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MARISA FRANCISCA DE NOVATO MACUÉRIA

WARM AND COLD EVENTS IN THE TROPICAL EASTERN ATLANTIC OFF ANGOLA

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MARISA FRANCISCA DE NOVATO MACUÉRIA

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Dissertação apresentada ao Programa de Pós-graduação em Oceanografia da Universidade Federal de Pernambuco, como requisito parcial para obtenção do título de Mestre em Oceanografia.

Área de concentração: Oceanografia Abiótica.

Orientador: Prof. Dr. Moacyr Cunha de Araújo Filho.

Coorientador: Prof. Dr. Marcus André Silva.

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ABSTRACT

Upwelling occurs along large portions of the Angola's coast enhancing biological productivity with positive reflex to local economy and food security. To investigate the occurrence of warm and cold events off the Angolan coast (006º-018ºS) 9,529 vertical profiles of temperature, salinity and dissolved oxygen collected during 1995-2016 in the austral summer (Feb-Apr) and winter (Jul-Aug) under the EAF-Nansen Program were analysed. The dataset was classified according to the occurrence of warm (Benguela Niño), cold (Benguela Niña) and neutral (normal) Sea Surface Temperature anomalies for each season. A strong seasonality in near surface temperature and salinity was detected. During austral summer the ocean off Angola is fresh and warm, while during austral winter it is saltier and colder. However extreme events Benguela Niño and Niña are more likely to occur during austral summer. Benguela Niño is marked by a poleward intrusion of warm equatorial water and by reduced upwelling. Results showed the strong influence of the Angola Current warm waters being transport southward. Low salinity waters (34) were observed associated to abnormally high river discharges (Congo and Kwanza) and direct precipitation that appears contribute to the development of warm events by enhancing the stratification. A maximum salinity value (35.8) was observed in the Angola-Benguela Front region while in the open sea salinity remained in the range of 35 along the entire platform. During Benguela Niña events cold and salty water masses were verified along the coast. Cold waters from the Benguela Current move northwards and reach Lobito (12°S). In the northern (6º-9°05'S) and central region (9°05'-13°S) temperature ranged from 21-24°C and at the south region (13-18°S) from 14° to 20°C. Salinity values along the coast ranged from 35.6 to 35.8 except in the area under the influence of the discharges of the Congo River. One of the world's most pronounced oxygen minimum zone (OMZ) is found below the productive surface layer of the Angola's Sea. Dissolved oxygen (DO) concentrations along the coast of Angola are in general lower during austral winter than during austral summer and much lower during normal and Benguela Niña years relative to Benguela Niño years. During the austral summer DO concentrations varies from 1.5 to 4.0 $mL.L^{-1}$ in normal, 2 to 3 $mL.L^{-1}$ in Benguela Niño years and 0.0 to 1.5 $mL.L^{-1}$ in Benguela Niña years. During austral winter DO varied from 2 to 3.5 $mL.L^{-1}$ in normal (except at 7°S where small lenses of the OMZ reached the coast) and 2-3 $mL.L^{-1}$ in Benguela Niño years. In the years of Benguela Niña the OMZ is spread offshore reaching ~7ºS. Along the coast, the DO ranged from 1.5 to 3 $mL.L^{-1}$, reaching 3.5 $mL.L^{-1}$ between 6º and 7º13'S.

Keywords: Eastern boundary currents. Trapped waves. Tropical Atlantic. Benguela Current. Angola Current. Benguela Niño/Niña.

RESUMO

A ressurgência ocorre ao longo de uma grande porção da costa de Angola, aumentando a produtividade biológica com reflexo positivo para a economia local e a segurança alimentar. Para investigar a ocorrência de eventos quentes e frios ao largo da costa angolana (06º-018ºS), foram analisados 9.529 perfis verticais de temperatura, salinidade e oxigênio dissolvido (OD) coletados durante o verão (F-A) e inverno (J-A) austrais de 1995-2016no âmbito do Programa EAF-Nansen. Os dados foram classificados de acordo com a ocorrência de anomalias de SST, sendo positivas para os anos extremamente quentes (Benguela Niño), negativas para os anos extremamente frios (Benguela Niña) e neutros (normais) para os anos dentro do padrão. Uma forte sazonalidade foi detectada na temperatura e salinidade próximas à superfície. No verão austral, o oceano ao largo de Angola é fresco e quente, enquanto no inverno austral é mais salgado e frio. No entanto, eventos de Benguela Niño/Niña são mais prováveis de ocorrer durante o verão austral. Benguela Niño é marcado por uma intrusão de água quente equatorial em direção aos polos e por uma ressurgência reduzida. Os resultados mostraram a forte influência das águas quentes da Corrente de Angola sendo transportadas para o sul. Águas de baixa salinidade (34) associadas à precipitação direta e a descargas anormalmente altas dos rios (Congo e Kwanza) foram observadas, o que parece contribuir para o desenvolvimento de eventos quentes com o aumento da estratificação. Um valor máximo de salinidade (35,8) foi observado na zona da frente Angola-Benguela, enquanto a salinidade permaneceu na faixa de 35 no mar aberto ao longo de toda a plataforma. Nos eventos de Benguela Niña, as massas de água fria e salgada foram observadas ao longo da costa. As águas frias da Corrente de Benguela se moveram na direção norte chegando à área de Lobito (12°S). No norte (6-9°05'S) e na região central (9°05'-13°S), a temperatura variou de 24 a 21°C e na região sul (13-18°S) de 14 a 20°C. A salinidade ao longo da costa variaram de 35,6 a 35,8, exceto na área sob a influência da descarga do rio Congo. Uma das zonas de mínimo oxigênio (*OMZ*) mais pronunciadas do mundo é encontrada abaixo da camada superficial produtiva do mar de Angola. As concentrações de OD ao longo da costa de Angola foram geralmente mais baixas durante o inverno austral do que durante o verão austral e muito mais baixas durante os anos normais e de Benguela Niña em relação aos anos de Benguela Niño. Durante o verão austral as concentrações de OD variam de 1,5-4,0 $mL.L^{-1}$ em anos normais, 2-3 $mL.L^{-1}$ em anos Benguela Niño e 0-1,5 $mL.L^{-1}$ em anos Benguela Niña. Durante o inverno austral a OD variou de 2-3,5 $mL.L^{-1}$ em anos normais (exceto em 7°S onde pequenas lentes do OMZ atingiram a costa) e 2-

3 $mL.L^{-1}$ em anos Benguela Niño. Nos anos de Benguela Niña o OMZ se estende até chegar a ~7ºS. Ao longo da costa, o OD variou de 1,5-3 $mL.L^{-1}$, atingindo 3,5 $mL.L^{-1}$ entre 6º e 7º13'S.

Palavras-chave: Correntes de borda leste. Ondas apresionadas. Atlântico Tropical. Corrente de Benguela. Corrente de Angola. Benguela Niño/Niña.

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LIST OF ACRONYMS

ABFZ	Angola-Benguela Frontal Zone (or Angola-Benguela Front, ABF)
AC	Angola Current
ACC	Antarctic Circumpolar Current
AD	Angola Dome
AG	Angola Gyre
AVHRR	Advanced Very High Resolution Radiometer
BC	Benguela Current
BUS	Boundary Upwelling System
CTWs	Coastal Trapped Waves
EBUS	Eastern Boundary Upwelling Systems
EKWs	Equatorial Kelvin Waves
EUC	Equatorial Undercurrent
FAO	Food and Agriculture Organization
GC	Gabon Current
IEKW	Inter-annual Equatorial Kelvin Wave
IWBC	Intermediate Western Boundary Current
MLD	Mixed Layer Depth
NADW	North Atlantic Deep Water
NBC	North Brazil Current
NBUS	Northern Benguela Upwelling System
NOAA	National Oceanic and Atmospheric Administration
NORAD	Norwegian Agency for Development Cooperation
OGCM	Ocean General Circulation Model
OMZ	Oxygen Minimum Zone
PUC	Poleward Undercurrent
SAA	South Atlantic Anticyclone
SACW	South Atlantic Central Water
SCOW	Scatterometer Climatology of Ocean Winds
SECC	South Equatorial Countercurrent
SEUC	South Equatorial Undecurrent
SST	Sea Surface Temperature
SSTA	Sea Surface Temperature Anomalies

TA	Tropical Atlantic
TMI	TRMM Microwave Imager
TJ	Tsuchiya Jet
TRMM	Tropical Rainfall Measurement Mission
WOCE	World Ocean Circulation Experiment

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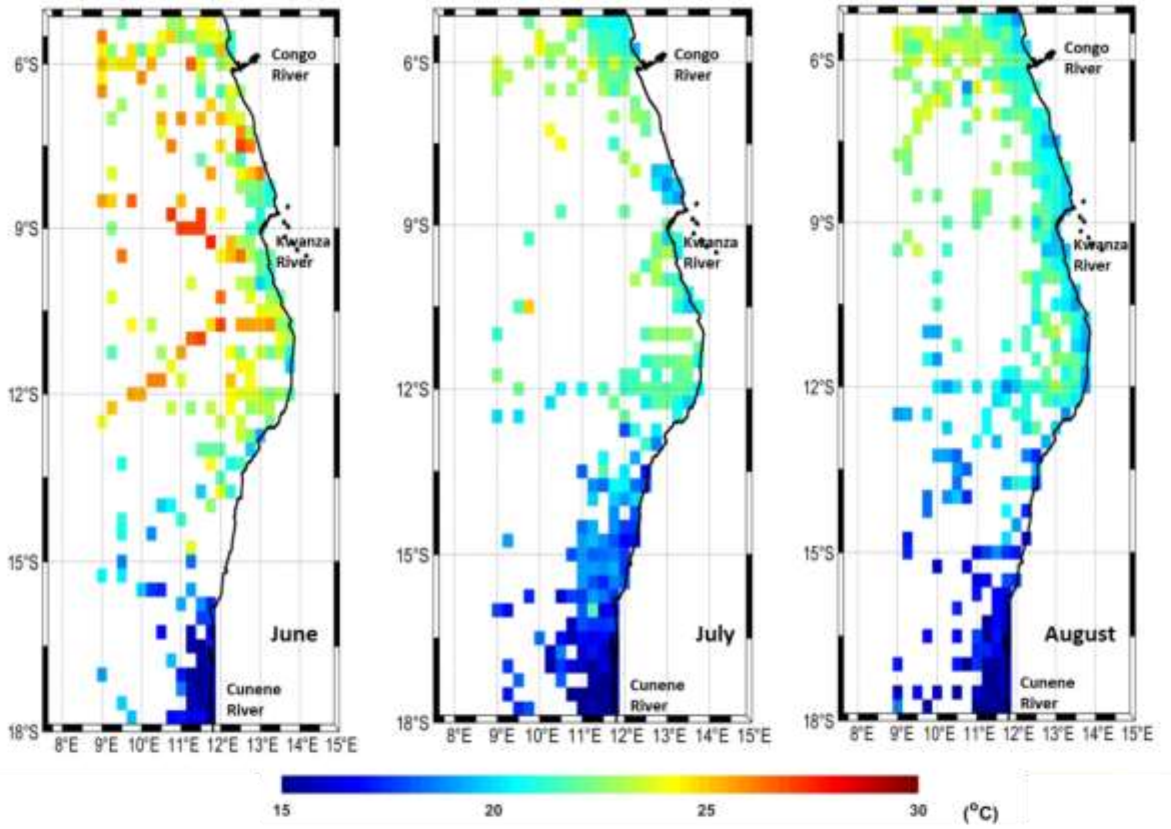
1 INTRODUCTION

The sea of Angola has a strong ecosystem due to the Benguela upwelling region, which is one of the four major Eastern Boundary Upwelling System (EBUS) found in the world oceans (CARR; KEARNS, 2003; CHAVEZ; MESSIÉ, 2009), being separated by the Angola-Benguela Frontal Zone (ABFZ) at its southern boundary (LASS *et al.*, 2000; MEEUWIS; LUTJEHARMS, 1990; SHANNON *et al.*, 1987), is position the tropical Angolan system. This is also a highly productive region, but the productivity appears to be supported by a different physical mechanism (OSTROWSKI *et al.*, 2009). Contrary to the major EBUSs, where persistent alongshore winds drive quasi-permanent coastal upwelling, winds off Angola are generally weak throughout the austral summer (February/March/April) (HELLERMAN, 1980). However, seasonal upwelling occurs in large parts of Angola's coastal zone mainly during austral winter (June to August; Fig.1), being of tremendous importance for the country's fishing sector and food security of the coastal population (KOPTE *et al.*, 2017). Previous studies propose that the seasonal conditions on the shelf of Angola are controlled to a large extent by seasonal Coastal Trapped Waves (CTWs), which originate in the equator (BERRIT, 1976; OSTROWSKI *et al.*, 2009; PICAUT, 1983; TCHIPALANGA *et al.*, 2018). Four seasonal waves per year propagate along the southwest coast of Africa down to 15ºS (satellite altimetry data) (LAZAR *et al.*, 2006; OSTROWSKI *et al.*, 2009; ROUAULT, 2012; SCHOUTEN *et al.*, 2005). The first downwelling (high sea level) propagation arrives at the Angolan coast in March/April, followed by an upwelling (low sea level) in July/August. The second cycle begins with downwelling in October and ends with weak upwelling in December/January, where CTW coincides with the main periods of downwelling and upwelling off the coast of Angola (BERRIT; DIAS, 1977; OSTROWSKI *et al.*, 2009). Oceanographic changes over the shelf are locked to this last cycle. During downwelling, concurrent with the rise in sea level, the thermocline deepens, the coastal current intensifies polewards and the top layer becomes dominated by warm and low-salinity water of equatorial origin. During upwelling, sea level drops, the thermocline shallows, the current decelerates, and masses of nutrient-rich, central water rise to within 20 m of the sea surface (OSTROWSKI, 2007). These features are consistent with published accounts of El Niño and La Niña events in the Pacific (HUYER *et al.*, 2002; KOSRO, 2002).

Ocean circulation in tropical Angola system is dominated by the poleward flowing Angola Current (AC). Supplied by the equatorial current system, the AC is assumed to represent a key component in the advection of warm tropical waters towards the northern Benguela, where it converges with the northward flowing Benguela Current (BC) (KOPTE *et al.*, 2017; PETERSON; STRAMMA, 1991; ROUAULT *et al.*, 2007; TCHIPALANGA *et al.*, 2018; WACONGNE; PITON, 1992). Descriptions of the exclusive AC relied on sporadic synoptic observations so far (DIAS, 1983a,b; KOPTE *et al.*, 2017; MERCIER *et al.*, 2003; MOHRHOLZ *et al.*, 2001; MOROSHKIN *et al.*, 1970), leading to the perception of a continuous poleward current, which is stronger during austral summer and weaker during austral winter. However, detailed assessments of the mean properties of these currents and its associated variability are still pending.

Oceanographic conditions and fish-stock distributions off Angolan coast show large variations on a broad range of time scales that can partly be associated with the occurrence of oceanic warm events in the region. On inter-annual time scales these intermittent events are known as Benguela Niños (SHANNON *et al.*, 1985) and often are thought to be induced by a wave response to the remote equatorial forcing in western equatorial Atlantic (BACHÈLERY *et al.*, 2016; FLORENCHIE *et al.*, 2003; LÜBBECKE *et al.*, 2010; ROUAULT *et al.*, 2007) Nonetheless, also local forcing is assumed to modulate the characteristics and strength of these extreme events (RICHTER *et al.*, 2010). Benguela Niño events are characterized by the poleward intrusion of warm tropical waters into the northern Benguela upwelling region located off Namibia coast. These events have substantial impact on primary production, fisheries and agricultural sectors of the adjacent countries (BOYER; HAMPTON, 2001; GAMMELSRØD *et al.*, 1998), as well as on rainfall variability over south western Africa (LUTZ *et al.*, 2015; ROUAULT *et al.*, 2003; ROUAULT *et al.*, 2009). In this context, the AC is expected to be a major transport agent for the anomalously strong poleward advection of warm tropical waters (ROUAULT *et al.*, 2007). In addition to the intrinsic climate variability, Angola's coastal zone faces challenges in response to global climate change (KOPTE *et al.*, 2017). Recent studies suggest that particularly EBUSs will be heavily impacted by different global warming stressors such as increasing temperatures, acidification and deoxygenation (GRUBER *et al.*, 2011; SCHROLLER-LOMNITZ *et al.*, 2019). Taking all of the above into account, the characterization and quantification of the variability of warm and cold anomalies events and the identification of the physical mechanisms that drive this variability is of the utmost importance for the Angola region.

Figure 1 - Monthly seasonal upwelling average composites of SST with 1/4° of resolution in the Angolan coastal zone during austral winter (June, July and August) derived for the period of 1995–2016 from climatology data set (LOCARNINI *et al.*, 2013).



Source: The author, 2019.

1.1 OBJECTIVES

The objective of this research is to identify, characterize and quantify the patterns of the hydrographic parameters of warm and cold anomalies events in the Angolan sea region.

1.1.1 Objective specific

- Characterize the patterns of the hydrographic parameters (temperature, salinity, oxygen) for the whole study region
- Identify the years of Benguela Niño and La Niña from the anomalies of temperature and characterize according to the salinity and oxygen anomalies
- Characterize the patterns for different regions of the study region.

2 FUNDAMENTAL CONCEPTS: AN OVERVIEW

In the following, the scientific background for this study is briefly introduced. Even though winds Angola are generally weak, present day knowledge show theory of eastern boundary circulation in the region (section 2.1). The equatorial wave's dynamics off the ocean circulation in the tropical e subtropical eastern boundary (section 2.2). The dynamics processes and hydrographic of the Angolan marine system coast (Section 2.3) and the Climate variability (anomalies, warm and cold events) off Angolan marine system coast (sections 2.4 and 2.5).

2.1 THEORY OF EASTERN BOUNDARY CIRCULATION

A number of studies have addressed the theory of wind-driven eastern boundary flows, using numerical or analytical models (ANDERSON; GILL, 1975; FENNEL, 1999; HURLBURT; THOMPSON, 1973; MCCREARY, 1981; MCCREARY; CHAO, 1985; PHILANDER; YOON, 1982; SUGINOHARA; KITAMURA, 1984; YOON; PHILANDER , 1982). According to Philander and Yoon (1982), the response of an inviscid coastal ocean to the sudden onset of a spatially homogeneous alongshore (equatorward) wind can be divided in three phases:

a) Immediately after the onset of the alongshore wind, an accelerating equatorward coastal trapped jet develops inside the wind band. During this phase the flow is two-dimensional, i.e. no alongshore variations are found. Thus, the offshore Ekman transport associated with the coastal current has to be balanced by coastal upwelling;
b) With the onset of the wind, CTWs were initially excited at the equatorward end of the forced region. Propagating poleward, these waves induce alongshore variations in the flow. After the time period the waves need to reach a certain location within the forced area the acceleration of the coastal jet is stopped at this particular spot, as the wind stress is now balanced by an alongshore pressure gradient. Furthermore, the CTWs introduce a Poleward Undercurrent (PUC) since the vertical structure of the waves differs from that of the surface jet. Another effect of the waves is the reduction of the intensity of the coastal upwelling. In a one-level model, upwelling ceases completely. In an N-layer model in which the Coriolis parameter f is constant, the passage of each baroclinic mode CTW would reduce the upwelling until upwelling has stopped after the passage of the Nth mode (PHILANDER; YOON, 1982). Also, each of the baroclinic modes would

modulate the vertical structure of the coastal jet and the PUC. However, since the upwelling has stopped, the Ekman rectification flow supplies the PUC after the passage of the CTWs. Only temporal variations of the wind field can excite new upwelling events (FENNEL, 1999). In reality, the established balance might also be disturbed by the passage of remotely forced waves (STRUB *et al.*, 2013) or coastline irregularities that generate CTWs in a similar manner as alongshore wind variations (CRÉPON *et al.*, 1984);

c) Considering the spherical shape of the Earth, the response is modified by the β-effect, i.e the variation of the Coriolis parameter f with latitude. The final phase to establish equilibrium conditions is then associated with the dispersion of the coastal jet into Rossby waves (ANDERSON; GILL, 1975). Equilibrium conditions are found in the wake of the Rossby waves, which would result in no motion at all in the case of an inviscid shallow water model forced by uniform alongshore winds.

