

## Low Oxygen Water (LOW) variability in the Benguela System: Key processes and forcing scales relevant to forecasting

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### INTRODUCTION

Low oxygen water (LOW) is an endemic characteristic of the Benguela system (Chapman and Shannon 1985; Bailey 1991; Monteiro *et al.* 2004). The ecological impacts of LOW were identified in the early research work undertaken in the system (Copenhagen 1953; Pieterse and van der Post 1967) and its close association to the incidence of elevated sulphide concentrations was also noted in a qualitative sense (Marchand 1928; Copenhagen 1953; Hart and Currie 1960; Pieterse and van der Post 1967). Events that resulted in significant losses of both demersal and bottom species have occurred in both the central (Namibia) and southern (South Africa) Benguela system (see case study).

At present, stock assessment models treat environmental factors as random sources of mortality that can be parameterised by a mortality factor - this assumes that there are no systematic shifts in the forcing and response to LOW. Similarly, ecosystem models are typically less than sensitive to environmental forcing which can impact fisheries and ecosystem behaviour, distribution and mortality (Shannon and Jarre-Teichmann 1999). The most recent time series data analysis supports the view that LOW variability is characterised by regime shifts in both remote forcing and local forcing factors which interact non-linearly to create LOW conditions and events of hitherto unpredicted magnitude (Monteiro *et al.* 2004).

The BCLME Transboundary diagnostic analysis (TDA) identified LOW as one of the key environmental factors governing the variability and commercial viability of fisheries and ultimately the ecosystem ([www.bclme.org](http://www.bclme.org)). Its implementation plan requires that not only should the causes of LOW variability be understood but the BCLME should also invest in developing a forecasting capability which could assist the optimal ecosystem management, anticipate its impacts, provide better understanding of the underlying complexity and support fisheries management. The forecasting goal for LOW in the Benguela requires that the processes and the forcing scales that drive events and their variability be better characterized and understood.

***The impact of LOW variability on hake fisheries: Namibia 1992 - 1994***

*Hake recruit mortalities off Namibia in 1992/3 (Woodhead et al. 1997a) and the hake recruitment failure off Walvis Bay in 1994 (Hamukuaya et al. 1998; Woodhead et al. 1997b) are examples of the decimating effect that LOW can have on the marine resources of the Benguela ecosystem. Although Cape hake *Merluccius capensis* have adapted both behaviourally and physiologically to tolerate hypoxic conditions to a degree (Woodhead et al. 1998) the severity and the prolonged duration of the hypoxic conditions over the central Benguela continental shelf between 1992 and 1994 is thought to have led to mass mortalities of the hake recruits during 1993 and 1994. In austral summer of 1992 to 1993 the juvenile hake were thought to have been trapped by the expansion of hypoxic conditions leading to loss of half the recruits (Woodhead et al. 1997a). During 1994 the juvenile Cape hake that did not succumb to the oxygen-depleted waters sought to avoid the LOW offshore but cannibalism by the adults that frequent the deeper shelf waters as well as discarding by trawlers targeting these adults are thought to have led to a recruit mortality of 70-84% (Hamukuaya et al. 1998; Woodhead et al. 1997b). Thus, at certain scales, LOW variability affects the abundance, distribution, availability and catchability of commercially fished stocks through modification of both behavioural and mortality responses. The non-random character of LOW impacts on fisheries also challenges the assumptions in fish stock assessment models of the relationship between mortality and environmental variability.*

**SYNTHESIS OF SYSTEM PROCESSES AND VARIABILITY**

Monteiro et al. (2004) have recently suggested that low oxygen variability in the Benguela system is forced by the interaction on varying scales of both large- (basin) and local- (shelf) scale forcing. The processes at these two scales form the core of the discussion. Furthermore, LOW variability in the Benguela system can be further divided into three physically characterised regimes:

Northern (Angola): LOW variability is completely advection controlled and tightly coupled to upwelling that peaks in June – August.

Central (Namibia) LOW variability is governed by a complex interaction between the remotely forced shelf boundary conditions, seasonal thermocline variability and biogeochemical carbon fluxes.

Southern (South Africa) LOW variability is largely driven by local seasonal wind characteristics and minimal remote forcing.

This synthesis is based on the following two foundation papers: a review of BCLME LOW formation assessing the importance of both remote and local forcing for the Benguela region (Monteiro *et al.* 2004) and a paper on sediment vs. water column hypoxia coupling (van der Plas *et al.* 2005). As neither of these papers is yet published, the essence of the thinking in both is reflected in this synthesis. The

physical oceanography focuses on processes that are directly relevant to the formation or advection of LOW. More general syntheses of large scale and shelf physical processes are provided elsewhere (Hardman-Mountford et al. 2003; Shillington et al. 2005). One of the key requirements of forecasting schemes is their ability to translate predicted LOW temporal and spatial characteristics into robust ecological risk categories. A revised set of categories using the most recent observational data is given in Table 1.

**Table 1.** Oxygen concentration thresholds that are of relevance to the linkages between predicted oxygen concentrations and their ecological consequences. These should be seen as guidelines to be interpreted more closely on a case by case basis because exposure times and frequencies are also relevant.

