Seasonal and interannual fluctuations of the Angola Benguela Frontal Zone (ABFZ) using high resolution satellite imagery from 1982 to 1999.

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Abstract. 18 years of high resolution satellite sea surface temperature (SST) data are used to analyse the surface expression of the Angola- Benguela Frontal Zone (ABFZ). The ABFZ is the convergence zone of the southward-flowing Angola Current and the northward extent of the Benguela upwelling regime. Although it has already been investigated a number of times in the past, the analyses within this report benefit from the extensive, high- temporal and spatial resolution of the data, made possible by satellite remote sensing. It is identified as a region of closely- spaced isotherms or, more specifically, a region of consistently steep SST gradients. Using the steep SST gradients indicative of the frontal zone, seasonal and interannual variability of the ABFZ (including characteristics such as width, offshore extent, orientation and intensity) are examined. Aside from a long-term intensification of the front, interannual variability of the ABFZ is also shown to be affected by warm and cool anomalies that occur periodically in the south-east Atlantic Ocean. Such anomalies and the reaction of the frontal zone to them are discussed.

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1. Introduction

The extensive upwelling regime off the west coast of southern Africa is an integral component of the successful fishing industry that exists there and as such it was documented as early as 1902 (Schott). The northern boundary of the upwelling regime is called the Angola-Benguela Frontal Zone (ABFZ). It corresponds to the convergence of the southward flowing warm Angola current with the cold water upwelled in the Benguela area. Despite several similarities with coastal processes in the Southeast Pacific, the ABFZ seems to be a specific feature of the southeast Atlantic. From visual analysis of weekly averaged AVHRR satellite sea surface temperature (SST) images of the period between 1982 and 1985, Meeuwis and Lutjeharms (1990) concluded that the region of closely-spaced isotherms with SST gradients of between 1°C per 28km and 1°C per 90km best described the position of the front. Using this method, they found that during their study period the surface expression of the frontal zone was between 15°S and 18°S and that steep SST gradients extended to a distance of 250km offshore. Nevertheless the authors expressed some concern about the accuracy for both location and resolution of the SST measurements.

Using various types of data sets, Shannon *et al.* (1987), Meeuwis and Lutjeharms (1990) and Kostianoy and Lutjeharms (1999) have all shown that the mid-frontal position fluctuates seasonally and lies furthest south during austral summer months. Meeuwis and Lutjeharms (1990) noted that the frontal zone is best defined in austral summer with steeper meridional SST gradients than in winter. They also observed the front to extend further offshore during spring and summer than during winter. Using a long time-series (1908-1985) of the monthly mean of *in situ* SST data from various sources for 6 salient areas in the South-East Atlantic, Taunton-Clark and

Shannon (1988) studied interannual SST anomalies in the region of the ABFZ and showed that major warm events occurred along the coast of Angola and Namibia with a periodicity of about 10 years. The similarity of these events with the Pacific El Niño phenomenon was first noted by Schott (1931) (cited in Shannon *et al.*, 1986) and Shannon *et al.* (1986) coined the term 'Benguela Niño' to describe these Atlantic events. Taunton-Clark and Shannon (1988) found evidence of the occurrence of Benguela Niños in 1908, 1923, 1934, 1950, 1964, 1974 and 1984, while the major event of 1995 has been documented by Gammelsrød *et al.* (1998) and Florenchie *et al.* (2003). Although Benguela Niños recur on a decadal cycle, minor warm anomalies have been observed throughout the record and appear to develop regularly in the ABFZ. Major cool anomalies also occurred over the last 20 years in 1982, 1983 and 1997 in the same area (Florenchie *et al.*, 2003).

Within this study, a high-resolution satellite SST data set spanning 18 years (1982- 1999) is used to present a more accurate description of the seasonal and interannual variability of surface thermal characteristics of the frontal zone. Long term trends within the ABFZ are also investigated. The lengthy period of consistently high resolution data allows for the calculation of a more precise climatology from which a more reliable analysis can be made of the typical surface expression of the frontal zone. A further advantage of this data set is that it includes both the 1984 and 1995 Benguela Niño events as well as several warm and cool anomalies. Perturbations to the surface thermal characteristics as well as the location of the frontal zone as a result of these events will be investigated. Therefore, this paper addresses (and, in some cases, revisits) the following questions:

- Where is the ABFZ located?

- How wide is it?
- What is its seasonal signal?
- What is its offshore extent and orientation?
- Has the surface thermal expression of the ABFZ been subject to any long term trends?
- What is the impact of major SST perturbations on the frontal zone?

The following section describes the data set and methods of analysis used for this study. In section 3.1 seasonal SST fluctuations along various transects are investigated. In section 3.2 abnormal events that occur across the frontal zone as well as long term SST trends are studied for the 18 year period. In section 3.3 their ensuing impacts, particularly within the frontal zone, are briefly analysed.