The response of the coastal ocean as described above has to be considered over simplified. As an example, frictional effects are not taken into account. Steady coastal upwelling is only possible for nonzero friction (FENNEL, 1999), which limits the propagation distance of the CTWs particularly for higher baroclinic modes. In addition, by considering spatial and temporal variations of the wind field, the response of the coastal ocean becomes more complex. For example, the existence of a wind stress curl (as introduced by spatial variations of the wind stress) alters the coastal circulation and upwelling strength (HURLBURT; THOMPSON, 1973; MCCREARY; CHAO, 1985). Contrary to the coastal upwelling, curl-driven upwelling is not affected by CTW propagation, and thus provides a mechanism that is able to maintain upwelling independent of the wave response at the coast.

However, as winds are rather weak off the Angolan coast, it seems likely that the response to the local wind as described above is very sensitive to external disturbances like the passage of remotely forced waves. Previous studies have indeed noted that the seasonal conditions on the shelf off the Angolan coast appear to be controlled to large extent by remotely forced waves emanating from the equator (OSTROWSKI *et al.*, 2009; ROUAULT, 2012). Furthermore, intermittent oceanic warm events in the region occurring on inter-annual time scales have often been explained with a wave response to anomalous wind forcing in the western equatorial Atlantic (e.g. BACHÈLERY *et al.*, 2016; FLORENCHIE *et al.*, 2003; LÜBBECKE *et al.*, 2010; ROUAULT *et al.* 2007).

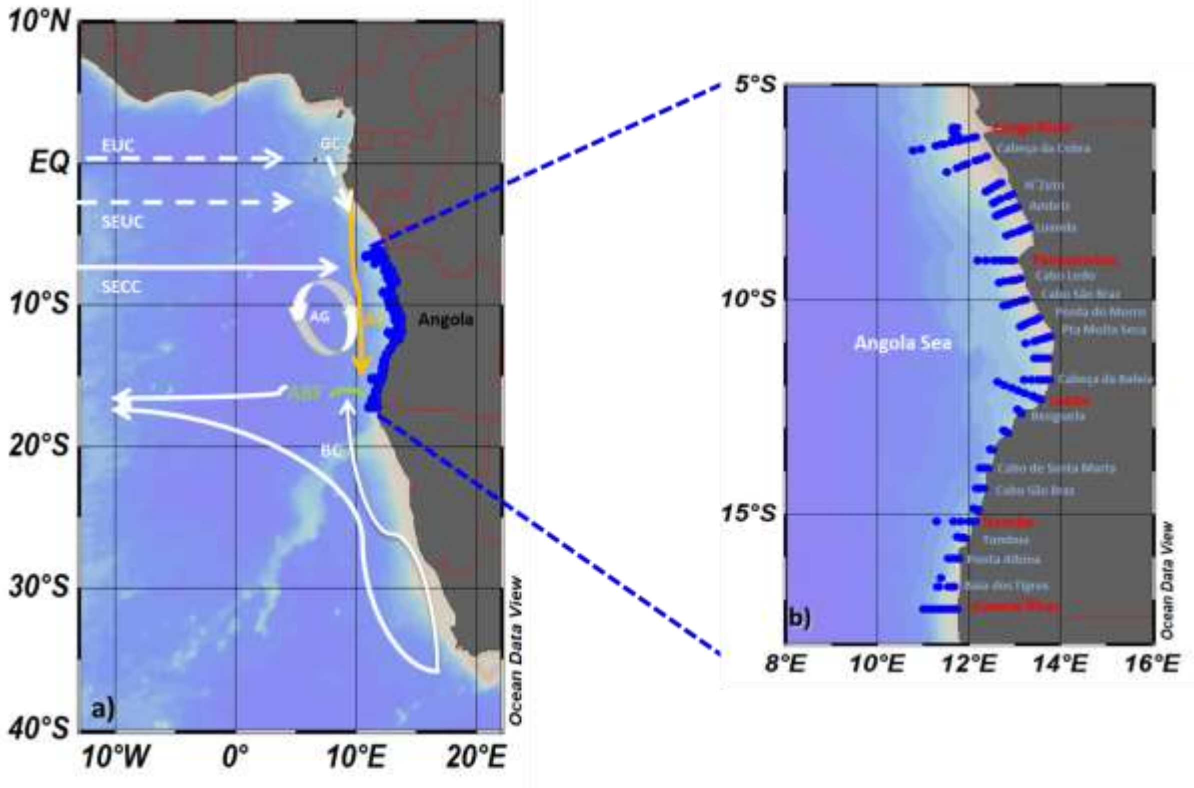
2.2 OCEAN CIRCULATION IN THE TROPICAL AND SUBTROPICAL EASTERN BOUNDARY

The ocean circulation off the southwestern African coast is highly sensitive to equatorial wave dynamics. Eastward propagating equatorial Kelvin waves (EKWs) are initiated by wind stress modulations in the equatorial Atlantic. Upon reaching the African coast, EKWs are reflected as westward-propagating Rossby waves. Additionally, part of the EKW energy is transmitted into poleward-propagating CTWs. Downwelling CTWs are associated with poleward intrusions of warm tropical waters across the ABFZ, eventually causing severe warm events in the northern coast of Benguela (BACHÈLERY *et al.*, 2016; FLORENCHIE *et al.*, 2003; LÜBBECKE *et al.*, 2010). Every few years, SST off the coast of Angola and Namibia reaches values of up to 5°C larger than seasonally normal. These warm events have been named Benguela Niños (SHANNON *et al.*, 1986) by analogy to their Pacific counterpart. In general, they tend to peak in March/April and are triggered by relaxing of wind speed along the Equator in January/February (FLORENCHIE *et al.*, 2003, 2004; LÜBBECKE *et al.*, 2010; ROUAULT *et al.*, 2007).

The ocean currents off the Angolan coast seem to represent a typical eastern boundary circulation system. They are under the influence of different type of currents flowing either at the surface or in the subsurface (countercurrents or poleward currents), as illustrated in Fig. 2a (KOPTE *et al.*, 2017; ROUAULT *et al.*, 2007), including from the equator to the South Pole. The Equatorial Undercurrent (EUC), which is an eastward flowing subsurface current, flows opposite to the trade winds following the depth-dependent eastward pressure gradient (BRANDT *et al.*, 2014). The EUC is mainly fed by the waters coming from the North Brazil Current (NBC), which flows northward along the Brazilian coast in the western part of the Atlantic Ocean (HAZELEGER; VRIES, 2003). The EUC transports high-saline and oxygen-rich water masses eastward along the equatorial Atlantic from the western boundary. Further east, from 1°S to ~6°S, the poleward Gabon Current (GC) is a subsurface current partly fed by the EUC (VERSTRAETE, 1992; WACONGNE, 1988). In the south of the EUC, the South Equatorial Undercurrent (SEUC) flows eastward below the thermocline between 3°S to 5°S (MERCIER *et al.*, 2003). South of the SEUC, between 7°S and 9°S (GORDON; BOSLEY, 1991), there is a remarkable eastward flowing current called the South Equatorial Countercurrent (SECC), which turns south towards the African coast. Like the EUC, relative maxima in salinity or oxygen characterize the SECC and SEUC. The SECC contributes to the northern limb of the Angola Gyre (AG; MERCIER *et al.*, 2003). The southward-flowing warm

Angola Current is found on the eastern limb of the AG. Past studies suggested that the AC is fed by the equatorial current system composed of the EUC, SEUC and the SECC (PETERSON; STRAMMA, 1991; WACONGNE; PITON, 1992). At about 16ºS, the AC converges with the northward flowing BC, thereby forming a highly variable thermal boundary known as the ABFZ (MEEUWIS; LUTJEHARMS, 1990; SHANNON *et al.*, 1987).

Figure 2 - (a) Schematic circulation in the Southeast Atlantic Ocean (modified from KOPTE *et al.*, 2017; ROUAULT *et al.*, 2007). (b) Enlargement of the study area indicating the positions of CTD monitoring lines.



Source: The author, 2019.

Main features are the Equatorial Undercurrent (EUC), South Equatorial Undercurrent (SEUC), South Equatorial Countercurrent (SECC), Gabon Current (GC), Angola Gyre (AG), Angola Current (AC), and Benguela Current (BC). The mean position of the Angola-Benguela Front (ABF) is indicated. Blue dots represent positions of all hydrographic profiles used in this study.

2.3 DESCRIPTION OF THE ANGOLAN MARINE SYSTEM COAST

The Angola marine system coast have one of world´s four major Eastern Boundary Upwelling System. Below are described the dynamic processes of the Angolan marine system coast.

2.3.1 Angola Current

The Angola Current (AC) represents a major feature of the boundary circulation in the southeastern tropical Atlantic, connecting the equatorial Atlantic with the coastal upwelling systems of Benguela (OSTROWSKI *et al.*, 2009; PETERSON; STRAMMA 1991; ROUAULT *et al.*, 2007). Historically, based on synoptic hydrographic data, the velocity structure and transport of the AC had been assumed as a continuous poleward current, yet seasonally varying in strength, thereby adverting warm tropical waters southwards (DIAS, 1983a; MERCIER *et al.*, 2003; MOROSHKIN *et al.*, 1970). These former studies reported subsurface geostrophic southward flow between the surface and 300 to 400 m depth having velocities between 30 $cm.s^{-1}$ and 50 $cm.s^{-1}$ and subsurface velocities exceeding 50 $cm.s^{-1}$ at times. Southward transports of the AC determined by Dias (1983a) were 1.2 Sv and 3.7 Sv from data collected in September 1970 and July 1971, respectively. However, Mercier *et al.* (2003) reported an AC transport of 11 Sv from an inverse study making use of World Ocean Circulation Experiment (WOCE) line A13, which was sampled during a major Benguela Niño event from January to March 1995 (GAMMELSRØD *et al.*, 1998). Since July 2013, two current meters have been in place on the continental slope near 11º8S to investigate both advective and coastally trapped wave (CTW) signals in the Angola Current (KOPTE *et al.*, 2017). These direct velocity observations revealed a strongly variable alongshore flow in the depth range between 45 and 450 m with periodically alternating poleward and equatorward velocities in the range of ±40$cm.s^{-1}$ on submonthly to intraseasonal time scales. A weak southward mean flow was found in the upper 200 m, representing the Angola Current with core velocities of 8 $cm.s^{-1}$ at about 50 m depth and an associated southward mean transport of 0.32 Sv (1 Sv =$10^6 m^{-3}.s^{-1}$; KOPTE *et al.*, 2017).

2.3.2 Benguela Current

The Benguela Current (BC) is the broad north-westward flow adjacent to southwestern African coast, forming the eastern limb of the South Atlantic Subtropical Gyre, which develops near Cape Agulhas (GARZOLI; GORDON, 1996; PETERSON; STRAMMA, 1991; STRAMMA; PETERSON, 1990). At 30ºS, as defined by the adjusted sea surface dynamic topography of Reid (1989), the entire Benguela Current is confined between the African coast and the Walvis Ridge. Reid (1989) shows that the northward flowing current primarily involves the thermocline and Antarctic Intermediate Water stratum, with deeper water generally spreading southward. Within the Benguela Current are an assortment of energetic anticyclonic eddies derived mostly from the Agulhas retroflection (GORDON *et al.*, 1992; SHANNON, 1985), which flows in a westerly direction between 8 and 22ºS (RODRIGUES *et al.*, 2007). At intermediate depth, the flow towards South America is more zonal and, once it reaches the boundary in the Santos Bifurcation (BOEBEL *et al.*, 2003), about two-thirds of the intermediate water contribute to the Brazil Current and one-third to the northward flowing Intermediate Western Boundary Current (BOEBEL *et al.*, 2003; DUNCOMBE RAE *et al.*, 1996; SCHMID *et al.*, 2000; SMYTHE-WRIGHT *et al.*, 1996).

The thermohaline fluxes of the Benguela Current are an important part of the South Atlantic meridional flux, balancing to some level the poleward movement of the warmer, saltier thermocline water within the Brazil Current. Special attention has been given to this aspect, as the heat flux across 30ºS in the South Atlantic is directed toward the equator (SAUNDERS; KING, 1995), attributed to the thermohaline circulation associated with North Atlantic Deep Water formation (GORDON, 1985). The water of the Benguela Current is considered to be drawn from three sources (GORDON *et al.*, 1992): The South Atlantic Current, which is the southern limb of the South Atlantic subtropical gyre; the Agulhas Current, the south Indian western boundary current; and the sub-Antarctic water from the Antarctic Circumpolar Current. Water from the Indian Ocean enters the Atlantic through the shedding of eddies from the Agulhas retroflection and a small amount through quasi-stationary branching of the Agulhas Current on the continental margin.

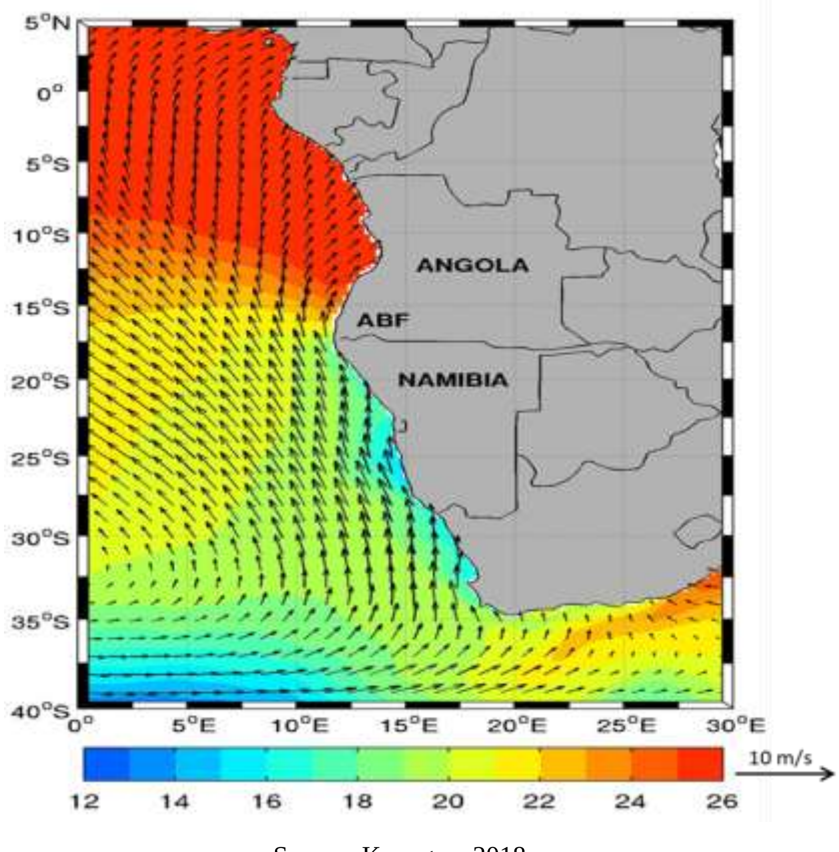
The Benguela upwelling system comprises several cells along the southwestern African coast (LUTJEHARMS; MEEUWIS, 1987). In the light of their study, and others, the Lüderitz cell, near 25ºS, is considered to be the most intense, with the lowest mean SST of the eight wind-driven cells they identified in the southeastern Atlantic, explained by the wide shelf and low eddy activity (LACHKAR; GRUBER, 2012). The northernmost is the Cunene cell, around 18ºS, where the Ekman drift is maximum, similarly to Lüderitz cell (PARRISH *et al.*, 1983).

2.3.3 Angola Benguela Frontal Zone

The Angola-Benguela Frontal Zone (ABFZ, see Figure 2), situated off the coast of Angola and Namibia, is a key oceanic feature in the southeastern Atlantic Ocean. The ABFZ separates the warm sea water of the Angola Current (e.g., KOPTE *et al.*, 2017) from the cold sea water associated with the Benguela Current and upwelling system (e.g., MOHRHOLZ *et al.*, 2004; COLBERG; REASON, 2006, 2007; VEITCH *et al.*, 2006; FENNEL *et al.*, 2012; CHEN *et al.*, 2012; SANTOS *et al.*, 2012; GOUBANOVA *et al.*, 2013; JUNKER *et al.*, 2015, 2017; VIZY *et al.*, 2018). The ABFZ is characterized by a smaller spatial extent and weaker sea surface temperature (SST) gradient compared to the major oceanic fronts generated by the western boundary currents.

Compared to the other EBUS, one of the main specific features of the Boundary Upwelling System (BUS) is that it is encircled by warm waters at his northern and southern boundaries: tropical water from the equatorial Atlantic in the north and warm-water coming from the Agulhas Current in the south. This is well observed in Figure 3 which illustrates the SST and wind stress in austral summer in the southeast Atlantic Ocean. The convergence zone between the warm equatorial waters and the cold upwelled waters from the BUS form a well-defined meridional thermal front called Angola-Benguela Front (ABF) (MOHRHOLZ *et al.*, 2001; SHANNON *et al.*, 1987; VEITCH *et al.*, 2006) as observed in Figure 3. Temperature values across the ABF (difference between the northern and southern boundaries of the frontal zonal) are 2.4°C in austral winter and 4.2°C in austral summer (VEITCH *et al.*, 2006).

Figure 3 - Averaged AVHRR SST and SCOW wind stress (RIESEN; CHELTON, 2008) during austral summer (October to March) from September 1999 to October 2009.



Source: Koungue, 2018.

Veitch *et al.* (2006) also found a meridional SST gradient of 1°C per 34 km across the ABF in austral summer, whereas a 4°C per degree latitude meridional gradient was estimated by Colberg; Reason (2006) in the middle of the ABF. The location of the ABF changes seasonally: ~16°S in austral winter (VEITCH *et al.*, 2006) and further south at ~17.5°S in austral summer (SHANNON *et al.*, 1986; COLBERG; REASON, 2006, 2007; VEITCH *et al.*, 2006, 2010). The ABF zone is also presented as a transition zone between the north tropical ecosystem in Angola and the Northern Benguela Upwelling System (NBUS, from 19°S to 24°S). The ABF is a challenging area to model. The ABF zone is indeed a zone of strong warm SST bias in numerical model especially in coupled ocean-atmosphere model (LI; XIE, 2012; RICHTER; XIE, 2008; RICHTER *et al.*, 2012, 2014; TONIAZZO; WOOLNOUGH, 2014).

