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OXYGEN AND CHLOROPHYLL DISTRIBUTION IN THE EASTERN ATLANTIC OCEAN FROM 0º TO 35ºS.

Mª DEL PILAR APARICIO RIZZO

Memoria presentada para la obtención del Diploma de estudios Avanzados

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TABLE OF CONTENTS

ABSTRACT

In the frame of CARBOOCEAN project the QUIMA-VOS line is monthly monitoring the eastern South Atlantic Ocean, measuring surface temperature, salinity, oxygen and chlorophyll *a*. In this work the annual pattern of oxygen, chlorophyll *a*, temperature and salinity are presented for seven different regions which from Equator to south: Equatorial Divergence Zone (0º-5ºS), Congo-Angola region (5º-10ºS), Angola Gyre region (10º-14ºS) and Northern Namibian region (14º-20ºS) all of them inside the Eastern Tropical Atlantic Province (ETRA). Central Namibian region between 20º-24ºS inside South Atlantic Gyral Province (SALT), Lüderitz region (24º-28ºS) and Southern Benguela region at 28º-33ºS inside the Benguela Current Coastal Province (BENG). An inverse correlation between the temperature and the oxygen is observed related to its effect on the solubility of the gas. The role and influences of the different oceanographic structures on the oxygen and chlorophyll *a* measurements is described considering the Angola Gyre, the Angola-Benguela Front, the Benguela Current system (oceanic and coastal) and the Benguela Upwelling system. The relationship between the parameters and the oceanographic structures divides the Southeast Atlantic in two big areas separated by the Angola Benguela Frontal Zone.

INTRODUCTION

The QUIMA-VOS line (Volunteer Observing Ship), as part of CARBOOCEAN Project, monthly connects Felixstowe (UK) and Cape Town (South Africa) stopping once per trip in Las Palmas harbour. The VOS line goes across three provinces of the South Eastern Atlantic Ocean: ETRA (Eastern tropical Atlantic province), SALT (South Atlantic Gyral province) and BENG (Benguela Current Coastal province) extending from 0-33ºS and 10ºW-18ºE. These provinces have been defined by Longhurst A. (1998) based in the differences in parameters as salinity, sea surface temperature, oxygen and chlorophyll (Fig. 1).

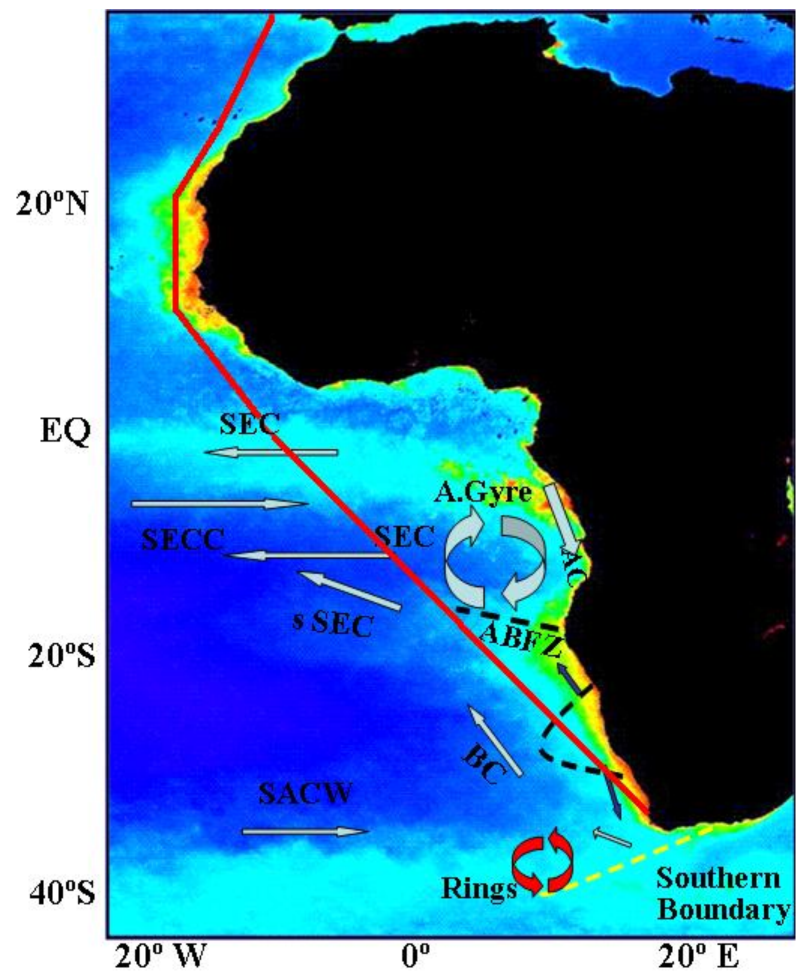


Fig. 1. Africa physical map.

The Equatorial Upwelling System is stronger coinciding with the cyclonic eddy located in Guinea Basin (~1-1.5ºS) during Winter season. A different feature in this area is observed in Summer when an offshore transport of upwelled water takes place at ~11ºS due to the presence of the Angola Dome and the upwelled water coming from Benguela Current by the Subtropical Gyre circulation. (Fig. 2) (Fig. 3)

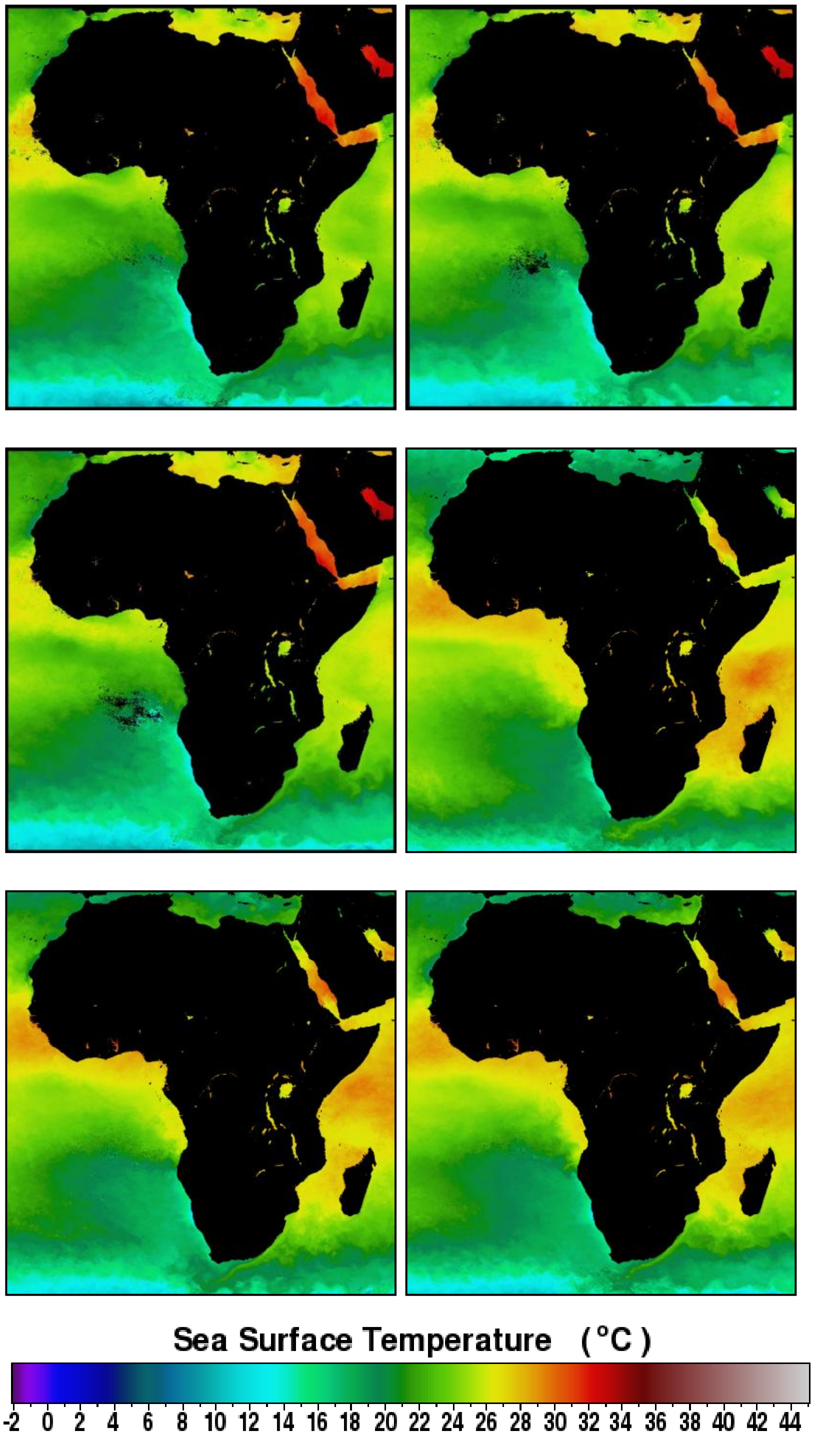


Fig. 2. Temperature profile during upwelling Winter season. a) August 2005, b) August 2006, c) August 2007, and Spring one d) December 2005, e) November 2006 and f) November 2007.

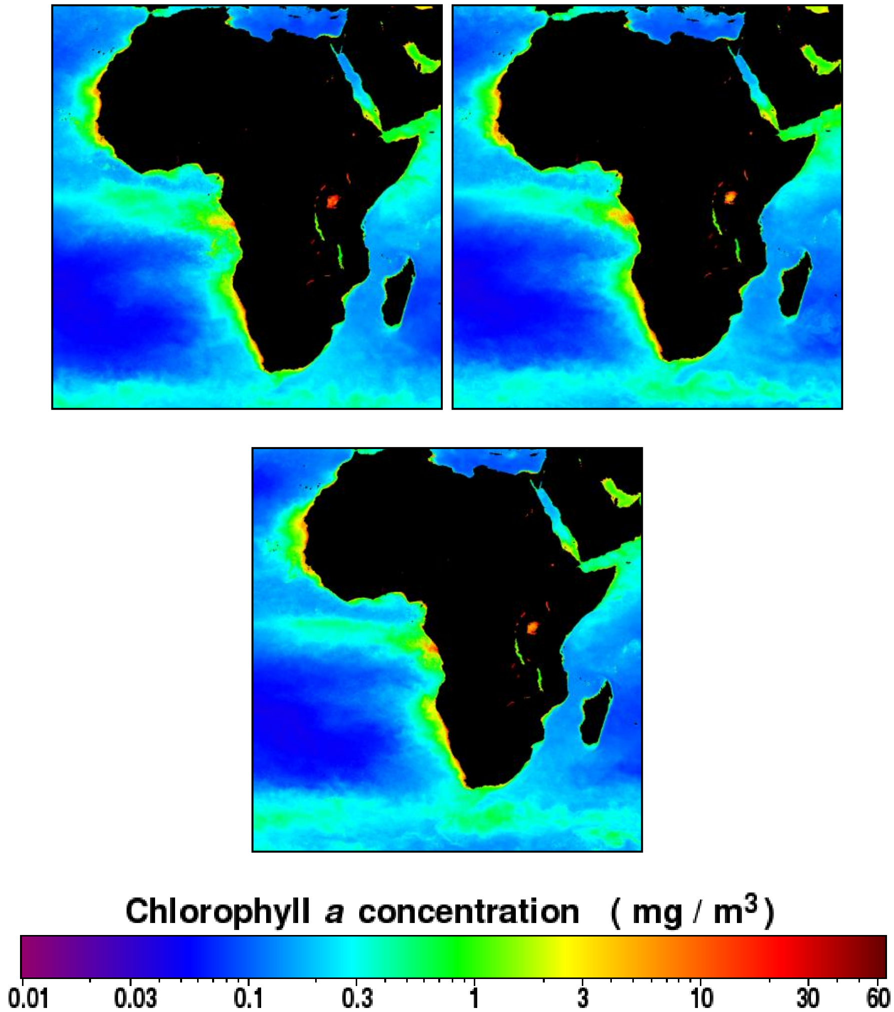


Fig. 3. Annual 2005, 2006 and 2007 Chl *a*.

The Angola Gyre (~12ºS), a cyclonic closed circulation pattern off Angola, is separated to the overall South Atlantic circulation. A special feature within the Angola Gyre is the Angola Dome (~10ºS-10ºE) whose position changes from year to year and which is seen to be linked to the uplift of the thermocline in the months from January to May while during austral Winter, it usually disappears. (Mohrholz et al., 2001; Mazeika P.A., 1967).

Angolan Gyre is characterized by the presence of the South Equatorial Countercurrent (SECC) on its northern slope and South Equatorial Current (SEC) and Benguela Current (BC) water on its southern slope. The SEC passes westwards across the ocean as two streams north and south of the weak SECC. The first one transport warm, low-salinity water from eastern Golf of Guinea, and the second one cooler and saltier from Benguela across a thermal front at about 10ºS in the west and 15ºS in the east at the Benguela divergence. (Mohrholz et al., 2001) (Fig. 1)

The Angola-Benguela Frontal Zone (ABFZ) (~15-17ºS) represents the convergence zone between the poleward surface flow of warm tropical surface water which is influence by inputs from the equatorial wave guide and the equatorward flow of cool Benguela water. Its position changes seasonality related with the strength of the South Atlantic Anticyclone (SAA) (Fig. 1)

The Benguela region is located between 16ºS to 33ºS, like another eastern boundary region is characterized by a coastal upwelling system, however it is bounded at both the equatorward and poleward ends by warm water. (Shannon et al., 1996; Shillington et al., 2006).

The major features depicted in temperature are the cooling associated with the presence of persistent upwelling cells (average SST lower than 16.7ºC) from Northern Namibia (~17ºS) to Cape Town (33º55') (Fig. 2) (Fig. 3). The wind field, topographic features (bathymetry and land features) and orientation of the coast result in the formation of a number of areas where upwelling is more intense. Nevertheless, as a general rule, the areas along the west coast of southern Africa where the southerly winds are consistently strongest are also the areas where upwelling is most pronounced. However coastal upwelling in Benguela is neither uniform in time or in space. (Shannon et al., 1999). Four major upwelling areas are observed:

- The Northern Namibia (Cape Frio ~17-19ºS) and the Central Namibia (~21-23ºS) with stronger events in Winter and sometimes in Spring, and where upwelled water could extend about 150km offshore. The mean temperature for the upwelled water is 19.5ºC at Cunene (~17ºS) and 18.5ºC in the Namibia cell. (Longhurst A., 1998).

- Lüderitz (~27ºS)-Walvis Bay (~23ºS) the most intense upwelling cell where strongest pseudo-wind stress and upwelling are seen nearly all year round near Lüderitz being greater in Summer and Spring, and whose filaments could reach 1000km offshore, separating northern and southern Benguela. (Longhurst A., 1998; Shillington et al., 2004).

- Namaqua (~29ºS) where maximum upwelling occurs during October-December (upwelling season) and minimum in May-July. The sign of this upwelling can be detected through cold filaments originating in this upwelling cell.

- The Cape Peninsula-Cape Columbine (~32.5-34.5ºS) where upwelling process is restricted to austral Summer trimester and may generate filaments that extends offshore.

A phenomenon associated with upwelling cells along the Benguela coast is the presence of shallow (50m) upwelling filaments that may extend several hundreds of kilometers from the coast into the South Atlantic Ocean. These are especially prevalent around the Lüderitz and Namaqua upwelling cells.

Wind plays an important role with a perennial favorable pattern to upwelling in Benguela region (Kamstra, 1985; Shannon et al., 1996). Seasonality in upwelling could be associated with seasonal trend of wind system. In the northern Benguela region cyclonic curl upwelling-favorable winds near Lüderitz and Cape Frio are persistent, while in the south the upwelling occurs mostly as a series of shorts pulses. The Intertropical convergence zone (ITCZ) changes position and its interaction with low pressure cells in the southeast Atlantic influence Trade Winds and the flow of the Benguela Current. The southern and northern trade winds are separated by calms at the atmospheric ITCZ which from November to April is stationary lying southwest across the ocean. The next three months ITCZ moves rapidly northward and southeast trade winds reflects it. (Longhurst A., 1998, Kamstra, 1985; Shannon et al., 1996). South of this area, between 30° to 35° south (also at 30° to 35° north) lies the region known as the horse latitudes or the subtropical high. This region of subsiding dry air and high pressure results in weak winds. (Longhurst A., 1998, Kamstra, 1985; Shannon et al., 1996)

Temperature shows a seasonal cycle pattern with higher ones during Summer-Autumn (January-May) and lower in Winter-Spring (July-December) (Hardman-Mountford et al., 2003; Verstraete, 1992). Temperature is influenced by the ABFZ position and Angola Dome presence as well as upwelling cells activity. During Autumn and Summer seasons a displacement of ABFZ southward can be observed fitting with Angola Current movement southward and westward and an increase of temperature in the region. Otherwise during Angola Dome presence, the temperature shows higher mean values in Angola Gyre region (10-14ºS) during Summer and the beginning of Autumn. However upwelling cells activity at Lüderitz (24-28ºS) and Southern Benguela region (28-33ºS) produces lower temperatures in the area.

