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14

Forecasting Shelf Processes of Relevance to Living Marine Resources in the BCLME

C.D. van der Lingen, P. Fréon, L. Hutchings, C. Roy, G.W. Bailey, C. Bartholomae, A.C. Cockcroft, J.G. Field, K.R. Peard and A.K. van der Plas

ABSTRACT

This chapter focuses on describing, discussing and evaluating the feasibility of forecasting selected shelf processes considered to be of relevance in terms of their impacts on commercially important living marine resources of the BCLME. The impact of shelf processes is examined with regard to both the availability of resources to fishing and their abundance. Three shelf processes, namely low oxygen water events, mesoscale processes, and boundary processes, are examined separately and in detail. For each of these processes, the resource impacted and its response, the type of forecast considered appropriate and feasible, the requirements for making such forecasts, and case studies illustrating examples of forecasting systems already in place, are provided. Other processes that may have significant impacts on living marine resources are briefly discussed. The technology for forecasting low oxygen water events is available and therefore the feasibility of making such predictions is good, although at present there are insufficient moored instruments dedicated to inshore oxygen monitoring in relevant areas, either in the northern or southern Benguela regions. Indices of mesoscale processes have been used in attempts to forecast anchovy recruitment variability in the southern Benguela, and indices of boundary processes to hindcast hake recruitment variability in the northern Benguela. For southern Benguela anchovy, the wealth of studies relating environmental variability to recruitment variability and the insights gained from simulating the incorporation of predictive models into management procedures for this stock, should allow the development of recruitment prediction models that can feasibly be incorporated into management procedures. However, the incorporation of environmentally-based recruitment or stock size prediction models into management procedures should take account of assumptions and uncertainties associated with such models, and their potential for utility to management should be tested through simulation.

INTRODUCTION

Living marine resources of the Benguela Current Large Marine Ecosystem (BCLME) exhibit seasonal, interannual and decadal-scale variability in their abundance,

Boundary processes (southward movement of the AB Front; Benguela Niños; permeability of the Lüderitz upwelling cell; Agenbag and Shannon 1988; Shannon and Nelson 1996; Florenchie et al. 2004)	NB + SB	Pelagic and demersal species, seasonal and interannual effect	1. AB Front and Benguela Niños - shifts in distribution, reduced reproductive effects, mortality due to high temperature (Luyeye 1995; Binet 2001; Boyer and Hampton 2001)
			2. Permeability of the LUC– colonisation of the NB by SB stocks (Hewitson 1988)
			3. Behaviour of the Agulhas Current– increased mixing/reduced stabilization linked to reduced quality in food environment for pelagic fish and consequent reproductive output; "predation" of eggs and larvae by Agulhas rings (Duncombe Rae et al. 1992; Hutchings et al. 2002a;)

The development of low oxygen waters in the BCLME has been described by Hart and Currie (1960), Stander (1964), De Decker (1970), Andrews and Hutchings (1980), and Bailey et al. (1985), and the larger scale development of the oxygen minimum zone in the tropical SE Atlantic by Moroshkin et al. (1970) and Bubnov (1972). Chapman and Shannon's (1985) review on the chemistry of the Benguela system summarised current thinking at that time concerning low oxygen water, which was that there was both a large-scale, remotely-sourced origin and more localized sources of hypoxia in the Benguela system. The relative magnitudes of these vary in both time and space, as has been advanced by Bailey (1991), Monteiro and van der Plas (Chapter 5, *this volume*) and Monteiro et al. (Chapter 13, *this volume*). The schematic produced by Chapman and Shannon (1985; see Figure 14-1) conveys the following ideas:

- Local production in the Angola Basin and the semi-closed, clockwise, gyral circulation formed by the Angola current, the offshore Benguela current and the equatorial counter current, govern the formation and persistence of the basin-wide oxygen minimum zone to the north of the Angola-Benguela Front.
- A combination of remotely derived hypoxic water originating in the Angola Basin that flows southwards onto the Namibian shelf, and locally formed low oxygen water, is responsible for the frequent low oxygen events occurring in the northern Benguela region, with occasional decadal-scale more extreme anoxic events, such as in 1994.

Low oxygen waters on the inner shelf of the southern Benguela region are mostly formed locally as a result of decay of planktonic detritus arising from the high levels of productivity. Using a sequence of five time-series oxygen sections constructed for 100m positions off Walvis Bay, Lüderitz, the Orange River Mouth, Roodewal Bay and Cape Columbine, Bailey (1991) demonstrated that there is a progressive southward
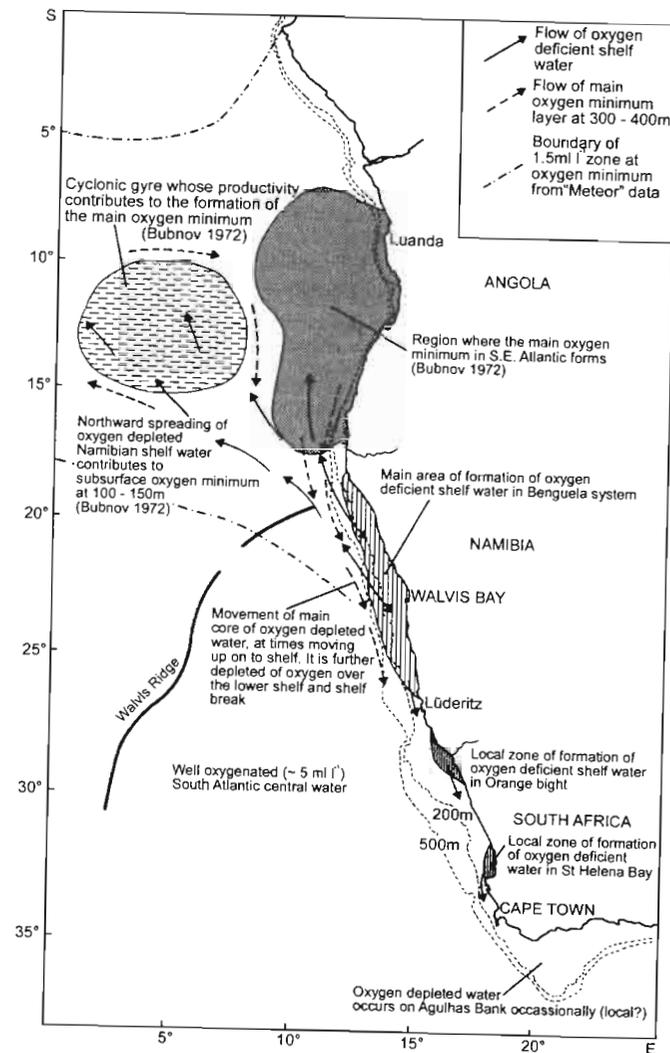

Figure 14-1. Conceptual model showing areas of low oxygen water formation in the BCLME and South East Atlantic (from Chapman and Shannon 1985).

increase in the seasonal development of hypoxia in the water column on the Benguela shelf. In the north, off Walvis Bay, the sub-thermocline is perennially hypoxic whereas off Cape Columbine there is a definite maximum in the extent and severity of hypoxia in late summer and a minimum in winter, when winter mixing and reduced surface primary production are thought to play a role in ventilating the shelf waters. At the time of publication of Bailey's (1991) paper, it was suggested that the

permanence of the bottom hypoxia off Walvis Bay might be a reflection of the southward advection of low oxygen bottom waters derived from the Angola current. Recent findings have suggested the chemical oxygen demand exerted by reduced compounds such as hydrogen sulphide, which is abundant in this area, may also play a role (Emeis et al. 2004).

Periodic low-oxygen induced mortality of fish in the Walvis Bay region was reported by Copenhagen (1953), who described an almost annual mortality of fish that took take place between December and March in the "Walvis region" off central Namibia. He noted the permanent lack of dissolved oxygen in the bottom layers of the water column, but cautioned that under certain conditions, hydrogen sulphide and dinoflagellates belonging to the genus *Gymnodinium,* both of which can be toxic to fish, were also present. Severely oxygen-depleted bottom waters that occurred inshore on the northern Benguela shelf in 1994 displaced juvenile Cape hake *Merluccius capensis* offshore, apparently increasing mortality caused by cannibalism and the discarding of juveniles caught during trawling (Hamakuaya et al. 1998). This mortality was estimated at 70% (Hamakuaya et al. 1998) which would have substantially reduced recruitment, although a published time-series suggests that hake recruitment was in fact above average in 1992-1994 (Voges et al. 2002). However, the abundance of *M. capensis* off Namibia estimated from demersal surveys shows a decrease in biomass over that period (Burmeister 2001), providing support for the contention of reduced recruitment by Hamakuaya et al. (1998).