The causes of the large warm SST biases in the ABF zone are still under debate. Meeuwis; Lutjeharms (1990) observed that the southeast Atlantic was under the influence of the seasonal shift of the South Atlantic Anticyclone (SAA), which also influences the location of the ABF. Figure 3 shows that along the west African coast, the wind stress is mostly southerly (alongshore). The wind stress is stronger south of the ABF, where it drives a strong upwelling mainly south of 15°S up to the southern tip of Africa (ROUAULT *et al.*, 2007). North of the ABF, the wind stress is weaker throughout the year (OSTROWSKI *et al.*, 2009). Another key feature in the southeast Atlantic is the presence of the Angola Gyre (AG) north of the ABF, illustrated in Figure 2a. However, due to its near-coastal location, the ABFZ plays important roles for the southern African continent, strongly impacting the local marine ecosystem (e.g.,

AUEL; VERHEYE, 2007; CHAVEZ; MESSIÉ, 2009) and regional climate (HIRST; HASTENRATH, 1983; ROUAULT *et al.*, 2003; HANSINGO; REASON, 2009; MANHIQUE *et al.*, 2015).

2.3.4 Angola Gyre

Based on geostrophic analysis, Moroshkin *et al.* (1970) and Gordon; Bosley (1991) revealed that the Angolan current is the eastern branch of the cyclonic Angola gyre, whose center is located at 13ºS and 4ºE (OBERHÃNSLI, 1991; STRAMMA; ENGLAND., 1999) and bounded between latitudes 5ºS and 15ºS. According to the mentioned above authors, the formation of this gyre with clockwise circulation is due to the northeast winds and the morphology of the topography of the continental shelf of the Angolan coast. The northern edge of the gyre is limited by the SEUC flowing eastwards, (MOLINARI, 1982; MOLINARI *et al.*, 1981; REID, 1964) and SECC, branches that feed Angola's current. The gyre has a surface layer of water that suffers from wind action up to about 300 m deep when the drag current reaches a speed of 50 cm.s $^{-1}$ in the coastal zone.

2.3.5 Angola Dome

The other hydrographic characteristics of the Angolan sea, consists of the outcrop structure in offshore, there are several thermal upwelling domes in the World Oceans. One of those in the South Atlantic Ocean is called the Angolan Dome (AD), which was originally identified by Mazeika (1967). He showed that the AD is located near 10ºS - 9ºE. The cold region extends north-westward from the West African coast and it is associated with the cyclonic turn of the SEUC off the Angola coast, which is also called the Tsuchiya Jet (TJ) in the South Atlantic (PETERSON; STRAMMA, 1991; TSUCHIYA, 1986). However, the existence of the AD remained uncertain because of the coarse observation (VOITURIEZ 1981; YAMAGATA; IIZUKA, 1995), using an Ocean General Circulation Model (OGCM), examined the seasonal variation of the AD. They concluded that it is cooled between March and August, and that the surface heat flux plays a major role in its seasonal variation. This is a stark contrast with other domes in the world as they are formed basically by the regional wind-induced upwelling (DOI *et al.*, 2007; MASUMOTO; YAMAGATA 1991; TOZUKA *et al.* 2002; UMATANI; YAMAGATA 1991; VINAYACHANDRAN; YAMAGATA, 1998).

They are characterized by the rise of thermocline, supplying the surface with nutrients (VOITUREZ, 1981; GAMMELSRØD *et al.*, 1998). The location of the Angolan Dome is variable and is generally between 10º and 12ºS. It is a region of high biological productivity, and serves cold outcrops in the centre, low salinity and high oxygen concentration; in the surrounding areas is retention area for eggs and fish larvae (MAZEIKA, 1967).

The AD has a large influence on the regional fisheries and climate of the surrounding countries. For example, when an influx of warm water from the equator toward Angola is unusually large, *Sardinella aurita*, a kind of sardine which likes cold upwelled waters, is repelled southward and is fished in northern Namibia (BINET *et al.*, 2001). Also, when the sea surface temperature (SST) off the Angola coast is anomalously high, the precipitation over Angola tends to become larger (HIRST; HASTENRATH, 1983; ROUAULT *et al.*, 2003). Gammelsrød *et al.* (1998) observed this cyclonic thermal gyre between 12°S and 11°E at 20 m depth. The dome is not visible to the surface and therefore not identifiable by remote sensing. In the eastern Atlantic, the Domes manifest themselves in the eastern parts of the northern and southern sub-surface counter-currents, which move permanently along the equator and are deflected north and south by the north and south trade winds. Current rotation causes the near geostrophic circulation that creates permanent sub-surface thermal domes. In light wind conditions with speeds of 4 $m.s^{-1}$ and poor directional stability, undercurrents are shifted to the surface to the surface, and the deep dome appears above the thermocline (VOITURIEZ, 1981).

Therefore, understanding the seasonal and inter-annual variability of the AD is very important from both societal and economical viewpoints. However, no study has been carried out on the inter-annual variations of the AD partly owing to the sparseness of observational data. One of the main modes of inter-annual climate variability in the Atlantic that may affect the AD is the Atlantic Niño. It is associated with a positive SST anomaly in the eastern equatorial Atlantic, which is similar to the Pacific El Niño (CARTON; HUANG, 1994; ZEBIAK, 1993) and peaks from austral autumn to austral winter. It is sometimes triggered by a relaxation of the zonal wind in the western equatorial Atlantic, which forces the downwelling equatorial Kelvin wave. After reaching the eastern boundary, it propagates poleward along the West African coast and may trigger the Benguela Niño, that is, the penetration of warm Angolan waters through the Frontal Zone (ABFZ) into much cooler Benguela regions located to the south of the Angola region (FLORENCHIE *et al.*, 2003; LASS *et al.*, 2000; MOHRHOLZ *et al.*, 2004; SHANNON *et al.*, 1986).

2.3.6 Angola's Rivers

In the Angola basin, other features likely to be considered are the Congo River and the Kwanza River runoffs. The Congo River is the second largest river in the world (after the Amazon) with an average discharge of 45 000 $m^3.s^{-1}$ and a large range from 23,000 to 80,000 $m^3.s^{-1}$ (EISMA; VAN BENNEKOM, 1978). The Congo River alone, whose drainage basin covers 4 million km^2 over Central Africa, releases every year 1,270 km^3 of freshwater into the ocean (WELDEAB *et al.*, 2007).

Eisma and Van Bennekom (1978) were the first to describe the Congo River plume, finding it to be oriented generally towards northwest (see also BRAGA *et al.*, 2004) rather than towards the south, as might be expected due to the location of the river (6°S) and the influence of the Coriolis effect. In the modelling study of Denamiel *et al.* (2013) it was suggested that the northward extension of the plume can be explained as a buoyancy-driven upstream coastal flow that is influenced by geomorphology of the Congo river estuary (see JANSEN *et al.*, 1984) and combined influences of ambient ocean current and winds. Using Soil Moisture and Ocean Salinity (SMOS) satellite surface salinity and chlorophyll data, Hopkins *et al.* (2013) also found that for most of the year, the main axis of the fresh water plume extends northwest between 400 and 1000 km along the coastline, extending to the Equator and even slightly further north. They suggested that plume is carried northwest by north to north-westerly wind driven currents and possibly the very northern branch of the Benguela Coastal Current.

The Kwanza River is the largest river in Angola with about 1000 km in extension and a river basin that covers an area of 147.690 km^2. It is born in the south of the province of Bié, crossing a vast region characterized by the abundant rainfall of the austral summer and flows into the sea, 70 km south of Luanda (SANGOLAY, 2004).

To the south of the Catumbela River, most of the waterways that can be found up to the Cunene River are intermittent, especially those crossing the Namibe Desert; namely the Caporolo River, Namangando, Bentiba, Giraul and Curoca. This regime briefly constitutes the possible major factor behind the absence of low salinity in this region.

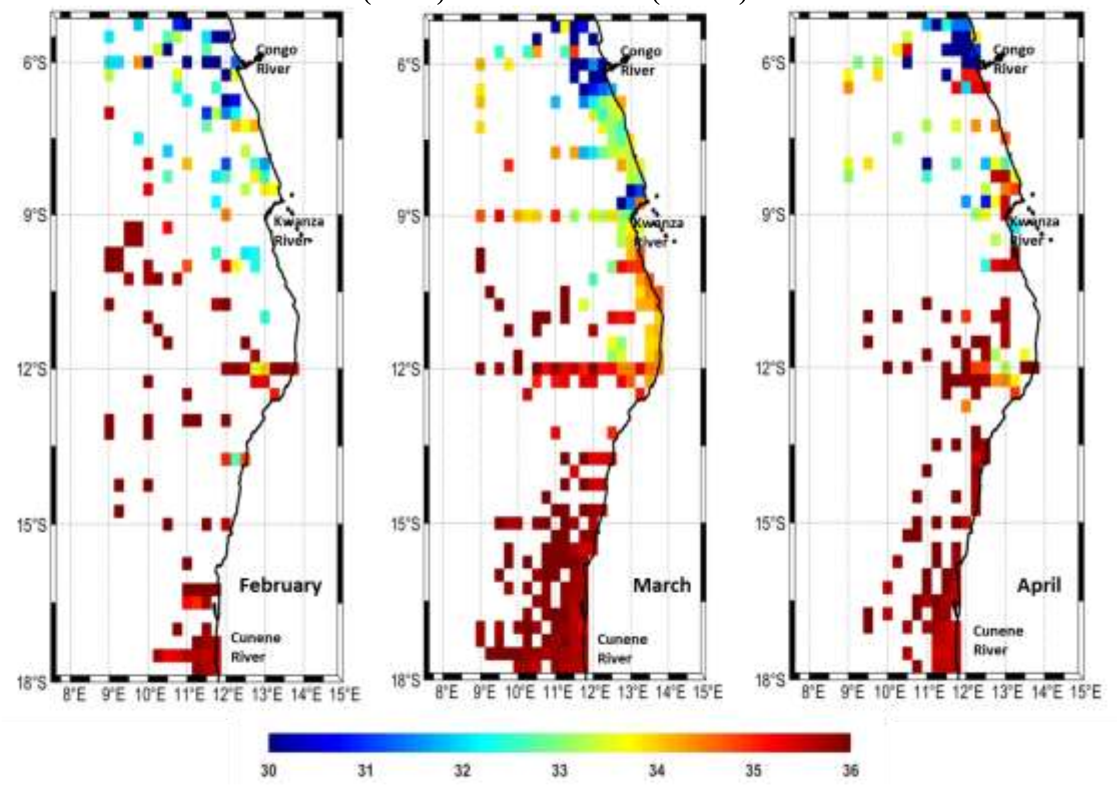
The Cunene River - Apart from the Congo River, the Cunene River occupies the 2nd place among rivers of Angola's coastal ocean in terms of flow and is very variable because it crosses regions with different climates. It is born in Huambo province and flows south of Tigers Bay (17°05'S). The main tributaries of the Cunene River are Calai, Cuvelai, Caculavar and Colui, and have a watershed of 96,400 km^2 (SANGOLAY, 2004).

The flux of freshwater from rivers can have a significant impact on ocean temperatures (e.g., CARTON, 1991; HOWDEN; MURTUGUDDE, 2001; MIGNOT *et al.*, 2012; PAILLER *et al.*, 1999; PARK *et al.*, 2011). To first order, the increased near-surface salinity stratification acts to suppress mixed layer cooling, by reducing entrainment and vertical mixing (BREUGEM *et al.*, 2008). This can lead to increases in mixed layer and SSTs. However, this increase in near-surface stratification usually results in a shallower mixed layer. This decrease in Mixed Layer Depth (MLD) increases the penetrative solar radiative flux leaving the mixed layer at its base. This can lead to a cooling of the mixed layer and hence reduced SSTs.

Studies have been conducted on the oceanic influence of the Amazon and Orinoco rivers (e.g., FERRY; REVERDIN, 2004; FFIELD, 2007; MASSON; DELECLUSE, 2001; PAILLER *et al.*, 1999), the rivers flowing into the Bay of Bengal (VINAYACHANDRAN *et al.*, 2012; HOWDEN; MURTUGUDDE, 2001), the Changjiang (PARK *et al.*, 2011), and Yangtze (DELCROIX; MURTUGUDDE, 2002) rivers, and the Congo River (CARTON, 1991; MATERIA *et al.*, 2012). Results generally show a warming response to the freshwater flux, with the exception of modeling studies by Masson and Delecluse (2001), who found no significant SST impact, and Howden and Murtugudde (2001), who found a cooling effect of river input. These last authors attribute this cooling to two effects: the shallowing of the mixed layer, resulting in a decrease in solar radiation absorbed within the mixed layer; and increased entrainment cooling due to strong current shears induced by the rivers.

According to Binet *et al.* (1983a), the Congo river flow variation associated with the rainfall variation in the zone has a marked repercussion in terms of surface salinity levels in the coastal region under the influence of the tropical climate (5°-13°S). Although the characteristics of the advection and convective processes of salinity reveal the tendency of the increase of this parameter to the south (13°S) to be attributed to the discharge of the Congo River (BINET *et al.*, 1983a; QUILANDA FIDEL, 2001), the figure below (Figure 3) and the description of the rivers presented in it may briefly illustrate the puzzle "low salinity in the north-central coastal Angola ocean".

Figure 4 - Location of major rivers in the coastal zone of Angola and the impact of freshwater on Sea Surface Salinity (SSS) during the austral summer (February, March and April); Congo River (6°00S), Kwanza River (9°30S) and Cunene River (17°12S).



Source: The author, 2019.

Climatology data set are available at Locarnini *et al.* (2013).

2.4 OXYGEN MINIMUM ZONES IN THE ANGOLA SEA

The oceanic oxygen distribution is generally characterised by slightly supersaturated oxygen levels in the surface layer, an intermediate oxygen minimum, and higher oxygen levels at depth (BRANDT *et al.*, 2015). This vertical structure is a consequence of the delicate balance between the supply of oxygen through ventilation and circulation, oxygen production by photosynthesis, and oxygen consumption by remineralisation of sinking organic matter. The horizontal distribution of oxygen shows major large-scale open ocean subsurface oxygen minimum zones (OMZs) in the eastern parts of the tropical Atlantic and Pacific oceans as well as in the northern Indian Ocean (BRANDT *et al.*, 2015). By analysing a combination of historical and modern observations, an expansion and intensification of OMZs in the tropical oceans has been detected (STRAMMA *et al.*, 2008b). OMZs in the tropical Atlantic were first identified by analysing hydrographic data from the German *Meteor* expedition from 1925 to 1927 (WATTENBERG, 1938). This data set revealed the existence of OMZs in both hemispheres of the eastern tropical Atlantic at depths between 300 and 700 m, situated equatorward of the subtropical gyres and separated by an equatorial oxygen maximum.

Off Angola, one of the most pronounced oxygen minimum zones of the global ocean is found below the productive surface layer. Mainly during austral summer the AC appears to be a key element for the southward spreading of warm, saline, low-oxygen South Atlantic Central Water (SACW) within the upper thermocline. SACW originally is formed in the subtropical convergence of the Brazil-Malvinas Confluence Zone (POOLE; TOMCZAK, 1999). It enters the tropical Southeast Atlantic Ocean via the equatorial current system, after being advected through the South Atlantic subtropical gyre. During this journey, SACW properties are constantly altered by continuous remineralization of organic matter causing oxygen depletion and nutrient enrichment plus weak entrainment of North Atlantic Central Water (NACW) within the equatorial current system (POOLE; TOMCZAK, 1999). After all these en route modifications an oxygen-poor subtype of SACW with an approximated pseudo-age of 50 years resides in the Angola Gyre (MOHRHOLZ *et al.*, 2008) that finally is advected poleward towards the northern Benguela by the Angola Current. With Eastern South Atlantic Central Water (ESACW) another central water subtype is present in the vicinity of the ABFZ. ESACW is formed in the Cape Basin representing a mixture of SACW from the subtropical gyre and Indian Central Water that is transferred to the South Atlantic by the Agulhas Current (MOHRHOLZ *et al.*, 2008). From its source region ESACW, which is richer in oxygen than SACW, is transported northward along the Southwest African shelf by the BC. Particularly for the frontal region, the water mass composition, consisting of a mixture of SACW and ESACW, is crucial for the oxygen balance over the shelf (MOHRHOLZ *et al.*, 2008) and strongly depends on the relative strength of the AC and BC.

2.5 PROPAGATION AND ORIGIN OF WARM AND COLD EVENTS

The El Niño Southern Oscillation (ENSO) is the dominant mode of inter-annual variability impacting on most regions throughout the world. Is involves a large-scale oscillation of atmospheric and upper-ocean circulation and properties in the tropical Pacific Ocean and has counterparts in other oceans. When anomalously warm (cold) SST is observed in the equatorial central and eastern Pacific region, such an event is defined as an El Niño (La Niña). El Niño can be further classified into three types; namely warm pool El Niño and cold tongue La Niña, as well as El Niño Modoki (ASHOK *et al.*, 2007). The latter associated with irregular occurrences of anomalous SST warming in the central equatorial Pacific resembling a horseshoe-like pattern, bordered on both sides along the equator by anomalously cooler SST. This phenomenon is similar to El Niño but its global climate implications are different from the conventional El Niño hence the name ‘Modoki’ derived from Japanese meaning ‘a similar but a different thing’. The cold tongue El Niño is characterized by relatively large SST anomalies in the region bounded by 5^0 latitudes (North and South) and 150-90^0 W longitudes whereas the warm pool El Niño tend to have SST anomalies confined in the (5^0N-5^0S, 160^0-150^0W) domain. Furthermore, Kug *et al.* (2009) showed that the precipitation, atmospheric convection and surface zonal wind anomalies associated with both El Niño types differs. Therefore, it is necessary that when measuring the intensity of an El Niño event that both indices are used. It is because of this reason that many studies when analyzing ENSO uses the SST anomalies in the (5^0N- 5^0S, 120^0- 170^0W) region known as the Niño3.4 index. This index comprises of both warm pool and cold tongue El Niño regions.

