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11

Developing a Basis for Detecting and Predicting Long-Term Ecosystem Changes

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ABSTRACT

Long-term ecosystem changes in the Benguela region include species alternations and regime shifts, which are sometimes obscured by large intra- and inter- annual variability in the ecosystem. This chapter proposes that no single model or approach can resolve this variability and effectively detect and predict long-term ecosystem changes; a coherent, robust, transparent and reproducible synthesis framework is required. Indicators and models are described that can be used to identify some aspects of the current state of ecosystem structure and to detect and monitor long-term change. A short-term challenge is to synthesize these varied sources of multidisciplinary (and sometimes contradictory) information in a logical and consistent fashion. An expert system approach is proposed to do this, consolidating results of different indicators and models within a dynamic process that uses feedbacks to validate predictions of the expert system, and to improve it. It is suggested that such an approach should be initiated in the short term, even as models and indicators are being developed further. In parallel, multivariate statistical tools should be refined and applied to existing time series, to identify past periods of ecosystem change. Current data gaps should be filled, including time series of primary production and the abundance of gelatinous zooplankton. In the medium term, the expert system model should evolve to a point where its results can be used to inform various management groups about the state of the ecosystem. Part of this evolution requires that ecosystem indicators be presented with error estimates or formal assessments of quality.

INTRODUCTION

The detection and prediction of ecosystem states and changes in those states is at the very heart of ocean observation programmes globally (IOC/GOOS 2003), and one of the key policy actions of the Benguela Current Large Marine Ecosystem (BCLME) Programme (O'Toole et al. 2001). Two cornerstones of this policy action are the development of an early warning system for monitoring major environmental events within the Benguela LME, and the improvement of the predictability of extreme events and their impacts. While extreme events can have severe impact in the region in the short and medium term (e.g., Chapters 4, 5 and 7, *this volume*), this contribution focuses on detecting and monitoring changes in the Benguela LME region in the long term.

The Benguela LME consists of three main sub-regions, (i) the subtropical shelf ecosystem north of the Angola Front, (ii) the northern Benguela ecosystem, a typical eastern boundary upwelling system bounded by the Angola-Benguela Front in the north and the Lüderitz upwelling cell in the south, and (iii) the southern Benguela ecosystem, which extends along South Africa's west and south coasts until approximately East London, and shows characteristics of both an eastern boundary current system and a temperate shelf ecosystem. The ecosystems in each of these sub-regions have their own characteristics and dynamics, and assessing and forecasting change is therefore a complex topic. It is unlikely that a single approach can be used across these systems. Indeed, it is unlikely that a single approach would be effective within any ecosystem, because of the range of scales involved, and the complex interactions that exist among living and non-living components of ecosystems. We focus instead on highlighting a suite of approaches to detect and monitor long-term change, and methodology to synthesise the results of different approaches. We emphasise a general procedure that should be applicable to any subsystem in the Benguela LME region.

Our focus on the long term includes analyses of causes and effects of species alternations (*sensu* Schwartzlose et al. 1999) as well as regime shifts (e.g., Cury and Shannon 2004). Consequently, our management concerns are strategic (i.e., on the time scale of 4-7 years) as opposed to tactical (1-3 years); we anticipate that the objectives of tactical management, typically single-species or fisheries-based, will be fashioned on the basis of strategic thinking guided by long-term ecosystem considerations. Similarly important on a strategic basis are changes that affect or manifest among communities (e.g. zooplankton communities, kelp-bed communities, benthic shelf communities) or changes that affect species with long population cycles (e.g., seabirds, cetaceans, predatory reef-fish), if there is an established link to ecosystem-level changes.

Van der Lingen et al. (*this volume*) propose a way forward in addressing long-term ecosystem change in the Benguela Current region. They emphasize the need to identify and understand different states of the ecosystem, the controls operating within ecosystems, and the processes by which change occurs. They further recommend that suites of ecosystem indicators be used to describe and quantify ecosystem change, and that these indicators be synthesized to allow predictions. The main objective of this chapter is to expand on these proposals. The chapter aims to answer a number of questions about the complex task of detecting and predicting long-term ecosystem changes. These include the kinds of changes that should be considered, and the many ways in which they might be measured and modelled. Composite indicators rather than single variables are believed to be most useful for depicting many ecosystem-level attributes, and the chapter asks which of these indicators will be most useful, and what models can be used to derive and test them. Finally, the chapter aims to outline a feasible way of combining models and measurements of key characteristics of ecosystems, by integrating the varied approaches that will probably be used in an "expert system model".

