

**Department of Oceanography  
University of Cape Town**

**SURFACE THERMAL CHARACTERISTICS  
OF THE ANGOLA- BENGUELA FRONT (ABFZ)  
FROM ANALYSIS OF 18 YEARS OF  
SATELLITE DATA.**

**Jennifer Veitch**

**November 2002**

**Supervisors:**

Professor Frank Shillington and  
Doctor Pierre Florenchie

**Submitted in partial fulfillment of the  
degree of Bachelor of Science (Honours)**

## **TABLE OF CONTENTS**

<b>LIST OF FIGURES</b>	<b>3</b>
<b>ABSTRACT</b>	<b>4</b>
<b>1. INTRODUCTION</b>	<b>5</b>
<b>2. BACKGROUND</b>	<b>6</b>
<b>3. DATA AND METHODS</b>	<b>10</b>
<b>4. RESULTS</b>	
<b>4.1 Climatology</b>	
• Transect 30km Offshore	12
<b>4.2 Seasonality and Long Term Trends</b>	
• Transect 30km Offshore	16
• Transect 250km Offshore	20
<b>4.3 SST Gradients</b>	
• Transect 30km Offshore	22
• Transect 250km Offshore	25
<b>4.4 Anomalies</b>	
• 30km Offshore	26
• 250km Offshore	28
• 1984 Benguela Niño	29
• 1995 Benguela Niño	32
• Minor Warm Events	34
• 1982/83 Cool Event	36
• 1997 Cool Event	38
<b>5. DISCUSSION</b>	
• The Angola-Benguela Frontal Zone (ABFZ)	40
• Anomalies	41
• Response of the ABFZ to warm and cool anomalies	44
<b>6. CONCLUDING REMARKS</b>	<b>45</b>
<b>ACKNOWLEDGMENTS</b>	<b>46</b>
<b>REFERENCES</b>	<b>46</b>

## LIST OF FIGURES

- Figure 1.1.** 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 3.1.** SSTs at the coast from the equator to 30°S, showing a recurring warm 'pool' during summer months.
- Figure 4.1.1:** Climatology of SST for a transect 30km Offshore from 8°S to 24°S
- Figure 4.1.2** Climatology of SST gradients across the frontal zone for the period from January 1982 to December 1999. The 20.5°C isotherm is overlaid.
- Figure 4.2.1.** Hoffmüller plot of the sea surface temperatures along a transect 30km offshore. The 20.5°C isotherm is overlaid.
- Figure 4.2.2.** Graph of the annual mean SSTs of the regions north (equator- 15.5°S) and south (17°S- 30°S) of the frontal zone, showing the disparity of the long-term warming trend
- Figure 4.2.3.** Graph of the annual mean SSTs of the frontal zone (15.5°S to 17°S), showing the long-term warming trend and the major warm and cold events.
- Figure 4.2.4.** Time- series of detrended mean SSTs for the region between 10°S to 20°S of a transect 30km offshore, showing a strong seasonal signal.
- Figure 4.2.5.** Hoffmüller plot of the sea surface temperatures along a transect 250km offshore with the 19°C and 22°C isotherm overlaid.
- Figure 4.2.6.** Graph of running mean of SSTs 250km offshore, showing that the warming trend persists offshore.
- Figure 4.3.1.** Hoffmüller plot of SST gradients from the equator to 30°S for the period of study with the 20.5°C isotherm overlaid.
- Figure 4.3.2.** The monthly mean SST gradient in the frontal zone (15.5°S- 17°S) is indicated by the green line. The monthly mean SST gradient between 23°S and 25°S is in red and the monthly mean SSTAs in the frontal zone are shown in blue.
- Figure 4.3.3.** Hoffmüller plot of SST gradients from the equator to 30°S.
- Figure 4.4.1.** Hoffmüller plot of the sea surface temperature anomalies (SSTA) for the period 1982-1999 from the equator to 30°S.
- Figure 4.4.2** Graph of mean SSTAs from 10°S and 20°S of a 30km offshore transect with long term warming trend removed.
- Figure 4.4.3.** Plot of SSTAs of a transect 250km offshore vs. time.
- Figure 4.4.4(a)** A plot of the SSTs 30km offshore from November 1983 to October 1984.
- Figure 4.4.4(b)** A plot of the corresponding SSTA's.
- Figure 4.4.5.** A Hoffmüller plot of the gradient of SSTs, 30km offshore from November 1983 to October 1984.
- Figure 4.4.6(a)** A plot of the SSTs 30km offshore from November 1994 to October 1995.
- Figure 4.4.6(b)** A plot of the SSTA's 30km offshore from November 1994 to October 1995.
- Figure 4.4.7.** A Hoffmüller plot of the gradient of SSTs, 30km offshore from November 1994 to October 1995.
- Figure 4.4.8(a)** A plot of the SSTs 30km offshore from November 1982 to October 1983.
- Figure 4.4.8(b)** A plot of the SST gradients 30km offshore from November 1982 to October 1983..
- Figure 4.4.9(a)** A plot of the SSTs 30km offshore from November 1996 to October 1997.
- Figure 4.4.9(b)** A plot of the SST gradients 30km offshore from November 1996 to October 1997
- Figure 5.1.** 'Snapshots' of the SSTs in the south- east Atlantic at the maximum extent of the major warm and cool anomalies. Shades of red correspond to highest temperatures, while shades of blue and green are lowest temperatures. The black gaps represent regions where cloud cover made data acquisition impossible.

---

## ABSTRACT

---

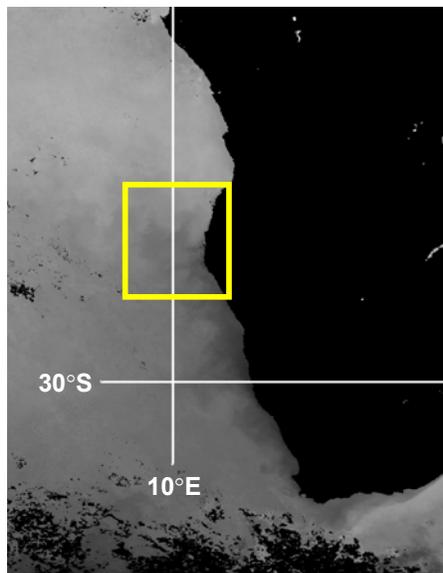
18 years of satellite sea surface temperature (SST) data are used to analyse the surface expression of the Angola- Benguela Frontal Zone (ABFZ). The ABFZ is the convergence zone of the southward- flowing Angola Current and the northward extent of the Benguela upwelling regime. It is identified as a region of closely spaced isotherms or, more specifically, a region of consistently steep SST gradients. Its position remains stable throughout the period of study, but it is about  $0.5^{\circ}$  of latitude broader in austral winter than in austral summer. At a distance of 30km offshore it is situated between  $15^{\circ}\text{S}$  and  $17^{\circ}\text{S}$  in winter. Further offshore the ABFZ becomes more diffuse with weaker SST gradients and at a distance of 250km, it is situated between  $12^{\circ}\text{S}$  and  $16^{\circ}\text{S}$ . SST gradients in the frontal zone at a distance of 30km offshore range from about  $1^{\circ}\text{C}$  per 60km in summer to about  $1^{\circ}\text{C}$  per 125km in winter and the corresponding temperature ranges across the ABFZ are  $4^{\circ}\text{C}$  and  $2^{\circ}\text{C}$  respectively. Temperatures in the frontal zone are about  $22^{\circ}\text{C}$  in summer and about  $19^{\circ}\text{C}$  in winter. From Hoffmüller plots of SST and sea surface temperature anomalies (SSTA), warm events are observed in 1984, 1986, 1988, 1991, 1995 and 1998/99 and major cool events occurred in 1982/83 and in 1997. The warm events in 1984 and 1995 have been distinguished as Benguela Niños because of their similarity to El Niño events that occur off the coast of Peru. They are similar in that the maximum southward extent of unusually warm water is in March for both events. The warm anomaly of 1984 extends to  $24^{\circ}\text{S}$  and lasts for approximately 5.5 months. On the other hand, the maximum southward extent of the 1995 event reaches as far as  $25^{\circ}\text{S}$  and lasts for only 4.5 months. All of the minor warm anomalies reach their maximum disturbance later in the year and, in most cases, are in phase with the seasonal upwelling event in winter. Both of the major cool events are associated with an unusual upwelling event between December and March from about  $15.5^{\circ}\text{S}$  to  $23^{\circ}\text{S}$  and cooler water flowing southwards. The major warm events cause a southward displacement of the ABFZ to between  $23^{\circ}\text{S}$  and  $25^{\circ}\text{S}$  for the duration of the warm anomaly. Except to induce slightly steeper SST gradients in the frontal zone, the minor warm and cool anomalies do not significantly affect the ABFZ.

## 1. Introduction

The zone of convergence between the Angola and Benguela systems, known as the Angola- Benguela frontal zone (ABFZ), has been under close scrutiny particularly since its southern boundary has been defined as the northern extent of the economically important Benguela upwelling regime.

Within this report, satellite sea surface temperature (SST) data spanning 18 years from 1982- 1999 are used to investigate the seasonal and interannual variability of thermal characteristics of the frontal zone.

The surface expression of the two major warm events termed 'Benguela Niño's' by Shannon *et al.* (1986), and of other minor warm episodes that occurred during the period of study are described in detail along two transects, as well as the thermal characteristics of the major cool events of 1982/83 and 1997.



**Figure 1.1.** 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.

The purpose of this report is to examine the seasonality of the Angola-Benguela front (ABF) and to monitor its response to the abnormal warm or cool events that take place in the area. The following questions will be addressed:

- What is the ABF?

- Where is it?
- How wide is it?
- How far does it extend offshore?
- How is the ABF affected by seasonality?
- What is the nature of the warm and cold anomalies?
- How is the ABF affected by the warm and cool anomalies?

## **2. Background**

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 distinct northern boundary of the upwelling regime was first described by Hart and Currie in 1960 and has since been understood as representing the southern boundary of the ABFZ. The northern boundary of the front has been identified as the southernmost extent of poleward moving Angola Current water. The Angola-Benguela Front is therefore defined as the convergence zone of the southward flowing Angola Current and the northward flowing cold water of the Benguela upwelling system. Via satellite images, the surface expression of the frontal zone has been observed by Meeuwis and Lutjeharms (1990) as a region of closely spaced isotherms that typically lies between 14°S and 16°S.

Since the discovery of the front, many aspects of the frontal zone have been investigated, with particular reference to those aspects that influence the economically important upwelling regime. Attention has been focused on thermal characteristics and latitudinal and offshore extent of the frontal zone. Kuderskiy and Strogalev (1973) (cited in Kostianoy and Lutjeharms (1999)) took a range of isotherms to be indicative of the frontal zone. They were the first to describe the seasonal displacement of the front as being situated furthest north in winter (July- September) and furthest south in summer (January-March). Subsequently, it has been found that the region of steepest temperature gradients between the Angola Current and the Benguela upwelling system is more definitive of the frontal zone. Using this definition,

the seasonal variations of the front has been studied in detail by Shannon *et al.* (1987), Meeuwis and Lutjeharms (1990) and Kostianoy and Lutjeharms (1999). All have noted that the mid-frontal position fluctuates seasonally within about 2° of latitude. Shannon *et al.* (1987) showed that the rate of movement of the mid-front was of the order of 50cm.s<sup>-1</sup>. An observed movement of 100cm.s<sup>-1</sup> was considered as an episodic event.

Using *in situ* data from the South African Data Centre for Oceanography (SADCO) and satellite SST data from the NOAA 9 and Nimbus-7 satellites, Shannon *et al.* (1987) showed that the front extends to a depth of 200m, but is particularly noticeable in the upper 50m, and that the thermal surface expression, identified as the zone of maximum horizontal gradient, is representative of the subsurface location. From sea surface temperatures obtained from thermal infrared imagery, Kostianoy (1996) (cited in Kostianoy and Lutjeharms (1999)) found that the northern and southern boundaries of the frontal zone have a tendency to move independently of one another. Kostianoy and Lutjeharms (1999) conducted a three-month study of the frontal zone from April to June 1988 using thermal infrared SST data from the NOAA-9 satellite. They identified two distinct fronts between 14.5°S and 18.5°S comprising the ABFZ from their characteristically steep temperature gradients. They confirmed the seasonal signal of the front by observing a clear secular trend as both the fronts representing the northern and southern boundaries of the front moved northwards. However, a disparity between the displacement of the northern and southern boundaries was evident whereby the northern boundary moved about 1° latitude northwards, while the southern boundary moved northwards by 1.5° latitude.

From visual analysis of Gosstcomp satellite SST images, Meeuwis and Lutjeharms (1990) concluded that frontal gradients of between 1°C per 28km and 1°C per 90km best described the position of the front. The sharpest temperature gradients were found between 15°S and 18° S and up to a distance of 250km offshore. They noted that the frontal zone was most clearly developed in austral summer with sharpest temperature gradients. In winter the front was less distinct with weaker temperature gradients indicative of the frontal zone. The front was observed to extend further offshore during spring

and summer than during winter when the cold Benguela upwelling regime penetrates northwards.

From a long time-series of SST (1906-1985) in the region of the ABFZ, Taunton-Clark and Shannon (1988) concluded that anomalous warm events have occurred throughout the environmental record with a periodicity of about 10 years. The first to compare these warm events with those that occur in the eastern tropical Pacific was Schott in 1931 during an investigation of the 1891 and 1925 Pacific El Niño events. He drew attention to the similarity in shape of the coastlines and to the comparable upwelling regimes in the eastern Tropical Atlantic and the eastern Tropical Pacific. Subsequently, the similarity between the Peruvian and Benguela warm episodes has been extensively investigated and substantiated, such that Shannon *et al.* (1986) coined the term Benguela Niño to describe the warming event in the eastern Atlantic. The El Niño and Benguela Niño events are both characterized by a relaxation or termination of the seasonal upwelling and a depression of the thermocline, thereby inhibiting the movement of cold, nutrient- rich water to the surface. The remote atmospheric forcing of the Niño events both in the Pacific and in the Atlantic and their similarity have been extensively studied by, among others, Hisard (1980), Merle (1980), Citeau *et al.*, (1984) and Servain (1985) (all cited in Shannon *et al.*, (1986)). In the case of the Benguela Niño, it has been shown by Walker (1987) that the Intertropical Convergence Zone (ITCZ) is situated further south during warm events and further north during 'cold years'. Servain (1985) indicated that there is a definite link between positive SST anomalies in the Benguela upwelling regime and the zonal wind stress in the western equatorial Atlantic.

