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Large Scale Physical Variability of the Benguela Current Large Marine Ecosystem (BCLME)

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INTRODUCTION

The Benguela Current Large Marine Ecosystem (BCLME) is situated off the west coast of Africa between 5-37ºS, 0-26ºE, and spans the three countries of Angola, Namibia and South Africa. It is one of the four major eastern boundary current upwelling systems of the world oceans (Hill et al. 1998), and although it has some similar characteristics to the other eastern boundary upwelling areas, a unique feature is that it is bounded on both the equatorial and poleward extremities by warm water current systems (the tropical warm Angola Current system in the north, and the Indian Ocean western boundary Agulhas Current System in the south; Shannon and Nelson, 1996; Shillington 1998; Shannon and O'Toole 2003). In the region between about 15-37ºS, the surface currents are generally equatorward, with vigorous coastal upwelling cells, strong and narrow equatorward shelf edge jets (near Cape Town which is situated at 34ºS, 18ºE and off Lüderitz; 28ºS, 15ºE), and a poleward undercurrent along the shelf slope and bottom. The warm tropical Angola Current System (Ajao and Houghton 1998) generally has southward moving coastal currents which meet the Benguela Upwelling System at the Angola-Benguela Frontal Zone (ABFZ) at ~15-17ºS (Shannon et al. 1987; Field and Shillington 2005; Monteiro and van der Plas, this volume; Veitch et al. 2006).

The Angola Current is affected by input from the equatorial wave guide, the South Equatorial Current (SEC) and the South Equatorial Counter Current (SECC) at ~5°S (Peterson and Stramma 1991). Details of the circulation of the Angola Gyre and the nature of the Angola Dome are addressed by Monteiro and van der Plas (this volume), and by Reason et al. (this volume).

At the centre of the BCLME region is an area of year-round coastal upwelling, 15-30°S (Boyer et al. 2000); and a region of seasonal upwelling, 30-34°S. Coastal trapped waves have been observed to propagate polewards on the continental shelf at regular synoptic time scales (~3-10 day periods) from Walvis Bay in Namibia (20°S), and to continue around the Cape of Good Hope and up to 800 km east along the eastern coast of South Africa (Brundrit et al. 1987; Schumann and Brink 1990).

At the southern end the BCLME region, the Agulhas Bank (see Fig. 1-1 in Chapter 1 for the shelf topography of the BCLME region) is a very wide shelf region along the southern coast of Africa from 18-26°E, that has a highly vertically stratified water column in the west in summer, and a well mixed water column in the winter (Schumann 1998). Closer to the coast, there is summer upwelling of cool nutrient rich water at the major coastal embayments on the African coast between these longitudes.

In the middle of the Agulhas Bank, there is a seasonal cold tongue apparent in surface and near-surface waters; the circulation around this feature appears to be cyclonic (Boyd and Shillington 1994). This feature is particularly visible as a ridge of elevated chlorophyll, occurring in the period from March-June (Demarcq et al 2003; Hardman-Mountford et al. 2003). The Agulhas Bank is very important for the spawning of pelagic fish such as anchovy and pilchard from September to March (Hutchings et al. 2002). After spawning, eggs and larvae drift northwards in the jet current past Cape Town, until juvenile fish recruitment occurs about 150 km north along the coast at ~32°S in St Helena Bay. Adult fish then make their way back to the Agulhas Bank to spawn in the following austral spring-summer (van der Lingen et al. this volume).

Large-scale, multiyear climatic variations in the Benguela upwelling region have been observed from time to time and have been dubbed "Benguela Niños" as an analogue to the Pacific event (Shannon et al. 1986). The Benguela Niño, like its Pacific counterpart, has a strong effect on regional fisheries and this in turn has led to an effort to forecast these events. Benguela Niños have been observed/reported in 1934, 1963, (1972/3), 1984, 1995 (Shannon et al. 1986; Gammelsrød et al. 1998). Field measurements of the 1995 Benguela Niño were reported by Gammelsrød et al. (1998).

More recently, Florenchie et al. (2003) and Florenchie et al. (2004) have examined the nature of the 1984 and 1995 Benguela Niños using an ocean general circulation model together with satellite derived sea surface temperature (SST) and sea surface height (SSH) data, to show how they can be related to local and remote wind forcing. Their results suggest that a possible forecast lead time of two months exists for anticipating strong positive SST anomalies propagating from the equatorial region, polewards beyond the Angola Benguela Frontal Zone (ABFZ). Benguela Niños represent the lowest frequency, largest-scale instance of variability in the BCLME. The main large scale physical features of the BCLME are summarised in the cartoon in Fig. 1-1 in Chapter 1.

The main purpose of this review is to set the scene for a discussion of potentially forecastable aspects of major importance in the BCLME. Questions that are central to this discussion are formulated below.

- What proportion of the BCLME large scale variability is associated with the seasonal forcing, and what part is related to inter-decadal events such as the Benguela Niño?
- What is the role of other large scale modes such as ENSO and the Southern Annular Mode in driving variability in the BCLME region ?

- Can monitoring the remote and/or local wind forcing in the western equatorial Atlantic region give an acceptable lead time for nowcasting/forecasting Benguela Niños at or south of the Angola Benguela Frontal Zone?
- How is the Benguela Niño signal transmitted/influenced by the poleward flowing Angola Current and what is the nature of the interaction with the northern part of the Benguela Upwelling at the ABFZ at ~15-17ºS?
- What is the nature and importance of the Angola Dome area for the large scale formation of low oxygen water, and is this water responsible for low oxygen water in the northern Benguela?
- What is the effect and importance of the variability of the outflow of the main large rivers (e.g. Congo/Zaire and Orange/Gariep Rivers) on the BCLME?
- Is it possible to nowcast/forecast changes in the extremely vigorous wind driven upwelling in the Lüderitz region, which tends to persist throughout the year?
- What is the nature of the predictability of the remote and local forcing of the southern Benguela Upwelling System from the poleward end via the influence of the Agulhas Current and its retroflection?
- Is there seasonality in the Agulhas Current and the shedding of Agulhas retroflection rings? Is the shedding of rings predictable or capable of being monitored sufficiently far "upstream in the Agulhas Current" to provide advance warning of interaction with the Benguela upwelling front?