The Salinity shows a high patchiness in its distribution, but with the highest value (~36.5) around 10-15ºS in the Angola Gyre region. This one can migrate affected by the ABFZ migration and Angola Dome presence, and also affected by the Subtropical Gyre Circulation. Its lowest value is located in the Southern Benguela (28-33ºS) where the presence of different water masses and wind stress can affect its distribution.

Although surface water temperature and salinity are not conservative parameters due to several physical and chemical aspects, several water masses can be identified in the region. The South Tropical Surface Water (STSW) and Tropical Surface Water (TSW) in the Equatorial Divergence Zone (EDZ) and Angola Gyre region, as well as Oceanic Surface Water (OSW) and South Atlantic Surface Water in the Southern regions have been identified (Shillington et al., 2004-2006).

The surface oxygen distribution presents a seasonal cycle with higher concentrations in Winter-Spring and lower in Summer-Autumn (Hardman-Mountford et al., 2003) being the temperature the principal process controlling the distribution and to be affected by the upwelling events. Nowadays Southeast Atlantic hardly ever has been studied especially out of sea, being all realized inshore. In the first 300m of the water column two minimum oxygen zones have been identified: the Equatorial minimum oxygen area where ventilated water is transported from Equator to South Atlantic Surface Water and the Angola Gyre, which represents the main oxygen minimum formation area. (Lass et al., 2007; Shannon et al., 1987). The surface oxygen concentration from Cape Frio (17ºS) and Walvis Bay (~23ºS) increases further south around Lüderitz cell (~27ºS) and north of Cape Town (~33ºS) (Longhurst A., 1998) (Shannon et al., 1996). There is also evidence that exist a slow southward advection of oxygen-deficient water throughout Benguela at least as far south as Cape Peninsula with lowest oxygen concentrations occurring during late

Summer/Autumn in the Southern Benguela. However, the oxygen-deficient water dynamics are not well understood.

A primary seasonal bloom in the Equatorial upwelling occurs in Winter in response to a seasonal strengthening of zonal winds, and a weaker secondary bloom in late Spring. Surface chlorophyll concentration in the whole Eastern South Atlantic Ocean shows an average values throughout the year of 0.8mg m^{-3}; although some satellite images suggest that an increase can be detected during Autumn and Winter (~2 mg m^{-3}). Otherwise, an important chlorophyll peak has been detected around ~5ºS (Fig. 3). This patch of chlorophyll could be found offshore extending almost halfway across the ocean. (Longhurst A., 1998; Velasca et al., 2005). Generally during upwelling episodes in Benguela area a clear nearly coastal band of maximum chlorophyll could be identified.

Objectives:

There is a lack of high resolution studies in surface waters properties in the South Atlantic Ocean. Most of the cruises carried out only cover short spatial and temporal resolution. The QUIMA-line allows us to monthly study the oxygen, temperature, salinity and chlorophyll variability along the ship line (Fig. 1) and to characterize the factors affecting such variability between 2005-2007. In this work we present the most important features observed for this period that will serve for future comparison.

METHODS

The data base has been obtained as part of the CARBOOCEAN project, through QUIMA-VOS (Volunteer Observing Ship) which monthly carries out the route along the Eastern Atlantic Ocean, from Felixstowe (UK) to Cape Town (South Africa) stopping once per trip in Las Palmas harbour. A total of 20 journeys (Table. 1) were carried out with three different ships from Summer 2005 to 2007 from the Mediterranean Shipping Company (MSC), where nowadays the equipment is in the MSC-Benedetta.

CRUISE	DATE	LATITUDE	LONGITUDE
MSC-Gina	21-31/08/05	33.3782º S-0.0097º S	17.7401º E-9.4797º W
MSC-Gina	20-24/09/05	0.9971º S- 25.864º S	10.0233º W- 11.2095º E
MSC-Gina	30/11-10/12/05	0.9961º S-30.0657º S	10.7074º W-31.0393º E
MSC-Gina	14-25/12/05	30.1241º S-0.979º N	31.0802º E-10.7085º W
MSC-Martina	08-26/03/06	0.9926º N-31.46º S	10.7554º W-15.7º E
MSC-Martina	11-19/05/06	30.1045º S-0.9984º N	31.0806º E-10.7618º W
MSC-Martina	01-06/08/06	0.997º N-33.7495º S	10.7673º W-18.1881º E
MSC-Martina	21-26/08/06	33.5739º S-0.995º N	17.8442º E-13.4705º W
MSC-Martina	19-27/09/06	0.918º N-34.1868º S	10.6951º W-25.51º E
MSC-Martina	13-21/10/06	33.6074º S-0.4929º N	18.0318º E-10.3589º W
MSC-Martina	22-27/11/06	0.9907º S-33.7915º S	10.1859º W-18.2192º E
MSC-Benedetta	12-19/01/07	0.9976º S-34.1385º S	10.2513º W-25.4918º E
MSC-Benedetta	24-01/02-02/07	30.3204º S-0.0067º S	30.9255º E-9.4802º W
MSC-Benedetta	28/02-08/03/07	0.9982º N-34.2743º S	10.2551º W-24.5668º E
MSC-Benedetta	13-27/03/07	33.9355º S-0.9886º N	26.2072º E-10.245º W
MSC-Benedetta	06-11/06/07	0.9895º N-31.0875º S	10.2446º W-15.6589º E
MSC-Benedetta	24-29/06/07	33.6112º S-2.0216º S	18.0413º E-7.9391º W
MSC-Benedetta	25-12/08/07	0.9981º N-34.0483º S	10.2563º W-18.2496º E
MSC-Benedetta	13-18/08/07	32.7254º S-0.9919º N	17.1136º E-10.2553º W
MSC-Benedetta	11-08-/09-10/07	0.0255º N-0.0097º S	9.509º W-9.4797º W

The hydrographic measurements were carried out with a Sea-bird 38 thermometer, with a 0.00025ºC maximum of resolution, allocated in the sea water intake pump (10m below the sea level) to process the sea-surface temperature (SST). Also a Seabird 21 thermosalinograph is used to obtain sea-surface salinity (SSS) and temperature (SST) (at the deck where the equipment was located). Accuracy's sensor temperature is a maximum temperature resolution of 0.0003ºC in thermosalinograph. The difference between the SST intake and the temperature measured with the thermosalinograph was around 0.05-0.1ºC. However they are influenced by the ship where the system is installed and by the distance between the Seabird 38 Thermometer and the thermosalinograph. Dissolved oxygen is analyzed by an Oxygen Optode 3835, where dissolved oxygen is corrected by equation (1) to convert values in fresh water (O_2^m) to Sea Surface Salinity (SSS). (Fig. 4)

$$O_2^{sss} = O_2^m \cdot EXP((S\cdot(-0.00624097 - 0.00693498 \cdot O_2 - 0.00690358 \cdot O_2^2 - 0.00429155 \cdot O_2^3) - 0.00000031168 \cdot S^2)) \quad (1)$$

Chlorophyll *a* data is obtained by a Turner Fluorometer 10-AU-005-CE, processed as fluorescence at 680nm and correct to chlorophyll *a* by equations (2) (before 2006) and (3) (after January 2007) determined by calibration with seawater extracted samples and with data from selected cruises:

$$\mathrm{Chla} = (\mathrm{F} - 0.025) \cdot 12.002 \quad (2)$$

$$\mathrm{Chla} = -0.196 \cdot \mathrm{F} + 2.0571 \cdot \mathrm{F}^2 \quad (3)$$

The accuracy of the dissolved oxygen and fluorometer reading devices have been carried out taking discrete samples and analyzing them by Winkler titration method (Table. 2) and fluorometric determination (data not shown), respectively. (Normative UNE-EN-25813) (Rutgers M.M. et al., 1999)

BOTELLA (gr.)	**OXYGEN (μmol l^{-1})**	**OXYGEN (μmol kg^{-1})**	**STADISTIC**
120.15	250.38	201.46	
117.31	250.07	201.21	**x=201.1221 σ =0.3810**
119.79	249.45	200.71	
116.71	252.48	203.14	
118.95	251.71	202.52	**x=202.8144 σ = 0.31503**
119.46	252.03	202.78	

Continuous underway measurements of surface temperature, salinity, oxygen and fluorescence were made during the cruise while data was recorded each three minutes using the software program system.

Meteorological parameters as wind speed were taken directly by the QuikSCAT wind data using a 6 hour 0.25º temporal and spatial resolution respectively, in longitude and latitude at 10m height as indicated by Boutin and Echeto (1995) and provided by LOCEAN, University Pierre et Marie Curie (http//www.locean-ipls.upmc.fr). The wind speed correlation coefficient ranges from 0.80-0.90 being the deviation of the QuikSCAT data from the buoys data around 3%. In fact, the wind data can be allocated at the same spatial and temporal resolution of the QUIMA-VOS line. A GPS has been used to know latitude and longitude whole time.

The whole system has been installed on board together with an autonomous pCO2 underway system developed by Craig Neills (University of Bergen) together with a meteorological station, including a barometer and a GPS system.

a) b)

Fig. 4. Instruments: a) Thermosalinograph (left) and Fluorometer (right), b) Optode sensor (down) and pCO2.

RESULTS

a) Water masses

1) Introduction

The Benguela Current Large Marine Ecosystem (BCLME), one of the four major eastern boundary current upwelling systems of the oceans, has some peculiars characteristics like to be bounded by two warm mass waters (tropical warm Angola Current system at the north and the Agulhas Current system at south), and has two major inputs of water: the equatorial Atlantic in the north and the South Atlantic/South Indian in the south. Otherwise, Benguela is separated from the Angola area by the ABFZ situated at ~15-17ºS playing an important role in the water masses moving northward or southward affecting Angola Current water displacement.

The large scale properties of the water masses in the surface layer are maintained by the equatorial surface water, diluted by excess of rainfall, upwelling water and river discharge, the saline Subtropical Surface Water off Angola, and the Benguela upwelling zone in the south which injects cold water from deeper layers with a lower salinity into the surface layer at the coast (Mohrholz et al., 2001; Lass et al., 2000). Generally, the upper layer can have a tropical influence with a high salinity and high temperature or an Antarctic or sub-Antarctic influence with a low salinity and low temperature (Duncombe Rae, 2004)

The main water masses above the thermocline could be identified using temperature and salinity data. Neither temperature nor salinity above thermocline are conservative parameters due to the heat action and the fresh water flux resulting in low salinity at the surface (Mohrholz et al., 2001), especially at Congo River (~6ºS) run-off, which could reach to shore off thousands of kilometers and also in the South of Benguela region where the run-off water of the Orange River (~29ºS) (ROW) and Oliphant (~32ºS) one, join to the intense rainfall, can be observed but with not so evidence and continuity on time like Congo River. (Duncombe Rae, 2004) However we used the water masses in the surface area even with these characteristics.

Four main water masses can be identified from the θ–S characteristics above the thermocline at Southeast Atlantic Ocean. The Subtropical Surface Water (STSW) it is located mainly at the northern area (~0-14ºS), characterized for its high salinity (35-36.5) and high surface temperature (15-23ºC) (Wyrtki, 1964; Shannon et al., 1999) and the Tropical Surface Water (TSW) with temperatures higher than 27ºC and high salinity ~36.5 (Table. 3)**.** Both water masses are distinguished in ETRA and SALT until Benguela province. The Subtropical Surface Water (STSW) is separated by the Angola-Benguela Frontal Zone (ABFZ), characterised by a relatively weak thermal gradient at ~15-17°S centred around the 18°C isotherm and salinity of 35.8. (Lass et al., 2000; Mohrholz et al., 2001)

FULL NAME	θ (ºC)	SALINITY	REFERENCES
Oceanic Surface Water (OSW)	16-22ºC	35.2-35.5	Mohrholz et al., 2001. Salat et al., 1992.
Subtropical Surface Water (STSW)	15-23ºC	35-36.5	Shannon et al., 1999. Wyrtki, 1964.
Tropical Surface Water (TSW)	<27ºC	~36.5	Mohrholz et al., 2001. Ducombe Rae,2004
South Atlantic Surface Water (SASW)	15.5-21.3ºC	35.3-35.7	Shannon L.V.,1985
Cool Upwelled Water (CUW)	12-18ºC	34.9-35.2	Salat et al., 1992

The Oceanic Surface Water (OSW) in the Benguela region is characterized by a temperature between 16-22ºC and salinity between 35.2-35.5 coming from the west to the coast in the Northern Namibia region between 19-22ºS mainly between Autumn and Summer (Salat et al., 1992; Mohrholz et al., 2001). Moreover, the South Atlantic Surface Water (SASW) (Table. 3) which is probably a mixture of Agulhas surface water coming from Retroflexion processes and South Atlantic Central Water (SACW) from south of Subtropical Front (STF) is also present with temperatures of 15.5-21.3ºC and salinity of 35.3-35.7.

Moreover, it should be considered the effects of the South Equatorial Current (SEC) moving westward (~0-20ºS) characterized by its low salinity and warm water and its southern branch (sSEC) situated at formation region (8-25ºS) where intense evaporation take place presenting higher salinity together with inclusions of the Benguela Current (BC) cold and salinity water (37-37.2). Moreover the South Equatorial Countercurrent (SECC) warm water and high surface salinity probably due to excess of evaporation moving eastward plays an important role in the Angola Gyre region at ~5ºS. (Lefèvre N., 2006)

2) Water masses data

The water masses have been identified in the following seven different regions: Equatorial Divergence Zone (EDZ) (0-5ºS), Congo-Angola (5-10ºS), Angola Gyre (10-14ºS), Northern Namibia (14-20ºS), Central Namibia (20-24ºS), Lüderitz (24-28ºS) and Southern Benguela (28-33ºS). This classification has been chosen to separate the complicate and different physical and chemical processes which characterized this area.

Furthermore the Angola Dome feature was considered inside Angola Gyre region during January-May (Summer-Autumn) when it is developed while in Winter months (July-

September) disappear. However during this time another dome (1.5ºS-8ºW) is detected. (Mazeika et al., 1967)

The different water masses with different distribution and behavior along regions have been identified using 2005 data. Along the Equatorial Divergence Zone (0-5ºS), STSW water is identified showing influence of SEC water on potential temperature (θ) data. Also it could be identified this one along Congo-Angola (5-10ºS) with the presence of SECC influence coming from Angola Gyre which drive it. In the Angola Gyre region (10-14ºS) STSW is the dominant water mass. The Northern Namibia region (14-20ºS) also shows the influence of the STSW.

The Central Namibia region (20-24ºS) is characterized by OSW during the year. In Lüderitz region (24-28ºS) OSW is the main water mass but in September, November and December during the strongest upwelling season, the Coastal Upwelled Water (CUW) and SASW can be detected. Finally Southern Benguela region is characterized by the presence of OSW influenced by CUW at the southern area where cruise is nearly coast and SASW, especially at November and December (upwelling season). (Fig. 5) (Fig. 6)(Fig. 7)

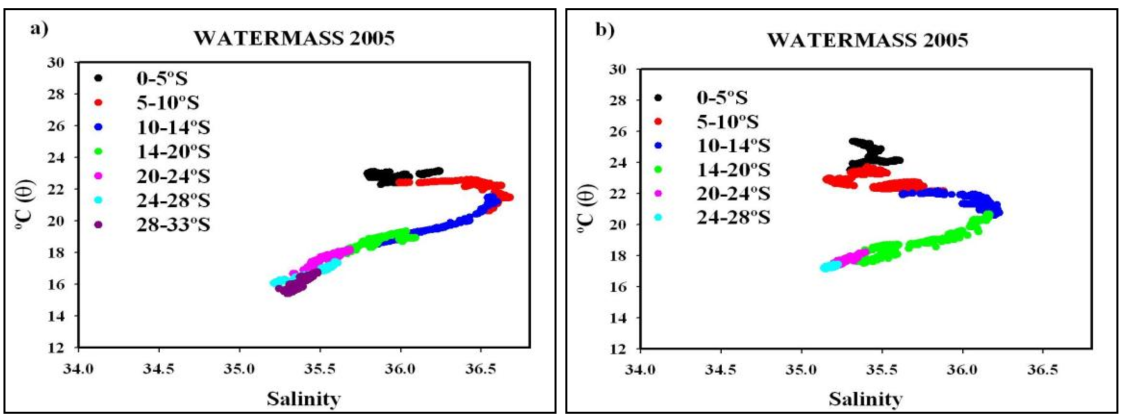


Fig. 6. Water masses during Winter season of 2005: a) August and b) September.