The impacts of low oxygen water events on rock lobster populations are felt along the whole Namibian coast, and along the South African west coast from the Orange River to approximately St Helena Bay. In the northern Benguela the areas most severely impacted are located from north of Lüderitz to Easter Cliffs (although there is insufficient information concerning reefs between Lüderitz and the Orange River), and mortalities have been recorded between Walvis Bay and the Ugab River. The impact of low oxygen water events on rock lobster in Namibia is largely restricted to the recreational fishery, due to the location of events causing mortalities.

Whereas low oxygen water is a permanent feature in the northern Benguela it is event-driven in the southern Benguela, where low oxygen water events impact in "nodes" along the area between Port Nolloth to St Helena Bay, particularly around Elands Bay (see Figure 14-2). Low oxygen events result in an onshore migration of rock lobster, leading to stranding and subsequent mortality, or death prior to washing up (which occurs mostly in Namibia). Walkouts range from single strandings on a scale of a day to multiple strandings over a period of a month, the number of stranding events depending on the severity and duration of the low oxygen event. Off South Africa, the short-term impact has highly negative consequences to the local fishery (Cockcroft 2001), and since the response of the resource in the area is directly related to the severity of event, may result in a substantial loss of income to fishing companies and local communities.

The long-term impact of low oxygen water events on local rock lobster populations depends on the severity of the event in the area affected, and whether or not hydrogen

sulphide (H_2S) was produced (Cockcroft 2001). Where no H_2S was produced the impact on the benthos is minimal, and recovery of lobster abundance is relatively rapid since re-colonisation occurred within four to 12 months, leading to a relatively minor direct impact on the lobster fishery in the area although growth rates may have been affected. Low oxygen water events during which H_2S was produced do have a major impact on the benthic community, and the recovery in lobster abundance takes around one to three years as re-colonisation is slower. However, the full impact of low oxygen water events may take even longer to transmit through the lobster population as a whole; because the bulk of stranded lobster are undersize females (based on South African data; Cockcroft 2001), the effects on egg production, recruitment and fishable biomass might be delayed by five to seven years.

In addition to causing walkouts, low oxygen water events also exert sublethal effects that affect a variety of lobster life stages. Reductions in growth rates, egg production, and larval quality have been reported (see references in Cockcroft 2001) with most information available on growth rates of adults, size at sexual maturity and egg production. These sub-lethal effects are observed in all Namibian commercial fishing grounds and the recreational fishery in northern Namibia, and off the west coast of South Africa are most evident in the northern area between Port Nolloth and Hondeklip Bay.
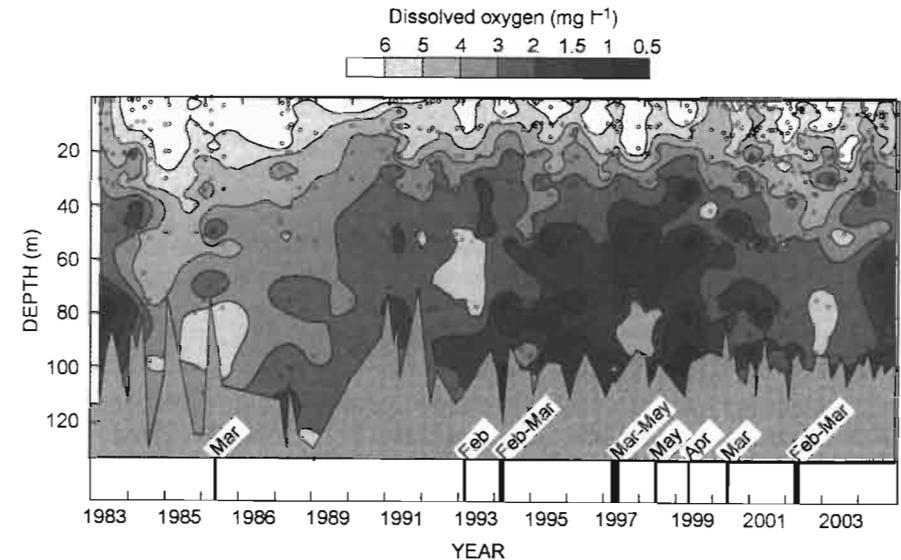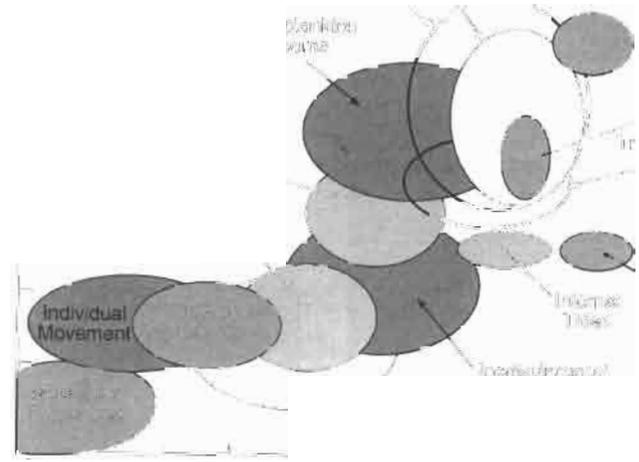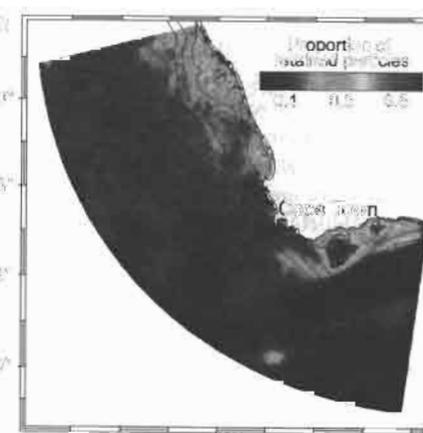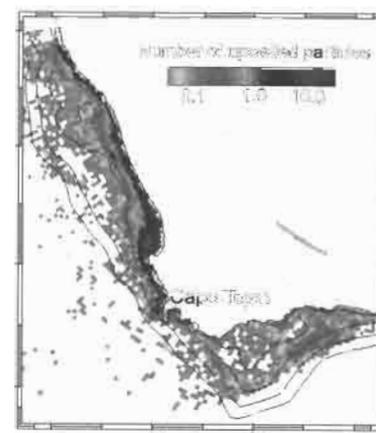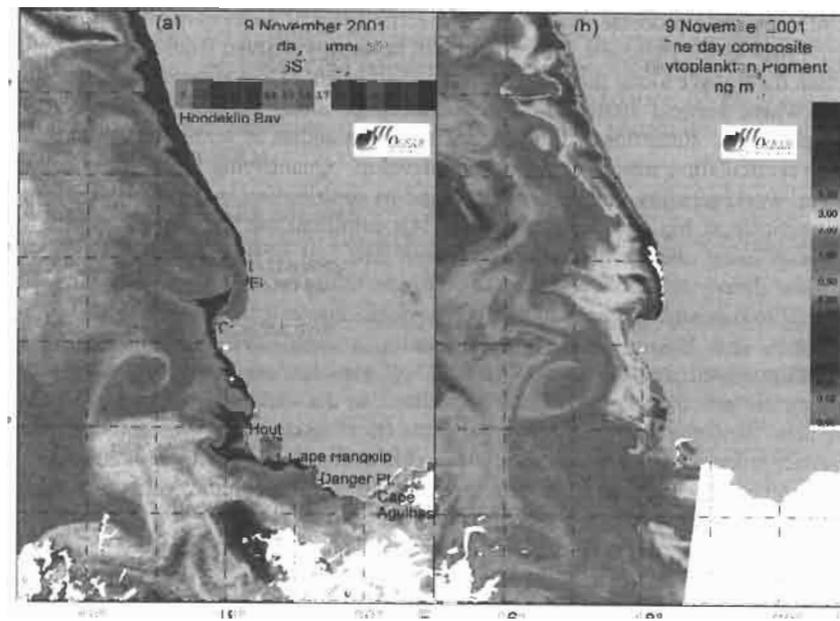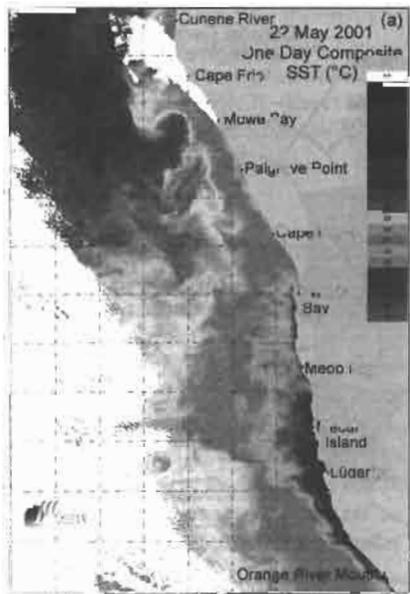

Figure 14-2. Time-series of variation in dissolved oxygen levels with depth at a station in St Helena Bay from March 1983 to December 2004. Sampling dates and depths are indicated by the small circles overlaid on the contour plot, and periods of rock lobster *Jasus lalandii* walkouts are indicated by the vertical bars at the bottom of the figure.