Major intrusions of sub-Antarctic water have been observed to interact with the outer boundary of the southern Benguela Ecosystem in 1987 (see Shannon et al. 1990 as cited in Hardman-Mountford et al. 2003). Are such intrusions of sub-Antarctic water into the southern Benguela System important sources of variability and are they predictable?

MAJOR PHYSICAL PROCESSES IN THE BCLME

The main dynamic processes in the BCLME are similar to other major eastern boundary upwelling systems (Hill et al. 1998). They include:

- Dominant equatorward wind stress inducing Ekman offshore transport of surface water, which is replaced by cool, nutrient rich subsurface central water (see detailed section below on recently measured water masses in the central Benguela). The upwelling process leads to the surfacing of cool, coastal nutrient rich water; the subsequent growth and decay, and instability of oceanic fronts, filaments and frontal jets e.g. Shillington (1998).
- A poleward undercurrent along the continental shelf break which later intrudes onto the shallower continental shelf in various places. The detailed mechanism responsible for this is not clear at present.
- Poleward propagating coastal trapped waves on the shelf, which are easily detected in coastal tide gauge recordings of sea level, e.g. Brundrit et al. (1987).
- Kelvin wave like disturbances travelling eastwards along the Atlantic Ocean equatorial waveguide, travel from South America to Africa, and later turn polewards along the Angolan coast. Temperature anomalies can give rise to either

local warm events, or in some cases, Benguela Niños that reach as far south as Walvis Bay (~22°S), e.g. Florenchie et al. (2004).

- Agulhas ring formation after the Agulhas Current Retroflection south and west of Cape Town, and the subsequent interaction of these rings with the southern Benguela upwelling frontal system, e.g. Duncombe Rae et al. (1992), Shillington (1998). This process is unique to the BCLME, and not found in any of the other major eastern boundary current systems.
- The seasonal and inter-annual meridional movement of the ABFZ, and the quasi-decadal variability of Benguela Niños, e.g. Veitch et al. (2006). This process appears to be unique to the BCLME, and not found in any of the other major Eastern Boundary Current Upwelling Systems.

The main transboundary areas of the BCLME are: the northern Angola Current border with the equatorial currents; the ABFZ; the Lüderitz-Orange River cone area (Duncombe Rae 2004); the Agulhas Current-Benguela upwelling interaction at the southern boundary of the Benguela upwelling area; the coastal transition zone between the cold upwelling coastal and continental shelf region and the deeper ocean.

ATMOSPHERIC FORCING OF THE BCLME

The atmospheric circulation of the BCLME region is dominated by the South Atlantic subtropical anticyclone which gives rise to southerly wind stress near the west coast of Africa. To the south of Africa and the region, there is generally a westerly flow, with changes in wind direction associated with west to east travelling mid-latitude cyclones.

During austral summer, surface heat induced low pressure systems develop over western South Africa, enhancing the zonal pressure gradient and leading to an intensification of the southerly wind stress off the west coast. A separate heat induced low pressure system develops over southern Angola/northern Namibia with an associated westerly windstress off the tropical SE Atlantic that feeds into the confluence between the ITCZ and the Congo air boundary. In winter, the major atmospheric circulation features shift north so that most of the BCLME region is dominated by low level southerlies. The exception to this is south of about 30°S, which is subjected to frequent atmospheric frontal activity (e.g. Hardman-Mountford et al. 2003).

Superimposed on these seasonal changes in the low level winds is considerable mesoscale, synoptic, intra-seasonal, inter-annual and longer time scale variability. On synoptic time scales, the predominant anticyclonic equatorward wind flow along southern Namibian and South African west coast is perturbed by cold fronts, coastally trapped low pressure systems, “cut off lows”, and mesoscale features such as “berg winds” and sea breezes. Sometimes berg winds are followed by “coastal lows” (Reason and Jury 1990) which tend to significantly perturb the coastal wind fields. Cold fronts are most common in the winter half of the year whereas “cut off lows” may occur in any season but tend to be more likely in the austral spring and autumn.

West coast troughs may affect the entire coast south of about 10°S but are more common in the north (south) during winter (summer).

All these weather systems interrupt the upwelling-favourable winds at a variety of space and time scales. Risien et al. (2004) examined sixteen months of QuikScat satellite derived windstress data in the Benguela System, using an artificial neural network (the Kohonen self organising map) to divide the region into six discrete regions, and wavelet analysis to extract the spatial and temporal variability scales between four and sixty four days. Chelton et al. (2004) have located significant time independent narrow bands of cyclonic curl (see Fig. 4-1; negative in the Southern Hemisphere) with large alongshore scales, adjacent to the western coastline of southern Africa from an analysis of four years of Quikscat windstress. The detailed structures and evolutions of these nearshore curl and divergence features were previously poorly resolved by historical ship observations. The implication of the long term averaged cyclonic curl of windstress is that the shallow eastern boundary Atlantic Ocean thermocline will be elevated upwards towards the surface, while the divergence will modulate the upwelling along the coast.