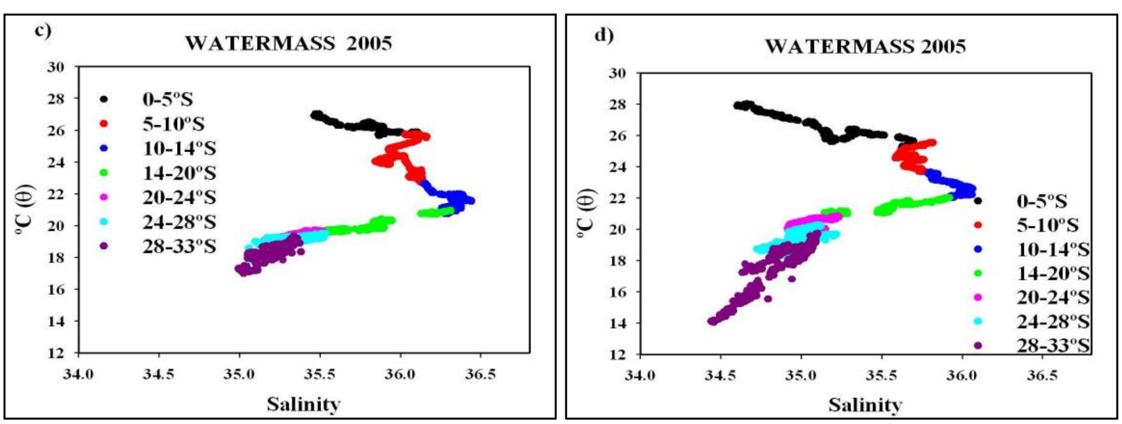


Fig. 7. Water masses during Spring season of 2005: c) November and d) December.

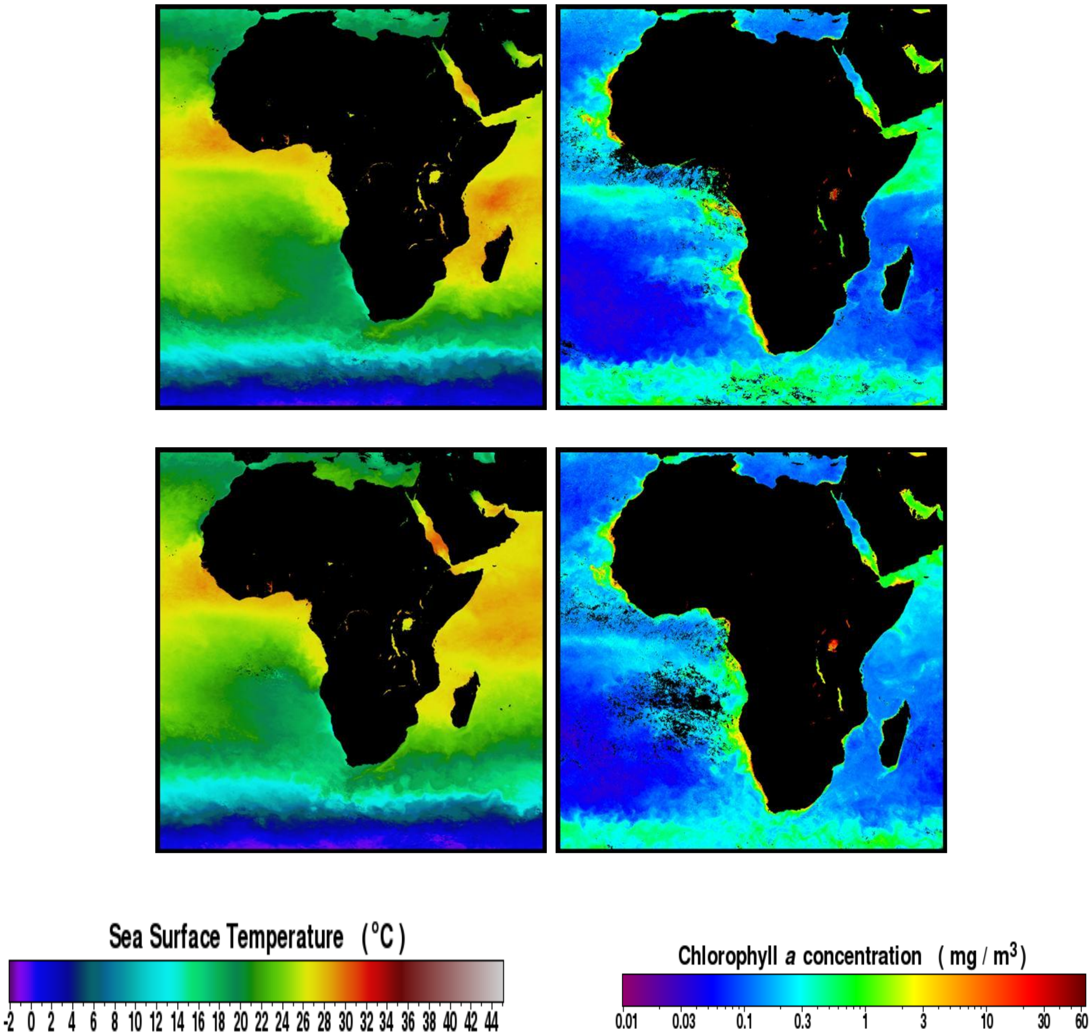


Fig. 5. Satellite Images of SST and Chl *a* of 2005: a) SST December (right/up), b) Chl *a* December (left/up), c) November SST (right/down) and d) Chl *a* November (left/down).

Through 2006 data STSW is presented along EDZ (0-5ºS) influenced by SEC. Moreover STSW has been identified along Congo-Angola region (5-10ºS) during the year but with SECC and TSW influence, especially in Summer months (March) when Angola Dome is more developed. Angola Gyre region (10-14ºS) shows STSW influence.

Along Northern Namibia region (14-20ºS) STSW can mainly be identified with OSW influence during November (Spring) in accordance with Mazeika et al. (1967). This water mass can also be identified in the Central Namibia region (20-24ºS) on August, October and November (Winter/Spring) with a clear influence of upwelling on potential temperature (θ) and salinity while March and May (Summer/Autumn) are distinguished by the presence of STSW. In the Lüderitz region (24-28ºS) March and May data (Summer/Autumn) show the influence of SASW and CUW, whereas August-November (Winter/Spring) show OSW with SASW during Winter months (August-September) and CUW in Spring (October-December). (Fig. 8)

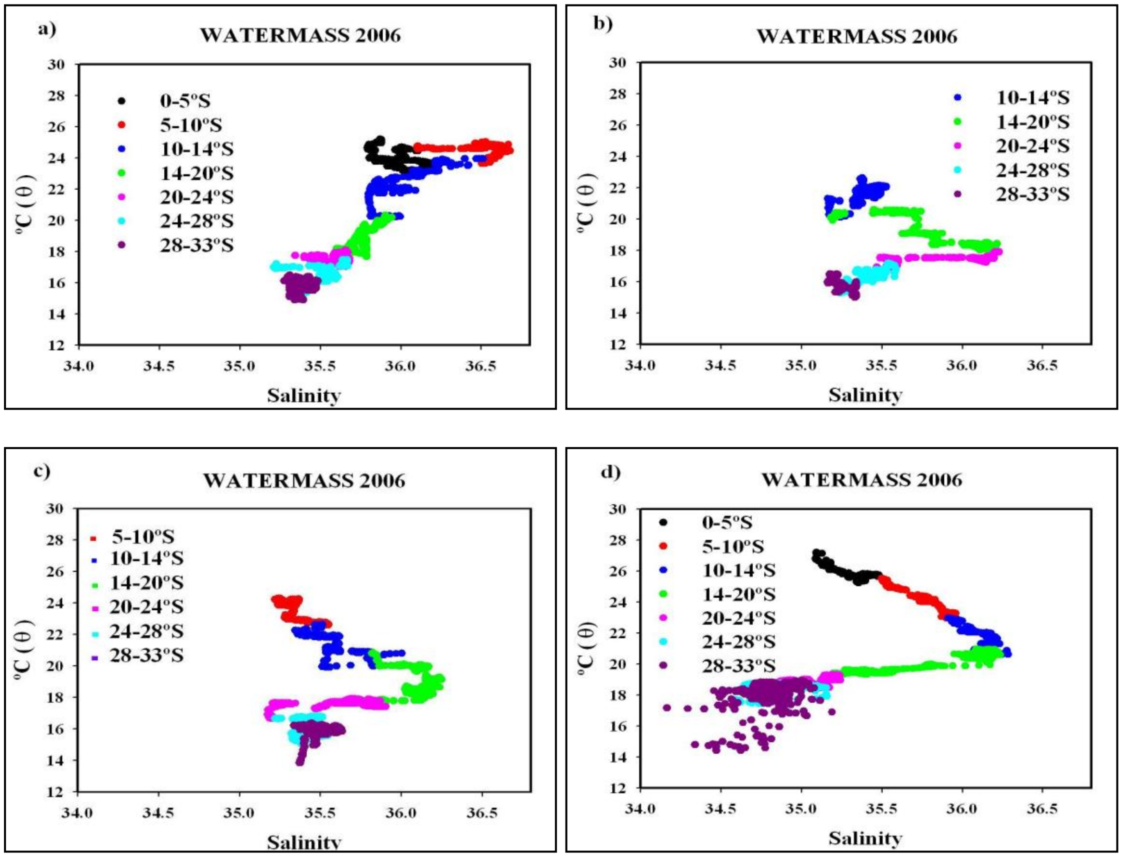


Fig. 8. Water masses during Winter and Spring seasons of 2006: a) August, b) September, c) October and d) November.

On 2007 data the EDZ (0-5ºS) show STSW with SEC influence. Moreover STSW can be detected along Congo-Angola region (5-10ºS) with SECC influences. Along Angola Gyre (10-14ºS) STSW (August-September) and TSW (January-February) can be identified. Northern Namibia region (14-20ºS) presents STSW while in February, SECC can also be present. In the Central Namibia region (20-24ºS) STSW and OSW has been identified during January-February and June (Summer-Autumn) and July-August (Winter) respectively. Also Lüderitz region (24-28ºS) shows OSW and SASW mainly with CUW influence in July data. Southern Benguela region (28-33ºS) shows SASW during February-March (Summer) and August-September (Winter) with CUW and OSW influence. OSW is observed on January, June and July influenced by CUW, appearing like filaments of upwelled water (Fig. 9). During September a decrease in salinity can be detected in EDZ (0-5ºS) due to the influence of the non-wind driven upwelling processes.

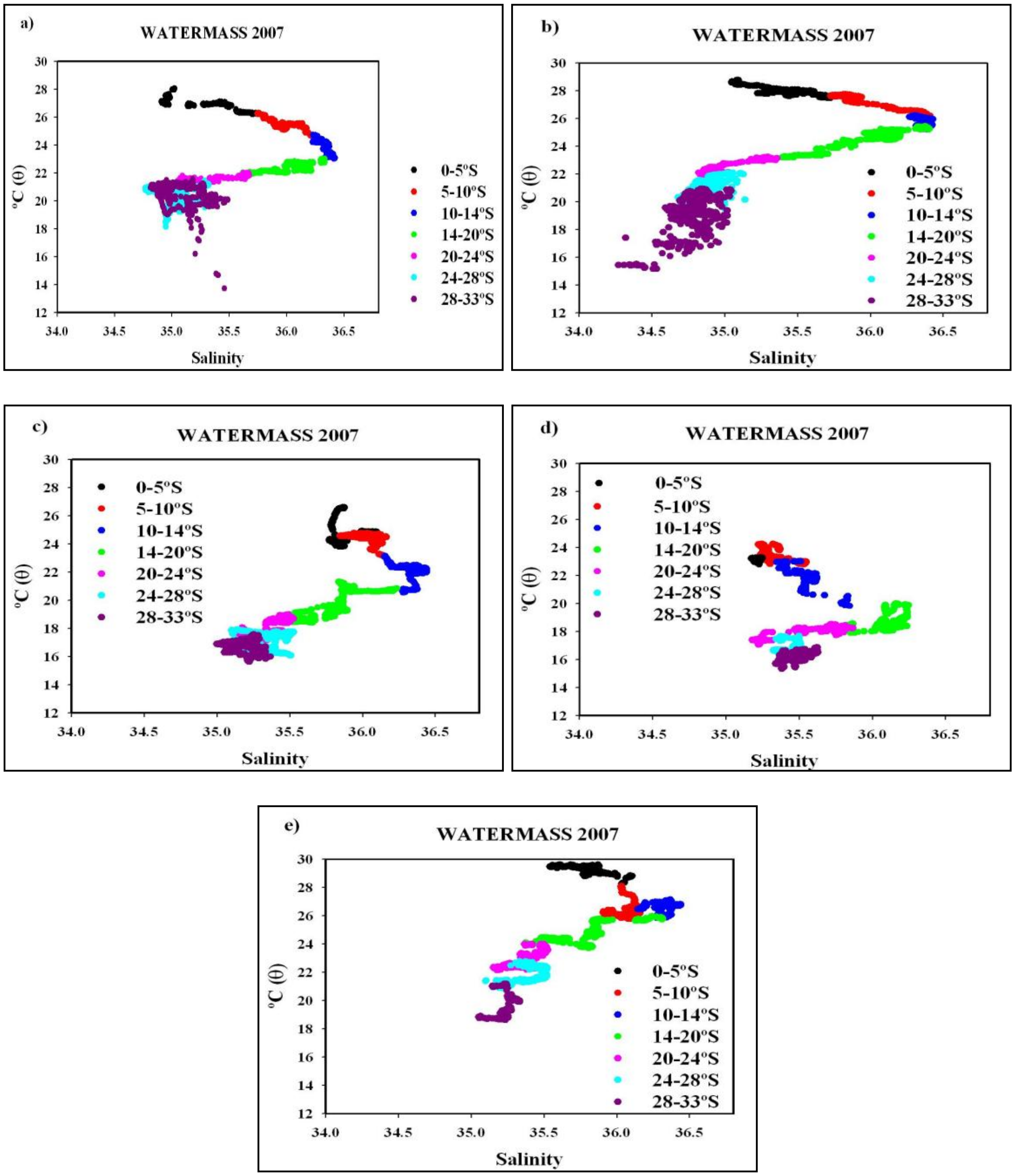


Fig. 12. Water masses during Summer, Winter and Autumn seasons of 2007: a) January, b) February c) July, d) August and e) June.

Influence of tropical warm and high salinity water can be observed in the first four regions (0-20ºS), while an Antarctic or sub- Antarctic influence with a low salinity and low temperature are evident in the last three regions (24-33ºS) as Duncombe Rae (2004) described.

Moreover during 2005 data the mean potential temperature (θ) around EDZ show a clear decrease with regard to 2006-2007 data which can be related to the strength of the cyclonic gyre at 1.5ºS-8ºW, in accordance with as Mazeika 1967. It is during the austral Winter when the Angola Dome disappears and the northern dome is developed.

b) Temperature and Salinity

1) Introduction

The upwelling processes that characterize this region modify temperature and salinity parameters, due to the upward of deeper water masses to the surface where it will be modified by solar heating when it is in contact with the atmosphere. (Gordon et al., 1994; Duncombe Rae, 2004; Salat et al., 1992).

In fact, in the Southeast Atlantic the Sea Surface Temperature (SST) is characterized to be colder due to Benguela Current water presence which is characterized by its low temperature and also the upwelling action which get upward water with SST lower than 16ºC. In this area it could be possible to find other structures as plumes, filaments, eddies from Agulhas and the discharge from Orange River which might affect salinity and temperature pattern.

Sea Surface Temperature (SST) presents the classical seasonal cycle with warmer temperatures in Summer and colder in Winter. It can be defined like a bimodal character with a warmer and a colder season during the year (Verstraete, 1992; Hardman-Mountford et al., 2003).

Sea Surface Temperature (SST) variability south of ABFZ (~15-17ºS) will be determined by the variability in wind. Warm events south of the ABF at 15ºS in the upwelling area are usually related to a weakening of the southerly wind or a spell of northerly wind. (Lass et al., 2000)

The Salinity (SSS) distribution presents the highest gradient in the ABFZ near 16°S. This maximum go down to the Equator and south reaching its lower value around 30ºS in Southern Benguela region where data could be around ~34.5.

This minimum in salinity around 30-33ºS could be explained by physical processes as upwelling season since data minimum, it agree with it but also discharge's rivers as Orange and Oliphant could affect the salinity of the area producing the ROW, and the filaments of the retroflexion Agulhas process join to sub-Antarctic water enriched with SACW from Southtropical Front (STF) low salinity water. In the same way, in northern latitudes during equatorial upwelling seasons (Winter-Spring) salinity reaches its lower values (Grodsky S.A. et al., 2007; Duncombe Rae, 2004; Shillington et al., 2004; Gordon, 1994)

Interannual, seasonal as well as mesoscale feature, cause great temporal and spatial variability in the area. During southward intrusions of warm, saline surface waters onto the Namibian shelf the Angola-Benguela Front (ABF) is displaced to about ~21ºS (Mohrholz et al., 2004; Shannon et al., 1987). The dynamics of the ABF is not well known. Shannon et al. (1987) assume that the Angola Dome may control the dynamics of the Front.

Other features such as anticyclonic eddies could be detected in the area of Walvis Bay, around 19-23ºS, although this structure has been observed near-shore it could reach several miles offshore (Salat et al., 1992).