There are many reasons for this, including difficulties in sampling both the relevant physical processes and organisms such as larvae and juveniles at the right scale, as well as the cost of ensuring long term monitoring. Another difficulty is that variation in populations results not from a single process but from an integrated set of processes affecting individuals at different time and space scales, depending on their development stages. In a given system, the existence of major bottlenecks should limit the number of processes requiring investigation, and identifying those bottlenecks is a necessary step before the setting-up of monitoring and forecasting systems. Hutchings (1992) identified a set of potential environmental contributors to the variability of fish recruitment that provides a good basis to elaborate forecasting capabilities in the southern Benguela region.

Presently, biological individual based models (IBMs) coupled to hydrodynamic models are being used to explore and better understand the processes (including mesoscale processes) responsible for recruitment fluctuations (e.g. Huggett et al. 2003; Mullon et al. 2003; Parada et al. 2003; Skogen et al. 2003; Miller et al. in press). Results from these IBMs have matched current knowledge based on field observations, providing confidence that inferences made from these IBMs are meaningful. Such experimental simulations are likely to improve our understanding of the key processes responsible for anchovy recruitment success in relation to their spawning strategy, a major step in predicting fluctuations in stock size, and may be used in the near future to hindcast recruitment. Additionally, these IBM simulations may be used to test a variety of what-if scenarios, including examining the likely impacts of climate change on recruitment variability.

Additional data and analysis of these and historical data are required, and particular attention should be paid to the three dimensional validation of hydrodynamic and productivity models. This could be achieved through moored ADCP arrays and by continuous vertical profilers (such as the YOYO-ANAIS; Provost et al. 1998; Thouron et al. 2003) in addition to ongoing monitoring lines for measuring physical and plankton parameters. In order to test the hypothesis of food limitation for fish larvae, the determination of the RNA/DNA ratio as a proxy for starvation (e.g. Clemmesen et al. 1997) would be useful. Furthermore, core sediments in anoxic areas would provide an idea of natural, multi-decadal variation of fish abundance in the absence of exploitation, as has been done for small pelagic fish populations in the northern Benguela (Baumgartner et al. 2004) and elsewhere (e.g. Baumgartner et al. 1996). To be pertinent the sampling design should cover, as far as possible, a substantial part of the fish habitat (see basin theory of MacCall 1990).

Requirements differ for now-casting or hindcasting compared to forecasting or what-if scenario predictions. In the former, historical and near-real-time data on wind and surface fluxes within the domain of the hydrodynamic model, and water current and Nutrient/Phytoplankton/Zooplankton/Detritus (NPZD) data at the boundaries of the domain are required. In the latter, forecasts at an adequate resolution of the forcing factors within the model domain and at its boundaries are needed, in addition to the existing monitoring lines of physical and plankton parameters plus possibly a few additional ones. An important need that is not presently satisfied is the analysis of

plankton data collected on monitoring lines. Because current techniques of collection and analysis of plankton are time consuming, it is suggested that modern techniques such as automated identification and size measurement of plankton from scanned images of samples coupled to image recognition and *in situ* Optical Particle Counter (OPC) and multi-frequency acoustic identification of organisms, are adopted.

Data collection and analysis (especially of historical records) should prioritize and focus on key biological stages and key spatio-temporal data such as spawning and transport areas. A general comment is that the value of data from monitoring systems is incremental in time. Additionally, the need for correcting the imbalance in monitoring and modelling capabilities was identified in the Benguela region, as well as the need for improving communication and coordination in environment monitoring systems.

There is a need to move from empirical-based predictions that often prove to fail sooner or later (see Myers 1998) to process-based predictions that should be more robust, although one cannot exclude changes in the key processes related to changes in the state of the ecosystem. Coupled hydrodynamic and individual based models will be particularly useful to understand these key processes, once identified, and allow for sensitivity analysis of the impact of the environment on living marine resources, such as the effect of changes in wind pattern or on the flow of the Agulhas Current. Presently, models must be seen as exploratory tools rather than predictive tools, because of the need of validation in three dimensions. Using such models to predict resource responses to environmental forcing should follow a two-phase approach; the first being in the short-term and comprising a 3-5-year learning period during which tentative predictions are made, and the second phase being the implementation of forecasting in management procedures over the mid-term (5-10 years). In the case of short-lived species such as pelagic fish, shrimps and squids, the expected major economic benefits of successful predictions concerning the impacts of mesoscale processes on such resources would be the prevention of stock collapse that would in turn lead to fishery collapse, with obvious economic and employment problems.

BOUNDARY PROCESSES

A number of boundaries exist within the BCLME, some of which are well defined and prominent, such as the Angola-Benguela Front, the Lüderitz upwelling cell or the Agulhas Current, while a number of the offshore frontal boundaries are highly variable and range from diffuse to very distinctive on short-term and seasonal time scales. Most of the major boundary features described below are shown in Figure 1-1 of this volume (Chapter 1), and the following text provides a brief description of these boundaries and their ecological roles, progressing from the north to the south.

Angola-Equatorial Front/Congo River mouth

This is a very seasonal front about which little is known, and much more data are needed to properly evaluate the nature of the boundary separating the subtropical Angolan coastal waters from the truly tropical Gulf of Guinea ecosystem. The Angola-Equatorial Front is characterised by a sharp discontinuity in salinity and is heavily influenced by the Congo River outflow. It is also the zone where equatorial counter-currents impinge on the coast and where Kelvin waves and coastally trapped waves are first detected close to the coast. This region is the centre of oil production in Angola, and operations are currently expanding into deeper water to the south.

BOUNDARY PROCESSES case study:
Predicting recruitment of hake Merluccius capensis off Namibia from environmental indices.

Recent research has used multinomial logistic regression analysis to calculate the probability of strong, average or weak recruitment of Cape hake off Namibia (Voges et al. 2002), and to identify environmental conditions that may be related to recruitment strength and could possibly explain some of the interannual variability in recruitment strength observed for this species. The model includes environmental indices (satellite-derived SST data) that describe the extent of warm water intrusion (southerly penetration of the Angola Current arising from a southward movement of the Angola-Benguela Front) as well as upwelling strength over the Namibian shelf, both during the spawning season and in the subsequent two years. The rationale for using these indices is that if warm water is widespread during the September-March spawning season and upwelling during the following May-September is reduced, eggs and early juveniles would be retained in favourable nursery areas which should increase the probability of strong recruitment. Intensified upwelling the following year (i.e. two years after spawning) should provide sufficient food for late juveniles, also increasing the probability of strong recruitment. Hake recruitment strength predicted from this model (as either strong, average or weak) corresponds well with the observed recruitment index derived from biomass surveys, and the model accounts for 79% of the variance in historical recruitment strength. The model correctly predicted strong and average recruitment 50 and 71% of the time, respectively, and weak recruitment 100% of the time. This last record is considered particularly important, since it permits anticipation of the worst-case scenario (i.e. weak recruitment) for the hake stock which could enable an appropriate adjustment of the management policy.

