A potential use of satellite derived upper ocean heat content for studying climate variability: an example for the South Atlantic

Wilton Zumpichiatti Arruda[1] , Carlos Alessandre Domingos Lentini[2,a] e
Edmo José Dias Campos[2,b]

[1] Instituto de Matemática, Universidade Federal do Rio de Janeiro (UFRJ)
Av. Brigadeiro Trompowsky s/n, Centro de Tecnologia, Bloco C,
Cidade Universitária - Ilha do Fundão.
Caixa Postal 68530, 21945-970 Rio de Janeiro - RJ, Brasil
Email: wilton@im.ufrj.br

[2] Instituto Oceanográfico da Universidade de São Paulo (IO-USP)
Praça do Oceanográfico, 191, Cidade Universitária – Butantã
Caixa Postal 05508-900 – São Paulo, S.P., Brasil
[a]Email: lentini@io.usp.br
[b]Email: edmo@io.usp.br

Abstract. The lack of continuous long-term hydrographic observations, especially in the South Atlantic Ocean, makes satellite-derived data an extremely useful tool to investigate time and spatial variability on a basin scale. Altimeter data, which is not affected by cloud coverage as infrared-derived data, provides extremely useful information on the vertical thermal and dynamical structure of the upper ocean when combined with climatological hydrographic through a diagnostic model. We present a semi-dynamic model that combines sea surface height anomalies from TOPEX/POSEIDON, infrared satellite-derived sea surface temperature, and World Ocean Atlas 2001 hydrographic data to generate maps of the Upper Ocean Heat Content Anomaly which is suitable for climate variability studies.

Key-words: altimeter data, SHA, South Atlantic Ocean, heat content, anomalies, South Atlantic Thermocline Waters, upper layer thickness, two-layer model.

Palavras-chave: altímetro, SHA, Oceano Atlântico Sul, conteúdo de calor, anomalias, Água de Termoclina do Atlântico Sul, espessura da camada superior, modelo de duas camadas.

1. Introduction

One of the principal goals of climate variability research is the prediction of relative long-term changes in global climate. Due to the ocean's high thermal inertia it is believed that the Earth's climate is adjusted by the ocean's troposphere, where heat flux exchange plays a vital role on air-sea process. Therefore, understanding the heat content within the upper layer of the ocean is crucial to comprehend the coupling between the atmosphere and the ocean and how they influence each other from short to long time scales.

The lack of continuous long-term hydrographic observations in some regions, especially in the South Atlantic Ocean, makes satellite-derived data an extremely useful tool to investigate time and spatial variability on a basin scale. Altimeter data, which is not affected by cloud coverage as infrared-derived data, provides extremely useful information on the vertical thermal and dynamical structure of the upper ocean when combined with climatological hydrographic through a diagnostic model (Goni *et al*., 1996; Garzoli and Goni, 2000).

Current research and operational weather models rely on satellite-based sea surface temperature (SST) measurements in combination with climatological data sets to infer the upper ocean thermal structure and Heat Content (HC). Our goal is to develop a procedure whereby altimetry-based heat content estimates can be used to accurately monitor the upper-ocean heat content in the South Atlantic Ocean. HC anomaly is systematically computed in the upper layer of the South Atlantic using altimeter data and sea surface temperature fields both referenced to a 1^o x 1^o fixed grid and covering the same time period.

For this particular study, three regions are selected: (1) the South Atlantic subtropical gyre, (2) the southwestern Atlantic sub-polar region and (3) the Agulhas retroflection. Emphasis is placed on these three different regions for practical oceanographic purposes. Regions 2 and 3 correspond to the two main pathways of cold and warm waters entering the South Atlantic, respectively. If an export imbalance of cold and warm waters occur one may expect different amounts of net heat flux transported northward, which, eventually, may impact the Earth's climate on a global scale.

The paper is organized as follows. Section 2 describes the data sets used and the methodology to compute the heat content and its anomalies. Results are then presented in section 3, where maps of heat content are computed for three different regions in the South Atlantic. Results are discussed in section 4, followed by summary and conclusions.

