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Interannual variability of the sea level height anomaly in the Southwestern Atlantic Ocean

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Abstract. This work presents a study of the spatial-temporal sea surface height anomaly (SSHA) variability in the Southwestern Atlantic Ocean (SWA) focusing on the biophysical provinces. This analysis is done using empirical orthogonal function (EOF) decomposition on the merged SSALTO/DUACS SSHA dataset from 1993 to 2006. The main results show that regions with higher amplitudes in the three leading EOF modes are coincident with the biophysical provinces previously defined in the literature. The annual signal is a common characteristic in all regions of the SWA and dominant in the Brazil-Malvinas Confluence. Moreover, interannual variability was also observed, especially in the areas located at the South Atlantic Gyral Province, Brazil Current overshoot and Southwest Atlantic Shelves Province.

Palavras-chave: altimetry, ocean variability, South Atlantic Ocean, biophysical provinces.

1. Introduction

The Southwestern Atlantic Ocean (SWA) is one of the most dynamic regions of the oceans, playing an important role in global climate. The main characteristic of this region is the Brazil-Malvinas Confluence (CBM), a collision of the warm and saline Brazil Current (BC), with the cold and less saline Malvinas Current (MC), generating instabilities which dominate the mesoescale variability of the SWA. In spite of the well-known importance in the global ocean, the influence of the SWA on the climate and weather in the south and southeast of Brazil is not yet completely understood.

Sea surface temperature (SST) and chlorophyll images have been extensively used to study the SWA (Lentini et al., 2006; Saraceno et al., 2004; Saraceno et al., 2005; Saraceno et al., 2006, Souza et al., 2006; Souza et al., 2007; Garcia and Garcia, 2008). Longhurst (1998), based on chlorophyll images among other datasets, divided the SWA in five biophysical provinces. They are: Brazil Current Coastal Province, Southwest Atlantic Shelves Province (FKLD), South Atlantic Gyral Province (SATL) and South Subtropical Convergence Province (SSTC) (Figure 1). Afterwards, Saraceno et al. (2005) identified 3 new regions using chlorophyll and SST images: Patagonian Shelf Break (PSB), Brazil Current Overshoot (BCO) and the Zapiola Rise region.

In addition to SST and chlorophyll images, SSHA maps are a valuable tool to identify spatial and temporal variability of features such as mesoascale eddies, current rings and Rossby waves (Cromwell, 2006; Lentini et al., 2006) among others. In this paper, we provide a description of the spatial-temporal sea surface height anomaly (SSHA) variability in the Southwest Atlantic Ocean focusing on the biophysical provinces.

2. Methodology

2.1. Study area

We analysed the SWA region, from 30 °S - 50 °S and 40 °W - 65 °W, and 5 smaller areas located in some of the biophysical provinces previously defined by Longhurst (1998) and Saraceno et al. (2005). This approach allows us to assess the main SSHA variability signals in different SWA regions, including the CBM region (area 2) and the Brazil Current overshoot (area 5). The location and name of the areas are shown in Figure 1 and Table 1.