Oxygen State	Oxygen Concentrations	Impacts
Super Saturated	> 100% saturation	Out-gassing to the Atmosphere $f(t,S)$ : typical in high surface primary production
Saturated	100% Saturation	Equilibrium with the atmosphere $f(t,S)$
Under saturated	3 – 100% Saturation	Range over which biological responses should be insignificant
Depleted	2 - 3 ml l <sup>-1</sup>	Biological impacts felt at behavioural level
Critical Hypoxia	1 – 2 ml l <sup>-1</sup>	Threshold that enables the system to go anoxic under a flux of bloom detritus. Organisms require physiological adaptation to survive
Hypoxic	0.5 – 1 ml l <sup>-1</sup>	Extreme stress and mortality in organisms. (denitrification)
Anoxic	< 0.5 ml l <sup>-1</sup>	Respiration dominated by anaerobes and sulphide / methane fluxes

## REMOTE FORCING: EASTERN TROPICAL SOUTHEAST ATLANTIC (ETSA – BENGUELA LINKAGE)

(Further supporting information in CD-ROM: LOWCH5.htm)

The ETSA region is recognised as the main reservoir of LOW in the region but its internal processes and its linkages to the Benguela are weakly understood (Chapman and Shannon, 1985; Voituriez and Herbland 1982). While the importance of temporal variability was understood early on (Chapman and Shannon 1987; Voituriez and Herbland 1982), limited progress has been made in understanding the processes that govern the scales of variability. The basin thermocline shallows eastwards and gets to within 50m of the surface in the ETSA zone, which is commonly referred to as the Angola gyre (Stramma and Schott 1999). It is here that occur the dominant processes of primary production, stratification and retention, which govern LOW formation,

transport and ultimately the boundary conditions of the Benguela shelf. The following processes are essential to the formation and maintenance of the ETSA LOW reservoir:

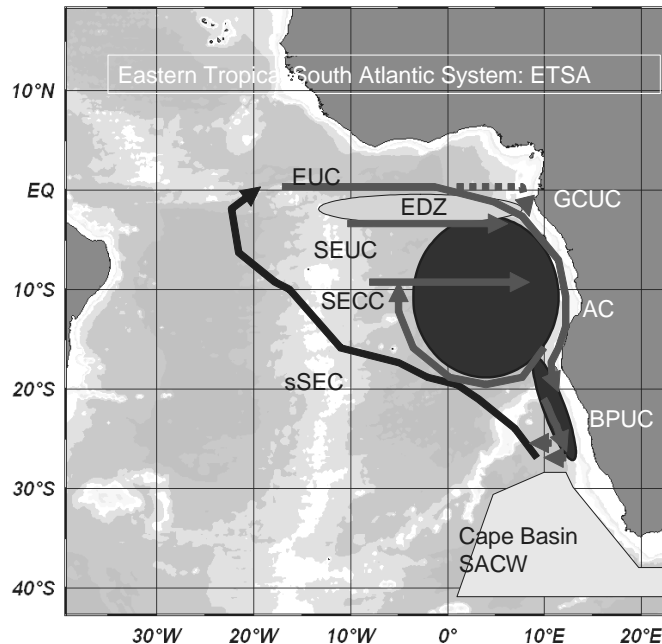
- The scale and variability of phytoplankton new production which provides the required electron donating capacity to the oxygen sink processes.
- A thermocline that limits the downward flux of oxygen across the thermocline to below the biogeochemical uptake rate.
- A retention zone that limits the rate of sub-thermocline ventilation by advected aerated water

In order to understand the generation and change of LOW in the ETSA circulation zone it is essential to characterise the scales of spatial and temporal variability. The main features and flows of the Eastern Tropical South Atlantic (ETSA) – Benguela region that are relevant to LOW variability (Figure 5-1) are briefly noted below.

The spatial and temporal characteristics of LOW oceanography in the tropical South Atlantic are governed by the cyclonic part of its circulation (Reid 1989). The core of LOW within the ETSA zone extends from the equatorial zone to two southern boundaries: one at 16 - 17°S and a second at 25 - 26°S (Figure 5-1). These two boundaries correspond to the southern edge of the Angola gyre and the southern edge of the sub-equatorial cyclonic circulation respectively. The sharp oxygen gradient across the latter boundary defines the transition between the two South Atlantic Central Water masses derived respectively from the hypoxic ETSA and the aerated Cape Basin (Figure 5-1). In the north, the equatorial divergence zone and its associated upwelled nutrient flux are driven by the seasonal easterly trade winds. This system supplies the main phytoplankton export production flux that creates the sub-thermocline oxygen demand within the Angola gyre. Although there are several intermittent divergent flow features here, such as the Angola dome, the only significant export flux of carbon is due to upwelling activity in the austral winter (Voituriez and Herbland 1982).

The current system in the region is fairly complex (Figure 5-1). The eastward flowing Equatorial Under Current (EUC) and South Equatorial Under Current (SEUC) converge, particularly during the seasonal (Dec - April) weakening in the trade winds, when the EUC intensifies to form the Guinea-Congo Undercurrent (GCUC; Stramma and Schott 1999). The combination of the GCUC and SEUC forms the southward flowing Angola Current (16 Sv), which is also the eastern boundary of the Angola gyre (Mohrholz et al. 2001; Mercier et al. 2003). The South Equatorial Counter Current (SECC) provides an additional inflow to the Angola Current during the austral winter. The Angola current splits into two flows, the main one (14 Sv) closing the Angola gyre while its southward extension becomes the Benguela Poleward Under Current (BPUC) along the Namibian shelf as far south as 27°S (Mercier et al. 2003). This southerly extension of ETSA-generated LOW establishes the boundary conditions for the northern and central Benguela system. The poleward undercurrent also feeds further south into the southern branch of the South Equatorial Current (SSEC), which together with the Benguela Current, closes the basin scale cyclonic gyre of the South

Atlantic thermocline waters (Stramma and England 1999). The BPUC also becomes the poleward undercurrent on the slope of the Benguela that acts as the main advective link for LOW between the ETSA and the Benguela systems.



