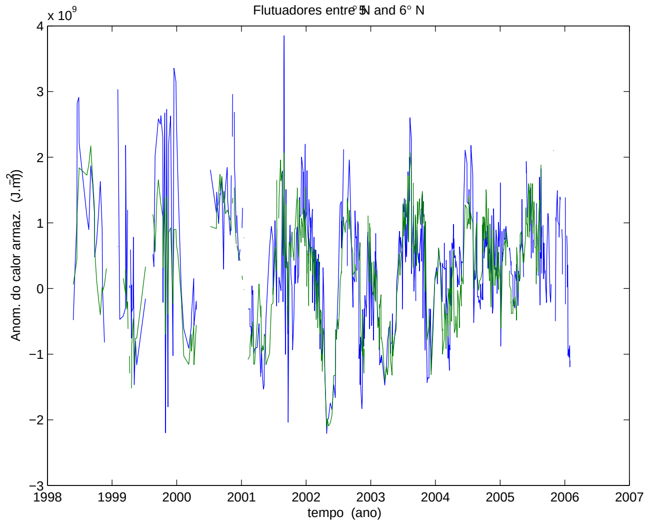

Figura 3. HS$'$ estimated from Argo (blue) and TJ data within 5 °N and 6 °N, filtered with three point moving average.

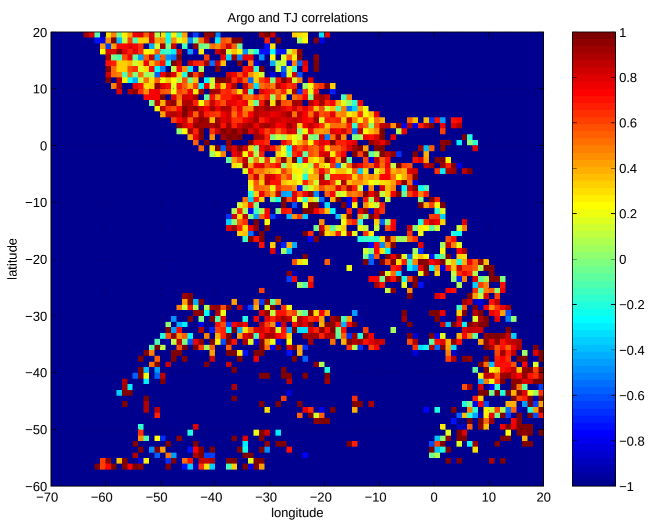

Figura 4. Correlation between the HS$'$ estimated from Argo and TJ data.

the influence of river discharge. To assess the importance of salinity, we determine the sea surface height anomaly due to haline effects only using equation 3.

Figure 5 shows the spatial distribution of the standard deviation of the sea surface anomaly due to salinity effects alone. The largest changes are observed near the region of the Brazil and Malvinas currents confluence zone, around 40°S with anomalies in the order of 20 cm. The salinity also plays an important role on the other side of the basin, possibly from the flow carried by the Agulhas currents. This region is generally marked by the presence of many eddies potentially responsible for the salinity anomalies. Curiously, the region offshore Amazon river discharge does not show a peak in variance. Apparently, although it is the largest freshwater contribution in the region, its variance is relatively small.

5. Conclusions

Temperature and salinity profiles from over 22,000 Argo floats in the Atlantic ocean from 20 °N and 60 °S, in the period between 1998 and 2005 were used to investigate the salinity variability and its influence in the estimation of heat storage anomaly. The *in situ* data are crucial to evaluate the importance of haline effects in the determination of the heat storage anomaly from sea surface height anomaly measured by satellite altimeter. Sato et al. (2000) showed that the