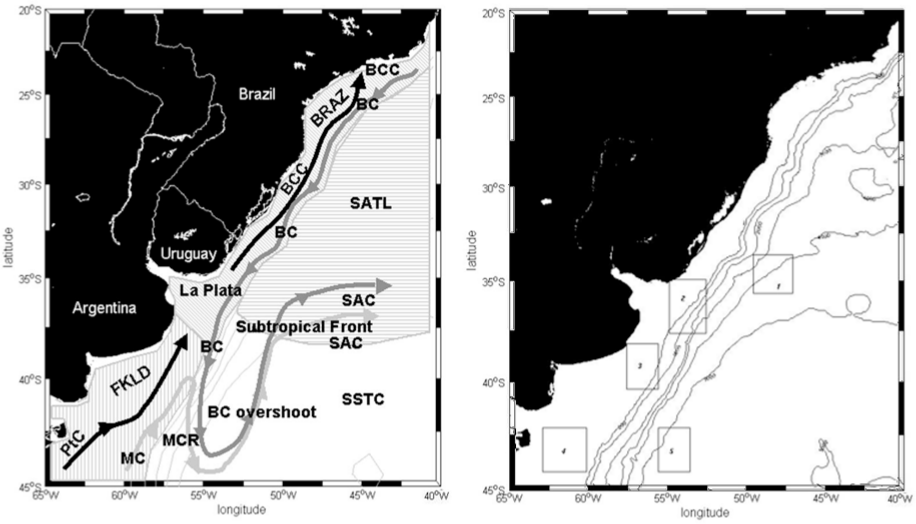

Figure 1. Study areas in the Southwestern Atlantic Ocean. The first panel shows the coastal and offshore currents represented by black and gray lines, respectively. PtC: Patagonian Current, BCC: Brazilian Coastal Current, MC: Malvinas Current, BC: Brazil Current, SAC: South Atlantic Current. The Subtropical (or Brazil Current) Front is formed after the BC overshoot (BCO) represented by the main loop of the BC at latitudes up to 45°S. The MC return flow (MCR) is also represented as the loop located west of the BC overshoot region. Light gray lines represent the bathymetry from 1000 m to 5000 m. The biophysical provinces of Longhurst (1998) are indicated as BRAZ (Brazil Current Coastal Province), FKLD (Southwest Atlantic Shelves Province), SATL (South Atlantic Gyral Province) and SSTC (South Subtropical Convergence Province). Source: adapted from Longhurst (1998) and Saraceno et al. (2005). The second panel shows the five smaller areas. The boxes and numbers represent the study areas and their respective dimension. Black lines represent the bathymetry from 200 m to 5000 m.

Table 1. Study areas from south towards north and the respective biophysical province.

Caixa	Nome	Latitudes	Longitudes
1	Brazil Current (CB) - SATL	33° 30’ S - 35° 30’ S	47° W - 49° 30’ W
2	Brazil-Malvinas Confluence (BMC)	34° 48’ S - 37° 30’ S	52° 30’ W - 54° 48’ W
3	Patagonian Current 1 (PC1) - FKLD	38° S - 40° 12’ S	55° 30’ W - 57° 30’ W
4	Patagonian Current 2 (PC2) - FKLD	42° S - 44° S	60° W - 62° 48’ W
5	Brazil Current overshoot (BC overshoot)	42° S - 44° S	53° 30’ W - 55° 30’ W

2.2. Data description

The SSHA dataset used here is the merged data produced by *Segment Sol multimissions d'ALTimétrie, d'Orbitographie et de localisation précise*/Data Unification and Altimeter Combination System (SSALTO/DUACS) and distributed by Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO), with support from *Centre National d’Etudes Spatiales*. The purpose of SSALTO/DUACS is to produce along track and gridded products from diverse altimeter missions (ERS and TOPEX/Poseidon satellites) in near-real time. The gridded products from SSALTO/DUACS are divided into updated (Upd) and reference (Ref) versions; both are available from October 1992 until the present with a temporal resolution of 7 days. The major difference between them is that the Upd product has a better quality but is not homogeneous over the time period, while the Ref product is homogeneous in time but may not have the best quality. In our case, as the BMC is a region with intense variability, we chose the Upd product. The dataset we used corresponds to monthly sea surface height anomaly (SSHA) gridded onto a 0.25^o degree Mercator projection from 1993 to 2006. The anomaly is computed with respect to the mean monthly value for the period 1993-1995. Details on the data processing are presented by SSALTO/DUACS User Handbook available at <http://www.jason.oceanobs.com>.

2.3. Empirical orthogonal function and wavelet analysis

Empirical orthogonal functions (EOF) are used to describe the spatial-temporal variability of the SSHA in the SWA. The EOF was applied to the SWA region between 30^o-50^{o}S and 40^o-65^{o}W and after for each area individually. The EOF modes are an efficient tool to represent the main spatial-temporal variability of a dataset (Emery and Thomson, 1997). The technique decomposes the dataset into uncorrelated spatial modes of variability (eigenvectors) and the temporal characteristics are given by the corresponding amplitude time series (eigenvalues). The EOFs are ordered according to the decrease of % variance explained in each mode.