**Figure 5-1.** A diagrammatic view of the main components of the Eastern Tropical South Atlantic System (ETSA) cyclonic circulation zone that are relevant to LOW variability in the Benguela. It shows the core cyclonic circulation, also known as the Angola gyre, supplied with three eastward flows, the Equatorial Under Current (EUC), South Equatorial UC (SEUC) and South Equatorial Counter Current (SECC). The eastern boundary comprises the seasonal Guinea-Congo UC (GCUC) (July – Sept), the southward coastal Angola Current (AC) (16 Sv), the Benguela southward extension as the Poleward Under Current (BPUC) (2 – 5 Sv) which defines the boundary conditions for the shelf upwelling system.

The closure of the Angola gyre by the main flow of the Angola current creates the recirculation retention zone that, together with its thermocline dynamics, establishes the conditions necessary for LOW formation. The main sources of ventilation for the sub-thermocline waters of the ETSA retention zone are the EUC, SEUC and SECC. These currents also may play an important role in the transport of the new production flux from the EDZ into the retention zone.

Within the Angola gyre, the Angola dome is a seasonally transient feature with apparently only limited impact on low oxygen variability. Although previously thought to be the main source of divergent transport that supported phytoplankton

production (Chapman and Shannon, 1985), its contribution to the overall oxygen demand is likely to be small compared to the upwelling at the equatorial divergence zone (EDZ). (Note that Chapman and Shannon did not consider the role of the EDZ in their paper.)

At the southern end of the Angola gyre is a surface feature known as the Angola-Benguela Front (ABF). The spatial and intensity characteristics of the ABF are governed by the seasonal relaxation of the equatorial easterly winds in the late austral summer (Feb - April), which drives the eastward and southward propagation of warm surface water probably as a baroclinic Kelvin wave (Stramma and Schott 1999; Lass et al. 2000; Mohrholz et al. 2001). The relevance of this process to LOW variability in the Benguela is that the resulting intensification of the thermocline intensifies the poleward transport of LOW in the slope and on the shelf.

Large perturbations of the Atlantic equatorial thermocline occur at approximately decadal intervals. These perturbations propagate eastward as a Kelvin wave and surface at the ABF. The effect is an anomalous warming of the surface layer, known as a Benguela Niño, that can then propagate onto the Namibian shelf (Florenchie et al. 2003). This process impacts LOW by intensifying the thermocline and increasing the poleward flow below it. Other associated but less well understood effects of the Benguela Niño include weakening of the equatorial thermocline and the EUC which impact on the ventilation of the ETSA and the ETSA Benguela linkage respectively. The Benguela Niño warming at the ABF should not be confused with the annual (late summer) warming that results from the seasonal relaxation of the equatorial easterly winds. These ETSA-derived features combine to drive the spatial and temporal characteristics of the LOW boundary conditions for the northern and central Benguela system, although not including the Lüderitz upwelling cell. The Lüderitz upwelling cell and the southern Benguela (28oS - 35oS) are defined by the SACW in the Cape Basin characterised by the well aerated boundary conditions driven from the sub-Polar domain.

## **BENGUELA SHELF VARIABILITY**

LOW variability in the Benguela (5°S – 35°S) has been separated into three recognizable domains according to the extent to which the variability is externally forced or locally generated. These are:

- Northern Benguela: Congo – Angola sub-system
- Central Benguela: Namibian sub-system
- Southern Benguela: South African sub-system

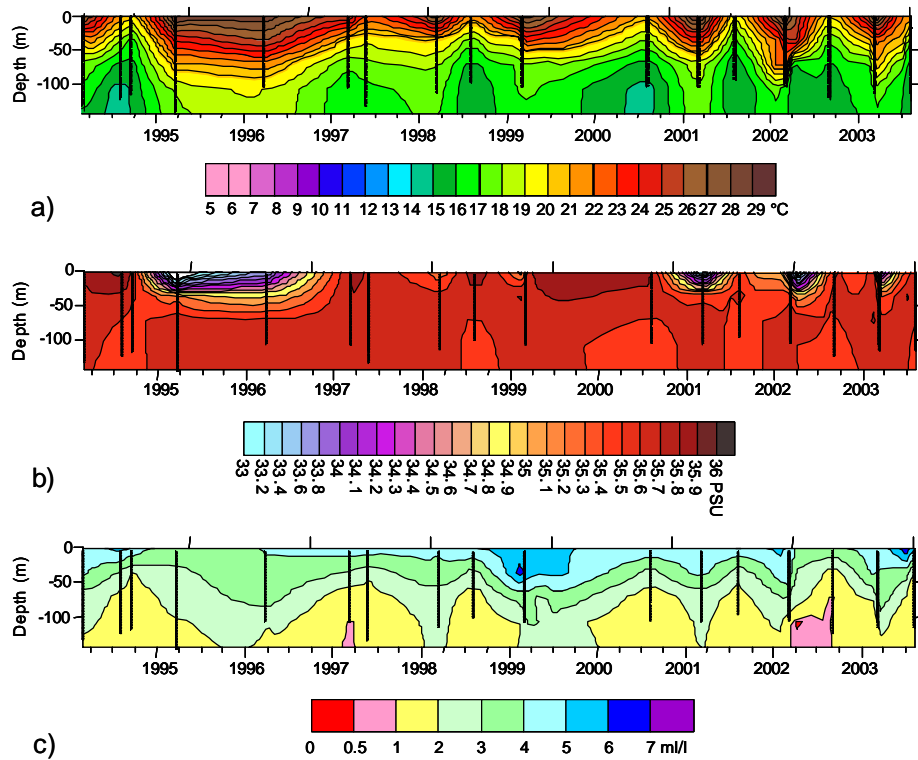
Whereas in the northern sub-system a narrow shelf results in a spatially extensive upwelling, in the central and southern sub-systems the slope – shelf link is at discrete sites also termed “gates” (Monteiro, 1996; Duncombe-Rae, 2004). Three main upwelling “gates” have been suggested to govern the slope – shelf exchange of SACW, Cape Frio (17 – 18°S), Lüderitz (25 – 26°S) and Oliphants Valley (33°S) (Monteiro 1996). Meridional and vertical shifts in the ETSA derived LOW core