2. Data and Methods

The Envifish data set of the monthly mean sea surface temperature (SST) values for the period from January 1982 to December 1999 were used for this study. The SST data are obtained from the 5-channel Advanced Very High Resolution Radiometers (AVHRR) on board the NOAA -7, -9, -11 and -14 polar orbiting satellites. The data was collated for the Cloud and Ocean Remote Sensing around Africa (CORSA) project of the Marine Environment Unit of the Space Applications Institute of the Joint Research Centre of the European Commission. The mean monthly data are mapped on a rectangular projection grid of 1000x775 pixels representing the area from the equator to 40°S and from 2°W to 29°E which includes the region of the ABFZ. There are 25 pixels per degree of latitude and longitude and the corresponding nominal ground resolution is 4.5km. Figure 1 shows mean monthly

SSTs for May 1985 with the region of the ABFZ demarcated by a yellow box. The darker shades of grey correspond to lower SSTs.

[Insert figure 1 about here]

From comparisons with *in situ* data (COADS) and data from another AVHRR product (Pathfinder) it was found that Envifish SSTs from September 1992 to August 1994 were up to 2.5°C warmer than both the COADS and Pathfinder data sets. This was corrected by removing the mean of the elevated values from the erroneously high period and replacing it with the mean of the SSTs outside of it (January 1982 to August 1992 and September 1994 to December 1999).

In order to capture the frontal zone realistically, and because the coast in the region of the ABFZ changes orientation quite markedly and is not strictly meridional, it was decided that transects parallel to the coastline would be analyzed in order to include the coastal upwelling features: a meridional transect will cut through the upwelling regime a short distance south of the frontal zone regardless of proximity to the coast and is likely to lead to misinterpretation by taking into account only a limited part of the coastal upwelling regime.

A transect at a distance of 30km offshore was found to be optimal to study the surface thermal expression of the front. Closer inshore, features such as the embayment at Baia dos Tigres (±16.5°S) affected the SST plots, while further offshore the ABFZ becomes more diffuse. The seaward extent and offshore characteristics of the ABFZ was then investigated from transects 100km, 250km, 500km and 700km offshore.

18 years of monthly mean sea surface temperatures (SSTs) were extracted from the Envifish data set along the various transects and were used to calculate SST climatologies, interannual SST anomalies (SSTAs) and SST climatological gradients. The SSTAs were detrended to remove any long-term tendency. Because we made the assumption that the front runs perpendicularly to the transects, the SST gradients corresponding to the front may be slightly underestimated, especially offshore. For clarity within the plots of the gradient, which were very noisy, it was decided to first smooth the SSTs meridionally by averaging every five pixels. Temperature gradients were then calculated between every three pixels from the equator to 30°S. Although weekly composite data are also available from the Envifish data set, mean monthly data were used as they produce a more complete data set as a result of much of the cloud cover being removed by averaging over a longer period of time. Nevertheless, it was necessary to firstly identify the ‘gaps’ in the data due to cloud cover, which correspond to a flag value of 8°C. For all pixels assigned with flag values an interpolated SST was calculated by taking the spatial average of the first two pixels with valid data on either side of the flag value. The process was iterated until all missing values were replaced.

3. Results

3.1. Climatology

As the confluence of the warm Angolan Current and the cool Benguela upwelling regime, the ABFZ is characterized by a striking change of SST across its boundaries associated with steep gradients. For this reason, a climatology of SST gradients has been calculated along various transects from the equator to 30°S to investigate the seasonal location, width and displacement of the frontal zone. Figure 2 represents the climatological SST gradient at a distance 30 km offshore. The ABFZ is evident as the most distinct region of consistently steep SST gradients at about 16°S. In order for the front to be explicitly isolated and identified, it was decided that gradients that exceeded 1°C per 60km would be indicative of the frontal zone. This lower value was chosen by visual analysis of Hoffmoller plots of SST gradients in the frontal zone. It appears from figure 2 that the width of the frontal zone fluctuates seasonally with an average of about 1.1° of latitude (roughly 120km) in winter and 1.5° of latitude (about 170km) in summer. At its narrowest in August (±60km) it spans between 16°S and 16.5°S while at its widest in December (±210km) it lies between 15.5°S and 17.5°S. A notable displacement of the northern and southern boundaries of the frontal zone occurs at the onset of winter. The boundaries appear to fluctuate out of phase: as the northern boundary moves southwards, the southern boundary is displaced northwards. Similarly, as the northern boundary shifts northwards at the onset of summer, the southern boundary moves southwards. From January to April the seasonal width of the ABFZ is remarkably constant. The range of latitudes through which the northern boundary moves annually is 0.5° (or about 50km) whereas the southern boundary moves through 0.83° of latitude (approximately 92km).

[Insert figure 2 about here]

Figure 2 shows us that steepest SST gradients are prevalent during summer (±1°C per 34km), whilst during winter the ABFZ is characterized by weakest gradients (±1°C per 40km). This appears to be somewhat counter-intuitive as a narrower front is expected to have steeper SST gradients and vice-versa. However, in this case a significantly greater range of temperatures is present in the frontal zone during summer than during winter resulting in the ABFZ being defined by consistently steep SST gradients over a broader region and weaker SST gradients that persist over a much narrower zone in winter. Therefore, in terms of both width and steepness of SST gradients, the ABFZ is unequivocally most intense during summer.