Whilst the feasibility of predicting hake recruitment strength using this model appears promising, it is based on a relatively short (14 years) time series and has only been tested for a limited number of years. For example, predictions of this model have indicated strong probabilities that good recruitment would result from the 2002 and 2003 year-classes. The resultant 2002 cohort was strong as predicted but results of the 2005 hake survey indicated a weak 2003 year-class. However, initial signs from seal scat information also pointed towards an average to above average 2003 year-class, but numbers dwindled as the year (2004) progressed. There is now strong evidence that the demise of the 2003 year-class resulted from cannibalism by the exceptionally strong 2002 cohort during their coexistence in the pelagic zone (2004). Incorporation of such information into this model is planned and should be tested to see if it improves the predictive capabilities of the model. However, without such updates and extensive testing, incorporation of the model in its present state for management procedures should be approached with caution.

There is probably a wealth of information utilised for operational purposes in the oil company databases. Pelagic fish such as *Sardinella* spp. are distributed on each side of the Angolan Front (Baptista 1977) although *Sardinella aurita* tend to avoid the Congo River plume of low-salinity and turbid water, as well as similar water masses from the Bay of Biafra that flow southward during certain years (Guinean Niños). This low tolerance of *S. aurita* to these conditions result in its becoming trapped between the coast and the Congo River plume during Benguela Niños (Binet et al. 2001). In contrast, *S. maderensis* prefers lower salinity waters, and in that respect the Angolan Front and the leakage of a tongue of coastal water from the Bay of Biafra appears to function ecologically as conduits, rather than as barriers, to this species and for some other organisms.

Angola-Benguela Frontal region

The Angola-Benguela Front represents the major boundary that separates the upwelling-dominated northern Benguela from the subtropical waters of Angola. This region is characterised by a sharp density front at the surface, complex mixing, and high variability in the short term. The Front shows regular latitudinal movement of about 2-3° on a seasonal basis, forced by the atmosphere, with a maximum northward movement in late austral winter (August) that coincides with maximum upwelling (Shannon et al. 1987). The Angola-Benguela Front is a convergent front between cool and warm coastal currents, and is associated with strong offshore (zonal) flow that carries coastal water rich in chlorophyll and often containing fish eggs and larvae far offshore into the South Atlantic. Phytoplankton from just south of the Angola-Benguela Front may sink offshore in the Angola Dome region, contributing to the oxygen deficit in subsurface waters there. Despite suitable temperatures, the high offshore losses and low retention restrict the area suitable for spawning to a small area adjacent to the coastline. The Angola-Benguela Front acts as a barrier, rather than a conduit, with major shifts in the dominant species composition of marine communities on either side. The nature of this barrier for deepwater species such as red crab (*Chaceon maritae)* or hakes (*Merluccius capensis/polli*) is uncertain.

Moderate interannual variability in the location of the Angola-Benguela Front is likely driven by local seasonal wind forcing (Shannon et al. 1987), and the extent of southerly penetration by Angola Current water onto the Namibian shelf has been used as an input parameter in a model aimed at predicting hake recruitment from environmental indices (Voges et al. 2002; see *Boundary Processes case study*). This model has potential for incorporation into management procedures since it could reduce by one year the 3-year delay between hake recruitment and its estimate from trawl surveys. An example of how an environmental stock-recruitment relationship could be incorporated into assessment and management procedures of an important demersal species (Pacific cod *Gadus macrocephalus*) has been provided by Sinclair and Crawford (2005).

Marked decadal scale variability is apparent in the location of the Angola-Benguela Front, with the Front moving further south than usual approximately every 10 years.

This results in a major warm-water intrusion penetrating into the northern Benguela upwelling region, with important ecological consequences, particularly for pelagic fish. These so-called Benguela Niños occur over the summer months, and the resultant warm-water anomalies change the community structure of the pelagic assemblage in the northern Benguela. The *Sardinella aurita* stock, which is at the southern limit of its distribution in southern Angolan waters, is driven towards Namibia, and whilst catches of this species off Angola are depressed (Luyeye 1995) significant landings may be made off Namibia (Thomas 1984). Benguela Niños also drive sardine (*Sardinops sagax*) southwards from Angolan to Namibian waters and closer to the main fishing harbour at Walvis Bay, and increases in the Namibian sardine catch were observed during and after the warm events of 1968 and 1973/74 (Hewitson et al. 1989). Shoreward intrusions of warm water that follow Benguela Niños also increase the catchability of horse mackerel (*Trachurus* spp.) on the Angolan shelf (Binet et al. 2001). These changes in distribution patterns indicate that fishery managers need to distinguish between changes in fish availability caused by displacements in water masses and genuine population increases, and should act conservatively in setting catch levels in years of southward intrusions of warm water. Management is further complicated by the fact that Benguela Niños appear to be linked to poor recruitment conditions in the normal nursery grounds off north-central Namibia for many important species, including anchovy, sardine, hake and horse mackerel (Boyer and Hampton 2001), which means that poor recruitment may follow greatly improved CPUE statistics. The northward penetration of cold Benguela water is important for feeding conditions for pelagic and demersal species in southern Angola.

Benguela Niños appear to be remotely forced from events in the west equatorial Atlantic off the Brazil coast (Shannon et al. 1986; see also Shillington et al. Chapter 4, *this volume*; Reason et al. Chapter 10, *this volume*; Brundrit et al. Chapter 16, *this volume*). The southward movement of the Angola-Benguela Front is predictable by about 2 months ahead at this stage (Florenchie et al. 2004), and links to the Pacific may extend these predictions. Information from the PIlot Research moored Array in the Tropical Atlantic (PIRATA) (Servain et al. 1998) on subsurface heat content and thermocline depth is considered a potentially valuable source of data for prediction purposes, as would be sea level recorders along the Angolan coast.

Central Namibian Oceanic boundary

This diffuse boundary zone (Figure 14-7) is up to 400 km wide (in terms of phytoplankton) from 14-22°S, and 150-200 km wide at 22-25°S. Hence productive waters extend well beyond the current domain of important fish stocks that are harvested on or close to the shelf. The Central Namibian Oceanic boundary is a potential refuge for early life history stages of neritic fish stocks, and has a high potential for enhancing their survival and subsequent recruitment, provided that young fish can return to the neritic zone as juveniles. There is a seasonal shoreward
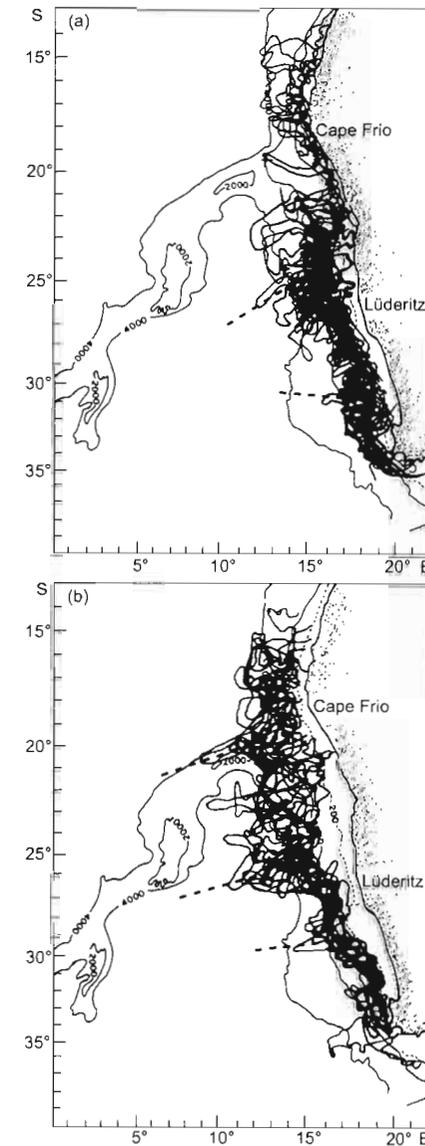

Figure 14-7. Montage of the frontal boundary of the BCLME for summer (December 1983-February 1984; top panel) and winter (June-August 1984; bottom panel) derived from METEOSAT II thermal infrared data and by superimposing the upwelling fronts as observed in each five-day period during the respective three month season. The 200, 1000, 2000 and 4000m depth contours are shown (thin lines) and thick broken lines indicate the main protrusion axes of the upwelling front. From Lutjeharms and Stockton (1987), reproduced with permission.

movement of this boundary region in summer months (C. Bartholomae, MFMR, unpublished data) which is predictable, and occasional shoreward movement that is associated with a lack of winds from the south. Such shoreward movement is relevant in terms of biogeography and life history strategies for population maintenance of euphausiids (Barange et al. 1992), and has also been suggested as driving the availability to fishing of demersal resources including hake (Macpherson et al. 1991).