Warm anomalies, similar to El Niño events, have been recorded by Gammelsrød *et al.* (1995), Hisard (1980, 1988), Hisard *et al.* (1986), Merle (1980), Rouault *et al.* (2003) and Shannon *et al.* (1986) in the tropical Atlantic. The connection between Pacific and Atlantic Walker atmospheric convection cells has been suggested as an explanation of the out-of-phase coupling of the Pacific ENSO and Atlantic Niños/Niñas alternance (PHILANDER, 1990). During a Pacific El Niño, a wide expansion of the zone of rising air over northern South America strengthens easterly winds over the Atlantic, while the reverse occurs during the opposite phase (La Niña): sinking air over the American continent weakens the trade winds and can reverse them to westerly winds. Changes in the wind stress induce changes in the thermocline depth, zonal currents and distribution of warm water masses. During the Atlantic warm phase (an Atlantic El Niño), internal long waves and strengthened eastward currents, triggered by the relaxation of the easterly trade winds, tend to accumulate warm water masses on the African side of the Atlantic. During these warm events, very high rainfalls occur on the northern coasts of the Gulf of Guinea and on the usually arid Angolan and Namibian coasts, and the cold waters of coastal upwelling regions are overlaid by warm waters with low salinity. An "Atlantic Niño" can include a "Benguela Niño" (GAMMELSRØD *et al.*, 1998; SHANNON *et al.*, 1986) and/or a warm event. The historical point of view has also been that the Benguela Niño's were caused by southward intrusion of the warm, saline Angolan current to the Namibian coast, while the most recent understanding is that they are rather caused by the advection of warm, saline" tropical and equatorial water from west and north west, again the same nature as its Pacific counterpart, (SHANNON; NELSON, 1995).The Benguela Niños have a strong impact on the coastal upwelling as low-nutrient, low-oxygen, warm Angola water is advected in the upwelling system in place of cold, nutrient rich upwelled water (MONTEIRO *et al.*, 2006; SHANNON *et al.*, 1986). Benguela Niños often lead to floods in Angola and Namibia and abundant rainfall in the usually arid Namib Desert (ROUAULT *et al.*, 2003; SHANNON *et al.*, 1986). When warm events occur in late austral summer, during the maximum of annual Sea Surface Temperature (SST) and rainfall, they further increase atmospheric instability and coastal rainfall (HIRST; HASTENRATH, 1983), southern African rainfall (NICHOLSON; ENTEKHABI, 1987) and the negative impact on fisheries (BOYER *et al.*, 2001).

2.5.1 The Benguela Niño: An El Niño – like Phenomenon

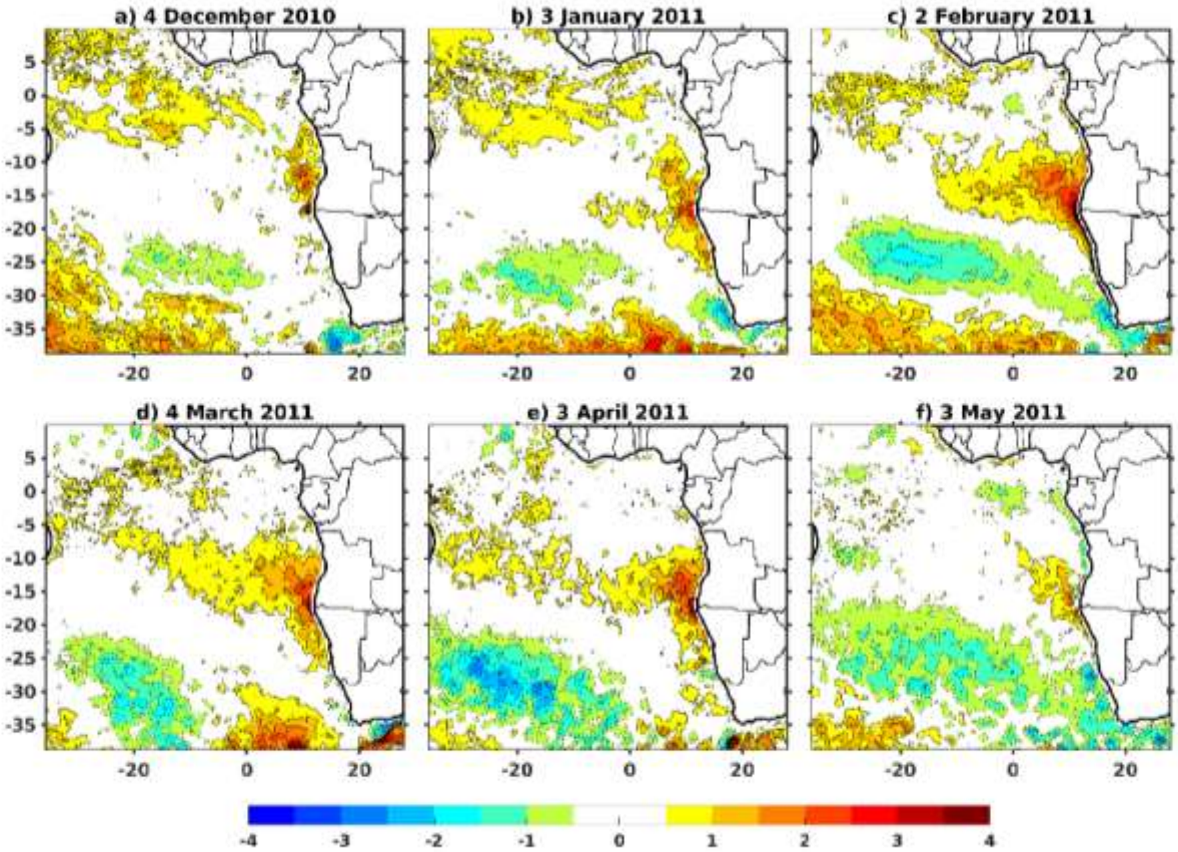
Every few years, an anomalous warming of the ocean surface occurs over the central and eastern equatorial Pacific, persisting for many months, with several impacts over the local ecosystem and climate. This phenomenon is know as El Niño and has been extensively studied (e.g., TRENBERTH, 1997; WANG *et al.*, 2012; YEH *et al.*, 2009). In the equatorial Atlantic, there is also a similar phenomenon, termed the Atlantic Niño (e.g., GARCÍA-SERRANO *et al.*, 2013). In the last decades, several authors have drawn attention to the occurrence of El Niño-like events in the southeast Atlantic, in the upwelling region of Angola-Benguela, which disrupts the climate (NICHOLSON, 1997; REASON; SMART, 2015) and the local ecosystems, with impacts on the marine productivity (BINET *et al.*, 2001). In spite of being less frequent and less intense than the El Niño (SHANNON *et al.*, 1986) given the similarity to its Pacific counterpart and its location, this phenomenon has been termed Benguela Niño (SHANNON *et al.*, 1986). For the same reason, an anomalously cold water event is termed Benguela Niña, following the La Niña in the Pacific.

Benguela Niño events are intermittent, usually peaking in late summer and may persist for period of months (FLORENCHIE *et al.*, 2003, 2004). Such events tend to enhance rainfall over the adjacent landmass (ROUAULT *et al.*, 2003) and are also attributed to drastic reduction of local fish catch (BOYER *et al.*, 2001 cited in ROUAULT, 2012). The 1984 and 1995 Benguela Niño episodes were the most intense (REASON *et al.*, 2006). Florenchie *et al.* (2003, 2004) showed how relaxation of the trade winds over the western tropical Atlantic led to the generation of warm SST anomalies there which propagated to the east as a Kelvin wave and then south along the Congo and Angolan coastlines. As the thermocline shoals towards the surface near the ABFZ, it is this region where the largest SST anomalies tend to be observed a few months after the trade wind relaxation. Thus, in the area between 10 - 20^0S and from 8° E stretching onto the continent, (FLORENCHIE *et al.*, 2004) found maximum SST deviations from the mean. Rouault (2012) showed that this intrusion of warm tropical waters in the Angola-Benguela region occurs twice in year: in the late summer and late spring. Consistent with Florenchie *et al.* (2003, 2004), Rouault (2012) also suggested that Benguela Niños are remotely forced by the weakening trades in the western tropical Atlantic. In addition, the local net heat fluxes at the air-sea interface and local wind stress may also have significant role in SST anomalies offshore of the southern Angola and Northern Namibia respectively. These anomalously warm events tend to reach their maximum during the late austral summer mainly during March-April and originate from the relaxation of zonal wind stress in the western part of the equatorial Atlantic in January-February (FLORENCHIE *et al.*, 2003, 2004; LÜBBECKE *et al.*, 2010; ROUAULT *et al.*, 2007). During a Benguela Niño event, SST can peak up to 4°C more than the seasonal average (ROUAULT *et al.*, 2017). These extreme coastal events can last from few months to half a year or more (FLORENCHIE *et al.*, 2004; ROUAULT, 2012; ROUAULT at al., 2003).

Fig. 5 illustrates the evolution of the 2010/2011 Benguela Niño using SST anomalies (SSTA) from monthly climatology derived from Tropical Rainfall Measurement Mission's (TRMM) Microwave Imager (TMI). The 2010/2011 Benguela Niño reaches its maximum in February 2011 along the Angola - Benguela Current system. SSTA persist till April 2011 and propagate poleward. May 2011 marks the demise of the warm event. The 2010/2011 Benguela Niño is different from the other Benguela Niños as it does not peak in March-April, but in

January and it starts in October 2010. The inverse of the Benguela Niño event is the Benguela Niña event (FLORENCHIE *et al.*, 2004) and Benguela Niña has not been extensively studied in the literature.

Figure 5 - From top to bottom and left to right: TRMM TMI SST inter-annual anomaly from December 2010 to May 2011. Dates correspond to the middle of the monthly time period considered for averaging. Anomalies are departures from the 1998-2011 monthly climatology



Source: Rouault *et al.* (2017).

2.5.2 Forcing mechanisms

Although some Benguela Niño events have already been studied, there is still no consensus about their forcing mechanisms, of local or remote origins, or even if the Benguela Niño is a standalone phenomenon or a southward extension of the Atlantic Niño (e.g., LÜBBECKE *et al.*, 2010), which occurs in the equatorial region of this oceanic basin.

Several hypotheses regarding the remote mechanisms which may force the Benguela Niño events have been suggested, mostly based on the inter and intra-basin relationships between the equatorial Pacific and Atlantic, the equatorial and southeast Atlantic (i.e., the Benguela region) and the equatorial Pacific and southeast Atlantic.

Through a time-space analysis of the evolution of the El Niño-Southern Oscillation (ENSO) signal in the Indic and Atlantic oceans, Nicholson (1997) suggested a connection between the Atlantic and the Pacific basins. The study shows that the equatorial Atlantic reaches its maximum cooling at the end of the year preceding the year of maximum warming on the Pacific (El Niño year). Furthermore, the maximum positive SST anomalies in the equatorial Atlantic are reached at the beginning of the year following the El Niño episode. Polo *et al.* (2014) added that an Atlantic Niño precedes a La Niña event in the Pacific, with a lag of six months between the two occurrences, assigning an order of events. On the other hand, Wang (2006) found no correlation between the Pacific and the Atlantic Niños, but states that the inter-basin SST gradient may influence tropical climate variability, instead of individual surface temperature anomalies. Colberg *et al.* (2004) showed that both the South Atlantic Ocean and its high-pressure system respond to an El Niño phase in the Pacific, with SSTs reaching their maximum at the end of the same year, and a weakening of the anticyclone throughout the year, thus changing the surface heat fluxes with a one-season lag. These results are mostly in agreement with Nicholson (1997). Nonetheless, the relationship between these events and the development of Benguela Niños is still not clear.

Using an ocean general circulation model together with satellite derived SST and sea surface height data, Florenchie *et al.* (2003) concluded that the anomalous warming which led to the Benguela Niños of 1984 and 1995 was originated near the equator, at a depth exceeding 50 m. This signal had progressed eastwards with a propagation rate consistent to the theoretical phase speed value of an equatorial Kelvin wave, until it reached the western coast of Africa, still in-depth. There, the warm anomaly started its propagation poleward, ascending to the surface at the Benguela region as a Benguela Niño event.

Lübbecke *et al.* (2010) agreed with the formation mechanism proposed by Florenchie *et al.* (2003), and added that the propagation of the Kelvin wave is caused by a modification of the trade winds intensity. These authors stated that the warm events at Benguela are preceded by a weakening of the South Atlantic Anticyclone (SAA), the dominant wind system over the basin, which comprises the mid latitude westerlies, the equatorward winds along the west coast of southern Africa and the south-easterly trade winds. A weakening of the anticyclone weakens the trade winds as well, generating equatorial Kelvin waves, which propagate eastward (WANG, 2002), deflecting the thermocline. The equatorial Atlantic SSTs will, therefore, increase, as well as the latent heat flux to the atmosphere (FLORENCHIE *et al.*, 2004).

Shannon *et al.* (1986) referred that changes in the alongshore local winds do not explain SST variations in the Angola-Benguela region. However, based on a coupled ocean-atmosphere model and satellite observations, Richter *et al.* (2010) argued that meridional anomalies in the local wind field are important for the development of a Benguela Niño event. These anomalies would weaken the South Atlantic high-pressure system, causing a warming at the Benguela coast 2 to 3 months later. Even though the authors do not discard the importance Kelvin waves might have on the development of warm events, they claim a variation on the local wind field has a great impact over the two regions.

The forcing mechanisms responsible for the inter-annual variability of SST in Angola - Benguela Current system are discussed in this section and are still under debate. Two principal forcing's mentioned in the literature: Firstly, the local atmospheric forcing mainly explained by variations in the coastal wind stress along the coast of Angola and Namibia. Secondly, the remote oceanic forcing mainly explained by the propagation of Inter-annual Equatorial Kelvin Waves (IEKW) along the equatorial Atlantic, which then, at the African coast, propagate poleward as Coastal Trapped Waves (CTW) (HARDMAN-MOUNTFJORD *et al.*, 2003; SCHOUTEN *et al.*, 2005; POLO *et al.*, 2008).

2.5.3 Impacts

An abnormal increase in sea surface temperature along an upwelling region is a disturbance to the balance already established and brings important consequences to local ecosystems. As the nutrient-rich upwelled water is replaced by saline, warm waters (SHANNON *et al.*, 1986), many species migrate in search of favorable conditions (BINET *et al.*, 2001; ROUAULT *et al.*, 2003; VAN DER LINGEN *et al.*, 2006).

Gammelsrød *et al.* (1998) reported that intrusions of warm waters have been associated with mortalities of sardine, horse mackerel and kob off the coasts of Angola and northern Namibia, and rock lobsters suffer significant mortality when migrating (COCKCROFT, 2001).

Many authors also reported that anomalous warm-water events in tropical southeast Atlantic were connected to increased rainfall in coastal Angola and also in northern Namibia (e.g., ROUAULT *et al.*, 2003; REASON; SMART, 2005; VAN DER LINGEN *et al.*, 2006).

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3 DATA AND METHODS

The next chapter presents results from an extensive in-situ data. The data was acquired within the EAF-Nansen program executed by the Food and Agricultural Organization of the United Nations and funded by Norwegian Agency for Development Cooperation. It provides hydrographic data acquired semiannually cruises on the Angolan continental margin covering more than 20 years. It facilitates the description of the mean seasonal structures of temperature, salinity and Oxygen along the entire Angolan coastline. On interannual time scales the data allows the analysis of anomalies and identification of with regard to Benguela Niño/Niña events in the last 21 years.

3.1 STUDY AREA

Angola coastline extends for 1,650 km and comprises a continental shelf of 51,000 km^2. The Angolan Exclusive Economic Zone (EEZ) extends up to 200 nautical miles from the baseline and occupies an area of 332,000 km^2. The sea of Angola is under the influence of two major marine systems, the Gulf of Guinea to the north and west, and the Benguela Cold Current from the south, with the Angola-Benguela Frontal Zone (ABFZ) located a couple miles north of its southern boundary (LASS *et al.*, 2000; MEEUWIS; LUTJEHARMS, 1990; SHANNON *et al.*, 1987).

The Angolan coast is characterized by high primary production due to coastal outcroppings, that favours a high biological productivity and biodiversity (BENEFIT, 2001; BIANCHI, 1986) thus conferring to the area a great potential for the development of marine resources and of fisheries and aquaculture activities (LONGHURST, 1995).

Most of the fishing in Angola takes place near the coast and from there up to a depth of 200 meters, corresponding to the continental shelf limit (average width of 30 km, maximum width > 95 km and minimum width <2 km).

The ocean currents off the Angolan coast seem to represent a typical eastern boundary circulation system. They are under the influence of different type of currents flowing either at the surface or in the subsurface (countercurrents or poleward currents), as illustrated in Fig. 2a (KOPTE *et al.*, 2017; ROUAULT *et al.*, 2007).

The Angolan coastal sea comprises the Angola River Basin and the 90 km-wide continental shelf south of the Congo River (but 30 km-wide near Luanda and even narrower in the Southern region), the Republic of Congo (Brazzaville) in the north and Namibia in the south

(VASCO, 2010). This coast is located between two ocean current systems, Angola and Benguela Currents, and is characterized by a specific oceanographic dynamic that induces variability, such as warm and cold anomalous events (TCHIPALANGA *et al.*, 2015). The region of Angola is under the influence of a tropical (005º to 013ºS) and a subtropical climate (13º to 17º20'S; EHRLICH *et al.*, 1977) with distinct oceanographic characteristics in the offshore.

In oceanographic terms, this difference is due to three main factors: i) the type of prevailing climate in each zone; ii) the different hydrological regimes that govern the north, centre and south; and iii) the predominant wind system in the north and south of the Angolan coast during each season of the year.

The coastal region between 05º and 13ºS, consisting of the north and centre areas of the Angolan coast, is characterized by the presence of warm waters that define the Angola current, while the subtropical area (013º to 017º20'S) is influenced by the Benguela current ecosystem (Fig. 2b).

3.2 SHIPBOARD DATA AND HYDROGRAPHIC MEASUREMENTS

Extensive oceanographic data set has been generated for the Angolan territorial waters since 1983, during repeated ship surveys as part of the EAF-Nansen Program "Supporting the Application of the Ecosystem Approach to Fisheries Management Considering Climate and Pollution Impacts". This program is executed by the Food and Agriculture Organization (FAO) of the United Nations in close collaboration with the Institute of Marine Research (IMR) of Bergen, Norway and funded by the Norwegian Agency for Development Cooperation (Norad).

Since 1995, semi-annual cruises (austral summer versus austral winter) have been carried out by R/V Dr. Fridtjof Nansen on regular basis. During these cruises, data has been collected to estimate the abundance and to map the distribution of the main commercially important fish species, as well as to perform biogeochemical measurement and to gather hydrographic data.

These biannual cruises were held during the months of February to April (mostly from March/April) and of June to August (mostly from July/August), which were considered as representative of austral summer and winter seasons, respectively, as no hydrographic information was available for the December/January months in this data set.

In the present work we analysed 9,529 records of temperature/salinity/oxygen profiles collected with a Seabird 911Plus CTD under the EAF-Nansen Program, from 1995 to 2016, along the Angola coast, between 06ºS and 18ºS. The CTD data was gathered along 25 shore normal profiles ~6 nautical miles apart, including 5 monitoring lines and 20 auxiliary transects. The monitoring lines was located of the Congo River (06º12' to 06º30'S), Luanda-Palmerinhas (9º05'S), Lobito (11º54' to 12º20'S), Namibe (15º09'S) and Cunene River (17º12'S) (Fig. 2b), and extended offshore up to 70 nautical miles, depending on the position of the thermocline. Oceanographic parameters were collected measuring the vertical profiles, and real time logging was carried out using the PC based Seabird Seasave software. For analyses purposes we considered the top 500m layer for stations equal or deeper than 500m and data from surface to 10 meters above the seabed for shallower stations.

3.3 AUXILIARY DATA

For the validation of times series data was performed climatology of the study area with data from World Ocean Atlas 2013 version 2 (WOA13V2) database in order to compare it with the CTD profiles. The data validation method is similar to that used in PIRATA project. The WOA13 v2: of Temperature and Salinity with a spatial resolution of 1/4º and 1º from Oxygen.

