BCLME
Benguela Current Large Marine Ecosystem Programme

THE CHANGING STATE OF THE BENGUELA CURRENT LARGE MARINE ECOSYSTEM: EXPERT WORKSHOP ON CLIMATE CHANGE AND VARIABILITY AND IMPACTS THEREOF IN THE BCLME REGION, 15-16 May 2007

Workshop report,
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TABLE OF CONTENTS

Workshop Objectives

Global change is an undeniable phenomenon that has received much attention in recent years. The 2007 IPCC (Intergovernmental Panel on Climate Change) report presents a multiplicity of evidence that 'global warming is unequivocal' (Hewitson, presentation, BCLME Climate WS). The extent to which the BCLME is subject to global warming or more generally, climate change, formed part of the focus of this workshop and is by no means a trivial exercise. This difficulty is exacerbated by the fact that the Atlantic Ocean, in particular, is subject to several modes of variability, so that the separation of 'signal' and climate change trends from 'noise' becomes an exceedingly challenging task.

Despite the difficulties involved in deciphering the several modes of variability in the Benguela system, the objectives of the workshop were firstly to address what has changed, by how much and at what rate (in terms of both the physical and biological environments), as well as to investigate the drivers of these changes. Secondly, the socio-economic consequences of ecosystem change were addressed and mitigation strategies that should be put in place in order to alleviate the effects of future changes. Finally, the foundation for future actions was addressed by prioritizing important issues and gaps in knowledge, documenting essential steps in the development of an affordable, implementable and sustainable ocean observing system for the region and by laying the foundation for for future problem-oriented ocean climate change-related research in the three BCLME countries. Based on these objectives, the key questions of the workshop were as follows:

1. Is there evidence of climate change and its impacts in the Benguela, or is the longer term (decadal) variability/change that is evident in the physical environment and biota purely an artifact of cyclical processes or fishing?
2. What are the potential consequences of climate variability and change which pose threats to sustainable management of the BCLME and/or to socio-economic progress in the region?
3. Are there any apparent trends in extreme events in the BCLME?
4. What are the critical processes within the BCLME that are already demonstrating instabilities of concern (cf. whether a possible “tipping point” has been reached)

Indeed, the climate change theme of the workshop was an ambitious one. Nevertheless, headway could be made by focusing on and documenting decadal-scale variability and changes observed in the greater BCLME region over the past 100 years. Deciphering the causal mechanisms of these changes was also a key objective, with particular emphasis on the importance of ocean-atmosphere and trophic-level interactions. Mitigation strategies were suggested in order to minimize the risks of a highly-changeable system.

1. Introduction

The Benguela Current Large Marine Ecosystem (BCLME) which borders the coasts of Angola, Namibia and South Africa at the eastern side of the South Atlantic is unique among comparable upwelling systems in that it is bounded on both northern and southern ends by tropical or sub-tropical regimes that have a significant impact on it. The Benguela is a highly productive but complex ecosystem – one that displays considerable environmental variability on several time and space scales, which is mirrored by variability in its living marine resources. Human impact on the BCLME, which includes fishing, pollution, mining and exploration for and extraction of oil and gas, is superimposed on the inherent natural variability of the ecosystem. Moreover, the flora and fauna of the Benguela and adjacent areas may be especially sensitive to long-term climate change as the region is situated at the choke point in the "global ocean climate conveyor belt", where, on time scales of decades to centuries, warm surface waters from the Indo-Pacific pass around Africa into the Atlantic. Indeed, it is thought that the BCLME may well be an early site for the manifestation of global climate change. Climate variability and change have the potential to alter the distribution and abundance of many Benguela species and cause the extinction of sensitive species, with consequential impacts on fisheries and tourism and the livelihoods of the coastal communities, who depend on these industries.

To date much of the focus of BCLME Programme (certainly of the environmental variability component) has been in documenting the *present* state of the ecosystem and short term variability, and undertaking work addressing system predictability. However, in order to establish a proper baseline against which to measure future variability and changes, it is necessary also to ascertain the extent of and trends in variability and change over the full period of record (50-100 years) . This is seen as an important element of the BCLME Programme – indeed was listed as a key policy action in the Strategic Action Programme which was endorsed by the governments of Angola, Namibia and South Africa, who saw the establishment of a baseline for the BCLME as a high priority regionally, and also important in the global context. Accordingly it is both appropriate and timeous to assess the long-term records within the context of climate change and variability.

The mean state of the physical environment of the BCLME is often summarized in cartoon-form (Figure 1), providing a glance at the dynamics of our prized upwelling ecosystem, but inevitably dismissing the intricacies of the many scales of temporal and spatial variability that are a key to the health and longevity of resources off the west coast of southern Africa. That said, a brief summary of the definitive structure and physical processes of the BCLME follows, providing a point of reference from which long-term trends and cycles of the system can be documented. Following this is a summary of the key biological features of the Benguela ecosystem.

The Benguela Current is the eastern limb of the South Atlantic sub-tropical gyre and also encompasses the Benguela upwelling system, which is bounded at both its northern and southern extremities by the warm water regimes of the Angola and Agulhas Currents respectively (Shannon and Nelson, 1996, Shillington, 1998). The northern boundary of the upwelling system is coincident with the Angola Benguela Frontal Zone (ABFZ) where the warm Angola Current meets the cool Benguela upwelling regime and the southern boundary is influenced by the thoroughfare of Agulhas rings that form at the retroflection (Duncombe-Rae, 1992, Shillington, 1998). Another boundary of significance in the BCLME separates the northern and southern upwelling regimes, on the basis of their disparate physical and biological characteristics and has come to be known as the Lüderitz Upwelling Cell and Orange River Cone (LUCORC) area (Shannon 1985; Taunton-Clark and Shannon 1988; Shannon and Pilar 1985; Lett et al. 2007).

Circulation features of the BCLME that are also inherent features of upwelling systems include offshore Ekman-transport at the surface that is driven by equatorward winds, a poleward undercurrent along the continental shelf-break and the growth and decay of frontal jets into meanders, eddies and filaments. Of particular importance to the successful transport of fish eggs from spawning to nursery grounds is the strong jet that extends from the Cape Peninsula to Cape Columbine (Fowler and Boyd 1998). A subsurface poleward flow has been observed near the shore all along the west coast fluctuating with a periodicity of approximately 3-10 days (Nelson 1989).

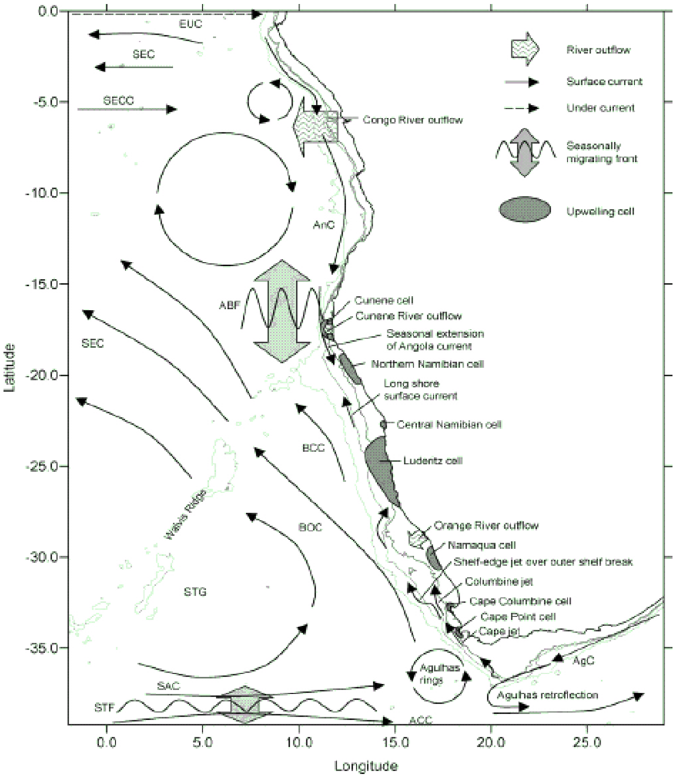

Figure 1: Schematic diagram of salient features of the South East Atlantic and Benguela upwelling system (from Hardman-Mountford *et al.*, 2003).

The South Atlantic high pressure system and its seasonal shift (northwest-southeast/autumn-spring) facilitates the upwelling-favorable, equatorward wind regime, which is dominant during summer in the southern Benguela and throughout the year in the northern Benguela. In summer, surface heating over western southern Africa induces low pressure systems that enhance the zonal pressure gradient and thus the upwelling-favorable wind stress. In winter, when the South Atlantic high pressure system (or, South Atlantic anticyclone: SAA) moves northward, the southern Benguela is influenced by the westward moving mid-latitude cyclones that induce northwesterly winds (Shillington 1998). This seasonal wind pattern, based on the movement of the SAA, is modulated by synoptic-scale fluctuations forced by berg winds and coastal lows. The maximum wind stress is located at a distance of the order of 200km offshore, thus inducing a negative wind stress curl in a coastal strip of similar dimensions, which has been mapped by Chelton et al. (2004) for the BCLME using QuikSCAT satellite wind stress data. The implications of a negative curl is to enhance upwelling as well to induce a poleward flow via the Sverdrup relation.

The physical environment of the Benguela system sets the scene for the highly productive ecosystem that exists there which is characterised by phytoplankton-rich coastal waters that can be observed from satellite using the high chlorophyll concentrations in this area as a proxy. Phytoplankton variability is driven by the non-linear relationships between upwelling favourable winds that bring nutrient-rich water to the surface, solar radiation, stabilization, sinking and the response times of individual species (Hutchings et al. 2006). Species of zooplankton provide a link between the primary producers and the larger heterotrophs, who tend to have preferential prey. The larger *Calanoides carinatus* is extensively preyed upon by anchovy *Engraulis encrasicolus*, while sardine *Sardinops sagax* prefers micro-plankton and small copepods (van der Lingen 1994). These predilections suggest the importance of zooplankton distributions to the composition and distribution of the pelagic fish resources.

Living marine resources of substantial commercial value that are supported by the Benguela upwelling system include small pelagic fish (anchovy, redeye round herring *Etrumenus whiteheadi*, sardine and *the sardinellas* Sardinella aurita and *S. maderensis*), mid-water fish species (Cape horse mackerel, *Trachurus trachurus capensis* and cunene horse mackerel, *T. t. trecae)* and demersal fish species (including the hakes *Merluccius capensis* and *M. paradoxus*) and the west coast rock lobster (*Jasus lalandii*) (van der Lingen et al., 2006). The abundances of these fish stocks depends not only on the variability of the physical environment and its influence on food availability, but also on fishing.

In turn, the diet of many top-predators depends on the availability of these economically important fish stocks, which they favour as prey. Crawford et al. (1995) discuss the usefulness of the analysis of the diets of predators as an indicator of the state of commercially exploited fish stocks. Particularly they noted that trends in the diet of Cape gannets *Morus capensis* corresponded to the abundance of anchovy and sardine off the west coast of South Africa. Similarly, the snoek *Thyrsites atun* diet appears to have changed from sardine to anchovy in 1964 when the dominance shifted from one to the other (Crawford et al., unpublished manuscript, cited in van der Lingen, 2006) Between 1989 and 1990 populations of the Cape cormorant *Phalacrocorax capensis* appear to have decreased in abundance as a response to competition for food with commercial fisheries. The diet of the South African fur seal *Arctocephalus pusillus pusillus* is quite varied, allowing it to thrive in regions (and regimes) of different prey abundances. The South African fur seal has long been regarded as a threat to the commercial fisheries (David, 1987) and, particularly since its change of status to a protected species in 1973, has been impacting upon certain species of sea birds including the Cape cormorant, the black cormorant *Phalacrocorax neglectus*, the crowned cormorant *Phalacrocorax coronatus,* the Cape gannet and the African penguin *Spheniscus demersus* (David et al., 2003). A shift from a sardine-abundant food source to an anchovy-abundant food source causes a decline in the African penguin population, which has also been observed to have difficulty coping with competition from commercial fisheries and other predators in the 20th century (Crawford, 1998).

The lucrative fisheries on the west coast are subject to both top-down and bottom-up ecosystem controls. The former include fluctuating activity by top predators including the increasing seal populations and commercial fishing industries, while the latter is a response to variations in primary productivity that are closely tied to environmental variability. As well as controlling high primary productivity, the atmospheric and oceanic dynamics of the Benguela system impact on the biota in other ways. For example, the jet southwest of Cape Point, first described by Bang and Andrews (1974), is instrumental to the survival of fish larvae by transporting them from the food-poor spawning ground on the Agulhas Bank to the productive west coast nursery ground. Also of importance to recruitment variability are advective losses due to Agulhas rings and mesoscale activity at the upwelling front during periods of intense upwelling (Duncombe-Rae et al. 1992; Hutchings et al. 1998). Furthermore, the significant role of the physical environment on the development, duration and areal extent of harmful algal blooms (Pitcher and Weeks 2006), hydrogen sulfide eruptions (Weeks et al. 2004) and low oxygen and anoxic conditions (Monteiro and van der Plas 2006), all of which can have detrimental implications for the biological environment, necessitates a thorough understanding of the nature and the scales of variability of the physical processes involved.

Setting the Scene

In order to improve our understanding of the Benguela ecosystem, we need to expand our interest to global scales and to the timescales of paleo-climates (Philander, presentation, BCLME Climate WS). A key factor in the success of our productive upwelling system is the shallow thermocline that is a result of its characteristic east-west shoaling across ocean basins. The nature of the vertical thermal structure of the ocean is maintained by the shallow, wind-driven circulation and the deep, thermohaline circulation. These circulation patterns are subject to, not only changes in the wind forcing (in the case of the former), but also to changes in global ocean-atmosphere heat fluxes (e.g. Boccaletti et al. 2004), the effect of salt (e.g. Fedorov et al. 2004) and their significance in maintaining a balanced global heat budget. For example, a freshening in the North Atlantic would lead to a decrease in the meridional density gradient and therefore to a decreased poleward transport of heat. In order to maintain a balanced heat budget, the decreased heat loss in the North Atlantic must be matched by an decrease in heat gain in the upwelling regions, which are normally subject to the most heat gain (based on their low SSTs). To achieve this, the thermocline deepens (as it is observed to do in the Pacific during an El Nino event), so that water that upwells to the surface is not as cold and therefore does not gain as much heat. Therefore, global climate change scenarios have significant implications for the Benguela upwelling system, thus emphasizing the need to embed the BCLME program in one of a much larger larger spatial scale. We also have to pay attention to paleo-climates, so that we have a better understanding of the longer-term scales of variability that might be misunderstood for a long-term trend or that is likely to modulate shorter-scale (i.e. decadal-multidecadal) variations.

The 2007 IPCC report listed definitive evidence of global climate change. Since 1971 there has been an increase in global surface temperatures, tropospheric temperatures, global SSTs, global sea level, water vapour, rainfall intensity, precipitation in the extratropics, hurricane intensity, drought, extreme high temperatures and heat waves and a decrease in northern hemisphere snow extent, Arctic sea ice, glaciers and cold temperatures (Hewitson, presentation, BCLME Climate WS). Climate models predict that the southern BCLME area will experience an increase in wind stress, while the region to the south of Africa and the northern Benguela will decrease in wind stress. This pattern shifts northward during winter months. The climate models are viewed with a mixture of uncertainty and agreement. Regions of low consensus are related, in part, to spatial positioning of boundaries of the climate processes. The regional scales of change therefore need to be given more attention. According to the 2007 IPCC report, anthropogenic climate change is one additional factor in a multi-stressor system, but arguably the single biggest long term and sustained factor. We need to get mitigation an adaptation strategies in place now if the multi-generational consequences are to be managed (Hewitson, presentation, BCLME Climate WS).

2. Variability in the BCLME over the last 50 years

The dearth of spatially and temporally cohesive long term ocean and atmospheric climate records in the BCLME restricts our ability to separate trends from cycles and therefore also to anticipate the evolution of a changing state. However, continuously improving effort and skill of data collection as well as advances in satellite products and modelling capabilities over the past 50 years have assisted the development of a relatively comprehensive database. Although these records are short relative to the geological time frame, some decadal rends and cycles are beginning to emerge. In this section, the most conspicuous physical and biological cycles and trends that we can extract from our data records will be documented.

The Physical Environment

Wind

Taunton-Clark and Shannon (1988) investigated interannual variability in six regions of the south-east Atlantic over the period 1906-1985 (see Figure 2). Their data was extracted from the South African Data Center for Oceanography (SADCO) and, though an impressively long time series, the density of observations varied considerably, increasing dramatically in the 1960s and was punctuated with periods of inadequate (during the two world wars) and depleted (early-1930s, 1946-1948 and after 1983) measurements. Despite these short-comings, the wind data collated by Taunton-Clark and Shannon (1988) suggests an increase of equatorward wind stress at offshore regions of the northern Benguela in 1964 and a distinct change in the wind stress appears to have occurred in 1975 (Figure 2). The annual mean equatorward pseudo wind stress anomalies from 1948-1989 for areas 1, 3, 4 and 5 in Shannon et al (1992) (Figure 3) confirm the increasing trend in the 1950s, 1960s and 1970s. An increase in easterly winds was also noted over their period of study, which is consistent with the southward shift in the South Atlantic Anticyclone (SAA) reported by Taunton-Clark and Kamstra (1988). They proposed two environmental states related to the position of the SAA: 'summer' conditions prevail when the position of the SAA is further south and characteristics of this state are strong equatorward winds and low coastal SSTs off Cape Town. Conversely, 'winter' conditions result in lower equatorward winds and higher coastal SSTs off Cape Town and occur when the SAA is further north. They suggest that 'summer' conditions persisted from the mid-1960s to the mid-1970s, while 'winter' conditions prevailed before and after this period.

More recently, Hardman-Mountford et al (2003) used 17 (1982-1999) years of model data obtained from the European Center for Medium-Range Weather Forecasts (ECMWF) to investigate the winds of the south east Atlantic (Figure 4a and b). They noted an increase in zonal wind stress of westerlies at the equator, with a switch from easterlies to westerlies in 1989 and a steep decline in westerly wind strength in 1997. Off Angola, the pattern is similar, but with a greater propensity for westerlies and the shift to westerlies appeared to occur in 1983 and the decline of the westerlies in 1996. A trend of increasing equatorward wind stress is observed at the equator and of a rather sudden and sustained increase of poleward winds off Angola from 1993. Both zonal and meridional wind stress on the northern and southern Benguela coasts did not show any conspicuous trends, while the area of the Agulhas retroflection showed only weak evidence of an increase in easterlies and northerlies in the early 1990s.