Taunton-Clark and Shannon (1988) found evidence of Benguela Niños having occurred in 1908, 1923, 1934, 1950, 1964, 1974 and 1984. Although the Benguela Niños occur only about once every 10 years, minor warm anomalies have been observed throughout the record and appear to occur more frequently. Major cool anomalies have also been documented and are thought to recur on a roughly decadal cycle.

The effect of the Benguela Niños on the fishing industry is immediately noticed by coastal communities and accordingly has been extensively studied. Shannon and Agenbag (1990) suggested that, to significantly influence fish

populations, environmental change needs to be persistent and/or very major because the fish resources in the Benguela Ecosystem are already highly adapted to environmental change. They show that prolonged anomalies as a result of abnormal equatorward wind stress tend to shift the distributions of a number of fish species (Crawford and Shannon, 1988 cited in Shannon and Agenbag, 1990). LeClus (1985) (cited in Gammelsrød, 1998) reported that the 1984 warm event resulted in a major southward displacement of sardine and the lowest recruit biomass of anchovy on record, with a marked decline off the Namibian coast. Mortalities of young horse mackerel, steenbras and kob were recorded over 1-2 day periods along the Namibian coast. The 1995 Niño resulted in similarly devastating effects. Gammelsrød *et al.* (1998) noted that the 1995 event was associated with mortalities of sardine, horse mackerel and kob occurred off the coast. A southward displacement of sardine stocks from Angola, resulting in increased pelagic fish off the Namibian coast was also noted. The fact that starvation induced mortalities of seal pups and adults occurred during the 1995 Niño (Gammelsrød *et al.*, 1998) emphasizes the severity of the warm event.

### **3. Data and Methods**

The data used for this study are from the envifish data set and are monthly mean sea surface temperature (SST) values for the period from January 1982 to December 1999. 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. There are 25 pixels per degree of latitude and longitude and the corresponding nominal ground resolution is 4.5km.

From comparisons with *in situ* data (COADS) and data from another AVHRR product (Pathfinder) it was found that envifish SST data from September 1992 to August 1994 was 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 (September 1992 to August 1994) and replacing it with the mean of the SSTs outside of it (January 1982 to August 1992 and September 1994 to December 1999).

Matlab software was used to process the envifish data and to extract monthly sea surface temperature (SST), a climatology, interannual SST anomalies (SSTAs) and SST gradients. The SSTAs were calculated by subtracting the climatology from SST. In order to remove the long-term warming tendency, the SSTA data were detrended using Matlab software. The SST gradients were obtained by calculating the difference in temperature between two chosen points along the transect. The values obtained were then smoothed in order to aid visualization. The gradients were calculated under the assumption that the front runs perpendicularly to the coast. Since this is not always the case, the SST gradients are likely to be slightly underestimated, especially offshore. The 18-year based climatology was created by calculating the mean of SST for each month from January to

December. The anomalies were calculated by subtracting the climatology from the actual SSTs.

Although weekly composite data are also available from the envifish data set, mean monthly data were used as it produces 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-set due to cloud cover and then to fill them by interpolation. Where SST values were equal to the flag value of 8°C, which corresponds to a missing data, a NaN (Not-a-Number) was assigned. The NaN values were filled by spatially averaging the first pixels on either side of it that contained valid data.

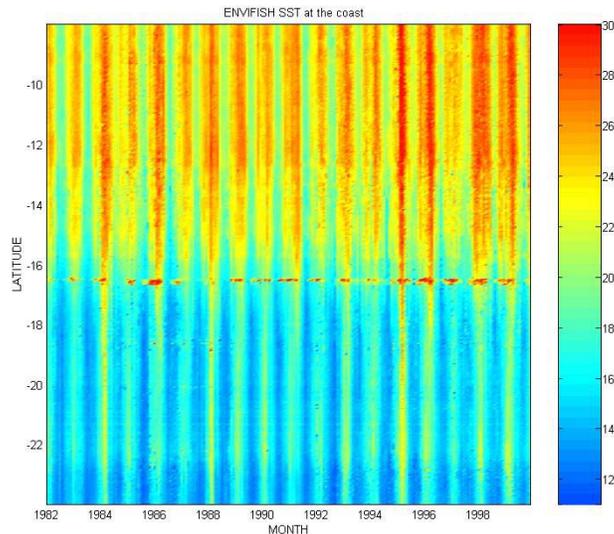
Rather than analyzing a meridional one, a transect following the coast was found to better represent the frontal zone, the regions to the north and particularly the upwelling regime to the south of the ABFZ. It appeared that a meridional transect might cut through the upwelling regime a short distance south of the frontal zone regardless of proximity to the coast near the ABFZ and is likely to lead to misinterpretation by taking into account only a limited part of the coastal upwelling regime.

A distance of 30km offshore for the coastal transect was found to be optimal to study the coastal expression of the front. The frontal characteristics are distinct at this distance without any interference from coastal features. Figure 3.1 is a plot of SSTs 4.5km from the coast for the whole period of study and shows that a 'pool' of warm water can be seen at about 16.5°S consistently during summer. From a similar plot 9km offshore (not shown) it is observed that this warm 'pool' persists at least this far, but not as far as 13.5km offshore. This warm seasonal signal is probably the surface thermal expression of the embayment at Baia dos Tigres that is a relatively enclosed feature and is therefore substantially warmed in summer.

The seaward extent of the ABFZ was investigated from transects taken as far as 250km offshore. The distance of 250km was chosen from visual inspection of images such as Figure 5.1, which show that at this distance the distinct frontal zone is at its maximum seaward extent.

In order to easily visualize the warm and cool events, monthly sea surface temperature anomalies were spatially averaged along the 30km

offshore transect between 10°S and 20°C and plotted against time (Figure 4.4.2). The time-series was detrended in order to remove the overall warming trend. An annual average of the SST for the frontal zone and for the regions north and south was calculated in order to remove the seasonal signal and to observe the long-term trends of each area separately (Figures 4.2.2 and 4.2.3).



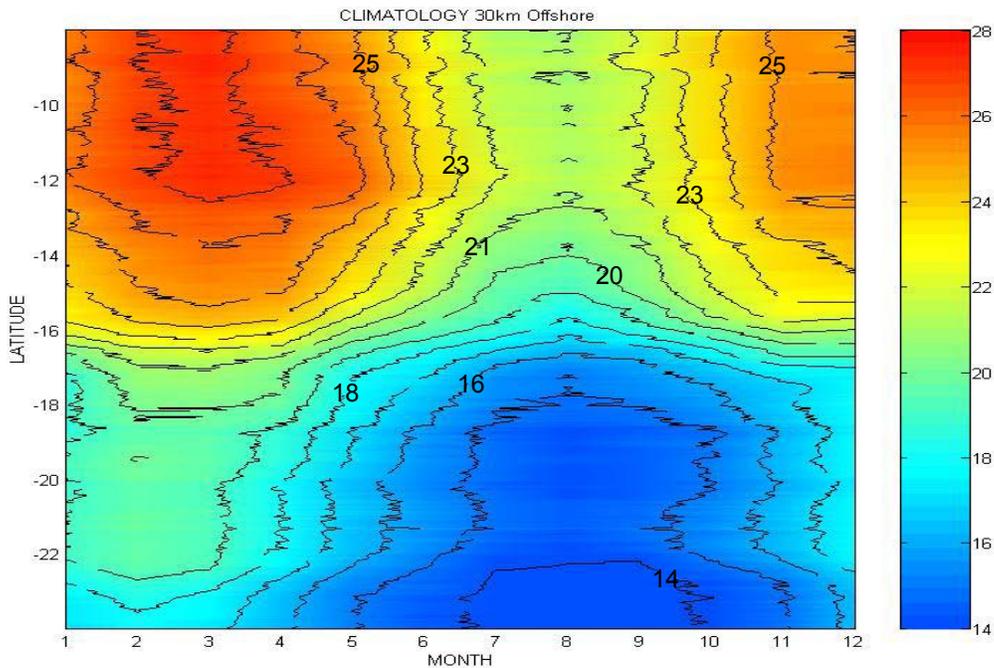
**Figure 3.1.** SSTs at the coast from the equator to 30°S, showing a recurring warm 'pool' during summer months.

## **4. Results**

### **4.1 Climatology**

#### **Transect 30km offshore**

The climatology of the sea surface temperatures of a transect 30km offshore calculated from 18 years of data shows a distinct compression of the isotherms (Fig. 4.1.1) between about 15.5°S and 17°S. This compression is clearly indicative of the frontal zone, which has previously been defined as a region of strong horizontal temperature gradients (Shannon *et al.*, (1987)). In mid-March the temperature across the frontal zone changes from approximately 24°C to about 21°C, but by August the temperatures at the northern and southern boundaries decrease to about 18°C and 16°C respectively.



**Fig. 4.1.1:** Climatology of SST for a transect 30km Offshore from 8°S to 24°S

In summer the frontal zone is characterized by the southernmost extent of the Angolan Current and in winter the frontal zone is defined by the northernmost extent of the Benguela upwelling system. The thermal characteristics of the front are therefore dependent on the seasonal fluctuations of the upwelling in the south and intrusion of the Angolan Current from the north. The warm water, characteristic of the region to the north of the front during spring and summer advances and retreats over greater distances and at a greater rate than the cool water that is present south of the front during winter months. This disparity is possibly due to the fact that the cool water to the south is a local seasonal upwelling feature, which is driven by the local winds (Mohrlolz *et al.*, 2001). The annual temperature range south of the frontal zone is smaller than to the north of the ABFZ. The smaller temperature in the Benguela upwelling regime to the south of the frontal zone is likely to be a related to the fact that aside from the major upwelling event in winter, short-term upwelling events occur throughout the year, bringing cold water to the surface. This supports Kostianoy and Lutjeharms' (1999) finding that the upwelling regime is driven by local winds and the position of the SAA, which

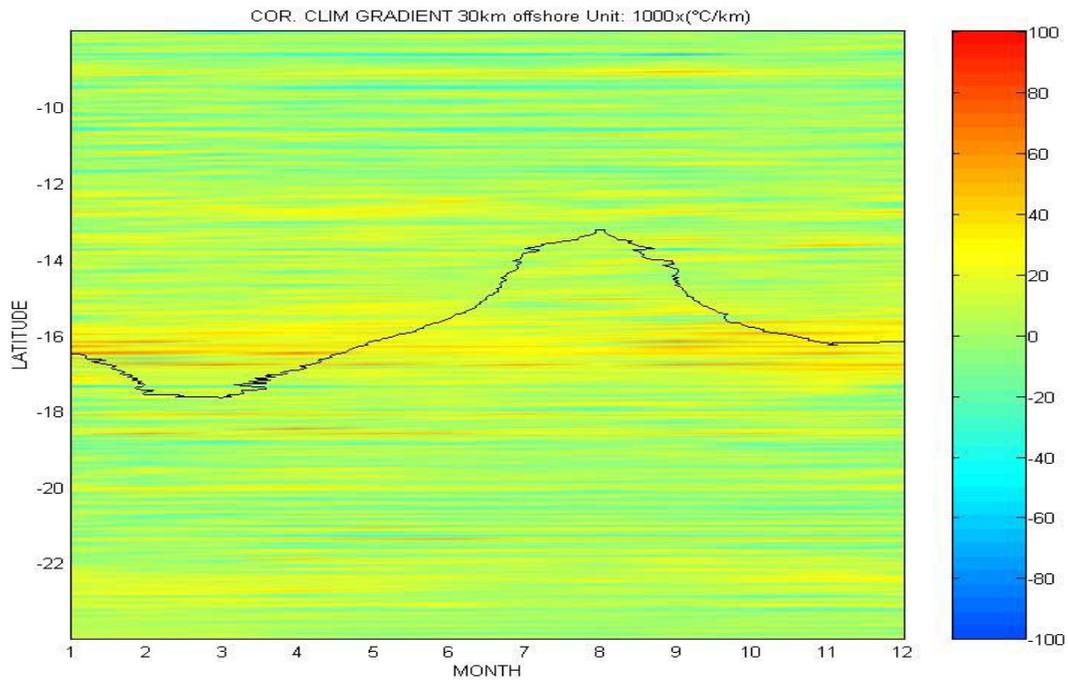
fluctuates intensively. The major upwelling event coincides with the most northern extent of the warm Angolan Current and therefore coolest temperatures north of the frontal zone. As a result, weaker frontal gradients occur in winter with temperature ranges of about 2°C across the frontal zone. In summer, the warm water to the north meets the cool water of the Benguela system giving rise to steeper SST gradients in the frontal zone and a temperature range of about 4°C across it.

From visual analysis of Hoffmüller plots of SST 30km offshore for the period of study, the 19°C and 22°C isotherms were found to be indicative of the warm Angolan and cool Benguela systems respectively. An alternative method of identifying variability within the frontal zone would be to follow the range of isotherms that lie between the 22°C isotherm, which is indicative of the warm water to the north of the ABFZ and the 19°C isotherm, which corresponds to the cool water south of the front. In this way, the position of the 20.5°C isotherm shows the seasonal variability of temperature within the frontal zone. Although this isotherm does not represent the position or displacement of the front, it can be used to observe anomalous warm or cold events whereby abnormally warm or cold water is found within the ABFZ and extends unusually far south or north respectively. On average, the 20.5°C isotherm lies at about 17.5°S in summer and 13°S in winter.