2) Temperature and Salinity data

Temperature data show a regular distribution pattern with a decrease from Equator to south as indicated by Mohrholz et al., 2001. (Fig. 13)

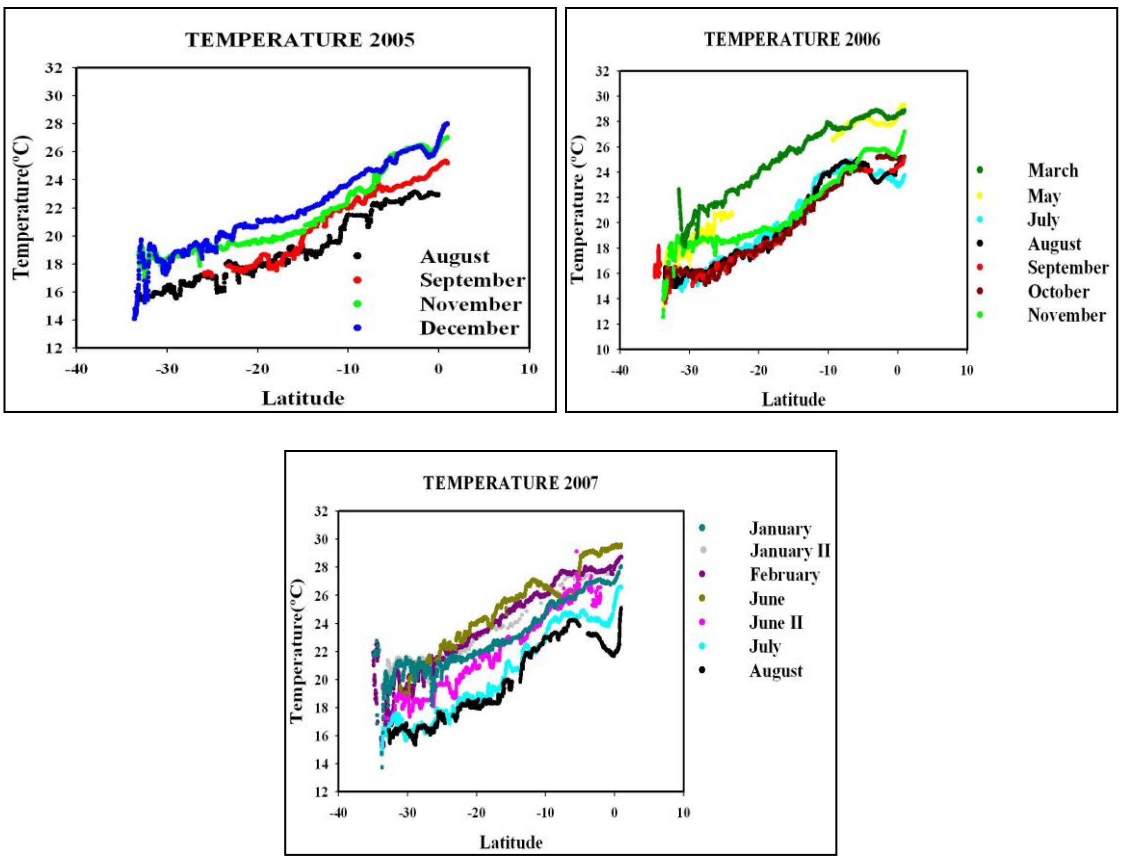


Fig. 13. Temperature 2005, 2006 and 2007.

Sea Surface Temperature (SST) show the classical seasonal cycle with warmer temperatures in Summer-Spring (January/March-October/December) and colder during Winter-Autumn (July-September) 2005, 2006 and 2007, reaching the maximum during the Summer, March 2006 and February 2007 at the northern latitudes (0-10ºS), and in the South (25-33ºS) during January 2007.

Differences in temperature between Winter and Summer are in the range of (~5-6ºC), with a clear difference in the Southern Benguela region (28-33ºS). Maximum in temperature (20-22ºC) has been detected during December 2005 near 25ºS and in Autumn (April-June) 2006 and 2007 while Summer months (January-March) also presented an increase in temperature. Otherwise minimum is detected around ~33ºS during Winter (July-September) 2006, 2007 and 2005.

Furthermore temperature shows a smooth inflection around 10-20ºS, between Angola Gyre and Northern Namibia region, with maximum values (28-29°C) to the northern latitudes (0-5ºS) in Summer, being 25°C the mean temperature and minimum values to the South (Benguela region). The minimum of temperature around 30-33ºS could be explained by physical processes as upwelling of Benguela region, getting upward cold water being the wind stress of the area whose benefit the upwelling process.

2005 data showed the bimodal cycle described with only two seasons, Winter (August-September) and Spring (November-December). In the first one SST maximum and minimum fluctuated between ~25-15.5ºC meanwhile, Spring season showed a wider temperature range between ~27-13.5ºC (Fig. 14). Furthermore during Winter season an important physical aspect is the strong equatorial upwelling effect at EDZ (0-5ºS) as well as the absence of Angola Dome effect situated between Congo-Angola (5-10ºS) and Angola Gyre region (10-14ºS) in the mean SST.

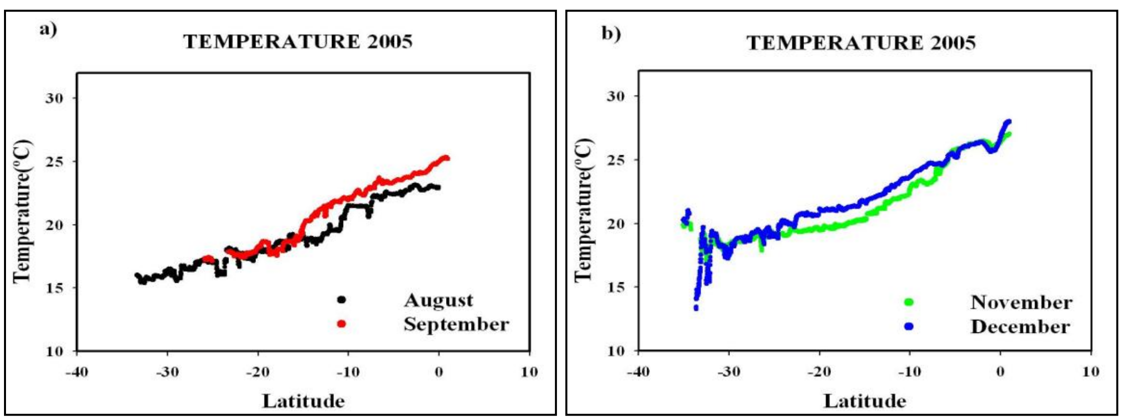


Fig. 14. Temperature profile during 2005: a) Winter and b) Spring.

Another important feature in the temperature distribution is the effect of upwelling process around Lüderitz (24-28ºS) and Southern Benguela (28-33ºS) regions, where the most important and permanent upwelling cells as Walvis Bay (24ºS) and Lüderitz (27ºS) and the seasonal affected Cape Peninsula (34.5ºS) and Cape Columbine (32.5ºS) can be identified (Fig. 15). Secondly, in Spring season EDZ (0-5ºS) presents a lower equatorial upwelling and the smaller amount of upwelled water is reflected on mean SST (27.9-25.8ºC) at equatorial latitude (0.9ºN-1.2ºS). Also the Angola Dome is absent at this season in Congo-Angola and Angola Gyre regions (5-14ºS) with the ABFZ in the Northern Namibia region as well identified. (Fig. 15)

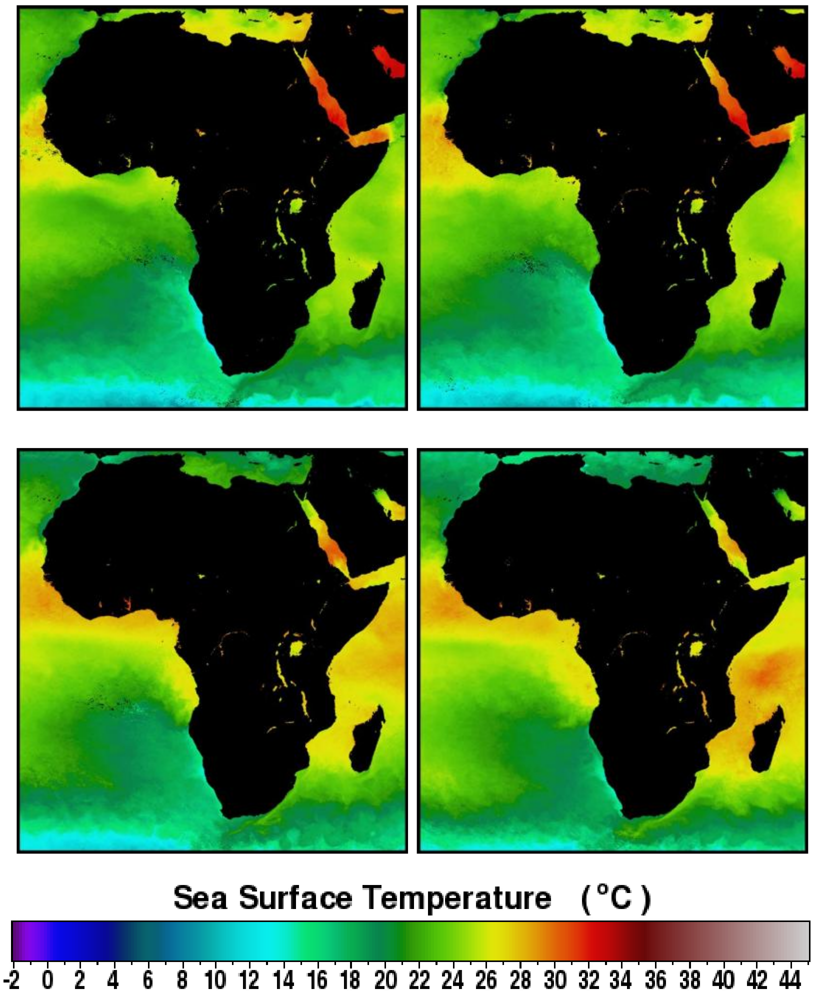


Fig. 15. Satellite images of Winter and Spring temperature of 2005: a) August, b) September, c) November and d) December.

2006 data (Fig. 16) for Summer-Autumn (Fig. 17) show high mean temperature ~29ºC at EDZ related to the absence of the (due to Angola Dome presence in Congo-Angola and Angola Gyre regions (5-14ºS)) equatorial upwelling. In Winter equatorial upwelling takes place with temperature of around 24-25ºC probably related to the Angola Dome absence (Mazeika, 1967). Spring mean temperature is affected by the lower equatorial upwelling (~27.4-20ºC) in EDZ, Congo-Angola and Angola Gyre regions joined to the absence of Angola Dome. Northern Namibia region (14-20ºS) presents the ABFZ developed as the transition zone between northern and southern. Otherwise Winter months (August-September) does not show so clear descend in temperature related to upwelling cells as happened during Autumn, only a descend in Southern Benguela region around ~34.5ºS (Cape Peninsula) and 32.5ºS (Cape Columbine) upwelling cells can be identified especially during November, when the upwelling season starts. Whereas descends in temperature at Southern regions in Namibia, Lüderitz and Southern Benguela it agrees to upwelling cells around ~28ºS (Lüderitz), 34.5ºS (Cape Peninsula) and 32.5ºS (Cape Columbine) during Spring season.

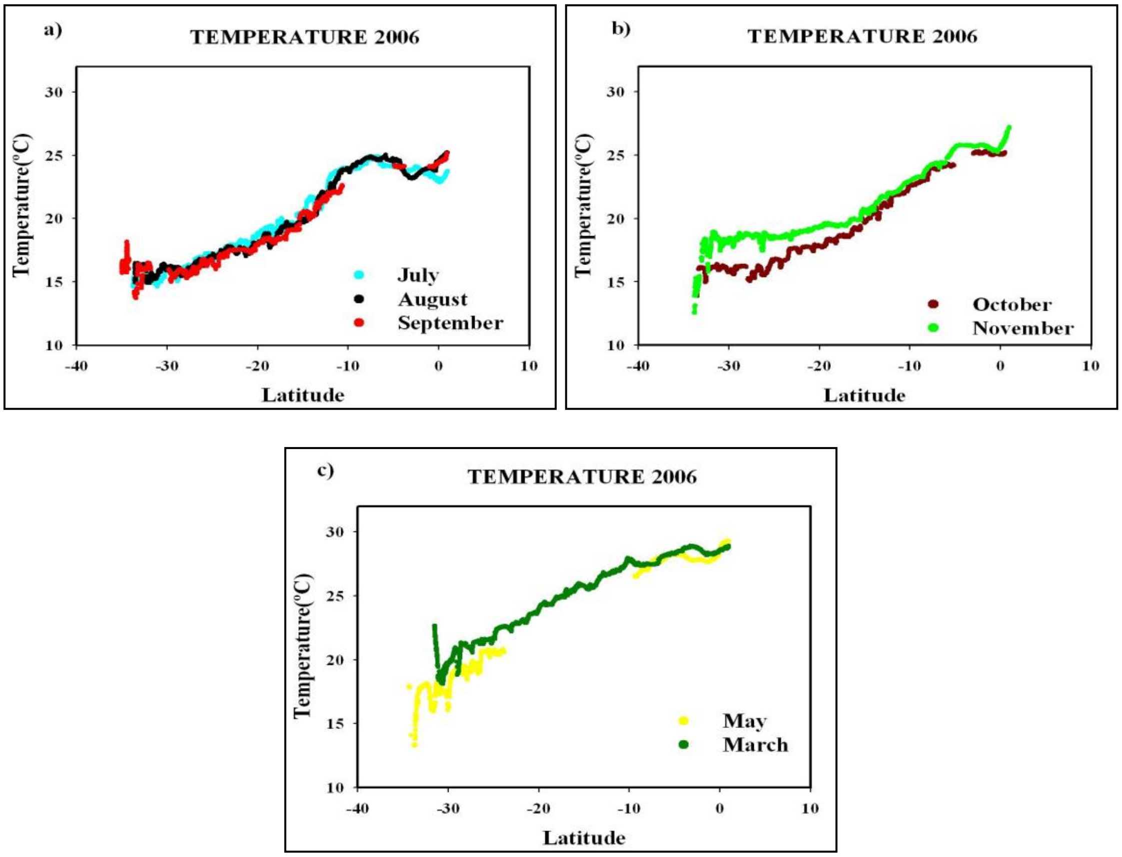
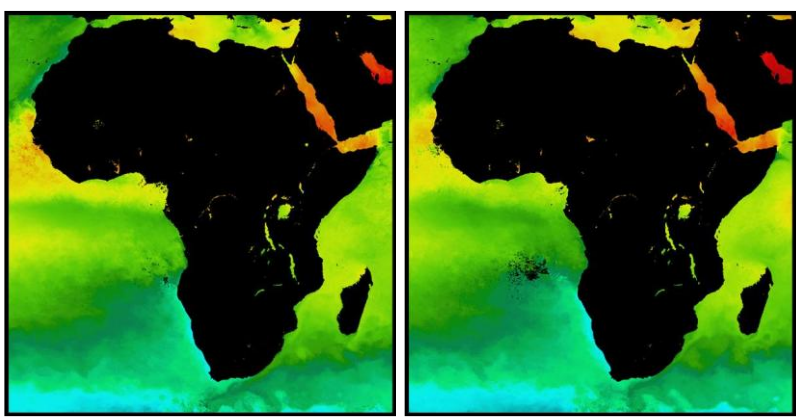


Fig. 16. Temperature profile during 2006: a) Winter, b) Spring and c) Autumn.