Subsurface current structures are much less documented than surface features, but are thought to be of major importance in controlling the position and location within the continental shelf of small organisms such as fish eggs or larvae (Sundby et al. 2001; Batchelder et al. 2002). In the northern Benguela, sardine eggs were found to be most abundant within the upper layers and sardine larvae were found deeper (Stenevik et al. 2001). This was explained as a behavioural adaptation to the vertical circulation structure over the shelf: by migrating at a depth deeper than the wind-induced offshore-moving surface layer, sardine larvae make use of the subsurface upwelling-compensatory flow to avoid advective loss and to enhance transport to and retention within the nearshore area (Stenevik et al. 2003).

Lüderitz/Orange River Cone boundary region

The perennial cell of intense upwelling situated off Lüderitz separates the northern and southern Benguela subsystems, and the Lüderitz Upwelling Centre / Orange River Cone (LUCORC) region experiences considerable offshore losses in the surface layers, strong surface mixing and low phytoplankton concentrations. It is considered a barrier to small pelagic fish such as anchovy and sardine, and their eggs and larvae, primarily because of high levels of wind-induced turbulence in the region of Meob Bay (24°30'S; Agenbag and Shannon 1988). This is probably less of a barrier to mesopelagic species such as lanternfish (*Lampanyctodes hectoris*), redeye (*Etrumeus whiteheadi*) or gobies (*Sufflogobius bibarbatus*), all of which are capable of more extensive vertical migration than the small epipelagic fish. The LUCORC boundary is characterised by changes in source water to the shelf region, differing in oxygen, salinity and a few zooplankton species. Subsurface currents that flow southwards in the northern Benguela off central Namibia, flow offshore near Lüderitz and are replaced by more oxygenated Eastern Atlantic Central water from the Cape Basin, which flows southwards. The LUCORC region therefore constitutes a subsurface as well as a surface boundary zone, and may impinge dramatically on the alongshore movement of demersal species such as hake, as well as on pelagic species.

The LUCORC barrier occasionally breaks down during periods of reduced southerly, upwelling-favourable wind, permitting the movement of biota between the northern and southern Benguela subsystems. For example, the record catch of 376 000t of anchovy that was taken off Namibia in 1987 was considered to have originated, in part, from the southern Benguela (Hewitson 1988). Anomalously warm sea surface conditions were recorded north of the Orange River in early 1987, suggesting that the LUCORC barrier had collapsed sufficiently to enable anchovy larvae and post-larvae to migrate from the southern to the northern Benguela and recruit to the population

targeted by the Namibian pelagic fishery (Hewitson 1988). Northward penetration of the LUCORC barrier by early stages of anchovy appears to depend in part upon recruitment strength, the distribution of anchovy spawning (whether confined to the Agulhas Bank or extending up the west coast, as was the case in 1987; van der Lingen et al. 2001) and the alongshore flow during the transport phase to advect larvae sufficiently far northwards along the South African west coast. Possible southward movement of biota across this boundary appears to be more likely to occur during austral autumn (April-June), a period when the distribution of low wind speeds (the cube of which is roughly proportional to turbulence) extends further south than during the rest of the year (Agenbag and Shannon 1988). The recent prolonged lack of winds in the late 1990's and early 2000's, which are likely to have weakened the LUCORC barrier, are in contrast to expectations of increased wind stress arising from climate change (Bakun 1990; Shannon et al. 1996).

The LUCORC boundary is the southern boundary of spawning habitat for shallow water hake, *Merluccius capensis*; (Sundby et al. 2001) and small pelagic species (King 1977) in the northern Benguela. Deep-water hake (*M. paradoxus*) have penetrated further north into the northern Benguela over the past two decades (see van der Lingen et al. Chapter 8 *this volume*), but apparently do not spawn off Namibia (Sundby et al. 2001). Identifying the nature of these changes is part of a continuing research program to understand and predict the factors affecting movement of deep-water hake.

The cross-shelf circulation, and particularly the strong offshore advection, is associated with the strength of the southerly winds in the Lüderitz (25°S) region, which is in turn associated with the mean position of the South Atlantic high pressure cell off the coast of southern Africa. The modes of variability of the South Atlantic are not well understood at present and a St Helena Island Index (HIX; Feistel et al. 2003) indicates an approximate 13 to 18-year mode but appears to be a poor indicator of local winds at Lüderitz. Unless empirical and theoretical modelling studies currently underway produce an advance in understanding of the mechanisms underlying the wind variability in the Lüderitz upwelling region, the probablility of forecasting remains poor. The subsurface boundary between the oxygen-poor water of Angolan origin, carried southward in the shelf-edge poleward undercurrent and the more oxygenated Central waters originating from the Cape basin in the SE Atlantic, are currently not well understood and more observations and modelling are required before feasible scenarios can be made. At best real time measurements should allow nowcasting or "what-if" scenario development.

West Coast Oceanic boundary

This boundary is more defined than its equivalent in the northern Benguela, and occurs between cool, productive, food-rich mature upwelled water inshore and warm, food-poor waters comprising a variable mixture from the Agulhas Current, the Agulhas Bank or offshore Atlantic surface water (Figure 14-7). Modelling studies indicate that much of the interannual signal in offshore temperature is derived from contributions from the Agulhas Bank or Current, rather than from local upwelling-favourable winds

movement of this boundary region in summer months (C. Bartholomae, MFMR, unpublished data) which is predictable, and occasional shoreward movement that is associated with a lack of winds from the south. Such shoreward movement is relevant in terms of biogeography and life history strategies for population maintenance of euphausiids (Barange et al. 1992), and has also been suggested as driving the availability to fishing of demersal resources including hake (Macpherson et al. 1991).

Subsurface current structures are much less documented than surface features, but are thought to be of major importance in controlling the position and location within the continental shelf of small organisms such as fish eggs or larvae (Sundby et al. 2001; Batchelder et al. 2002). In the northern Benguela, sardine eggs were found to be most abundant within the upper layers and sardine larvae were found deeper (Stenevik et al. 2001). This was explained as a behavioural adaptation to the vertical circulation structure over the shelf: by migrating at a depth deeper than the wind-induced offshore-moving surface layer, sardine larvae make use of the subsurface upwelling-compensatory flow to avoid advective loss and to enhance transport to and retention within the nearshore area (Stenevik et al. 2003).

Lüderitz/Orange River Cone boundary region

The perennial cell of intense upwelling situated off Lüderitz separates the northern and southern Benguela subsystems, and the Lüderitz Upwelling Centre / Orange River Cone (LUCORC) region experiences considerable offshore losses in the surface layers, strong surface mixing and low phytoplankton concentrations. It is considered a barrier to small pelagic fish such as anchovy and sardine, and their eggs and larvae, primarily because of high levels of wind-induced turbulence in the region of Meob Bay (24°30'S; Agenbag and Shannon 1988). This is probably less of a barrier to mesopelagic species such as lanternfish (*Lampanyctodes hectoris*), redeye (*Etrumeus whiteheadi*) or gobies (*Sufflogobius bibarbatus*), all of which are capable of more extensive vertical migration than the small epipelagic fish. The LUCORC boundary is characterised by changes in source water to the shelf region, differing in oxygen, salinity and a few zooplankton species. Subsurface currents that flow southwards in the northern Benguela off central Namibia, flow offshore near Lüderitz and are replaced by more oxygenated Eastern Atlantic Central water from the Cape Basin, which flows southwards. The LUCORC region therefore constitutes a subsurface as well as a surface boundary zone, and may impinge dramatically on the alongshore movement of demersal species such as hake, as well as on pelagic species.