The gradient of the climatology (Fig. 4.1.2) supports the fact that the frontal zone, when viewed as the region of greatest thermal gradients, is a particularly stable feature and is situated, on average, between 15.5°S and 17°S. Figure 4.1.2 shows that from September to April the frontal zone is narrowest (15.5°S to 17°S) and has the steepest thermal gradients of the order of about 1°C per 14km, whereas from May to August it is broader (15°S to 17°S) with less intense thermal gradients of about 1°C per 29km. The mid-front position therefore moves northwards only about 28km in winter when the front is widest.

Overlaid on Figure 4.1.2, is the 20.5°C isotherm, which represents the position midway between the warm water to the north and cold water to the south of the frontal zone. The 20.5°C isotherm fluctuates about the mean frontal position and is furthest south in summer when the front is narrowest and furthest north when the front is wide. The fluctuation of the 20.5°C

isotherm is a function of seasonal heating and cooling so it can neither be thought of as indicative of the frontal zone, nor can it be thought of as being definitive of the water masses to the north or south of the frontal zone. It is however useful as an indicator of warm and cool anomalies.

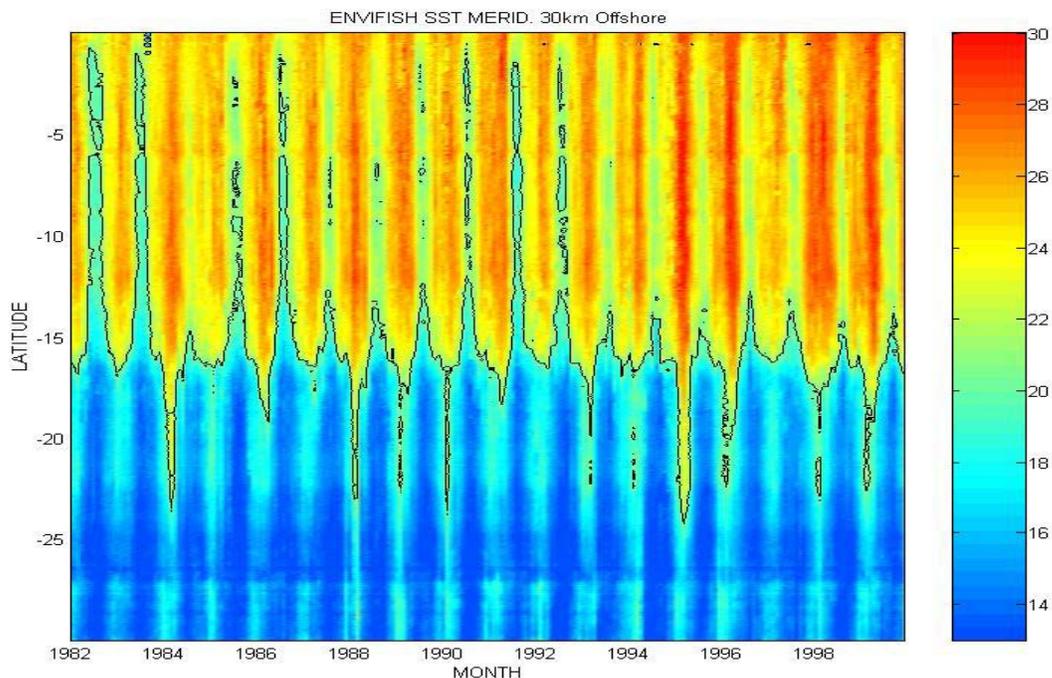


**Figure 4.1.2** Climatology of SST gradients across the frontal zone for the period from January 1982 to December 1999. The 20.5°C isotherm is overlaid.

## 4.2 Seasonality and long-term trends.

### Transect 30km offshore

Figure 4.2.1 is a plot of sea surface temperature through time along a transect at a distance of 30km offshore from the equator to 30°S. It shows that though the temperature range of the frontal zone fluctuates seasonally, the position of the front, when viewed as region that corresponds to both the southern extent of the Angolan system and the northern extent of the Benguela system, remains relatively stable.



**Fig. 4.2.1.** Hoffmüller plot of the sea surface temperatures along a transect 30km offshore.

The 20.5°C isotherm is overlaid.

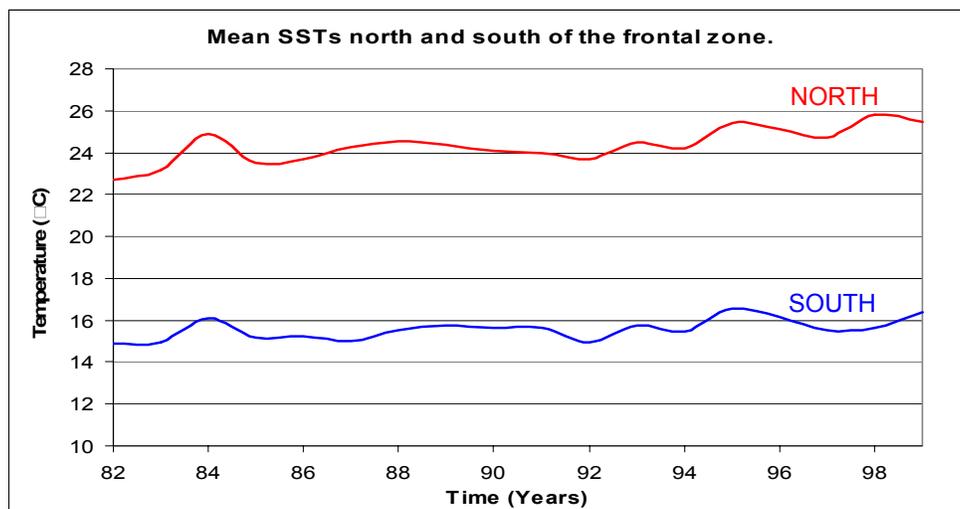
Over the 18 year period, the southward extent of warm Angolan water in summer months (roughly indicated by the 20.5°C isotherm on Figure 4.2.1) is fairly consistent with the exception of years that experienced warm and cool anomalies. In Figure 4.2.1, warm events are evident as the unusual southward extent of the 20.5°C isotherm, particularly during the summers of 1984, 1986, 1988, 1995, 1996, 1998 and 1999. The major cool events of 1997 and 1982/83 can be identified by an abnormally northern position of the southward extent of warm Angolan water. The regularity of the southern

extent of the Angolan Current is tied in with the fact that it is forced by the zonal wind stress in the equatorial Atlantic, the corresponding position of the Intertropical Convergence Zone (ITCZ) and ultimately to the apparent position of the sun. When the ITCZ lies further south than usual, the zonal wind stress at low latitudes is relaxed causing the sea level to rise in the eastern tropical Atlantic and for a compensatory southward flow of warm Angolan water to extend beyond the frontal zone, resulting in a 'Benguela Niño' (Shannon *et al.*, 1986 and Ruiz-Barradas *et al.*, 2000). On the other hand, an anomalously northerly position of the ITCZ results in a 'cold event' in which the southernmost extent of the Angolan Current is further north than usual.

From Figure 4.2.1, a general warming trend is evident, affecting both the Angolan and Benguela systems to the north and south of the frontal zone respectively. Figure 4.2.2 is a plot of the mean annual SSTs for the region to the north (equator- 15°S) and south (18°S- 30°S) of the frontal zone. It shows the major anomalies of 1984 and 1995 clearly in the long-term trends of both regions north and south of the frontal zone. Although warming is evident in both systems, warming of the Angolan system exceeds that of the Benguela system. Over the 18 year period, the Angolan system warmed by about 3°C, while the Benguela system warmed by only about 1.5°C. For both systems, a marked increase in temperature seems to have occurred between 1992 and 1995. Figure 4.2.3 is a graph of the mean annual SSTs across the frontal zone (15.5°S to 17°S) and shows that the general warming trend there is about 2.5°C. From a study of variability in the south- east Atlantic during the 20<sup>th</sup> century conducted by Taunton-Clark and Shannon (1988), an overall warming of 1°C was noted between the 1920's and 1985.

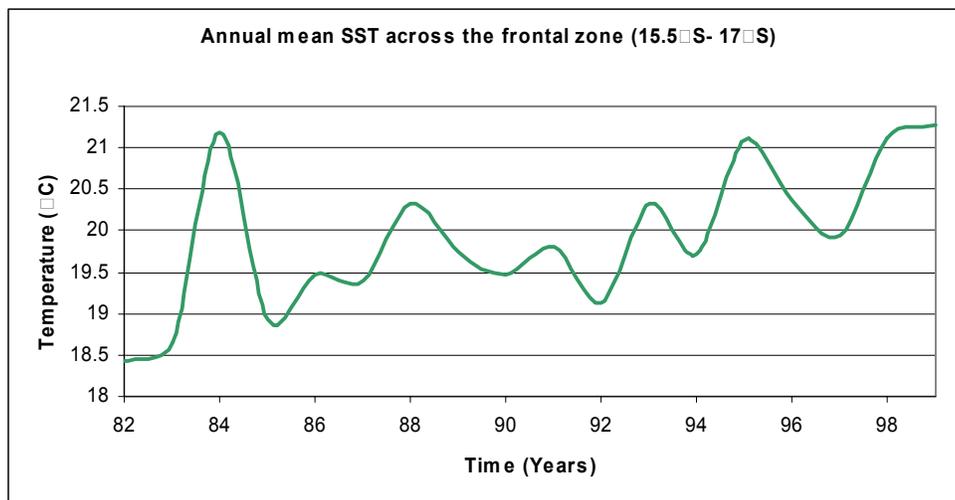
The two major warm events, or 'Benguela Niño's' that occurred in 1984 and 1995, can be clearly identified in Figure 4.2.1, whereby the 20.5°C isotherm extends unusually far south to about 24°S in the case of the former and to approximately 25°S in the case of the latter. Apart from these events, less intense warm events occurred in 1986, 1988, 1996 and 1998/99 and are seen as marked southern intrusions of warm water. Like the major warm events, the 1988 warm event has been associated with positive wind stress anomalies at the equator by Ruiz- Barradas *et al.*, 2000, but has been

distinguished from the major warm events by Carton and Huang (1994) who showed that the wind stress anomalies related to the 1988 event occurred later than the anomalies associated with the major warm events. Years in which the southern extent of warm water appears to be relatively extreme, but narrow and intermittent such as in 1989 and 1990 are not likely to be the result of equatorial wind stress, but rather eddies and filaments that advect warm water into the frontal zone from offshore. Cool events occur in 1982, 1983 and 1997 and are characterized by a weak and particularly short-lived southward intrusion of warm water. The existence of a cool period in the early 80's is in agreement with McClain *et al.* (1985) who identified 1981/82 as the most marked cool event during the period 1971- 1984 and with Walker (1987) who used principle component analysis, which clearly identified a prolonged cold event in 1981/83. Using a montage of satellite and *in situ* data Shannon and Agenbag (1990) further substantiate the anomalously cold conditions in the early 80's. In 1997 a similar cold event is evident during which the southward penetrating water was cooler than usual and only extended as far south as about 15°S.



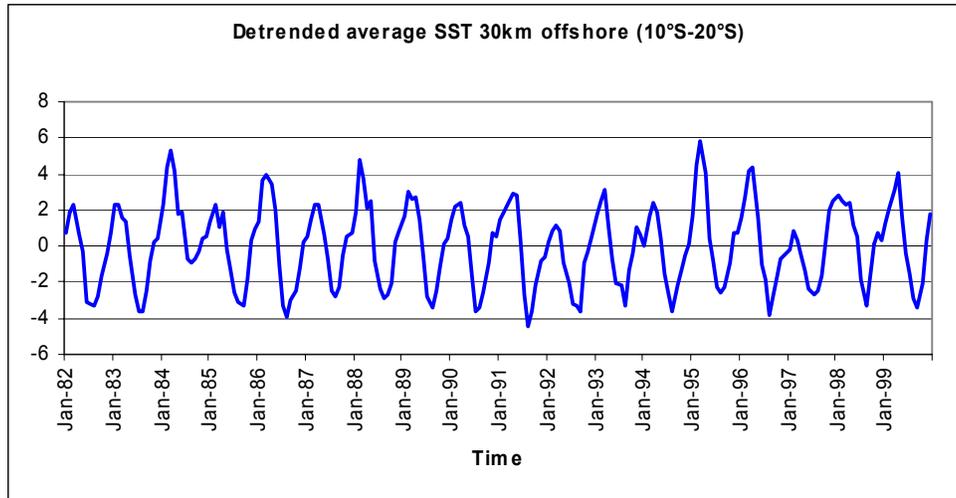
**Figure 4.2.2.** Graph of the annual mean SSTs of the regions north (equator- 15.5°S) and south (17°S- 30°S) of the frontal zone, showing the disparity of the long-term warming trend.

From Figure 4.2.2, it is shown that a general warming of about 2°C occurred north of the frontal zone and warming of only about 1°C occurred south of the frontal zone during the 1984 Benguela Niño. During the 1995 Benguela Niño a 1.5°C increase in temperature occurred north of the frontal zone, while an increase of about 1°C is observed south of the frontal zone. Despite the seemingly small increase in overall temperature, the 1995 event was nonetheless extreme as it occurred during a period of intense overall warming. Also because of its concurrence with the general warming trend, the cold anomaly of 1997 seems particularly significant, with a general temperature decrease of about 1.5°C. From Figures 4.2.2 and 4.2.3 it can be seen that the warm event of 1998/99 is evident within the frontal zone and north of it, but it is absent south of the frontal zone.



**Figure 4.2.3.** Graph of the annual mean SSTs of the frontal zone (15.5°S to 17°S), showing the long-term warming trend and the major warm and cold events.

Despite the warm and cool anomalies and the long-term warming tendency that look quite extreme in Figures 4.2.2 and 4.2.3 due to the elimination of the seasonal signal, Figure 4.2.1 and a time-series of detrended mean SSTs (Figure 4.2.4) clearly show that the seasonal signal of both the northern and southern regime of the frontal zone remains strong and appears to be the dominant signal.