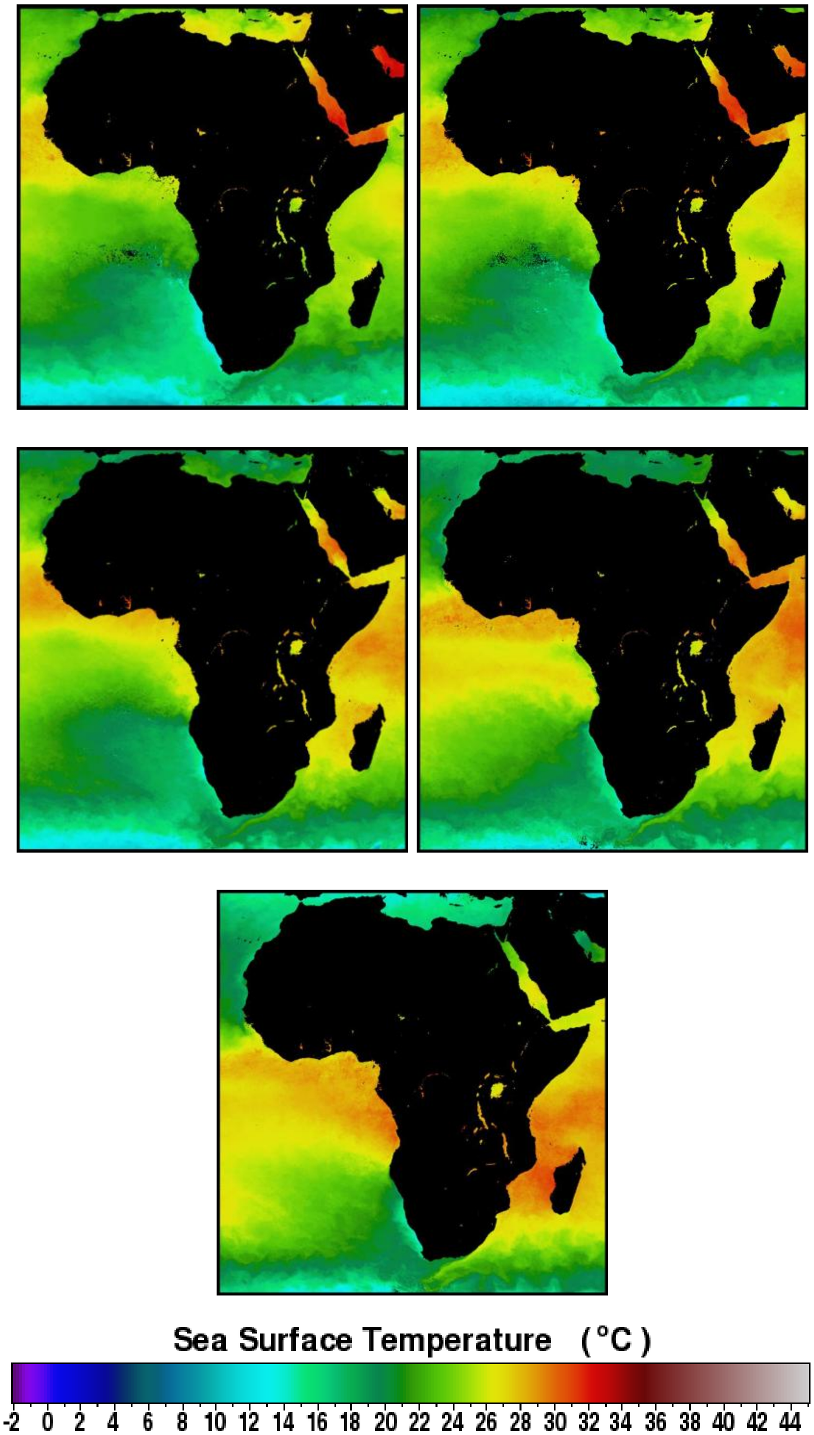


Fig. 17. Satellite Images of Winter, Spring and Autumn seasons temperature 2006: a) July, b) August, c) September, d) October, e) November, f) March and g) May.

2007 Summer season (Fig. 19) presented the highest mean temperature (~28ºC) in EDZ depicting equatorial upwelling absence and Angola Dome presence in Congo-Angola and Angola Gyre regions. On Winter time (July-September) the equatorial upwelling effect (0.9ºN-0.11ºS) in EDZ as well as the absence of Angola Dome can be reflected on the mean temperature (~23ºC). On the other hand, the ABFZ effect can be detected in Namibia Northern region and the Lüderitz and Southern Benguela regions presented upwelling cell activity. Furthermore the effects of the upwelling cells around 13.5-16ºS (ABFZ), 23ºS (Walvis Bay), 27ºS (Lüderitz) and 34ºS are more developed during Summer time due to winds in favoring the upwelling season. (Fig. 18)

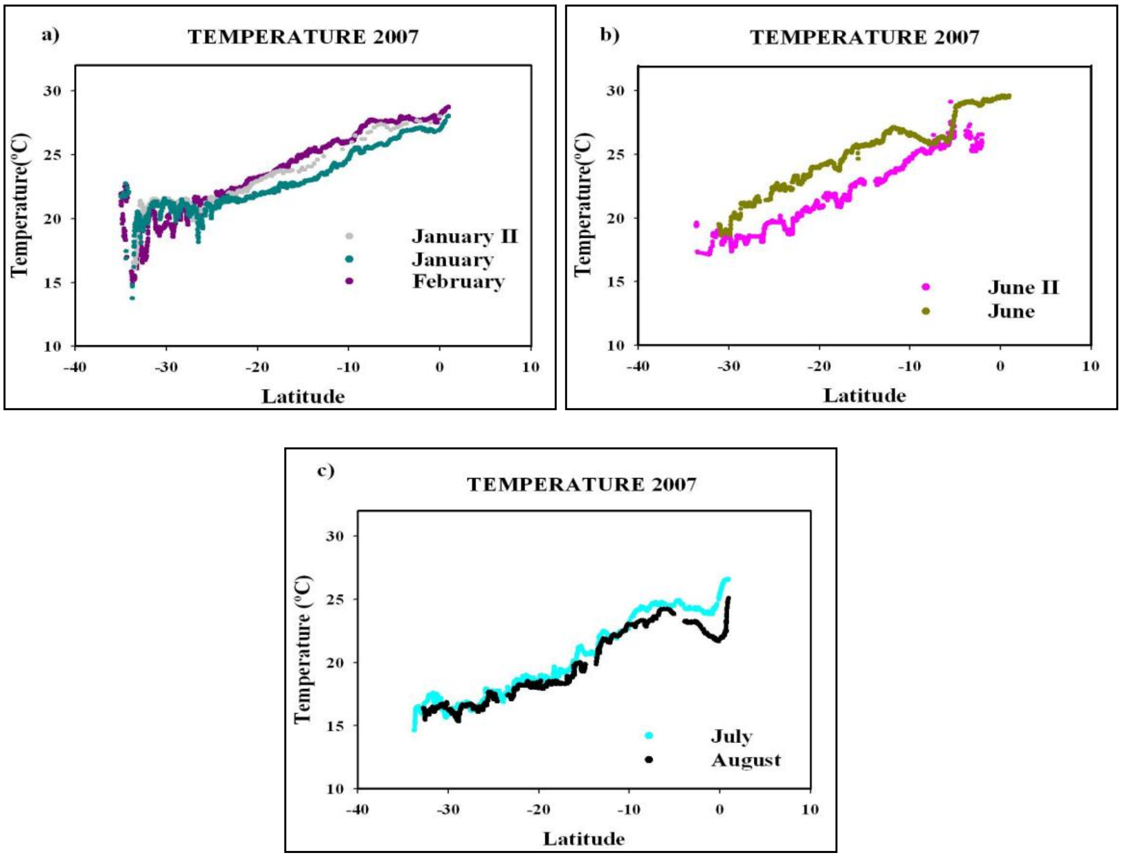
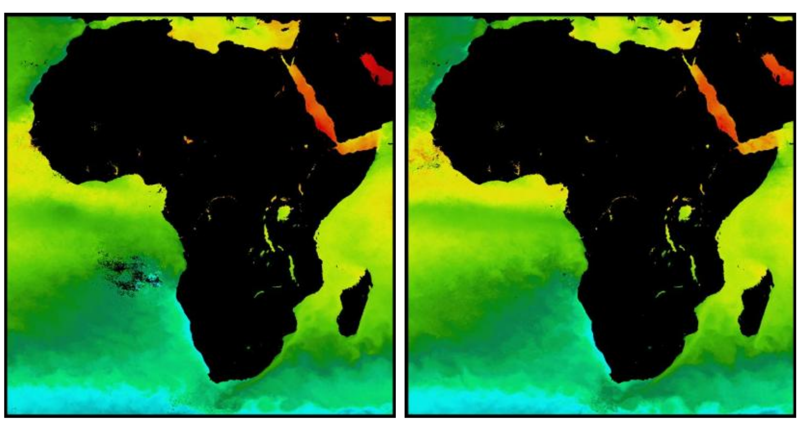


Fig. 18. Temperature during 2007: a) Summer, b) Autumn and c) Winter.



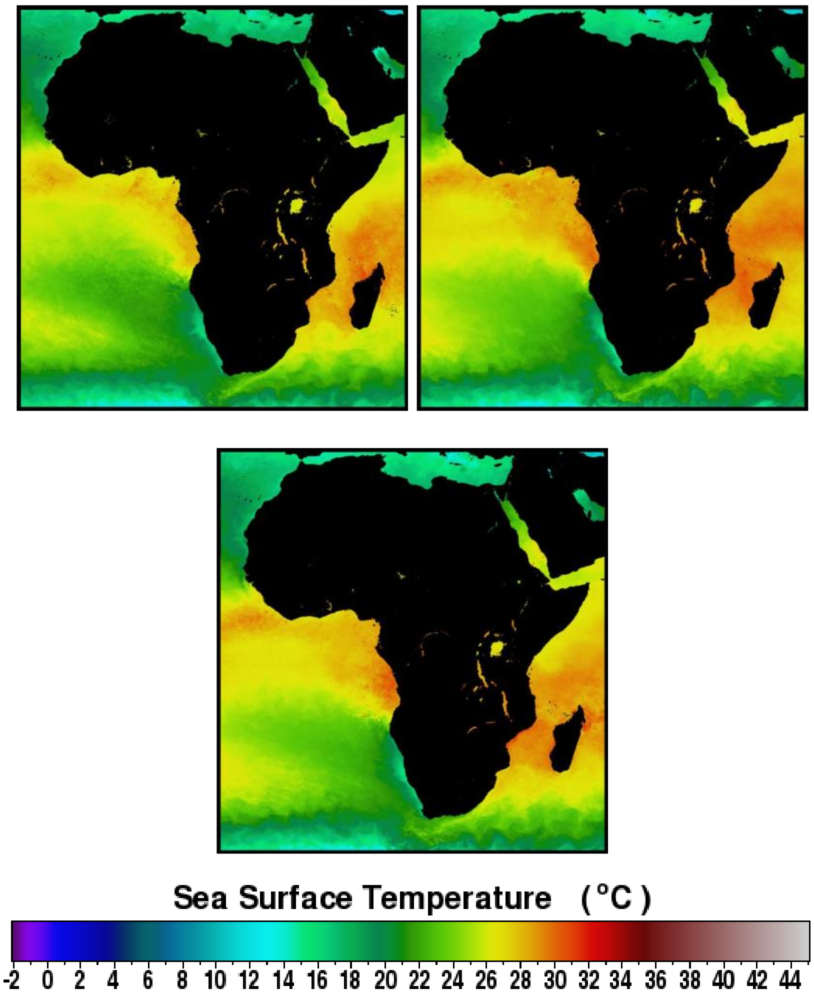


Fig. 19. Satellite Images of Winter and Summer seasons temperature 2007: a) July, b) August, c) January, d) February and e) March.

Fig. 20 shows, as Longhurst A. (1998) established, a pattern of minimum temperatures during upwelling events in Cape Columbine (32.5ºS) and Cape peninsula (34.5ºS) area along the Summer trimester, through 2005, 2006 and 2007. This process could be detected through the filaments that upwelling generated and extended offshore 500-700km. It also shows a correlative increasing in temperature from Winter to Summer.

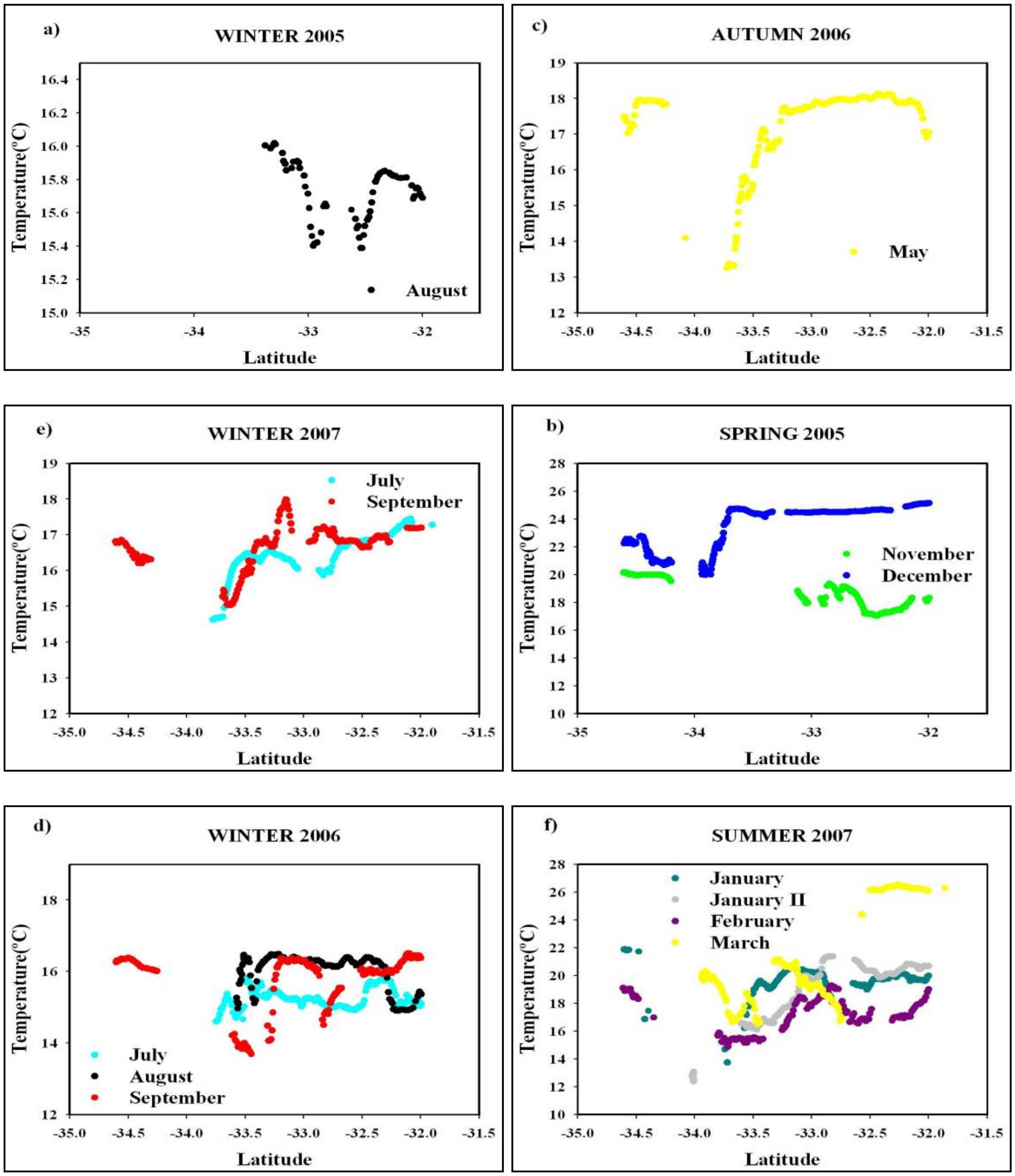


Fig. 20. Cape Columbine and Cape Peninsula SST difference along 2005-2007: a) Winter 2005, b) Spring 2005, c) Autumn 2006, d) Winter 2006, e) Winter 2007 and f) Summer 2007.

Fig. 21 shows an annual different latitudinal pattern of minimum temperatures around Autumn-Winter with an average of ~21ºC, and warmer (~25ºC) time around Spring as well as higher temperatures from Equator (0º) to south (34ºS). This pattern could be confirmed with the bimodal cycle described before. This character has a relationship with the upwelling process and could be confirmed with data of 2007 and 2006 (Fig. 22). However 2005 data show a sharp descend in temperature and salinity in 2005 compare to 2006 and 2007 during Summer, in particular December. Data represent values determinated along the

VOS line track. A polynomial 4 degree fit was used to establish the general behavior observed for each year.

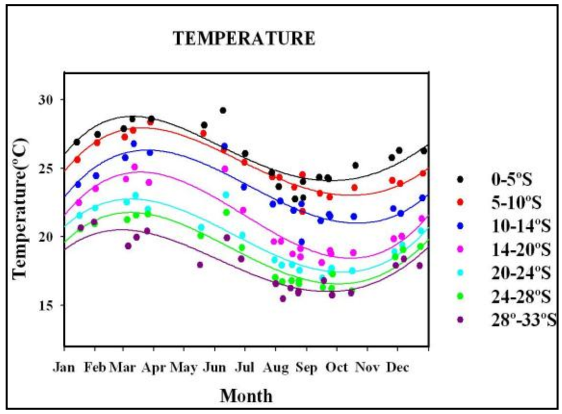
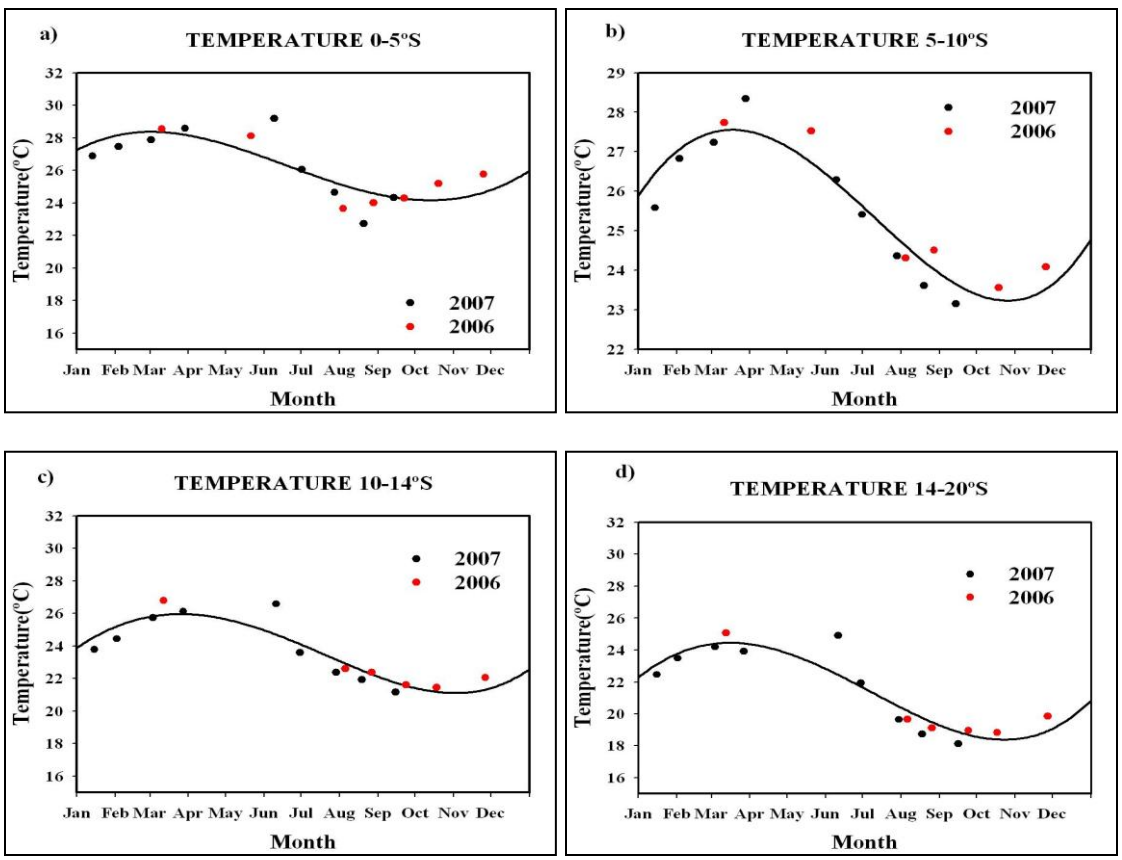


Fig. 21. Annual 2005/06/07 temperature trend.