In order to obtain a more detailed structure of the interannual variability in time and frequency domain we performed the wavelet transform (WT). This technique has been successfully used in the areas of oceanography and meteorology (Cromwell, 2006; Pezzi and Kayano, 2008). WT, similar to Fourier Transform, decomposes the signal in different time scales, but also allows one to identify how these signals vary in time. We used a continuous WT (Morlet), which provides a flexible window that narrows (widens) when focused on high (low) frequency oscillations (Weng and Lau, 1994). The WT was applied on the amplitude series of the first three modes from the EOF analysis. The spectra are significant at the 95% confidence level assuming a background red noise. Details of the WT can be found in Weng and Lau (1994) and Torrence and Compo (1998).

3. Results and discussion

We first discuss the results related to the SSHA in the Southwestern Atlantic Ocean. Figure 2 presents the spatial patterns of the three leading amplitude modes of the ASSH fields for the period between 1993 and 2006. These three EOF modes account for 34 % of the total variance of the series. The first EOF (EOF1) accounts for 21 % while modes two and three represent 7 % and 6 % of the total variance, respectively. The low variance obtained by each EOF may be related to the intense variability of the SWA, as described by Chelton et al. (1990). Moreover, SSHA variability can be influenced by subsurface ocean dynamics of the oceans such as thermal processes (Fu and Cazenave, 2001; Robinson, 2004).

In spite of the low variance obtained in the first three EOFs, the spatial variability of the amplitude maps coincides with the biophysical provinces defined by Longhurst (1998) and Saraceno et al. (2005). The EOF1 amplitude map shows higher variability over the continental shelf, where the biophysical BRAZ and FKLD provinces are located. It is similar to the SST anomaly amplitude map of mode 1 obtained by Souza et al. (2007) as well. The dominant periods computed by the global wavelet spectrum (GWS) are centred at about 1.2

and 3.3 years. Saraceno et al. (2005) also observed strong interannual variability over the Patagonian shelf and shelf break in 11 years of chlorophyll images.

Amplitudes of EOF2 are higher at SATL Gyral Province, Zapiola Rise region (45 ^{o}W - 45 ^{o}S, Saraceno et al., 2005), BC overshoot region, Malvinas return flow and the border between the Patagonian shelf break and the Malvinas Current. This mode is mostly related to the annual cycle with some interannual variability at 2.8 and 5.3 years. As for EOF3, the BMC, the Zapiola Rise and the MC display high SSHA variability at 2.1 and 4.6 years.