The core of the ABFZ has been defined as the position between its northern and southern boundaries (the mid-frontal position), which, in most instances, corresponds to the region of steepest SST gradients within the frontal zone. Other than a weak southward shift in June and July and an equally small northward displacement in August and September, the mid-frontal position remains very steady throughout the year and its mean location is approximately 16.4°S. At the mid-frontal position the steepest temperature gradient occurs in January and is of the order of 1°C per 27km, while weakest gradients of about 1°C per 54km occur at the mid- frontal position in August.

Evident in figure 2 are other zones of significantly steep SST gradients. North of the front, two zones of alternating positive and negative gradients from south to north seem to be directly related to river discharges and are situated at about 6°S and 9°S, coincident with the mouth of the Congo and the Coanza Rivers respectively. In this area heaviest rainfall occurs in summer leading to greater discharge rates at the mouth of these rivers. However, the temperature of the river water contrasts more with the ambient SST during winter than during summer, resulting in the steeper temperature gradients seen on figure 2. A detailed analysis of the yearly mean SST gradients along the coast tends to indicate a northward flow of Congo River discharge. The zone of strongly negative SST gradients at 27°S is persistent throughout the year, although significantly weaker during winter months (figure 2). It is related to an abrupt northward cooling of coastal SSTs corresponding to the Lüderitz upwelling cell which extends from Luderitz to about 20°S. It is active for 95% of the year, slackening off in autumn (Meeuwis and Lutjeharms, 1987).

The origin of steep SST gradients in two other zones as seen in figure 2 (at approximately 12.5°S and as a banded feature between about 22.5°S and 24°S) is still unclear. The feature at 12.5°S for instance might be related to local river discharges. On the other hand, we note that in both areas the orientation of the coastline is markedly changed by prominent bays.

Figure 3 represents the climatology of the SSTs from the equator to 30°S at a distance of 30km offshore with the mid-frontal position overlaid. The mid-frontal position corresponds to the core of the ABFZ. The mean temperature at the core of the frontal zone is 20.7°C in summer and 18°C in winter showing a mean seasonal range of 2.7°C throughout the year. However, at the northern boundary the difference between the mean winter and summer temperature is 3.6°C (from 23.1°C to 19.5°C) and at the southern boundary it is a mere 1.8°C (from 18.9°C in summer to 17.12°C in winter). The disparity of the annual range of temperatures at these three locations within and encompassing the ABFZ may be related to differing seasonal fluctuations that operate in the regions north and south of the ABFZ: the latter is related to quasi-permanent wind-driven upwelling cells which tend to inhibit SSTs seasonal signal along the coast. A calculation of the standard deviation of the SST climatology along the transect reveals two distinct areas, north and south of 20°S. In the northern area until about 3°S, the seasonal SST variability shows high values with a maximum at the frontal zone and a distinct minimum near the Congo River mouth at about 6°S. South of 20°S and along the Lüderitz cell, the seasonal variability is much lower with the minimum of the entire transect situated near Lüderitz at 27°S. Conversely, seasonal SST gradient variability along the transect shows two distinct maxima at 27°S and 6°S. Congo River discharge, as well as upwelling dynamics south of the ABFZ maintains a relatively constant temperature of coastal waters in those areas throughout the year. This is in contrast with the surrounding waters that experience normal seasonal fluctuations. As a result, these two areas show low seasonal SST variability but induce strong seasonal SST gradient variations.

[Insert figure 3 about here]

The temperature range between the northern and southern boundaries of the frontal zone is, on average, 4.1°C in summer and 2.4°C in winter. The much larger temperature range across the frontal zone in summer complies with the fact that in summer when the front is widest, SST gradients are steepest. Table 1 summarizes the thermal characteristics of the ABFZ discussed in the previous section at a distance 30km offshore.

[Insert table 1 about here]

Climatologies of the SSTs and of the SST gradients at distances of 100km, 250km, 500km and 700km offshore as well as the standard deviation of the SST gradients (not shown) were similarly investigated in order to establish the offshore extent of the ABFZ. At 100km offshore the ABFZ is present between ±12.5°S and 17.25°S and has typical SST gradients of about 1 °C per 100 km. Steepest gradients occur in the region 15°S – 17.25°S during spring and autumn and are weakest during winter. Average temperatures in the frontal zone are 22.5°C in summer and 20.6°C in winter. Other than a brief and slight southward movement during spring, the position of the front remains very stable throughout the year. The ABFZ is present at 250km as a diffuse, but nonetheless distinct region of consistently steeper SST gradients that is relatively stable and exists between 12°S and 16°S. Typical SST gradients in this region are in the range of 1°C per 112km and again, are slightly elevated during spring and summer. During summer the average temperature in the frontal zone is 23.2°C and in winter it is 21.3°C. At 500km offshore SST gradients in the region between 12°S and 16°S are low (±1°C per 164km), but are consistently higher than the surrounding area and are significantly steeper during spring and summer. This indicates that there is a weak frontal signal at this distance offshore all year round, with a slight intensification during spring and summer. The average temperature within this zone is 22.7°C and 20.1°C in summer and in winter respectively. 700km offshore, a region of slightly elevated SST gradients, exists between about 8°S and 15°S during spring and summer. This suggests that vestiges of the frontal zone, though very weak, extend further offshore during summer months than during winter.