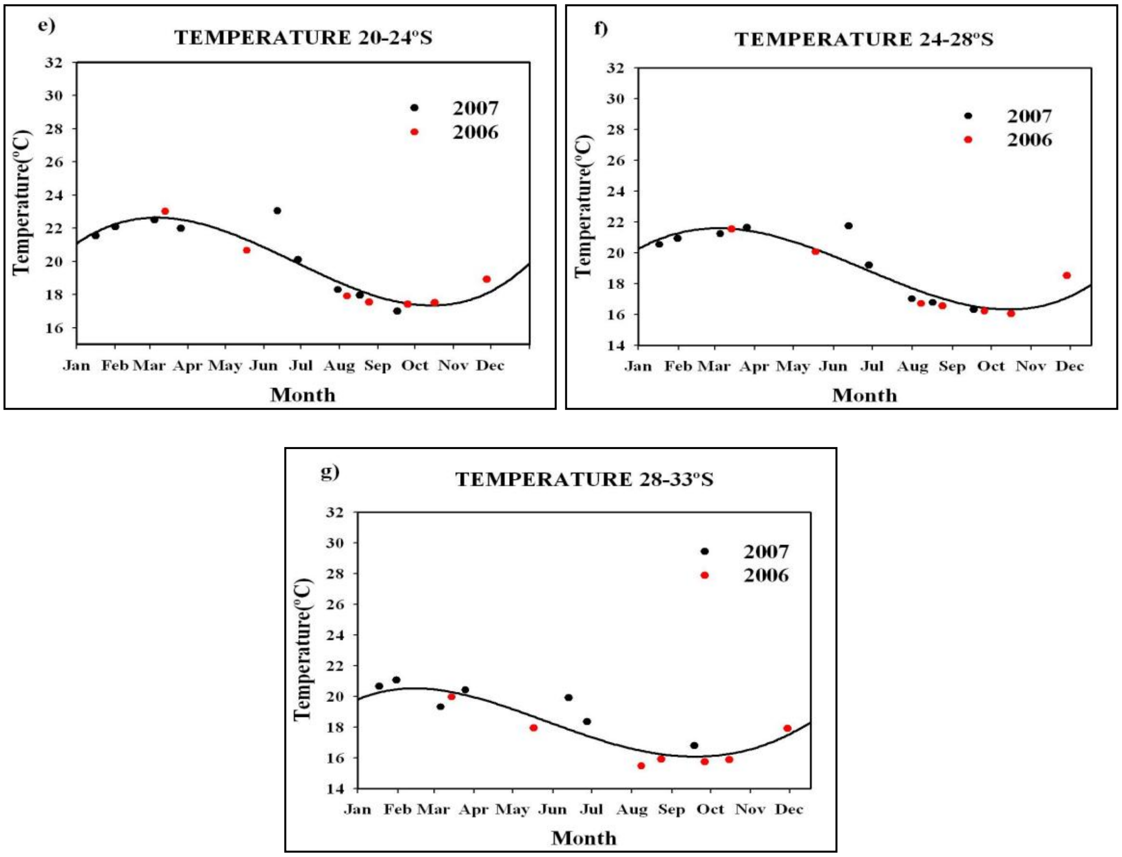


Fig. 22. Annual 2006/07 temperature trend: a) EDZ (0-5ºS), b) Congo-Angola region (5-10ºS), c) Angola Gyre region (10-14ºS), d) Northern Namibia region (14-20ºS), e) Central Namibia region (20-24ºS), f) Lüderitz region (24-28ºS) and g) Southern Benguela region (28-33ºS).

In spite of, data were collected in Open Ocean, processes such as the outflow of the Congo River and Angola's one can affect the meridional gradient of the salinity in the northern part while the upwelling processes have a similar effect in the southern area by injecting water with lower salinity in the surface from sub-Antarctic influence.

Compared with the SST, the salinity distribution shows a high patchiness. The general structure in Sea Surface Salinity (SSS) is characterised by salinity higher than 35.8 in the Subtropical Surface Water in the northern area (0-15ºS) and salinity less than 35.6 for the Benguela upwelling water.

Around ~10-20ºS a rise in salinity which can change the position between years and seasons in relation with the ABFZ position, is observed. This maximum in salinity of ~36.5 detected in the surface layer could be also corroborated by water mass data (Table. 3)

Data of 2005, 2006 and 2007 show this maximum between 10-20ºS, which could be explained by the nearby of Angola's Dome (10-13ºS/9-10ºE) and its constitution in SEC and SECC which are characterized by its high salinity and temperature and the presence of South Atlantic Anticyclone (SAA), which is influenced by the ABFZ's position. (Fig. 23)

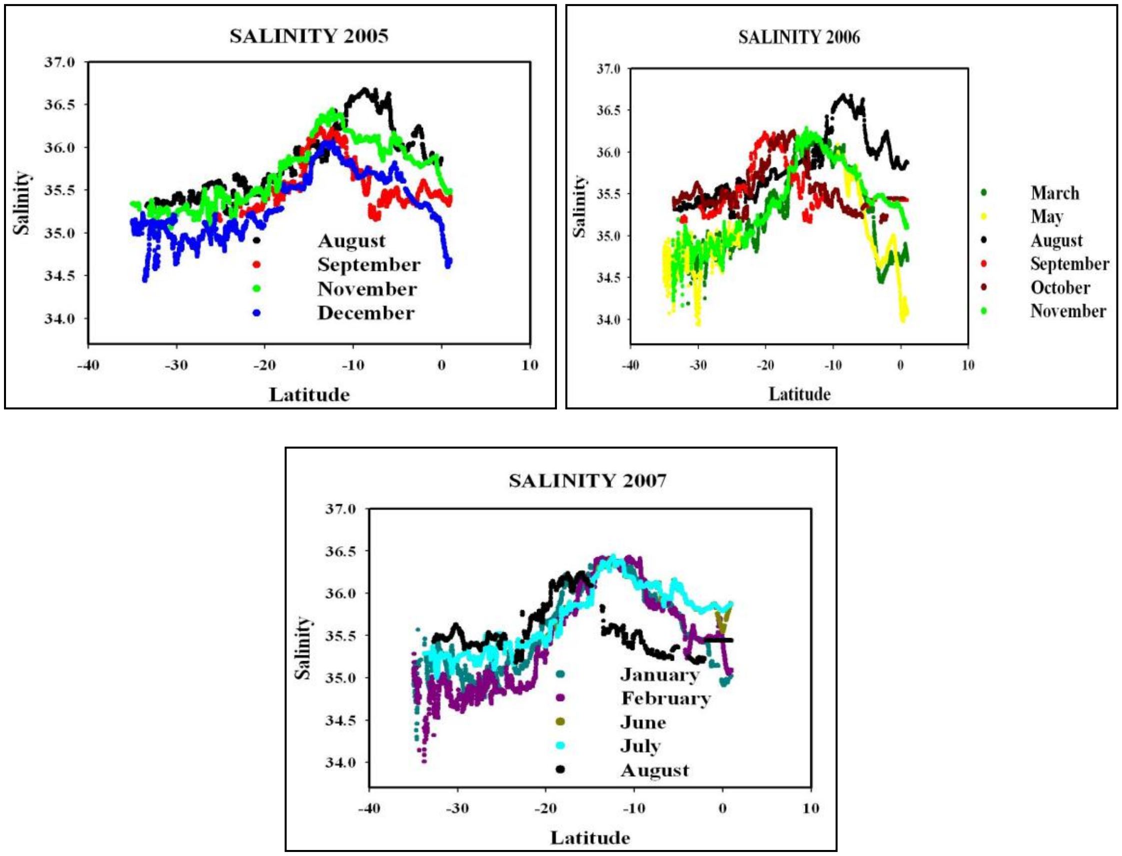


Fig. 23. Salinity annual distribution during 2005, 2006 and 2007.

The maximum salinity during the second part of 2005 is situated around ~13ºS. August presented a maximum (36.7) around ~8.5ºS inside Congo-Angola region. During Winter season (August-September) around ~3ºS (36.25-35.6) another peak is identified in the EDZ. On the other hand, Spring (November-December) maximum salinity (~13ºS) fluctuates between 36.5-36 in the Angola Gyre region due to SEC and SECC salinity water effects moved by cyclonic gyre circulation. Located around 5ºS between EDZ and Congo-Angola region there is another peak (36.15-35.8) due to equatorial upwelling effect and the high evaporation effect detected in the area. (Fig. 24)

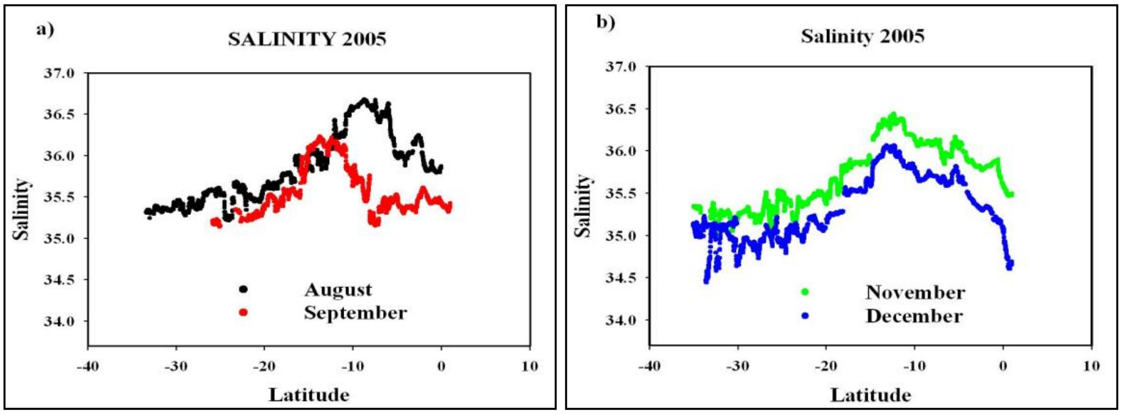


Fig. 24. Salinity Seasonal 2005 distribution: a) Winter and b) Spring.

2006 salinity showed a complicated pattern along the year with a maximum (13ºS) in the Angola Gyre region around 36.2 in Autumn, Spring and during Winter but with different latitudinal position (17-20ºS). However the maximum in August (Winter) 36.7 is displaced around 8.5ºS showing another peak (36.25) around 3ºS. In March (Autumn) and November (Spring) another peak (35.5) around 3ºS is also observed in EDZ. (Fig. 25)

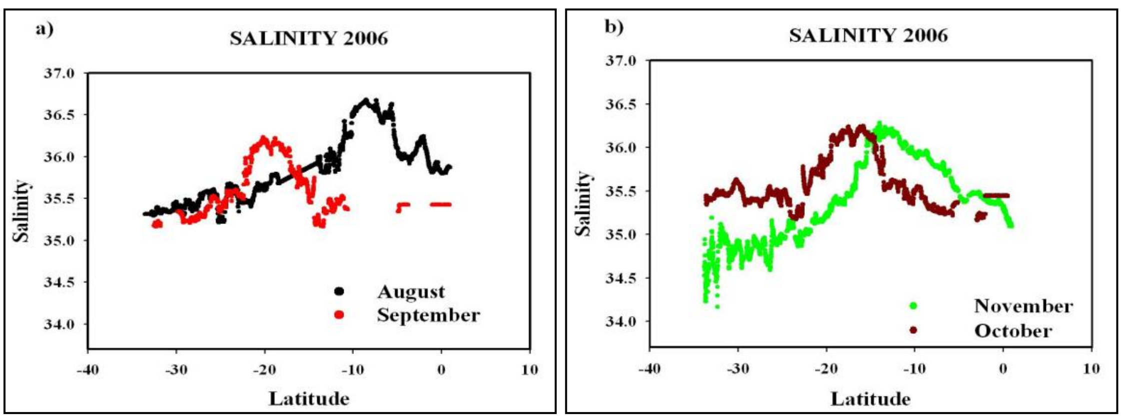


Fig. 25. Seasonality Salinity 2006: a) Winter, b) Spring.

2007 maximum salinity in Summer (January-February) (~36.5) is situated around 13ºS in the Angola Gyre region as well as in Autumn (June). However in Winter (July-September) a displacement can be observed especially in August where maximum (36.3) can be detected around 16ºS. Also around Winter and Autumn seasons a second maximum can be identified in Congo-Angola region around 5ºS. (Fig. 26)

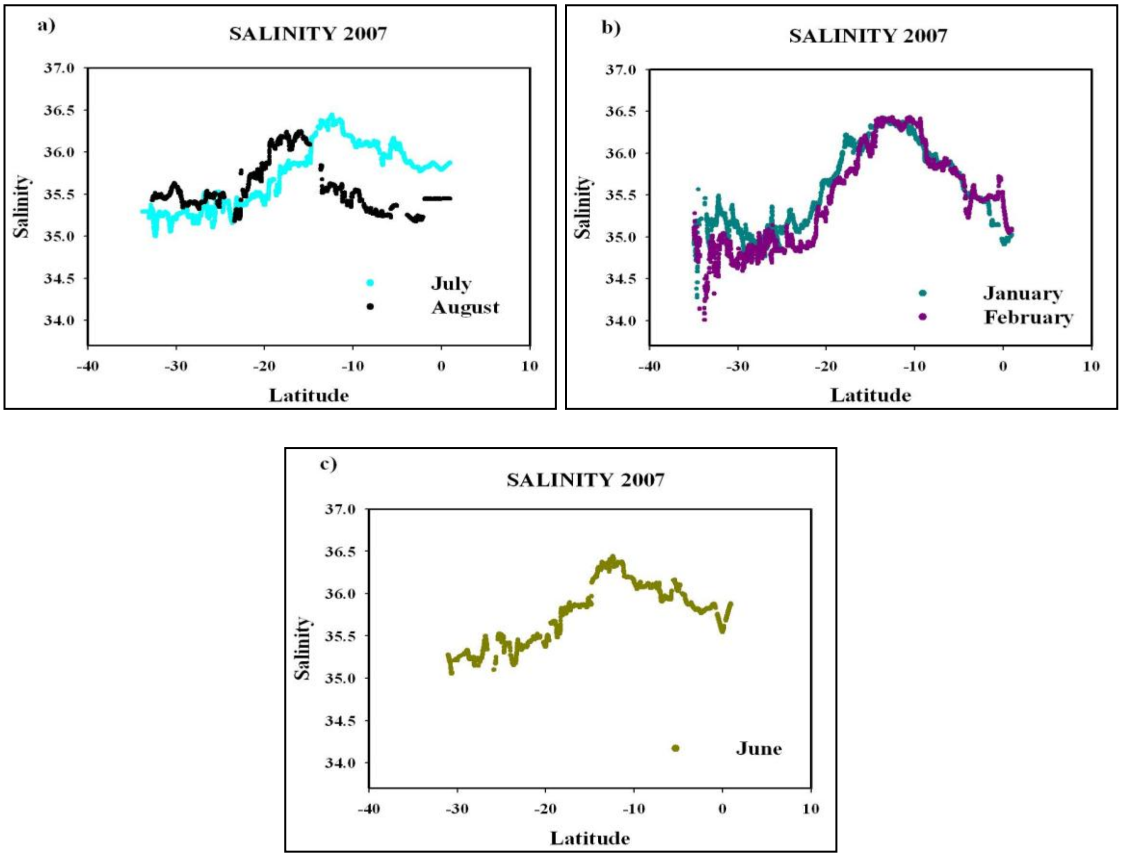


Fig. 26. Seasonality Salinity 2007: a) Winter, b) Summer and c) Autumn.