2. Data and Methods

Both altimeter and sea surface temperature have the same grid (i.e., 1^o x 1^o) with all gaps filled in by optimal interpolation methods. For further information, the reader should check the PO.DACC on-line documentation (http://podaac.jpl.nasa.gov/products/). The hydrographic data from World Ocean Atlas 2001 (WOA01) is obtained at http://www.nodc.noaa.gov/OC5/WOA01/pr_woa01.html. This data set contains temperature and salinity values at standard levels with the same grid as the satellite data.

2.1. Altimeter Data

In this work we use the TOPEX/POSEIDON (T/P) Sea Surface Height Anomalies (SHA) for the period from October 1992 to December 2001, averaged over 10 days and referenced to the 1993-2001 mean, with tidal and inverted barometer effects removed. The altimeter-derived sea height anomaly, η', is the value of the deviation of the actual sea height, η, referred to the mean sea height, $\overline{\eta}$, which is computed over a period of time of several years:

$$\eta'(x,y,t) = \eta(x,y,t) - \overline{\eta}(x,y) . \quad (1)$$

2.2. Sea Surface Temperature Data

For the Sea Surface Temperature (SST) we use the NOAA/AVHRR product, for January 1990 to December 2001, averaged over 10 days, using version 4.1 of the Pathfinder algorithm to convert radiances to SST.

2.3. Two-Layer Model Approximation

Climatological temperature and salinity data from WOA01 is used to compute the mean value of the HC for the region of study, which extends from the surface to the depth of the 10^oC isotherm and the reduced gravity. The choice of using the 10^oC isotherm is two-fold. Scatter plots between altimeter measurements and inverted echo sounders for the confluence region and the Agulhas retroflection show a high correlation (Goni *et al*., 1996) and it is a good proxy to define the lower subsurface limit of the South Atlantic Thermocline Water (SATW) in the subtropical gyre (A. Piola, 2001, pers. comm.; S. Garzoli, 2002, pers. comm.).

The reduced gravity field, *g*', is computed using the mean upper and lower layers densities:

$$g'(x,y) = \varepsilon(x,y)g = \frac{\rho_2(x,y) - \rho_1(x,y)}{\rho_2(x,y)} g(y) \qquad (2)$$

where g is the acceleration of gravity, and ρ_1 and ρ_2 are the mean densities of the upper and lower layers, respectively. The lower layer is defined as the layer between the depth of the 10°C isotherm and 1500 m or the sea floor. Hence, the reduced gravity provides a measure of the vertical stratification in the region. These climatologically-derived values are then used in conjunction with the sea height anomalies within a two-layer reduced gravity scheme to obtain the absolute field of the depth of the 10°C isotherm (**Fig. 1**).

The understanding of the relationship between the sea surface height signal and the upper ocean thermal and dynamic structures is a key-factor to assessing the limitations of altimeter-derived SHA data. The SHA together with historical hydrographic data is used to estimate the upper layer thickness. In a baroclinic ocean, each change in thermocline depth will be compensated by a change in sea level (**Fig. 1**). Using a two layer model approximation, the upper layer thickness, h , is (Goni *et al*, 1996):

$$h(x,y,t) = \bar{h}(x,y) + \frac{1}{\varepsilon(x,y)}\left[\eta'(x,y,t) - \bar{B}'(x,y)\right], \qquad (3)$$

where $\bar{h}$ is the climatological 10°C isotherm depth calculated from the WOA01 (i.e., the mean upper layer thickness), and *B´* is the barotropic contribution to the sea height anomaly. This last parameter can be estimated, for example, when simultaneous observations of sea height anomaly and thermocline depth are available. In this study, *B´* is assumed to be extremely small when compared to SHA and is therefore disregarded here (Goni *et al*, 1996).