control the oxygen characteristics of upwelled water at the Lüderitz and the Cape Frio upwelling centres, the main slope – shelf exchange “gates” in the central Benguela system (Monteiro 1996; Duncombe-Rae 2004). Influxes of more oxygenated SACW at the Oliphants Valley zone will shift the southern Benguela shelf system away from hypoxic conditions even under intense upwelling derived new production fluxes.

**Northern Benguela: Congo – Angola sub-system**

The temporal variability of LOW in the narrow Congo – Angola shelf system (Figure 5-2) shows that it is strongly driven by the boundary conditions characteristic of the

**Lobito (12°S, 110m to 150m bottom depth)**



**Figure 5-2a-c:** Time series of temperature (a), salinity (b) and oxygen (c) variability on the Angolan shelf for the period 1994 – 2003. It highlights the strong relationship between the incidence of low oxygen waters (< 2ml<sup>-1</sup>) and cold upwelled water (< 16°C). Because of the narrow shelf the incidence of LOW is driven almost completely by the upwelling driven advection of ETSA LOW rather than any shelf based modification. In this part of the system oxygen behaves conservatively with temperature. Sampling periods and depths are indicated on the diagrams.

ETSA region along the shelf. The narrow shelf means that ETSA- LOW is upwelled from the slope onto the shelf along the entire coastal system and LOW seasonal variability is strongly correlated to temperature. This correlation indicates that the variability is governed by the advection of upwelled water rather than by any shelf domain processes. Seasonal variability in the northern sector of the system (Figure 5-2) shows that LOW intensifies in the 3rd and 4th quarter of the year linked to the intensification of the equatorial easterlies. Moreover, higher oxygen conditions of the system (Figure 5-2) are driven by downwelling and aeration linked to the southward advection of tropical warm water during the relaxation of the equatorial easterlies in the 1st quarter. For the remainder of the year the combined effects of the narrow shelf and proximity to the domed core of the ETSA LOW system mean that the oxygen concentrations are low and closely correlated to temperature (Figure 5-2).

#### **Central Benguela: Namibian sub-system**

LOW variability in the Central Benguela shelf is governed primarily by the boundary characteristics at the two main upwelling centres of Cape Frio and Lüderitz. The linkage between these boundaries and the ETSA is of key importance. We suggest that the relative contribution from these two sources of shelf water is strongly dependent on the characteristics and the poleward extent of the warm tropical surface water and the impact it has on the thermocline characteristics on the shelf.

As stated above, the poleward extent of the warm tropical surface water governs the strength of the sub-thermocline poleward flow which regulates the spatial scale of the impact of the hypoxic waters upwelled at Cape Frio. Under conditions of weak stratification and south easterly wind stress, typical of the early upwelling season in the 3rd and 4th quarters of the year, the dominant flow on the Namibian shelf is equatorward, driven by the barotropic pressure gradient and a weak or non-existent poleward flow on the shelf. When stratification intensifies, either as a result of seasonal or interannual warm events, the sub-thermocline poleward flow strengthens due to the increasing forcing of the baroclinic pressure gradient. While the former condition favours a larger contribution of mostly aerated water (Cape Basin SACW) derived from the Lüderitz gate, the latter favours a greater magnitude from the hypoxic Cape Frio flux. Thus, we believe that the LOW environment on the Namibian shelf is modulated by the changing contributions of water from the two input fluxes driven indirectly by the strength of the warm water events. This dynamic is suggested to govern the magnitude of both the seasonal and the interannual LOW signal in this part of the system.

Combining these ideas of stratification and shelf transport allows LOW variability over a 10 year period (1995 – 2004) within the central part of the Central Benguela to be better understood (Figure 5-3a-c). The time series of oxygen concentration at the outer shelf in the mid-Central Benguela (Figure 5-3) shows that the variability of the hypoxic water is driven by both the stratification as well as the LOW boundary