This maximum data went down north and south, reaching the lowest value around 30ºS in Southern Benguela where data are around ~34.5. This minimum in salinity around 30-33ºS could be explained by physical processes as rivers discharge (Orange and Oliphant) which affect the salinity of the area producing the ROW (river orange water), that could explain the low salinity detected in the area, and the filaments of the retroflexion Agulhas process joined to sub-Antarctic water enriched with SACW from Southtropical Front (STF) low salinity water.

c) Oxygen

1) Introduction

The core of Oceanic Water (OW) within the Eastern Tropical Southeast Atlantic (ETSA), as was indicated above, extends from the equatorial zone to two southern boundaries: one at 16-17°S and the second at 25-26°S.

These two boundaries correspond to the southern edge of the Angola Gyre and the southern edge of the sub-equatorial cyclonic circulation respectively. The sharp oxygen gradient across the latter boundary defines the transition between the two South Atlantic Central Water masses derived respectively from the hypoxic ETSA and the aerated Cape Basin. (Monteiro et al., 2006). Otherwise in ETSA area ventilation process for the sub-thermocline waters take placed across the main currents of the zone like Equatorial Undercurrent (EUC), South Equatorial Undercurrent (SEUC) and South Equatorial Countercurrent (SECC). The closure of the Angola Gyre by the main flow of the Angola Current creates the recirculation retention zone that, together with its thermocline dynamics, establishes the conditions necessary for Low Oxygen Water (LOW) formation. (Monteiro et al., 2006)

The minimum oxygen in Angola Gyre developed below thermocline seems to propagate poleward and affects the oxygen budget of the Benguela upwelling system. (Mohrholz et al., 2001)

The tropical ocean has low oxygen content (central-intermediate waters) due to the high temperature yielding a low oxygen saturation value. Moderate biological activity quickly leads to even lower oxygen concentrations in waters leaving the tropical regions. (Duncombe Rae, 2000)

The northern boundary of the South Eastern Atlantic at 5ºS would encompass the Angola Dome and the area in which the main oxygen minimum in the South Atlantic forms, the dynamics of which are inextricably linked with that off Namibia. (Shannon et al., 2003)

In the region of the Lüderitz upwelling cell, consistent with Monteiro (2006), the southward moving water in the poleward undercurrent appears directed off-shore at about the same level as a local oxygen minimum in the central water of the Cape Basin gyre. (Duncombe Rae, 2000)

At Southern Benguela region a mix of Indian and South Atlantic subtropical thermocline water could be detected, with significant contributions of saline, low oxygen tropical Atlantic water and cooler, fresher sub-Antarctic water. (Hardman-Mountford et al., 2003)

The oxygen distribution has been explained considering seven different regions: Equatorial Divergence Zone (EDZ) (0-5ºS), Congo-Angola (5-10ºS), Angola Gyre (10-14ºS), Northern Namibia (14-20ºS), Central Namibia (20-24ºS), Lüderitz (24-28ºS) and Southern Benguela (28-33ºS), following the hydrographic parameters. This classification let us to understand the behavior of this chemical element inside of this complicated system.

2) Oxygen data

Data show a regular pattern during 2005, 2006 and 2007 with maximum in the southeast (30-33ºS) and minimum around Equator (Fig. 27). The maximum could be detected during the three years; one of the various explanations is the interannual variability in the equatoward component of the upwelling winds in the area and also the influences of the processes near the shore where the influx of oxygenated SACW is present around Oliphant's valley.

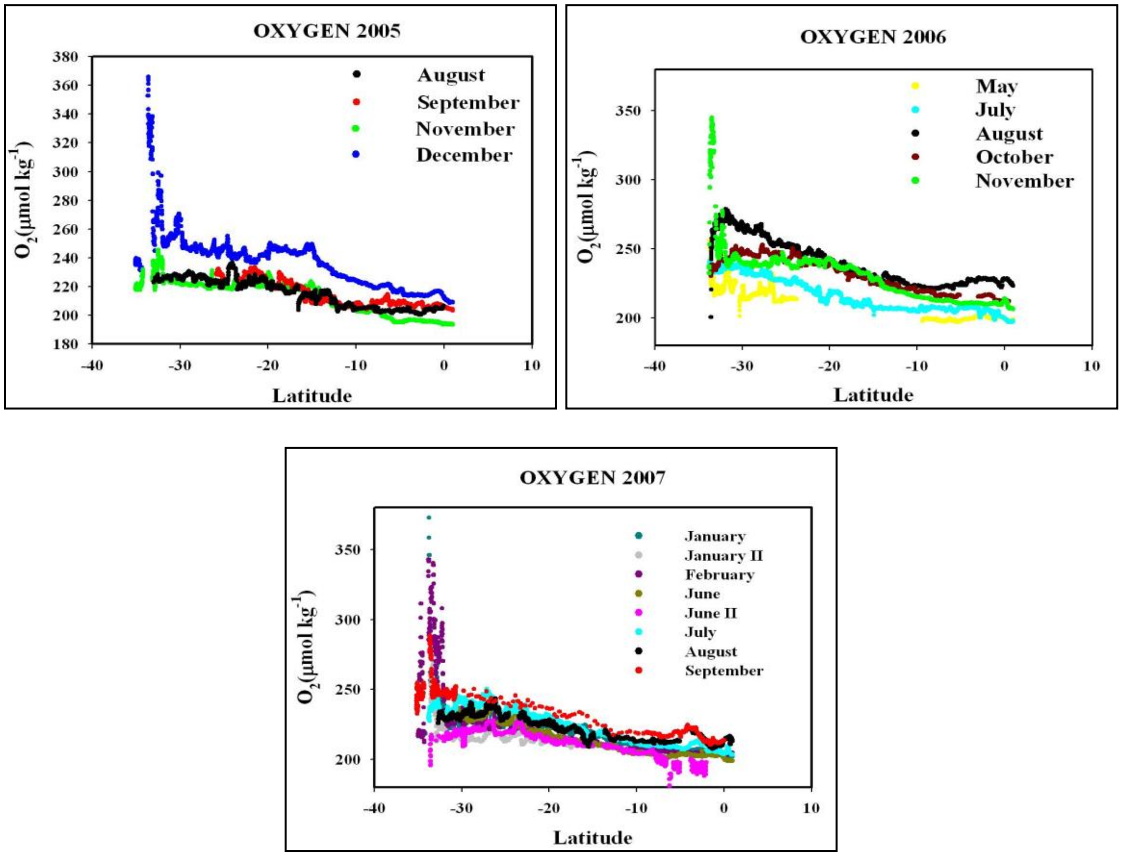


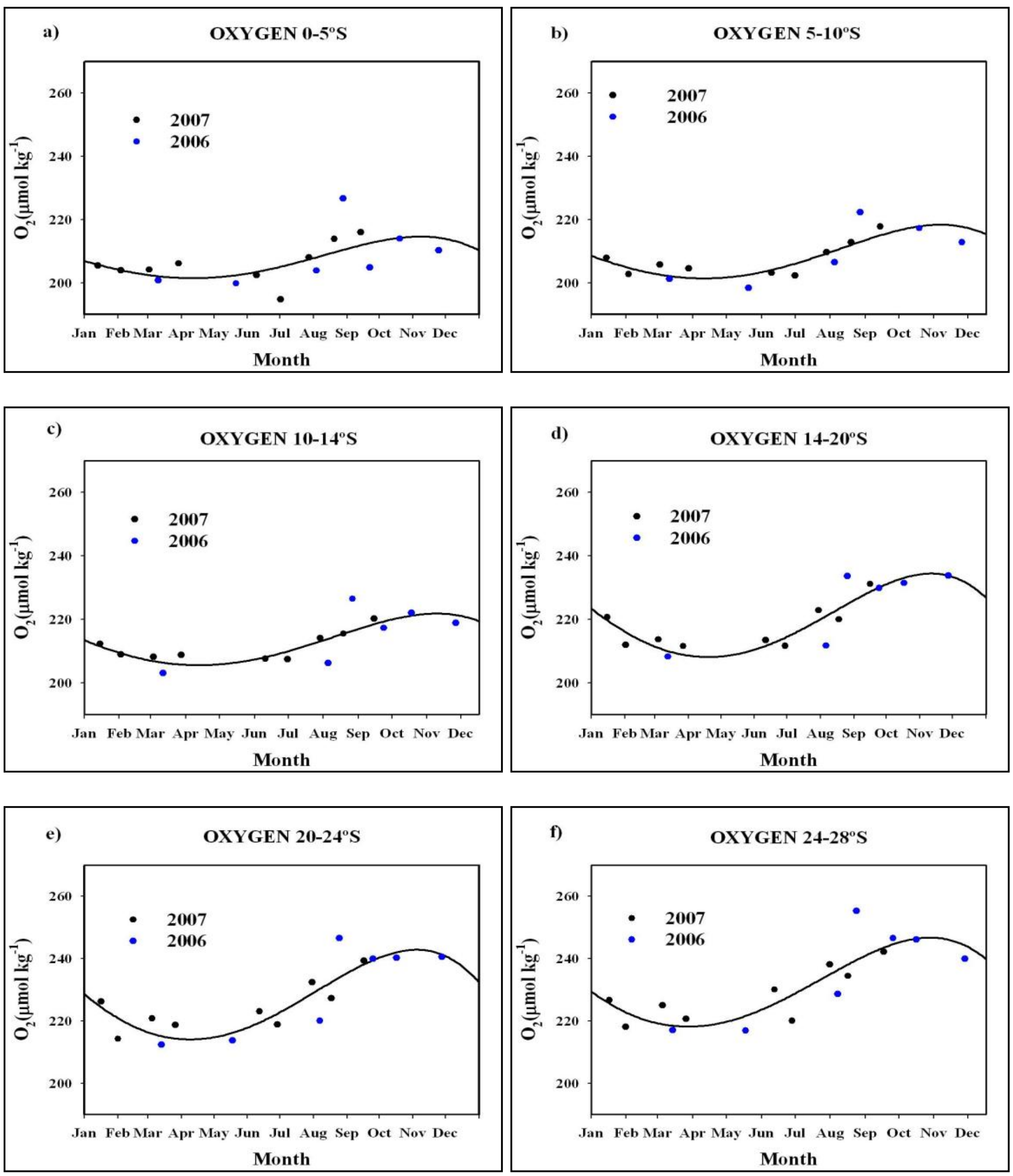
Fig. 27. Oxygen distribution pattern along 2005, 2006 and 2007.

Mohrholz (2001) describe from 300m to surface water, around 20-23ºS (Walvis Bay), the lowest oxygen concentration inside Benguela area with an increase in the oxygen concentration pattern further south. This situation can be detected in our data with an increase in oxygen concentration south of 20ºS along the three years. Furthermore the increase in oxygen concentration southern 20ºS is fitted on with the minimum oxygen boundary from R/V Meteor 34/1 data (Shannon et al., 1996).

Otherwise the minimum around 0ºS in the EDZ (194.3µmol kg^{-1}) is related to the water masses and currents in the area, in particular SEC and SECC. They are part of the Angola Gyre which is characterized by low oxygen shallow thermocline water (Monteiro et al., 2006). Also the southward advection of poor oxygen tropical warm water contributes to the low oxygen concentration. The Congo River which produces the highest discharges of Africa's Southeast coast fresh water reaching to the VOS track line has to be considered.

Around 10-20ºS is observed an inflexion in oxygen concentration mainly due to the presence of Angola's Gyre (12ºS) upside which has been described to have poor oxygen water with origin in SECC and sSEC and the presence of AFBZ. Other features observed in the oxygen concentrations distribution reflects the spatial separated inputs of Cape Frio (17ºS) and Lüderitz (27ºS) upwelling cells. (Monteiro et al., 2006).

Another pattern is the bimodal annual character described by the data showing maximum, in Winter and Spring; and minimum during Summer and Autumn. This pattern has a relationship with the seasonal temperature variation and the upwelling process. It could be confirmed with data of 2007 and 2006 (Fig. 28). 2005 data show higher oxygen concentration during Summer (December). It could be linked to a sharp decrease in temperature and salinity during 2005 compared with 2006 and 2007, but data are not enough that year to prove it.



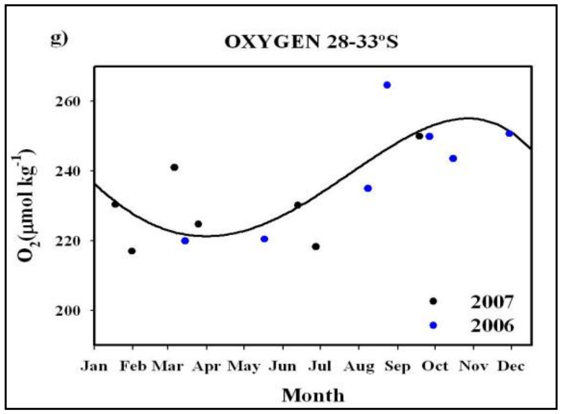


Fig. 28. Oxygen bimodal pattern: a) EDZ (0-5ºS), b) Congo-Angola region (5-10ºS), c) Angola Gyre region (10-14ºS), d) Northern Namibia region (14-20ºS), e) Central Namibia Region (20-24ºS), f) Lüderitz region (24-28ºS) and g) Southern Benguela region (28-33ºS).

The data have been processed using a 4 order polynomial equation. Results presented a regression coefficient between 0.47 – 0.83. Lower coefficients have been found in EDZ (0-5ºS) and Southern Benguela region (28-33ºS), the first one presented tropical low oxygen water and the second high oxygen concentration waters from SACW through upwelling processes which are present in a constant and perennial character.

Also data at 20ºS showed an increase in oxygen concentration comparatively to other latitudinal data where oxygen values during the three years showed cycle pattern distribution on maximum and minimum which coincided with those mentioned before in Summer and Winter.

Also using latitudinal bands for the three years, oxygen variability is established showing the cycle distribution pattern. The minimum (194.3µmol kg^{-1}) could be detected around Spring months when maximum of temperature are identified, and maximum in oxygen (265µmol kg^{-1}) is identified around Autumn-Winter when temperature begins to reduce (Fig. 29). Having the lowest annual coefficients the EDZ (0-5ºS) and Northern Namibia region (14-20ºS) both characterized to be focus of Low oxygen water.

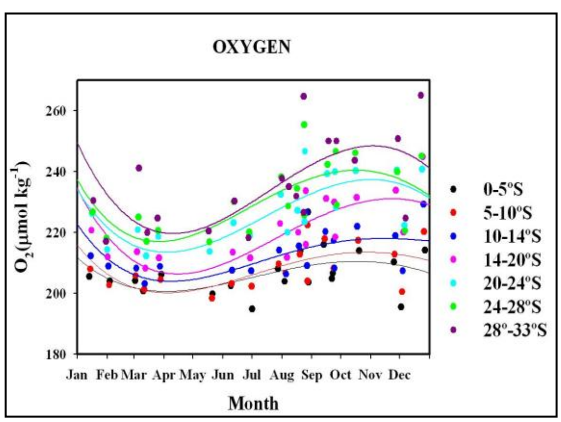


Fig. 29. Annual oxygen distribution.

During November 2005 the Apparent Oxygen Utilized (AOU) showed positive values with several inflexions related to the position of the upwelling cells, the biggest ones at 20ºS and 32ºS both with negatives values, related with chlorophyll peaks. Otherwise September data presented positive values with a maximum around 15ºS and a minimum below zero around 6ºS, where chlorophyll concentration peak appeared. December 2005 presented the same scheme with negative values and a strong peak in Southern Benguela region (34ºS), where temperature is low and wind strong. During August AOU showed all positive values with only an increase around 13ºS. (Fig. 30)

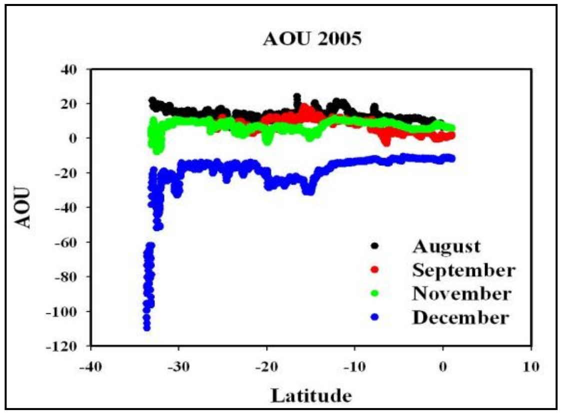


Fig. 30. AOU 2005.