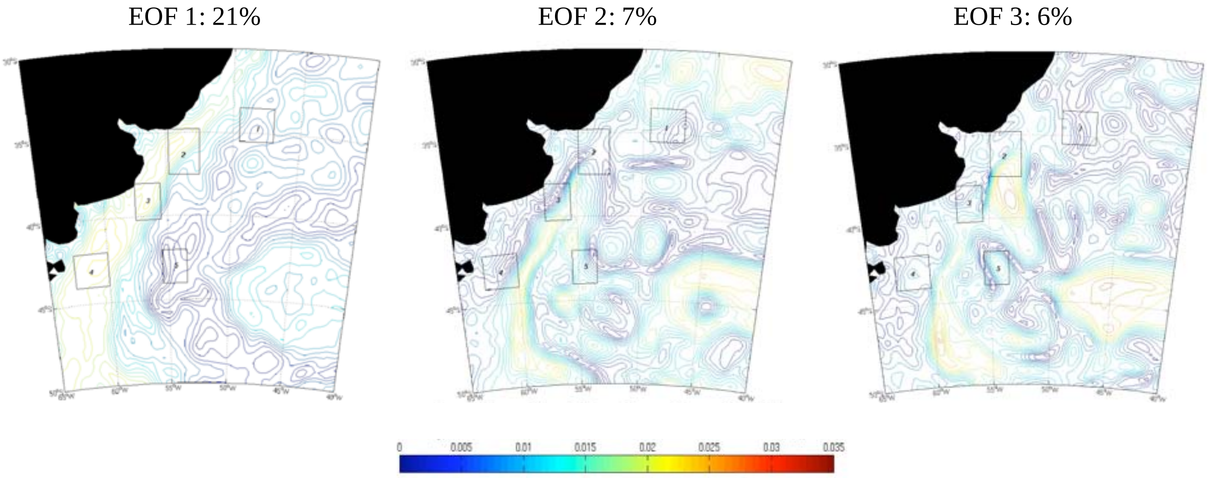

Figure 2. Spatial patterns for the first three empirical orthogonal functions (EOFs) of sea level height anomaly over the Southwestern Atlantic Ocean. Amplitudes are plotted in coloured contours (arbitrary units).

We now concentrate on the SWA biophysical provinces. The percentages of the explained variance obtained by the three leading modes and the dominant timescales obtained by the GWS are summarized in Table 2. The results of the WT are presented in Figure 3 to 7. However, due to space restrictions, we only present the results of the leading EOF amplitude series of each area.

Table 2**.** Summary of the characteristics of the three leading EOF modes and GWS of SSHA in the Southwestern Atlantic Ocean sub-areas for the period between January 1993 - December 2006.

Areas	EOF1 % variability and dominant timescales		EOF2 % variability and dominant timescales		EOF3 % variability and dominant timescales	
1	50	~ 3.3, 5.2, 1.7 years	19	~ 6.2, 3.2, 0.8 years	13	~ 1.2 years
2	69	~ 1.2, 7, 3.2 years	14	~ 1.5 years	03	~ 0.5 years
3	69	~ 1.2, 1.8, 3.7 years	14	~ 0.4 years	05	*
4	80	~ 4.5, 1.2 years	09	~ 1, 0.4 years	04	~ 0.4 years
5	45	~ 5.3, 3.7, 2.3, 1 years	21	~ 5.5, 1 years	18	~ 3, 1.5 years

* No significance at 95% of confidence level.

In agreement with previous works (Saraceno et al., 2005; Souza et al., 2007), the annual signal is a common characteristic in all regions of the SWA (Table 2). In area 1, located at the SATL Gyral Province, the three leading EOF modes account for 82 % of the total variance. The local wavelet spectrum (LWS) of the first mode shows strong oscillation centred at 1.7 years between 2002-2003. We also observed strong interannual variability at 3.3 and 5.2 years from 1997 to 2002 (Figure 3), in contrast with the results from Saraceno et al. (2005) who reported a low interannual variability of the chlorophyll and SST over the SATL. Mode 2 shows a 3.3-year oscillation at 1997-2002 period in the LWS. The GWS shows the highest variability at 6.2 years, but it must be analyzed with caution due to the limited length of the amplitude series. The third mode has a dominant peak at annual cycle during 1995-1997 and 2000-2004.

In the BMC region, area 2, the three leading modes comprise 86 % of the total variability. The annual cycle is the dominant signal in this area, particularly from 1996 to 2004 in mode 1 (Figure 4) and from 1995 to 1997 in mode 2. In the third mode, some patches of high power occur at semi-annual scale. Saraceno et al. (2004) studied the variability of the fronts in the SWA with SST images and their results showed that the annual cycle explains 67% of the variance of the BMC front intensity. Apart from the annual cycle, some interannual variability was also detected in the LWS of mode 1 at 7 and 3.2 years, concordant with the 3.4-year SST signal described by Saraceno et al. 2004.