The above analysis shows that the ABFZ remains a distinct feature throughout the year up to at least 250km offshore, but with increasing distance offshore the frontal zone becomes significantly more diffuse. At 500km and 700km offshore evidence of the frontal zone is very weak, other than during spring and summer when slightly steeper SST gradients are present within the frontal zone, thus implying that the ABFZ extends further offshore during spring and summer than during winter.

The fact that the zonal area encompassing ABFZ appears to move northwards with distance offshore implies that it is oriented in a roughly northwesterly direction from the coastline, as could be seen on figure 1.

3.2 Warm and cold events and long term trends along the transects

Figure 4 is a plot of the actual SSTs from the equator to 30°S of the transect 30km offshore for the 18-year period with the approximate location of mid-frontal position (as described in the section 3.1) overlaid. The 22°C and 16°C isotherms are also overlaid in an attempt to isolate variability of the regimes to the north and to the south of the ABFZ. During 'normal' years the mid-frontal position seems to act as a barrier to the southward and northward extents of 22°C and 16°C water respectively. Therefore, unusual southward warming across the mid-frontal position that occurs periodically can be easily identified on figure 4.

[Insert figure 4 about here]

Particularly severe warm intrusions occurred during the Benguela Niños of 1984 and 1995 when the 22°C isotherm penetrated across the mid-frontal position to about 22°S and 24°S respectively in late summer. Minor southward incursions of warm water took place in 1986, 1988, 1996 and 1999, mostly in March/April, but in most instances the 22°C isotherm did not penetrate further than 18°S. Following the 1995 major warm event, unusually warm water prevailed within the frontal zone, other than during the April 1997 cold event when water within the ABFZ was abnormally cool in summer. Cold years in which the southerly extent of the 22°C was unusually far north, at about 16°S, correspond to extended events in 1982, 1983 and again in 1997.

From figure 4, a general warming trend is evident and appears to have affected both the Angolan and Benguela systems. A plot of the mean annual SSTs for the regions north (equator- 15.4°S), south (17.6°- 30°S) and within the ABFZ (15.5°S –

17.5°S) (not shown) indicates the disparity between the warming trend in these three areas. The long-term increase in annual mean temperature for the study period was 3°C to the north of the frontal zone, 2.5°C within the frontal zone and only 1°C south of it. A similar plot of the mean annual SSTs of offshore transects (not shown) shows that the long- term warming trend is not merely a coastal phenomenon as it prevails offshore, however it is less extreme and the discrepancy of the temperature increase north, south and within the frontal zone is smaller. Although the ABFZ is something of a barrier to the seasonal southward penetration of warm water, it does not appear to be an obstacle to the long term warming trend. This suggests that the warming tendency is an extensive phenomenon that occurs throughout the southeast Atlantic.

Detrended SST anomalies from the equator to 30°S of a transect 30km offshore for the period from 1982 to 1999 are illustrated in figure 5. Evident in this plot are the major warm SST anomalies of the 1984 and 1995 Benguela Niños. Other minor warm anomalies occurred in 1986, 1988, 1991, 1996, 1998, and 1999. They are all associated with the unusually far southward extent of warm water across the ABFZ previously mentioned. Major cool anomalies of 1982/83 and 1997 are also apparent and are conversely associated with a southward limit of the 22°C isotherm that does not penetrate past the mid-frontal position. Similar to all events is that the most extreme temperature anomaly appears within the region of the frontal zone. Standard deviation of SSTAs in this region validates this as it illustrates that the most extreme variability of anomalies along the transect occurs within the ABFZ, the maximum being situated at 17°S. This result suggests meridional shifts of the frontal zone during warm or cold events inducing strong SST anomalies in the area.

[Insert figure 5 about here]

SSTAs of the 30km offshore transect have been averaged in the region of the frontal zone (15.5°S to 17.5°S) and over the regions north and south of it. They further corroborate that the most extreme anomalies (both positive and negative) occur within the frontal zone and that during both the 1984 and the 1995 Benguela Niños, maximum positive anomalies of the order about 3.5°C transpired. Positive anomalies in excess of 2°C persisted within the frontal zone from January until December during the 1984 episode, but only from February to April during the 1995 event. Although the former event lasted considerably longer than the latter, the southward extent of the 1995 warm anomaly was greater than during 1984 incident (25°S as opposed to 23°S). Although the minor warm anomalies of 1986, 1988, 1991, 1996 and 1998 produced temperature increases in the frontal zone that were comparable to major anomalies, anomalies to the north and south of the ABFZ were less significant and did not exceed +1.5°C. The major cool events of 1982/83 and 1997 correspond to average temperature decreases within the frontal zone of about 2.5°C and 4°C. For both cool events, the average negative anomaly is most severe in the frontal zone and more intense to the north than to the south of it.