During 2006 AOU showed different pattern along the year. Along May (Autumn) negatives values in the EDZ are identified due to Angola Dome presence moving up low oxygen water. Spring (October-November) is characterized by negative values along transect. But Winter (August-September) showed different behavior with positive values during July while August and also September showed all negative values except at 17ºS where September has positive ones. (Fig. 31)

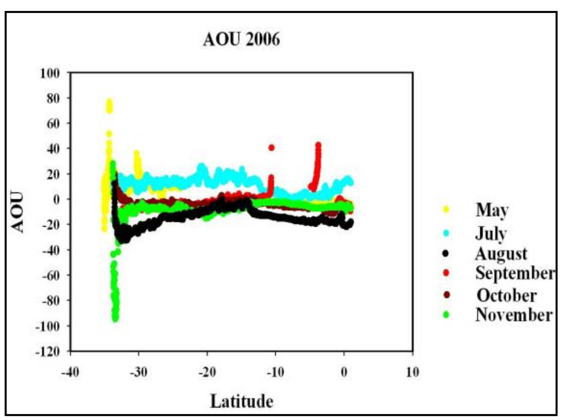


Fig. 31. AOU 2006.

January 2007 presented a negative scheme in the values with a strong peak in Southern Benguela region, where temperature is low and wind strong agree with strongest upwelling season. This pattern is presented also during February where constant negative values with a strong peak in the Southern Benguela region (28-33ºS) can be observed, this feature it agree with upwelling season along equatorial area and also Southern Benguela region. During June (Autumn) AOU negative values can also be detected.

During Winter (July-August-September) the situation changed and AOU is positive in Southern Benguela region reaching during July its biggest value and taking only negative values at equatorial latitude in EDZ and Congo-Angola region agree with the strongest upwelling season but with a light positive peak around 2ºS. September 2007 showed, around 13-20ºS latitudinal position, positive values area agree with Northern Namibia region characterized to have low oxygen water. (Fig. 32)

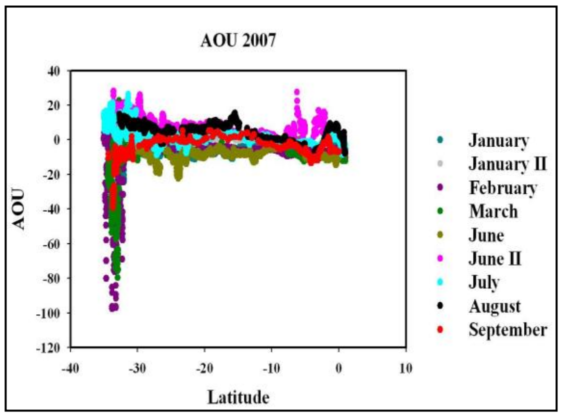


Fig. 32. AOU 2007.

d) Chlorophyll

1) Introduction

Chlorophyll biomass showed high spatial and temporal variability managing to be complicated the establishment of distribution pattern.

ETRA province has an oligotrophic profile through chlorophyll (0.16-0.5mg m^{-3}). SALT province also present poor chlorophyll concentration. (Velasca et al., 2005)

In the northern part, the Angola Dome (~11ºS) contributes to the enhancement of chlorophyll concentration during the boreal Winter when the nutricline is closer to the surface (Longhurst A., 1998).

The Upwelling cells play an important role and have a strong relationship with chlorophyll pattern.

From Lüderitz to Walvis Bay (~21-27ºS) chlorophyll concentration is intense due to upwelling constant events that can reach several kilometers offshore.

The Orange's River- Namaqua cell (~29ºS) have chlorophyll enhancement due to upwelling events and Orange Water River discharge seaward extend.

Cape Columbine-Cape Peninsula (~32.5-34.5ºS) shows the growth and decay of several tongues of upwelled cool water due to wind. (Longhurst A. 1998; Shannon L.V. et al. 1985)

The Southern Benguela region presents the greatest values during the Summer upwelling season and in Winter along the central Namibian coast. At Lüderitz, wind mixing is strong for most of the year however chlorophyll biomass is low, beginning to enhance downstream of this upwelling cell. This low chlorophyll biomass in areas of very strong wind mixing is probably because the wind mixes the phytoplankton out of the well-lit surface water, thereby limiting photosynthesis despite the enhanced nutrient levels. Otherwise, elevated chlorophyll levels are observed downstream during peak upwelling in the Namaqua and Cape Frio cells. (Hardman- Mountford N.J. et al., 2003).

Nowadays, Satellite Images allows to obtain chlorophyll data in situ. However some physical aspects as plumes could increase chlorophyll levels which can affect determination by satellite. In fact, findings within 500km offshore show higher chlorophyll concentrations at Lüderitz than equatorward. Otherwise, Lüderitz’s filaments have been observed over 1000km offshore. Such differences could be due to the influence of cloudiness which differs between regions. Thus, northern region seaward cloud coverage is almost constant whereas upwelling areas cloudiness was much lower. (Campillo-Campbell et al., 2004).

2) Chlorophyll Data

Chlorophyll concentration for 2005, 2006 and 2007 along the track ship line showed similar patterns with higher values during upwelling seasons and at the position of upwelling cells areas.

September 2005 data (Fig. 33) showed maximum (~3mg m^{-3}) at 1.8º and 21.5ºS coincided with equatorial upwelling area in EDZ and Walvis Bay upwelling cell in Central Namibia region, but other peaks are identified (~1.9mg m^{-3}) at 6.5ºS in Congo-Angola region and 14.5ºS in Northern Namibia region and another input in Lüderitz region (26ºS) (~2.56mg m^{-3}) linked with the upwelling cells areas.

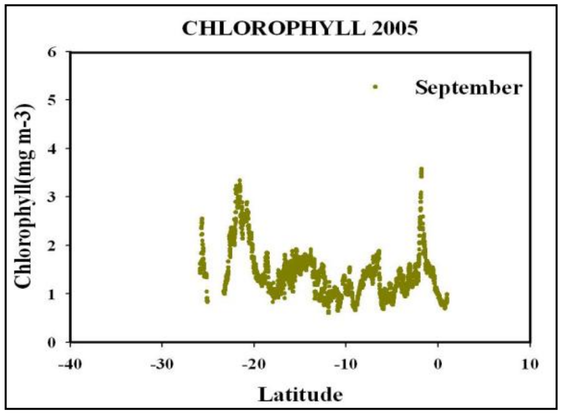


Fig. 33. Chlorophyll 2005.

2006 chlorophyll data (Fig. 34) showed a relatively similar pattern during the year. In fact, during Winter (July-August-September) chlorophyll concentration showed its highest values (~5-2mg m^{-3}) in Southern Benguela region (28-33ºS). During Spring (October) a decrease in mean chlorophyll concentration can be observed even in the upwelling cell areas. Furthermore from 0º to 28ºS a light increase in the regular chlorophyll concentration can be identified fitting to the permanent upwelling cells ~3º-14º-21º-28ºS during Winter and Spring.

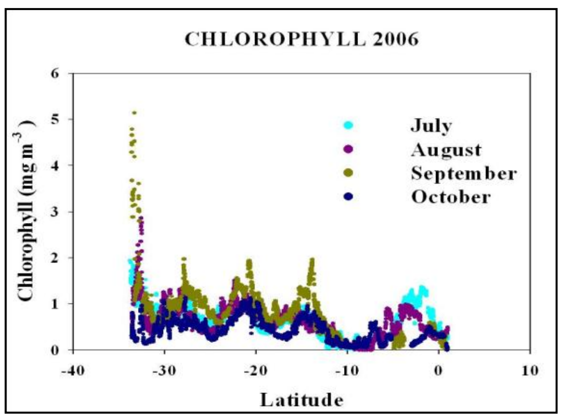


Fig. 34. Chlorophyll 2006.

During 2007 Winter (July-September) chlorophyll peak (~1.7mg m^{-3} August) has been detected around ~4ºS in EDZ coinciding with equatorial upwelling strongest season. However, July chlorophyll concentration in this region decreased (0.80-0.85mg m^{-3}) but it is over the mean. Otherwise along this season other peaks in chlorophyll can be detected (1.30mg m^{-3}) at Lüderitz region (27ºS) during July and August and (1-0.90mg m^{-3}) at Central Namibia region (23ºS). In Autumn (June) the maximum (~1.43 mg.m^{-3}) is located at 23ºS in Central Namibia region with another peak (0.64mg m^{-3}) observed at ~13ºS in Angola Gyre region. (Fig. 35)

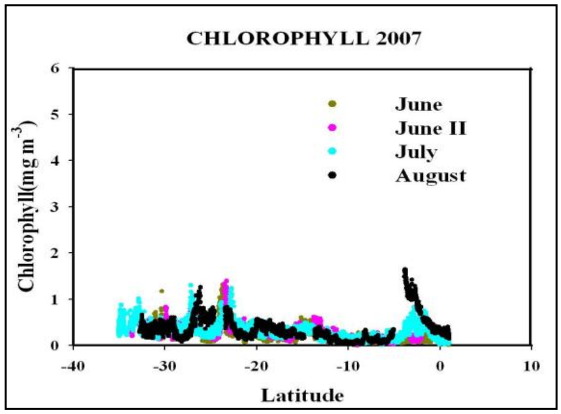
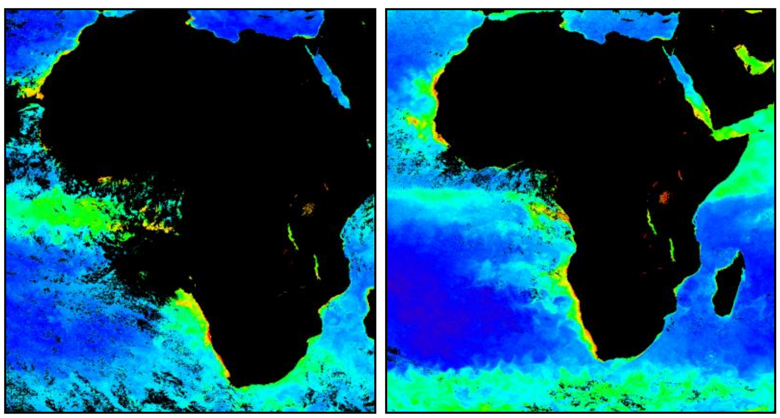


Fig. 35. Chlorophyll 2007**.**

Some peaks of chlorophyll have been observed along data 2005, 2006 and 2007 at similar latitudinal position. These have a strong relationship with upwelling cells from Lüderitz to Walvis Bay (~21-24ºS), the Orange's River- Namaqua cell (~29ºS) and Cape Columbine-Cape Peninsula (~32.5-34.5ºS). (Fig. 36)



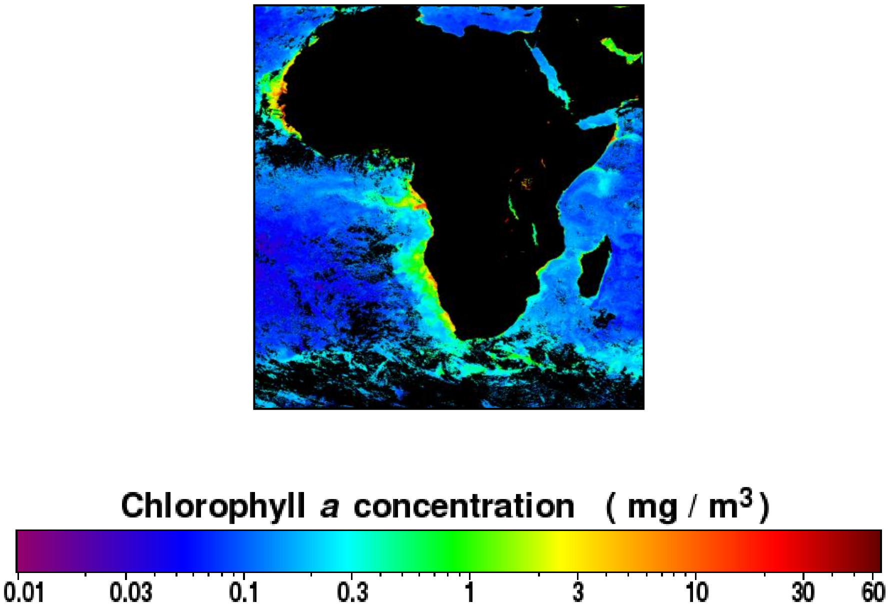


Fig. 36.Satellite Images: a) August 2007, b) December 2005 and c) May 2006.

CONCLUSIONS

Southeast Atlantic hardly ever has been study especially offshore until ~30ºS, being all study carried out until nowadays inshore. This study has been realized offshore during long time and allows us to understand the behavior of parameters such as temperature, salinity, oxygen and chlorophyll *a* in this complicated area, and will serve as starting point for future studies about climatic change.

To study this area at the Southeast Atlantic Ocean we considered seven different regions. Nearly regions such as EDZ and Angola Gyre show clear different pattern in the same season due to the presence of physical structures like the equatorial upwelling or the Angola Gyre together with Angola Dome linked to the Subtropical Gyre Circulation. Everything allow us to establish two identified general areas, the northern one being above the ABFZ until Equator characterized by saline, warm and low oxygen waters of tropical-subtropical origin; and the southern one from ABFZ until around 34ºS characterized by oceanic waters (OW) under SACW and sub-Antarctic influence with low temperature and salinity.

During the study important finding were defined:

Temperature. - Shows a bimodal pattern with higher values in Summer-Autumn and lower during Winter-Spring. Otherwise temperatures are higher around Equator latitude decreasing nearly Southern Benguela region. Meanwhile regions study allow us to detected an increase of temperature in the northern ones during Summer-Autumn (January-May) agree with the Angola Dome (10ºS) presence, as well as the temperature decrease in the area during the Dome absence in the second part of the year. This feature agrees with the upwelling equatorial season being absent in Summer-Autumn when temperatures are higher and developed in Winter-Spring when a decrease in temperature is detected (0-7ºS) linked to the Subtropical Gyre Circulation.

Salinity. - water masses and currents for the area, as well as the precipitations and river discharges, influence salinity values; lower ones (34.5) have detected in Southern Benguela region (28-34ºS) due to the cold and low salinity water of sub-Antarctic influence linked to the cold upwelling Benguela Current water as well as the warm waters forming part of the retroflexion process. Meanwhile highest values (36.8) have been processed mainly in Angola Gyre region (10-14ºS) detecting a new decrease towards Equator but no so strong.

Oxygen. - oxygen also shows a bimodal pattern in the annual distribution inversely related to SST with the highest values during Winter-Spring and lower in Summer-Autumn. Otherwise lowest values (195µmol kg^{-1}) can be detected around Equator due to tropical-subtropical low oxygen water, showing an increasing around 20ºS where oceanic waters dominate. In fact, going down southward oxygen concentration (in surface water) reaches its highest value (265µmol kg^{-1}) in Southern Benguela region where rich oxygen water from SACW, STF and from upwelling process are present.

Chlorophyll *a*. - A pattern in the concentration with values around 2mg m^{-3} related to the upwelling season in the Equator can be detected (Winter/Spring). Otherwise it can be identified around upwelling perennial areas along Southeast Atlantic higher chlorophyll concentration especially in the Southern Benguela region (28-34ºS) where chlorophyll values can reach 4mg m^{-3} due to the nearby shore and processes like upwelling rich-nutrient water as well as filaments and retroflexion process.

Equatorial upwelling (0-7ºS) is stronger in Winter showing lower temperatures and higher chlorophyll *a* and a second one during Spring linked to the Subtropical Gyre Circulation system and the presence of cyclonic gyred centred at 1.5ºS.

The Angola Cyclones (12ºS) favours the water masses circulation offshore together with the Angola Dome during Summer-Autumn seasons (January-May). The SST is higher when the Dome is developed, showing also chlorophyll *a* and oxygen of Oceanic Water characteristics.

ABFZ (~15-17ºS) can be considered as the limit between northern and southern regions having different water masses, temperature and oxygen content. This physical boundary migrates southward during Autumn fitting with water masses movements.

More studies are planned to increase our knowledge about interannual variability and its relation with large scale climatologically forcing.

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GLOSARY

VOS: Volunteer Observing Ship.
ETRA: Eastern Tropical Atlantic Province.
SALT: South Atlantic Gyral Province.
BENG: Benguela Current Coastal Province.
EDZ: Equatorial Divergence Zone.
ABFZ: Angola-Benguela Frontal Zone.
SAA: South Atlantic Anticyclone.
SEC: South Equatorial Current.
sSEC: Southern South Equatorial Current.
SECC: South Equatorial Countercurrent.
BC: Benguela Current.
ITCZ: Intertropical Convergence Zone.
STSW: South Tropical Surface Water.
TSW: Tropical Surface Water.
OSW: Oceanic Surface Water.
MSC: Mediterranean Shipping Company.
SST: Sea Surface Temperature.
SSS: Sea Surface Salinity.
BCLME: Benguela Current Large Marine Ecosystem.
ROW: River Orange Water.
SASW: South Atlantic Surface Water.
SACW: South Atlantic Central Water.
CUW: Cool Upwelled Water.
STF: Subtropical Front.
ETSA: Eastern Tropical Southeast Atlantic.
EU: Equatorial Undercurrent.
SEUC: Southern Equatorial Undercurrent.
LOW: Low Oxygen Water.
AOU: Apparent Oxygen Utilized.