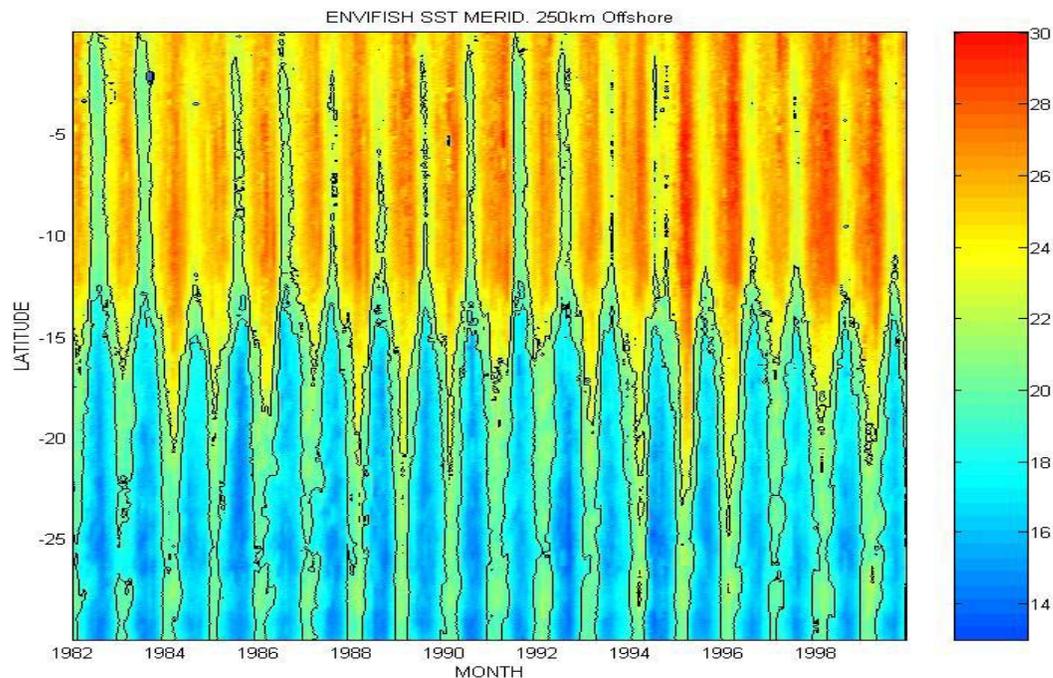


**Figure 4.2.4.** Time-series of detrended mean SSTs for the region between 10°S to 20°S of a transect 30km offshore, showing a strong seasonal signal.

#### Transect 250km offshore

The ABFZ, roughly related to region between the southern extent of warm Angolan water and the northern intrusion of cold water from the Benguela system, is still fairly distinct 250km offshore, but is more diffuse, existing over a broader region.

Figure 4.2.5 shows that the northern extent of the cold upwelled water to the south of the frontal zone lies between about 12.5°S and 15.5°S. The southern-most extent of the warm Angolan water lies between about 16°S and 18°S. Like the situation 30km offshore, significant southward excursions of warm Angolan water occurred in 1984, 1988, 1995, 1996 and 1998/99 (see Figure 4.2.5). The major warm events are either present as a prolonged southward extension (e.g. 1984) or a relatively brief, but extreme migration of very warm water (e.g. 1995). Again, the major cool events of 1982/83 and 1997 are evident and are associated with cooler water penetrating southwards, but not unusually far south. Also, the cool events seem to be related to a prolonged upwelling event, particularly evident during the 1982/82 cool event, shown in Figure 4.2.5 as a broader zone of upwelling.

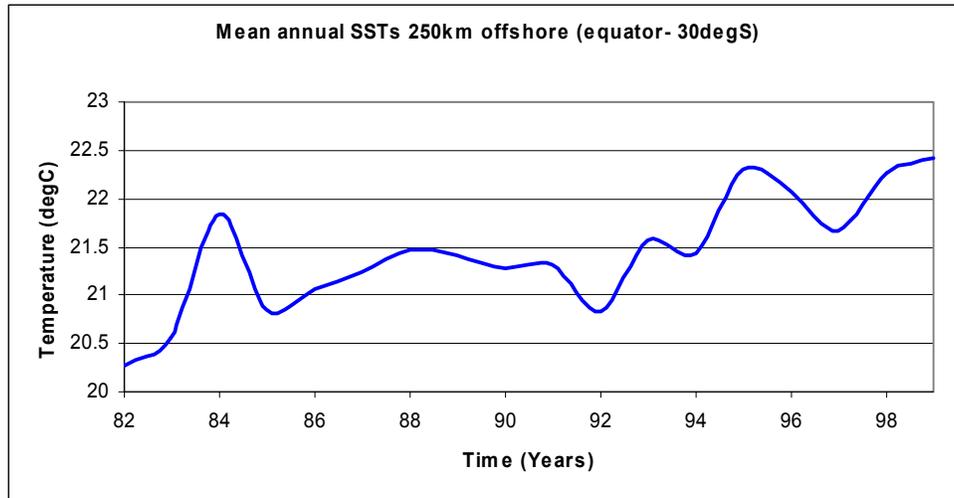


**Figure. 4.2.5.** Hoffmüller plot of the sea surface temperatures along a transect 250km offshore with the 19°C and 22°C isotherm overlaid.

The mean SST 250km offshore is about 1.5°C warmer than the 30km offshore transect. This difference in average SST's is due to the fact that intense upwelling at the coast lowers the average SST there significantly. From a time-series of the mean annual SSTs 250km offshore from the equator to 30°S (Figure 4.2.6) a general warming trend is once again evident whereby both the Angola and Benguela systems show an increase in temperature of about 2.2°C over the 18-year period, with a particularly marked step in temperature between 1992 and 1995.

The Benguela Niños of 1984 and 1995 are evident as distinct peaks of mean annual SST in Figure 4.2.6., an average SST increase of about 1.7°C occurred in 1984 and an increase of about 1°C occurred in 1995. The major cool event of 1997 is a pronounced 'dip' corresponding to a drop in SST of about 1°C. The minor warm events of 1986 and 1988 can also be identified in Figure 4.2.6. as slight intensifications of the mean annual SSTs. The average SSTs 250km offshore therefore also seem to be subject to the major

anomalies and the overall warming trends that are evident closer inshore. However, the major events are less intense and, though evident, the minor events do not affect the mean SSTs 250km offshore significantly.



**Figure 4.2.6.** Graph of running mean of SSTs 250km offshore, showing that the warming trend persists offshore.

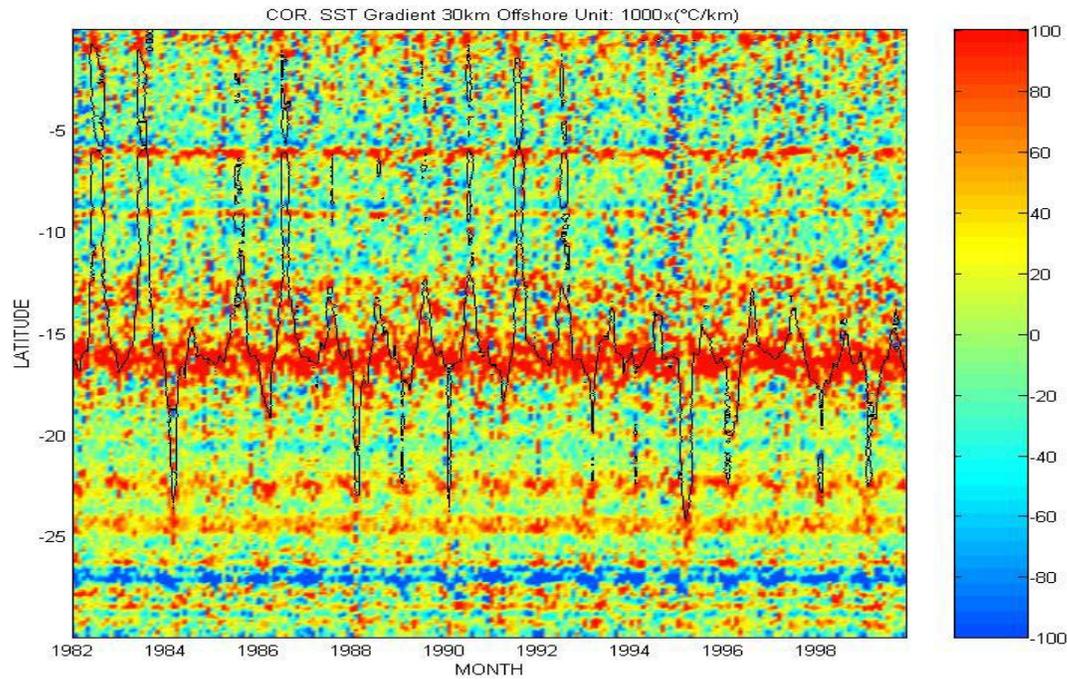
### 4.3 SST Gradients

#### 30km Offshore

A plot of the gradient of SST's through time from the equator to 30°S (Figure 4.3.1) shows that despite episodic warm and cold events and a long-term warming trend, the position of the front is very stable throughout the period of study and is situated between approximately 15.5°S and 17°S. Figure 4.3.1 substantiates that the SST gradients within the frontal zone have a seasonal signal and are generally more intense in summer than in winter. Although the position of the frontal zone has remained stable over the period of study, the region of steep SST gradients indicative of the frontal zone has broadened. The widening of the frontal zone is possibly related to the long-term warming trend and the fact that it is more extreme to the north of the front than to the south of it.

Superimposed on Figure 4.3.1 is the 20.5°C isotherm, which is indicative of the region between the warm water to the north of the frontal zone and the cool water to the south and as such it provides a good indication

of warm and cool events. The position of the front is a result of the interplay between the southernmost extent of warm, Angolan water and the northernmost extent of cold Benguela water. It is partly because of this interplay that the region of most intense thermal gradients correlating to the frontal zone remains quite stable.



**Figure 4.3.1.** Hoffmüller plot of SST gradients from the equator to 30°S for the period of study with the 20.5°C isotherm overlaid.

Major warm episodes such as the 1984 and 1995 events, correspond to a severe southward displacement of the 20.5°C isotherm in Figure 4.3.1. During such events, the steep temperature gradients of the frontal zone tend to weaken, but unusually steep gradients are evident at about 25°S during both events. The implication of this is that the major warm events cause an extreme southward displacement of the frontal zone. On the other hand, the major cool events tend to confine the region of steepest temperature gradients to a relatively small area and effectively result in a more intense (i.e. narrower with steeper SST gradients) frontal zone. The response of the frontal zone to warm and cool anomalies will be discussed in detail in the next section.

Coincident with the 1995 warm event, unusually high but relatively diffuse SST gradients are present from north of 5°S to the frontal zone. The high SST gradients to the north of the frontal zone are possibly related to the sudden intrusion and equally sudden retreat of unusually high temperatures into the region. Despite the consistently high SST gradients that extend northwards from the front during the summer of 1995, the frontal zone remains distinct as a region of particularly concentrated and strongly positive SST gradients.

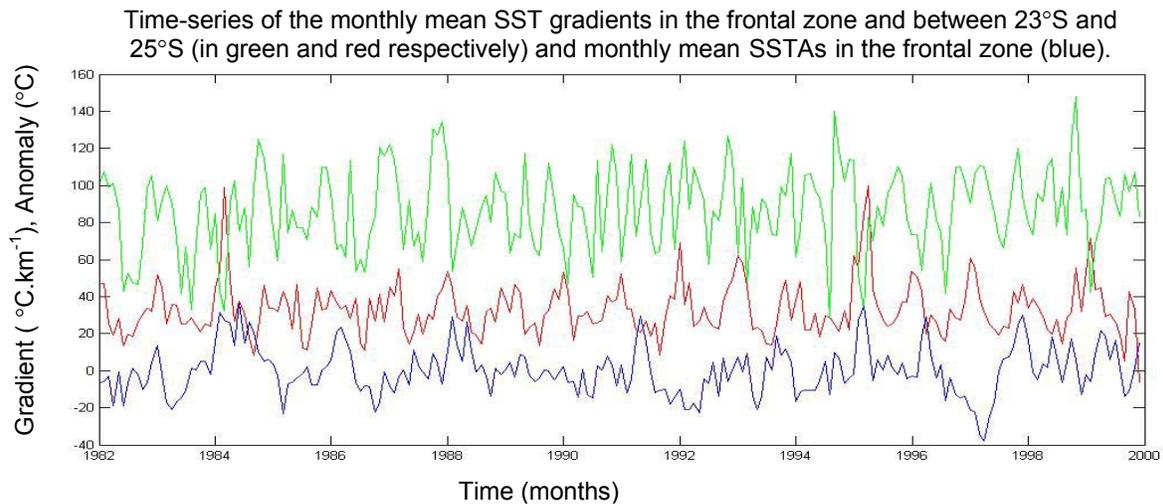
A zone of distinctly higher SST gradients of around 1°C per 12.5km exists at approximately 22°S to 23°S. This zone of high SST gradients is clearly seasonal, evident only during spring and summer. Over the period of study, the SST gradients in this zone tend to become more intense, possibly as a result of the disparity in the rate of warming of the Angola and Benguela systems.

Another zone of significantly elevated SST gradients exists from the northern boundary of the frontal zone ABFZ and extends northwards to about 12.5°S. The gradients in this zone are more variable and range from between 1°C per 12.5km and 1°C per 100km. This zone has a seasonal signal with steepest SST gradients in summer. During the major warm event of 1984, this frontal zone was not discernable. On the other hand, cool events seem to intensify the SST gradients in this zone. This is particularly noticeable as having occurred during the cool events of 1991/92 and 1997. Again, the SST gradients in this zone have become consistently steeper, with a marked intensification in the early 1990's.