Standard deviations of SSTAs from the equator to 30°S, at distances of 100km, 250km, 500km and 700km offshore were calculated (not shown). They give an indication of the location of the most extreme temperature perturbations of each offshore transect. The region of most variability for all transects at all distances offshore coincides with the location of the ABFZ and, like the frontal zone, broadens and moves progressively northwards offshore._SST anomalies within the frontal zone at 250km, 500km and 700km offshore show that the warm and cool anomalies persist until at least 500km offshore. By 700km offshore only the smallest traces of the major warm anomalies exist, but they do not stand out as major positive anomalies. The 1997 cool anomaly is the only extreme event recorded at closer inshore locations that remains significant at 700km offshore.

3.3 Response of the ABFZ to warm and cold events

A plot of the gradient of SSTs through time from the equator to 30°S (figure 6) of a 30km offshore transect shows that although the position of the frontal zone has remained relatively stable throughout the 18 year period, the region of steep SST gradients indicative of the frontal zone has broadened progressively. The widening of the frontal zone is possibly related to the long term warming trend which is stronger to the north of the front than to the south of it (hence the increasing intensity of the front). The two bands of steep SST gradients that exist mainly during summer months at about 22.5°S and at 25°S are evident throughout the 18 year period. From a preliminary visual inspection of figure 6 it appears that during the major warm anomalies of 1984 and 1995, these regions experience a severe strengthening of SST gradients. On the other hand, SST gradients in the region defined as the frontal zone seem to weaken during the major warm episodes.

[Insert figure 6 about here]

SST gradients have been averaged over the frontal zone and between 22°S to 25°S. These plots validate that during major warm anomalies the SST gradients weaken in the frontal zone and are significantly steepened in the region to the south of it, thus implying that the ABFZ shifts or spreads southwards by approximately 8° (±896km) during major warm anomalies. The southward displacement of the frontal zone is observed during not only major, but also minor warm anomalies. The peak of the warm anomaly generally occurs about a month prior to both the weakening of SST gradients in the ABFZ and to the strengthening of the gradients to the south of it. Therefore, the warm anomalies take about a month to affect the position of the ABFZ. Other than a slight weakening of temperature gradients in both the frontal zone and in the zone to the south of it, the ABFZ is not notably affected by cool anomalies.

Hoffmoller plots of the SST gradients from the equator to 30°S for the 18 year period for distances of 100km, 250km, 500km and 700km offshore (not shown) reveal that the long term broadening and southward displacement of the ABFZ has persisted until a distance of at least 700km offshore, although the long term tendencies become less notable with distance from the coast. SST gradients averaged in the ABFZ and in the zone south of it between 22°S and 25°S at the same offshore distances indicate that the ABFZ is similarly affected by warm and cool anomalies up to at least 700km offshore. SST gradients in the frontal zone weaken and strengthen between 22°S and 25°S during warm anomalies, but are not notably affected by cool anomalies. However, with increasing distance from the coast the SST gradients in each of the regions are modified by a smaller degree.

4. Summary of results and concluding remarks

- The ABFZ is a region of consistently steep surface temperature gradients (> 1°C per 60km) and is a permanent feature whose width fluctuates seasonally. 30km offshore it exists approximately between 16°S and 17°S in winter and between 15°30'S and 17°S in summer. It is therefore broader in summer (spanning ±1.5° of latitude) than in winter (±1° of latitude).

- The northern and southern boundaries of the ABFZ fluctuate independently of one another. In winter the northern boundary moves southwards while the southern boundary moves northwards, the converse happens at the onset of summer.
- The mid-frontal position is a relatively stable feature, and is situated at approximately 16.4°S. Because it is generally situated in the region of steepest temperature gradients within the frontal zone, it can be thought of as the core of the ABFZ.
- Average temperatures at the core of the frontal zone are 20.7°C in summer and 18°C in winter. The temperature range across the ABFZ is 2.4°C in winter and 4.2°C in summer. The greater range of temperatures in summer ties in with the fact that the warm regime to the north of the ABFZ experiences more seasonal variability than the cool regime to the south.
- SST gradients in the frontal zone are steepest in summer (1°C per 34km) and persist over a wider zonal area. In winter, although the ABFZ remains apparent, the SST gradients indicative of the front are weaker (1°C per 40km) and are prevalent over a narrower region than during summer. This rather unexpected relationship between temperature gradients and width is a consequence of the fact that a far greater range of temperatures intrudes into the ABFZ from the north during summer than from the south during winter.
- With increasing distance offshore the ABFZ broadens and moves northwards and the SST gradients within it weaken. The front remains a distinct feature throughout the year up to a distance of 250km offshore, but up to at least 700km offshore vestiges of it can only be identified during spring and

summer. The ABFZ therefore extends further offshore during spring and summer.