The LUCORC barrier occasionally breaks down during periods of reduced southerly, upwelling-favourable wind, permitting the movement of biota between the northern and southern Benguela subsystems. For example, the record catch of 376 000t of anchovy that was taken off Namibia in 1987 was considered to have originated, in part, from the southern Benguela (Hewitson 1988). Anomalously warm sea surface conditions were recorded north of the Orange River in early 1987, suggesting that the LUCORC barrier had collapsed sufficiently to enable anchovy larvae and post-larvae to migrate from the southern to the northern Benguela and recruit to the population

targeted by the Namibian pelagic fishery (Hewitson 1988). Northward penetration of the LUCORC barrier by early stages of anchovy appears to depend in part upon recruitment strength, the distribution of anchovy spawning (whether confined to the Agulhas Bank or extending up the west coast, as was the case in 1987; van der Lingen et al. 2001) and the alongshore flow during the transport phase to advect larvae sufficiently far northwards along the South African west coast. Possible southward movement of biota across this boundary appears to be more likely to occur during austral autumn (April-June), a period when the distribution of low wind speeds (the cube of which is roughly proportional to turbulence) extends further south than during the rest of the year (Agenbag and Shannon 1988). The recent prolonged lack of winds in the late 1990's and early 2000's, which are likely to have weakened the LUCORC barrier, are in contrast to expectations of increased wind stress arising from climate change (Bakun 1990; Shannon et al. 1996).

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(Penven et al. 2001; Blanke et al. 2002; 2005). The boundary is diffuse in winter but more defined in summer and autumn, when it is associated with alongshore, northward jet currents. Alongshore transport dominates over across-shore movement, but mesoscale eddies and filaments can alter the pathway and the feeding conditions, and mesoscale processes are considered particularly important in this region. Larvae and pre-recruits of pelagic fish which spawn further south on the Agulhas Bank and the shelf edge must cross over this boundary to enter the inshore nursery areas off the west coast (Hutchings et al. 2002a), either by actively swimming towards the shore or by being carried passively as winds abate at the end of summer and surface waters move shorewards, or by vertical migration using subsurface shoreward moving currents as modelled by Parada et al. (submitted).

Studies of plankton productivity and abundance are needed to assess and predict the energy supply for young fish in this boundary region, and the role of the seasonal wind decline in autumn and its contribution to shoreward movement of pre-recruits needs evaluation. Furthermore, measurements or models of shoreward transport success are needed in order to estimate or predict anchovy recruitment success. Anchovy pre-recruit abundance is not well correlated with recruitment measured three months later (van der Lingen and Huggett 2003), and the timescale of the process for pre-recruits to move onshore is considered to be of the order of 1-3 months. An anchovy larva of 20mm TL swimming at a cruising speed of 1 body length.s^{-1} (Hunter 1972) for 12 h.d^{-1} would take 105 days to swim the 180 km from offshore of the continental shelf to the coast, if water movement either toward or away from the coast were zero. However, this is probably too long a period for active swimming to be solely responsible for onshore movement of larvae. Pre-recruits may respond to offshore Ekman surface flow and food availability by altering their vertical distribution patterns through diel vertical migration, and field observations indicate that they show Type 1 vertical migration, being deeper (around 20-40m) during day and in surface waters at night (van der Lingen and Hutchings unpublished data). The mechanisms involved in transporting pre-recruits from offshore to onshore require further investigation.

Suitably-located wind measurements and hydrodynamic numerical modelling may help improve our understanding of processes for nowcasting, but forecasting shoreward transport (and hence anchovy recruitment success) over longer periods is probably best approached in terms of testing scenarios of varying wind strength or Agulhas Bank water intrusions. The feasibility of making such forecasts is considered moderate. The economic value of such a forecast is modest, since anchovy recruitment starts in April and recruitment strength is estimated three months later through hydroacoustic surveys, and field data for such a forecast is collected by March. Requirements for forecasting include high resolution wind measurements, a set of hydrodynamic, biogeochemical and IBM models (see Penven et al. 2001; Mullon et al. 2003; Koné et al. submitted), information on the behaviour of pre-recruits, and indices of food availability and the strength of Agulhas Bank water intrusions on to the west coast. The timescale of forecast possible is about one month, possibly extended up to six months, with limited feasibility of applying this forecast in management.

Agulhas Bank to West Coast Frontal Jet Boundary

A strong, northward-flowing jet current from Cape Point along the shelf-edge is associated with a marked thermal front between cold upwelled water and warm oceanic water in this region (Bang and Andrews 1974; Shelton and Hutchings 1990). Resources impacted by this boundary include small pelagic fish species, horse mackerel and hake, all of which spawn on the Agulhas Bank or the shelf slope in the extreme south of the Benguela but recruit to the inshore west coast nursery grounds (Hutchings et al. 2002a). Eggs and larvae of pelagic fish are advected rapidly alongshore between the Agulhas Bank and the west coast via the jet current during October-March, and recruitment strength should be proportional to transport "success". If the drift of eggs and larvae is purely passive, anchovy recruitment should be inversely proportional to pathway length. However, measurements of seasonal variability in jet strength and convolutions, which would impact on pathway length, are needed from models and observations. The location of eggs and larvae in relation to the jet core is important in terms of offshore losses and feeding conditions within the convergent front (Hutchings et al. 1998). Furthermore, the strength and position of the jet relative to the coast would obviously impact on transport success. While little is known about the control of wind forcing on the behaviour of the jet, it is quite likely that wind-induced variability of the jet current contributes to explaining the inverse correlation that has been observed between southeast wind intensity and anchovy recruitment (Boyd et al. 1998).

Forecasts of transport/recruitment success of anchovy based on the first half of the spawning season, from October to December, would be most useful for predicting relative recruitment strength six months later. Hindcasts to verify various models have been attempted on a number of occasions, utilising transport, feeding conditions and fish condition factors (e.g. Bloomer et al. 1994; Boyd et al. 1998; Korrûbel et al. 1998; Painting et al. 1998; see *Mesoscale Processes* case study), while Shannon et al. (1996) has described scenarios of increased or decreased upwelling on transport success from the Agulhas Bank to the west coast. The feasibility of the forecast is considered to be moderate, as the jet current is a very persistent feature both in hydrodynamic models of the region (Penven et al. 2001) and observations. But other factors are likely to impact on recruitment during (cannibalism and predation) and after (offshore advection, starvation, predation) the transport phase. The economic value of the forecast is considered to be substantial, as a prediction based on the first half of spawning season would allow a 6-month forecast. Replacing the currently assumed median anchovy recruitment value with one determined in part by environmental conditions during the transport phase and the size and location of the spawning stock, can easily be implemented into the operational management plan (De Oliveira and Butterworth 2005), but longer-term forecasts are not feasible until predictions of seasonal climate variability improve.

Boundaries associated with the Agulhas Bank

The Agulhas Bank is an important spawning area for a large number of valuable resources, including small pelagic fish, horse mackerel, kingklip (*Genypterus capensis*), South Coast rock lobster (*Palinurus gilchristi*), and squid (*Loligo vulgaris reynaudii*). In addition, the Bank itself is an important nursery area for several organisms which spawn upstream on the narrow eastern coastal shelf and whose eggs and larvae are advected southwards onto the Agulhas Bank (Beckley 1993; Hutchings et al. 2002a). Three boundary processes associated with the Agulhas Bank are briefly considered here, including warm water intrusions from the Agulhas Current, the draw-off of coastal waters through premature retroflection of the Agulhas Current, and the "cool ridge" (see below).

As the austral summer advances, warm water of Agulhas Current origin penetrates onto the shallow shelf of the Agulhas Bank, deepening the thermocline and reducing productivity. Internal waves produce oscillations in the thermocline, temporarily exposing nutrient-rich water to higher light levels, and increased winds may erode the thermocline deeper, mixing nutrients into the euphotic zone. During the austral winter months, the diminished heating effects and strong winds break down the water stratification to depths of 80-100m, while re-establishment of the stratification usually occurs in the October-December period (Shannon et al. 1984). Occasionally, large meanders of the Agulhas Current associated with the Natal Pulse (van Leeuwen et al. 2000) result in strong intrusions of Agulhas Current water across the Bank, or the removal of large quantities of shelf water and associated biota into the south west Indian Ocean interior. Additionally, retroflection of the Agulhas Current occasionally results in the formation of Agulhas rings (Duncombe Rae 1991) that move into the south Atlantic. These rings may entrain frontal water and draw it off from the Benguela system, possibly removing eggs, larvae and pre-recruits of small pelagic fish and hence negatively impacting on recruitment (Duncombe Rae et al. 1992).