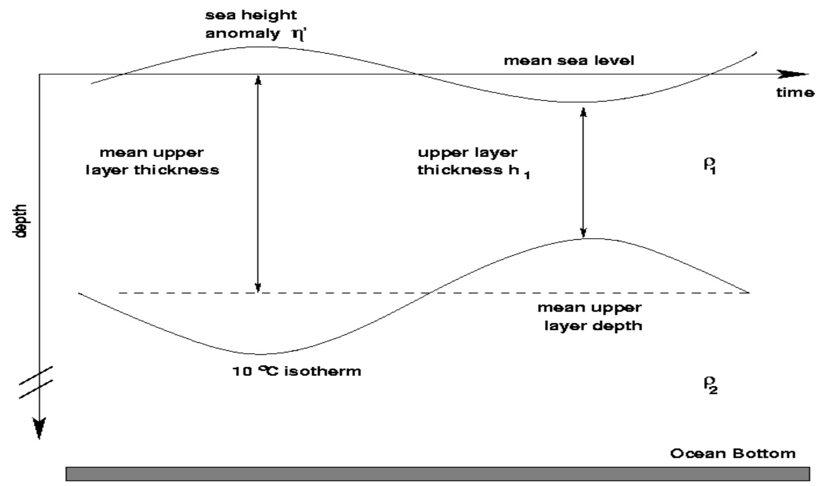


Figure 1. Schematics of the two-layer reduced gravity approximation, with an upper layer of mean density ρ_1, thickness h that extends to the depth of the 10°C isotherm and a lower layer with mean density ρ_2. The ocean surface has a sea height anomaly η'.

2.5. Upper Layer Heat Content

The Heat Content (HC) in the upper layer is defined as,

$$\mathrm{HC}(x,y,t) = \rho_0 C_p \int_{h(x,y,t)}^{0} \mathrm{T}(x,y,z,t)\,dz\,. \qquad (4)$$

The value of the integral in equation (4) is calculated from AVHRR-SST and the regression coefficients computed between $\overline{\mathrm{SST}}(x,y)$ and the $\int_{\overline{h}(x,y)}^{0} \overline{\mathrm{T}}(x,y,z)\,dz$, where the over bars denote the climatological values . In this case, the HC in the upper layer derived from the T/P-SHA and AVHRR-SST can be calculated by,

$$\mathrm{HC}(x,y,t) = \rho_0 \mathrm{C_p} \left(\alpha_0 \mathrm{SST}(x,y,t) + \alpha_1\right) h(x,y,t), \tag{5}$$

where α_0 e α_1 are the correlation coefficients, ρ_0 is the mean density reference profile of seawater and Cp is the specific heat of seawater (Fig. 2). The Heat Content Anomaly (HCA) is obtained subtracting (5) from the climatologial mean of (4) calculated from the WOA01. A similar approach has been successfully used to study the impact of Hurricane Opal in the Gulf of Mexico (Shay *et al.*, 2000).

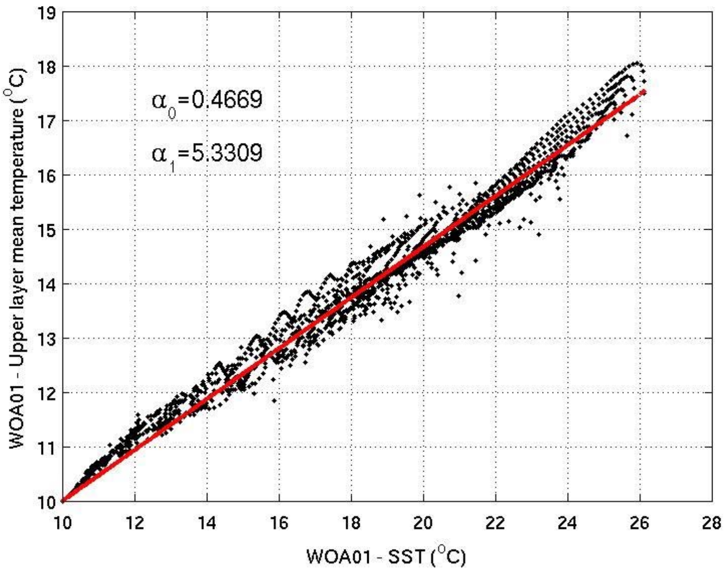


Figure 2. Linear regression between SST and upper layer mean temperature calculated from WOA01. The scatter plot contains all data points in the region 45S-19S, 70.5W-30.5E.