The narrow zone of strongly positive SST gradients at about 6°S also has a seasonal signal, but is generally most intense during winter months. Its geographical location corresponds to a marked change in the orientation of the coastline and to the mouth of the Congo River. At a distance of only 30km offshore, this zone of steep gradients is likely to be a function of these major coastal features.

Figure 4.3.2 is a time-series of the monthly mean of SST gradients in the frontal zone (15.5°S- 17°S) and between 23°S and 25°S, shown in green and red respectively. The blue line in Figure 4.3.2 is the monthly mean of SSTAs in the frontal zone. Although fairly noisy, Figure 4.3.2 shows that

during warm anomalies (represented by peaks of the blue line) the mean SST gradient in the frontal zone weakens considerably. However, at a distance of about 675km south of the frontal zone, at between 23°S and 25°S, the SST gradient steepens markedly at the time of the warm anomalies. This pattern is particularly obvious during the major warm events of 1984 and 1995. This substantiates the suggestion that the front is displaced southwards during major warm events.



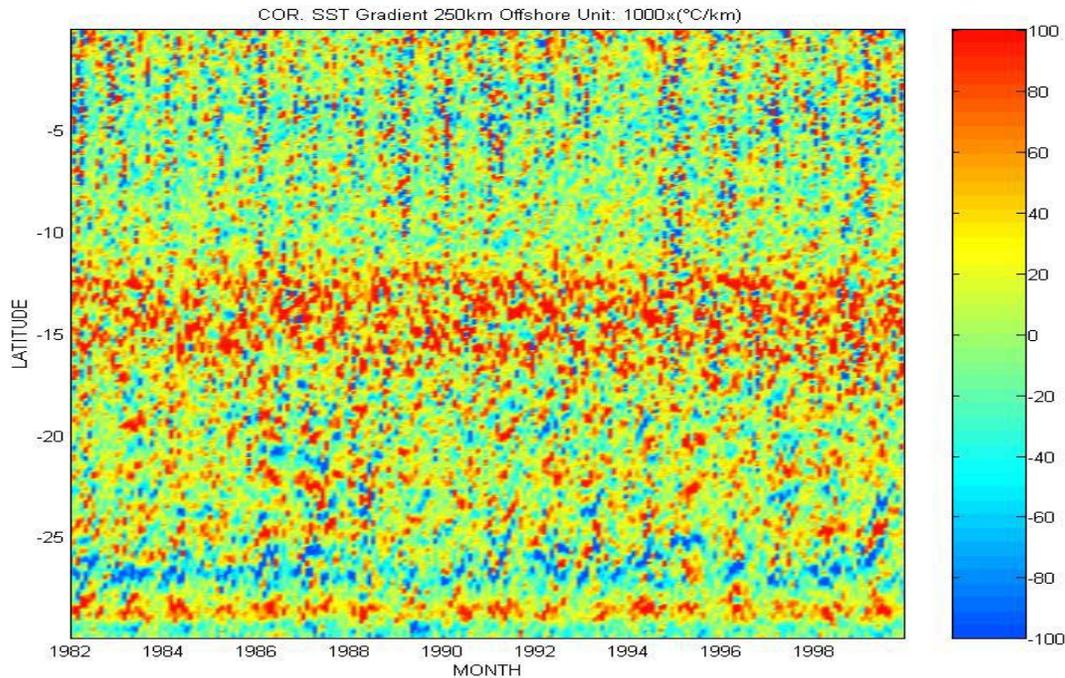
**Figure 4.3.2.** The monthly mean SST gradient in the frontal zone (15.5°S- 17°S) is indicated by the green line. The monthly mean SST gradient between 23°S and 25°S is in red and the monthly mean SSTAs in the frontal zone are shown in blue.

### 250km Offshore

A Hoffmüller plot of the gradient of SST's 250km offshore (Figure 4.3.3) shows that the ABFZ is present as a diffuse zone of steep SST gradients, with strongest gradients in spring summer and is situated between about 12°S and 16°S. Over the 18 year period, the region of steep SST gradients representative of the frontal zone 250km offshore has broadened and its mid-frontal position has moved slightly southwards.

Like the situation inshore, during the warm events SST gradients in the frontal zone are weakened, but unusually steep gradients are present between about 20°S and 26°S during the major 1995 warm event and minor warm event of 1988. The major warm event of 1984 does not seem to have induced elevated SST gradients south of the frontal zone.

The major cool events do not significantly affect the ABFZ 250km offshore.



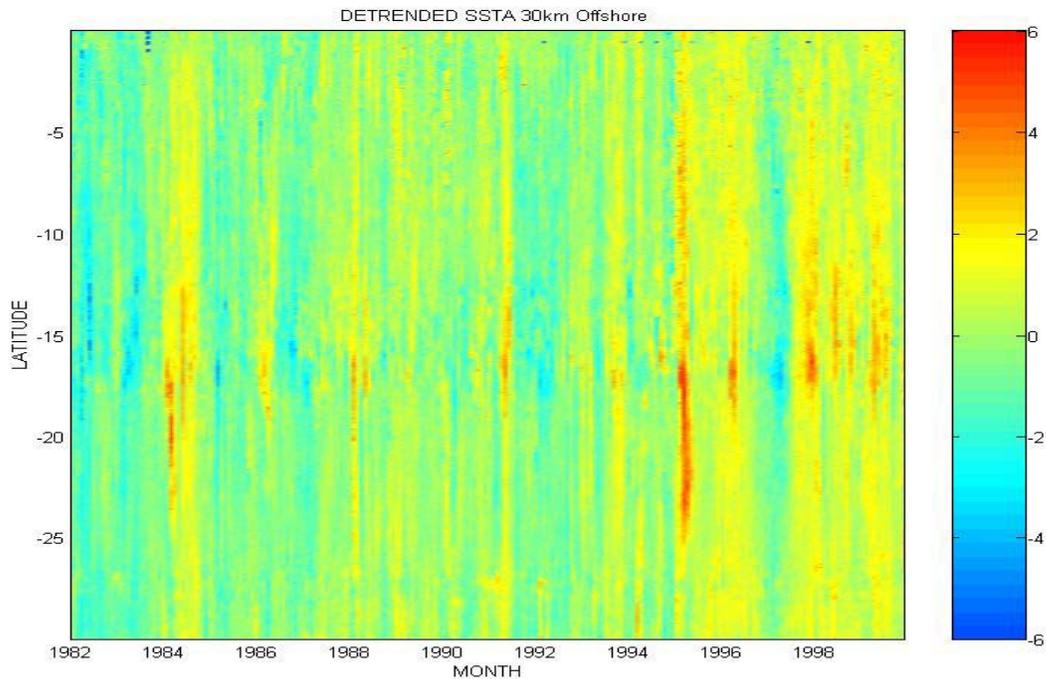
**Figure 4.3.3.** Hoffmüller plot of SST gradients 250km offshore from the equator to 30°S.

#### 4.4 Anomalies

The sea surface temperature anomalies (SSTAs) from the equator to 30°S for the period from 1982 to 1999 are illustrated in Figure 4.4.1. The warm events of 1984 and 1995 are obvious and correspond to positive SSTAs that extend far southwards. The major cold events that occur during this period, namely the 1982/83 and 1997 events, correspond to the distinct negative anomalies in the region of the frontal zone.

Shannon *et al.* (1986) described the 1984 warm event in detail and concluded that similarly extreme positive anomalies occur about once every ten years. The decadal cycle of the major warm events or Benguela Niño's has since been substantiated by analysis of a long time series of SST data by Taunton-Clark and Shannon (1988). Though Figure 4.4.1 shows only 18 years of data the recurrence of not only major positive anomalies, but

seemingly also of major negative anomalies is consistent with the decadal cycle revealed in previous studies.

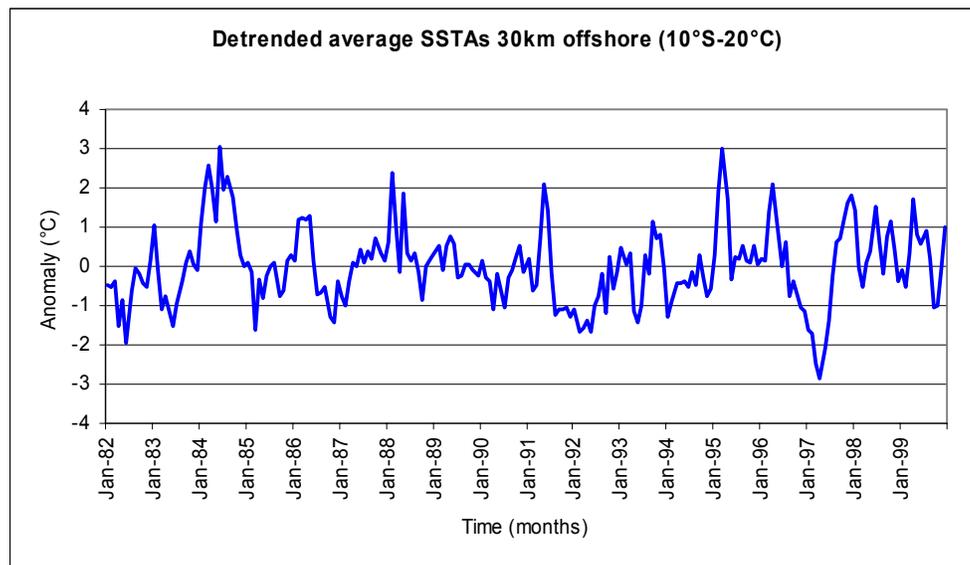


**Figure 4.4.1.** Hoffmüller plot of the sea surface temperature anomalies (SSTA) for the period 1982-1999 from the equator to 30°S.

Apart from the two major warm events that have been described as Benguela Niño's, less severe but equally noteworthy positive anomalies occurred in 1986, 1988, 1991, 1996, 1998 and 1999. These positive anomalies as well as the major warm and cool events are evident in a time series of detrended monthly mean SSTAs from the equator to 30°S, 30km offshore (Figures 4.4.2). Although the positive anomalies during the late 90's appear to be comparable to the major warm events, they do not extend far south of the frontal zone. Aside from the severe cold event of 1997, the overall warming might have resulted in the consistently positive anomalies throughout the region of study from 1995 to 1999. Because of the intensification of overall warming in about 1995, the severe negative anomaly of 1997 appears very distinctly in Figure 4.4.1.

The positive and negative anomalies are most intense in the region of the frontal zone, but during major events extend significantly south of the frontal

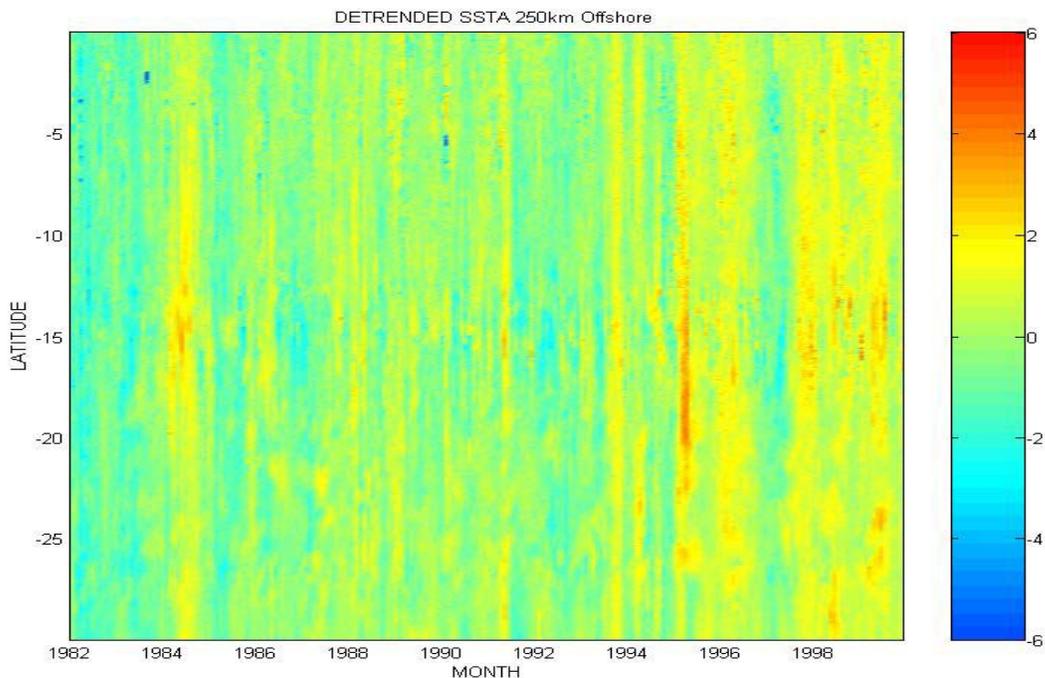
zone. Though the Benguela Niño events of 1984 and 1995 were similarly severe, differences existed between the surface thermal expressions of each, likewise for the two major cold events. Despite these differences, it has been shown by Shannon *et al.* (1986) that the forcing mechanism of the major events are similar and Carton and Huang (1994) distinguishes them from the anomalies that are less extreme and not considered to be major, such as the warm event of 1988.



**Figure 4.4.2** Graph of mean SSTAs from 10°S and 20°S of a 30km offshore transect with the long term warming trend removed.

### 250km Offshore

Figure 4.4.3 is a plot of the SSTAs 250km offshore and shows that the major warm events extend to at least that distance offshore, but except for a fairly pronounced seasonal cooling, the cool anomalies are not significant 250km offshore. Apart from a slightly warmer seasonal signal, the minor warm anomalies also do not appear to extend offshore.