ECOSYSTEM CHANGES TO BE MONITORED

What is ecosystem change?

There is neither a consistent definition of regime shift, nor is there a consistent approach to determining ecosystem state, changes in the state, or the relation between the physical, chemical and biological environment that might trigger a regime shift or ecosystem change (de Young et al. 2004). Several proposed definitions of regime shifts are given (Table 11-1). We adopt the definition that a regime shift is a rapid change from a quantifiable state, representing substantial restructuring of the ecosystem, acting over large spatial scales and persisting for long enough that a new quasi-equilibrium state can be observed (de Young et al. 2004). If 'ecosystem state' were to be defined, a change in state would need to be measurable. However, unlike (closed) freshwater/lake systems (e.g. Scheffer et al. 2001, Scheffer and van Nes, 2004), determination of ecosystem state in (large and open) marine ecosystems proves difficult, remaining an unresolved, imprecise problem (see e.g. Longhurst 1998). Therefore, at present, we have to be satisfied with a broader, and perhaps less ecologically precise, definition of "regime shift" in marine ecosystems. Nevertheless, appropriate statistical analyses need to be developed and applied before concluding whether or not a regime shift has occurred (or is occurring).

Throughout this chapter we distinguish between bottom-up environmental forcing (e.g. by changes in winds, ocean currents, temperatures, oxygen concentrations, etc) and anthropogenic forcing (which can be bottom-up through e.g. pollution, or top-down through e.g. fishing). The response of the ecosystem to environmental or anthropogenic forcing will depend on the ecosystem state and its functioning, underlining the need to understand the inherent characteristics of the ecosystem to be able to predict probable shifts or changes. Collie et al. (2004a,b), similarly also de Young et al. (2004), exemplify three ways in which regime shifts occur:

1. Gradual change e.g. shifts between dominance of coral and macroalgae around Jamaica, which is generally reversible,
2. Abrupt change e.g. the cod collapse in the North Sea, which is not necessarily reversible, and
3. Discontinuous shift e.g. the increased abundance of jellyfish off Namibia, caused by fishing or environmental forcing and which is unlikely to be easily reversible.

Following Mantua's (2004) definition (see Table 11-1) and the stability landscape model of Scheffer et al. (2001), two diagrammatic representations are presented to assist in visualising the idea of stable states and attractors (Figures 11-1 and 11-2). Unlike during regime shifts, ecosystem structure and functioning are not necessarily altered during replacements or alternations (see Table 11-1) of species at similar

Table 11-1. Some definitions of regime, regime shift, and species replacement/alternation important to the BCLME.

Reference	Definition
Regime	
Mantua (2004)	A period of quasi-stable biotic or abiotic system behaviour where temporal variations in key state variables are concentrated near distinct dynamical attractors, or stability wells, within phase space.
Lluch-Belda et al. (1989,1992)	Prolonged periods of high or low abundance of species.
Isaacs (1976)	Distinct climatic and/or ecosystem states and is multifarious, involving biology or climate, or oceanography, or migrations, temperature, or weather, or combinations of these.
Regime shift	
Bakun (2004)	Persistent radical shift in typical levels of abundance or productivity of multiple important components of marine biological community structure, occurring at multiple trophic levels and on a geographical scale that is at least regional in extent.
Cury and Shannon (2004)	Sudden shift in structure and functioning, which affect several living components and which result in an alternate state.
Wooster and Zhang (2004)	Abrupt change in a marine ecosystem and its abiotic environment from one stationary state to another.
Polovina (2005)	High-amplitude changes in community composition, species abundance and trophic structure, thought to be a response to shifts in the oceanic and atmospheric climate, and therefore relatively coherent with climate changes.
de Young et al. (2004)	Changes in marine system structure and functioning that are relatively abrupt, persistent, occurring at large spatial scales, observed at different trophic levels, and related to climate forcing.
Mantua (2004)	Relatively brief time period in which key state variables of a system are transitioning between different quasi-stable attractors in phase space.
Mantua and Hare (2002)	Abrupt change in relation to the duration of a regime, from one characteristic behaviour to another.
Reid et al. (2001)	Large decadal-scale switches in the abundance and composition of plankton and fish.
Miller and Schneider (2000)	Change from a persistent and relatively stable period of biological productivity after a similarly stable period in physical oceanographic variables.
Caddy and Garibaldi (2000)	"Punctuated equilibria" involving fundamental changes in ecosystems and reflecting ecological change.
Beamish and Mahnken (1999)	The process whereby a large marine ecosystem that is climate-linked, undergoes a shift in state over a 10-30 year period, and to which fish and other marine biota respond by changes in their dynamics;
Steele (1996, 1998)	Concurrent change in several stocks at longer time scales, and causally connected. Implies a coherent response, at the community level, to external stresses.
Lluch-Belda et al. (1989,1992)	Dramatic and long-lasting switches between periods of sardine and anchovy-dominated states in upwelling systems of eastern boundary current systems.
Species replacement or alternation	
Cury and Shannon (2004)	Species composition of an ecosystem changes, but ecosystem is not necessarily altered in terms of its structure (e.g., food-web, size composition) and functioning.
Lluch-Belda et al. (1992)	Negative correlation observed between similar species (e.g. sardine and anchovy) in the same ecosystem