If we decompose the variables in (5) as a sum of a mean value plus a perturbation,

$$h(x,y,t) = \overline{h}(x,y) + h'(x,y,t), \tag{6}$$

$$\mathrm{SST}(x,y,t) = \overline{\mathrm{SST}}(x,y) + \mathrm{SST}'(x,y,t), \tag{7}$$

$$\mathrm{HC}(x,y,t) = \overline{\mathrm{HC}}(x,y) + \mathrm{HC}'(x,y,t). \tag{8}$$

Substituting (6)-(8) into (5) we get,

$$\begin{aligned} HC'(x,y,t) &= \rho \mathrm{C}_p \left(\alpha_0 \mathrm{SST}'(x,y,t)\overline{h}(x,y)\right) + \rho \mathrm{C}_p \left(\alpha_0 \mathrm{SST}'(x,y,t) h'(x,y,t)\right) \\ &\quad + \rho \mathrm{C}_p \left(\overline{\mathrm{T}}(x,y) h'(x,y,t)\right), \end{aligned} \tag{9}$$

where $\overline{\mathrm{T}}(x,y) = \alpha_0\,\overline{\mathrm{SST}}(x,y) + \alpha_1$ is the mean upper layer temperature. Equation (9) allows us to study the contribution of each term in the upper layer heat content variability. The first term in (9) is the contribution of SST variation alone, the second term is a mixed contribution of variations of SST and upper layer depth, and the third term is the contribution of upper layer depth alone. At this point, it is worth to call the reader's attention to the third term. As discussed in great detail by Gill and Niiler (1976) and Stammer (1997), the time varying component of the sea surface height has a steric contribution due to seasonal changes in solar irradiation which is most prominent outside the tropics.

3. Results

The mean depth of the 10^{o}C isotherm is shown in Figure 3. It shows a relatively deep thermocline depth (> 600-m) in the center of the subtropical gyre (Region 1) as a response to the Sverdrup regime and to the Ekman surface divergence. Region 2 shows a monotonic poleward decrease in the depth of the thermocline, whereas the deepest climatological values are observed in Region 3 as a consequence of western boundary current dynamics.

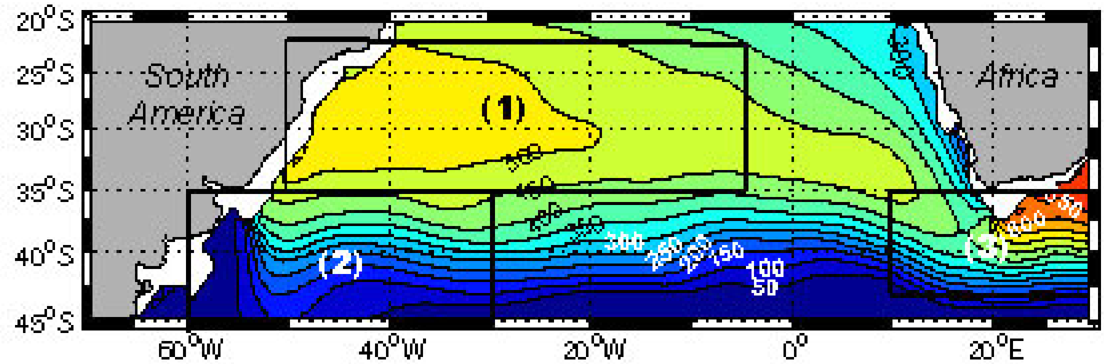
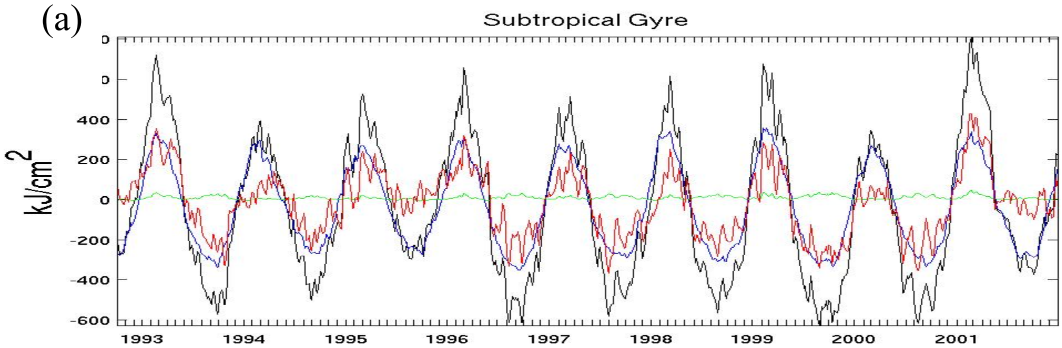