A cool, subsurface ridge often occurs on the central Agulhas Bank (Swart and Largier 1987; Boyd and Shillington 1994), driven by a complex interactions of coastal upwelling with meanders in the Agulhas Current along the shelf edge. The ridge is visible seasonally in satellite ocean colour images (Demarcq et al. 2003), and is characterised by shallow thermoclines and raised phytoplankton (Probyn et al. 1995) and zooplankton (Peterson et al. 1992) concentrations. This *in situ* production supplements the energy reserves of spawning fish to allow sustained serial spawning over the prolonged summer period from October to March. Cyclonic circulation patterns associated with the cool ridge (Boyd and Shillington 1994) may retain early stages of copepods over the inshore regions of the central and eastern Agulhas Bank, providing an important food source for both fish larvae (Hutchings et al. 2002a) and squid paralarvae (Augustyn et al. 1994). Additionally, the inshore, eastward-moving part of the cyclonic circulation pattern may be important in the eastward migration of horse mackerel (Barange et al. 1998).

The response of the fish to changes in these boundaries processes that occur in the vicinity of the Agulhas Bank is unknown as the influence of the Agulhas Current on shelf water processes is not well understood. At this stage only hindcast and simulation models are feasible for comparison with observations, particularly with an expanded hydrodynamic model configuration (known as the Southern Africa Experiment or SAFE; Pierrick Penven, IRD, *pers. com.*). However, should forecasting of these processes and their impacts on the living marine resources be achieved, the potential economic value of such is considered to be high, particularly for squid and small pelagic fish species.

Regional model simulations need to be verified with available observations on the Agulhas Bank. The data requirements are linked to an explicit understanding of the links between Agulhas Current rings and meanders, inshore eddies, early and late retroflections and intrusions onto the Bank in relation to the circulation on the Bank itself. The effect of local winds on the circulation and retention on the Bank itself, relative to offshore losses, is also important, particularly at the eastern and southern extremities of the Bank. Monitoring the Agulhas Current upstream of the Agulhas Bank will prove useful, particularly as the suspected sources of variability in the Mozambique Channel and south of Madagascar propagate southwards 1-2 months later. Further knowledge regarding biological interactions on the Agulhas Bank is also important. In particular, the role of predation and cannibalism on eggs and larvae of small pelagic fish that spawn over the Agulhas Bank during the summer months, and predation by medium-sized predatory fish on those small pelagic spawners, require investigation. The energy reserves of small pelagic fish required for sustained serial spawning and extended migration is an important biological forcing function, currently estimated via fish condition indices (see van der Lingen and Hutchings 2005), but requires further study.

OTHER SHELF PROCESSES

Other shelf processes not detailed above are also of major importance for the BCLME (Table 14-1), and some of them could be forecasted in the near future. Extensive sulphide eruptions are often observed in the northern Benguela, and their occurrence is likely to increase with the intensification of the trade winds in response to global greenhouse warming (Bakun and Weeks 2004). Such eruptions have a direct toxic impact as well as a secondary effect of depleting oxygen from the water, so that marine organisms suffer from severe hypoxia and anoxia. Moreover, additional mortality from predation can result from sulphide events because of exclusion of fish from their favoured near-coastal habitat by lingering anoxia, an example being the loss in the austral summer of 1992-93 of about half of the recruit population of Namibian Cape hake thought to have died as a result of being trapped by widespread anoxia in shelf bottom waters (Hamukuaya and O'Toole 1994). As a result, the size of the entire hake population of central Namibia is estimated to have fallen to less than 30% of its abundance level of the previous year (Hamukuaya et al. 1998). Sulphide eruptions are detected by ocean colour from satellite (Weeks et al. 2002; 2004), and although little can be done to prevent their negative impact, the development of continuous monitoring of the northern Benguela via satellite could facilitate the implementation of

management measures designed to limit the detrimental interaction of exploitation activities with eruptions.

A challenging question in modern fishery science is to understand the processes driving the large interdecadal variability in recruitment success of some species, mainly the pelagic and semi-pelagic species, a typical example being the sardine stocks in the northern and southern Benguela subsystems. This long-term variability is often larger than the interannual variability (Schwartzlose et al. 1999), and some degree of regional or even global synchrony appears although the latter might be spurious (Fréon et al. 2004). Although the process(es) driving this interdecadal variability are largely unknown, except for some evidence of empirical correlation with environmental variables (Klyashtorin 1998), the fact that the signal is a long-term one (pseudo-periodicity of 40 to 60 years) opens the door for a certain degree of predictability and consequently the implementation of management actions. This may be particularly appropriate for resources such as sardine, which have been documented as showing a 50-60 year time scale of population expansion and contraction in other systems (Baumgartner et al. 1996 for sardine in the California Current). Fréon et al. (2005) suggested investigating a two-level (short- and long-term) management strategy, in which the second level takes into account this predictability by trying to limit the negative effects of overcapitalization in the fishing industry.

Harmful algal blooms (HABs), often referred to as red tides, are mostly attributed to dinoflagellate species. Their negative impacts are due either directly through the production of toxins, or indirectly when a high biomass of dinoflagellates impacts the coastal environment and, through their decay, results in the formation of low oxygen water and, in some cases, the production of hydrogen sulphide (Pitcher and Weeks, Chapter 7, *this volume*). Bernard et al. (Chapter 12, *this volume*) explore the feasibility of forecasting HABs based on real-time observations to effectively overcome the present difficulty in modelling biological processes associated with HAB development (e.g. stochasticity of species selection, species variability in swimming, growth, mortality, nutrient and light acquisition, etc.). Those authors propose the implementation of an observation network that would utilise high frequency data from multi-sensor coastal observation platforms situated at locations critical to both preliminary bloom detection and resultant advective transport, in addition to synoptic satellite-derived data. Forecasting will be based on two complementary methods: firstly, a probabilistic "ecological window" or fuzzy logic model whereby the probability HAB occurrence is determined from observations of physical, chemical and biological conditions in real time, and secondly via short term predictions of impact and transport prediction, likely in turn to be based on a concomitant meteorological forecast (Bernard et al. Chapter 12, *this volume*; Pitcher et al. in press).

Another area where transport prediction is essential is forecasting the transport of unexpected release of contaminants, such as oil spills and other hazardous or criminal wastes, of chemicals which result in harmful exposure of marine organisms (including top predators like sea-birds, mammals and their land-based habitat, farmed species of fish and shelfish) and require expensive cleanup of the coastal environment. The response to harmful wastes depends on projections of where winds and currents will

take the contaminants. Spill forecasting requires a detailed knowledge of contaminant release dynamics, oceanography, meteorology, contaminant chemistry, and slick observations when feasible as in the case of oil spills that can be tracked by remote sensors. Some national agencies, such as NOAA or Meteo France, implement dedicated software to track oil spills and to forecast their drift according to weather scenarios (Daniel 1996; Beegle-Krause 2001). Such an operational feature-tracking model could be implemented in the Benguela to predict the shoreline impact and retention of spills, but it will be highly dependent upon observational ability and the temporal limitations of meteorological forecasts. A major issue will be to merge real-time surface currents given by hydrodynamic models with the wave and wind-induced drift calculated by such feature-tracking models, which are mostly wind and wave driven and would not be able to incorporate features such as the Agulhas Current and eddies or filaments. Dynamic circulation models ideally should assimilate real-time physical data, in particular wind data, SST and sea level information provided by remote and land-based sensors. Remote sensing products considered most useful. in this respect include the NOAA AVHRR and NASA MODIS sensor for daily SST data at ~ 1 km spatial resolution, the NASA QuikSCAT sensor for daily surface winds at ~ 25 km spatial resolution (but without coverage within 50 km from coast), and the ESA MeteoSat Second Generation (MSG) sensor that provides 3 km spatial resolution and a 15 minutes sampling frequency allowing efficient de-clouding. The physical processes underlying the concentration, dispersion and advection are relatively well-known and should allow identifying important transport pathways and essential dynamics that may support the transport and dispersal of contaminants, or similarly, sediment plumes generated by offshore mining (Bernard et al. Chapter 12, *this volume*; Grundlingh et al. Chapter 15, *this volume*). Pollution tracking, if associated with early warning and preventative actions, could allow a saving on cleaning costs and may reduce damage to sensitive estuarine or near shore areas. Furthermore, colonies of bird and mammal species, some of which are classified as endangered or vulnerable, may also be protected. There are also direct and indirect benefits that can be expected on tourism activities (cleaner beaches, eco-tourism, etc.).