levels, where only species composition changes (Cury and Shannon 2004). Nevertheless, species alternations (e.g. replacement by a commercially less desirable species) may have severe socio-economic implications, and are important for fisheries management. Species alternation is often associated with changes in spatial distribution of fish (e.g., van der Lingen et al., *this volume*) and hence availability to fisheries as well as to top predators such as commercially valuable large pelagics and vulnerable seabird species. Processes triggering regime shifts or species replacements may include both environmental changes and anthropogenic effects, e.g., fishing, which may act synergistically or antagonistically (Cury and Shannon 2004, van der Lingen et al. *this volume*).

What changes in the ecosystem might be caused by fishing, pollution, environment, or climate?

Probably the most well-known changes in the upwelling ecosystems are the decadal-scale species alternations/regime shifts involving sardines and anchovies, which have been observed worldwide (Lluch-Belda et al. 1989). These changes have important management implications as they may alter the structure and functioning of ecosystems and the way in which they respond to fishing (Rothschild and Shannon 2004). It is often difficult to disentangle the possible drivers of these and other changes. Anthropogenic impacts (fishing, pollution) cause change from the pristine situation, and these changes can have undesirable consequences for the ecosystem but might be desirable for humans. For example, overfishing predators off West Africa (Caddy and Rodhouse 1998) resulted in a lucrative octopus fishery being supported. "Natural" impacts (environment, climate) can have links to human activities, but the anthropogenic effect is indirect. Often, in these cases, the forcing for the change is density-independent (displaying synchrony between biological populations on a global or basin scale) and external to the biological ecosystem, usually forced through the physical climate system (de Young et al. 2004) and triggering a series of concomitant physical and biological processes. For instance, in the northern hemisphere, large-scale climate cycles and warming trends (e.g. Hare and Mantua 2000, Beaugrand et al. 2002) – in addition to anthropogenic disturbance (e.g. eutrophication, e.g., Brander et al. 2003) – have been implicated in long-term changes in plankton abundance and community structure. Changes at these lower trophic levels have been shown to propagate up the foodweb, causing changes at higher trophic levels (e.g. Beaugrand et al. 2003), including harvested fish populations (e.g. Reid et al. 2003).

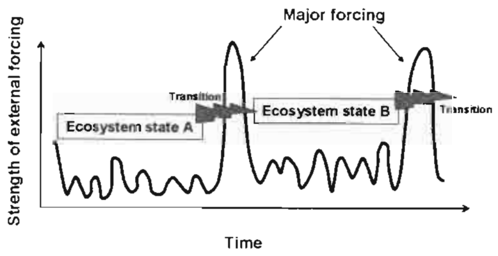

Figure 11-1. Illustration of external (natural and/or anthropogenic) forcing leading to regime changes in an ecosystem. Under weak to moderate external forcing, the ecosystem maintains its structure and functions largely in an unchanged way (A), whereas major external forcing can cause functional changes in the ecosystem that may manifest themselves in another period of weak to moderate forcing into a new regime (B). Within any regime, switching between "pseudo-states" (e.g., species dominance patterns) is generally reversible. New major forcing events may cause completely new regimes, or return the system into previous ones.