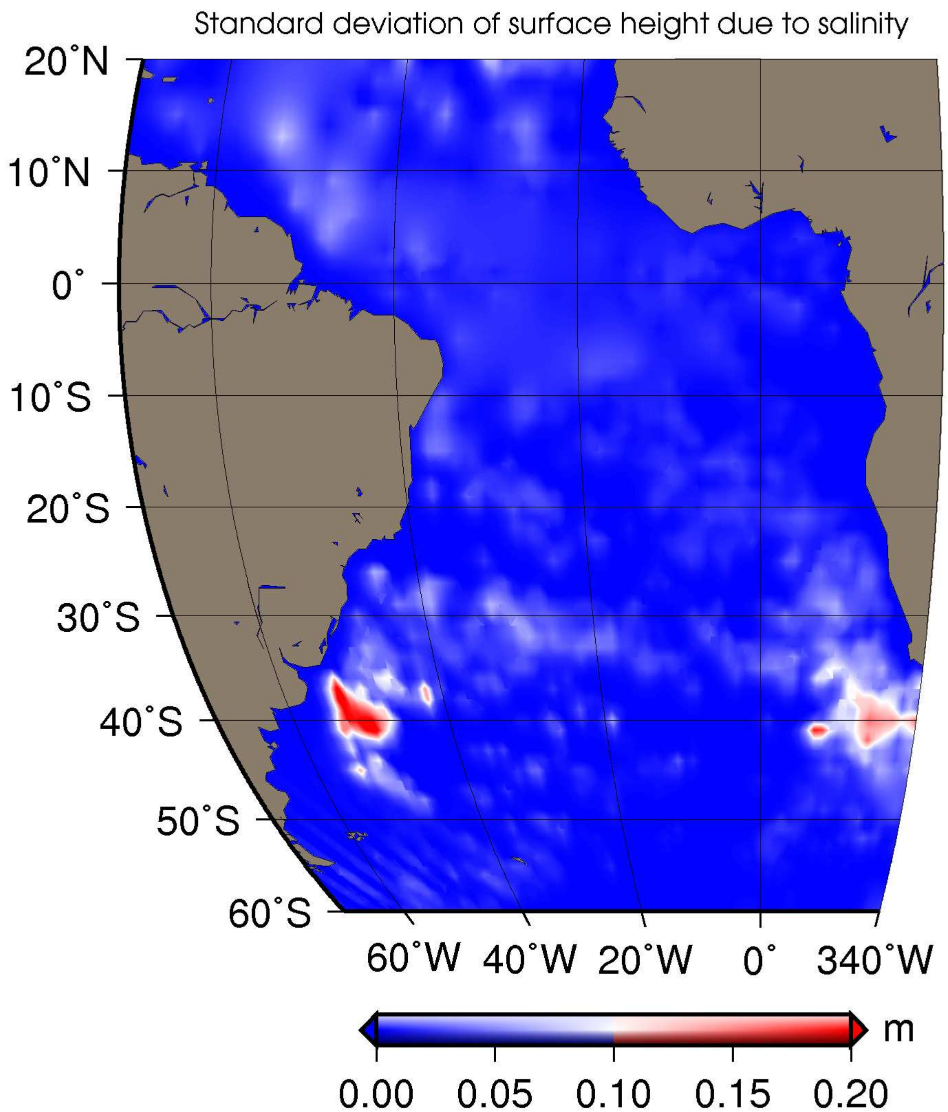

Figura 5. Standard deviation of the sea surface height anomaly due to salinity effects. The anomaly is estimated from Argo relative to climatological data.

use of in situ salinity estimates significantly augmented the correlations and decreased the rms differences in the HS′ estimates.

The sea surface height anomaly due to salinity effects showed high variance at 40°S on both sides of basin. On the western side, the largest standard deviation (> 0.2m) are found near the Brazil and Malvinas currents confluence zone. On the eastern side, we found larger changes in the height due to salinity effects possibly associated with salinity anomalies brought by Agulhas currents eddies. These results should be considered with caution because the South Atlantic data found in the Argo data base are from floats launched after 2002. These results would represent a more recent trend in the salinity anomalies. To corroborate these results, longer times series should be used.

The study allowed us to investigate the correlations between the heat storage anomaly estimated from Argo *in situ* and from TOPEX/Poseidon and Jason 1 altimeter data. As the Argo data do not present as time series, the comparison with the altimeter data are not possible at each point in space. Alternatively, we estimate the correlation between the altimeter heat storage time series with all the *in situ* measurements found at each 1°×1 ° bin for the whole basin.

The correlations between the two measurements are reasonably good. The largest discrepancies are found near the Brazil and Malvinas currents Confluence zone and the eastern South Atlantic. Weak correlations near the coastal regions are expected. Low values in the eastern North Atlantic could be related to the flux of salty waters from the Mediterranean Sea in the lower layers.

The incorporation of salinity effects would improve the measurements of heat storage anomaly measured by the altimeters. As a consequence, the monitoring of the oceanic heat storage and its variability would become more reliable for climate prediction purposes.

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