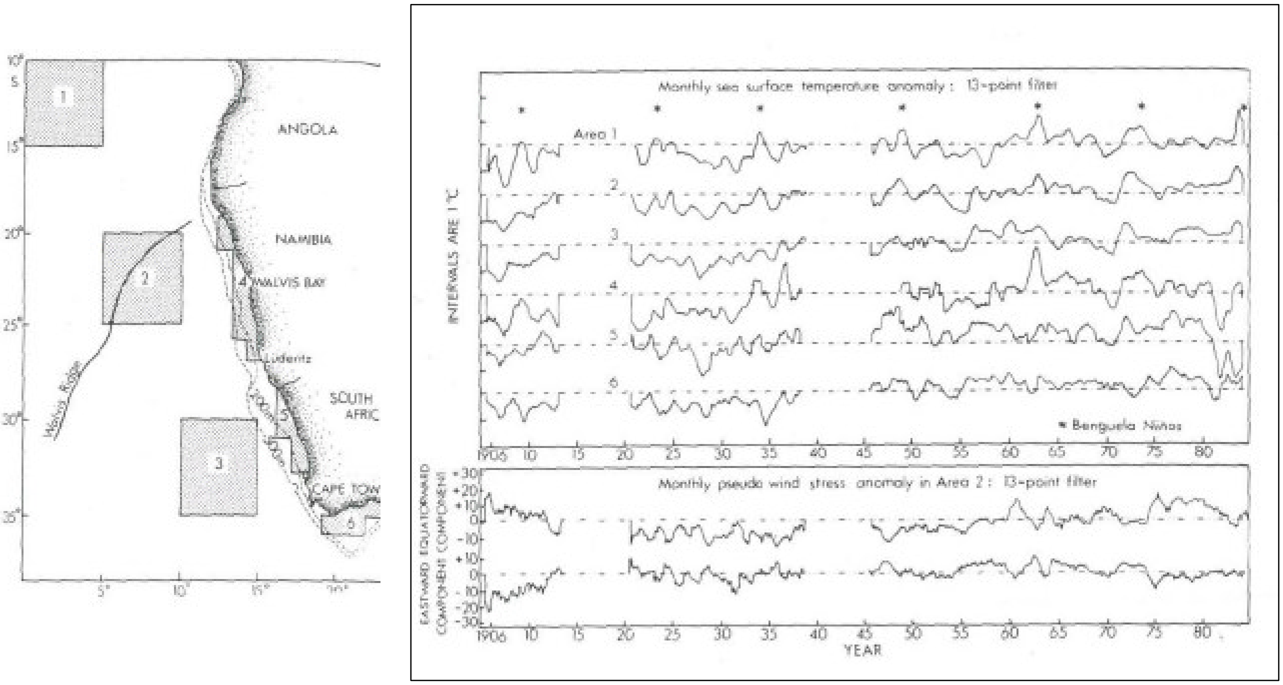

Figure 2 (above): 13-point smoothed monthly sea surface temperature (SST) anomalies for areas 1-6 and eastward pseudo-wind stress anomalies for area 2 (right). The figure on the left shows the positions of the areas corresponding to the plot on the right. From Shannon et al. (1988).

A linear trend of seasonal NCEP reanalysis wind data from 1982 to 2005 (Rouault, presentation, BCLME Climate WS) is shown in Figure 5 (his slide 13). The seasonally averaged decadal trends reveal that the sharpest trends over the past 24 years occurs in summer (January, February and March), particularly off the Namibian coast (which is dominated by an increase in equatorward winds), but with secondary maxima off the Cape Peninsula (an increase in south-easterlies) and in central Angola (an increase in westerlies/ north-westerlies). Throughout the rest of the year there is little trend in the winds in the southern Benguela compared with the winds in the northern Benguela, except for autumn (April, May, June) when there is a fairly strong tendency toward increasing easterlies south of Africa and in the Agulhas retroflection area. Although this is a fairly extensive data set, the resolution is coarse (1°x1°) and the analysis assumes that any trends between 1982 and 2005 are linear. However, according to the data analyzed in Taunton-Clark et al (1988) and the model data used by Hardman-Mountford et al (2003) this does not necessarily seem to be the case. Despite these short-comings, Figure 5 does give us an idea of the seasonal fluctuations of the large-scale wind tendencies of the Benguela upwelling system.

Wind monitoring sites at Lobito, Namibe, Möwe Point, Lüderitz, Cape Columbine and Cape Point have provided relatively long data sets from which we can examine trends, but also emphasize the inherent 'noise' and high variability of the system. The difficulty of extracting a trend from these data sets was addressed by Hutchings and Taunton-Clark (1990) in their investigation of the wind fields at Cape Point and Cape Columbine. They found very little coherence of wind variability between these stations, only 150 km apart, and noted that daily and seasonal variations were of higher amplitude than the interannual signal thus highlighting the difficulty of integrating data into an annual mean. Seasonal mean wind anomalies at Cape Columbine from 1960 to 1994 and annual mean anomalies at Cape Point reveal that both stations experienced a marked change in the wind regime during the 1980s, following the El Niño event of 1982/83 (Figure 6 and 7 respectively).

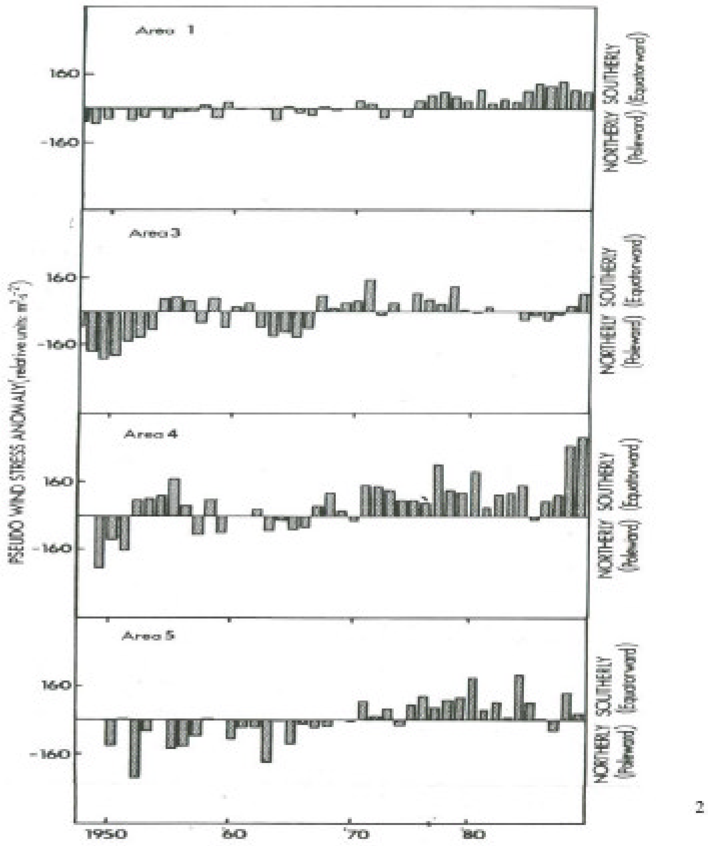

Figure 3: Annual averaged anomalies of equatorward wind stress for areas 1,3,4 and 5 as defined in Figure 2 (left) (Shannon et al. 1992).

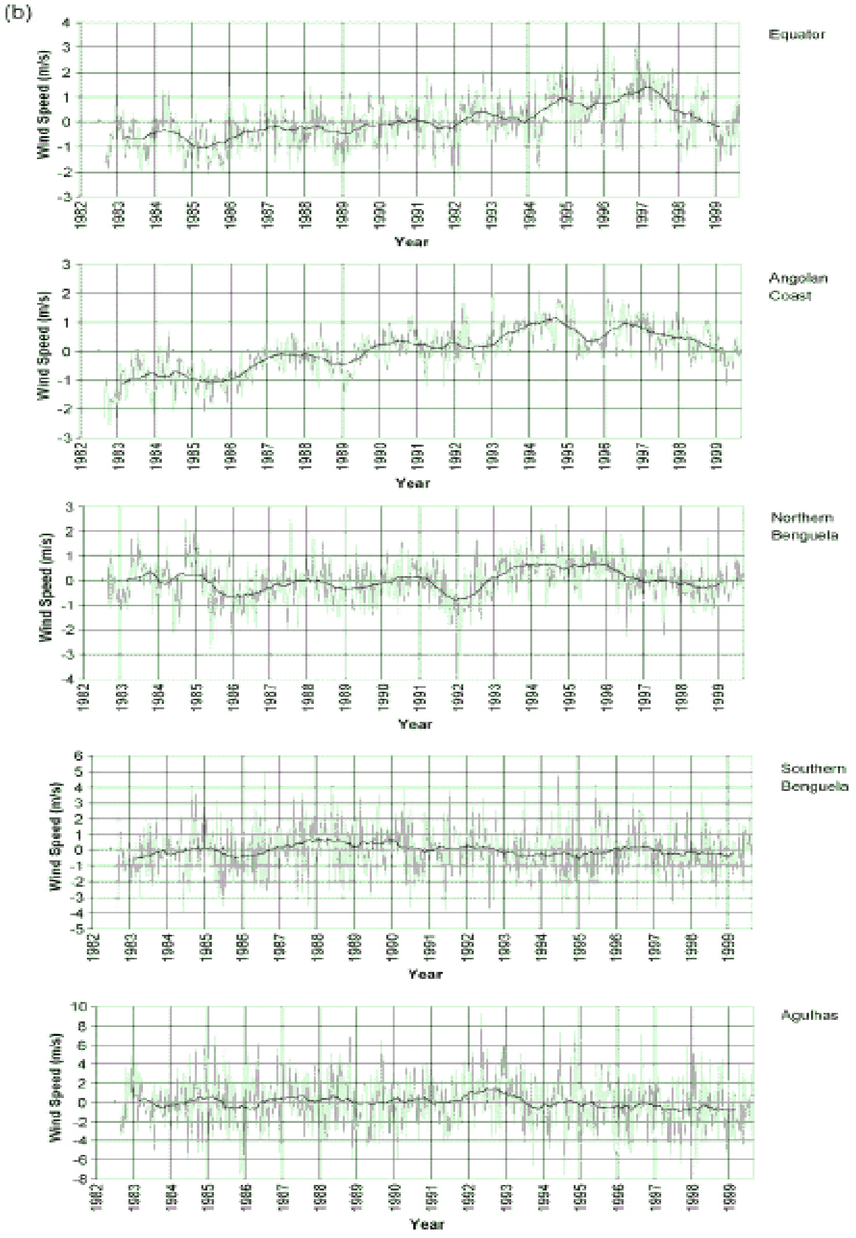

Figure 4a: Timeseries (grey line) of surface zonal wind anomalies, spanning 1982-1999. The anomalies for the timeseries was smoothed using an annual running mean filter in order to emphasise interannual-scale variability (black line) (Hardman-Mountford et al. 2003).

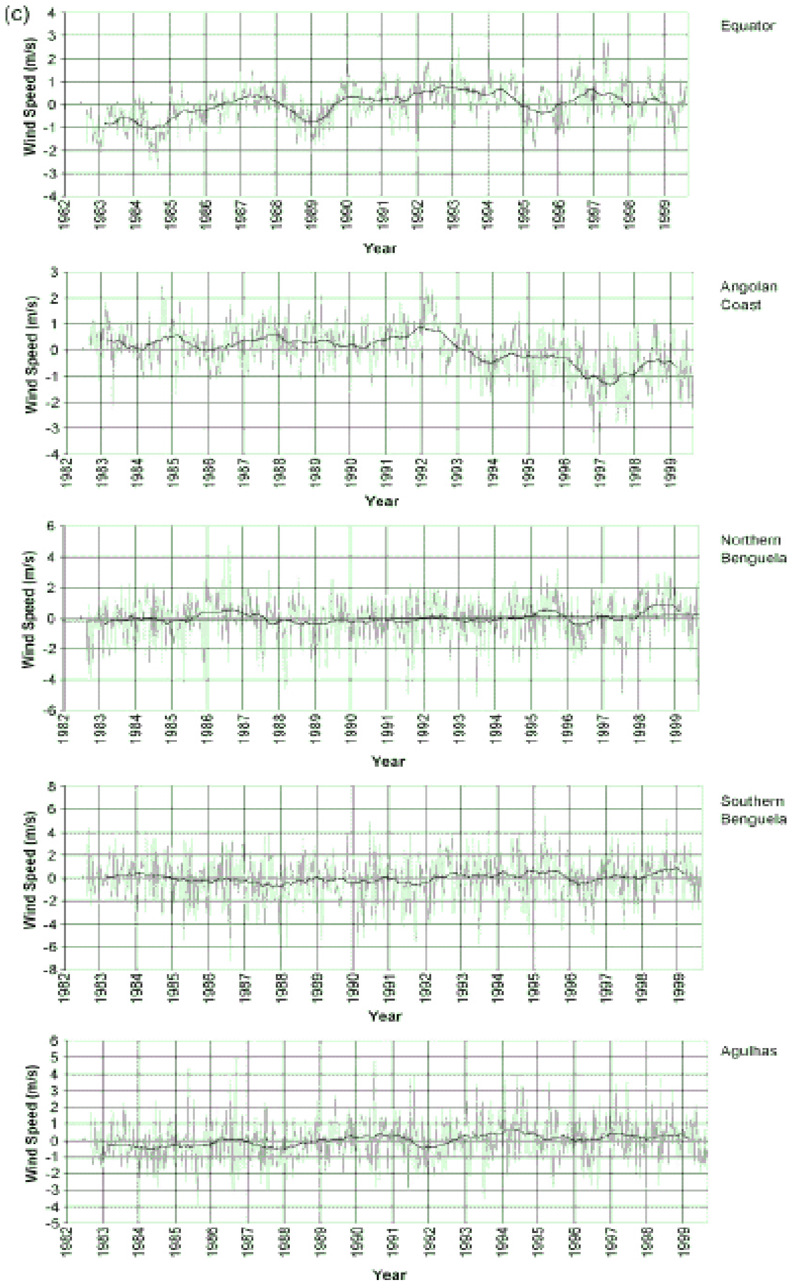

Figure 4b: Timeseries (grey line) of surface meridional wind anomalies, spanning 1982-1999. The anomalies for the timeseries was smoothed using an annual running mean filter in order to emphasise interannual-scale variability (black line) (Hardman-Mountford et al. 2003).

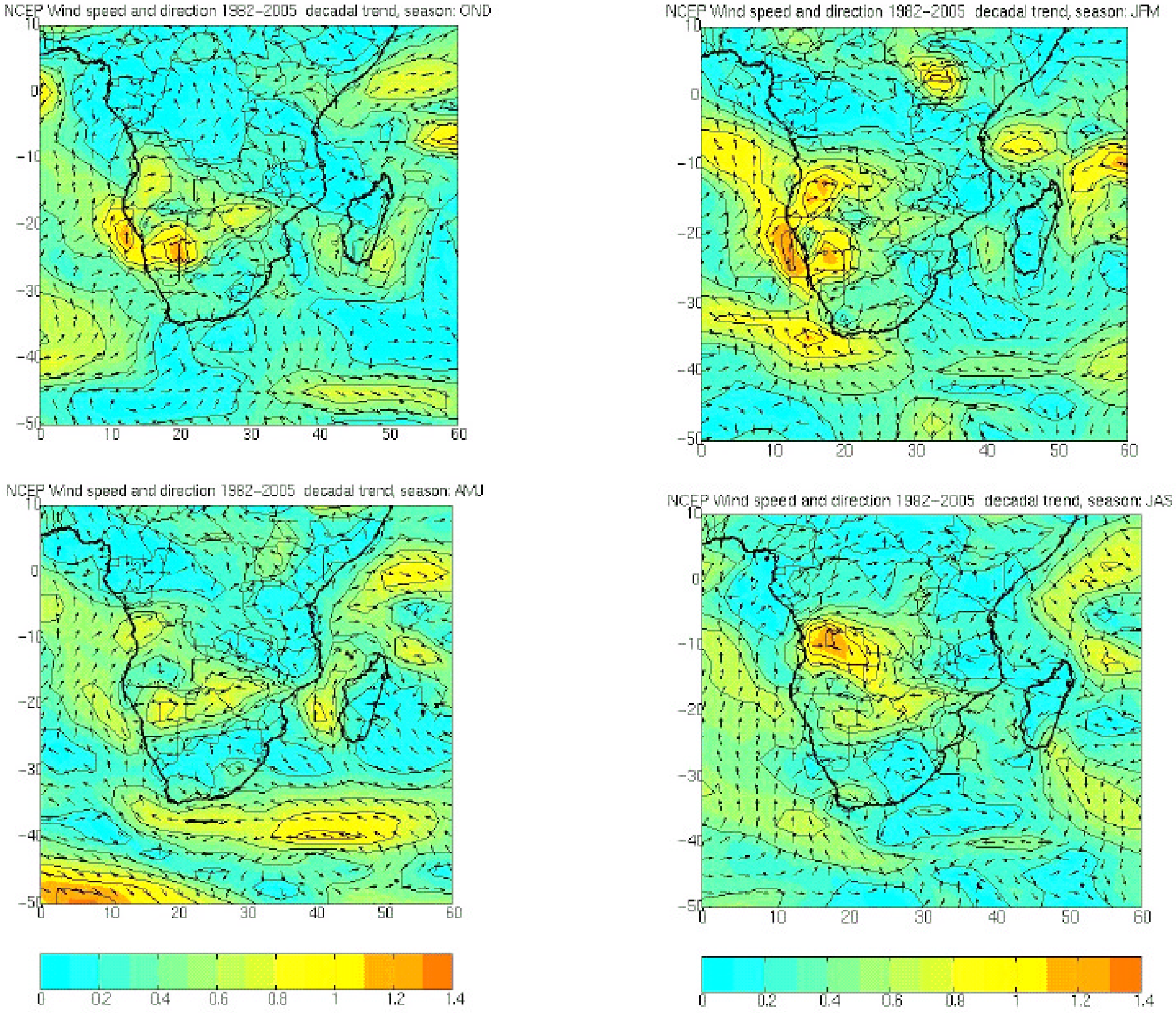

Figure 5: Decadal trend of NCEP wind data for each season, spanning 1982-2005 (from Rouault, presentation, BCLME Climate WS)

Johnson and Nelson (1999) studied Ekman-induced upwelling based on the extensive Cape Columbine wind record. The seasonally-filtered plot of volume transport (Figure 8) can be used as a proxy for the secular trend of upwelling favourable wind stress. Their three-month averages showed that upwelling is perennial on this time-scale and that a peak and a trough of strong upwelling occurred about every 7 years up to 1983 when a rapid decrease in upwelling took place and only recovered in 1990. Figure 9 shows the cumulative north-south wind anomalies based on data from the Lüderitz and Möwe Point weather stations (Bartholomae et al., presentation, BCLME Climate WS). The former extends from 1960 to present, while the latter is only available from 1979. An increase in upwelling favourable-winds occurs from ~1976 to ~1988 at Lüderitz and again from early-1997 to early-2000. At Möwe Point the upwelling-favourable wind increases from the start of the record (1979) to about 1993 and has been decreasing in intensity since then. In Angola, wind records are available from Namibe airport, spanning 1992-2004 (Figure 10 Fidel, BCLME Climate WS). A clear peak in wind velocity occurs in 1994, it decreases rapidly until 1997 and then gradually increases with peaks in 2000 and mid-2002. NCEP u- and v-components of wind velocity from 1967-1998 were extracted for the area of Lobito (Figure 11 from Fidel, presenation, BCLME Climate WS). No obvious long term trend can be discerned, but it is noteworthy that, from 1982/83 to the early-1990s the u- and v- components seem to fluctuate out of phase of one another, while outside of this period they oscillate in phase. Furthermore, from 1991 to 1997 the zonal wind velocity exceeds the meridional wind velocity.