- The northward displacement of the frontal zone with increasing distance offshore implies that the front has a northwesterly orientation. This is verified by figure 1, which is a grey-scale plot of the SSTs in the region of the frontal zone.
- Both major and minor warm anomalies tend to displace the frontal zone southwards to a banded frontal region between 22°S and 25°S, with a lag of about a month. This region seems to act as a 'barrier' to the southward intrusion of warm water and therefore might limit the southward extent of anomalies. Other than a slight weakening of temperature gradients, cool anomalies do not significantly affect the ABFZ.
- Although the warm anomalies persist until at least 700km offshore, they are markedly less severe, particularly by 700km from the coast. Despite the progressively weaker anomalies offshore, the ABFZ is similarly affected by them as it is closer inshore.

Future studies could take this work further by extending the data set in order to include more major warm events thereby improving the analysis of frontal zone responses to Benguela Niños. Also, an extended data set would provide a more representative climatology. The temporal resolution could be improved by using the mean weekly data available from the Envifish data set.

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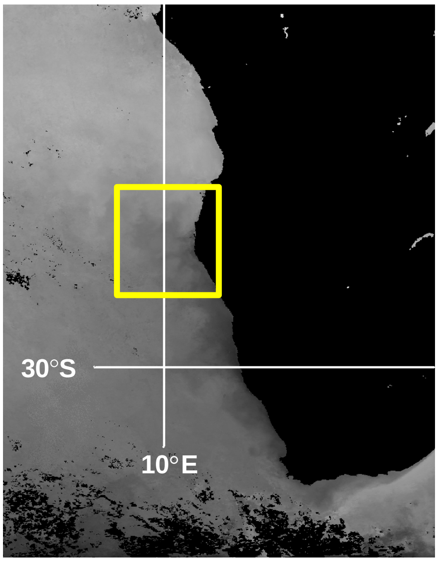

figure 1. Mean monthly SSTs for May 1985 with the region of interest demarcated by a yellow box. The darker shades of grey correspond to lower SSTs.

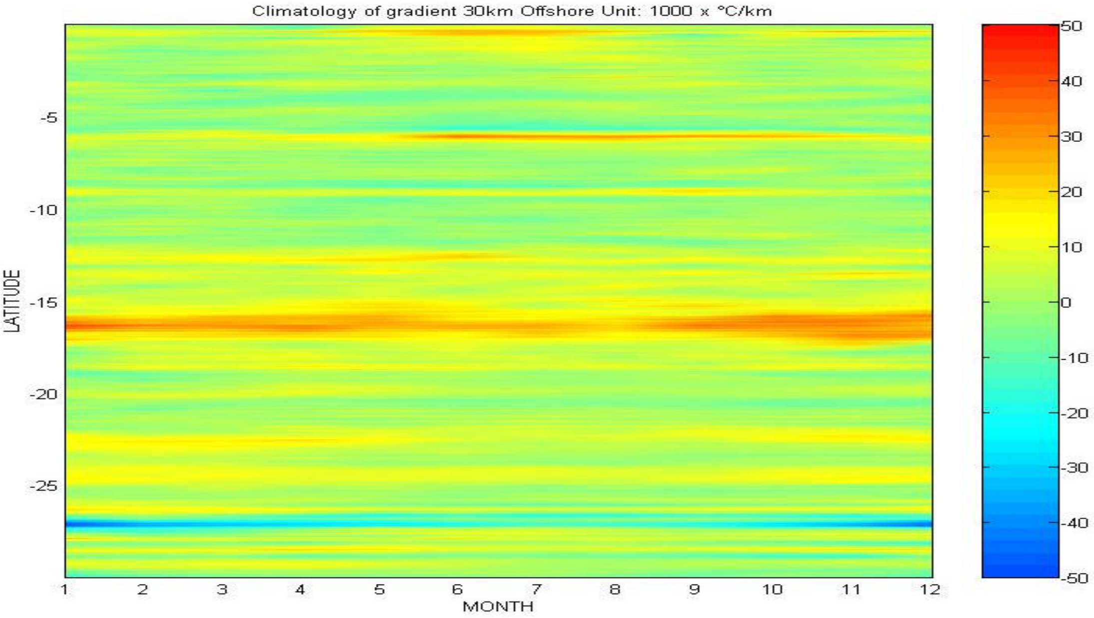

figure 2. Climatology of SST gradients of a transect 30kms offshore extending from the equator to 30°S.