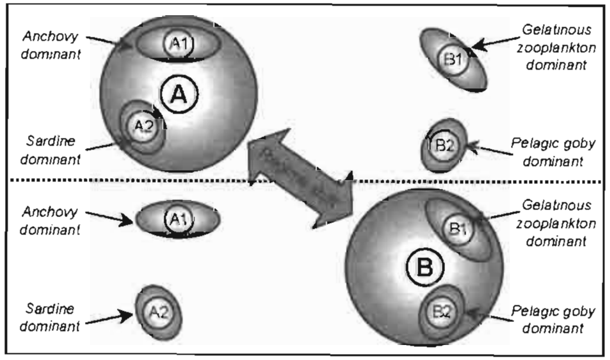

Figure 11-2. Illustration of regime change using solar systems as analogy. Any regime is assumed to be represented by a solar system with one single major attractor (A or B). Various "pseudo-states" (e.g., species dominance patterns) can exist, these are represented by sub-attractors (A1 & A2 versus B1 and B2). The mechanism by which the major attractor may change from A to B is unclear, but could be based on major external forcing as illustrated in Fig. 11-1.

Although environmental forcing typically acts from the bottom-up (via phytoplankton or zooplankton resource limitation, e.g., Verheye et al. 1998, Hutchings et al. *this volume*), it can also manifest itself in a wasp-waist manner (via direct effects on pelagic fish recruitment, Cury et al. 2003). Often, wasp-waist structures appear through pelagic fish structuring the dynamics of their ecosystem, by controlling species at both higher and lower trophic levels (Cury et al. 2003). Overfishing of one particular pelagic fish can alter the abundance, composition and distribution of others as well as other components of the pelagic community, inducing drastic changes of state.

Top-down control (predation) is considered to be the most important source of mortality for exploited species, and can affect the whole ecosystem because predation tightly connects species. Fishing, acting as a top predator, targets preferentially large fish species and, in a top-down structure, causes a shift from a large-predatory fish dominated ecosystem to one dominated by small pelagic fish, which are more sensitive to environmental change. Such changes are generally not likely to be reversible since most large fish populations are not very resilient. Fishing may not only be a cause of species alternation, but it may also be a source of additional variability (over and above natural variability) and may hasten stock collapses or slow down stock recoveries (Beverton 1990).

Land-based and airborne pollution is probably less of a problem for the Benguela than for other shelf areas (e.g., the European waters), but local effects are observed (Pitcher and Weeks, *this volume*). Pollution by shipping and sea-based structures can be severe and may have severe system consequences, e.g., by affecting top predators in the system (Gründlingh et al. *this volume*)

It is uncertain whether ecosystem manipulation is a viable possibility for future ecosystem management. What is certain is that it is very difficult to manipulate Benguela LME regions by virtue of their open boundaries and complex, dynamic ecological interactions, offering no guarantees that the desired ecosystem state will be reached (e.g., Moloney et al. 2004). For instance, attempts have failed to encourage a commercially valuable species to increase in abundance by fishing more heavily on its competitors.

What are the causal processes driving ecosystem changes?

The major driving forces in the pelagic marine ecosystems in the three Benguela LME sub-regions are winds and ocean currents. Changes in the wind forcing occur either as a change in magnitude (optimal environmental window), a change in direction, or a change in patterning (seasonal or event scale), affecting the stability of the water column and nutrient supply to the euphotic zone. This, in turn, determines the proportion of large vs. small cells in the plankton, and primary and secondary productivity. Here, only persistent changes over prolonged periods (i.e. large scale features such as changes in the South Atlantic high pressure cell off the southern African west coast) are likely to lead to regime shifts.

The large-scale current systems operating in the Bengulea region include (Shannon, 1985): (i) the South Equatorial Counter Current and Angolan Current at the northern boundary; (ii) the Agulhas Current in the south; (iii) the Benguela Current, which includes the broad drift as part of the South Atlantic gyre and the upwelling belt along the eastern edge; and (iv) the northward penetration of subantarctic water masses from the subtropical convergence in the south. Thus, currents at its boundaries set one of the main physical conditions for the ecosystem, the three others being atmospheric forcing, solar radiation and the bottom/coastline topography. Changes in the current systems affect the distribution of particular organisms or processes, such as fronts, eddies or transport. Again a persistent change is required to alter ecosystem state. Considerable feedback and secondary interactions between wind, currents and radiation can be expected to accompany changes over decades, requiring long-term monitoring programmes.