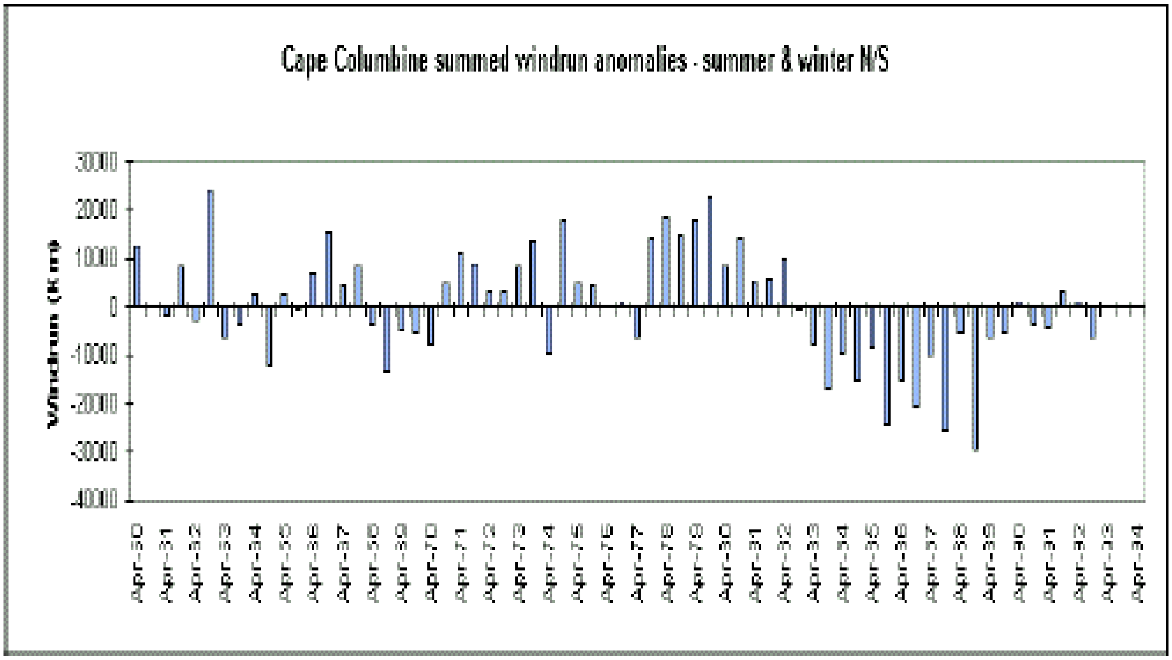

Figure 6: Summer and winter wind anomalies at Cape Columbine for the period 1960-1994 (from Hutchings, presentation, BCLME WS)

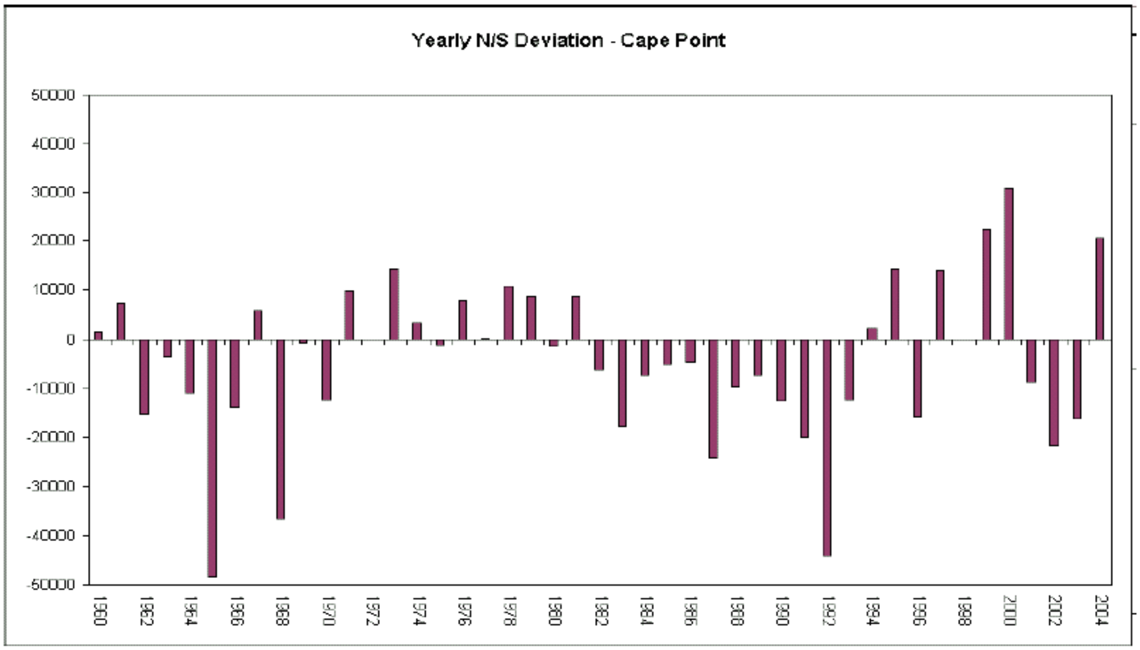

Figure 7: Annual wind anomalies at Cape Point for the period 1960-2004 (from Hutchings, presentation, BCLME WS)

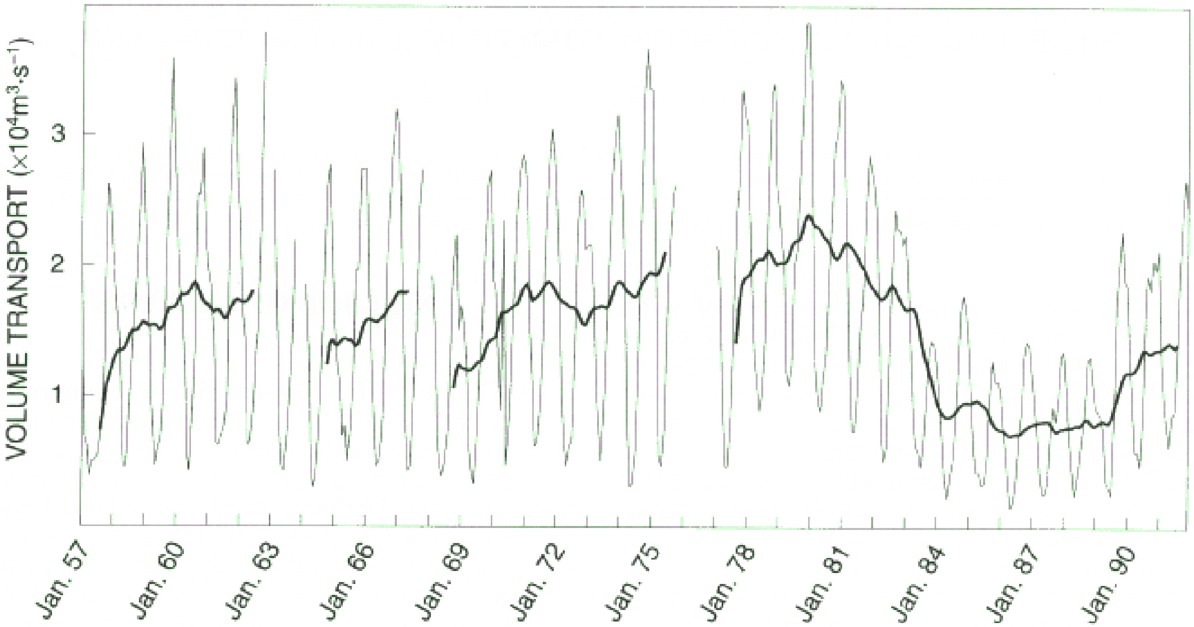

Figure 8: Offshore Ekman volume transport (a proxy for upwelling-favourable windstress intensity) at Cape Columbine for the period 1957-1992 (Johnson and Nelson, 1999).

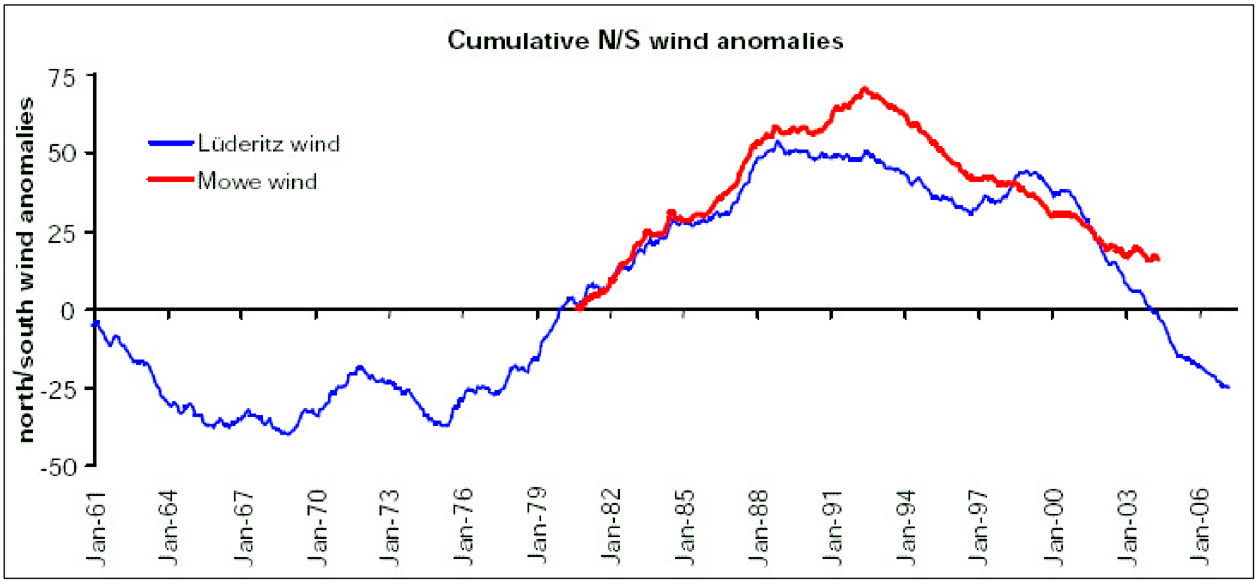

Figure 9: Cumulative north/south wind anomalies at Lüderitz, and Möwe Bay spanning 1961-2006 and 1979-2006 respectively (from Bartholomae et al., presentation, BCLME Climate WS).

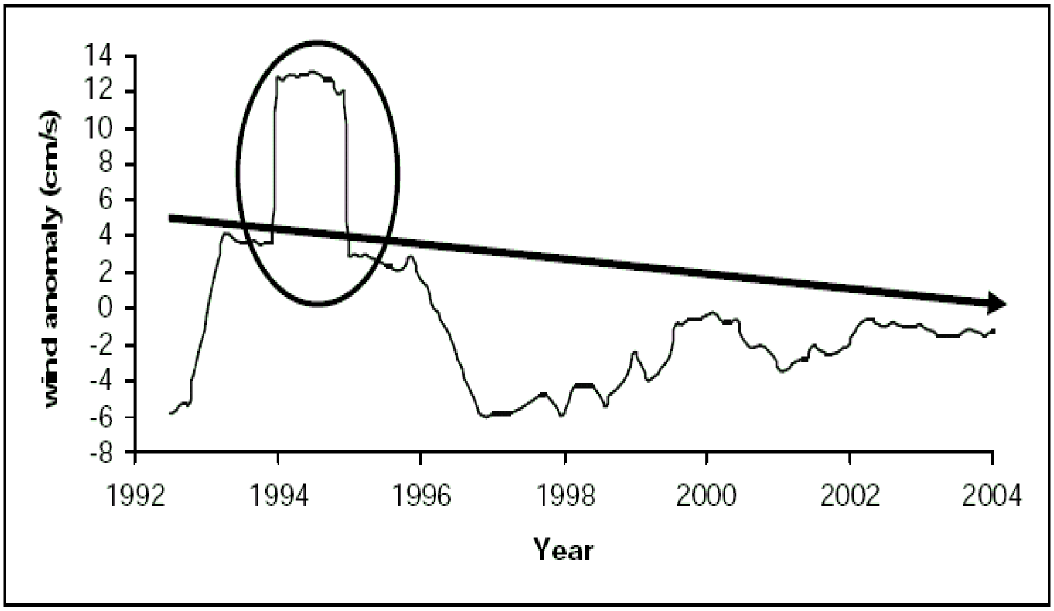

Figure 10: Wind velocity anomalies at Namib airport, Angola for the period 1992-2004 (from Fidel, presentation, BCLME Climate WS)

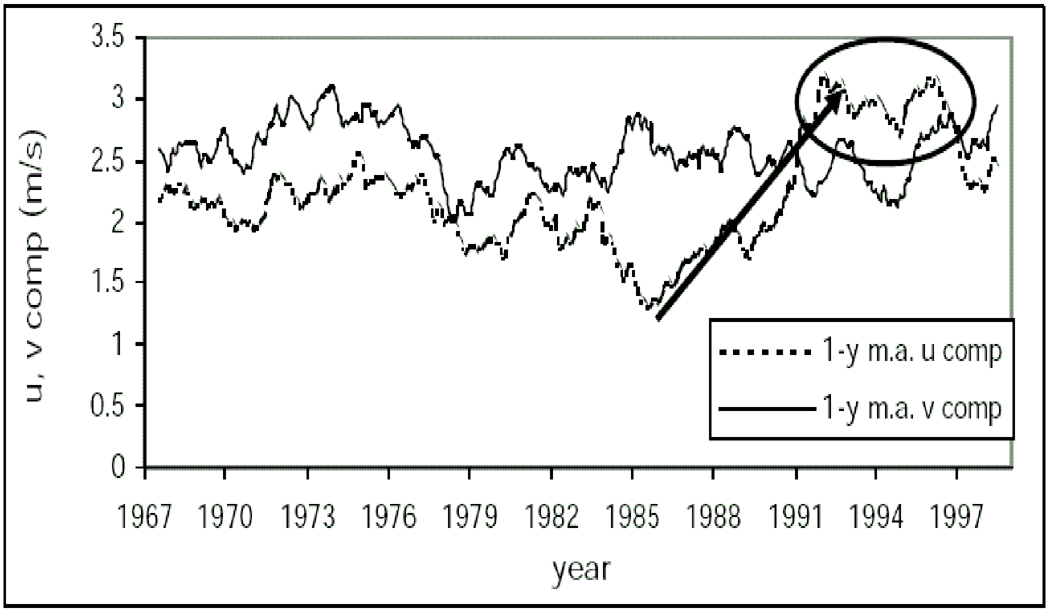

Figure 11: NCEP u- and v- wind components extracted for the area off Lobito for 1967-1999 (from Fidel, presentation, BCLME Climate WS)

Sea Surface Temperature
A long timeseries of SST data collated and analyzed by Taunton-Clark and Shannon (1988) for 5 areas of the south east Atlantic (refer to Figure 2) reveals an SST warming trend inclusive of the whole south east Atlantic, of ~1°C. Despite the dominance of the seasonal signal in the south east Atlantic, a cycle of 8-10 years was extracted from the SST data.

Annual mean SSTs for the coastal and offshore areas of the northern and southern Benguela (areas 1, 3, 4 and 5 of Figure 2a) from 1947-1989 were analyzed by Shannon et al (1992) (Figure 12). From this investigation they concluded that warming occurred in both the offshore areas (1 and 3), but no trend could be identified for the coastal areas, other than a period of sustained cooling from April 1982 to April 1986, particularly in the near-shore areas of the southern Benguela. They noted that 1988/89 marked a distinct change in both the Atlantic and Indian Oceans, represented by the termination of a large-scale warm phase (refer to their Figure 3). It should be noted that their annual anomalies were calculated using an annual mean based on the calendar year (i.e. January-December), which mixes the second half of the upwelling season with the first half of the next. A more accurate annual mean would run from October to September or from July to June, thereby including an entire upwelling season.

In more recent years, satellite products have provided more complete data sets from which to monitor the changing state of the Benguela upwelling area. From a high resolution (4.5 km) satellite SST data-set, spanning 1982 to 1999, Hardman-Mountford et al. (2003) discerned an increasing trend of positive anomalies, divided into three separate periods: 1982-1986 was generally cool, 1987-1994 was intermediate and 1995-1999 was warm. The warming trend was found to be most pronounced near the equator, lessening toward the south (refer to Figure 13). The fact that from 1997 the Agulhas area has been warming up more consistently than the southern Benguela implies an intensification of the SST gradients in that area, which has implications for the jet current that transports eggs from their spawning ground to the nursery area of St Helena Bay.

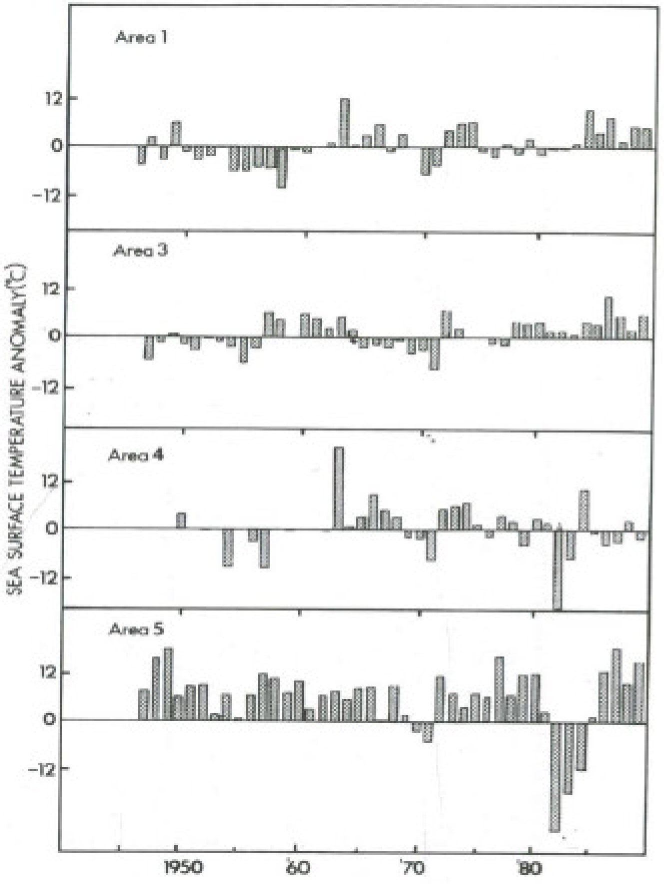

Figure 12: Annual averaged anomalies of SST for areas 1,3,4 and 5 as defined in Figure 2 (left) from 1947 to 1989 (Shannon et al. 1992)

Work done by Veitch et al. (2006) on the same data set shows that the warming trend at the northern boundary, across the Angola Benguela Frontal Zone (ABFZ) occurs relatively uniformly between 1982 to 1997, with slight intensification in the region of steepest temperature gradients within this period. The somewhat uniform warming trend across the ABFZ suggests that the position and intensity of the thermal front definitive of the ABFZ remains relatively stable (other than during major warm and cool anomalies) over the 15 year period. It was suggested by Shannon (1987) that fluctuations of the position of the ABFZ are related to meridional shifts in the South Atlantic Anticyclone (SAA). This hypothesis was tested in the model investigation of Colberg (2006). He found that a northward (southward) shift in the SAA leads to a northward (southward) shift of the ABFZ. Colberg (2006) also found that the intensity of the frontal zone is tied to the strength of the longshore wind stress that controls upwelling and therefore the meridional temperature gradients that are definitive of the ABFZ. From several sensitivity studies he was also able to show that although the intensities of the trade winds do not affect the position of the front significantly, they do influence the intensity of the front (i.e. more intense trade winds result in a more distinct frontal system).