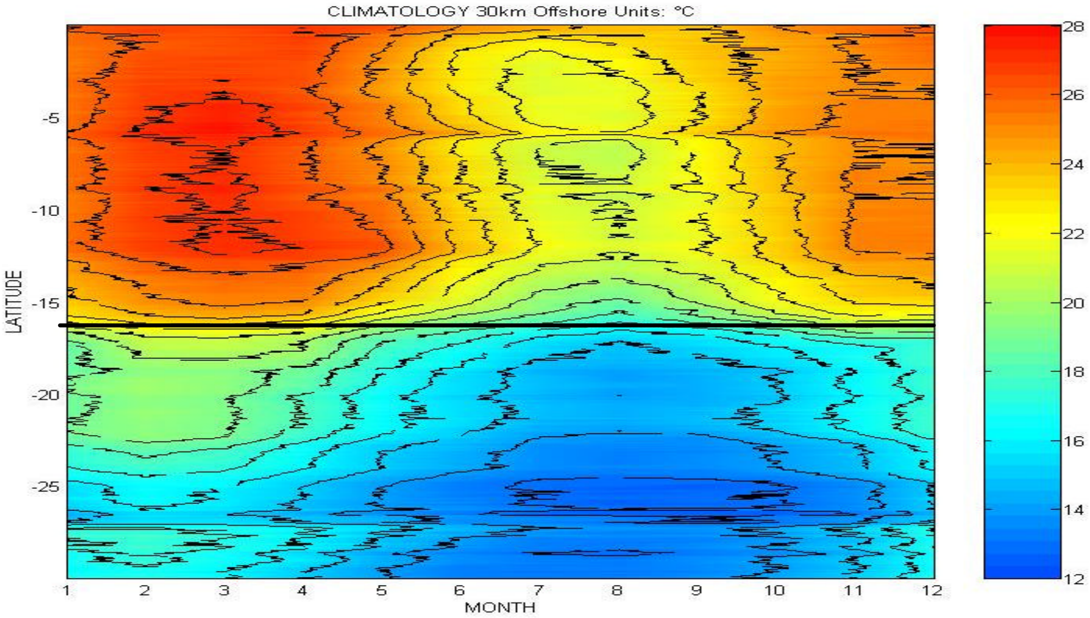

figure 3. Climatology of SSTs of a transect 30km offshore extending from the equator to 30°S with the mid-frontal position overlaid.

Season	Boundary	Position	Width	Mean SST	Temperature range across boundaries	Mean SST gradient at the MFP*
Summer	North	15.5°S	1.5° (±170km)	23.1°C	4.2 °C	1°C per 34 km
	South	17°S		18.9°C		
	MFP*	±16.45°S		20.7°C		
Winter	North	16°S	1° (±115km)	19.5°C	2.4°C	1°C per 40 km
	South	17°S		17.1°C		
	MFP*	±16.4°S		18°C		

table 1. Thermal characteristics of the ABFZ at a distance of 30km offshore (MFP = Mid-frontal position).

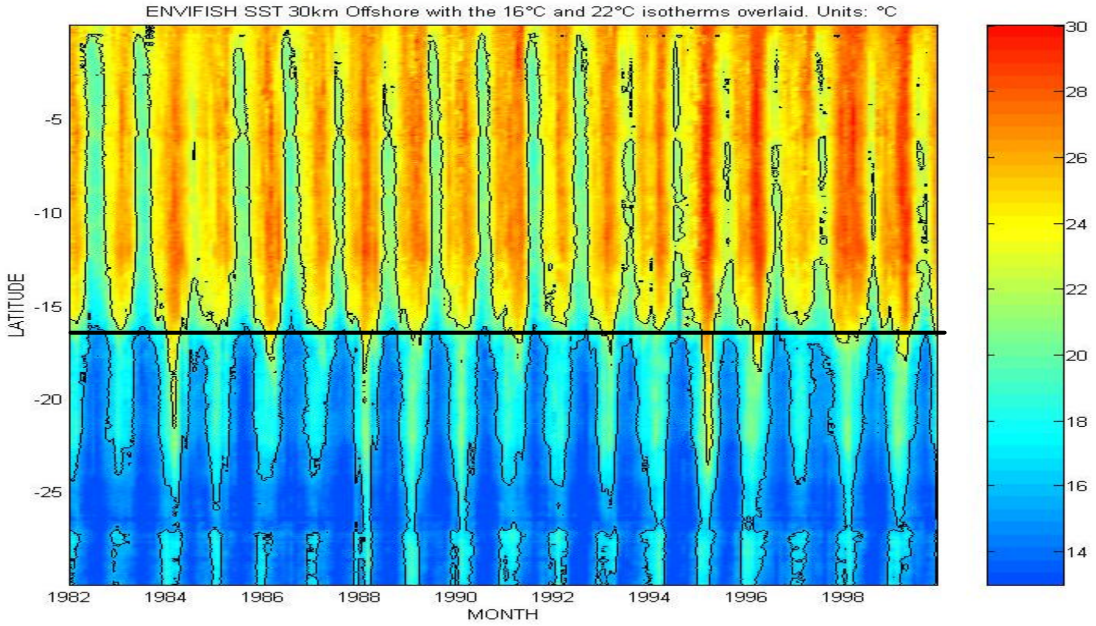

figure 4. Hoffmöller plot of the SSTs of a transect 30km offshore extending from the equator to 30°S for the period from January 1982 to December 1999.