The LWS of areas 3 and 4, both located over the Patagonian shelf, are presented in figures 5 and 6. In area 3, the LWS of the leading mode indicates a strong annual cycle between 1995-1997 and in 2003 (Figure 5). Mode 2 presents patches of high power from 1997 to 1998 at a 3-year cycle and a second one beginning in 2003 at a 1.6-year cycle. Mode 3 shows peaks at semi-annual and annual time scales. The sum of the three leading modes accounts for 88 %. Area 4 has 93 % of the total variance concentrated in the first three leading modes. The LWS shows a strong annual cycle between 1995-1996 in mode 1 (Figure 6). In addition, the GWS reveals a second cycle at 4.5 years. The other two modes, EOF1 and EOF2, are mostly related to annual cycle. Here, it is important to point out that near the coast, mainly the first 50 km, some corrections such as tides are less accurate and therefore may affect the SSH estimates.

The total variance explained by the first three EOF modes of area 5 is 84 %. The LWS of the leading mode shows a region with intense power between 1999-2002 over the period range of 1-5 years (~14-64 months) (Figure 7). Mode 2 is related to the interannual variability, mainly at 2.6 and 5.5 years according to the LWS and the GWS respectively. Mode 3 presents most of the power concentrated in the 1.3 and 2.6 years interval, with a peak at 2000-2001.

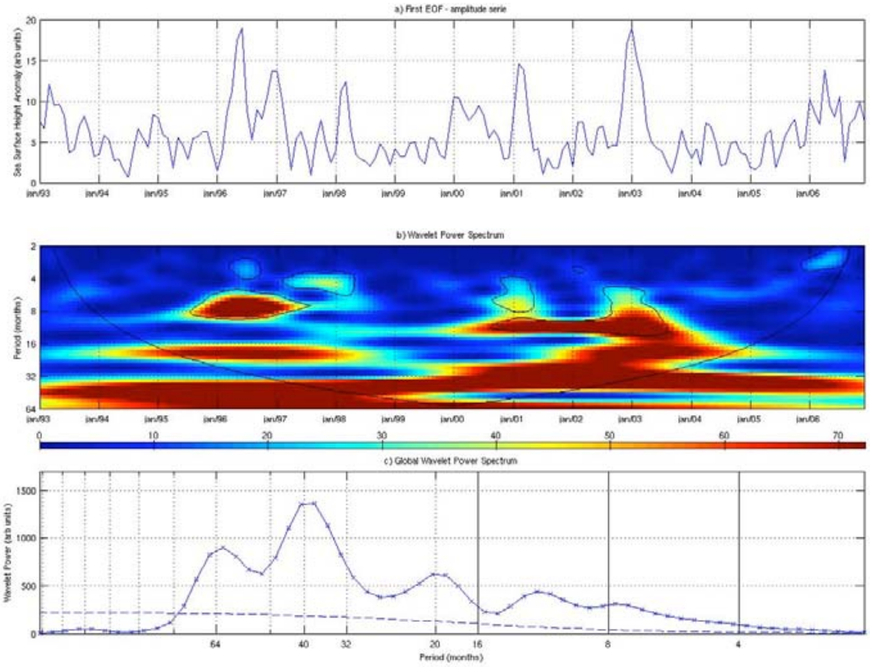

Figure 3 – Wavelet analysis of the principal component amplitude associated with the leading EOF of SSHA in area 1. a) Amplitude time series of PC1. b) local wavelet power spectrum of (a). The semi-circle indicates the cone of influence, where analysis is not appropriate due to edge effects. The black contour is the 95% confidence level for the corresponding red-noise spectrum. The left axis of (b) is represented in logarithmic scale. Colorbars

represent different wavelet amplitudes, whose units are non dimensional. c) global wavelet power spectrum. A dashed line indicates the 95% of confidence level.