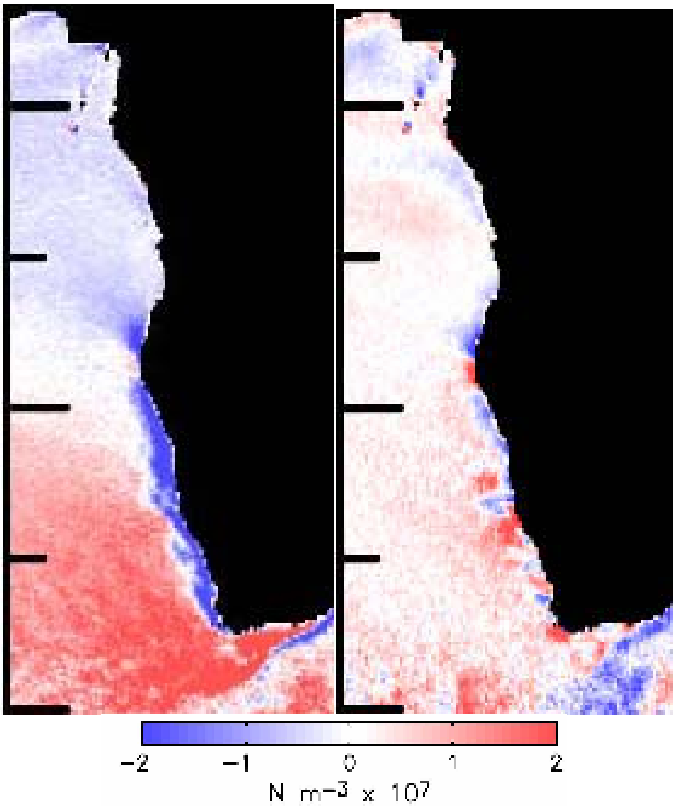

Figure 4-1. Four year average windstress curl (left) and divergence (right) calculated from Quikscat. Units are N m^{-3} x 10^{7}. (After Chelton et al. 2004)

LARGE SCALE MODES OF VARIABILITY

A number of large-scale modes of variability influence the atmospheric circulation over the South Atlantic, and hence the BCLME region. These include ENSO, which primarily influences the region via the Pacific-South America pattern (Mo and Paegle 2001; Colberg et al. 2004), the semi-annual oscillation (van Loon 1967), the Antarctic Oscillation or Southern Annular Mode (Kidson 1988), and large-scale modulations of the subtropical anticyclone which may be locally forced (Venegas et al. 1996; 1997; 1998) or related to near-hemispheric modulations of the subtropical high pressure belt (Jones and Allan 1998; Reason 2000). Modulations in the trades over the western tropical Atlantic may generate Benguela Ninos (Florenchie et al. 2004) which may then influence the atmospheric circulation over the northern Benguela region (Rouault et al. 2003). In addition, shifts in the atmospheric wave number three pattern can often produce dipole-like SST variability in the South Atlantic and South Indian Oceans (Fauchereau et al. 2003; Hermes and Reason 2005) that tends to occur during the summer. There are several other large-scale modes that are important for the tropical Atlantic (meridional gradient mode, zonal mode, North Atlantic Oscillation) and whose potential influence on the BCLME region needs to be assessed (see Chapter 10: Reason et al. this volume).

WATER MASSES AND VERTICAL STRUCTURE OF THE BCLME

The major oceanic influences on the Benguela upwelling system are derived from the equatorial Atlantic in the north and the South Atlantic/South Indian to the south. Direct water mass analysis in the BCLME (Figs. 4-2 and 4-3) can be used to discriminate the influence of tropical water entering from the Angola Basin and the northern Benguela, from that being upwelled in the southern Benguela. A recent comparative study of the historical record of nutrients and hydrographic properties of the Benguela has been made by Kearns and Carr (2003). Antarctic Intermediate Water (AAIW) that is formed at the surface in the sub-polar and polar regions has a salinity minimum deep in the water column, with distinct characteristics in the northern and southern Benguela (Shannon and Hunter 1988; Talley, 1996). From the Angola Basin a high (relative to the southern Benguela water type) salinity AAIW (HSAIW) enters the northern Benguela in a poleward undercurrent along the shelf edge. The southern Benguela has a low salinity AAIW (LSAIW) close to the Subtropical Front.

Similarly the South Atlantic central water in the Benguela has a relatively High Salinity component (HSCW) originating in the tropical Angola Basin and relatively Low Salinity Central Water (LSCW) in the Cape Basin.

Above the central waters there is higher salinity, warm Oceanic Surface Water (OSW). The surface water is subject to the influence of precipitation and continental runoff from rivers into the Angola Basin resulting in low salinities at the surface (Mohrholz et al. 2001). In the southern Benguela the run-off from the Orange River is intermittent and controlled by dams and therefore less evident in extent and persistence than in the north.

The central water on the shelf is upwelled near the coast by the persistent equatorward component of the wind. Because of the atmospheric modification of temperature and salinity it is designated Modified Upwelled Water (MUW).

In general terms, the intermediate, central, and upper waters can be summarised as having either (a) a high salinity, high temperature character indicating a tropical influence; or (b) a low salinity, low temperature character indicating an Antarctic or sub-Antarctic influence. Appropriate modifications of the surface and upwelled water occur during contact with the atmosphere due to solar heating and turbulent mixing processes.