25 years of 1x1° resolution, optimally interpolated NCEP Reynolds SSTs, derived from satellite as well as from *in situ* data is available from the NASA website.[1] A seasonal linear trend of this data set (Figure 14 from Rouault, presentation, BCLME Climate WS) reveals that the most intense warming occurs at the northern and southern boundaries of the Benguela upwelling system throughout the year. During autumn and winter months cooling prevails in a narrow strip on the south and southern-west coasts, while warming occurs offshore and throughout the rest of the Benguela upwelling area. This pattern is in accordance with the strengthening of the SST gradients at the southern boundary, implied by the work of Hardman-Mountford et al. (2003).

Part of the importance of SSTs is its role in the intricately linked ocean-atmosphere system and the interactions involving the transfer of heat, moisture and momentum at the air-sea interface. As such, the role of SSTs in influencing continental rainfall and climate is undisputed and several studies have investigated this relationship (e.g. Walker 1987; Walker 1990; Walker and Shillington 1990; Fontaine and Janicot 1996 and Reason and Rouault 2006). Walker (1990) studied the links between southern African summer rainfall and temperature variability of the Agulhas and Benguela current systems and was able to identify positive correlations between summer rainfall and the SSTs of the Mozambique/ Agulhas Current region, the Agulhas retroflection region and the northern Benguela Current system. Fontaine and Janicot (1996) investigated the connection between regional and global SSTs and west African rainfall anomalies. Using data spanning 40 years (1950 to 1990) they were able to conclude that rainfall anomalies over the whole of west Africa are correlated with various combinations and phases of SST anomalies in the eastern Pacific and Indian Oceans as well as the north and south Atlantic ocean. Reason and Rouault (2006) focused specifically on the south coast of West Africa (5°W-5°E, 5°N-10°N) and found that the area west of Angola and northern Namibia is a localized source of moisture and therefore SSTs in this region can affect its rainfall in the coastal regions. The strongest relationships were found to exist between April-May SSTs and May-June heat fluxes in the ABFZ area with July-August rainfall over the region 5°W-5°E, 5°N-10°N.

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[1] http://podaac-www.jpl.nasa.gov

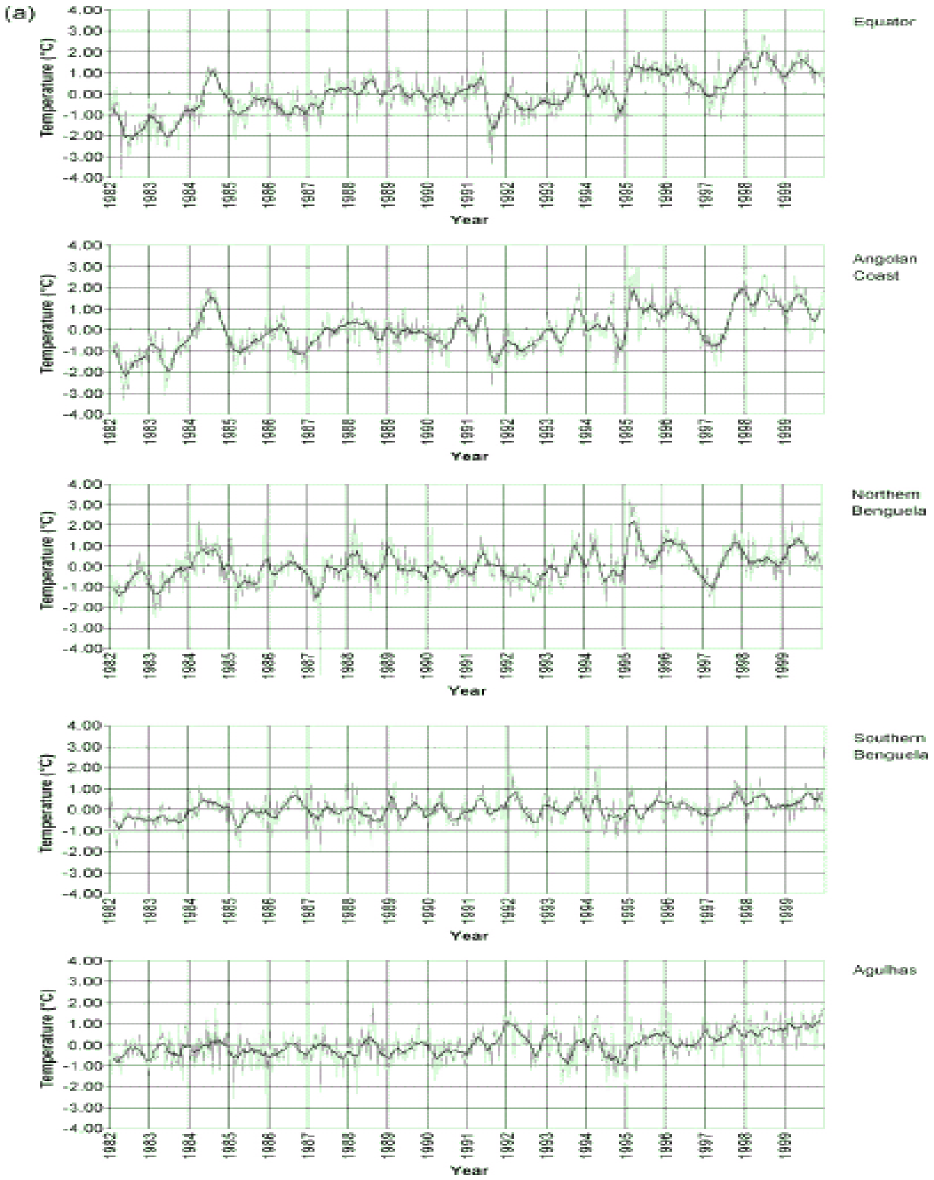

Figure 13: Timeseries (grey line) of SST anomalies, spanning 1982-1999. The anomalies for the timeseries was smoothed using an annual running mean filter in order to emphasise interannual-scale variability (black line) (Hardman-Mountford et al. 2003).

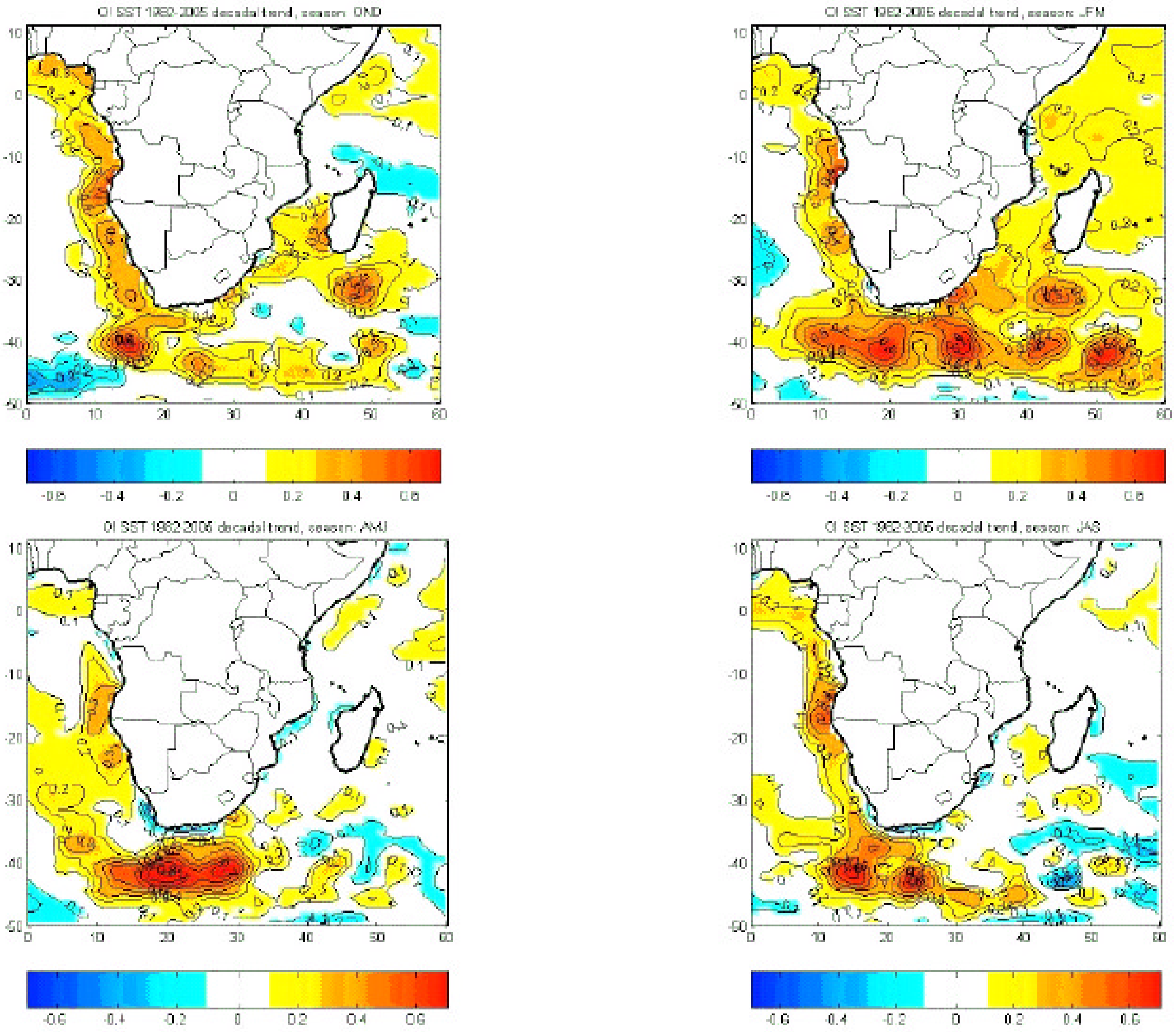

Figure 14: Decadal trend of Reynolds NCEP SSTs for each season, spanning 1982-2006 (from Rouault, presentation, BCLME Climate WS)

Sea Level

Commonly, sea level rise is used as a proxy for global warming, but it can also be used to make inferences about short- and long-term changes in the physical environment (particularly with regards to changes in currents and density structures). Using tide-gauge measurements from several locations along the south African west coast spanning 1957-1975, Brundrit (1984) noted that at most of the sites sea level was of the order of 5cm higher in 1963 than in 1959, 1961 and 1965 and that a correlation seemed to exist between SST and sea level. During the period, 1979 to 1983 a downward trend of sea level was observed for all sites, but this could be a result of an anomalous seasonal response in 1982 essentially masking the increasing sea level trend.

Hardman-Mounford et al. (2003) obtained and investigated a sea level product from AVISO (Archiving, Validation and Interpretation of Satellite Data in Oceanography) based on 7 years (1993-1999) of TOPEX/POSEIDON, ERS-1 and ERS-2 sea level difference data with a resolution of 0.25° at the equator, a temporal resolution of 10 days and an accuracy of 2 cm. Figure 15 shows the sea level anomaly for the equatorial region, the Angolan coast and the northern and southern Benguela coastal areas. The sea level anomalies in these area seem to be in phase with one another, with peaks in 1993, 1995/96 and 1998 and troughs in 1994 and 1996/97. A distinct difference between these areas is that the amplitude of interannual sea level fluctuations is largest at the equator and decreases further south.

The mean sea level rise in the Benguela upwelling area is of the order of the global average, which has been calculated as ~1.8mm.yr^{-1} according to the 2005 IPCC report[2]. Sea level rise off the west coast of southern Africa over a 20 year period has been observed from tide-gauge measurements (Brundrit, 1984) to beof the order of the global average, but is not considered to be a threat along the south west African coast due to the fact that relatively few low-lying developments exist there.

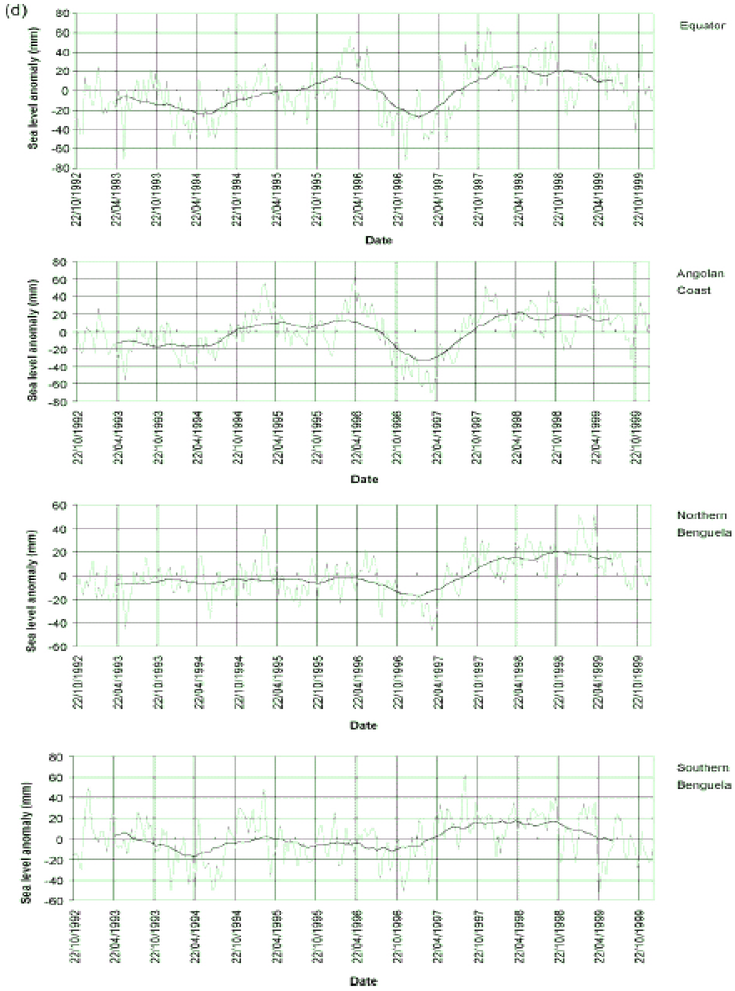

Figure 15 (left): Timeseries (grey line) of sea level anomalies, spanning 1992-1999. The anomalies for the timeseries was smoothed using an annual running mean filter in order to emphasise interannual-scale variability (black line) (Hardman-Mountford et al. 2003).

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[2] http://www.ipcc.ch/meet/meet_rep.htm

Oxygen

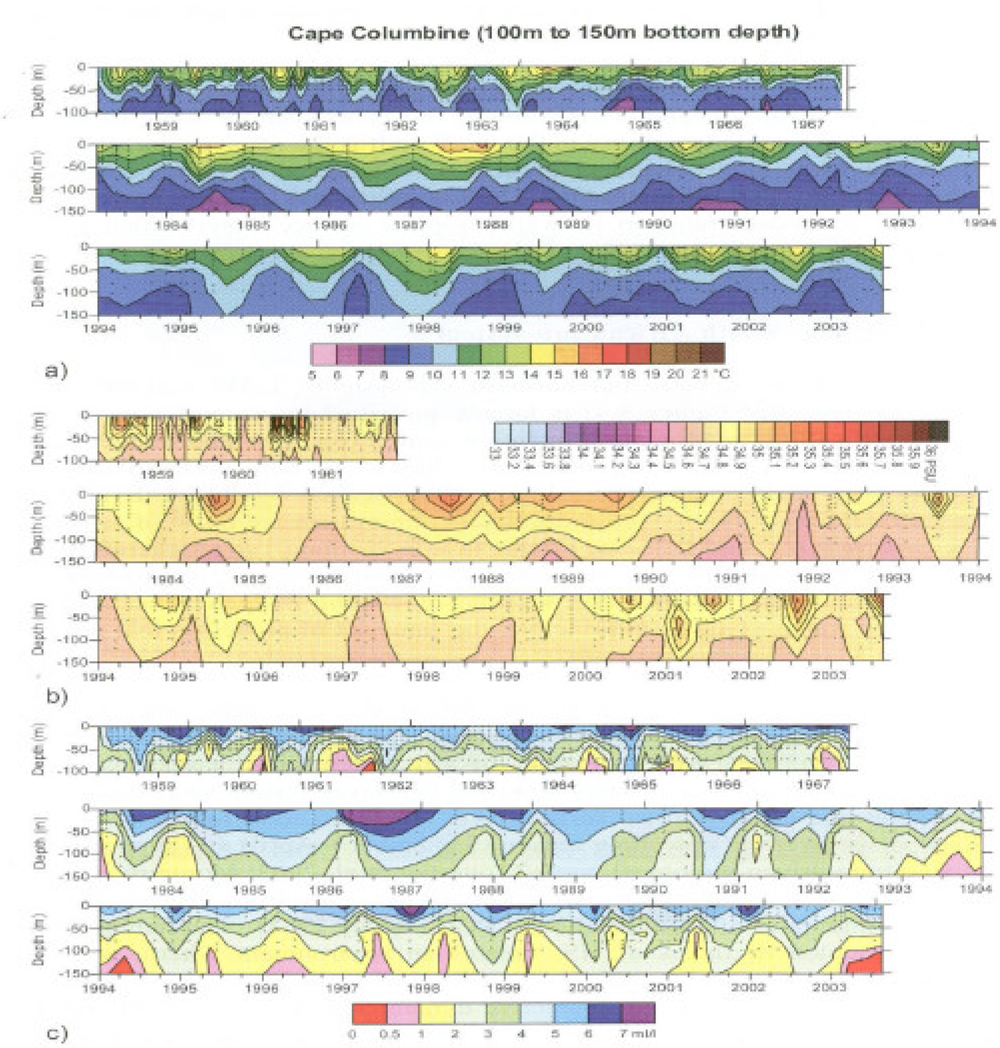
To some extent oxygen can be thought of as an integrator of the physical and biological environments of the Benguela upwelling area. This can be said as low oxygen water (LOW) variability depends on physical as well as biogeochemical processes and has the ability to impact considerably on the living marine resources of the Southern African west coast. Monteiro and van der Plas (2006) define three regimes of low oxygen variability (LOW) in the Benguela system: (1) LOW variability in the northern Benguela (Angola) is entirely advection controlled and is strongly linked to the upwelling that peaks in June to August, (2) in the central Benguela (Namibia) a complex interaction between remotely forced shelf processes, seasonal thermocline variability and biogeochemical carbon fluxes control the LOW fluctuations and, (3) in the southern Benguela (South Africa) LOW variability is primarily driven by local seasonal winds, with very little remote influence. The importance of wind variability is elucidated by the fact that a 20% decrease in the winds corresponds to an 80% decrease in productivity (Monterio et al., BCLME Climate WS). The periodicity of the wind regimes is an essential component of LOW as it is the timing of wind relaxation events that are instrumental in generating hypoxic conditions.