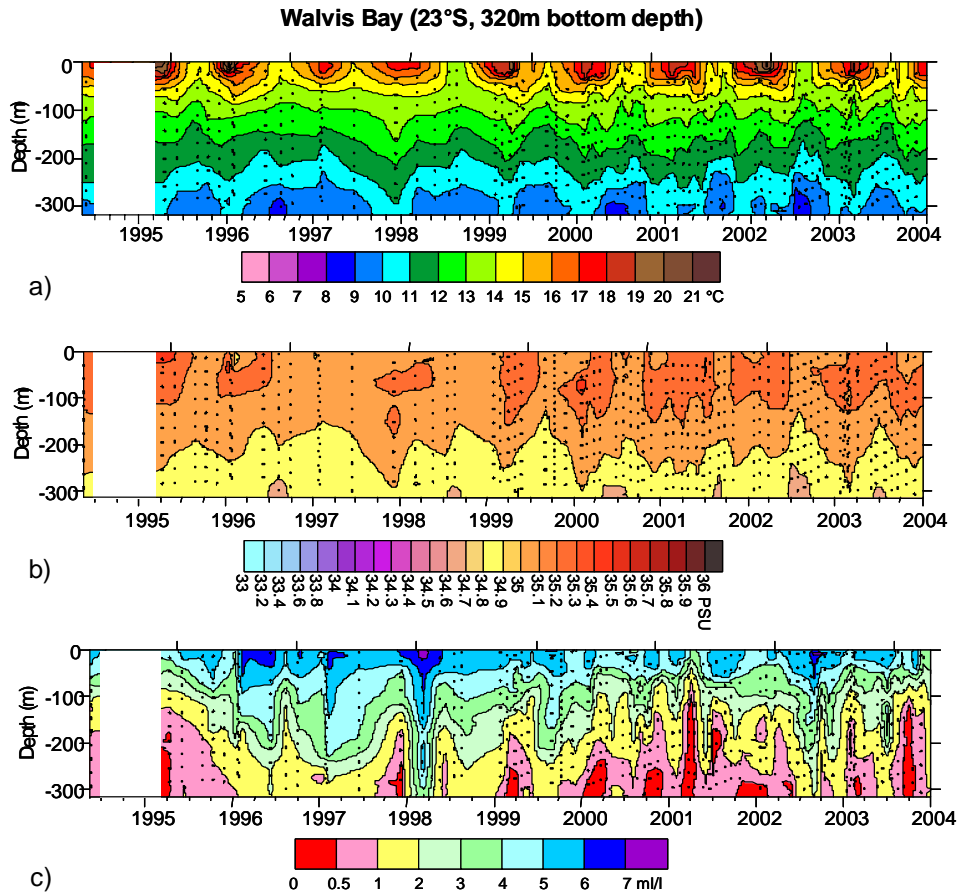
conditions, with the strength of the stratification, which according to the model drives the poleward transport, modulating the boundary condition LOW signal on the shelf. In periods when the stratification weakens the hypoxic signal is also weakened because there is a greater contribution from water upwelled at Lüderitz and moving equatorward. This happens every year in the winter – spring upwelling period and occasionally, such as in 1997 – 1998, it covers an interannual scale when stratification remains weak and water column oxygen concentrations are relatively higher ( $< 2\text{ml l}^{-1}$ ; Figure 5-3). In this period salinities remained low, supporting the prediction that the system would under these conditions have a stronger forcing from Lüderitz. Salinities then increase as predicted from the result of the increasing contribution from the Cape Frio upwelling centre.

The data shows that there are consistent differences in oxygen content between the inner and outer shelf areas of the central Benguela. The inner shelf concentrations are consistently lower. Differences in LOW variability between the inner and outer shelf zones are due to the lag effect caused by the biogeochemical oxygen demand driven by the respiration rates in the inner shelf mud belt where much of the surface derived new production accumulates (Monteiro and Roychoudhury 2005). The sediment ecosystem in the mud belt can exist in two redox states, aerobic and anaerobic. Both states create oxygen demand fluxes but whereas in the aerobic condition this is directly related to the metabolism of the flux of organic carbon, in the anaerobic condition it includes also the additional oxygen demand fluxes driven by reduced metabolic products such as  $\text{HS}^-$ ,  $\text{CH}_4$  and  $\text{NH}_4^+$ . Once the system switches to the anaerobic condition, the lagged flux of reduced products driven by accumulated organic carbon maintains an oxygen sink that increases the persistence of hypoxic / anoxic conditions. The lag in the consumption of the electron donors as well as the flux of reduced products damps the variability in the inner shelf region of Namibia.

However, it is not the upwelling-derived flux of organic carbon that governs the shift from aerobic to anaerobic conditions, but the boundary derived LOW signal of  $\text{O}_2 < 1.5\text{ml l}^{-1}$ . If this condition is not achieved, either because of boundary conditions at Cape Frio or an increased contribution from Lüderitz, the anaerobic fluxes weaken and the system will after one or two seasons switch to an aerobic state (e.g. 1997-1998). Despite the lag effect of the locally forced anaerobic conditions, LOW variability is still characterised by a seasonality where water column hypoxia is deepened in the later summer – autumn period and weakened in the winter – early spring period (Figure 5-3). The importance of this finding is that it supports the view that the toxic events driven by methane and sulphide are a response to boundary forcing rather than a forcing factor. The unexpected aspect is just how weak the local generation signal really is. It controls persistence, intensity as measured by water column depth, and toxicity to local fauna but not the incidence.

In summary, while LOW variability in the outer shelf is governed by both the boundary conditions and dynamic interaction of fluxes between the Lüderitz and Cape Frio upwelling centres, the variability in the inner shelf is the result of the same factors as well as the local biogeochemical processes. Measured oxygen concentrations reflect the spatially separated inputs from the Cape Frio and Lüderitz upwelling cells

as well as the poleward transport of warm tropical surface water which exerts its impact through the baroclinic pressure gradient.



**Figure 5-3:** Variability of temperature (a), salinity (b) and oxygen (c) at an outer shelf location at 23°S in the Central Benguela between 1994 and 2004. The oxygen variability is modulated by both seasonal (summer / late summer) and interannual (1996 – 1999 vs 2000 – 2002) scales. The significant point is to link the period of enhanced LOW (2000 – 2002) to increased surface warming and higher salinities. In contrast, the 1996 – 1999 periods reflect weaker hypoxia. Sampling periods and depths are indicated on the diagrams.