Sea Surface Temperature Anomalies (SSTA) have been elaborated for the areas where the largest rivers are located, namely the Congo River (~ 6ºS) and the Kwanza River (~ 9º30S) that drain large freshwater discharges off the coast of Angola in order to identify the warm and cold events and correlate these years with precipitation in these areas. Data on SSTA were taken from a SODA reanalysis set (CARTON; GIESE, 2008).

For precipitation data were taken from the Global Precipitation Climatology Project (GPCP) database resolution 1°. Monthly averages were calculated per year for the period from January 1998 to December 2016, it was possible to observe precipitation in the areas of the Congo River and Kwanza River.

3.4 CLASSIFICATION OF EASTERN EXTREME COASTAL EVENTS

According to the characteristics described in the literature (Binet *et al.*, 2001; Florenchie *et al.*, 2004; Gammelsrød *et al.*, 1998; Hardman-Mountford *et al.*, 2003; Imbol Koungue *et al.*, 2017, 2019; Lübbecke *et al.*, 2010, 2019; Mohrholz *et al.*, 2001; Ostrowski *et al.*, 2009; Reason *et al.*, 2006; Rouault, 2012; Rouault *et al.*, 2007, 2018), it was possible to identify some of these extreme events. The data was then classified as years of warm Benguela Niño (1995, 2001, 2011 and 2016), years of cold Benguela Niña (1997, 2004, 2009 and 2014) and normal years (1996, 1998, 1999, 2000, 2002, 2003, 2005, 2006, 2007, 2008, 2010, 2012 e 2015).

The horizontal mean was obtained for each previous class (Niño, Niña and Normal) from the vertical averages for each station horizontally interpolated for each year. For the vertical profiles, the stations were selected within predefined regions for each year and then the mean and standard deviation of the years of each class were obtained.

According to the National Institute of Fisheries and Marine Research (INIPM), the Angolan coast can be subdivided into 3 regions (North, Center and South) on bases of climatic aspects and features of the continental shelf. The North region goes from Cabinda to Luanda-Palmerinhas (05º-09º05’S) and is characterized by a tropical climate and a wide continental shelf. The central region runs from Luanda to Benguela (09º05’-13ºS) and experiences a transitional subtropical climate under the influence of the seasonal presence of a thermal front and presents a continental shelf essentially made up of hard and medium sized funds. The southern region goes from Benguela to the mouth of the Cunene River (013º-018ºS) and is characterized by a temperate climate that extends to Namibia. Here the continental shelf is relatively wide up to Tombwa that correspond to the front zone of the currents of Benguela and Angola. This same division was adopted in the present work. Three monitoring lines: Congo River (06º12’S), Palmerinhas (009º05S) and Namibe (015º09’S) were chosen to respectively represent the north, center and south regions.

4 RESULTS

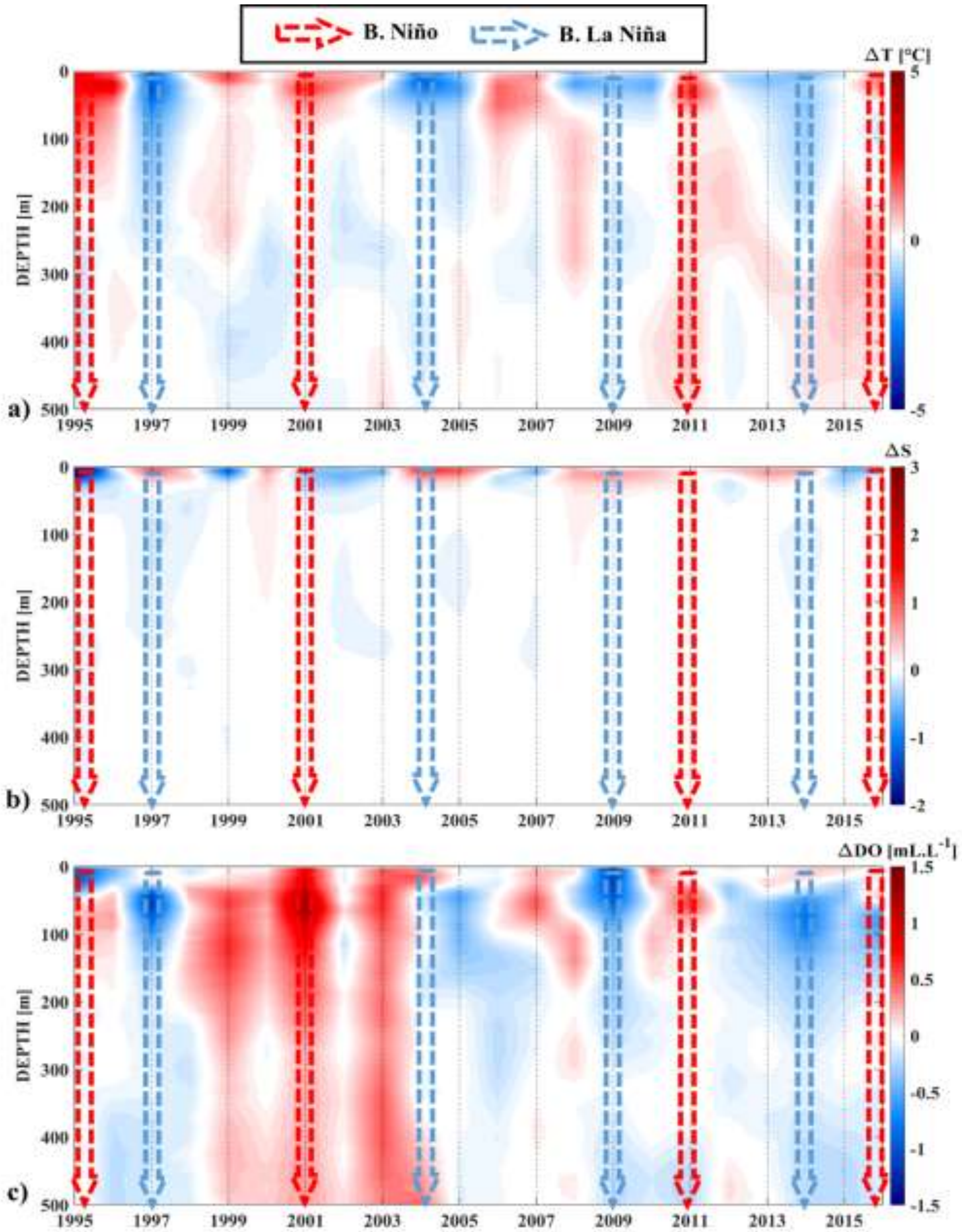
Vertical profiles of temperature, salinity and dissolved oxygen (DO) anomalies in the late austral summer (February/March/April-FMA) and austral winter (June/July/August-JJA) for the time series (1995-2016) allowed the identification of extreme warm coastal events (Benguela Niños) and the cold coastal events (Benguela Niñas) on the Angolan coast (Fig. 6).

Observation of the temperature anomalies in those time series during the summer (Fig. 6a), made possible to identify the years of Benguela Niños (1995, 2001, 2011, 2016) and Benguela Niñas (1997, 2004, 2009, 2014). These years are in the same order of extreme events pointed out in the literature. Events of Benguela Niños were detected for the year of 1995 (GAMMELSRØD *et al.*, 1998), of 2001 (ROUAULT *et al.*, 2007), of 2011 (ROUAULT *et al.*, 2018), and of 2016 (LÜBBECKE *et al.*, 2019) as well as events of Benguela Niñas like the one observed in 2009 (BURMEISTER *et al.*, 2016; FOLTZ *et al.*, 2010). Gammelsrød *et al.* (1998) were the firsts to describe the warm event in 1995, identifying it in the late austral summer of that year. A more intense warming area (>2°) between the surface to ~150 m depth (dark red area) shown in Fig. 6a corresponds to the warm event identified for the austral summer of 1995. In the distribution of extreme heat and cold events to the coastal domain, it is possible to observe a maximum of occurrences between March and April. This agrees with previous studies (FLORENCHIE *et al.*, 2004; LÜBBECKE *et al.*, 2010), which observed that March-April period seems to be the peak season for Benguela Niño and Niña inter-annual events

The year of 2009 was an extreme year for Tropical Atlantic (TA). The resulting inter-hemispheric SST gradient across the Atlantic equator was the strongest within the last 30 years (FOLTZ; MCPHADEN, 2010). In the literature, two mechanisms have been discussed that provide possible explanations for the observed cold event in the TA in 2009. Foltz and McPhaden (2010) suggested that upwelling equatorial Kelvin waves, which were generated by the reflection of Rossby waves, caused the cold event in 2009. On the other hand, RICHTER *et al.* (2010) did not find that planetary waves are a main driver in the development of non-canonical warm events. They proposed instead that direct meridional advection can trigger non-canonical events as the one in the Equatorial Atlantic in 2009.

The salinity anomaly profiles (Fig. 6b) presented lower concentrations during Benguela Niño events and higher concentrations during Benguela Niña ones. For dissolved oxygen anomalies, a uniform variation was observed throughout the time series for Benguela Niño events, except in 2001, where an intense anomaly (high levels) between 0-260 m depths was noticed. Though, the anomalies for Benguela Niña events were more homogeneous over those 4 years, presenting low level (Fig. 6c).

Figure 6 - Anomalies of (a) temperature (°C), (b) salinity, and (c) dissolved oxygen (mL L^{-1}) in austral summer.



Source: The author, 2019.

4.1 HORIZONTAL COMPOSITES FOR NORMAL AND EXTREME EVENTS DURING AUSTRAL SUMMER AND WINTER

Based on the temperature anomalies during the summer periods, it was possible to identify the normal/neutral years (1996, 1998, 1999, 2000, 2002, 2003, 2005, 2006, 2007, 2008, 2010, 2012, 2013 and 2015), the Benguela Niño years (1995, 2001, 2011 and 2016) and the Benguela Niña years (1997, 2004, 2009 and 2014). Once these years were identified, composites of temperature (°C), salinity and dissolved oxygen ($mL.L^{-1}$) were elaborated as averaged values for the same class of event for each location through the study area, in order to observe the variability of these parameters in regimes of normal and extreme events, as well as their seasonality.

4.1.1 Temperature

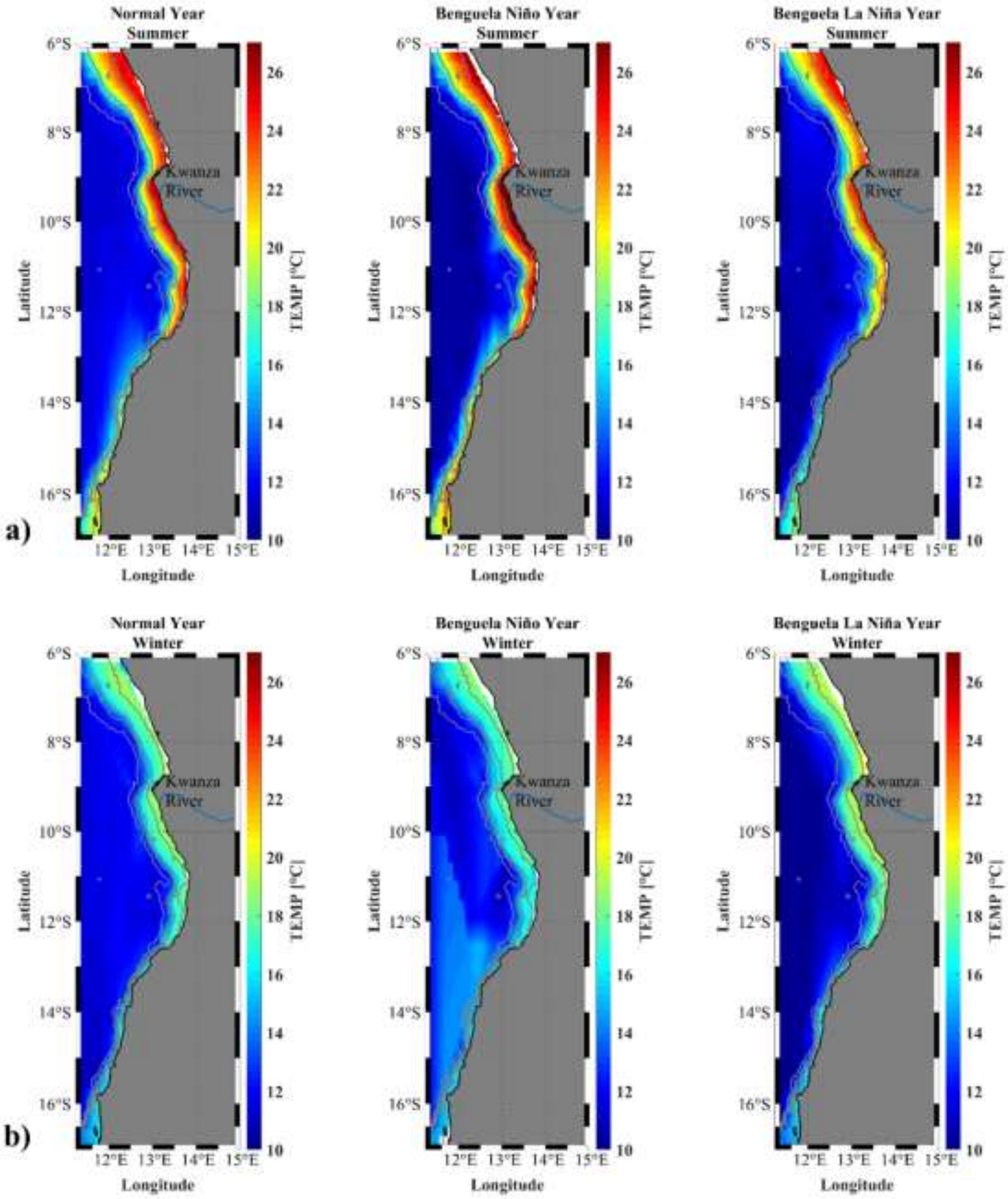
During the austral summer periods, a standard distribution is observed with high temperatures (22° to 26°C) near the coastal zone in the years considered normal (Fig. 7a - left).

Between the north (06° to 09°05'S) and the center (09°05' to 13°S) there is a strong influence of the Angolan current (CA), which is predominant in the austral summer. In the south (13° to 18°S), the temperature gradually decreases (18° to 20°C) due to the influence of southwest winds from the Benguela Current (BC) jets (NICHOLSON, 2010).

During the austral summer periods in the years of Benguela Niño (Fig. 7a - center), the temperature is ~4ºC higher than in the normal years (SHANNON *et al.*, 1986). In this extreme warm event, the hot water mass can reach Namibia (~25°S) and sometimes inhibit the coastal resurgence process in the Benguela ecosystem area. Higher temperatures (30°C) were observed in the central region (009°05' to 013°S) and warm water mass (~23°C) observed in the southern region near the Angola-Benguela front (~15° to 19°S), inhibiting the process of coastal resurgence in the area.

Still during the austral summer periods in the years of Benguela Niña (Fig. 7a - right), there is a temperature decline along the coast. In this extreme cold event, cold water mass coming from the Benguela Current reaches the north of Lobito (Benguela; 012°S). In the northern (005° to 009°05'S) and the central (009°05' to 013°S) regions, the temperature varied from 21° to 24°C along the coastal area. Below the monitoring line from Lobito (Benguela; 12°S) to the southern region (13° to 18°S), the temperature varied from 14° to 20°C.

Figure 7 - Temperature (ºC) composites and its respective anomaly for normal (left), Benguela Niño (center), and Benguela Niña (right) year cases obtained from CTD data; (a) in austral summer (FMA) and (b) in austral winter (JJA).



Source: The author, 2019.

During the austral winter periods, it is observed in the normal years (Fig. 7b - left) that there is a small cell with a temperature of ~16ºC near the coast, in the northern region below the Congo River monitoring line (6º12S), possibly due to the influence of fresh water runoff from the Congo River. Except for this area, the temperature varies little between the north and the central regions (18º to 20ºC) but reaches 17ºC in the southern region.

In the Benguela Niño years (Fig. 7b - center), the temperature varies from 17º to 20ºC along the coast. In the open sea/offshore, there is a minimum temperature of 14ºC between the north-central and south regions, as one can see a water mass of 15ºC northwards.

In the years of Benguela Niña (Fig. 7b - right), low temperatures are observed along the coast, ranging from 16° to 18°C in the north (05° to 09°05'S) and central (09°05' to 13°S) regions. The temperature varies from 14° to 16°C in the southern area, and from 12° to 14°C in the open sea/offshore.

4.1.2 Salinity

The salinity has a marked variability between regions. In the summer periods, the influence of waters with low salinity concentration coming from the discharge of two large rivers (Congo and Kwanza) is perceptible in normal and Benguela Niño years.

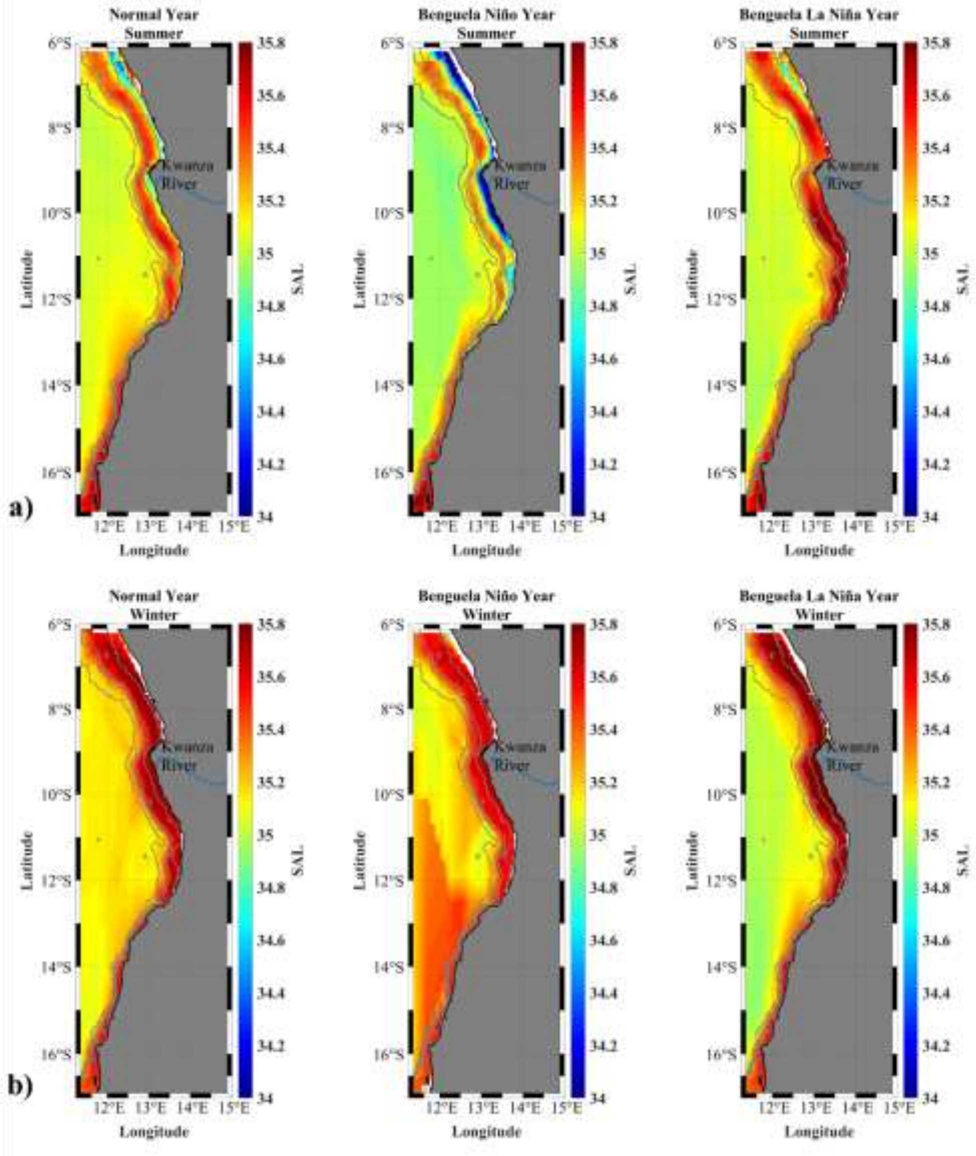
During the austral summer periods, Fig. 8(a) on the left presents the salinity composites for normal years. This figure illustrates the mass of water of low salinity concentration (34.6) in regions of the north (05º to 09º05'S) and a part of the center (09º05 to 10ºS) near the coast, from the discharges of the Congo (~06°12S) and Kwanza rivers (~9°S). Between the 10º and 18ºS, a gradual increase in salinity (35.2 to 35.6) is observed and, in the open sea, it varies from 35 to 35.2.