In the southern Benguela LOW variability is largely governed by a combination of local physical (stratification, recirculation and advection) and biogeochemical factors (upwelling-driven new production). For the area of Cape Columbine temperature, oxygen and salinity data extends as far back as 1959 (see Figure 16). A decadal-scale cycle of the frequency of LOW events appears to dominate this timeseries: the aerated 1980s coincided with weak upwelling wind stresses, while the anoxic 1990s where subject to strong upwelling-favourable winds.

The LOW advected into the northern and central Benguela originates from the Angola Gyre area of the Southeast Atlantic where the processes of primary production, stratification and retention facilitate the maintenance of LOW in this area. The South Equatorial Undercurrent forms the northern boundary of the Angola Gyre, which feeds the Gabon-Congo Undercurrent and the Angola Current which, in turn, form the eastern boundary of the gyre. As the Angola Current moves southward it deepens to form the Benguela Poleward Undercurrent which extends to 27°S and forms the LOW boundary conditions for the northern and central Benguela systems. The highly active Lüderitz upwelling cell as well as the whole southern Benguela system are situated in the realm of the well-aerated South Atlantic central water (SACW).

A time series of oxygen, temperature and salinity on the Angolan shelf for the period 1994-2003 is shown in Figure 17 (from Monteiro and van der Plas, 2006). The narrow shelf in this region is conducive to the seasonal upwelling of water originating from the LOW reservoir and explains the correlation between seasonal oxygen and temperature measurements. A glance at Figure 17 reveals that from 2000 there seems to be an increase in the frequency of warm events as well as LOW events.

LOW variability on the central Benguela shelf is not in phase with upwelling intensity and hence temperatures (see Figure 18, which is a timeseries of temperature, salinity and oxygen off Walvis Bay for 1994-2004) . This is because it is subject to a number of processes and conditions that are not directly linked. Factors that govern LOW variability in the central Benguela are the boundary conditions set by the LOW reservoir in the Angola Gyre area, the incidence and intensity of warm events and upwelling at both Cape Frio and Lüderitz. These factors are modulated by local production on the inner shelf. The change in phase of the Cape Frio and Lüderitz upwelling centers from 11 to 18 weeks over a period spanning 1981-1998 is thought to be a key factor in the decadal variations in hypoxic conditons in this area (Monteiro et al., 2007).



<u>Figure 16:</u> Temperature (a), salinity (b) and oxygen (c) at a mid-shelf position for the period 1984-2004 for Cape Columbine (from Monteiro and van der Plas 2006).

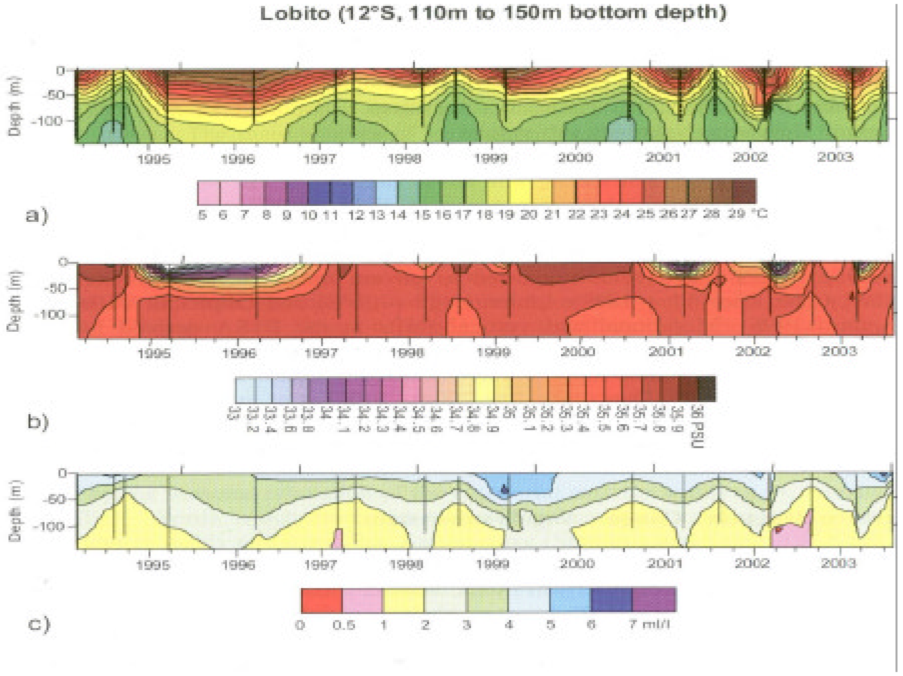


Figure 17: Temperature (a), salinity (b) and oxygen (c) on the Angolan shelf for the period 1994-2003 (from Monteiro and van der Plas 2006).

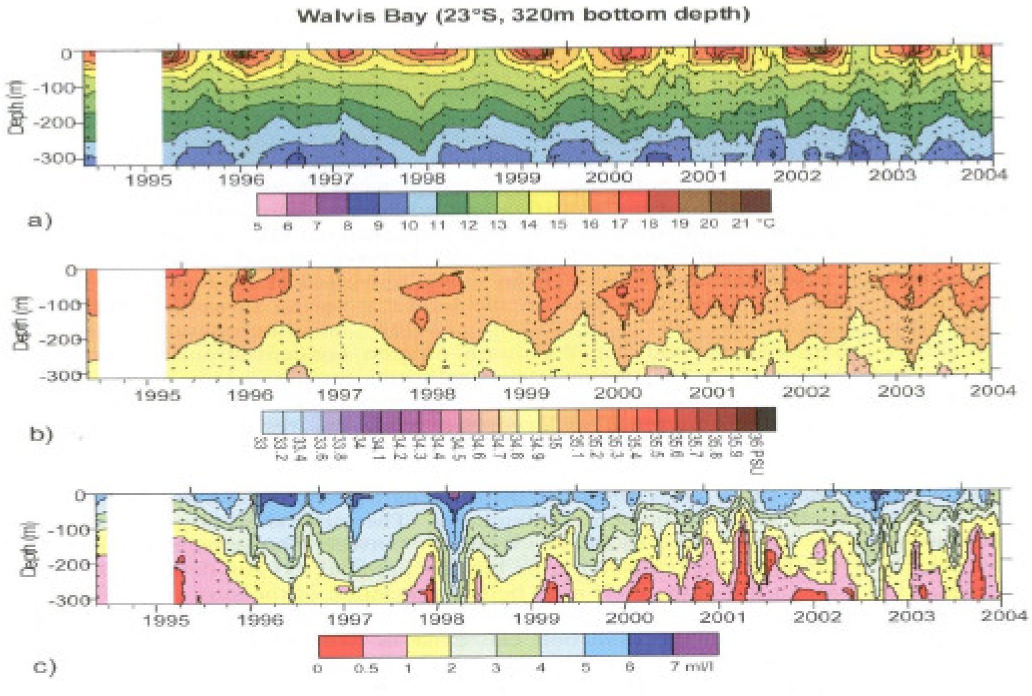


Figure 18: Temperature (a), salinity (b) and oxygen (c) on the outer shelf of the central Benguela for the period 1994-2004 (from Monteiro and van der Plas 2006).

The Biological Environment

Phytoplankton

The seasonal cycle of primary production in eastern boundary current systems is closely tied to the success of the equatorward winds in producing nutrient-rich surface waters via the process of upwelling. Legendre (1981) shows that most efficient phytoplankton production occurs in the presence of periodic upwelling, induced by wind events that last a few days. This theory is recapitulated by Nelson (1992), who investigated primary productivity in the Benguela system. Long term climate change has been linked to changes in plankton abundance, distribution and species composition (Colijn et al. 1998 and Perry et al. 2004, cited in Hutchings et al. 2006) and therefore also to changes in the foodweb.

From ocean chlorophyll data obtained from the coastal zone colour scanner for the period 1979 to 1986, De Villiers (1998) investigated the seasonal and interannual variability in phytoplankton biomass on the southern African continental shelf. It was found that interannual trends in phytoplankton biomass in the Benguela system correspond to SST records rather than to upwelling favourable winds. This finding suggests that interannual trends in primary production are related to large-scale oceanic circulation features and forcing mechanisms, rather than to the well-defined seasonal signal. A likely causative mechanism is the advection of warm Agulhas current water into areas of usually high biomass. Although she noted events of particularly low biomass between 1979 to 1986 (Figure 19) that she related to SST anomalies, no obvious trend in phytoplankton biomass was observed at any of the sites (eastern and western Agulhas bank, Cape Peninsula, Cape Columbine and Namaqua) over the 7 year period.

Figure 20 shows a time-series of monthly averages of chlorophyll biomass integrated between the coast and the offshore extent of chlorophyll concentrations higher than 1 mg.m^{-3} for the period 1997 to 2003 and from 12-35°S (from Demarcq, unpublished data, cited in Hutchings et al., 2006). There are consistent spatial discontinuities and seasonal fluctuations of chlorophyll concentrations along the coastline, but no obvious long-term trend is discernible in this time-series.

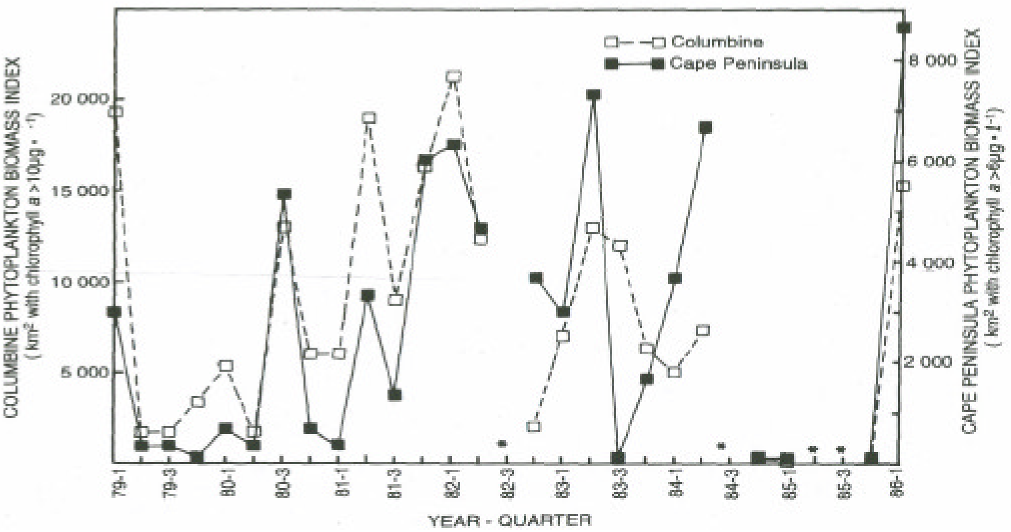


Figure 19: Comparative quarterly values of areas in Cape Columbine and Cape Penninsula represented by chlorophyll values exceeding 10 and 6 µg.l^{-1} respectively for the period 1979-1986 (from De Villiers et al. 1998).

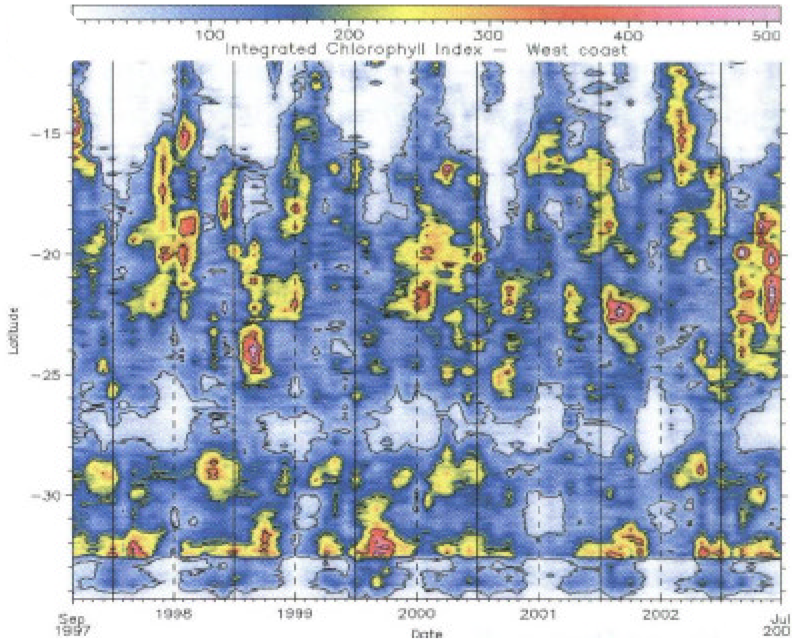


Figure 20: Timeseries (September 1997-July 2003) of monthly averages of chlorophyll biomass integrated between the coast and this limit, showing seasonal and interannual variability and spatial patterns within the Benguela showing opposing trends (Demarcq et al. submitted).

Zooplankton

Verheye et al. (1998) investigated zooplankton abundances in St Helena Bay spanning 1950 to 1995 and noticed a 100-fold increase over this time-frame (Figure 21). Also, they observed a shift in zooplankton community size structure from large to small, which corresponded with the change in dominance from sardine to anchovy. Similar long-term trends were observed for equatorward wind stress anomalies and consecutively increasing trophic levels (Figure 22), illustrating the role of long-term changes in wind stress on the ecosystem as a whole. By the mid-1990's the zooplankton community of St. Helena Bay started decreasing to present levels that are 10 times smaller than the peak population. It is particularly the larger copepod species (that is favoured by anchovy) that go into steep decline possibly due to an increase in anchovy biomass. From about 2001 the anchovies begin to decline due to their predation resulting in the reduction of prey. Such a top-down control of zooplankton abundances, illustrated in the out of phase relationship between copepod abundances and pelagic fish stocks, is operative on the west and south coasts (Hutchings et al. 2006). Species-specific long term responses to forcing mechanisms at various rates of change was noted to characterise the southern Benguela by Verheye (presentation, BCLME climate change workshop*)*.

Zooplankton abundances in the northern Benguela have not been subject to as comprehensive analysis. Monthly zooplankton data collected during the 1970s and 1980s as part of the SWAPELS (South West African Pelagic Egg and Larval Surveys) collection has only recently been analysed under the auspices of the BENEFIT (Benguela Environment and Fisheries Interactions and Training) program (Tsotsobe et al. 2003 and 2004, cited in Hutchings et al., 2006 and Verheye et al., 2005). There is some evidence to suggest a decline in zooplankton abundance in the northern Benguela from the 1950's to the early 1980's, and increase until the early-2000s and a subsequent decline (Hans Verheye; presentation, BCLME workshop). The 1983/84 change from a declining trend to an increasing trend of total copepod abundance in the northern Benguela corresponds with the timing of the Benguela Niño that is associated with an unusually extreme southward displacement of warm water Hans Verheye et al; presentation, BCLME Climate WS*)*. In terms of the effect of Benguela Niño events on zooplankton communities, it is noteworthy that Stander and De Decker (1969) observed a significant reduction in only one species of zooplankton (*Paracalanus parvus*) during the warm event that occurred in spring 1963. Comparing the relative abundances of different species archived in the SWAPELS data, Hansen et al. (2005) observed a shift to larger copepod species over the past four decades.

The nature of zooplankton data for both the northern and southern Benguela systems is somewhat patchy, therefore robust conclusions should be made with a degree of caution. Even in the absence of a temporally and spatially cohesive data set, it seems clear that the northern and southern Benguela systems do not appear to be synchronous with respect to interannual variability and trends of zooplankton abundances and community structure. However, over the past 5 decades, the overall zooplankton abundances has increased 10 fold in both the northern and southern Benguela ecosystems (Figure 21b)

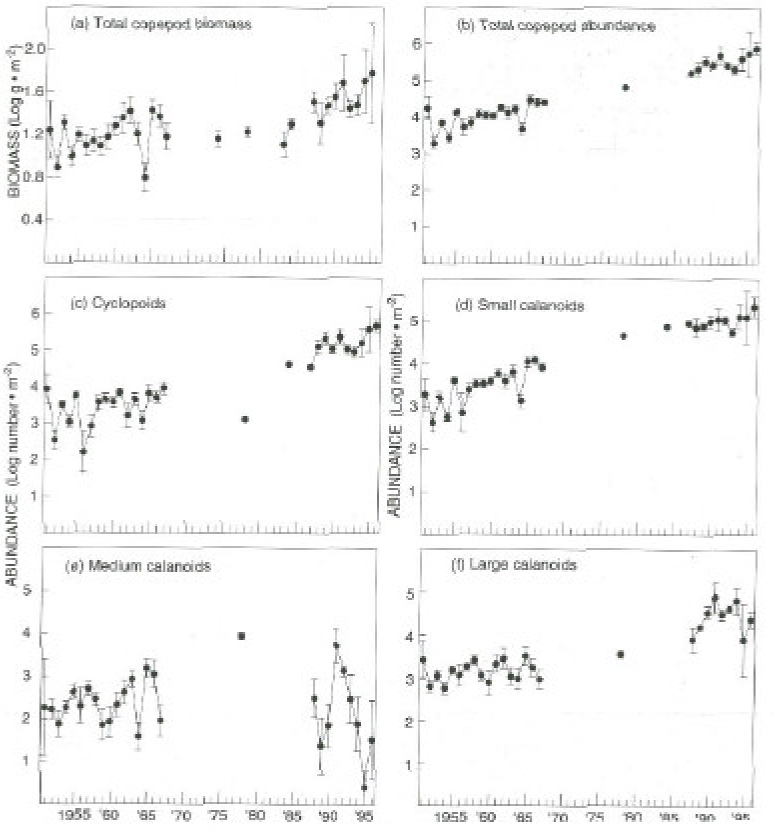


Figure 21(a): Timeseries of annual means of (a) the wet mass of biomass, (b) the abundance of all copepods, c) the abundance of cyclopoids, (d) small, (e) medium and (f) large calanoid coprpods between 1951 and 1996 in St Helena Bay (from Verheye et al. 1998).