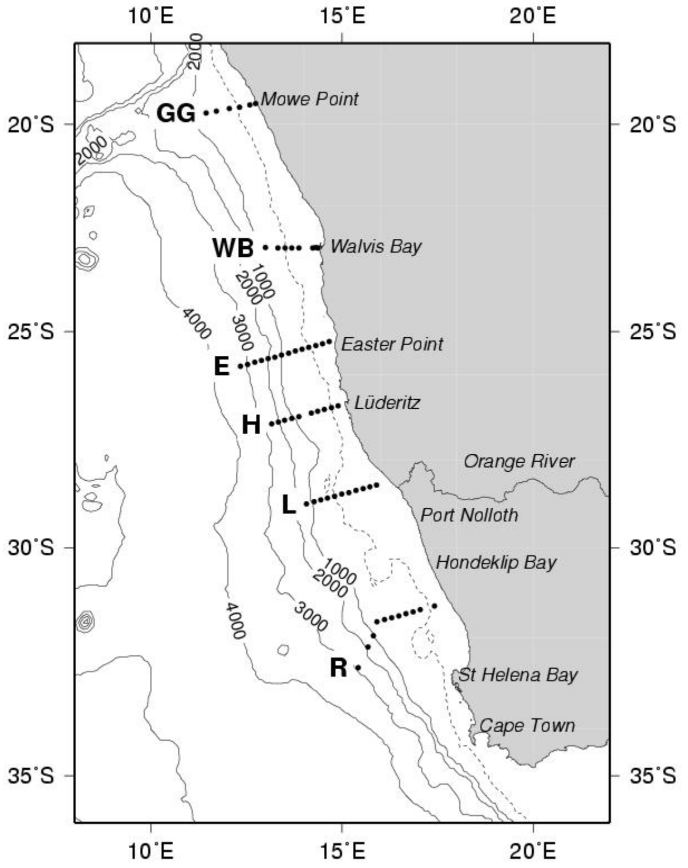

Figure 4-2. The data are from the BENEFIT cruises of Africana in 1999 (lines GG, WB) and 2002 (lines E, H, L), and from the ASTTEX deployment cruise of RV Melville in 2003 (line R). The dashed contour represents the 200 m isobath. Other isobaths are labelled.

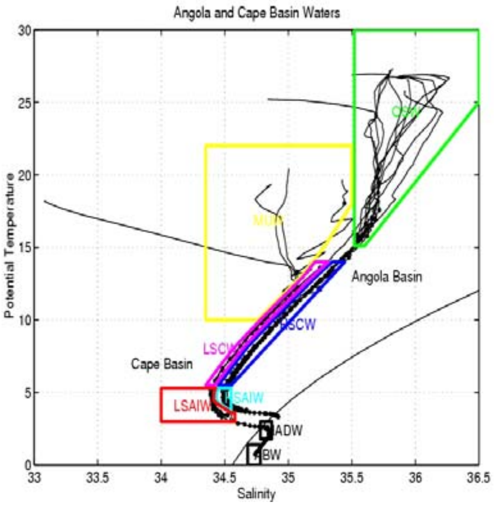

Figure 4-3. Θ-S diagram of the water column profiles from the northern and southern Benguela. Note the clear salinity difference between the central waters of the two extremes. The water mass definitions used in the text are superimposed. The water mass definitions used in the text are superimposed. The water masses labelled are: ABW – Antarctic Bottom Water; NADW– North Atlantic Deep Water; LSAIW – Low Salinity Antarctic Intermediate Water; HSAIW – High Salinity Antarctic Intermediate Water; LSCW – Low Salinity Central Water; HSCW – High Salinity Central Water; MUW – Modified Upwelled Water; OSW–Oceanic Surface Water. The very low salinity seen in the surface water of some stations is due to continental run-off. Water masses below the isopycnal shown (σt= 27.75 kg.m.-3) are not discussed in detail in the text.

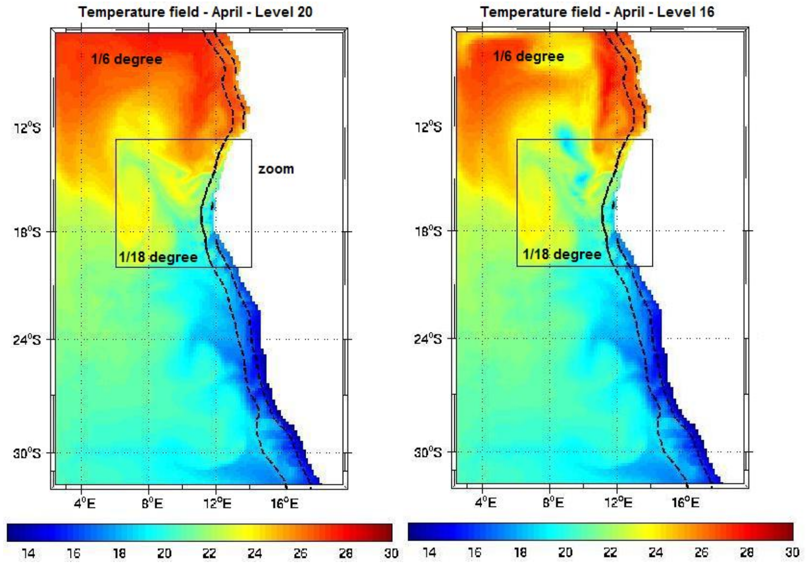

Figure 4-4. Monthly temperature fields in April at level 20 (surfaceleft panel) and at level 16 (approximating the mixed layer, right panel) from ROMS model.

The waters of the South Atlantic Ocean thermocline (central water) layer originate in two source water mass regimes (Poole and Tomczak 1999): Eastern South Atlantic Central Water (ESACW) and Western South Atlantic Central Water (WSACW). The ESACW is derived from the Indian Central Water through the Agulhas Current, and the WSACW is derived from the Brazil Current through the Brazil/Malvinas Confluence in the western South Atlantic subtropical gyre. In the eastern basins of the South Atlantic, the WSACW is present in the Angola Basin while the ESACW is found in the Cape Basin. The characteristics of WSACW are modified in the region of the ABFZ from their source water characteristics by upper layers processes in the equatorial Atlantic (Mohrholz et al. 2001).

Below the main thermocline, the AAIW on the west coast of southern Africa has a salinity of 34.35, rising to 34.50 near the ABFZ (Talley 1996; Duncombe Rae 1998; Shannon and Hunter 1988; Mohrholz et al. 2001). Higher salinities are found in the intermediate water on the east coast, and in the Agulhas Current, due to the influence of occasional intrusions of Red Sea Water (Gründlingh 1985). These latter high salinity AAIW sources, however, appear not to influence the intermediate water of the central Benguela.

The broad circulation of the water masses (described by Shannon and Nelson, 1996, after Chapman and Shannon, 1985) is indicated in detail by the steric height anomaly at 500 dbar (Reid 1989) and shows two opposing gyres within the South Atlantic which have a confluence in the region of the Lüderitz upwelling cell (Mercier et al. 2003).