The physical processes described above might cause, or at least play a role in species alternations in the Benguela LME, and notably those involving anchovies and sardines. These species alternations are potentially important for the ecosystem and consequently, to the management of human activites in the ecosystem. Species alternations might be mediated through subtle changes in feeding niches (James 1987, 1988, van der Lingen 2002) and spawning/recruitment habitat preferences (van der Lingen et al. 2001, 2002, van der Lingen and Huggett 2003) or, possibly, external factors like changes in the bio-chemical properties of the water masses entering the ecosystem. However, mechanisms maintaining the persistence of one species over the other are not yet clear (Hutchings et al. 1998, Schwartzlose et al. 1999). Fishing could also drive, or add to, the factors leading to species alternations. In the southern Benguela, the bycatch inflicted upon sardine juveniles during anchovy-directed purse seine operations when anchovies are dominant, is also important for sardine dynamics (De Oliveira et al. 1998). In the northern Benguela, the area of suitable spawning habitat appears to have remained the same in terms of temperature and phytoplankton, but the removal of "southern" sardine spawners by overfishing, the increased frequency of warm water intrusions across the Angola-Benguela front and the role of large jellyfish, which may be predators of fish eggs or larvae or competitors with sardines for zooplankton prey, are all possible mechanisms contributing to the decline in sardines. Horse mackerel increased in abundance in the northern Benguela and may play a role in suppressing sardine by preying on sardine and anchovy larvae or by enmeshing sardines in "school traps." These occur when a species at low abundance (e.g., sardine) subordinates its specific needs to those of a more abundant species by aggregating in a mixed school, potentially affecting individual fitness and reducing the population's chances of recovery (Bakun and Cury 1999). Fréon and Misund (1999) concluded that, for small pelagic fish, the urge to become a member of a school of similarly-sized fish of similar body form, regardless of species, is a dominating aspect of behaviour, and anchovy, sardine and horse mackerel have frequently been observed to aggregate in mixed schools. The midwater trawl fishery could have a significant bycatch (e.g. 5-10%) of adult sardines together with the 200,000 to 400,000 tons of horse mackerel caught annually. Sardines, currently at a much reduced population size, are probably only utilising a small fraction of the suitable habitat, and so are subject to severe predation by predators (snoek, seals, hake) which can also utilise alternative prey to maintain high population densities.

What ecosystem changes is it desirable and/or possible to monitor?

Monitoring upwelling areas to detect ecosystem changes is a daunting task, as boundary effects dominate the narrow, ribbon-like features on the eastern edges of ocean basins. A number of easily measured, remotely sensed parameters are obvious choices, which include surface temperature, water-leaving irradiance, wind strength and sea surface height. From these measurements a number of indices based on the habitat preferences of the dominant organisms can be derived (e.g., Hardman-Mountford et al. 2003, Daskalov et al. 2003, Agenbag et al. 2003, and also see references in Table 11-2). These tend to cover the spatial attributes of populations as related to boundary or average conditions. There are a few important parameters which require ground-truthing (e.g. primary production) or which cannot be measured remotely, which include zooplankton (micro-, meso- and macro-), extent of oxygen-depleted water, water column stratification and aggregations of prey organisms at interfaces. These parameters represent a much more difficult task as high mesoscale variability needs to be integrated over much longer space and time scales to be pertinent for ecosystem changes. Remote sensing, buoy deployment, regular shipboard monitoring and widespread but infrequent coverage during cruises of opportunity, such as fish survey cruises, need to be integrated using dynamic ecosystem models and simulated using coupled hydrodynamic/ IBM approaches. Feedback between theory and observations allows experiments to be conducted which simulate extreme conditions, determine thresholds, and minimise sampling redundancy.

A number of critical areas and processes have already been identified in the southern Benguela and theorised in the northern Benguela (Moloney et al. 2004, Hutchings et al. 2002). In the southern Benguela the SARP line off the SW Cape monitors the transport of pelagic eggs and larvae spawned on the western Agulhas Bank to the west coast. However the shift in spawning further eastwards to the central and eastern Agulhas Bank has confounded this time series to some extent. The St. Helena Bay Monitoring Line was designed to monitor:

- the feeding conditions of early recruits as they entered the west coast ecosystem;
- the feeding conditions of pelagic recruits inshore on the west coast as they grow and build up fat reserves for the migration southwards to the Agulhas Bank;
- the seasonal changes in the phytoplankton, including harmful algal blooms and micro- and mesozooplankton across the west coast shelf;
- the extent of low oxygen water on the inshore part of the shelf;
- the distribution of epipelagic and mesopelagic fish and other sound-scatterers across the shelf;
- the feeding patterns of large pelagic fish across the shelf; and

- the seasonal changes in the hydrodynamic structure and fertility of the west coast.