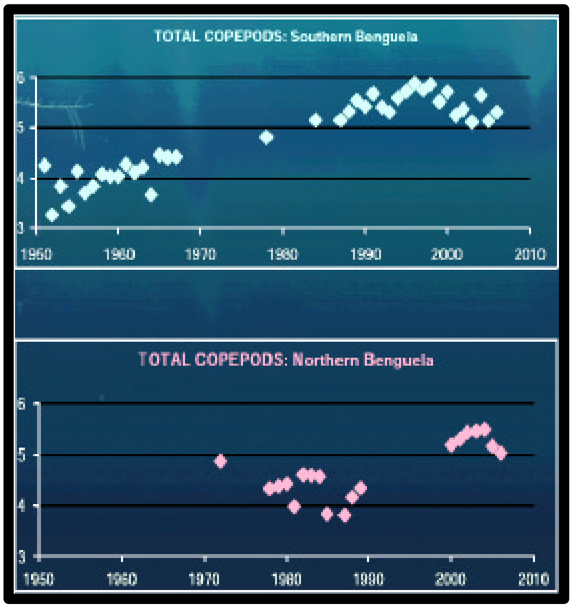


Figure 21(b): Total annual mean copepod abundances in the northern and southern Benguela systems on a log scale spanning the period 1950-2006 (from Verheye et al., presentation, BCLME Climate WS).

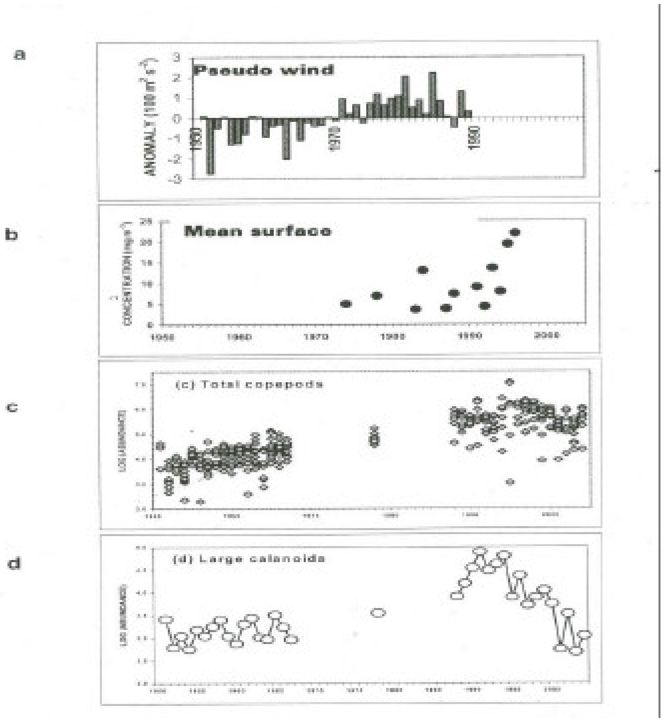


Figure 22: Bottom-up control of zooplankton in the southern Benguela: long-term timeseries of: (a) and upwelling index as a proxy for equatorward wind, (b) phytoplankton biomass (as annual mean surface chlorophyll), (c) mesozooplankton abundance (as annual mean total copepods) and (d) large calanoid copepods (in Hutchings et al. 2006)

Commercial Resources

Data for these resources are difficult to interpret in the light of climate change, as supply and demand, quota, effort and restrictions affect the catch rates, which are then a poor proxy for fish abundance.

Pelagic Resources

Prior to 1984 and the advent of hydroacoustic surveys, fish stock assessments relied on the relatively unreliable Virtual Population Analysis (VPA) techniques. From these methods it appeared that anchovy biomass in the southern Benguela doubled from 1974 to 1979 and then dropped again (Crawford et al. 1987). Peaks in recruitment and biomass of anchovy were observed in 1986 and 1987 in the southern Benguela, after which a steep decline occurred in 1989 and 1990 (corresponding to a smaller area dominated by anchovy, primarily limited to the south coast), followed by a relatively strong year-class in 1991 (Shannon et al., 1992). From 50 years of fisheries data obtained from NATMIRC, MCM and IIM, van der Lingen et al. (2006) observed that the overall pelagic fish resources in the southern Benguela have remained relatively constant, with a replacement of sardine for anchovy in the mid-1960s and a reduction in the contribution from horse mackerel from the mid-1970's (Figure 23b). The sudden decline of sardine stock in the 1960s only started gradually increasing in the late-1980s and 1990s and presently is approaching a level comparable to that before its collapse (see Figure 23a). The decadal-scale variability in sardine abundance is reminiscent of a characteristic of small pelagic fish to fluctuate in dominance between anchovy and sardine over a timescale of 50-60 years that has been observed in the California upwelling system by Baumgartner et al. (199) (cited in van der Lingen et al., 2006). Schwartzlose et al. (1999) studied worldwide fluctuations of sardine and anchovy and similarly found that their abundances fluctuated out-of-phase with one another. Anchovy in the southern Benguela have shown only moderate interannual variability in recruitment over the 50 year timeseries, most notably, increasing population sizes are observed after a significant minimum in the mid-1990s. The fact that sardine and anchovy abundances are both at near-record highs in the southern Benguela seem to be contrary to the observations and hypotheses by Baumgartner et al. (1999) and Schwartzlose et al. (1999) that suggest a time-dependent out-of-phase fluctuation between the relative abundances. This contradiction is perhaps related to the fact that our anchovy data only extends from the mid-1960s and thus we are not able to draw firm conclusions of the nature of the decadal fluctuations anchovy abundances (van der Lingen, 2006).

Roy et al. (2001) showed that the high levels of anchovy recruitment in the southern Benguela in 2000 was linked to intra-seasonal wind variability with a decline in the local south-easterly wind forcing that minimized advective losses of eggs and larva during their transport phase from their spawning ground on the Agulhas Bank to their nursery areas on the west coast where food for juveniles was abundant later, in March 2006, due to increased upwelling intensity. Despite the fact that these conditions have not been repeated since then, anchovy abundances have remained high, suggesting that processes other than environmental may be important to the control of egg and larval survival and the subsequent recruitment success. The observed decadal-scale changes in sardine abundance appear to be a result of fishing pressure rather than to environmental variability, this is in contrast to other upwelling systems where changes in small pelagic species are found to be related to interannual environmental variations (van der Lingen and Coetzee, presentation, BCLME Climate WS). However, the 'pelagic outburst' in the late-1990s and early 2000s in the southern Benguela is a result of good recruitment that appears to have been environmentally-mediated. The distributional shift in anchovy may be related to environmental variability as well as spatial differences in fishing pressure.

Over the past 50 years commercially valuable fish-stocks in the northern Benguela (anchovy, sardine and sardinella) have dwindled significantly: relatively constant levels of approximately 0.5 million tons were caught during the period 1960-1980 (with a significant peak of 1.5 million tons in 1968), while present levels are around 100 000 tons and are made-up primarily of sardinella (see Figure 23b). The sardine population of the northern Benguela has not managed to recover since its crash in the late 1960s, other than a slight increase in the early-1990s. The Benguela Niño warm event of 1984 had dire consequences for the anchovy fisheries in the northern Benguela, with catches plummeting to a paltry 14 000 tons and remaining low in the following two years (Boyd et al. 1985, cited in Shannon et al., 1992). In the already seriously depleted-state of sardine and other key resources in the northern Benguela since the early-1980s, a further decline between 1993 and 1996 has been ascribed to the environmental changes brought on by extensive hypoxic shelf waters of 1993/94 and the Benguela Niño of 1995 (Boyer et al., 2001). Continued fishing pressure during this time is thought to have exacerbated the poor recruitment levels (Boyer et al., 2001), but reduced fishing efforts since 2000, do not appear to have aided the recovery of the stock (van der Lingen et al., 2006). At present, the only pelagic fish stock that is more abundant in the northern Benguela than in the southern Benguela is the horse mackerel that are close to the record-highs of the early-1980s. A perplexing contradiction of the Namibian ecosystem is that the environment is presently good (with high levels of zooplankton), but the sardines have decreased in abundance (Hutchings, BCLME Climate WS). Until the 1990s, fishing pressure appeared to be the major cause of pelagic variability, but subsequently the major cause appears to be closely tied to environmental conditioning.

A long term change in the distribution of spawning areas for small pelagic fish in the Benguela system have been observed. In the southern Benguela, the major spawning area of anchovies has shifted eastward from the western Agulhas Bank since 1996 (van der Lingen, 2002). Sardine spawning grounds in the southern Benguela have exhibited greater variability in their distribution over our record period. Crawford (1981) noted that the major spawning grounds for sardine in the early-1960s was along the west and south coasts of South Africa and between 1965-67, corresponding to a period of low abundance, was limited to the south coast. Since this time the primary spawning ground has fluctuated between the west coast (1987/88, 1994-2000), the central and eastern Agulhas Bank (1989-1993, 2001-present). The shift from south coast to west coast spawning in the 1990s has been related to the increased population size and the relative abundances of sardine and anchovy, but the cause of the 2001 south coast shift in small pelagic fish remains unresolved (van der Lingen et al. 2006).

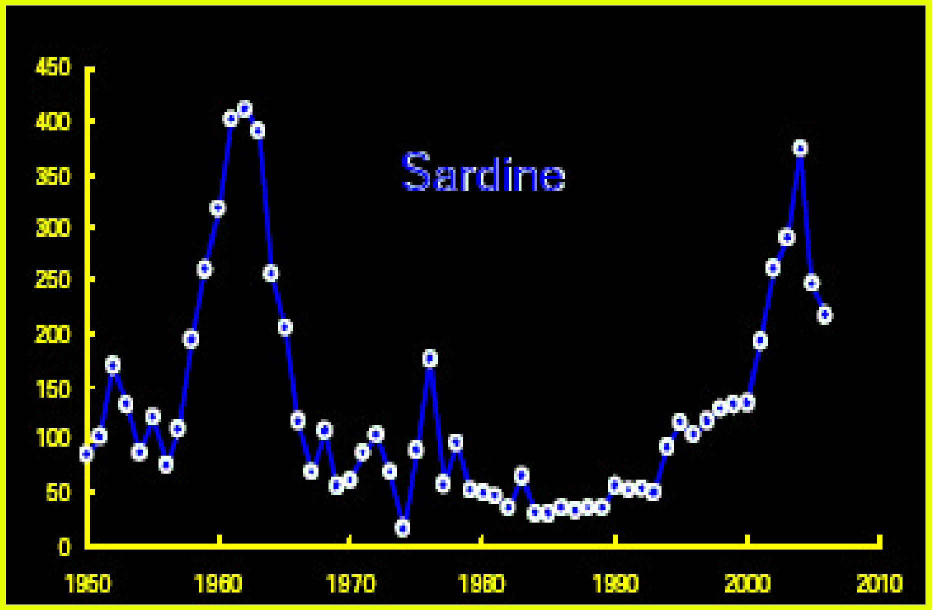


Figure 23a: Change of sardine abundance in the southern Benguela from 1950 to 2006 (from van der Lingen and Coetzee, presentation, BCLME Climate WS) .

Hake

The hakes of the northern and southern Benguela have declined to about a third and a fifth of catches in the early-1970s (see Figure 23b and 24). The reduction in hake catches occurred soon after the advent of large-scale and intensive foreign trawl fishing (in 1965 in the northern Benguela and 1960 in the southern Benguela) (van der Lingen et al. 2006). Swept area surveys in the northern Benguela show an increasing trend in hakes was observed from the early-1990s, but reversed and reached an all time low in 1997 due to adverse environmental conditions relating to the major low oxygen event in 1994. They have not recovered significantly since then (van der Westhuizen 2001). In recent years, deep-water hake in the northern Benguela have shifted further north (Burmeister et al., 2001, cited in van der Lingen et al., 2006) and the dominant species has changed from *Merluccius capensis* in the 1980s to *M. paradoxus* at present (van der Westhuizen 2001).

The extension of LOW events and the corresponding hypoxic bottom waters from their usual limited expanse on the inner-shelf to a widespread area over the shelf appears to be detrimental to the health of the juvenile Cape hake population buy displacing them further offshore and subjecting them to predation by larger hake species and commercial trawling (Hamukuaya et al. 1998). The LOW events that impact the hakes in the central Benguela are likely to occur more frequently due to the change in phase of the period of ventilation at the Lüderitz upwelling cell and warming (and advection of LOW) from the north. The phasing has changed from 11 weeks to 18 weeks, so that hypoxic events are more likely to develop due to the later re-ventilation phase.

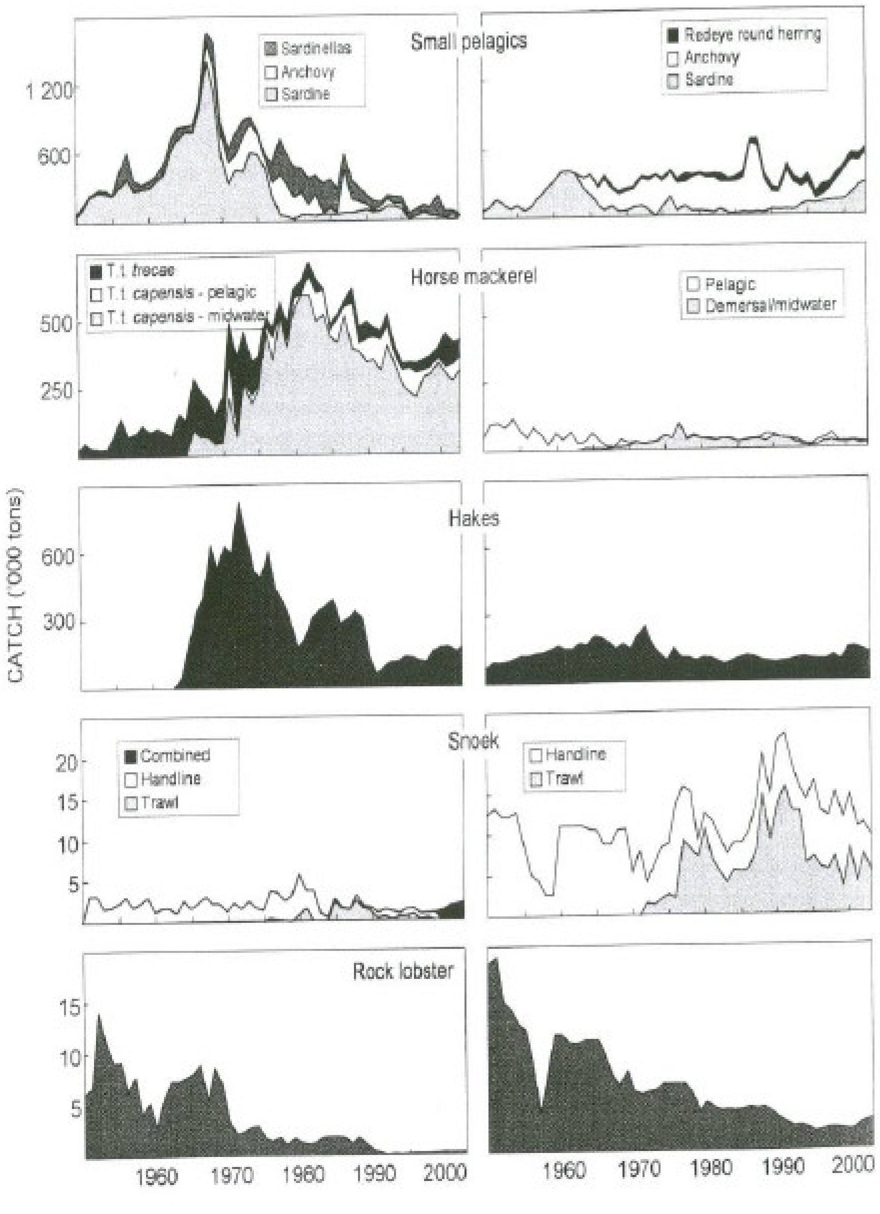


Figure 23b: Variability of important fish resources in the northern (left panel) and southern (right panel) Benguela systems (from van der Lingen et al. 2006).

Rock Lobsters

While most resources have remained relatively stable in the southern Benguela, rock lobster catches have shown a marked decline (Figure 23b). The rock lobster population in the northern Benguela has followed suit and diminished significantly from catches exceeding 5 000 tons prior to 1970 to less than a few hundred tons at present. A large-scale distributional shift in the rock lobster has been observed in the southern Benguela, in which they have moved into shallow water between Cape Hangklip and Danger Point. This is evident in Figure 25, which shows the percentage distribution of rock lobster on the west and south coasts and in the area of Dassen Island (area 7). This movement was first noted in 1994 by Tarr et al. (1996) but the population of rock lobsters in this area has been increasing since the late 1980s and has proved to be catastrophic to the sea urchin *Parechinus angulosis* that completely disappeared.

Episodic LOW events in the near-shore environment of the southern Benguela have led to catastrophic lobster 'walk-outs', resulting in significant mortality rates (Cockroft, 2001). Cochrane et al. (2004) has attributed the shift of rock lobsters to the Cape south coast to large-scale environmental forcing.

Top predators

Seals

A recovery of the Cape fur seal since their over exploitation during the 18th and 19th centuries can be quantified as an annual rate of increase between 2-4% from the 70s to the mid-90s. Substantial interannual fluctuations of their population can be seen in the northern Benguela in Figure 24 and is linked to a change in both food availability and environmental conditions (Roux, 1998). The seal population in the southern Benguela increased gradually from the early-1970s. Pup numbers have increased from approximately 60 000 in 1971 to 100 000 in 2004, but appear to be leveling off (Figure 24).

Birds

Endemic to South Africa and Namibia are the breeding species of the Cape gannet and African penguin and are classified as vulnerable according to IUCN (The International Union for the Conservation of Nature and Natural Resources) criteria. The Cape gannet has declined drastically in the northern Benguela from the late 1950s, but has sustained a gradual increase in the southern Benguela (see Figure 24). Gannet's feed pelagically and their diet is closely tied to anchovy abundances (Crawford and Dyer, 1995). In the Benguela and western Agulhas areas, the adult population of the African penguin has dwindled in the last century from in excess of 1.5 million to ~0.18 million, though regional differences have been observed (Crawford et al., 2001). The regional differences are related to the distribution and abundances of their preferential food sources (species of anchovy *Engraulis capensis* and sardine *Sardinops sagax*) and a shift of breeding colonies. Breeding colonies moved from colonies south of Lüderitz to Ichaboe and Mercury Islands (north of Lüderitz), which increased in size from 1990, followed by a steady decline in 1995 and 1998 respectively. The situation is slightly more positive in the southern Benguela, although numbers decreased fairly rapidly from the 1950s, a recent increase in the African penguin was observed from 2000. However, according to Crawford et al. (2001) the survival of this species into the 21st century remains tenuous.

A significant threat to certain species of sea birds (especially the African penguin and the Cape gannet) is predation by the Cape fur seal, a species that has undergone a significant population 'boom' over the last 40 years.