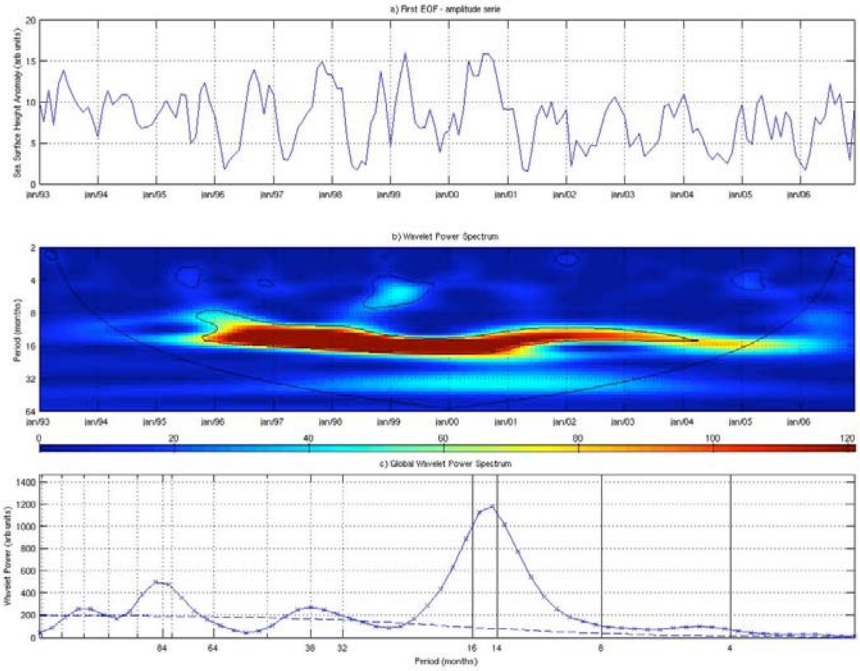

Figure 4 – Same as in Figure 3 but for area 2.

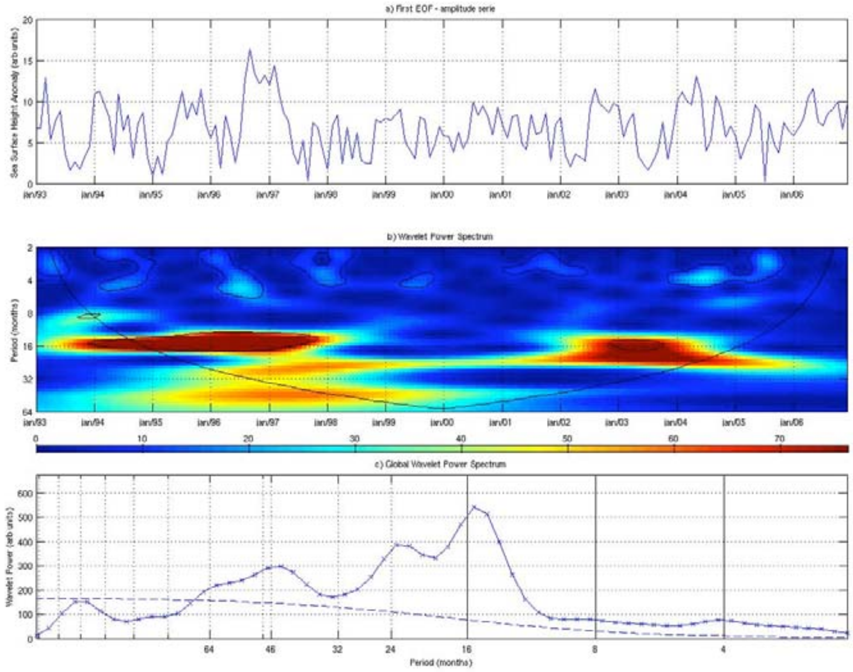

Figure 5 – Same as in Figure 3 but for area 3.