### Southern Benguela: South African sub-system

In contrast to both the central and northern sub-systems, LOW variability in the southern sector (e.g. see Figure 5-4) is largely governed by a combination of local physical (stratification, recirculation-retention and advection) and biogeochemical processes (upwelling driven new production). Moreover, both northern and central

sub-systems have shelf boundary conditions characterised by ETSA-derived LOW whereas the boundary conditions in the southern sub-system are those of aerated sub-Antarctic SACW ( $O_2 > 4\text{ml l}^{-1}$ ) - see Chapman and Shannon 1987. Therefore, rather than being “primed” with remote sourced LOW, local formation has to rely on the physics of retention and stratification to bring down the oxygen concentrations of newly upwelled water. This is, in principle, the same set of processes that govern the ETSA zone on a larger spatial scale.

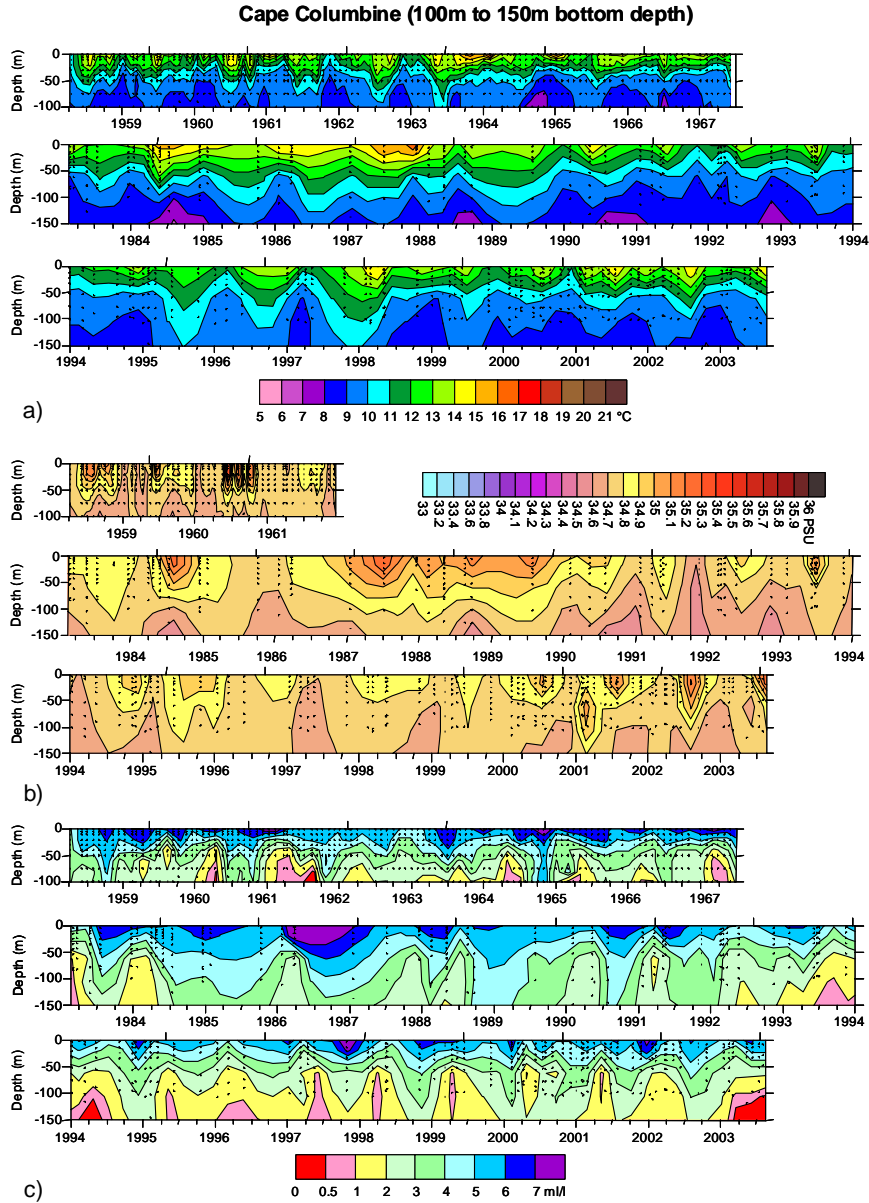
The main LOW generation zone is the St Helena Bay retention zone (31 - 33°S) downwind from the Cape Columbine upwelling centre (Bailey and Chapman 1979; Taunton-Clark 1979; Penven et al. 2000). The hydrodynamics of this system drive a seasonal cyclonic circulation that gives rise to a strongly stratified two layer system sustained with cold upwelled water and a sun-warmed surface layer (Waldron and Probyn 1991). These conditions persist over the upwelling season (September – April) and support a highly productive nitrate-driven biological pump (Touratier et al. 2003; Monteiro and Roychoudhury 2005), which coupled to the physically driven nutrient fluxes, lead to high rates of sedimentation of POC (Bailey 1983). The remineralization of the POC coupled to fluxes of HS- creates an environment where, with strong stratification that reduces the aeration rates of sub-thermocline waters, the seasonal LOW is generated. The detailed interactive dynamics that govern LOW variability and which form the basis to a possible forecasting system are described in greater detail in the section dealing with LOW forecasting scales (see Chapter 13).

LOW variability in the remainder of the southern Benguela sub-system shelf is the result of equatorward advection of LOW formed in St Helena Bay. The relatively low salinity values ( $S < 34.9$ ) over a decade-long time series support the view that ETSA waters do not make a significant contribution to the water and LOW in the southern Benguela. The northward transport is depicted in the distribution of the integrated surface chlorophyll from St Helena Bay (see composite images in Figures 7-2 and 7-4 in Pitcher and Weeks – this volume, Chapter 7). LOW variability off Hondeklip Bay (30°S) is closely correlated to temperature (Monteiro et al. 2004) which is an expected outcome from advection-controlled variability. We agree with Johnson and Nelson (1999) that interannual LOW variability in the southern Benguela is governed mainly by the interannual variability in the equatorward component of the seasonal upwelling winds. This is in contrast to the controls on the boundary conditions of the northern and central Benguela system that are exerted by the seasonal, interannual and decadal shifts in the easterly equatorward winds.