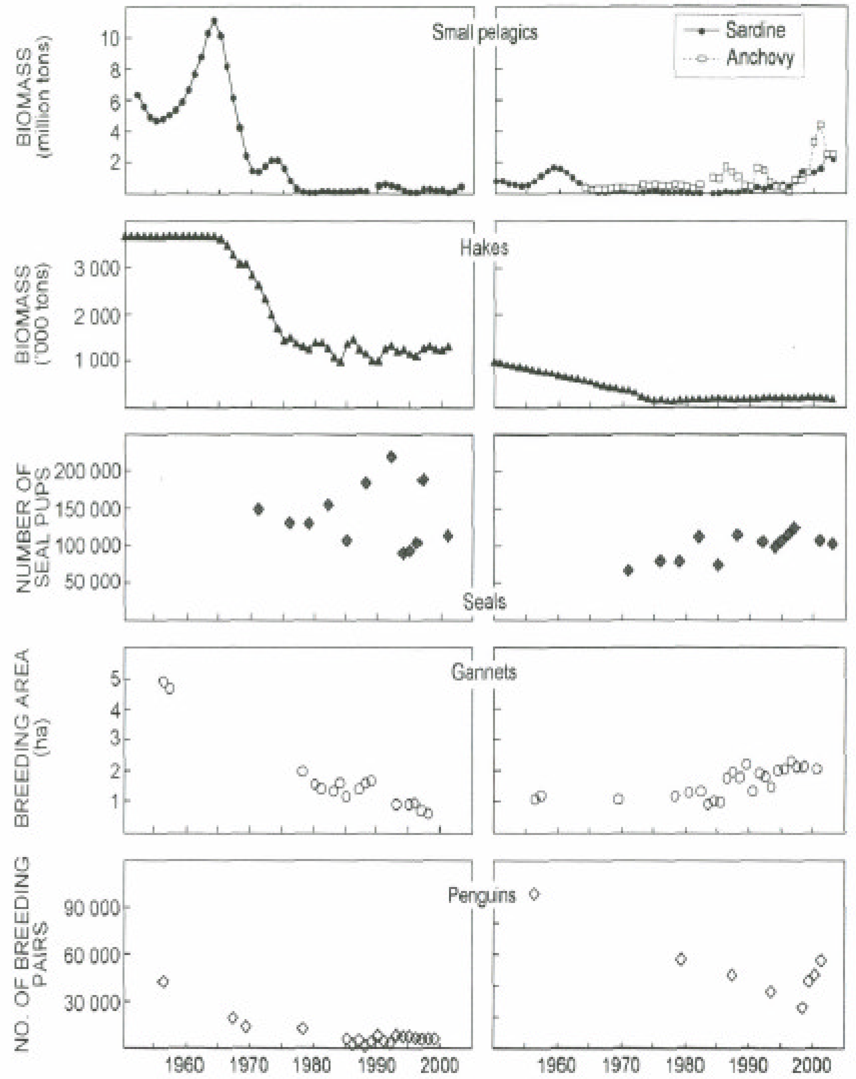


Figure 24: Variability in the abundance of important fish resources and top predators in the northern (left panel) and southern (right panel) Benguela systems (from van der Lingen et al. 2006).

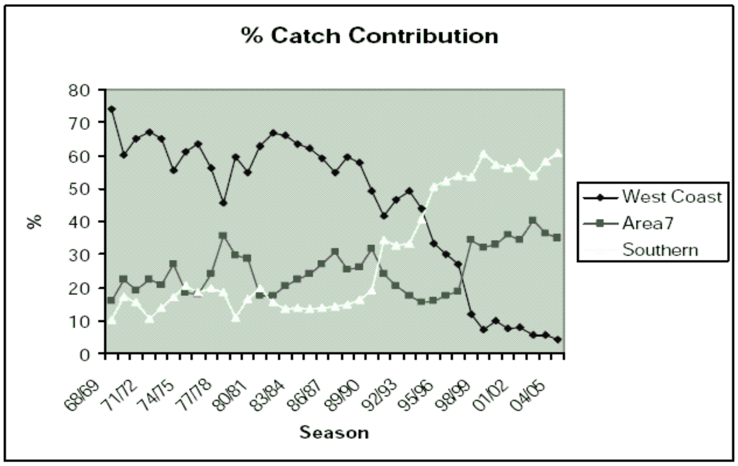


Figure 25: Change in distribution of rock lobster catches from the late-1960s to 2004 (from Cockroft, presentation, BCLME Climate WS).

Snoek

Snoek is commercially more viable in the southern than in the northern Benguela (Figure 23b) and has been throughout the 50 year record. The low yield of snoek in the northern Benguela remained somewhat constant from 1950 to about 1980 when there was a peak in handline catches. Since this peak the snoek-catch has decreased, but for a slight peak in the late-1980s (when fishing efforts were dominated by trawling) and a gradual increase in the last 5 years of combined handline and trawl catches). In the southern Benguela, the snoek catch has increased from the beginning of the record (1950) to a peak in the early-1990s, followed by a consistent decline.

3. Regime Shifts and Ecosystem Changes

The previous section elucidates the differences between the northern and southern Benguela systems in terms of both their biological and physical functioning as well as their disparate manifestations of ecosystem change. Currently, the ecosystem and trophic-functioning of the northern Benguela is very different from its character in the 1970s. Prior to 1970, the sardine resource was abundant in the northern Benguela, but today the shallow-water fish resources are scarce, while the mid-water horse mackerel are abundant and the system is still abundant in jellyfish *Chrysoara hysoscella* and *Aequorea aquorea*. This is an example of what we call a 'regime shift'. In the southern Benguela, though resources have changed substantially since the 1980s, it does not appear to have been subject to a shift to a completely new ecosystem state, instead it experienced a pelagic species replacement that did not affect the ecosystem functioning significantly (Cury and Shannon, 2004).

The open boundaries of the marine environment complicate the understanding of the factors that contribute to regime shifts. Several definitions of 'regime shift' exist and are listed in Table 11-1 in Jarre et al. (2006). For the Benguela system, an appropriate definition is: ' a relatively abrupt, persistent change in marine system functioning that occurs at large spatial scales and is observed in multiple aspects of the physical and biological system' (Jarre et al., presentation, BCLME Climate WS). The functioning and state of the ecosystem characteristic of any regime is integral to its response to environmental or anthropogenic forcing. Thus, it is essential that we are able to define and quantify the ecosystem state in order to predict regime shifts that can be gradual, abrupt or discontinuous. Processes that trigger regime shifts ('tipping points' or 'turning points') can be environmental, anthopogenic (e.g. fishing) or both.

A number of climate change scenarios and their influence on the Namibian ecosystem was outlined by Roux and Kreiner (presentation, BCLME Climate WS). A reduction in coastal upwelling would replace the cool, productive upwelling system to a warm, tropical and low productive system, which would have disastrous effects on fisheries (i.e. the irreversible reduction of fish stock and therefore, a decline in catches). On the other hand, enhanced upwelling-favourable wind stress would lead to enhanced productivity, increased turbulence and offshore advection. Negative consequences would include the increase of *in situ* production of oxygen depleted waters and an therefore, an increased risk of hydrogen sulfide eruptions. By increasing the variability of the system and by promoting rapidly fluctuating populations, an increase in the severity and frequency of Benguela Nino warm events would lead to a decrease in productivity, reduced levels of safe exploitation and an increased risk of collapse. Finally, if the effects of climate change are of low amplitude and are general in nature, the ecosystem responses are likely to be non-linear and a succession of rapid regime shifts between semi-stable states will be observed. It is this final scenario that will have the most impact on the pelagic fisheries.

In order to explicitly identify regime shifts in the southern Benguela, specifically between Hondeklip Bay and St. Helena Bay, linking SSTs (as a proxy for environmental change) with biology, Howard et al. (in prep) used the STARS (Sequential T-test for the Analysis of Regime Shifts) algorithm developed by Sergei Rodionov (2004). From this method they identified the existence of four regimes from 1957:

1. 1957-1970 was characterised by a warm west coast and a warm, unproductive south coast. Prior to 1957, horse mackerel dominated these areas and within this regime, sardines were high in abundance.
2. 1971-1980s had a very cold west coast and an unproductive south coast and was abundant in anchovy due to their proclivity for cold water.
3. 1990s was dominated by a warm west coast and a cold, more productive south coast and a coexistence of anchovies and sardines with a move toward the east.
4. In 2001 the system shifts southward.

Figure 26 shows the possible pelagic fish scenarios for a cold west coast and a warm south coast (i.e. the 1971-late-1980s/1990 regime). For the STARS algorithm to produce accurate and meaningful regimes, it is necessary that reliable timeseries' are used. However, from our available data, this algorithm produced and, in some cases, validated a decadal variability (5-10 years) that is distinct in both our biological and physical records and that should have an integral role in the design of management strategies in this area.

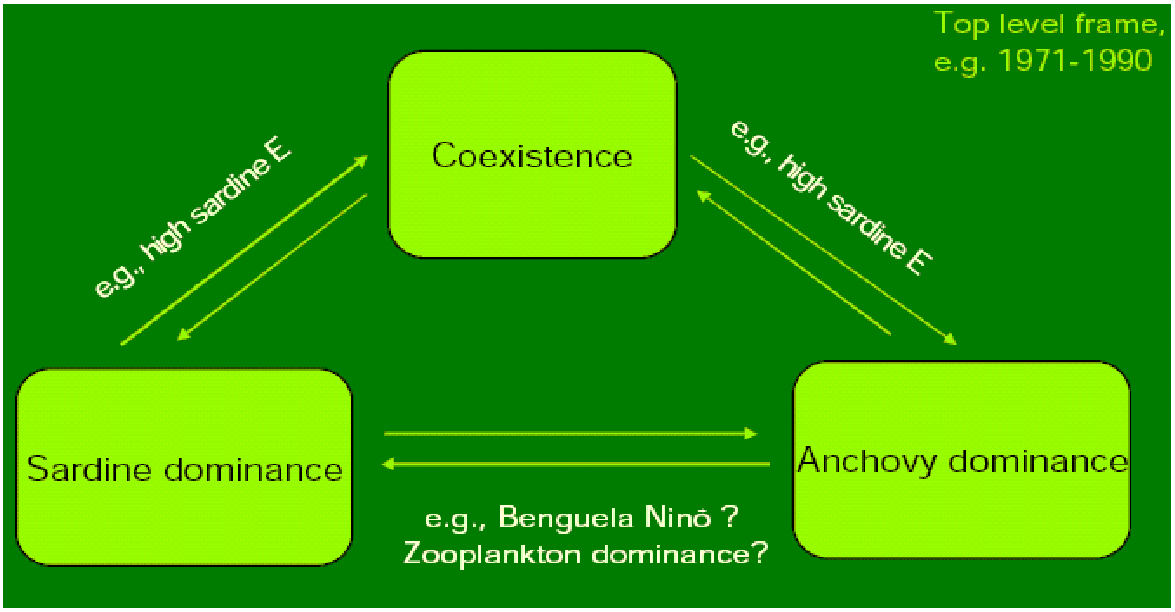


Figure 26: Pelagic fish scenarios for a regime dominated by a cold west coast and an unproductive south coast (e.g. the 1971-late-1980s/1990 regime) (Jarre et al., presentation, BCLME Climate WS).

4. Drivers of Change

Large-scale climate modes

A thorough understanding of the large-scale external forcing mechanisms of the BCLME area is essential in our goal to accurately diagnose past and present regime shifts and is thus a necessity in our success at anticipating future ecosystem changes. Characteristic of the interannual variability of the BCLME area is its pronounced decadal-multidecadal natural variability. The large-scale Benguela Niño and El Niño Southern Oscillation (ENSO) are important contributors, but they are not the only modes that generate change in the Benguela system. It is a complex system that is bounded at both its northern and southern limits by dynamic warm water regimes that may influence the BCLME with their own modes of variability. For example, the Agulhas Current directly impacts on the southern Benguela in the form of meanders and eddies emanating from the retroflection which, in turn, can be affected by atmospheric anomalies originating in the Indian and Pacific Oceans. Partly in consequence of its proximity to the Southern and the South West Indian Oceans, the BCLME region experiences a high degree of variability and it is difficult to separate 'noise' from signal.

The dominant global mode of variability on interannual timescales is ENSO and, in the South Atlantic, it is connected with atmospheric circulation and SSTs (Reason et al., 2006). From EOF analysis NCEP reanalysis SST data, Colberg et al.(2004) was able to show a robust ENSO signal over large areas of the South Atlantic, particularly the central southern Benguela areas. The effect of ENSO on the southern Benguela was documented by Roy et al. (2001), who connected the high levels of anchovy in 2000 to the La Nina event of 1999/2000. ENSO-induced fluctuations of the trade winds and the mid-latitude westerlies have been connected to the generation of Benguela Niño events and smaller warm and cold events in the Benguela system (Shannon et al., 1986, Florenchie et al., 2003, Florenchie et al., 2004).

The South Atlantic is bounded to the south by the Southern Ocean, which is also in relative proximity to the Benguela upwelling system. High-latitude modes of variability are therefore likely to influence climate and regime shifts within the BCLME. The dominant mode of variability south of 20°S is the Antarctic Oscillation (AAO) or the Southern Annular Mode, which is defined as out-of-phase pressure anomalies centered in the Antarctic and at ~40-50°S (Reason et al., 2006). In recent decades, it has been in a positive phase, meaning that high pressure anomalies dominate the mid-latitudes and low pressure anomalies prevail in the Antarctic. Reason et al. (2002) and Reason and Rouault (2005) showed that the AAO influences western South African rainfall by modulating the surface heat flux exchange and atmospheric circulation over the mid-latitudes of the South Atlantic. The fact that the AAO has been shown to modulate winds in the mid-latitudes implies a definite impact on the Benguela upwelling system.

The semi-annual oscillation (SAO) of sea level pressure, winds and rainfall is another prominent mode of variability that exerts its influence over the area 35-65°S (van Loon, 1967, cited in Reason et al., 2006). Decadal variability of the SAO has been observed and is also suggested by a wavelet analysis of NCEP re-analysis meridional wind that shows an intensification of the SAO between 1950 to 1985. The SAO affects the frequency of cut-of lows over South Africa and probably impacts on the southern Benguela and southern Agulhas systems (Reason, presentation, BCLME Climate WS). Rouault et al. (2005) speculate that there has been a phase change of the SAO since 1980 in which the peak occurs later in autumn.

The decadal and quasi-decadal pulsing of the South Atlantic anticyclone (SAA) (Reason et al., 2005 and Venegas et al., 1996) are important and are likely to impact on the Benguela system significantly by modulating the surface winds and SSTs. Also likely to impact on the BCLME region is an interannual dipole-like pattern that occurs during austral summer, characterized by anomalies of one sign in the northeast (i.e. in, and extending offshore from, the central and northern Benguela region) and the opposite sign in the midlatitude southwest Atlantic (Fauchereau et al. 2005; Hermes and Reason 2005). This mode seems to be related to modulations of the subtropical anticyclone and the circumpolar trough and provides an atmospheric linkage between variability in the South Atlantic and other regions of the subtropics and midlatitudes of the Southern Hemisphere.

Benguela Ninos

From a long time-series of SST (1906-1985) in the region of the ABFZ, Taunton-Clark and Shannon (1988) concluded that anomalous warm events have occurred throughout the environmental record with a periodicity of about 10 years. The term Benguela Niño was coined by Shannon *et al.* (1986) to describe this warming, which is associated with poleward intrusions of warm, saline tropical surface waters along the Angolan and Namibian coastlines, associated with an unusually far southward displacement of the ABFZ, which is plotted in Figure 27 for the period 1982-2003 (the major warm events of 1984 and 1995 result in a very conspicuous southward displacement). Benguela Niños occur in late austral summer and early autumn and have been recorded in the following years: 1934, 1963, 1984 and 1995. The surface expression of the 1984 and 1995 events (for the month of March) is shown in Figure 28. In situ measurements from Walvis Bay spanning 1958 to 2004 (Figure 29) show that the frequency of unusually warm water appears to have increased since the early-1990s.

Shannon *et al.* (1986) investigated the Benguela Niño events of 1934, 1963 and 1984 and noticed that they coincided with reduced wind stress in the western tropical Atlantic Ocean and were associated with anomalous flow of the equatorial current system. Horel (1986) suggested that a sudden change in zonal wind stress in the western tropical Atlantic was more important than the absolute anomaly of wind stress in generating a Benguela Niño. This is supported by the work of Florenchie *et al.* (2003), who propose that a sudden change in the wind stress in the western tropical Atlantic excites an eastward propagating Kelvin-wave-like disturbance that continues southward and northward as a coastally trapped wave upon reaching the coast. The disturbance can be tracked using the sea level anomaly it is associated with, which has been suggested by Florenchie *et al.* (2004) to have an average eastward speed of 1.7m.s^{-1}. Florenchie *et al.* (2003) provide evidence that the warm anomaly is a subsurface feature as it travels southward along the African coast and outcrops at the surface off Angola when it reaches the Benguela upwelling regime. Also, they noted that the timing of warm anomalies appears to be a crucial factor of the development of a Benguela Nino event, which tend to occur in February/March. Colberg (2006) investigates the possibility that the cycle of Benguela Nino events is forced partly by intrinsic variability within the ABFZ and partly by a larger-scale mode. Several large-scale modes of variability have been shown to influence regional scale processes; for example, the El Nino Southern Oscillation (ENSO) has been associated with variability in the South East Atlantic (Colberg *et al.*, 2004; Sterl and Hazeleger, 2003 and Reason, 2000).

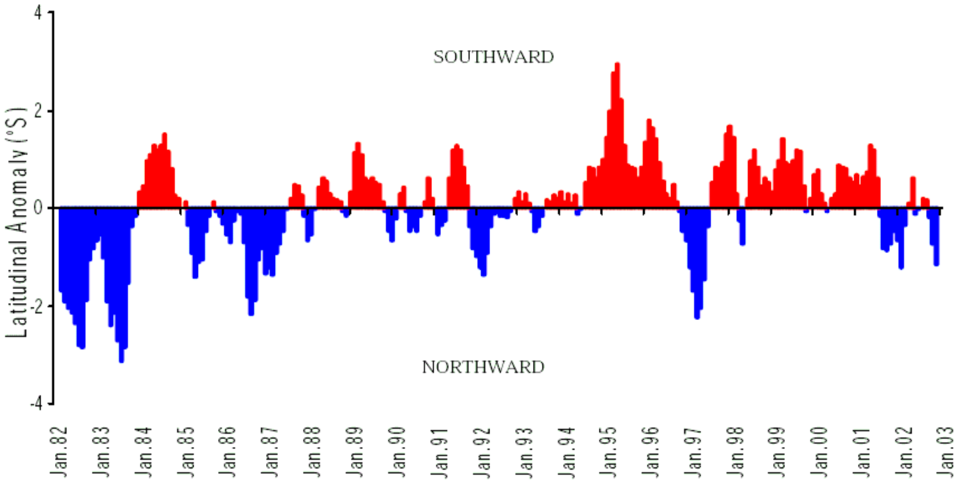


Figure 27: Timeseries of the latitudinal anomaly of the position of the ABFZ over a 19 year period (1982-2003) (from Barthlomae and van der Plas 2007)

Ecosystem effects of Benguela Niño events include the displacement and mortality of certain fish species (see LeClus, 1985; Shannon and Agenbag, 1987; Crawford and Shannon, 1988 and Gammelsr?d *et al.*, 1998; among others) as well as increased rainfall in coastal areas of Angola and Namibia (Rouault *et al.*, 2003). The effect of Benguela Niño events is immediately noticed by coastal communities and accordingly warrants a thorough investigation of the possibilities for predictability in order to allay socio-economic consequences of such events.