Figure 3. Contours of the climatological upper layer depth referenced to the 10^{o}C isotherm. Three regions are indicated: (1) The Subtropical Gyre; (2) The Brazil-Malvinas Confluence Region; (3) The Agulhas Retroflection Region

The contribution of each term in (9) is computed for each region (**Fig. 3**). **Fig. 4** shows that in any region the second term in (9) is negligible as compared with the other two. In the subtropical gyre (**Fig. 4a**) the first and third terms in (9) have comparable amplitudes most of the time, but it is worth to note that the first term shows a marked annual cycle while the third term has significant deviations from the annual cycle. These deviations from the seasonal cycle are indicative of interannual variability in the HCA. This result leads us to conclude that a large percentage of the seasonal HC is mostly dominated by contributions from the first term than from the third one. In the Brazil-Malvinas Confluence (**Fig. 4b**) the HC variability is mostly controlled by the third term, although a marked annual cycle is also observed. Like Region 1, the HC of the Agulhas retroflection region (**Fig. 4c**) also seems to be governed by the first term which is associated with the seasonal signal.

(a)



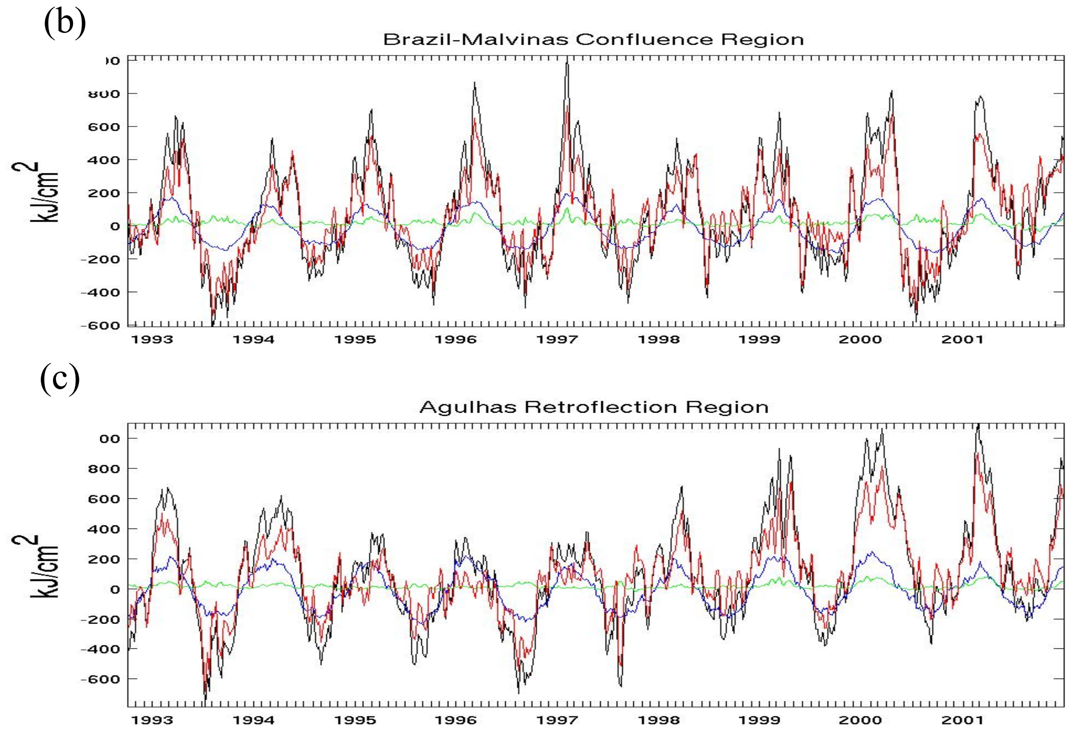


Figure 4. Black line: Upper layer heat Content (HC); **Blue line**: First term in (9);**Green line**: Second term in (9); and **Red line**: Third term in equation (9), averaged on each one of the regions indicated in Figure 3.