DISCUSSION AND CONCLUSIONS

In this chapter we focused on examining shelf processes that impact on commercially important living marine resources of the BCLME, particularly rock lobster, demersal fish and pelagic fish species. We examined three processes in detail (low oxygen events, mesoscale processes, and boundary processes) and, although treated separately, these processes are not necessarily distinct: changes in boundary conditions and/or advection may be implicated in the evolution of major low oxygen events in the northern Benguela, and features arising from mesoscale processes such as upwelling plumes, eddies etc. are important in particular boundary regions, such as the oceanic boundaries. The all-encompassing influence of physical forcing in determining the dynamics of the BCLME and other upwelling systems means that there is a high degree of correlation between the various physical processes.

Impacts on biomass may be direct, e.g. mass mortalities of rock lobster following "walkout" events due to low oxygen events; or they may be indirect, e.g. increased (or decreased) recruitment of pelagic and demersal fish that arise from a particular set or sequence of shelf processes, and reductions in growth rates etc. of rock lobster exposed to low oxygen events. Impacts on availability are direct, in that shelf processes may cause stocks to move into or away from a particular region. This may be of importance to fishery managers if such stocks cross national boundaries, as is the case with *Sardinella* spp. moving into Namibian waters during Benguela Niño events, and highlights the mismatch between static geopolitical boundaries and dynamic ecological boundaries. This problem will be exacerbated if climate change effects increase the likelihood and/or extent of such movements of transboundary stocks, or induces their latitudinal shifts. However, in some instances it may not be easy to discriminate between changes in availability and changes in abundance, and doing so effectively is a significant challenge that fishery managers will have to meet. Confusing the two can have serious consequences, e.g. if an increase in availability is taken as an increase in population abundance and fishing pressure is then increased, this may expose the stock to excessive fishing mortality (Fréon and Misund 1999). Being able to forecast the impacts of shelf processes on living marine resources will have obvious positive consequences for management of commercially important resources of the BCLME.

The likely large-scale impacts of climate change in the Benguela region are briefly discussed by van der Lingen et al. (*this volume*). Altered wind stress leading to increased coastal upwelling will increase primary productivity which, in turn, increases organic loading and hence the likelihood (in terms of both frequency and intensity) of low oxygen events and sulphide eruptions (Bakun and Weeks 2004). Climate change is also likely to affect the intensity of a boundary (i.e. thermal gradient), and may also result in a consistent displacement in the modal position of a boundary. Alternatively, the modal position may stay the same but there could be a greater spatial extent and hence variability in the boundary's location. The impacts of climate change on shelf processes, and the responses of living marine resources in the BCLME to these impacts, may best be examined through scenario testing using hydrodynamic models coupled to ecological models.

Even if a good understanding of the likely impacts on living marine resources of oceanographic processes is available, and even if forecasting of these processes is feasible, addressing the question of how to incorporate such predictions into management procedures is critical. Environmental indices that have been directly used in the management of fish stocks are generally rare. For a review of the use of environmental indices in the management of small pelagic fish populations see Barange (2001; 2003). Simulation studies for South Africa's pelagic fishery have indicated that environmental indices need to explain 50% or more of the total variation in anchovy recruitment before showing benefits in terms of management procedures (De Oliveira and Butterworth 2005). Additionally, the benefits of using environmental indices to predict recruitment may be compromised by uncertainties related to the real degrees of freedom, the mode of selection of explanatory variables, and errors in the values of explanatory variables (co-linearity, spurious correlation, etc.) and in the functional forms assumed for environment-recruitment relationships.

An example of how an environment-recruitment relationship may change through time (i.e. show non-stationarity) has been provided by Daskalov et al. (2003), who related recruitment strength of northern Benguela sardine to two environmental indices (sea surface temperature in the tropical Atlantic and coastal wind stress at Lüderitz) over the period 1960-2000. Those authors found that sardine recruitment was positively correlated with SST and negatively correlated with wind prior to the mid-1980s, but that these relationships were reversed (recruitment being negatively correlated with SST and positively correlated with wind) thereafter. Daskalov et al. (2003) proposed two hypotheses to explain this reversal, the first of which suggested a switch between environmental regimes that occurred during the mid-1980s from an environment characterized by weak stratification and strong enrichment to one characterized by strong stratification and weak enrichment. Their second hypothesis suggested that the observed reversal could be attributed to changes in population structure, distribution and migration, arising from severe overfishing of the sardine stock and resulting in a change in spawning habitat from the vicinity of Walvis Bay to further north (see van der Lingen et al. Chapter 8, *this volume*, for further details on changes in northern Benguela sardine spawning habitat). The above example clearly illustrates the difficulty regarding the making of forecasts when not all processes are clearly identified. By contrast, it is technically relatively simple to implement an early warning signal of major changes in the environmental forcing used in the model of Daskalov et al. (2003; see for instance a pre-project of a Benguela Niño warning system set up as the result of this international workshop at: http://drmroull.sea.uct.ac.za/).

The unsuccessful attempt to use a significant relationship between an upwelling index and recruitment determined for Bay of Biscay anchovy (Borja et al. 1998) to set total allowable catches for this species (ICES 2000; 2001) has been partially attributed (De Oliveira and Butterworth 2005) to a failure to take proper account of risks associated with the uncertainties listed above, although a lack of clear management objectives for that fishery, and conflicting requirements between French and Spanish fishermen, is considered the major issue (M. Barange, GLOBEC IPO, pers. comm.). Nonetheless, the wealth of studies that have examined anchovy recruitment variability and its predictability in the Southern Benguela (Hutchings et al. 1998; Mullon et al. 2003; van der Lingen and Huggett 2003), and the insights gained from simulating the incorporation of predictive models into management procedures for this stock, should allow the development of recruitment prediction models that can feasibly be incorporated into management procedures. A suggested way forward is to update previous approaches to predicting anchovy recruitment by including recent data (such as the eastward shift in spawning intensity on the Agulhas Bank; van der Lingen et al. 2002) and then combining these individual approaches into an expert system in which the recruitment predictions are weighted according to quantitative (e.g. r^2 value of the environment-recruitment value, where available) and/or qualitative (e.g. perceptions of the "realism" of the approach and its ability to capture the underlying process) criteria in order to arrive at a single most likely prediction. Regarding sardine recruitment forecasting, the long-term autocorrelation observed in catch and abundance time series (Baumgartner et al. 1996; Fréon et al. 2005) could be incorporated into management procedures in the absence of further evidence that the observed pseudo-periodicity is environmentally driven (Klyashtorin 1998). However, periods of high and low

productivity (as evidenced by estimates of instantaneous surplus production rate [ISPR] and annual surplus production [ASP]) of sardine populations from a variety of regions have been linked to environmental variability (Jacobson et al. 2001), and an environmentally responsive management approach that adaptively controls catch by shifting fishing effort in response to changing stock productivity has been suggested for Japanese sardine (Yatsu et al. 2005).

Finally, we emphasize that predictions should be based on a solid understanding of the processes involved and their spatio-temporal location in terms of the life history of the marine resource on which they impact, rather than solely on statistical correlations between process and resource that are poorly explained and/or not understood, and often break down after a number of years (see Myers 1998), although inter-decadal changes might be an exception to this rule.

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Benguela: Predicting a Large Marine Ecosystem

Edited by

Vere Shannon
Honorary Professor, Department of Oceanography
University of Cape Town
South Africa

Gotthilf Hempel
Science Advisor, Senate of Bremen, Germany
Emeritus Professor, Bremen and Kiel Universities
Germany

Paola Malanotte-Rizzoli
Professor, Department of Earth, Atmospheric and Planetary Sciences
Massachusetts Institute of Technology
Cambridge, Massachusetts
United States

Coleen Moloney
Senior Lecturer, Department of Zoology
University of Cape Town
South Africa

John Woods
Emeritus Professor, Department of Earth Science and Engineering
Imperial College London
United Kingdom

Technical editor
Sara P. Adams - Large Marine Ecosystem Program - Narragansett RI - USA

On the cover

The main cover picture illustrating the complexity of the Benguela Current Large
Marine Ecosystem (BCLME) and adjacent regions is an AQUA MODIS level three,
4 km resolution, chlorophyll image for the week 2-10 February 2004, obtained from
the NASA Oceancolor webpage: http://oceancolor.gsfc.nasa.gov/cgi/level3.pl

The top picture, with the BCLME box inset, is the global map of average primary
productivity and the boundaries of the 64 Large Marine Ecosystems (LMEs) of the
world, available at www.edc.uri.edu/lme. The annual productivity estimates are
based on SeaWIFS data collected between September 1998 and August 1999. The
color enhanced image was provided by Rutgers University.