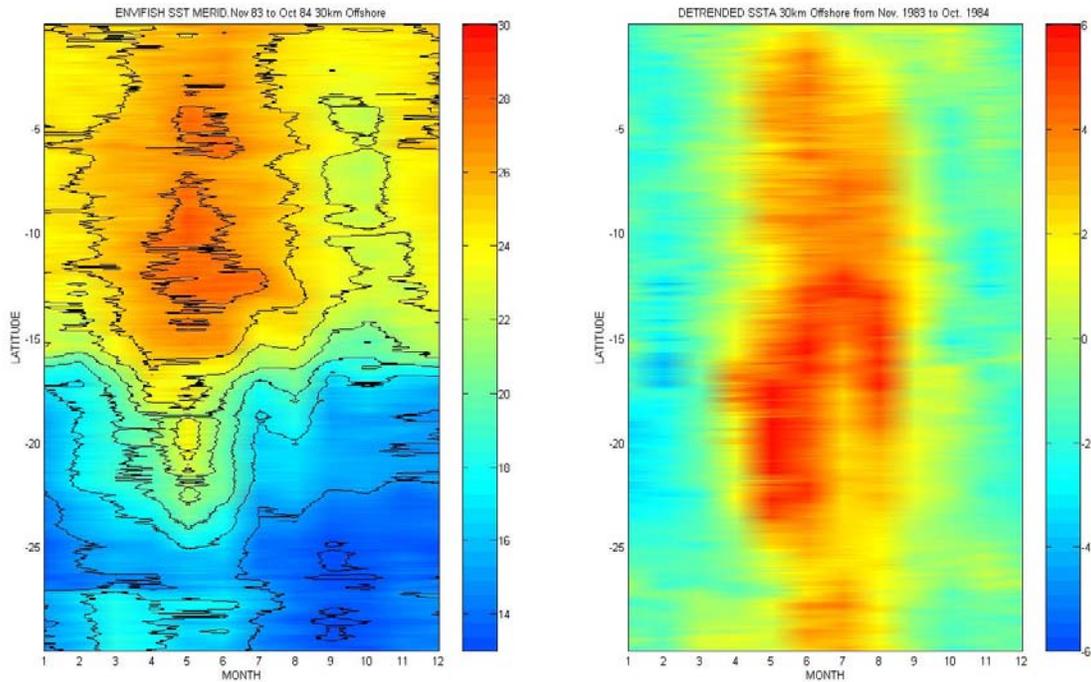


**Figure 4.4.3.** Plot of SSTAs of a transect 250km offshore from the equator to 30°S.

#### 1984 Benguela Niño

Figure 4.4.4(a) shows that the maximum southward extent of warm water during the 1984 Benguela Niño was during March when water of about 20°C existed 30km offshore at roughly 24°S. It can be seen that the initial intrusion began its northward retreat in April resulting in near-normal SSTs as far north as 17°S. However, this 'normal' situation was particularly short-lived as the warm water began moving southwards once again in May and reached its southernmost position in June. This 'double' intrusion is in agreement with the findings of Shannon *et al.*, (1986), who from sea-level and satellite data, found that though the major intrusion commenced its retreat in April, *in situ* data indicated that SSTs off Walvis Bay remained unusually high until at least August. Because the warm intrusion of the 1984 Benguela Niño persisted for 5.5 months of the year, it encroached on the upwelling regime that normally begins to increase northwards in about April. Although the upwelling event of 1984 extended northwards quite suddenly in April as the warm intrusion

began its temporary retreat, its northward extension was suppressed in June as the warm water once again moved southwards.

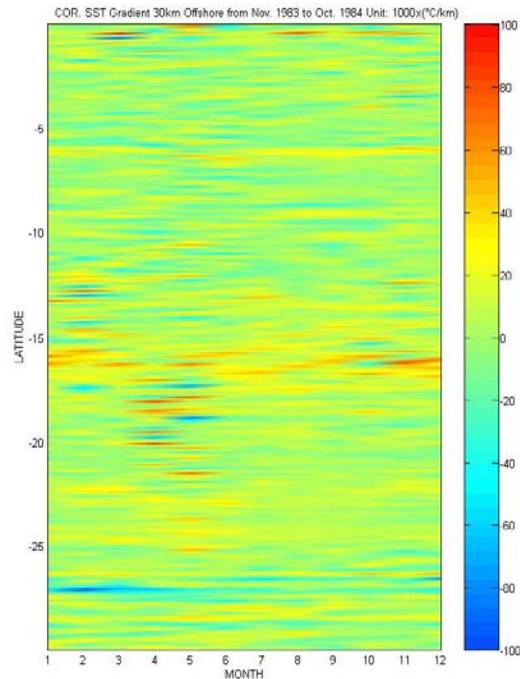


**Figure 4.4.4(a) (left).** A plot of the SSTs 30km offshore from November 1983 to October 1984. **Figure 4.4.4(b) (right)** A plot of the corresponding SSTA's.

The two distinct pools of positive sea surface temperature anomalies shown in figure 4.4.4(b) supports the fact that warm water extended unusually far south in a 'double' event. The first intrusion of warm water coincided with the seasonal advance of the Angolan Current therefore, the unusually extreme southward extent resulted in particularly strong and extensive ( $\pm 12^{\circ}\text{S}$  to  $24^{\circ}\text{S}$ ) positive anomalies of the order of  $+6^{\circ}\text{C}$ . The second, less intense anomalous southward intrusion of warm water was more or less in phase with the advent of the seasonal upwelling regime. Consequently, the corresponding region of strong positive anomalies of about  $+4^{\circ}\text{C}$  to  $+6^{\circ}\text{C}$  is less extensive and extends to only about  $19^{\circ}\text{S}$ .

A plot of the sea surface gradients in the frontal zone (Figure 4.4.5) shows that the first major intrusion seems to have induced a southward excursion of the front. From mid- January to April the SST gradients between

15.5°S and 17°S weaken, but south of the front to about 25°S unusually steep SST gradients persist. The region of steep SST gradients indicative of the frontal zone returned to its usual position in accord with the rather sudden retreat of the first warm water intrusion in April. The second intrusion of warm water doesn't seem to have affected the position of the frontal zone.



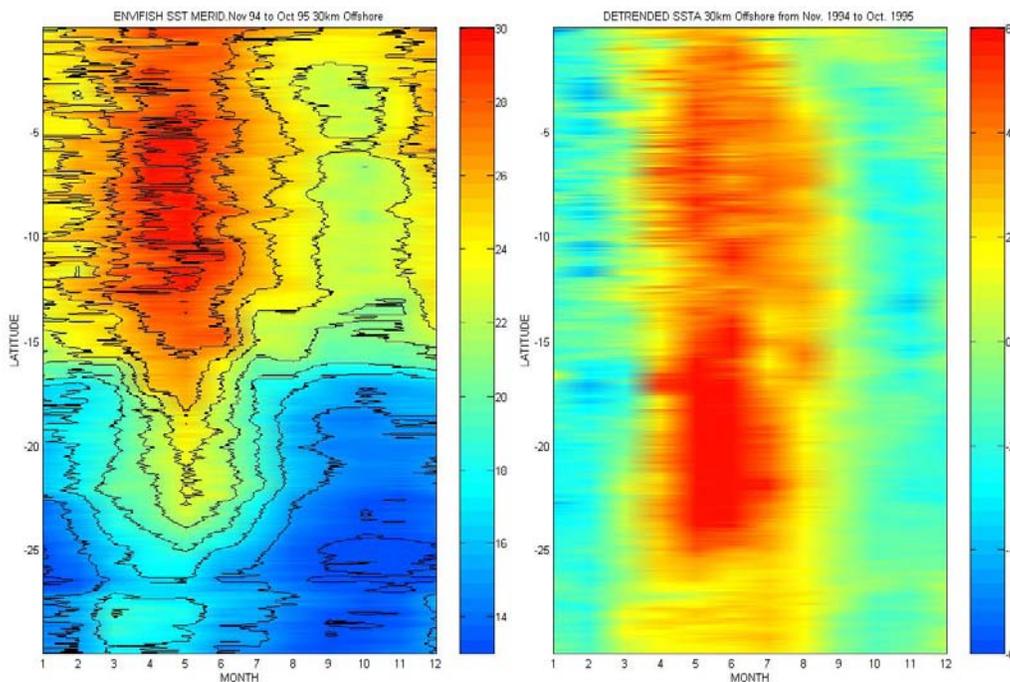
**Figure 4.4.5.** A Hoffmüller plot of the gradient of SSTs, 30km offshore from November 1983 to October 1984.

From inspection of Hoffmüller plots of SSTs, SSTAs and SST gradients 250km offshore (not shown) it is clear that the 1984 Benguela Niño extended at least as far as 250km offshore. The SSTA plot shows that the two distinct 'pools' of extreme positive anomalies persist 250km offshore, but do not penetrate as far south, reaching a maximum southward extent of about 18.5°S and 16°S respectively. The region of elevated SST gradients indicative of the frontal zone is markedly diffuse 250km offshore and is present between about 12°S and 17°S. Between February and April a series of steep gradients is evident from 12°S to 20°S, showing that during this time the front extended

unusually southwards. It is noteworthy that the abnormal southerly excursion of the front closer inshore occurred a month prior to this and lasted longer.

### 1995 Benguela Niño

The unusually warm conditions during March 1995 were the warmest recorded since the Benguela Niño of 1984 (Gammolsrod *et al.*, 1998). This and other similarities have supported the classification of the 1995 warm anomaly as a Niño event. Despite the obvious similarities, the surface thermal characteristics of the 1995 event are different from the 1984 Niño and as such warrants a detailed description. The most conspicuous difference between the two major warm events is that the latter appears to have extended further south, but to have persisted for a shorter period of time than the 1984 Benguela Niño.



**Figure 4.4.6(a) (left).** A plot of the SSTs 30km offshore from November 1994 to October 1995. **Figure 4.4.6(b) (right)** A plot of the corresponding SSTA's.

The abnormal southward intrusion of warm water during 1995 occurred from February and lasted until about mid- May. Unlike the 1984 event, it occurred as a single event as is evident from the 'pool' of strongly positive SSTAs in Figure 4.4.6(b). Consistently strong positive anomalies of the order of +6°C exist in the region of about 15°S to 25°S over the austral summer/autumn period between February and May. The maximum southward extension of anomalously warm water occurred between the end of February and the beginning of March; this is in agreement with the findings of Gammelsrød *et al.*, (1998) who documented a maximum southward extension on the 3 March.

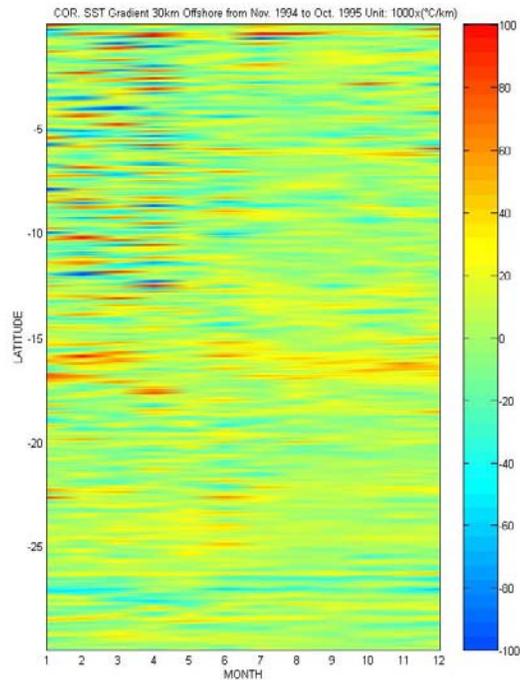
Although the major warm intrusion retreats quite suddenly between mid-March and May, extreme warm anomalies persist south of the frontal zone until at least mid-to-late- May and north of the frontal zone until mid-June. From Figure 4.4.6(a) a slight hiatus is evident in the retreat of warm water between May and July resulting in a small 'pool' of unusually warm water restricted to the region of the frontal zone (see Figure 4.4.6(b)).

Because 1995 event was shorter-lived and ended earlier than the 1984 event, the upwelling signal in the winter of 1995 appears to be less affected by the extreme warming that preceded it. A noteworthy similarity between the Benguela Niño's of 1984 and 1995 is the significant positive anomaly that is present (Figures 4.4.5(b) and 4.4.6(b)) within the frontal zone leading up to each major intrusion of warm water.

The gradient of the sea surface temperatures for the period November 1994 to December 1995 (Figure 4.4.7) is uniformly strong in the region of 15.5°S and 17°S, except during the warm anomaly when SST gradients are distinctly weaker in the frontal zone. However, coincident with the advent of the major warm anomaly in February, present as a marked 'pool' of warm water in the frontal zone (Figure 4.4.6(b)), exists a region of strong SST gradients that extends to about 25°S.

A plot of the SSTAs 250km offshore for the same period (not shown) shows that 250km offshore the 'pool' of extreme positive anomalies coincided with the warm anomaly inshore and was as intense, but existed only between about 12.5°S and 22.5°S. Offshore the front is more diffuse, but remains evident as a zone of consistently higher SST gradients. There is evidence of a

southward excursion of the front from February to May to about 26.5°S, where an area of relatively steep SST gradients is present.



**Figure 4.4.7.** A Hoffmüller plot of the gradient of SSTs, 30km offshore from November 1994 to October 1995.

### Minor Warm Events

Although only two warm anomalies during the period of study have been categorized as Benguela Niño's, several other warm anomalies have occurred and, though not extreme events, they are nevertheless worthy of a brief discussion. From Figure 4.4.1 it is clear that distinct and rather isolated warm anomalies occurred in 1986, 1988 and 1991. Apart from the major cool event in 1997, a warm anomaly appears to have persisted in the region of the frontal zone since the Benguela Niño of 1995 (this is in agreement with the findings of Florenchie *et al.*, 2002).