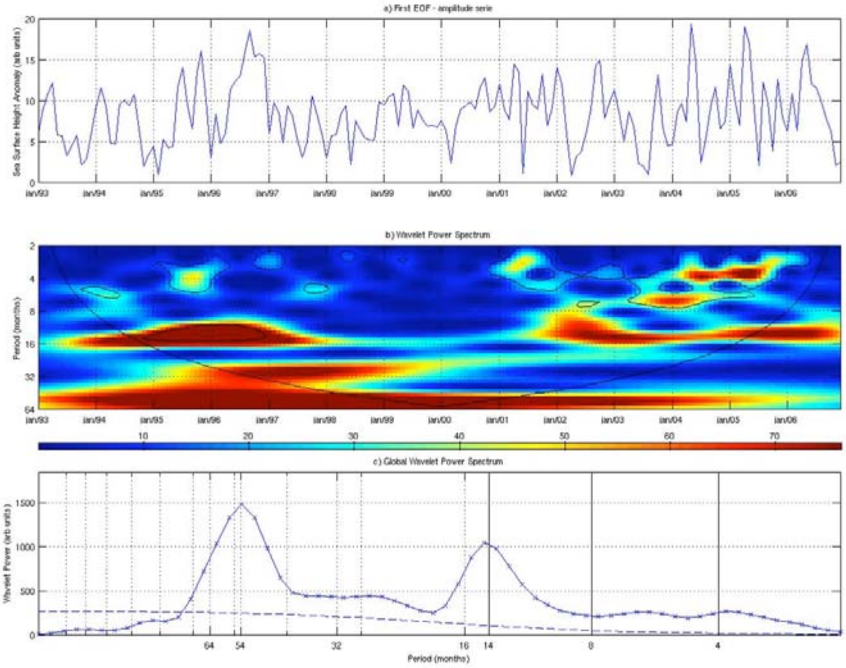

Figure 6 – Same as in Figure 3 but for area 4.

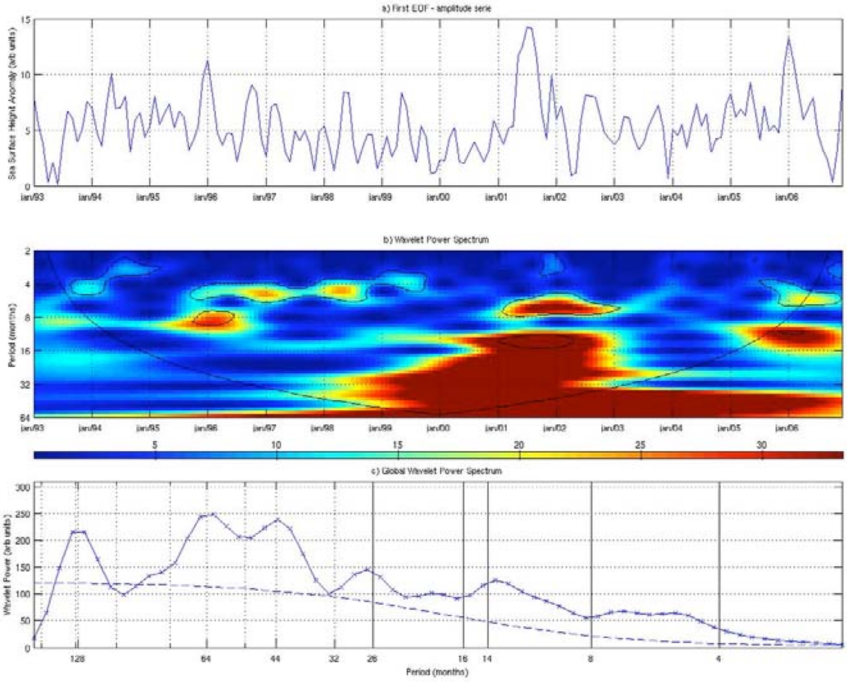

Figure 7 – Same as in Figure 3 but for area 5.

4. Conclusions

In addition to chlorophyll and SST, sea surface height anomaly has proved to be a valuable tool to identify biogeographical regions in the oceans. In the first three EOF modes, the regions with higher amplitudes are coincident with the biophysical provinces of the SWA defined by Longhurst (1998) and Saraceno et al. (2005). In terms of the temporal variability, the annual signal is a common characteristic in all regions of the SWA and dominant in the Brazil-Malvinas Confluence. Apart from the annual cycle, the interannual variability is also an important signal in the biophysical provinces and are similar to those reported by other authors.

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