In the Benguela Niño years, Fig. 8a in the center, illustrates the low salinity water mass (34.0) from river discharges (Congo and Kwanza), decreasing the value of salinity between both regions (north and south). The high precipitation rate associated with SST anomalies end up correlating with the contribution of freshwater discharges and the decrease in salinity in this period of Benguela Niño. From 13°S onwards, salinity increases significantly with a maximum value (35.8) observed in the area of the Angola-Benguela front (15° to 19°S). In the open sea, the salinity stays in the range of 35 along the entire continental shelf.

In the Benguela Niña years, Fig. 8a on the right, illustrates the salinity values along the coast, ranging from 35.6 to 35.8, except for a small zone to the north (~06º to 07º37'S), where it is still possible to observe the influence of the Congo River discharge. The cold water, originating from the Benguela Current, covers the entire platform and heads north.

During the austral winter periods, cold (Fig. 7b) and salty (Fig. 8b) waters predominates along the Angola coast with little variation in salinity.

Figure 8 - Salinity composites and its respective anomaly for normal (left), Benguela Niño (center), and Benguela Niña (right) year cases obtained from CTD data; (a) in austral summer (FMA) and (b) in austral winter (JJA).



Source: The author, 2019.

In the normal years, Fig. 8b on the left, illustrates the cold waters covering the entire coastal area, with salinity reaching 35.7. In the open sea/offshore, the salinity remains around 35.2.

For the Benguela Niño years, Fig. 8b in the center illustrates a small variation in salinity in the open sea/offshore. The salinity varies between 35.0 and 35.4 between the north and central regions. However, it remains around 35.6 near the coast.

In the years of Benguela Niña, Fig. 8b on the right shows the mass of cold and saline water range along the coast with the salinity of 36. In the open sea, a small variation in salinity (between 35 and 35.2) is observed.

4.1.3 Oxygen

The variability of the oxygen in the summer periods (Fig. 9a) is observed in the coastal regions (north, center and south).

In the normal years, Fig. 9a on the left illustrates high values (4 $mL.L^{-1}$) of DO along the north (05º to 09º05'S) and center (09º05 to 13ºS) regions. In the south (13º to 18ºS), the oxygen gradually decreases (2 to 3 $mL.L^{-1}$), and it increases to 3.5 $mL.L^{-1}$ between Ponta Albina (016º12'S) and Cunene River (017º12'S). In the south part of the open sea/offshore, there is a low oxygen water mass (1.5 $mL.L^{-1}$) that goes toward the central region.

In the Benguela Niño years, Fig. 9a in the center, presents a variation similar to the normal years, except for areas with low levels of oxygen (1.5 $mL.L^{-1}$), which is located in the central region (09º30' to 12ºS) and in a small area between 13º to 014ºS.

For the Benguela Niña years, Fig. 5a on the right shows that the oxygen varied from 2 to 3 $mL.L^{-1}$ due to the process of coastal upwelling in the southern region (13º to 18ºS). In the open sea/offshore of the northern region (005º to 009º05'S), the low oxygen water mass varies from 0,0 to 1.5 $mL.L^{-1}$ and heads to Ambriz area (~08º02'S).

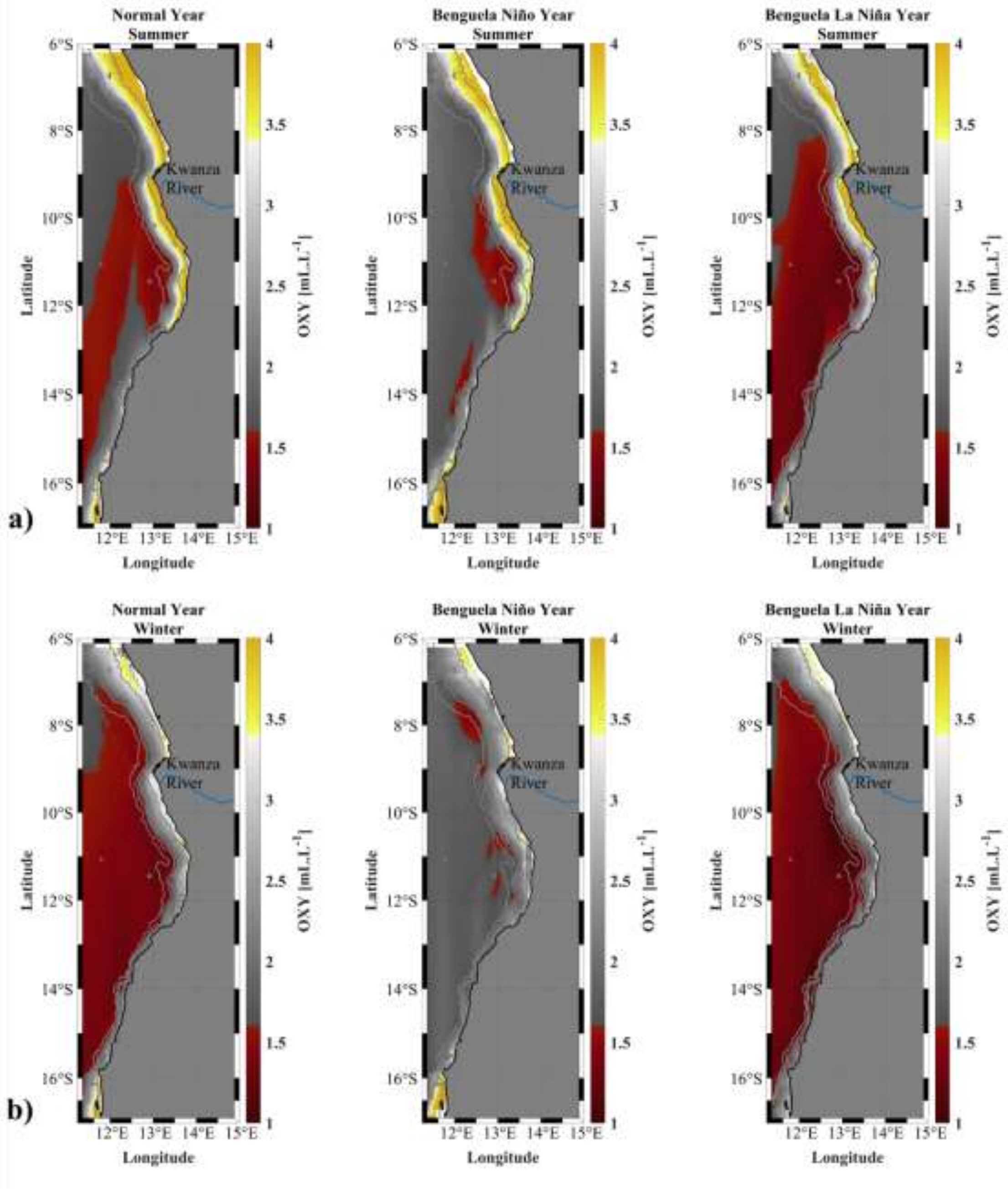
During the austral winter, the position of the Oxygen Minimum Zone (OMZ) is observed in the coast of Angola and predominates in the normal and Benguela Niña years.

In the normal years, Fig. 9b on the left, illustrates the increase of the OMZ (<1 $mL.L^{-1}$), reaching 07º13'S toward the north and near the coast, where oxygen varies between 2 to 3 $mL.L^{-1}$. The oxygen reaches 3.5 $mL.L^{-1}$ in the areas of Congo River (006º12'S), Ambriz (~08º02'S) and between Ponta Albina (16º12'S) and Cunene River (017º50S).

For the Benguela Niño years, Fig. 9b in the center presents the oxygen with a variation between 2 and 3 $mL.L^{-1}$ along the coast. Small OMZ points (<1 $mL.L^{-1}$) are observed in the north, between N'Zeto (~ 07º37'S) and Palmerinhas (009º05'S), as well as between ~16º and 18ºS in the south.

In the Benguela Niña years, Fig. 9b on the right shows the intensity of the OMZ (< 1 mL,L^{-1}) along the coast, reaching ~07ºS. Near the coast, the oxygen varies between 1,5 and 3 $mL.L^{-1}$, and it reaches 3.5 $mL.L^{-1}$ between 06º and 7º13'S.

Figure 9 - Oxygen (mL.L^{-1}) composites and its respective anomaly for normal (left), Benguela Niño (center), and Benguela Niña (right) year cases obtained from CTD data; (a) in austral summer (FMA) and (b) in austral winter (JJA).



Source: The author, 2019.

4.2 VERTICAL PROFILE COMPOSITES FOR NORMAL AND EXTREME EVENTS DURING AUSTRAL SUMMER

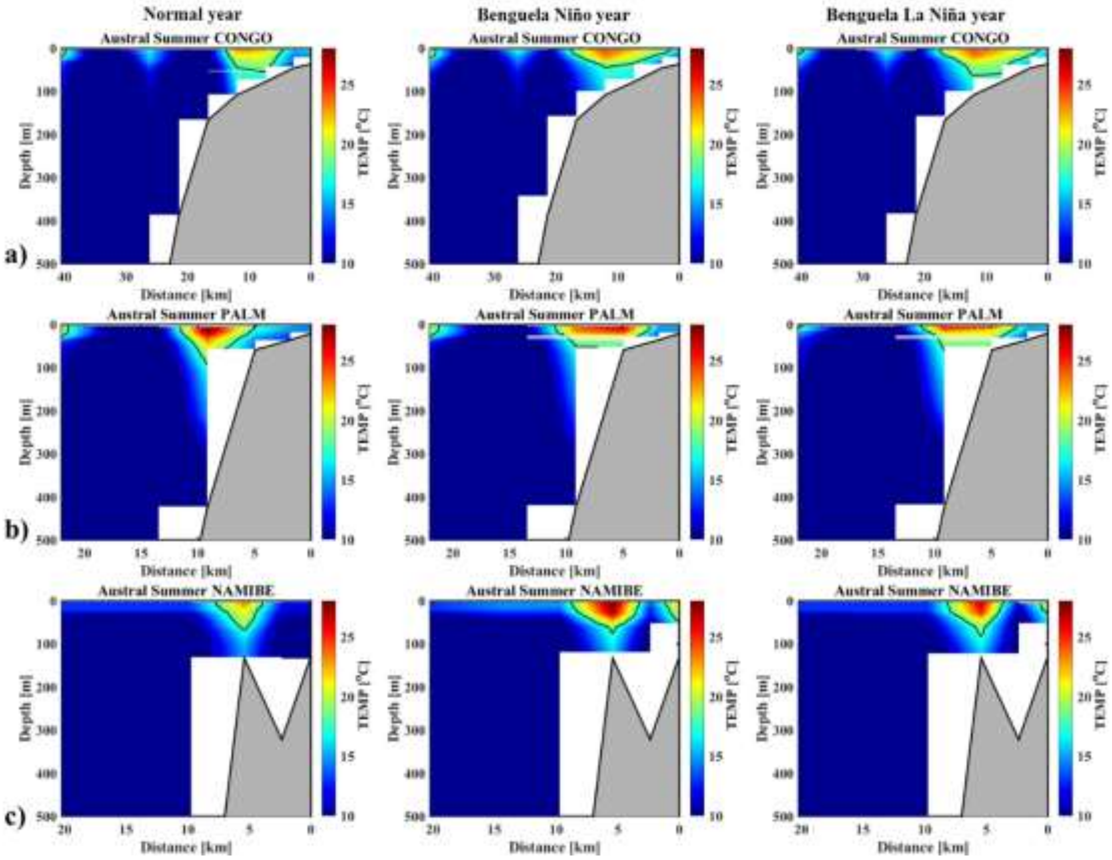
In order to observe the variability in temperature and dissolved oxygen in each one of those 3 regions (north, center and south) of the Angolan Coast vertical profile composites were generates for the monitoring lines of the Congo River, Palmeirinhas and Namibe.

Vertical salinity gradients, calculated from the CTD data, are present only closer to the surface and near coast. Thus, salt composites for vertical transects along the monitoring lines were not presented here.

4.2.1 Temperature

In the Congo River section, Fig. 10 shows variation between the normal, Benguela Niño and Benguela Niña years. Between the surface and 100 m depth, close to the coast, the intrusion of hot water mass (18º-28ºC) is observed north of the river mouth, probably caused by the warm Angola Current (AC), predominant during the austral summer. This body of warm water becomes more pronounced in the year of Benguela Niño. In the Palmerinhas section, we observe the propagation of warm water mass over the normal, Benguela Niño and Benguela Niña years. In the Namibe section, the temperature of the warm water mass decreases (18º-23ºC) in normal and Benguela Niña years. For the year of Benguela Niño, the temperature increases (~28ºC) near the area of the Angola-Benguela Front (015º-019ºS).

Figure 10 - Temperature (ºC) vertical profile composites for normal (left), Benguela Niño (center), and Benguela Niña (right) year cases obtained from CTD data in austral summer (FMA) for the transects of (a) Congo River (b) Palmerinhas and (c) Namibe. The continuous black line corresponds to the 18ºC isotherm.

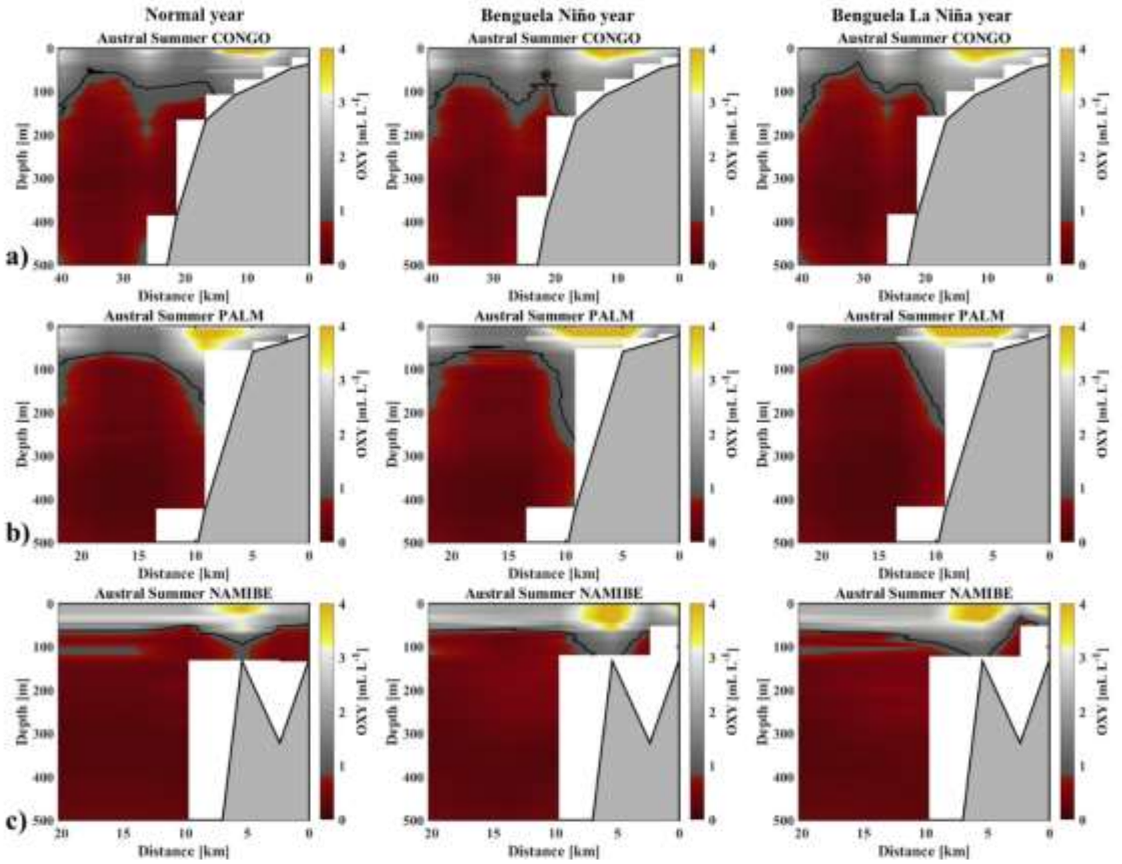


Source: The author, 2019.

4.2.2 Dissolved Oxygen

In the Section of the Congo River, the figures show variation between 1.5-4.0 mL.L^{-1} from surface to 120 m depth, near the coastal area for the normal, Benguela Niño and Benguela Niña years (Fig.11a). In the Palmerinhas section (Fig. 11b), a layer of water mass rich in DO (~2.0-5.5 mL.L^{-1}) is observed near the coast and is propagating towards the open sea (5-30 km). This contribution of nutrients of continental origin is probably associated with discharges from the Kwanza River and such gradient is observed every year. In the Namibe section (Fig. 11c), an increase of the OMZ (<1.5 mL.L^{-1}) is observed, reaching a depth of ~50 m in the open sea and near the coastal area at ~120 m depth.

Figure 11 - Oxygen (mL.L^{-1}) vertical profile composites for normal (left), Benguela Niño (center), and Benguela Niña (right) year cases obtained from CTD data in austral summer (FMA) for the transects of (a) Congo River (b) Palmerinhas and (c) Namibe. The continuous black line corresponds to 1 mL.L^{-1} of dissolved oxygen concentration.



Source: The author, 2019.