Due to the lack of precise models to estimate surface heat fluxes especially in the South Atlantic, which are necessary to correct for steric changes in SHA, a least-square sinusoidal curve is adjusted to the original time series as a first guess to eliminate the seasonal steric effect. A seasonal cycle consisting of an annual plus a semiannual signal is fitted to each time series of HC (**Fig. 5** upper panels). The amplitude of the annual cycle in the subtropical gyre is larger than in the other two areas. There is no significant phase change although in the Brazil-Malvinas confluence (**Fig. 5b** upper panel) the semiannual cycle has a more evident contribution. The **Fig. 5** lower panels show (for each region) the HCA deviations relative to the seasonal cycle. The black line represents the original time series while the blue line is the filtered time series with a cut-off frequency of 360 days. To do so, a 36-point Hanning filter (ie, filtering window of 360 days) is applied to the original time series. We can observe that in all three regions there is a marked interannual variability with periods between 2 and 4 years. Spectral analysis computations shows statistically significant energy peaks above the 95% confidence level at this frequency bands (not shown here). Moreover, the residual after the extraction of the sinusoidal signal reveals an interesting scenario. The Agulhas retroflection region (**Fig. 5c** lower panel) shows a positive trend from 1996 until the end of 2001.This trend is not clearly observed in the other two regions (**Fig. 5a,b** lower panels). The residuals from the fit for the subtropical gyre (**Fig. 5a** lower panel) seem to experience a positive trend from 1994-1996 and from 2000-2001. The Brazil-Malvinas confluence, however, shows a relatively small though positive trend from 1994 until 2001 (**Fig. 5b** lower panel). Year 2000 has a maximum of about 300 kJ/cm2.