The work of Florenchie *et al.* (2003 & 2004) alludes to the possibility of anticipating Benguela Nino events by tracking the oceanic disturbance that results from the sudden change in zonal wind stress in the western equatorial Atlantic. Furthermore, they have estimated a lead time of approximately 2 months, which is based on the time it takes for the disturbance to cross the Atlantic and travel poleward along the coast. However, the several modes of variability that influence the oceanic environment of the South East Atlantic make the solution somewhat more complicated and should not be neglected when attempting to forecast extreme events.

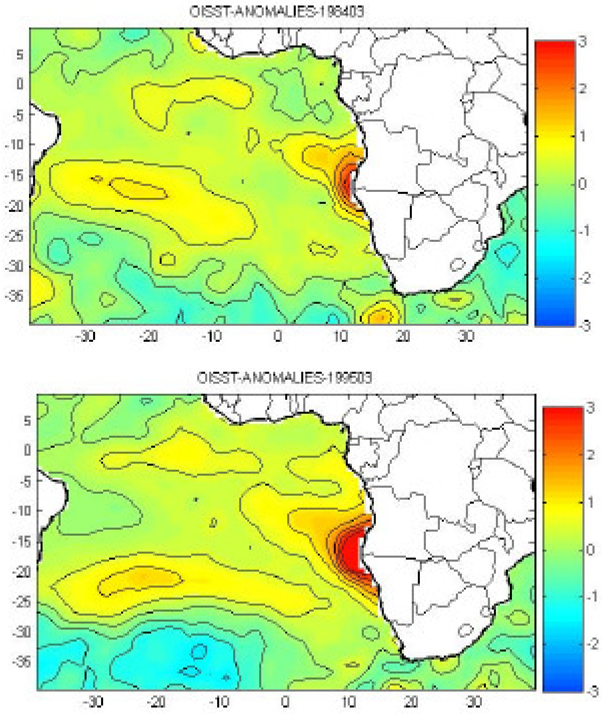


Figure 28: Surface expression of the 1985 and 1994 Benguela Nino warm events (from Florenchie et al. 2004)

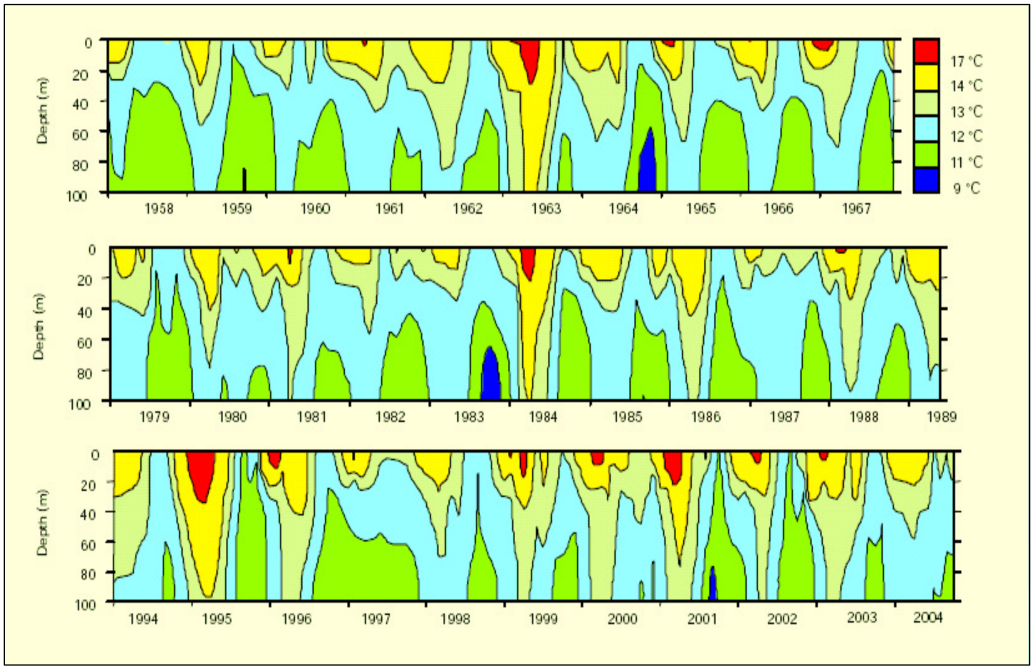


Figure 29: Temperatures off Walvis Bay from the surface to 100m depth for the period, 1958-2004 (Bartholomae and van der Plas 2007).

Environment vs Fishing

Ecosystem regime shifts cannot be unequivocally attributed to either environmental variability, brought on by climate change, or to changes in fishing practices. It is a complex system, involving several interacting tropic-levels, that are both cause and consequence of many scales of variability. Before even considering the effects of climate change and fishing, natural cycles of species (such as the 40-60 year anchovy/ sardine cycle) in the Benguela system and the ramifications for the rest of the food web need to be sufficiently resolved in order to form a baseline from which to investigate other sources of change. This is no simple task, especially since we only have reliable data (that, in some cases, are highly fragmented in space and time) spanning the last 50 years or so. The scarcity of data is just one of many difficulties we encounter when attempting to unravel the poorly understood enigma of regime shifts. Another is that when an ecosystem is overexploited, it is more responsive to bottom-up forcing thus complicating the quantification of the relative importance of top-down versus bottom-up controls.

Despite this 'catch-22' situation, regime shifts in the Benguela are thought to be primarily governed by environmental forcing (van der Lingen et al., 2006), in which a bottom-up control is set-up via phytoplankton or zooplankton resource limitations (Verheye et al., 1998). Hypotheses of the impacts of different climate change scenarios have been suggested by several authors, for example altered wind stress would enhance or inhibit coastal upwelling (Bakun 1990; Bakun, 1992; Shannon et al., 1996). Environment changes can also impact the ecosystem in a wasp-waist manner in which pelagic fish recruitment is directly impacted and control species at both higher and lower trophic levels (Cury et al., 2003). Top-down control (predation) is an important control of pelagic species mortality rates as predation connects species (Jarre et al., 2006). Fishing can be viewed as a top-predator and, though it is not the only source of species variability, it may hasten stock collapse, suppress stock recoveries (Beverton 1990) or alter marine ecosystem structure (e.g. Pitcher 2000; Pitcher and Pauly 1998) and it is likely that the southern Benguela shifted rapidly from a pristine state following the advent of heavy fishing pressure (van der Lingen et al. 2006).

Using an Ecopath modelling approach, Watermyer et al. (presentation, BCLME Climate WS) indicated that prior to the onset of large-scale fishing, the northern ans southern Benguela systems functioned in a somewhat similar manner and were buffered against environmental perturbations. Following heavy exploitation, the systems appear to be more susceptible to environmental influences, so environmental control is now an important determinant of ecosystem status.

5. Consequences of Change and Mitigation Strategies

Drastic changes in the Benguela ecosystem have impacted upon jobs, demography and development in South Africa, Namibia and Angola over the past 50years. The following climate and resource fluctuations have had the most conspicuous societal consequences:

- There have been substantial changes in the distribution of horse mackerel and *Sardinella* species off Angola.
- The rock lobster fishery in the central Benguela collapsed in the 1970s and impacted coastal communities in Lüderitz and Port Nolloth in particular.
- There was a massive decline in the Namibian sardine in the late 1960s and 1970s and anchovy in the 1980s, with no subsequent recovery of these stocks. This decimated the Walvis Bay canning industry, and led to losses of a large number of jobs.
- Harm was done to the hake resource in Namibia through environmental effects (hypoxia and Benguela Niños) in the early 1990s and stocks there have failed to recover subsequently to expected levels under conditions of conservative management. This has been a serious setback for the Namibian economy and for employment in Walvis Bay and Lüderitz.
- The decline of the South African west coast rock lobster fishery and its displacement eastwards inshore along the south coast has had serious socio-economic impacts on coastal communities.
- In addition mass mortalities of rock lobsters during the past two decades in the St Helena Bay area as a consequence of hypoxia and harmful algal blooms have had negative financial and ecosystem impacts.
- The eastward shift of sardine in South Africa over past decade has had major implications for fishing vessel deployment, catching and processing of fish, employment, and use and development of infrastructure. There are difficulties associated with catching epipelagic fish in warm water and delivering fish, which spoil easily, in good condition to canning plants.
- For central-place foragers, such as African penguins, the shift of epipelagic fish stocks to a region with few islands available for breeding has led to a 50% decrease in the breeding population in the 21st century, exacerbating the already precarious conservation status of this endemic species, Africa's only penguin.
- There has been a decline in other top predators, which has impacted on tourism in some

localities. Cape gannets stopped breeding at Lambert's Bay in 2005. Tour buses no longer visit this town.

- Major storms accompanied by abnormally large swells a few years back in Cape Town and more recently in Kwazulu/Natal resulted in damage to maritime operations and coastal infrastructure and financial loss in the shipping and other maritime industries.
- Problems associated with harmful algal blooms have had a negative impact on the developing mariculture industry.
- All the above have impacted on jobs, demographics and development.
- Not all changes have been negative, e.g. the eastward shift in the distribution of sardine in South African waters has stimulated economic development in Mossel Bay.
- Market changes have meant closure of some lobster processing plants, but have created new jobs in exporting live lobsters.

The Benguela system is subject to persistent decadal-scale fluctuations. Our relatively short timeseries makes it difficult to unequivocally implicate either climate change, inherent natural oscillations or fishing as the driver of these changes. Nevertheless, the fact that we are able to extract a fairly robust cycle from the data we have available is the first step in designing an ecosystem management strategy to best minimize the impacts of regime shifts. The strategy should be adaptive on timescales similar to the influential decadal-scale forcing of the BCLMA region (5-15 years). Other management strategies aimed at mitigating the socio-economic impacts of ecosystem change could include training for employment outside of the fishing industry and developing the mariculture/aquaculture industry.

5. The Way Forward

Identification of the limitations and gaps in our knowledge of Benguela ecosystem functioning provides a foundation on which we can pave the way forward. One of the most striking limitations to our understanding is the shortage of reliable data, in both the biological and physical domains, that are spatially as well as temporally cohesive. Our comprehension of cycles and apparent trends in the BCLME suffers from the poor understanding of palaeo-scale oscillations within the system that are likely to modulate the higher frequency fluctuations of the system. Also, our knowledge of the processes that maintain the Benguela ecosystem at its current state needs to be improved if we hope to get a handle on thresholds and tipping points that could send the system into a regime shift.

The outstanding issues, gaps in knowledge and steps that should be taken in order to ameliorate the situation can be prioritized as follows:

1. On the issue of inadequate data: reanalysis data-sets (e.g. SODA: Simple Ocean Data Assimilation[3]), in which data from models, satellite and *in situ* observations are combined need to be easily accessible. Global warming will require that we embrace models as well as other sources of data. A model can be thought of as a tool for integrating the data that we already have, to help reconstruct the past 50 years.
2. Patterns and theory need to be brought closer together. In order to do this we need to

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[3] http://www.met.rdg.ac.uk/~swr02ldc/SODA.html

develop our theoretical understanding, which will be elucidated by the observation of patterns.

3. Integrating meteorology and oceanography more fully by coordinating the atmosphere and ocean weather/climate services will assist us in resolving the bigger picture. It needs to be made known that they depend closely on one another (e.g. atmospheric/ocean interaction via heat transfer is important and the whole global warming debate rests on the different albedo and absorption effects of different types of clouds). The weather office has exceeded oceanographic institutions in their advances in scientific understanding due to the fact that they offer a service, therefore a way forward for operational oceanography would be to integrate it into the weather service.
4. We need to focus on research looking for thresholds, with an emphasis on biology.
5. Existing data sets need to be collated, reviewed and compared with model output so that we may have the opportunity to improve and refine our modelling capabilities.
6. The importance of oceanography for, not only fishing resources, but also for climate change (and the subsequent effects on biodiversity conservation) needs to be stressed, thereby widening the purpose of oceanography.

In general, a stronger case needs to be made for monitoring a host of variables, in particular those relevant for weather and climate. The framework for storing such data exists in the form of SADCO (the South African Data Center for Oceanography), SEIS (the State of the Ecosystem Information System) and SAEON (the South African Environmental Observation Network). These archives need to be populated with biological, oceanographic and atmospheric climatologies as well as historical data by each of the countries bordering the BCLME and should be accessible to all of them.

7. Summary

The highly variable nature of the South Atlantic complicates our ability to separate a clear climate change 'signal' from the persistent 'noise' of the Benguela ecosystem. In part, the highly variable nature of the BCLME can be attributed to the fact that it is influenced by the dynamic equatorial system of currents (via the Angolan Current) at its northern boundary, the highly dynamic Agulhas Current (that, in turn, is influenced by modes of variability operating in the South West Indian Ocean) at its southern boundary that is also subject to oscillations originating in the Southern Ocean. Therefore, it can be said that the large-scale basins surrounding the Benguela upwelling system are integral to the state of the environment and ecosystem there.

A review of ocean and atmosphere climate records and biological data spanning the last 50 years has enabled us to extract and, in some cases quantify, cycles and trends that exist in our period of record. Analysis of, the often co-evolving, physical and biological records has provided insight into the nature of regime shifts in the BCLME.

Conspicuous cycles and trends that have been extracted from our data form the basis of our views of change in the Benguela ecosystem. The most striking are:

- A warming trend at both the northern and southern boundaries of the system. The nature of the warming trends at the northern and southern boundaries differ in that the warming in the north has occurred across the boundary so that temperature gradients remain unchanged, while at the southern boundary warming has dominated the inshore areas of the Agulhas Bank and slight cooling has occurred in the southern Benguela so that temperature gradients in this area have intensified.

- Over the past decade there has been an increased frequency of warm events off southern Angola and northern Benguela. A change in the seasonal warming in the north may lead to an increased occurrence of hypoxic episodes on the Namibian shelf, which has dire implications for important fish resources such as the hake stock.
- In the southern Benguela, there has been a long-term increase in the upwelling-favourable wind field that is subject to decadal-scale modulations. The winds in the northern Benguela also have a decadal cycle and are currently in a low phase.
- The mean sea level rise in the Benguela upwelling area is of the order of the global average, but is not considered to be a threat along the south west African coast.
- Zooplankton populations have increased approximately 10 fold throughout the Benguela system due to an increase in upwelling favourable winds and were regulated by the pelagic boom in the southern Benguela in 2000-2003.
- Pelagic fish resources have been heavily exploited in the northern and southern Benguela systems, resulting in the collapse of the sardine stocks in the 1960s. The Namibian fish stock has failed to recover, in spite of decreased fishing efforts in the 1990s. It is thought that this could be related to the warming trend, competition with the increased horse mackerel abundances or heavy predation. Sardine stocks in the southern Benguela appear to be decreasing, but anchovy remain at a higher than average level. The distribution of the pelagic fish in the southern Benguela has shifted eastward. This distributional change appears to be cyclical and has significant socio-economic ramifications.
- The increase of horse mackerel stocks in Namibia occurred after the collapse of sardines, but has recently begun to decline. Similarly, the stock of a different horse mackerel species found off Angola has also sharply declined in recent years. This has resulted in a ban on the exploitation of horse mackerel in Angola and the necessity for the importation of fish for local consumption.
- Rock lobster abundances have declined in the central Benguela and their population has shifted south and eastward from the southern Benguela.
- Top predators respond in different ways to changes in fish availability: the seals have expanded northward, seabirds have declined considerably due to the shift of pelagic fish toward the east. Increases in outbreaks of avian flu and cholera have been reported and are associated with stressed populations.

In general, the Benguela ecosystem is subject to regime shifts that occur with a periodicity of approximately 5-15 years, but that are difficult to unequivocally attribute to either climate change or to inherent natural variability. Nevertheless, this decadal oscillation is fairly robust and it is in the framework of this time-scale that mitigation strategies need to be developed.

We need to make a much stronger case for monitoring a host of variables, in particular those relevant for weather and climate. Future research should be focused on monitoring approaches that have scope for broad spatial and temporal scales (inclusive of the global- and palaeo-scales). This is essential for integrated ecosystem management and is likely to enhance the accuracy of forecasting seasonal and longer term weather and climate change in the region. To this end, closer collaboration between the ocean and atmospheric institutions in South Africa is necessary and could be facilitated by the newly established Benguela Coastal Commission (BCC).

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Presentations at the BCLME Climate Workshop, 15-16 May 2007 (Kirstenbosch, Cape Town)

Bartholomae, C., A. van der Plas and K. Peard: The Namibian record, part 1. Environment.

Cockcroft, A.: Changes in the distribution and productivity of the west coast rock lobster over the period of review.

Fidel, Q.: Angola environmental record.

Field, J.: Importance of an appropriate observing system.

Hewitson, B.: Southern African climate change results related to the IPCC AR4.

Hutchings, L.: Climate variability (change) and Benguela resources, an overview: noise, trends and cycles.

Jarre., A., J. Howard, L. Shannon and C. Moloney: Is there evidence of climate-driven change at the ecosystem level in the BCLME?

Kirkman, S.P, J. Kemper, W.H. Oosthuizen, J.-P. Roux, L.G. Underhill and R. Crawford: Benguela's top predators-indicators of change?

Monteiro, P.M.S., A. van der Plas, W. Joubert, T. Quieroz, A. Kemp, J.-L. Melice, P. Florenchie and G. Bailey: Hypoxia: extreme events and shifty scales (of wind).

Philander, G.: Global warming and upwelling systems.

Reason, C.: Climate variability in the BCLME region: What is the low frequency variability in the generally upwelling favourable winds?

Rouault, M.: Observed trends in the ocean and atmosphere around southern Africa over the past 50 years.

Roux, J.-P. and A. Kreiner: The Namibian record, part 2.

Tennant, W.: Modelling capacity in the South African weather service and how weather systems over the Benguela are affected by climate variability.

Terblanche, D., W. Landman, W. Tennant and A. Kruger: Climate change and variability in southern Africa. A perspective from the SA weather service.

van der Lingen, C. and J. Coetzee: Patterns of variability in pelagic resources in the southern Benguela.

Verheye, H.M., F. Cazassus and A. Kreiner: Decadal changes in abundance and species composition of zooplankton in the Benguela Large Marine Ecosystem (BCLME).

Watermeyer, K., L.J. Shannon and C.L. Griffiths: The Benguela ecosystem prior to and after the onset of large scale commercial fishing.