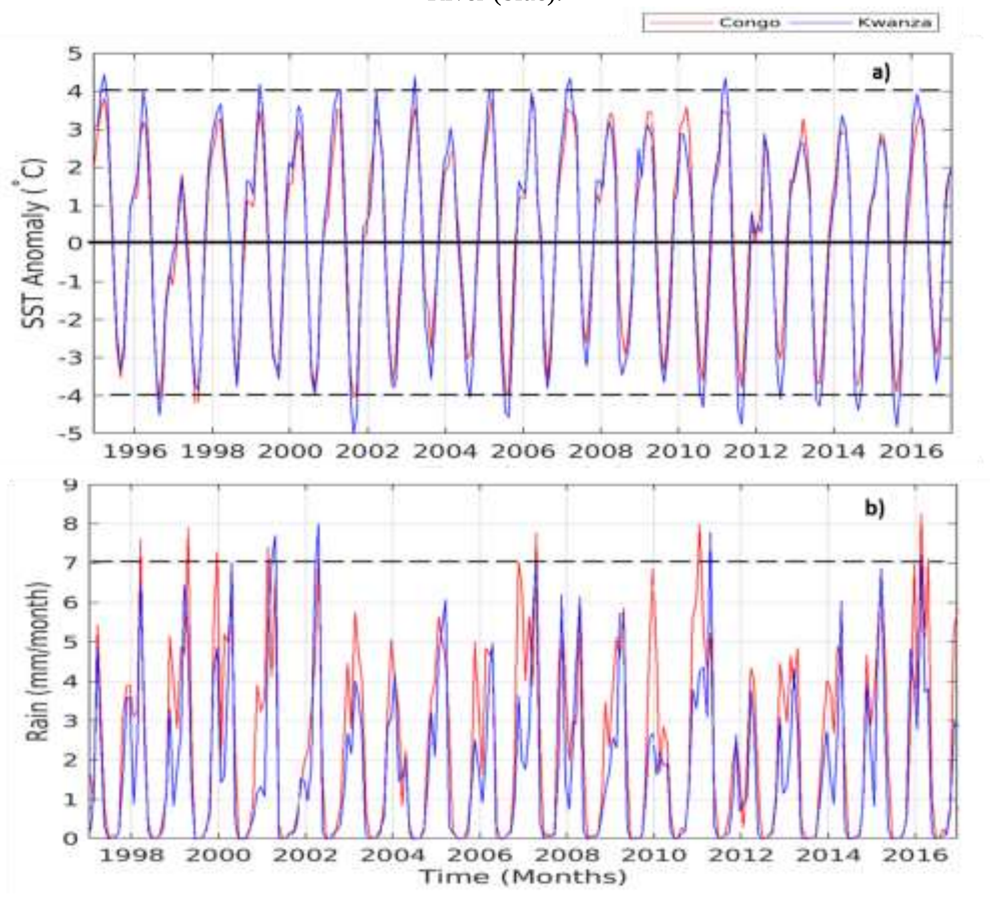
4.3 THE SEAN SURFACE TEMPERATURE ANOMALY AND RAINFALL

One important driver of African rainfall variability is tropical southeast Atlantic sea surface temperature (SST).

Based on Sea Surface Temperature Anomaly (SSTA), monthly averages were made, from January 1995 to December 2016 (Fig. 12a), it was possible to identify the years of positive SSTA (extreme coastal warm event) (1995, 1999, 2003, 2007 and 2011) and the years of negative SSTA (extreme coastal cold event) (1997, 2002, 2005, 2012 and 2015) with predominance in the Kwanza River area. Also identified were years of moderate coastal warm events (2001, 2005 and 2016) and moderate coastal cold events (2000, 2004, 2010, 2013 and 2014) (Figure 14a).

Years with the highest rainfall (1998, 1999, 2007, 2011 and 2016) were observed in the Congo River area, with the most intense rainfall being 2016. For the Kwanza River area the most precipitation years were 2001, 2002, 2007, 2011 and 2016 (Fig. 12b).

Figure 12 - (a) SST anomaly for the rivers region during the period January 1998 to December 2016. (b) Rainfall for the rivers region during the period January 1996 to December 2016. Congo River (red line) and Kwanza River (blue).



Source: The author, 2019.

Correlating the SST anomalies with rainfall proves that the years of extreme coastal warm events (1995, 2001, 2011 and 2016) influence the local rainfall rate, in this case the river areas (Congo and Kwanza), resulting in large freshwater flows to the sea. Similar connection between SST-Rainfall was observed by (ROUAULT *et al.*, 2003; REASON; ROUAULT, 2006; POLO *et al.*, 2008; HANSHINGO; REASON, 2009; LUTZ *et al.*, 2015).

5 DISCUSSION AND CONCLUSIONS

In this study we have identified the extreme coastal events anomalies that occurred in the Angola Sea. We compared the variability for temperature, salinity and dissolved oxygen composites for the Normal, Benguela Niño and Benguela Niña years. The Seasonality of temperature and salinity at the Normal, Benguela Niños and Niñas years reflects mainly the major seasons of downwelling and upwelling periods from February through April and from June through August, respectively.

The results show that events of Benguela Niños are marked by a poleward intrusion of warm equatorial water and by reduced upwelling. A strong seasonality in near surface temperature and salinity off along coast was detected. The abnormally high freshwater input due to both local precipitation and river discharge seems to play a role in the development of the warm event by enhancing the stratification.

During austral summer the ocean off Angola is fresh and warm, while during austral winter it is saltier and colder. Monthly flux climatology (e.g. PRAVEEN KUMAR *et al.*, 2012) suggest that evaporation to exceed precipitation during the whole season (e.g. LUDKE, 2016) leaving river run off as the only explanation for the fresh water anomaly detected during the austral summer. The discharge of the Congo River being the solely significant continental fresh water source to this region, and that peaks from November to January (DAI *et al.*, 2009). The Rainfall variability is also sensitive to any anomalous change in position or intensity of systems. In addition, positive (negative) SSTA act to increase (decrease) atmospheric instability and therefore further contribute to anomalous rainfall (HIRST; HASTENRATH, 1983).

Within the tropical Angolan system, the Angola Current (AC) is one key element in the poleward advection of warm tropical waters (KOPTE *et al.*, 2017). Its variability in strength is found to be partly controlled by the passage of Coastally Trapped Waves (CTW) (KOPTE *et al.*, 2017; OSTROWSKI *et al.*, 2009; ROUAULT *et al.*, 2012). These waves communicate equatorial oceanic variability along the continental margin of Angola to the northern Benguela upwelling region (TCHIPALANGA *et al.*, 2018).

In the austral summer, during Benguela Niños, the results showed the strong influence of the warm waters the Angola Current (AC) being transport southward into the northern Benguela. The same was observed during Benguela Niño event the 1995 (GAMMELSRØD *et al.*, 1998; ROUAULT *et al.*, 2007). From the analysis of satellite data, four CTW events per year were described to propagate along the southwest coast of Africa as far south as 20ºS

(KOPTE *et al.*, 2017; LAZAR *et al.*, 2006; SCHOUTEN *et al.*, 2005; TCHIPALANGA *et al.*, 2018).

An important implication of the warm and cold events is the influence oxygen concentration in the water column. While Oxygen Minimum Zones (OMZs) in the eastern tropical seas represent the largest contiguous areas of naturally occurring hypoxia (PRINCE *et al.*, 2010) in the world's oceans; recent observations suggest that the oxygen content of the oceans and particularly in the south eastern Atlantic is declining and that oxygen minimum zones are expanding with some modulations related to the variability of our climate system (SCHMIDTKO *et al.*, 2017; STRAMMA *et al.*, 2008).

Is evident the pronounced oxygen minimum zone found below the productive surface layer of the Angola's Sea. The AC appears to be a key element for the southward spreading of warm, saline, low-oxygen South Atlantic Central Water (SACW) within the upper thermocline (KOPTE *et al.*, 2017), mainly during austral summer. Predominantly during this season, the AC is thought to transport warm, saline, low-oxygen South Atlantic Central Water (SACW) southward into the coastal upwelling region, possibly resulting in hypoxic to anoxic situations on the shelf (MOHRHOLZ *et al.*, 2008; MONTEIRO *et al.*, 2008).

In the results of the Normal and Benguela Niña years, we observe the propagation of the Oxygen Minimum Zones in the Angolan basin and the expansion and elevation of this zones in the water column. OMZs are located in regions with specific characteristics in both, biogeochemical cycling and physical ocean ventilation. From the biogeochemical point of view, the OMZs are located in Eastern Boundary Upwelling Areas (EBUAS) with high productivity and rather complex cycling of nutrients (e.g. HELLY; LEVIN, 2004). In respect to the physics of ocean ventilation OMZs are seen as a consequence of minimal lateral replenishment of surface waters (REID, 1965) since they are located in the so called 'shadow zones', unventilated by the basin scale wind-driven circulation (e.g. LUYTEN *et al.*, 1983). For the marine organisms, this expansion of the OMZ can have important implications in structuring the habitat, therefore affecting the living resources and fisheries (BERTRAND *et al.*, 2011). Possible consequences of to the marine ecosystem include loss of vertical habitat for high-oxygen-demand tropical pelagic fishes (WHITNEY *et al.*, 2007; PRINCE *et al.*, 2006; 2010).

There is an increasing need for the definition of OMZ thresholds, as up until now there is no agreed upon this limits (KARSTENSEN *et al.*, 2008). There is also the implication of the added decrease of ventilation, as consequence of the climatic changes, and how this phenomenon can overlap with cold events. The continuity of the monitoring of the extension and oxygen levels in the Oxygen Minimum Zones in the Angolan basin could yield some keys on understanding local effect of global climatic change.

Coastal countries of southwest Africa strongly depend upon their ocean: societal development, fisheries, and tourism face important changes associated with climate variability and global change. As an example, Angolan fisheries are currently reporting reduced catches that may be associated to variability of the eastern boundary circulation, water masses and oxygen minimum zones along the Angolan continental margin. Warm and cold anomalies in upper thermocline are strongly correlated to the Angola-Benguela area index and precede the respective sea surface temperature signal (TCHIPALANGA *et al.*, 2018).

6 FINAL CONSIDERATIONS

- In austral summer the ocean off Angola is fresh and warm and in during austral winter it is saltier and colder;
- the Angola Current (AC) is one key element in the poleward advection of warm tropical waters;
- Events of Benguela Niños are marked by a poleward intrusion of warm equatorial water and by reduced upwelling;
- Benguela Niño events can cause a stronger rainfall than. This is observed, e.g. in northern and in centre Angola;
- The abnormally high freshwater input due to both local precipitation and river discharge seems to play a role in the development of the warm event by enhancing the stratification;
- One important driver of African rainfall variability is tropical southeast Atlantic sea surface temperatures (SSTs);
- In austral winter, the position of the OMZ is observed in the coast of Angola and predominates in the normal and Benguela Niña years;
- The expansion of the OMZ in Benguela La Niña years can have important consequences for marine life and fisheries.

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APPENDIX A – VERTICAL PROFILES

Figure A1 - Vertical profiles of temperature (°C), Salinity and dissolved oxygen (ml/l^{-1}) of north region (6° to 9º05S) for Normal years (Soft Blue) Benguela Niño years (Soft Green) and Benguela Niña years (Soft Pink) during the austral summer (February/March/April) and austral winter(June/July/August) from CTD data.

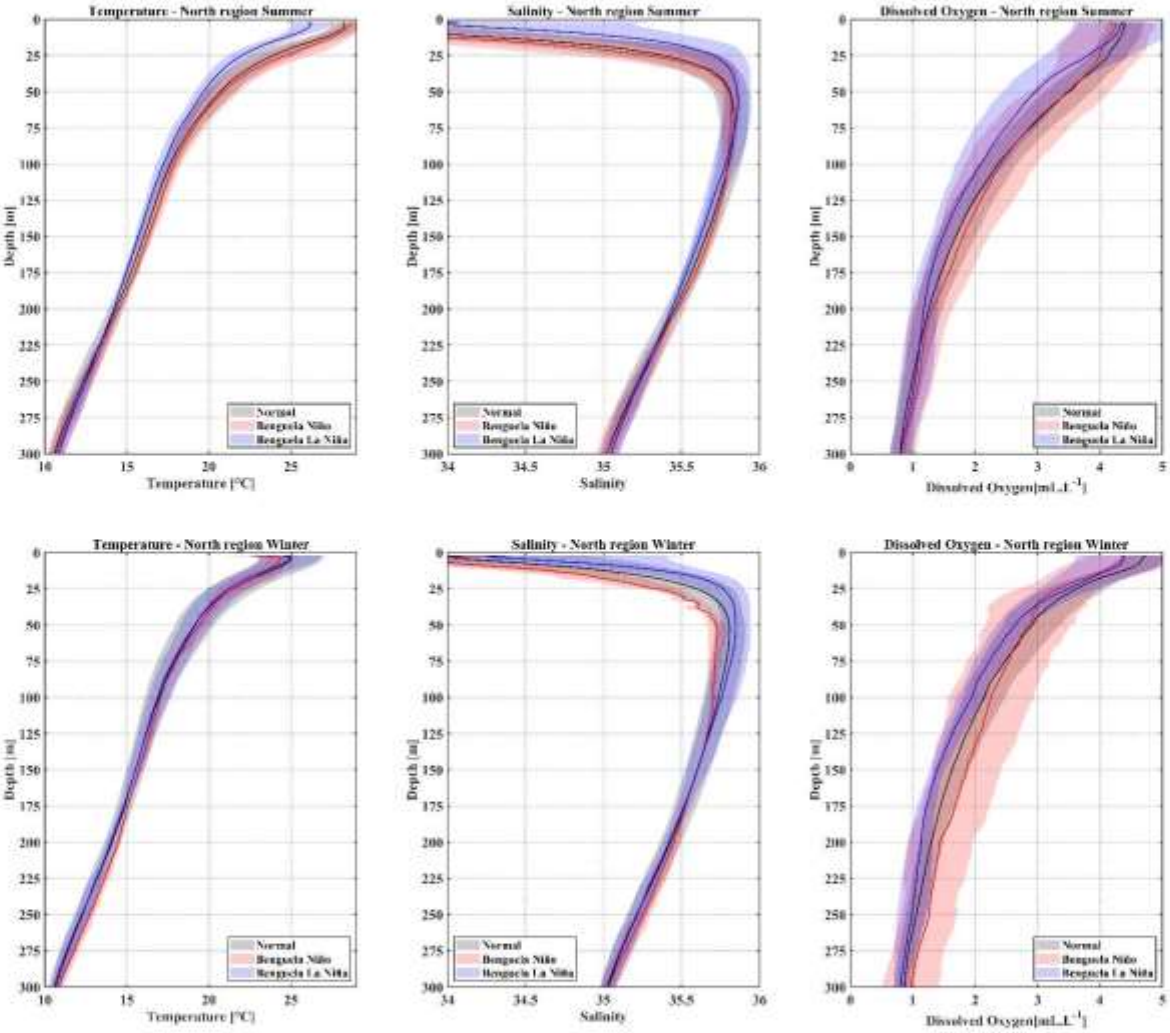


Figure A2 - Vertical profiles of temperature (°C), Salinity and dissolved oxygen (ml/l^{-1}) of monitoring line of Congo River (6º12S) for Normal years (Soft Blue) Benguela Niño years (Soft Green) and Benguela Niña years (Soft Pink) during the austral summer (February/March/April) and austral winter(June/July/August) from CTD data.

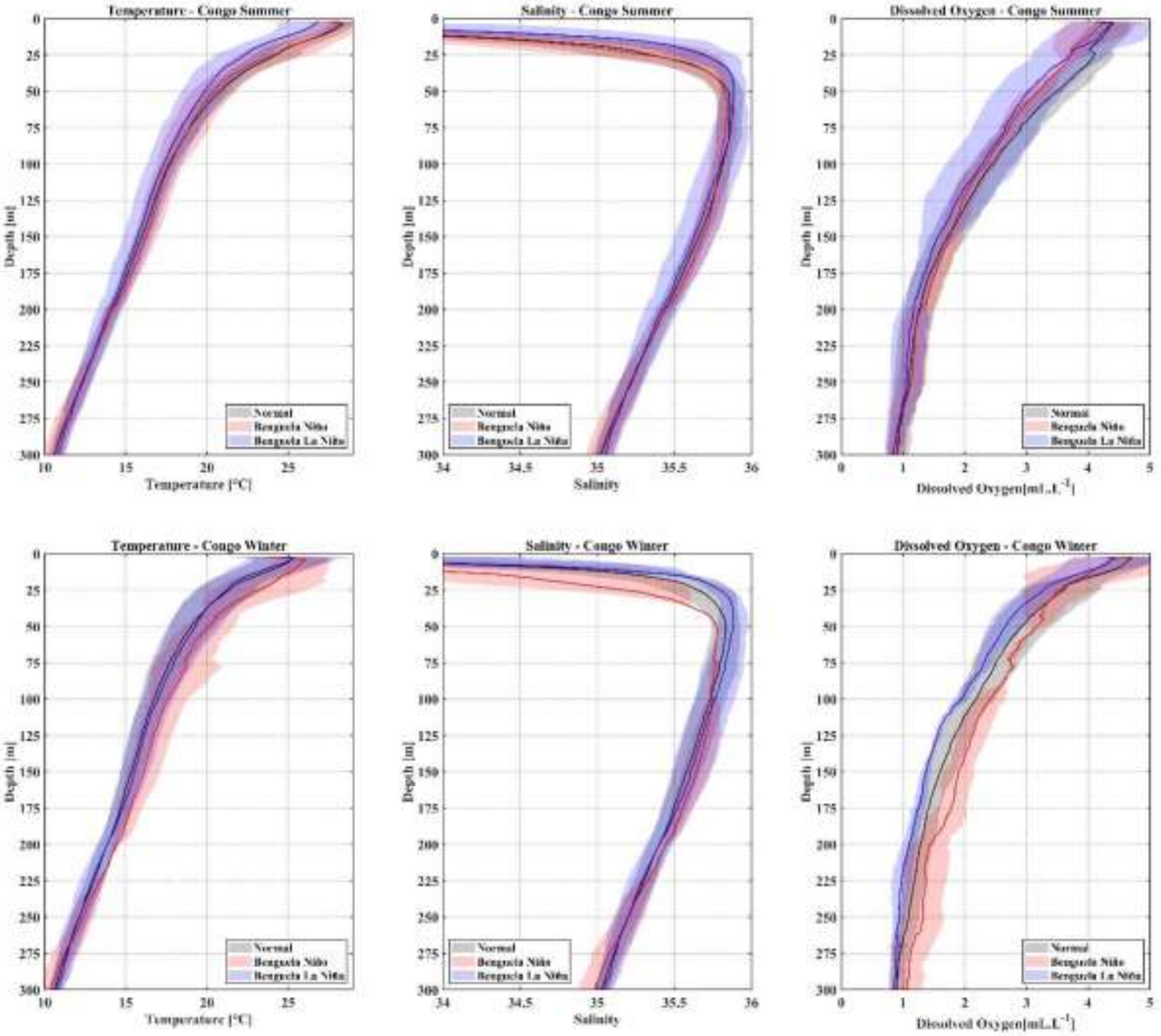


Figure A3 - Vertical profiles of temperature (°C), Salinity and dissolved oxygen (ml/l^{-1}) of central region (9º05 to 13ºS) for Normal years (Soft Blue) Benguela Niño years (Soft Green) and Benguela Niña years (Soft Pink) during the austral summer (February/March/April) and austral winter (June/July/August) from CTD data.