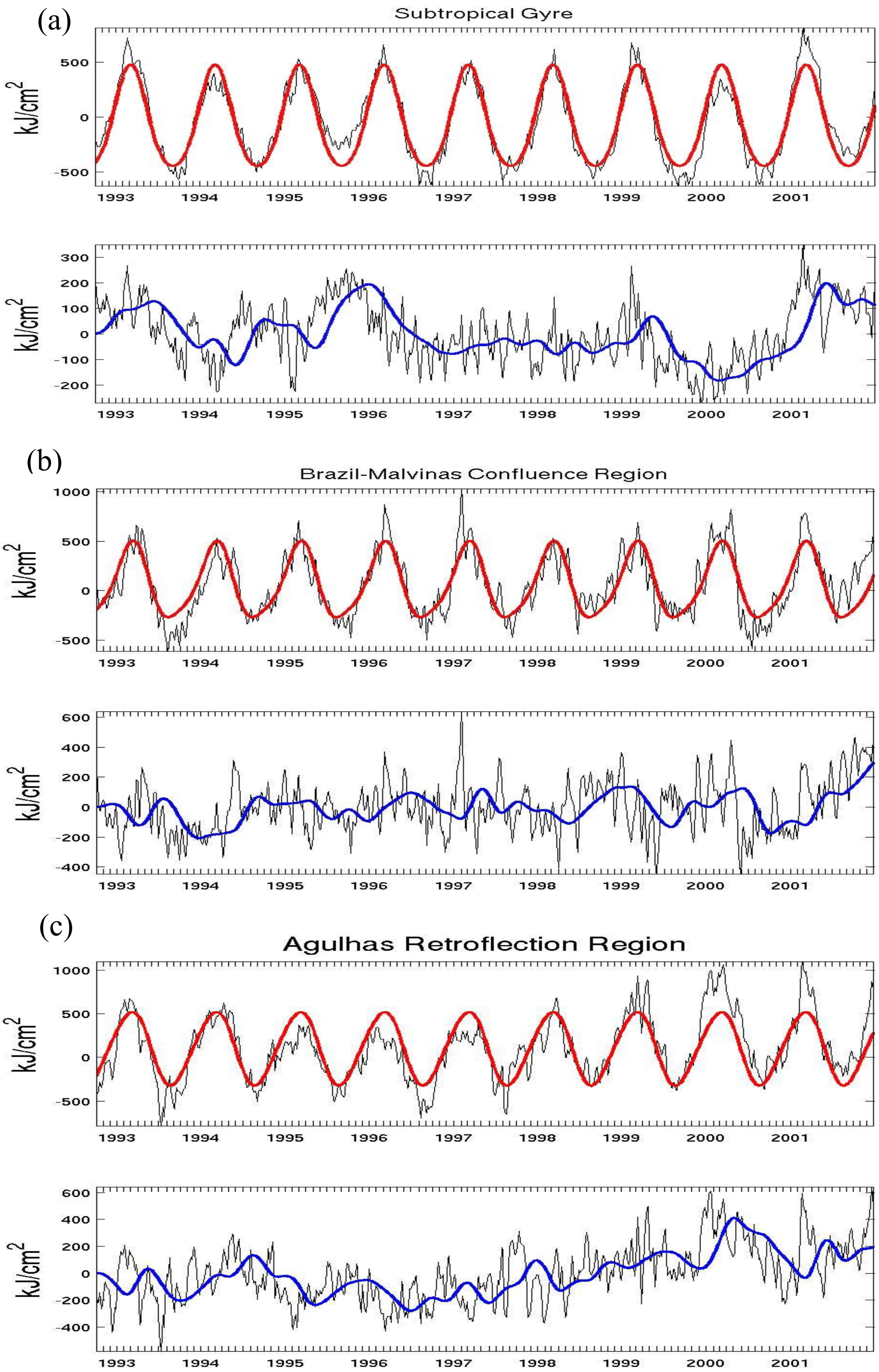


Figure 5. Each panel has two plots. **Top plot: Black line**: Average upper layer heat content (HC); **Red line**: Annual plus semiannual cycles for the Average upper layer heat content. **Bottom plot**: **Black line:** Upper layer heat content minus annual plus semiannual cycles; **Blue line**: The same as the black line but filtered.

4. Discussion

On annual time scales and basin-wide pronounced seasonal heat storage in the upper ocean is observed. As pointed by Stammer (1997), the steric component of the SHA has a clear annual cycle and it is the most significant component of the sea height variability outside the tropics. Physically, this seasonal signal appears as a response to the complex response between the atmosphere and ocean surface heat exchange.

After removal of the seasonal cycle, relative strong interannual amplitudes are also observed which are comparable to the annual cycle itself. Understanding them can be crucial to unveil the role played by these relatively short-term climate oscillations (order of 10 years or less). The 2-4-year period has been reported on previous works in the southwestern Atlantic (Venegas *et al*., 1997; Lentini, 2002) from both observations and numerical model outputs. However, none of these studies points out a reasonable explanation for the statistically significant energy peak at this frequency band. Horizontal maps of HCA (not show here) clearly indicate a westward propagation of patterns which can be identified in most extra-tropical latitudes. These propagating patterns move westward with phase speeds of the order of the first mode baroclinic Rossby waves. Results from a fully coupled atmosphere-ocean model for the South Atlantic corroborate this hypothesis (Lentini *et a*l., 2004). After the spin-up time, the coupled model is forced with surface latent heat flux anomalies which resembles the South Atlantic dipole (Sterl and Hazeleger, 2003). Surface SST anomalies generated by these anomalous surface latent heat fluxes are subducted and injected below the mixed-layer due to Ekman convergence during austral fall-winter season. These subsurface temperature anomalies are then compensated by salinity increases. Salinity-induced sub-surface perturbations end up exciting first mode baroclinic Rossby waves which propagate westward. It takes 3-4 years for these waves to cross the whole basin from east to west around the 35^{o}S latitudinal band. Eventually, these waves reach the South American east coast. Part of these signals are advected southward within the Brazil Current and towards the confluence region. Therefore, it is reasonable to believe that the observed periodicities in the subtropical gyre time series and the Brazil-Malvinas time series are related to some extent to mid-latitude oceanic adjustments to changes in external forcing fields.

5. Conclusions

The present results clearly illustrate the truly basin scale character of variations on heat content in the ocean's troposphere. From a relatively simple combination of a mathematical model and statistical tools, one can investigate the contribution of the cold and warm water pathways into an ocean basin from short to long time scales. Particularly, the South Atlantic case is more appealing because it is the only ocean where the net heat flux is equatorward. Moreover, it has a direct impact on the thermohaline circulation which regulates the Earth's climate on long time scales. The ultimate objective is to develop a near real-time capability for estimating the upper-ocean thermal structure from altimetry to use as input into research and operational forecast models.

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