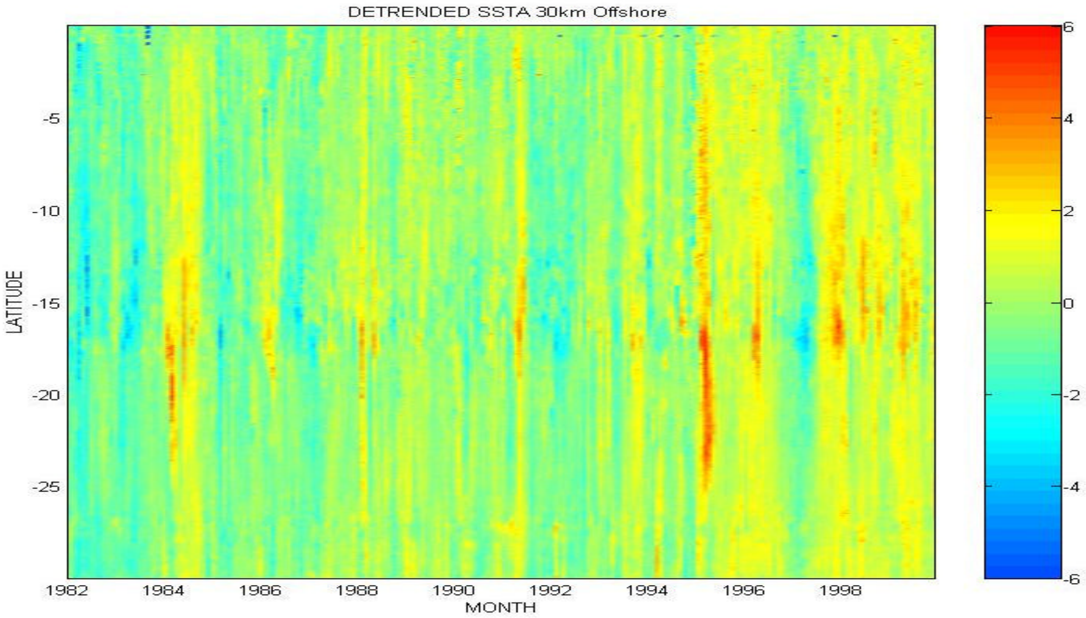

figure 5. Hoffmöller plot of the SSTAs of a transect 30km offshore extending from the equator to 30°S for the period from January 1982 to December 1999.

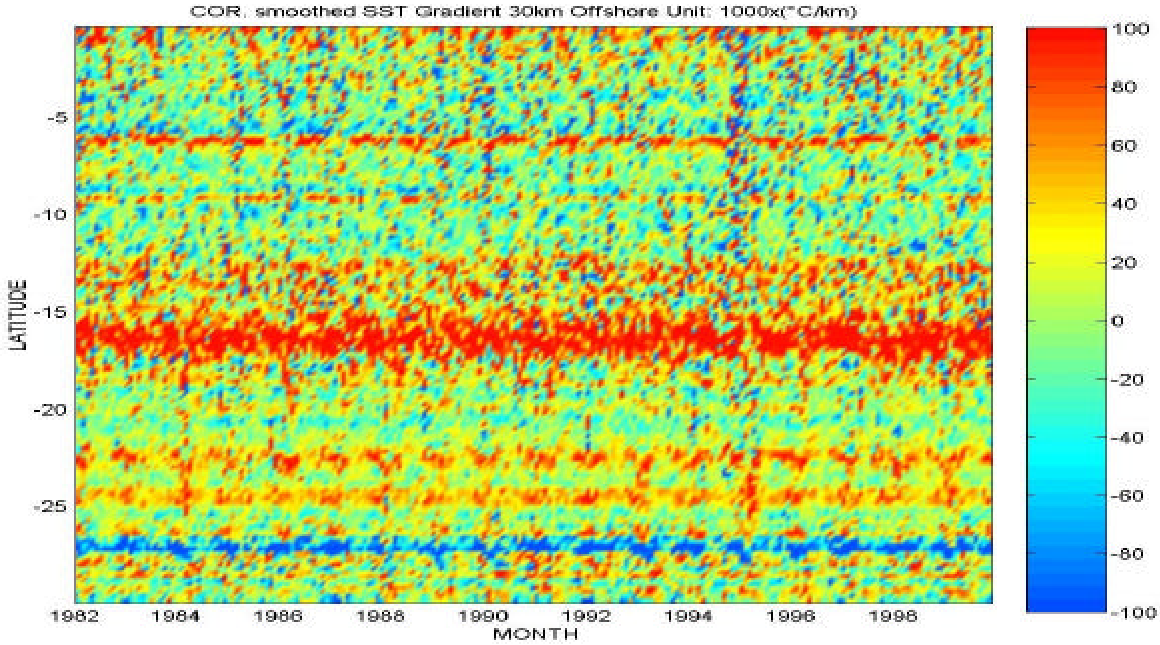

figure 6. Hoffmöller plot of the SST gradients of a transect 30km offshore extending from the equator to 30°S for the period from January 1982 to December 1999.