## **SUMMARY**

The characteristics of LOW variability in the Benguela can be summarised into three modes:

**Northern Benguela:** The Angolan shelf system is directly coupled to the boundary conditions and the variability in LOW is largely predicted by its strong correlation to



**Fig. 5-4:** The variability of temperature (a), salinity (b) and oxygen (c) at a mid-shelf position in the period 1984 – 2004. It shows a remarkable contrast in oxygen regimes between the 1980's (aerated) and the 1990's which were oxygen deficient / hypoxic. The explanation lies in the quasi-decadal scale changes in the upwelling wind regimes. The 1980's were characterised by relatively weak winds whereas the 1990's by strong upwelling conditions. Hypoxia is related to changes in the retention characteristics of the St Helena Bay retention area. temperature. Its variability is driven exclusively by the variability of the ETS characteristics

**Central Benguela:** LOW variability on the Namibian shelf is non-linear in respect of upwelling because it is dependent on a conjunction of processes and conditions that are not directly linked. The factors that govern LOW variability on the Namibian shelf are thought to be ETSA characteristics that set the boundary conditions, the incidence and strength of warm surface events, and upwelling rates at both Cape Frio and Lüderitz. These are amplified by the local production fluxes in the inner shelf.

**Southern Benguela:** LOW variability in the Southern Benguela is largely governed by the interannual variability in the equatorward component of the seasonal upwelling winds.

The importance of this characterisation is that it helps to define key scales of forcing and response that are sub-system specific and perhaps result in a more sensitive forecasting or at least predictive system.

## PROCESSES REQUIRING DIAGNOSTIC ASSESSMENT

The recently completed review identified a number of new possible processes that may govern low oxygen variability over a wide range of space and time scales (Monteiro *et al.*, 2004). While these new proposed explanations were consistent with the data sets used in the review it is not certain whether the dynamics proposed to account for their impact on LOW variability are consistent.

### **The most important process uncertainties driving remote forcing are:**

- The combination of processes that govern the formation and variability of LOW in the ETSA zone
- The coupling of warm surface flow and sub-thermocline poleward flow which may be the mechanism that transports LOW from the ETSA to the Benguela boundaries
- The Slope – Shelf coupling which transports LOW onto the shelf at preferential sites such as the Cape Frio or Lüderitz upwelling centres
- The coupling between warm surface flow and sub thermocline transport on the shelf through the strengthening of the thermocline
- Coupling between remote and local forcing

The dynamic consistency of these proposed mechanisms needs to be evaluated using appropriately set up hydrodynamic models through a set of modelling experiments. These do not need to be undertaken in simulation mode but in synthetic domains set up at scales that are comparable to the actual mechanism in question. This is the proposed approach in the follow up Chapter 12 that focuses on processes and scales that are amenable to forecasting.

### **Coupled remote and local forcing**

The dependence of LOW variability on the coupling between remote and local forcing is a key finding which makes the forecasting potential of LOW variability and its impacts a possibility (van der Plas *et al.* 2005). This is because it is remote forcing that defines the regime modes that govern variability in the northern and central Benguela through the boundary conditions. Regime mode shifts on a basin scale that eventually impact on the Benguela boundaries may not only be forecast on a time scale of months but their impact on a time scale of years – decades may perhaps be evaluated through scenario modelling. However this forecasting potential depends sensitively on the proposed biogeochemical coupling between remote and local forcing (van der Plas *et al.*, 2005). It is important that this hypothesised link be tested using a combination of modelling and observational data. The coupling was proposed using steady state assumptions and its incidence in a time varying sense needs to be tested (van der Plas *et al.* 2005).

### **PROCESSES WITH FORECASTING POTENTIAL**

The table of processes below (Table 2) shows that the cost effective observational capacity of the individual processes is mostly good but the forecasting of LOW variability depends largely on how well the linkages that transfer the equatorial signal to the Benguela are understood and modelled.

Three different temporal or forecasting scales of LOW variability are evident from the table:

- the short term events of a few days with localised impact
- medium term events of a few months duration and with shelf wide impact
- long lasting LOW variability of year to decade scale and with system wide impact (scenarios)

Any future operational LOW forecasting system will need to combine modelling with data assimilation and verification platforms. It is envisaged that such a system would make use of “real time large scale models” running predominantly with data assimilation into which will be nested the LOW region specific model domains. These would derive their boundary conditions from the large scale models, advect the signal and drive the internal processes that govern LOW variability in critical habitat areas. Forecasting in region specific domains would be based on “free running” models rather than on data assimilation and would be verified against real time data sets. The LOW scales and processes that are most amenable to forecasting whether for scientific reasons or because they are relevant to ecosystem management perspectives are addressed in detail in the companion Chapter 13 (Monteiro *et al.* 2006).

**Table 2:** Physical processes that have a bearing on the variability of Low Oxygen Waters in the Benguela and may be worth forecasting.