In vertical sections across the shelf the high salinity water appears constrained to the shelf edge, consistent with a poleward undercurrent of Angola Basin origin. In the region of the Lüderitz upwelling centre, consistent with Monteiro (1996), the southward moving water in the poleward undercurrent appears directed off-shore at about the same level as a local oxygen minimum in the central water of the Cape Basin gyre. Discontinuity in water masses between this latitude and the Orange River Mouth suggests that the Lüderitz upwelling cell at 26°40’S diverts the southward movement of high salinity central water in the poleward undercurrent.

As an indication of the extent of the exchange between the two kinds of central water, the proportion of the HSCW within the water column was determined as a fraction of the central water as defined above. The distribution of this proportion shows the exchange between the two extremes of the system occurring between Lüderitz and Cape Frio. As the vertical sections of water mass show, the water masses remain separable showing little mixing. It is only the extent of the denser high salinity portion that becomes less as the Lüderitz cell is approached.

NUMERICAL OCEAN MODELLING IN THE BCLME

The numerical modelling of the oceanic properties is a central aspect for oceanic forecasting in the BCLME. During the last 25 years, several models have been applied to the Benguela Current System. While a number of these models concentrate uniquely on a limited portion of the ocean around southern Africa, others include ocean basins such as the South Atlantic or the Indian Ocean. With the tremendous increase in power of the supercomputers, Ocean General Circulation Models (OGCMs) might now be able to possess sufficient resolution to resolve the major processes in the Benguela.

Coastal models

Van Foreest and Brundrit (1982) designed the first model for the South African west coast. The originality of their approach lay in the decomposition of the equations of motion into two vertical modes. The model domain extended from 70 km south of Cape Peninsula to North of St Helena Bay and to more than 150 km offshore. Open boundaries were applied at the connection with the open ocean. Although the model was forced with a constant wind and the duration of the simulation was brief (3 days), the solution showed some interesting spatial variability.

The ocean modelling group at the CSIR is currently developing a high resolution model for the circulation in St Helena Bay (Monteiro and Kemp, personal communication). They use the Delft3D-FLOW ocean model with a variable grid resolution that ranges from a few kilometres offshore, to a few hundreds meters close to the coastline. The vertical grid is decomposed into 8 sigma layers and the model is forced by real time winds calibrated by a coastal weather station. This model is expected to resolve the coastal poleward flow during upwelling relaxations.

To understand the retention of fish larvae in St Helena Bay, an idealized barotropic model (Penven et al. 2000) was designed and implemented during the VIBES-IDYLE project. The shallow water equations were solved on a 5 km resolution grid in a periodic channel forced by a constant alongshore wind. In the lee of Cape Columbine, the model produced a cyclonic recirculation that is able to retain biological elements. To extend the analysis to the different oceanic processes which might affect pelagic fish recruitment along the South Africa West Coast, a 3D regional configuration based on the Regional Ocean Modelling System (ROMS) has been implemented by Penven et al. (2001a). The model grid followed the coastline from Cape St Francis, 100 km west of Port Elizabeth to Luderitz (see Fig. 1-1 in Chapter 1). The horizontal resolution ranges from 9 km at the coast to 18 km offshore. On the vertical, 20 sigma levels are stretched to keep a sufficient resolution close to the surface. The information at the open boundaries is provided by a basin scale model, and the atmospheric forcing was derived from the comprehensive ocean and atmosphere dataset (COADS) climatology. Using this model configuration, Blanke et al. (2002) quantified the wind contribution to inter-annual SST variability. They found that while the west coast is affected by mesoscale activity, the wind appears to be the dominant driving for the variability over the Agulhas Bank. By coupling the physical model to an individual based model, Parada et al. (2003) quantified the influence of eggs floatability on the transport from the Agulhas Bank to St Helena Bay, while Mullon et al. (2002) tested the "obstinate nature" hypothesis for the selection of the spawning zone, and Hugget et al. (2003) examined the influence of different environmental factors on the transport of fish eggs and larvae in the Southern Benguela.

Larger scale models

At a regional scale, Skogen (1999) adapted NORWECOM, a model based on the Princeton Ocean Model, to simulate the ocean around the whole south-western southern Africa (i.e. including the coasts of Angola, Namibia and South Africa). The resolution was 20 km, and the model was forced by the National Centre for Environmental Prediction (NCEP) winds, with a surface nudging of SST and no surface salinity flux. Below 500 m, a relaxation towards Levitus climatology prevented the solution from drifting numerically. The physical model has been coupled to a biogeochemical model and to an Individual Based Model to simulate the fate of sardine larvae in the Northern Benguela (Stenevik et al. 2003).

Speich et al. (2004) have especially designed a model to explore the Agulhas Retroflection, and its influence on the BCLME. They used ROMS at 1/6° and 1/10° degree resolution, with 32 vertical levels, forced by a monthly wind climatology derived from QuickSCAT scatterometer data and OGCM data for the open boundaries. Their simulations show the sensitivity of the Agulhas Current to the bottom slope steepness and its variations.

Basin scale and global models

Barnier et al. (1998) performed one of the first basin scale experiments using a sigma coordinate model. They applied SPEM for the Southern Atlantic at 1.375° resolution. The model had 20 vertical sigma levels and was forced by the Hellerman and Rosenstein wind stress climatology. Although very coarse, this model was able to capture some of the large scale features in the Benguela region.

Biastoch and Krauß (1999) took advantage of the curvilinear coordinate in MOM2 to design a model at coarse resolution over the South Atlantic and the South Indian Oceans, but with an increase of resolution in the South African waters (1/3°). The model was forced by ECMWF winds and used data from an OGCM for its lateral boundary conditions. From this simulation, Reason et al. (2003) derived a heat export into the Southern Atlantic at 20°E of 1 PW in winter and 0.7 PW in summer.