From a Hoffmüller plot of the SSTAs from November 1987 to October 1988 (not shown) it can be seen that the peak of the major positive SST anomaly in 1988 occurred in May and was most pronounced north of, and including, the frontal zone. Prior to this however, unusual warming is evident south of the frontal zone between January and April but seems to be an

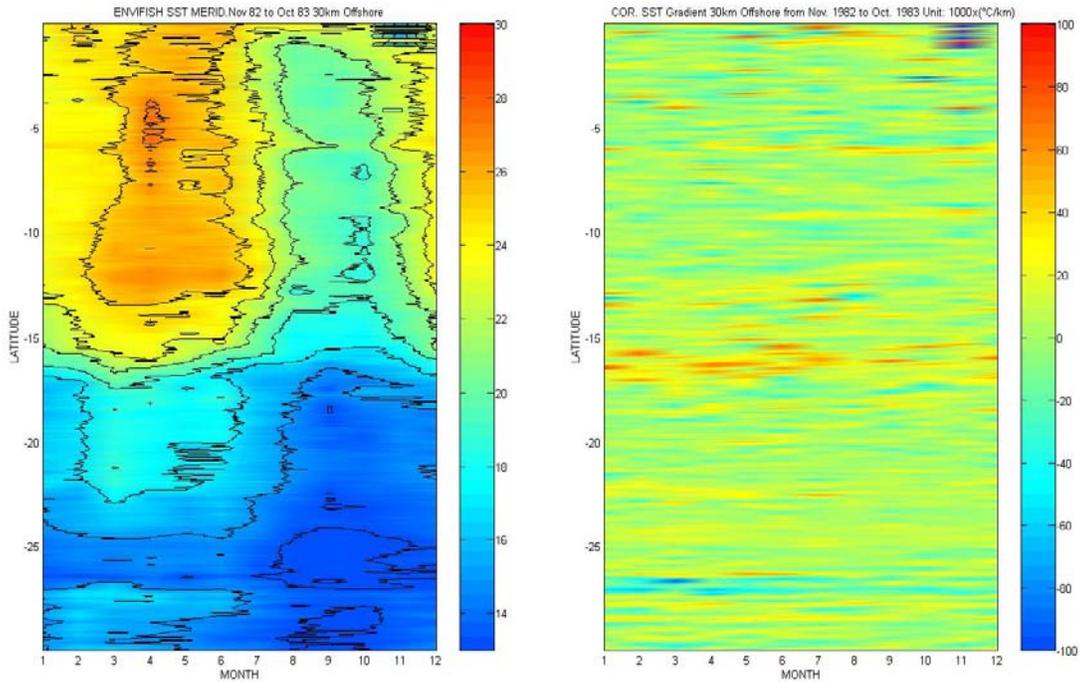
isolated event as the anomaly does not extend north of the frontal zone. The implication of this is that the forcing mechanism of the first warm anomaly is likely to be locally driven, while the latter, more intense anomaly is probably forced by a similar mechanism to Benguela Niño events, but slightly later in the year. The fact that the warm event of 1988 was probably forced by the same remote mechanism as that drives Niño events, but at a later in the year has been shown by Carton and Huang (1994). Because the warm anomaly appeared later in the year, its southward flow is likely to have been inhibited by the northward intrusion of the upwelling regime. From a Hoffmüller plot of the SST gradients for this period (not shown), the mean position of the ABFZ during the 1988 warm event seems to have remained relatively stable at between about 15°S and 17.5°S. The temperature gradients at the frontal zone were most intense and narrow in austral spring and summer and, during winter and particularly at the time of the warm anomaly, the gradients were less intense but the front moved slightly southwards and widened from about 16°S to 18.5°S.

The anomalously warm periods that seem to have persisted throughout the mid- to-late 90's, save the 1997 cold event, are all relatively intense but none seem to have significantly affected the ABFZ. The SSTAs for each of the warm events during this period show that in each case the region of greatest positive anomaly exists north of the ABFZ and peaks later in the year and for a shorter period of time than the Niño events. From a plot of SST gradients for the duration of the 1998 and 1999 events (not shown), it can be seen that SST gradients in the region of the frontal zone in 1998 and 1999 were more intense than usual, but did not extend abnormally far south. Although the extended period of unusual warming in the 90's is reasonably extreme, none of the events since the major anomaly of 1995 evolved into a Benguela Niño event. Florenchie *et al.*, (2002) speculated that this might be a result of the fact that they did not occur in phase with the seasonal southward advance of the Angolan Current as is the case for both the 1984 and 1995 major warm events.

### 1982/83 Cool Event

The cool event that persisted from 1981 to 1983 has been documented by several authors including Walker (1987) who, using principle component analysis (PCA) identified the maximum southward expression of the cool anomaly to exist at about 26°S. He also found that the cool anomaly did not extend offshore, but that the SSTs offshore were in fact higher than normal. The fact that the cool anomaly seems to have been confined to the region of upwelling brought Gillooly and Walker (1984) to the conclusion that it was the result of an abnormal eastward protrusion of warm surface water. Also using PCA, Walker (1987) was able to conclude that the cool anomaly was not related to the intense equatorward winds, but rather to more local tropical atmospheric forcing. At the time of the of cool event of 1981 to 1983 a warm event occurred on the South African West coast in 1982/83 as reported by Walker *et al.* (1984). Gillooly and Walker (1984) linked the warm event on the South African West coast between 1982 and 1982 to the unusually far northerly position of the Subtropical Convergence (STC) and the South Atlantic High.

Figure 4.4.8(a) shows the SSTs 30km offshore from the equator to 30°S for the period from November 1982 to October 1983. From a comparison with the climatology of SSTs (Figure 4.4.1) it is evident that the southern migration of the Angolan Current is inhibited by unusually cold SSTs near the southern boundary of the frontal zone (17.5°S). Furthermore, the warm water moving southwards is about 2°C cooler than usual. The major cold event of 1982/83 therefore seems to be a consequence of a combination of cooler water intruding from the north and an unusual upwelling event from December to April between 17°S and 23°S. The fact that the anomalous cool region at and south of the southern boundary of the frontal zone is indeed an area of upwelling can be confirmed by a transect of SSTs 250km offshore (not shown) that shows that the cool anomaly does not persist offshore and is therefore likely to be a result of intense upwelling at the coast. 250km offshore the water to the north of the frontal zone remains cooler than usual, supporting the assumption that, like the Benguela Niño's, its forcing mechanism is more remote and possibly originates at the equator as a southward propagating Kelvin wave (Florenchie *et al.*, 2002).



**Figure 4.4.8(a) (left).** A plot of the SSTs 30km offshore from November 1982 to October 1983. **Figure 4.4.8(b) (right)** A plot of the corresponding gradients of SST's.

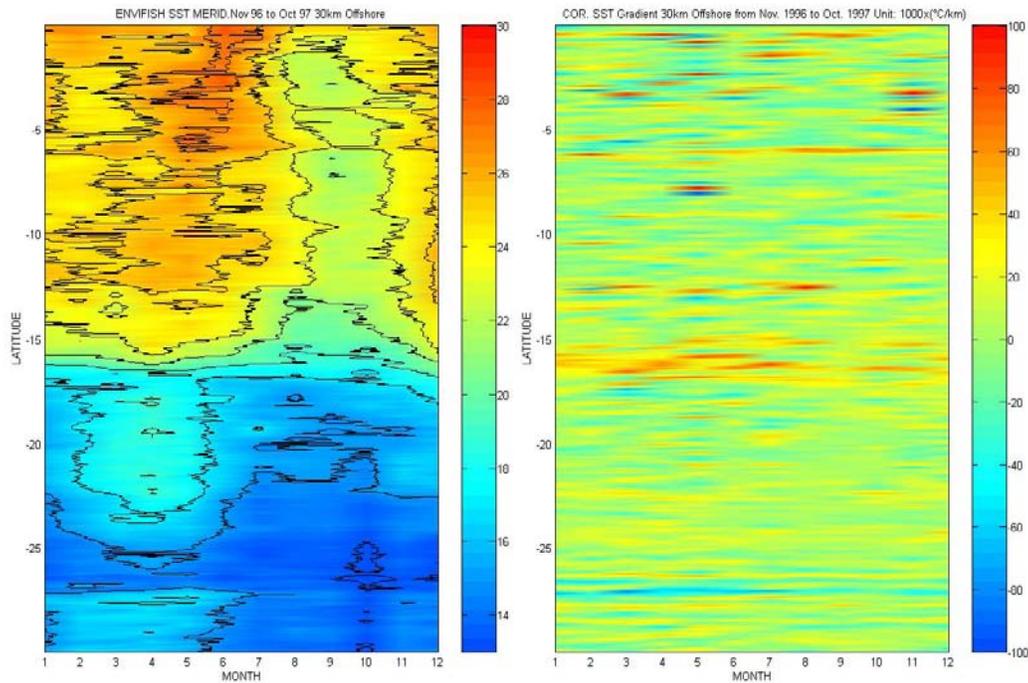
Figure 4.4.8(b) is a plot of the SST gradients and shows that the region of consistently steep SST gradients that characterizes the frontal zone is relatively distinct between November 1982 and October 1983. Despite the major cold event, the position of the front in general seems to have remained quite stable between about 15.5°S and 17°S. However, the cold anomaly seems to have induced consistently steep SST gradients in a fairly broad region indicative of the ABFZ for the duration of the cool event. Coincident with the northward retreat of warm water and the advent of the usual upwelling event in June, the SST gradients in the ABFZ weaken and the front becomes narrower.

### 1997 Cool Event

The cool event of 1997, also documented by Florenchie *et al.* (2002), is comparable in magnitude to the cool event in 1982/83 and is significant as it occurred during an extended period of warm anomalies.

Figure 4.4.9(a) shows that the 1997 event was similar to the cold event of 1982/83 whereby unusual cooling in the region of about 15.5°S and 23°S between December and April hindered the seasonal migration of warm water. From plots of SSTA's 250km offshore (not shown) it can be noted that this unusual cooling south of the frontal zone is not present offshore, implying that the cause of the anomaly is a result of local winds that induce upwelling near the coast. Once again, like the 1982/83 event, the water intruding into the frontal zone from the north is slightly cooler than usual and does not penetrate as far south as it normally would. The seasonal retreat of the Angolan Current occurred slightly later in the year than during the 1982/83 event and overlapped the usual seasonal upwelling regime by about a month. The major cool anomaly of 1997 therefore seems to be combination of the unusual upwelling event between December and April and the unusually cool water intruding from the north.

Figure 4.4.9(b) shows that throughout the duration of the cold event, the position of the frontal zone remains relatively stable and distinct and is situated between 15°S and 17.5°S. The gradients of SST are particularly steep from mid-December and mid- June and the frontal zone is widest between mid-February and mid-June. The steep gradients in the frontal zone match the duration of the unusual upwelling event in summer/ autumn and the overlapping period of the northward advancing upwelling regime and the retreating Angola Current. During winter (mid- July) when the normal seasonal upwelling regime is at its peak and the warm water from the north is at its most northerly position, the frontal zone is characterized by much weaker temperature gradients.



**Figure 4.4.9(a) (left).** A plot of the SSTs 30km offshore from November 1996 to October 1997. **Figure 4.4.9(b) (right)** A plot of the corresponding gradients of SST's.

## **5. DISCUSSION**

### **The Angola-Benguela Frontal Zone**

The ABFZ, identified as a zone of consistently steep horizontal surface temperature gradients, is a permanent feature and is situated between 15.5°S and 17°S. During spring and summer the frontal zone is particularly distinct and is characterized by steep temperature gradients of the order of 1°C per 17km, in winter however temperature gradients in the frontal zone become weaker and are in the range of about 1°C per 20- 30 km. The ABFZ is narrowest in summer (15.5°S- 17°S) and widest in winter (15.5°S- 17°S) when the mid-front position moves northwards a distance of about 28km.

Despite obvious seasonal fluctuations in the frontal zone, shown in Figure 4.2.4, its position remains remarkably stable throughout the year. This is somewhat surprising as the seasonal cycle of this region and the south-east Atlantic in general is known to be the dominant mode of variability (Picaut, 2001 and Ruiz-Barradas, 2000) and one would presume that such a strong seasonal would affect the position of the ABFZ. Shannon *et al.* (1987) offered

an explanation as to why this is not in fact the case. They concluded that the mechanisms that maintain the consistency of the location of the frontal zone are persistent and include factors such as coastline orientation, bathymetry, stratification and wind stress. Between 15°S and 19°S the coastline changes orientation in two places, which imparts obvious consequences for upwelling. The bathymetry is affected by the following changes: the width of the shelf and the steepness and direction of the continental slope change markedly between 15°S and 20°S. North of 16°S, stratification is strong throughout the year but in the region of the ABFZ a distinct change in stratification occurs. Furthermore, they found that north of the frontal zone, wind speeds are relatively low throughout the year, but at about 18°S strong upwelling-favourable winds are consistent, resulting in a significant gradient of upwelling- favourable winds in the region of the frontal zone.

Although the position of the front is largely unaffected by seasonality, the temperature range across it changes considerably in response to the seasons. The average temperature in the frontal zone in summer is about 22°C and in winter it is 19°C. The temperature range across the frontal zone also varies significantly with the seasons and in summer it is about 4°C and in winter it is about 2°C. This agrees with the fact that the temperature gradient across the ABFZ is steeper in summer than in winter.

Except for its expression 250km offshore, the seaward extent of the frontal zone has not been studied in detail, but certain conclusions can nevertheless be drawn. From analysis of the 250km offshore transect and visual analysis of images of the mean monthly SSTs for the region from 2°W to 20°E and from the equator to 30°S (such as the images shown in Figure 5.1) frontal characteristics such as orientation and offshore extent have been investigated. The distinct frontal zone associated with summer months extends to between 250km and 300km offshore and has a roughly southwesterly seaward orientation. The plot of SST gradients 250km offshore (Figure 4.3.3) validates the fact that the frontal zone has persisted at least as far as that throughout the period of study in spite of it being more diffuse, situated between 12°S and 16°S, than its manifestation closer inshore.

During winter months, the frontal zone in general is less intense, but it tends to extend much further offshore and there are signs of it reaching

distances of up to 1000km offshore within the period of study. The frontal orientation in winter is westerly to north-westerly.