Domain	Forcing System	Processes	Scales of variability	Observational Potential	Worthwhile to Forecast	
Remote	ETSA	Equatorial upwelling and new production	Seasonal - interannual	Good: Ocean Colour	Maybe	
		Intensity and timing of trade winds	Seasonal - Interannual	GCM	Yes	
		Equatorial stratification	Interannual – decadal (Benguela Nino)	Good: Ocean Buoys	Yes	
		Angola Current	Seasonal - interannual	Good: Altimetry and AVHRR	Yes	
		LOW in the ETSA	Interannual - decadal	Good: Ocean Buoy	Yes	
		Depth of the upper boundary of $O_2 < 2ml\ l^{-1}$	Interannual - decadal	Good: Ocean Buoy	Yes	
		Depth range of $O_2 < 2ml\ l^{-1}$	Interannual - decadal	Good: Ocean Buoy	Yes	
Local	Upwelling centres	Poleward transport of LOW into Benguela	Seasonal - Interannual	Good: Ocean Buoy	Yes	
		Upwelling driven new production	Days - weeks	Good (ocean colour remote sensing)	Yes	
		Upwelling wind variability	Days - weeks	Good	Maybe	
		Relaxation events in the southern Benguela	Days - weeks	Good	Maybe	
	Ecosystem responses	Transport and dispersion of LOW	Spatial scales of depositional areas	10 – 1000km	Good	Yes
			Transport and dispersion of LOW	10 – 1000km	Poor	Yes
			Transport and dispersion of sulphide in water column	10 – 100km	Poor	Yes

## **WHAT ARE THE GAPS?**

### **Time series observations**

The Lüderitz upwelling centre plays a pivotal role in forcing the system by supplying upwelled water to both the central and southern Benguela shelf. However, the attempts to understand this role are severely limited by the paucity of data from this area. The most important forcing point has the weakest data set. The temporal resolution of the data from the second most important upwelling “gate” in the Benguela, Cape Frio, is also quarterly at best. (Refer also to Shillington et al. and Reason et al. Chapters 4 and 10 respectively, this volume)

### **Slope - Shelf exchange**

An observational programme should be put in place that will elucidate the mechanisms of slope-shelf exchange of LOW. The proposed observationally based early warning system should make use of the understanding derived from both the literature review and the data based advances.

The observational programme to support a first early warning system should aim to make use of existing freely available data products. These should include modelling, remote sensing and observational programmes that are already in place. The processes that need to be monitored include:

- The thermocline characteristics in the ETSA area which governs the LOW characteristics for the Benguela;
- Poleward advection of warm tropical water:
- This was shown to be one of the most sensitive indicators of the southward propagation of LOW
- from the ETSA to the Benguela off the shelf
- the shelf based southward displacement of tropical surface waters e.g.: ABF; and
- The thermocline depth and strength on the slope (1000 – 2000m) and on the shelf (100m)

The recommended additional observational programmes are the monitoring of oxygen and temperature in the ETSA region and at the two main upwelling centres that cover the Central and Southern Benguela. This is most likely best done using large ocean buoys with temperature records at 50 m intervals and oxygen observations at 50m intervals in the upper 200m and 100m spacing below 200m. The buoys should be located on the slope in the zone of the 1000 – 2000m depth range. These should also provide telemetry based data streams that allow the data quality to be assessed and test linkages with response scales at the monthly monitoring sites off Walvis Bay and St Helena Bay. It is recommended that when this proposed programme is accepted that the BCLME commission a regional facility to provide the products to the community. This first phase early warning system is expected to be operational for a period of two



years by which time the modelling platforms for the BCLME should be operational and providing a second and later third phase forecasting.

### **Remote - local coupling**

Advection vs. local formation: Local formation of hypoxic or anoxic LOW depends on the boundary conditions being at or below a critical threshold (approximately 1.5ml l<sup>-1</sup> O<sub>2</sub>) at which the physical supply rate of dissolved oxygen falls below the biogeochemical demand and the system rapidly switches to anaerobic respiration (van der Plas *et al.* 2005). Thus the magnitude and persistence of LOW variability on the Benguela shelf is primarily the result of the degree of oxygen depletion in incoming water across the boundary and only secondarily the local oxygen demand driven by the sedimenting flux of upwelling-linked new production. The latter is, however, responsible for modulating the response of the system to boundary forcing (Monteiro *et al.* 2004).

It has been proposed that state of environment (SOE) indicators be devised to monitor the LOW status over the Benguela shelf. The SOE indicator effort should be focussed on the areas where regular spatial monitoring can take place at least once a month. The indicators are a measure of the response of the system and should therefore also ideally be located in areas where measuring that response is of relevance. The present monthly monitoring lines in the southern, central and northern Benguela partially fulfil these requirements as the location of the lines is for historical reasons pragmatically close to the sponsoring institution. The following thresholds are suggested: depth of oxygen under-saturation in two zones of the shelf, namely at depth < 100m and depth > 100m.

### **SUMMARY**

LOW variability in the Benguela is governed by varying scales of remote and local forcing linked to both Equatorial and Cape Basin systems. The nature of these non-linear interactions is not clearly understood because scales are large and their elucidation through observational programmes alone is not cost effective. Models are required to characterise the complexity of the most important forcing and response scales in both time and space. It will be necessary to approach this as a multi-phase process, beginning with a diagnostic emphasis which evolves to a forecasting system through hindcasting focussed specifically on large scale events of the past. It is clear that not all the variability scales are amenable to forecasting either because the driving process scales are too uncertain or because they are of little management or policy interest. Two scales were defined as being of interest to both these criteria:

- **Short term** (7 day) scale related to forecasting conditions leading to the walkout or mortality of rock lobster in the southern Benguela
- **Medium term** (2 month) forecasting of the intensification of the remote forcing of ETSA derived LOW which has a bearing on the Namibian hake fishery

These two scales are discussed in detail in the companion Chapter 13.

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