The behaviour of the Agulhas retroflection has been extensively studied in the Fine Resolution Antarctic Model (FRAM) simulation (Lutjeharms and Webb, 1995). FRAM is based on the Bryan-Cox-Semtner ocean model, it encompasses the totality of the Southern Ocean from 24° S to the Antarctic at a resolution of 1/2° in longitude and 1/4° in latitude (i. e. approximately 27 km around 60°S). FRAM appeared to be able to reproduce several observed patterns of the Agulhas retroflection, but displayed too much regularity in the subsequent path of the Agulhas Rings into the Atlantic Ocean, compared with observations.

For the same period, simulation experiments of the basin scale circulation were also conducted by Florenchie and Veron (1998) with an eddy-resolving 1/6° quasi-geostrophic model. By means of a nudging data assimilation procedure along satellite tracks, Topex/Poseidon and ERS1 altimeter measurements were introduced in the model to control the simulation. The assimilation procedure enabled to produce schematic diagrams of the circulation in which patterns ranging from basin-scale currents to mesoscale eddies were portrayed in a realistic way.

Treguier et al. (2003) have analyzed the generation and the fate of cyclonic and anticyclonic eddies from the Agulhas retroflection in an eddy resolving simulation of the whole Atlantic Ocean (CLIPPER). The model employed is OPA, at 1/6° resolution, with 42 z-levels, and forced by ECMWF ERA15 data from 1979-1993.
OGCMs now start to have sufficient resolution to be relevant for the Benguela region. The United States National Research Laboratory (NRL) Layered Ocean Model (NLOM) and the NRL Coastal Ocean Model (NCOM) are presently running globally in real-time at respectively 1/16° and 1/8° resolution (Rhodes et al. 2002). In Japan, the enormous computational power of the "earth simulator" made it possible to run a global simulation at a resolution of 1/10° (Masumoto 2004). The respective role for the transport of heat and salt of cyclonic and anticyclonic eddies that are generated in the Agulhas region has been quantified in a global simulation based on POCM (Parallel Ocean Circulation Model) at 1/4° resolution (Matano and Beier 2003).

SCHEMATIC CIRCULATION DEDUCED FROM A NUMERICAL MODEL

There is a dearth of observations in the northern BCLME. Therefore one of the BCLME projects has examined the output from a numerical ocean model such as ROMS (e.g. Fig 4-4) and CLIPPER. These model outputs could then be used as a cost effective method to test various hypotheses, and to guide the observational programme of monitoring the environment in this region of the BCLME.

The CLIPPER numerical simulation model

The most recent CLIPPER experiment is a simulation of the global Atlantic oceanic circulation (http://www.ifremer.fr/lpo/clipper/present.html) based on the OPA model (http://www.lodyc.jussieu.fr/opa/). From 1990-1992 (the period of the spin up), the model is forced by a windstress climatology based on the European Earth Resources Satellite (ERS) derived wind fields. For the period 1993-2000, the model is forced directly by the more realistic varying direct ERS wind field products. The European Centre for Medium Range Weather Forecasting (ECMWF) heat and freshwater fluxes are used in combination with the Reynolds sea surface temperature (SST) for the heat feedback term for the period 1990-2000. The model domain covers most of the

Atlantic Ocean and extends from 60°S-60°N. The model output has been examined to determine aspects of the seasonal circulation from 0-30°S.

Surface layers (0 to 30m)

The modelled shelf circulation appears to be dominated by a narrow coastal current flowing northward all year long from about 30°S to the ABFZ near 18°S. Its intensity is higher during austral summer (January-March) and lower in winter (June to August). The coastal area between 26-22°S is somewhat different: the northward flow is less intense and it exhibits a weaker seasonal cycle. In fact there is an abrupt change in the current field immediately north of Lüderitz (28°S). From 30-26°S, the maximum velocity in the core of the current remains constant, with a value of about 25 cm s^{-1} in summer. At 26°S, the current speed maximum decreases abruptly to values of about 15 cm s^{-1} and the current intensity fluctuates as far southwards as 22°S. North of 22°S, the current speed increases once again. Figure 4-5 is a schematic representation of the model circulation at the surface (Fig. 4-5a – Lev 01) and at a 40m depth (Fig. 4-5b – Lev 04): Figure 4-5a is representative of the perennial modelled coastal circulation. However the northward coastal current (1 and 3 on the figure) is weaker during austral winter.

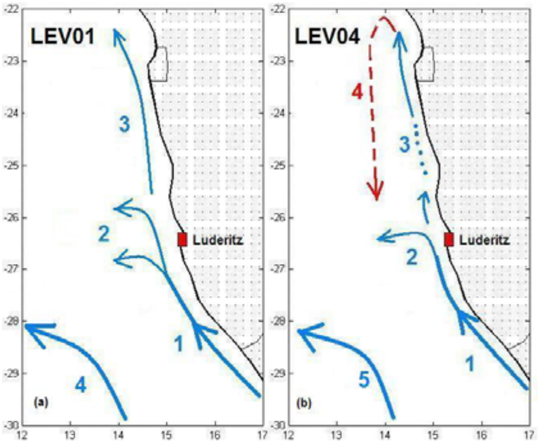

Figure 4-5 Schematic circulation reproduced by the CLIPPER model at the surface (a) and at 40 m (b).

The current is always stronger south of Lüderitz (branch 1). Then it bifurcates partly westward (branches 2) leading to a decrease of its transport and intensity north of 26°S. The orientation of the coast also changes near Lüderitz from northwest to north. Windstress in the area shows a regular northwestward direction all year long and it is stronger in summer south of 26°S. As a result, the surface discontinuity observed in the coastal current at 26°S might originate from the orientation of the coast, the wind field strength and its direction. The westward circulation in (4) does not seem to interact with the coastal circulation pattern.