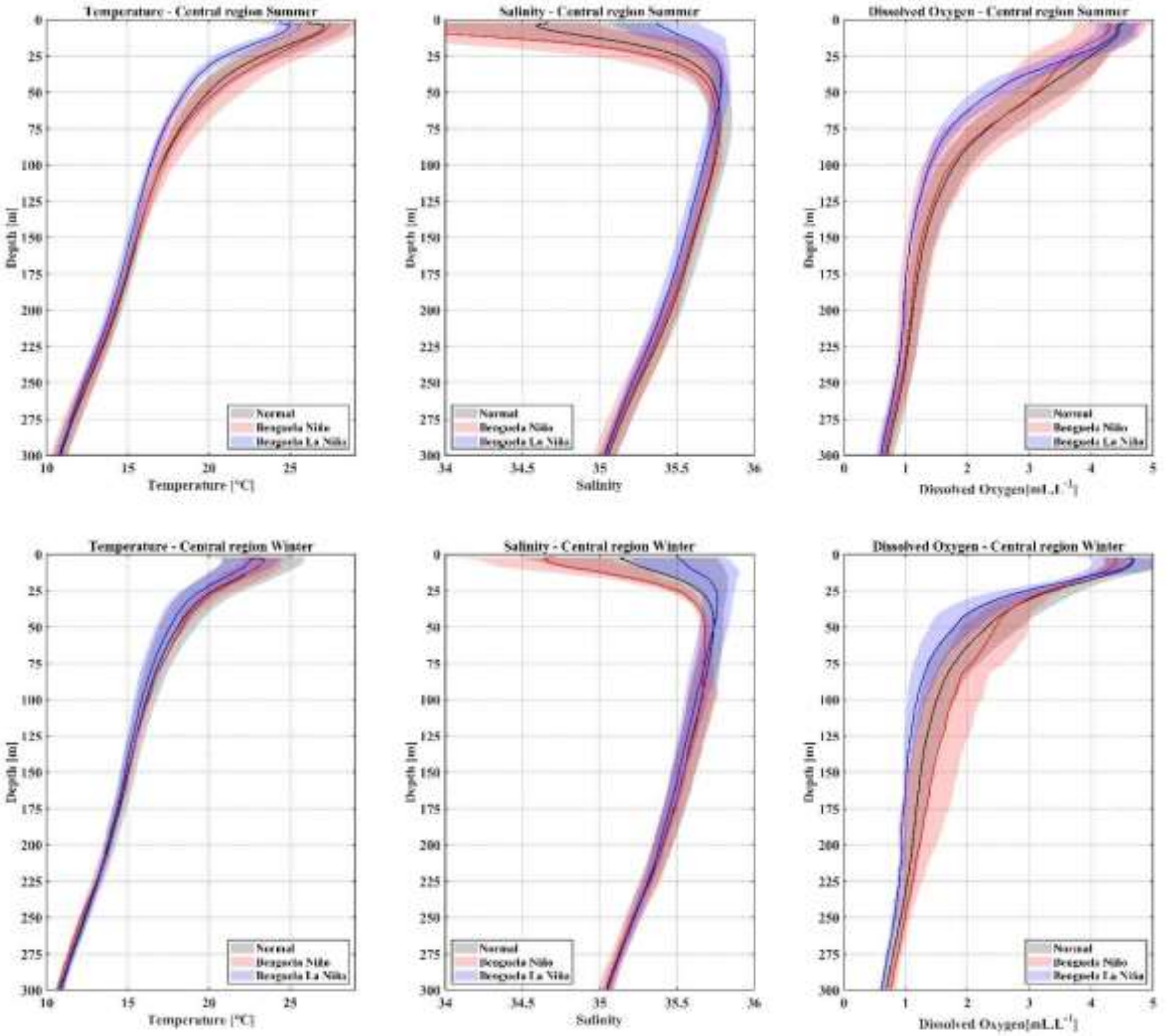


Figure A4 - Vertical profiles of temperature (°C), Salinity and dissolved oxygen (ml/l^{-1}) of monitoring line of Palmerinhas-Luanda (9º05S) for Normal years (Soft Blue) Benguela Niño years (Soft Green) and Benguela Niña years (Soft Pink) during the austral summer (February/March/April) and in austral winter (June/July/August) from CTD data.

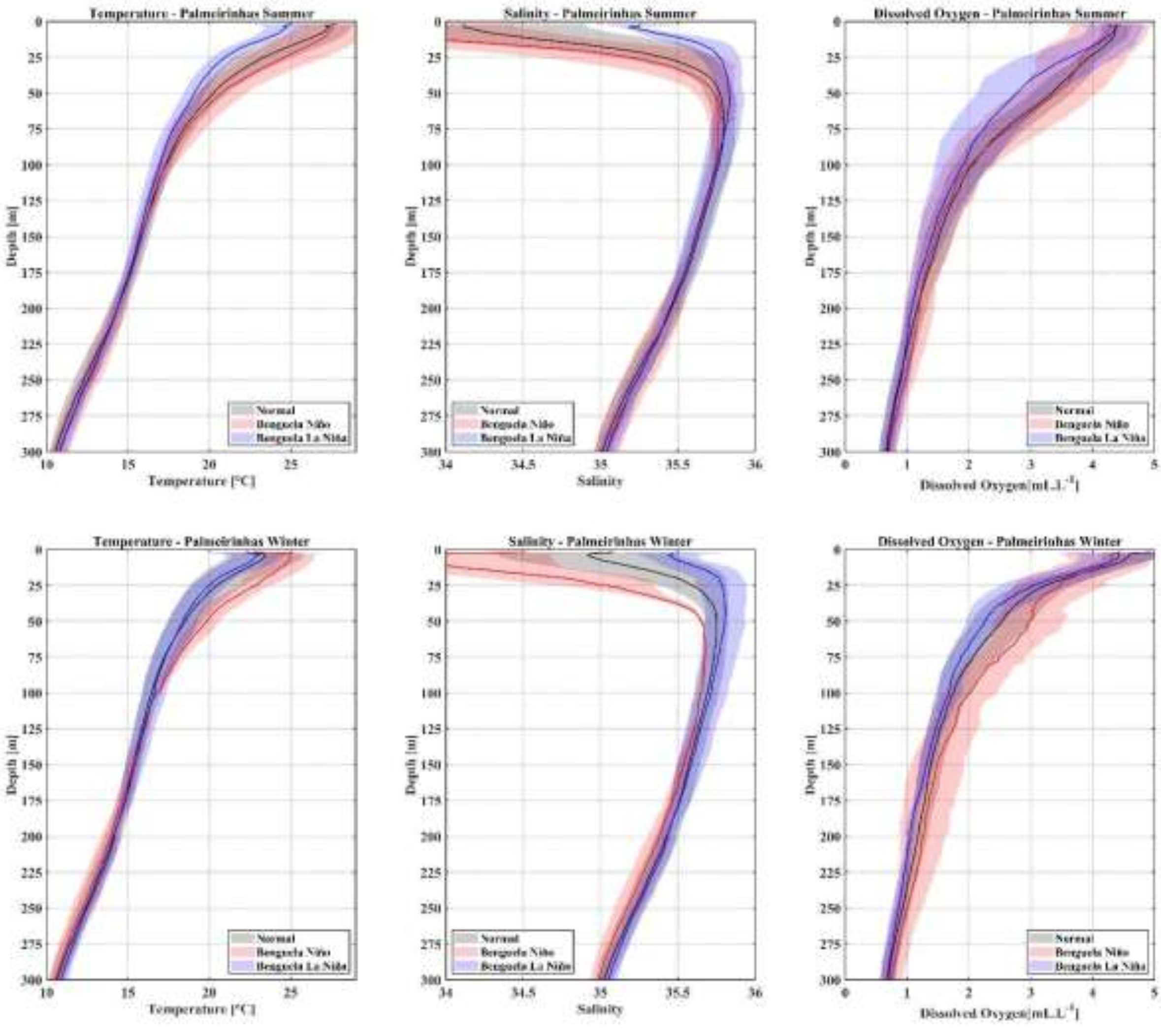


Figure A5 - Vertical profiles of temperature (°C), Salinity and dissolved oxygen (ml/l^{-1}) of south region (13º to 18ºS) for Normal years (Soft Blue) Benguela Niño years (Soft Green) and Benguela Niña years (Soft Pink) during the austral summer (February/March/April) and austral winter (June/July/August) from CTD data.

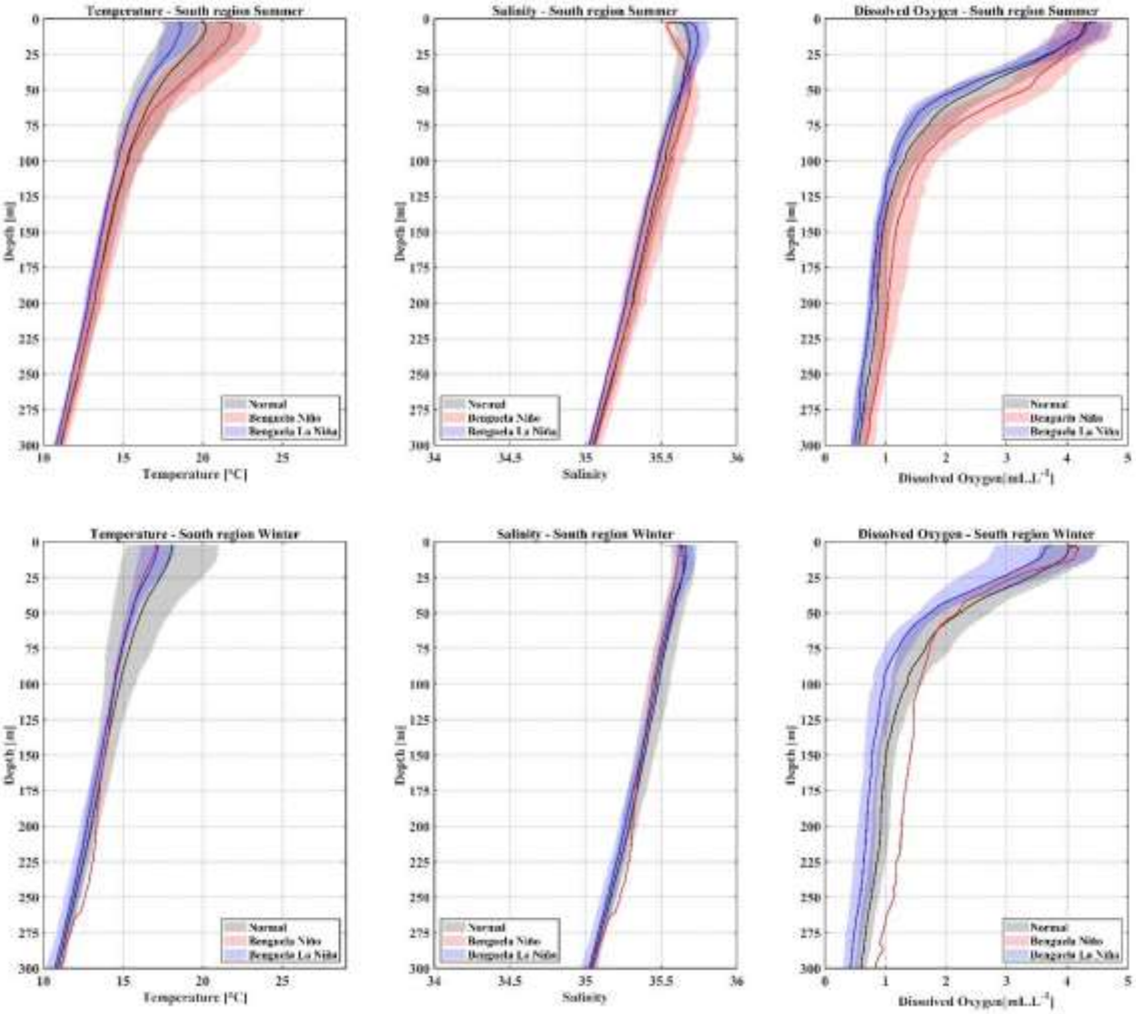
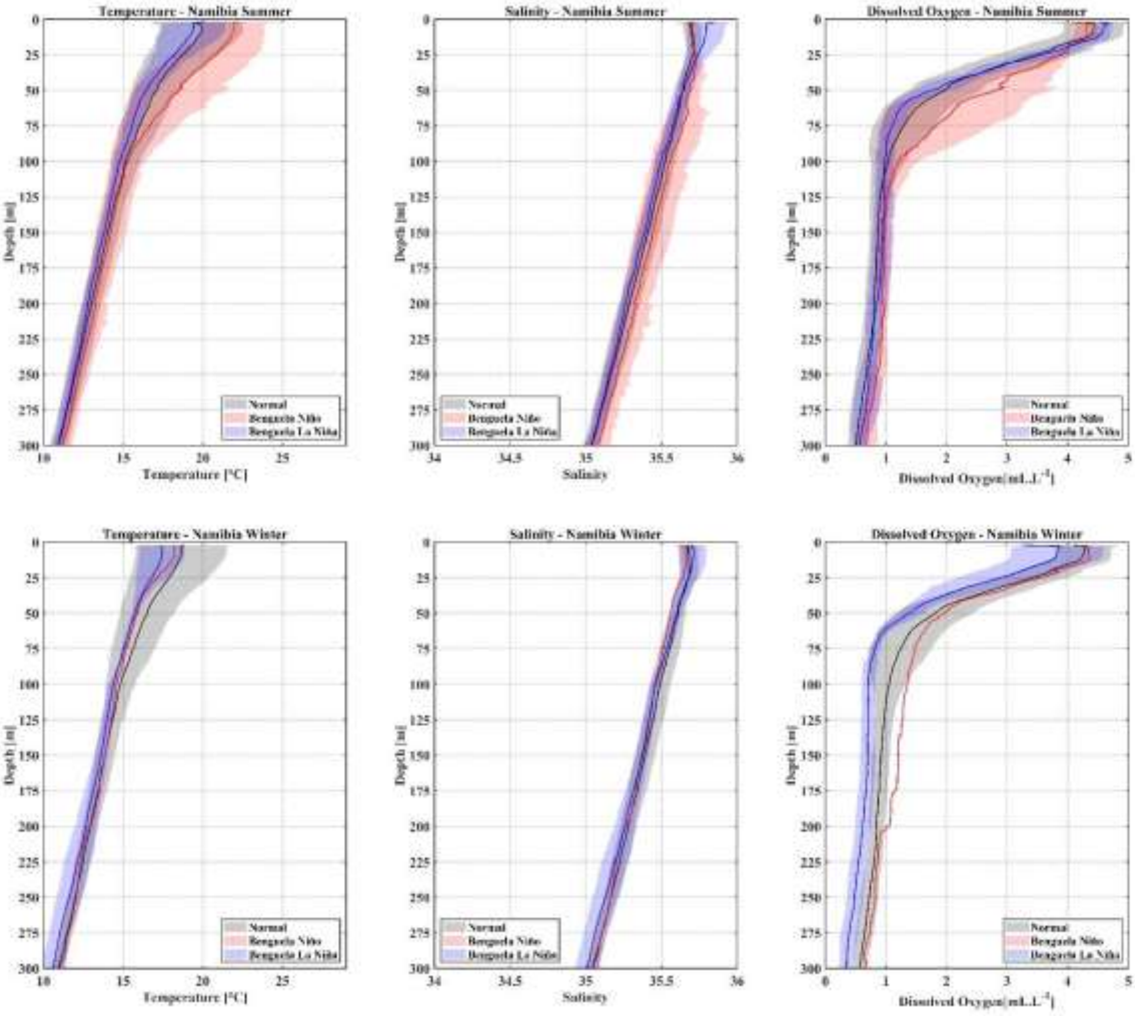


Figure A6 - Vertical profiles of temperature (°C), Salinity and dissolved oxygen (ml/l^{-1}) of monitoring line of Namibe (15º09S) for Normal years (Soft Blue) Benguela Niño years (Soft Green) and Benguela Niña years (Soft Pink) during the austral summer (February/March/April) and austral winter (June/July/August) from CTD data.



APPENDIX B – RESERCH PAPER SUBMITED TO JOURNAL OF MARINE SYSTEMS: WARM AND COLD EVENTS IN THE TROPICAL EASTERN ATLANTIC OFF ANGOLA

Journal of Marine Systems

Warm and cold events in the tropical eastern Atlantic off Angola

--Manuscript Draft--

Manuscript Number:	
Article Type:	Research Paper
Keywords:	Eastern boundary currents; Trapped Waves; Tropical Atlantic; Benguela Current; Angola Current; Benguela Niño/Niña
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Abstract:	Upwelling occurs along large portions of the Angola's coast enhancing biological productivity with positive reflex to local economy and food security. To investigate the occurrence of warm and cold events off the Angolan coast (006°-018°S) 9,529 vertical profiles of temperature, salinity and dissolved oxygen collected during the austral summer (Mar-Apr/1995-2016) and winter (Jul-Aug/1995-2016) under the EAF-Nansen Program were analyzed. The dataset was initially split out according to the occurrence of warm (Benguela Niño), cold (Benguela Niña) and neutral (Normal) SST anomalies for each season. A strong seasonality in near surface temperature and salinity was detected. During austral summer the ocean off Angola is fresh and warm, while during austral winter it is more salty and cold. However extreme events Benguela Niño and Niña are more likely to occur during austral summer. Benguela Niño is marked by a poleward intrusion of warm equatorial water and by reduced upwelling. Results showed the strong influence of the Angola Current (AC) warm waters being transport southward. Low salinity waters (34) were observed associated to abnormally high river discharges (Congo and Kwanza) and direct precipitation that appears contribute to the development of warm events by enhancing the stratification. A maximum salinity value (35.8) was observed in the ABF region while in the open sea salinity remained in the range of 35 along the entire platform. During Benguela Niña events cold and salty water masses were verified along the coast. Cold waters from the Benguela Current moves northwards and reaches Lobito (12 0 S). In the northern (006-009°05'S) and central region (009 0 05'-013 0 S) temperature ranged from 21-24 0 C and at the south region (013-018°S) from 14 0 to 20 0 C. Salinity values along the coast ranged from 35.6 to 35.8 except in the area under the influence of the discharges of the Congo River. One of the world's most pronounced oxygen minimum zone (OMZ) is found below the productive surface layer of the Angola's Sea. Dissolved oxygen concentrations along the coast of Angola are in general lower during austral winter than during austral summer and much lower during normal and Benguela Niña years relative to Benguela Niño years. During the austral summer DO concentrations varies from 1.5 to 4.0 mL.L -1 in normal and Benguela years and from 2 to 3 in Benguela Niña years with offshore values of 0,0 to 1.5 mL.L -1 . During austral winter DO varied from 2-3 mL.L -1 in Benguela Niño years and from 2 to 3.5 mL.L -1 in Normal years, except at 7S where small lenses of the Minimum Oxygen Zone (OZM; DO<1 mL.L -1) reached the coast. In the years of Benguela Niña the OMZ is spread offshore reaching ~7°S. Along the coast, the DO ranged from 1.5 to 3 mL.L -1 , reaching 3.5 mL.L -1 between 6° and 7°13S.
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