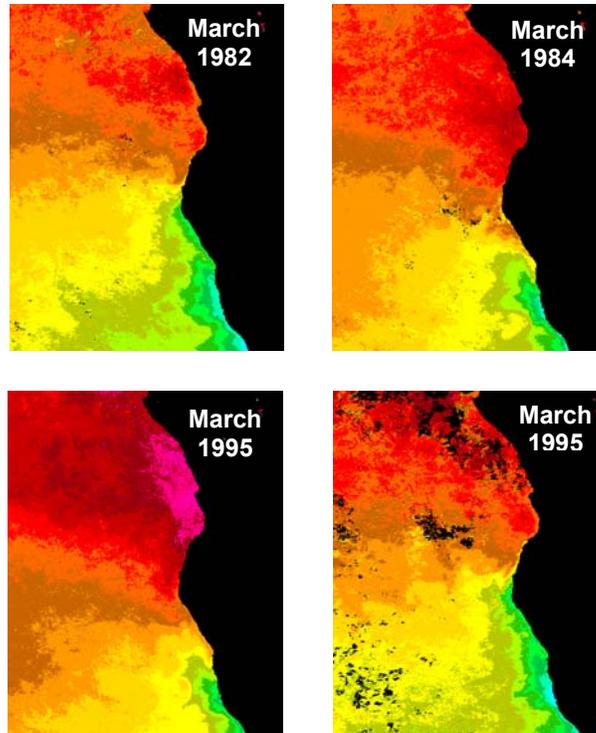
### Anomalies

The two Benguela Niño's that occurred during the period of study, namely the 1984 and 1995 events, reached their maximum intensity in March/April and both seemed to be associated with above average rainfall in south-western Africa (Shannon *et al.*, (1986) and Gammelsrød *et al.*, (1998)) also, both were met with extreme consequence, some devastating, to the fishing industries off Angola and Namibia (Shannon *et al.*, (1990) and Gammelsrød *et al.*, (1998)). It has been postulated by Florenchie *et al.*, (2002) that when a warm anomaly coincides with the high rainfall season in northern Namibia and southern Angola (March/ April), it results in an extreme warm event. For this reason, though at least 3 other significant warm anomalies are evident during the period of study (1988, 1991 and 1998/99), none evolved into extreme events as their peak disturbance occurred later in the year.

Though equally extreme, the major warm events have quite different surface thermal characteristics. A time series of the detrended mean SSTA (Figure 4.4.2) shows that the 1984 Benguela Niño lasted for longer than the 1995 event with higher than normal SSTs persisting until spring of 1984. The 1995 event resulted in a slightly more extreme departure from 'normal' SSTs, but did not persist for as long. The maximum southward extent of both warm anomalies was in March and was observed at about 24°S in 1984 and about 25°S in 1995. Figure 5.1 shows the maximum extent of each major event (warm and cool) and supports the fact that the maximum disturbance of the 1995 event was characterized by higher temperatures and a further southward extent. From the transect of SSTAs 250km offshore (Figure 4.4.3) it is evident that both the 1984 and 1985 warm anomalies extend to at least 250km offshore, but are not as intense.

The fact that the 1984 Benguela Niño was preceded by an extended period of rigorous upwelling has been documented as a major cool anomaly by, among others, Taunton-Clark (1988) and Shannon (1986). Like this cool anomaly, the 1997 major cool anomaly also precedes an abnormally warm year. Both of the major cool anomalies occurred between December and

April. It seems plausible that the major cool anomalies would result in accordingly dry rainfall seasons in south-western Africa. This is substantiated by Taunton-Clark and Shannon (1988) who, through personal communication with G. Schultze of the South African Weather Bureau, found that southern Africa experienced its most severe drought in at least 80 years during the summer of 1982/83.



**Figure 5.1.** ‘Snapshots’ of the SSTs in the south- east Atlantic at the maximum extent of the major warm and cool anomalies. Shades of red correspond to highest temperatures, while shades of blue and green are lowest temperatures. The black gaps represent regions where cloud cover made data acquisition impossible.

The 1997 cool event was a very marked cool anomaly due, in part, to the fact that it occurred during an extended period of warming. On the other hand, the 1982 event appears to be the tail end of a less intense but more persistent event (this relates to the cool event between 1981 and 1983 documented by Walker (1987)). A transect of SSTAs 250km offshore (Figure 4.4.3) shows that the cool anomalies do not appear to extend as far offshore as that. Figure 5.1 shows the 1982 and 1997 cool events at their maximum intensity and from

these images it is clear that the surface thermal characteristics of each event are quite similar. The unusually intense upwelling event south of the frontal zone is evident in the SST images of 1982 and 1997 in Figure 5.1.

#### Response of ABFZ to warm and cool anomalies

The major intrusion of warm water in 1984 resulted in a southward excursion of the frontal zone to 21.5°S and a weakening of the SST gradients in the frontal zone. The southward displacement of the frontal zone is exactly coincident with the warm anomaly and reaches its most southerly position at the beginning of March and retreats in April. By winter the front returns to its usual position, but has stronger SST gradients than normal. Similarly, 250km offshore there is evidence of the frontal zone having displaced southwards, but the excursion does not last as long and occurs a month later than the southerly excursion 30km offshore. The warm event of 1995 also displaced the position of the front for the duration of the warm anomaly and induced stronger temperature gradients across the frontal zone in winter. The 1995 Benguela Niño displaced the front to a position of 26.5°S, but for a correspondingly shorter period than its southward displacement during the more persistent intrusion of warm water during 1984.

The minor warm anomalies of 1988 and 1991 resulted in an intensification of the frontal zone whereby the temperature gradients strengthened and the frontal zone widened slightly. Again, coincident with the retreat of the warm water the temperature gradients in the frontal zone weakened. The warm anomaly that is observed to have persisted during the late- 90's did not affect the position or width of the frontal zone, but induced elevated temperature gradients across the frontal zone.

The disparity between the affect of the warm events on the frontal zone is likely to be the result of a combination of factors including the severity of the anomaly, time of occurrence and the interplay of remote and local forcing mechanisms.

Both of the major cool anomalies of the study period, namely the 1982 and 1997 events do not seem to have affected the position of the ABFZ, other than to have induced slightly elevated temperature gradients within the frontal zone at the time of the cool anomalies. The fact that the major cool

anomalies did not have a very extreme effect on the frontal zone implies that it is the anomalously southward extent of the warm Angolan water during summer months that plays the dominant role in altering the surface thermal characteristics of the frontal zone.

## **6. SUMMARY OF RESULTS AND CONCLUDING REMARKS**

- The ABFZ is a region of consistently strong surface temperature gradients and is a permanent feature whose width fluctuates seasonally. 30km offshore it exists between 15°S and 17°S in summer and between 15°S and 17°S in winter.
- SST gradients of 1°C per 60km are typical in the frontal zone in summer and gradients of 1°C per 125km are common in winter.
- The temperature range across the frontal zone ranges from 4°C in summer to 2°C in winter with average temperatures within the frontal zone of 22°C and 19°C respectively.
- The frontal zone is narrowest in with most intense SST gradients near the coast. It extends to at least 250km offshore, but is more diffuse, existing over a wider region (between 12°S and 16°S) with weaker SST gradients.
- The mid-frontal position moves northwards by only about 30km in winter.
- It moves southwards in response to major intrusions of the warm Angola Current (Benguela Niños) but does not seem to be significantly affected by major cool anomalies.

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 response 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. Though the causal mechanism for the major warm event were not within the

scope of this report, the inclusion of equatorial wind-stress data and sea-level data would provide a clearer picture of the sequence of events that lead up to Benguela Niños and the ensuing effect on the frontal zone.

### **ACKNOWLEDGEMENTS**

I am grateful to my supervisors, Professor Frank Shillington and Doctor Pierre Florenchie for their invaluable advice and much-needed encouragement. An especially big thank you to Dr. Florenchie for his huge amount of help with Matlab programming, and for going through my first-draft with a fine-toothed comb.

### **REFERENCES**

1. Boyd, A. J. and Agenbag, J. J. 1984: Seasonal Temperature and Salinity Trends off Central Namibia between 1978 and 1983 with Particular Reference to the Cool Winter of 1982. *S. Afr. J. Sci.*, **80**, 77-79.
2. Carton, J. A. and Huang, B., 1994: Warm Events in the Tropical Atlantic. *J. Phys. Oceano.*, **24**, 888-903.
3. Crawford, R. J. M. and Shannon, L. V., 1988: Long term changes in the distribution of fish catches in the Benguela. In *Long Term Changes in Marine Fish Populations*. Wyatt, T and M. G. Larrañeta (Eds). Vigo; Instituto de Investigaciones Marinas de Vigo: 449-480 (Proceedings of a symposium held in Vigo, November 1986).
4. Citeau, J., Guillot, B., Lae, R. and Therpenier, M. 1984: Warm and Cold Oceanic Events in the Tropical Atlantic and their relationship with the Intertropical Convergence Zone. *Tropical Ocean-Atmos. Newsletter*, **23**, 19-20.

5. Florenchie, P., Reason, C., Lutjeharms, J.R.E and Musson, S. 2002: Warm and Cold Events in the SE Atlantic (submitted to *J. Geophys. Res.*)
6. Gammelsrød, T., Bartholomae, C. H., Boyer, D. C., Filipe, V. L. L. and O'Toole, M. J. 1998: Intrusion of Warm Surface Water along the Angolan-Namibian Coast in February 1995: The 1995 Benguela Niño. *S. Afr. J. mar. Sci.*, **19**, 41-56.
7. Gillooly, J. F. and Walker, N. D. 1984: Spatial and Temporal Behaviour of Sea-surface Temperatures in the South Atlantic. *S. Afr. J. Sci.*, **80**, 97-100.
8. Hisard, P. 1980: Observation de réponse de type 'El Niño' dans l'Atlantique tropical oriental- Golf de Guinée. *Ocean. Acta.*, **3**, 69-78.
9. Jury, M. R. and Courtney, S. 1995: Climatic Determinants of Benguela SST Variability. *Cont. Shelf. Res.*, **15**, 1 339- 1354.
10. Kostianoy, A. G., 1996: Use of satellite data for the analysis of the fronts of the S.E. Atlantic (with as example the Angola- Benguela Frontal Zone) (In Russian), *Issled. Zemli Kosmosa*, **4**, 77- 86.
11. Kostianoy, A. G. and Lutjeharms, J. R. E. 1999: Atmospheric Effects in the Angola-Benguela Frontal Zone. *J. Geophys. Res.*, **104(9)**, 20 963-20 970.
12. Kuderskiy, S.K. and Strogalev, V.D. 1973: The Angola Current in the tropical zone of the S.E. Atlantic Ocean (In Russian), *Tr. Atl. Nauchno-Issled. Inst. Ryb. Khoz. Okeanogr.*, **51**, 5-13.

13. LeClus, F., 1985: Effects of a warm water intrusion on the anchovy fishery in Namibia. *Colln scient. Pap. Int. Commn SE. Atl. Fish.* **12**(1):99-106.
14. McLain, D.R., Brainard, R.E. and Norton, J.G. 1985: Anomalous Warm Events in Eastern Boundary Current Systems. *Rep. Calif. Coop. oceanic Fish. Invest.* **26**: 51-64.
15. Meeuwis, J. M. and Lutjeharms, J. R. E. 1990: Surface Thermal Characteristics of the Angola-Benguela Front. *S. Afr. J. Sci.*, **9**, 261-279.
16. Merle, J. 1980: Variabilité thermique anuelle et interanuelle de l'Océan Atlantique équatorial Est. L'hypothèse dun 'El Niño' Atlantique. *Ocean Acta*, **3**, 209-220.
17. Mohrholz, V., Schmidt, M. and Lutjeharms, J. R. E. 2001: The Hydrography and Dynamics of the Angola-Benguela Frontal Zone and Environment in April 1999. *S. Afr. J. Sci.*, **97**, 199-208.
18. Picaut, J. 1985: Major Dynamics Affecting the Eastern Tropical Atlantic and Pacific Oceans. *CalCOFI Rep.*, **26**, 41-49.
19. Picaut, J. 2001: Chapter 4: Tropical Ocean Variability. *Satellite Altimetry and Earth Sciences* (Academic Press), 217-233.
20. Ruiz-Barradas, A., Carton, J. A. and Nigam, S. 2000: Structure of Interannual-to-Decadal Climate Variability in the Tropical Atlantic Sector. *J. Climate*, **13**, 3 285-3 296.
21. Servain, J., Legler D., Picaut, J., Verbeque, V. and Seva, M. 1985: Oceanic Variability and Wind Stress Forcing in the Tropical Atlantic Ocean. *IAMAP/IAPSO Joint Assembly, 5-16 August 1985, Honolulu, HI, Paper 06-16.*

22. Shannon, L. V., Boyd, A. J., Brundrit, G. B. and Taunton-Clark, J. 1986: On the existence of an El Niño-type Phenomenon in the Benguela System. *J. mar. Res.*, **44**, 495- 520.
23. Shannon, L. V., Agenbag, J. J. and Buys, M. E. L. 1987: Large- and Mesoscale Features of the Angola-Benguela Front. *S. Afr. J. mar. Sci.*, **5**, 11-34.
24. Shannon, L. V. and Agenbag, J. J. 1990: A Large-Scale Perspective on Interannual Variability in the Environment in the South-East Atlantic. *S. Afr. J. mar. Sci.*, **9**, 161-168.
25. Taunton-Clark, J. and Shannon, L.V. 1988: Annual and Interannual Variability in the South-East Atlantic during the 20<sup>th</sup> Century. *S. Afr. J. mar. Sci.*, **6**, 97- 106.
26. Walker, N. D., Taunton-Clark, J. and Pugh, J. 1984: Sea Temperatures off the South African West Coast as Indicators of Benguela Warm Events. *S. Afr. J. Sci.*, **80**, 72-77.
27. Walker, N. D. 1987: Interannual Sea Surface Temperature Variability and Associated Atmospheric Forcing within the Benguela System. *S. Afr. J. mar. Sci.*, **5**, 121-132.