Circulation at 40m depth (lev04)

The model circulation at 40m is globally identical to the surface, although weaker (Figure 4-5b). The maximum current speed in branch 1 is about 20 cm s^{-1} in summer. The northward coastal current experiences a similar seasonal cycle with minimum intensity during austral winter. The discontinuity at 26°S is still present. The dotted line of branch 3 means that the current is not always clearly defined. The main change in Figure 4-5b concerns a new seasonal pattern in the circulation that occurs twice a year in February-March and October: a poleward current centred at 14°E develops off shore in the north and reaches a latitude of about 25-26°S at its maximum in October (branch 4). The dotted arrow indicates that the current is not permanent throughout the year. Its temperature is about 4°C higher than the coastal current with slightly higher salinity levels. It does not seem to interact much with the northward current.

Circulation at 80m and 130m depths (lev07 and lev10)

Figure 4-6 represents diagrams based on the model circulation at 80m and 130m depths for the same area. Dotted arrows indicate that the current is intermittent and shows some seasonal variability.

It is at this model level in which the main major differences occur when a comparison is made with the surface layers. The northward coastal current is much weaker with maximum speeds of about 10 cm s^{-1} and it is not as clearly identifiable. It still shows a seasonal cycle but its intensity is higher in July and August, instead of summer. Branches feeding the current south of Lüderitz (1) are unstable and not well defined. Despite this, the northward current still reaches its maximum intensity in the Lüderitz area. The southward current (branch 4) intensifies in comparison with upper levels and is now noticeable from September-April. It exhibits two maxima: one in October and another in March, respectively. On these occasions the current meets the westward branch (2) of the coastal current near 26°S. It is more saline than the surrounding water and its temperature is about 2°C higher than the coastal water temperature. The circulation at model levels 08 through 10 (Figure 4-6b) reproduces the circulation patterns encountered at levels 04 and 07 with a marked seasonal shift. The cycle divides the whole area in two separate domains; September-March, the circulation is dominated by a southward flow north of Lüderitz (current 3). This flow develops along the coast as well and the northward current (branch 2) disappears. The southernmost extent of this flow occurs in February (26°S) and in October (27.5°S) with maximum speeds of about 10 cm s^{-1}. From April to August, the situation is somewhat reversed. There is no more poleward flow. The cold northward current intensifies in the south (branch 1) with speeds of about 5 cm s^{-1}. It reaches the Lüderitz area and its intensity north of 26°S remains very weak.

At this depth, the Lüderitz area displays a natural border between two opposing seasonal regimes, a northern one associated with warmer and more saline waters flowing southward from October-March, a southern one concerning cold and fresher

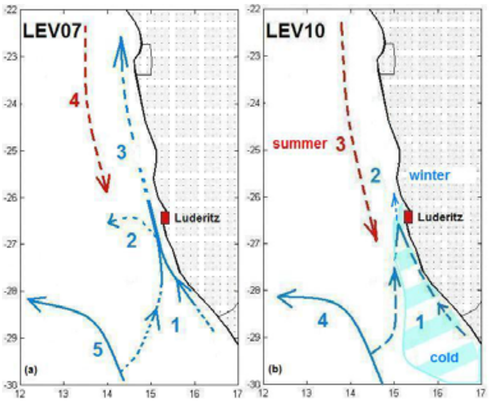

Figure 4-6. Schematic circulation reproduced by the CLIPPER model at 80m (a) and at 130 m (b) depths.

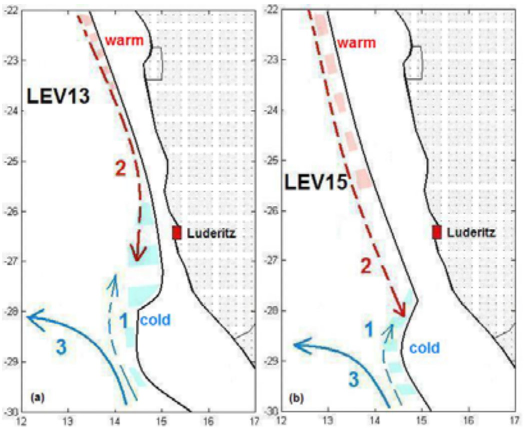

Figure 4-7. Schematic circulation reproduced by the CLIPPER model at 230m (a) and at 350 m (b) depths.

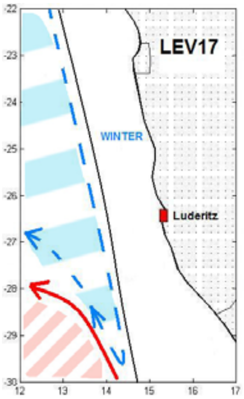

Figure 4-8. Schematic circulation reproduced by the CLIPPER model at 575m depth.

waters flowing northward from April/May-August. The cold pool shown on Figure 4-6b underlines the fact that along the coast the Lüderitz area constitutes a transition between the warm and the cold regimes. Temperature in the cold pool is about 10-11°C whereas it is about 13°C north of 26°S. The cold pool appears to be a permanent feature with quite regular shape and size all year long.

Circulation at 230m and 350m depths (lev13 and lev15)

At deeper model levels, the circulation along the shelf is poleward almost all year long with maxima occurring in February and October. Speeds are of the order of a few centimetres per second. The two diagrams (Fig. 4-7) illustrate the model circulation at 230m and 350m depths. The poleward current brings warmer waters south of the Luderitz area until 28°S where it reaches the cold pool. At this depth this permanent feature is less developed and its temperature is about 2°C lower than the poleward flow temperature. The northward current along the shelf (branch 1) develops in winter with very low speeds. Once again the current represented by the branch 3 does not seem to interact with it.

Circulation at 570m depth (lev17)

The circulation is dominated by the permanent northwestward flow associated with relatively warmer water masses (Fig. 4-8, red arrow). Along the coast, a poleward coastal current develops from July to September during the winter period. Its maximum southward extent occurs in August. It meets the northward dominant flow near 30 and retroflects northward. In terms of temperature the whole area can be divided in two persistent parts; north of the warm current (red arrow) the water is about 1.5°C colder compared to the south (respectively 5.5°C and 7°C). The temperature variability throughout the year is small.

DISCUSSION AND CONCLUSIONS

Processes with forecasting potential (see also Monteiro and Van Der Plas , this Volume – Chapter 5)

Good progress has been made recently in the study of the Benguela Current Large Marine Ecosystem, as evidenced by the reviews in part two of this volume. In particular, considerable effort has been invested in trying to understand the mechanisms underlying the formation and evolution Benguela Niños (Florenchie et al. 2003; Florenchie et al. 2004). From our present understanding, by using appropriate observing systems in the equatorial region, it may be possible to get a forecast lead time of about two months for major warm events arriving at, and progressing polewards beyond the Angola Benguela Frontal zone.

It is expected that aspects of the large scale variability of the BCLME are likely to be amenable to near real time observation and/or short term forecast. The most likely processes that have been identified to have potential in an early warning/forecasting system in the BCLME are set out in Table 1. The table is divided into an area

(Domain), the most important forcing component, the main type of forcing process responsible for the variability, the approximate time scale of variability, the potential for being able to observe the phenomenon in near real time, and the subjective forecast/early warning potential with present limited capacity and resources. A three point scale: poor, fair and good is used. The scheme notes that anomalous signals propagate both from the equatorial Atlantic Ocean and into the northern BCLME, and from the Agulhas Current in the Indian Ocean, into the southern BCLME. The discussion starts with the remote wind forcing in the western equatorial Atlantic Ocean, and its likely effects on the northern part of the BCLME (Angola and Namibia), via warm and cool anomalous signals propagating southwards along the Angolan coast. Severe warm SST anomalies at or south of the ABFZ are classed as Benguela Niños, the last well documented one occurring in 1995 (e.g. Florenchie et al. 2003). The main variability influence on the southern BCLME is from Agulhas Current ring shedding, early retroflection and intrusions of subantarctic cold water. The most difficult processes to forecast are the local influences on the upwelling centres at relatively short time scales of days-months. It is vital for the sustainable management of the BCLME, that extreme events (e.g. Roy et al. 2001) are recognised and understood, and if possible, forecast with a reasonable lead time. A regular state of the environment (SOE) reporting system, together with better communication for the BCLME would improve BCLME management advice.

NUMERICAL MODELLING OF THE PHYSICAL PROCESSES IN THE BCLME

In the past five years, there has been a sharp increase in the hydrodynamic modelling of the southern Benguela Upwelling ecosystem by implementing the 3-D ROMS numerical code and using seasonal wind forcing, (Penven et al. 2001a; Penven et al., 2001b) and then by refining the wind forcing with realistic winds from ERS (Blanke et al. 2002). The influence of the Agulhas Current shear edge instabilities on the southern border of the BCLME has been partially addressed (Lutjeharms et al. 2003). A ten-year model run with a time resolution of two days, and variable horizontal grid spacing from 9-18 km has provided the community with output for use of a number of individual based model (IBM) configurations (Field and Shillington 2005).

With the advent of the BCLME, a dedicated group is presently modelling both the large scale influences on the BCLME, and using a nested approach to gain a better understanding of the local variability. Good synergy is maintained between the BCLME project and the IRD Upwelling Ecosystems project which is undertaking a comparative study of the Benguela, Canary and Humboldt Upwelling Systems.

Project: SAfE (Southern Africa Experiment)

Around the Southern African coasts, several different questions can be posed to the numerical ocean modeller. For example, how do the Benguela Niños propagate into the BCLME? Or, what is the role of Mozambique channel eddies in the shedding of

Agulhas rings into the Atlantic Ocean, and their subsequent interaction with the BCLME? Or, why is there a cool ridge on the Agulhas Bank? To address each of these questions, the modeller needs a high degree of spatial resolution in the model

Table 1. Processes that are likely to have a cost effective observational capacity (satellite remote sensing or large scale in situ measurements). The forecasting potential is judged on a subjective scale of poor, fair and good. The forecasting potential of the large scale BCLME variability depends mainly on how well the linkages and processes that transfer the equatorial signals, and those from the Agulhas Retroflection, to the Benguela are understood.

Domain	Forcing System	Processes	Scales of variability	Observing Potential	Forecast potential
Remote	Eastern Tropical South Atlantic	Equatorial upwelling	Seasonal - interannual	Good: Altimetry, Ocean Colour	Good
		Intensity and timing of trade winds	Seasonal - Interannual	Quikscat, PIRATA, GCM	Good
		Equatorial stratification	Interannual – decadal (Benguela Niño)	Good: Ocean Buoys	Fair
		Angola Current	Seasonal - interannual	Fair: Altimetry and AVHRR	Poor
		Angola-Benguela Frontal Zone	Twice annual	Good: SST, colour	Good
Remote	Agulhas Retroflection	Ring shedding	Episodic: few times per annum	Good: Altimetry, SST	Good
Local	Upwelling centres	Benguela Poleward transport	Seasonal - Interannual	Fair: Ocean Buoy	Fair
		Upwelling wind variability	Days - weeks	Good: wind forecasts	Fair
		Relaxation events in the southern Benguela	Days - weeks	Good: SST, colour	Fair

region of interest, as well as a correct representation of the large scale ocean dynamics. To do this, a modelling platform under the auspices of the BCLME has been set up for the simulation of the ocean around Southern Africa (SAfE: Southern Africa Experiment). The model is based on ROMS and takes advantage of its nesting capabilities. The parent grid includes the ocean around Southern Africa at a reasonable resolution (i.e. ~20-25 km). Several levels of child grids can be embedded into the parent grid, to reach locally a resolution of a few kilometers to a few hundred meters (see for example the grid set up for the ABFZ in Fig. 4-4). The Parent model is inexpensive to run: 30 hours of computing for 1 year of simulation on a PC workstation. Hence, it is possible to rapidly test new configurations and developments. Once the parent solution is satisfactory in its representation of the large scale solution, the presently one way nested high resolution "child" model configurations are added to provide the fine scale information. These simulations will be coupled to biogeochemical models (Monteiro 2005, pers. com) in one of the BCLME projects.

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