Areas not covered by current monitoring programmes in the southern Benguela include the western, central and eastern Agulhas Bank, including the cold ridge, the area off Port Elizabeth and off the tip of the Agulhas Bank, which Hutchings et al (2002) identified as critical transport gateways and the Lüderitz/Orange River cone area, i.e., the northern boundary of the southern Benguela subsystem.

Table 11-2. Indicators relevant to detecting long-term change in the BCLME

Indicator class and type	**Indicator examples**	**Key references for the BCLME**
Environmental and habitat indicators		
Pressure	- Indices related to effects of global warming - Pollution indices, e.g., number of pollution events by category	Bakun (1990) Reinikainen & Molloy (2003)
State	- SST, wind stress, offshore extension index; upwelling index - wind pulses; - thermogradient, stratification indices (e.g. depth of the thermocline) - intensity and position of fronts, deviation from mean position of the front; - other indices of large scale forcing, e.g., Benguela Niño; - LOW indices; - Phytoplankton biomass and productivity; - Size distribution or spectra of phytoplankton and zooplankton; - Ratio large/small zooplankton; - Total zooplankton abundance.	Richardson et al. (1998) Roy et al. (2001) Demarcq et al. (2003) Reinikainen & Molloy (2003) Hardman-Mountford et al. (2003) Shillington et al. (*this volume*) Monteiro et al. (*this volume*) Painting et al. (1998) Verheye et al. (1998))
Single species indicators[1]		
Pressure	- Number of non-target species caught by method, area and season or year - Exerted effort, total capacity in suitable categories - Abundance/ biomass of pollution indicator species	Nel et al. (2003)
State	- Abundance of gelatinous organisms - Abundance, condition, breeding success/ recruitment of sensitive species (e.g. seals, gannets, penguins) and/or top predators (e.g., hake) and/or indicator plankton forms (if any) - Dominance and distribution of species indicative of environmental change, e.g., sardine / anchovy ratio (aimed at tracking alternation between species) - Species diversity (by community) - Genetic diversity (by species) - Abundance of exotic species - Spawner biomass & recruitment trends, age (or length) at first maturity, growth rate trends, condition factor of trends species sensitive to fishing.	Roux & Shannon (2004) Kemper et al. (2001) Roux & Mercenero (2004) Hutchings et al. (1998) van der Lingen et al. (2001) Crawford et al. (1985) Reinikainen & Molloy (2003) Korrûbel et al. (1998) Barange et al. (1999) Kreiner et al. (2001) Fairweather et al. (in prep.a,b)
Size-based indicators		
Pressure	- Minimum authorized mesh-size on fishing gears - Minimum authorized fish size per species or group of species	
State	– Mean and maximum length of populations sensitive to ecosystem change – Size at maturity, condition at size of selected (not necessarily target) populations – Medium and maximum length of a community, Slope of the size spectrum	Fairweather et al. (in prep.a,b), Shin et al. (2005) Yemane et al. (2004)
Trophodynamic indicators		
Pressure	– FiB – Mean trophic level of catch (incl. bycatch)	Cury et al. (2005a)
State	– Catch and biomass ratios, production and consumption ratios of selected groups/guilds (e.g., pelagic vs. demersal, planktivores vs. piscivores) – Primary production required to sustain production of selected groups/guilds – Mixed trophic impact and similar indices of trophic dependency	Cury et al. (2005a) Moloney et al. (2005)
Spatial indicators		
Pressure	– Mean ratio between exploited area and distribution area by species, – Exploited fraction of the ecosystem	Fréon et al. (2005b)
State	– Spawning distribution of adults and eggs of populations exploited by the fishery – Total distribution area of the stocks, fraction of habitat actually used	Drapeau et al. (2004) Pecquerie et al. (2004)

[1] Defined here as species that are important for ecosystem structure and functioning, not necessarily limited to fisheries' target species.

In the northern Benguela system, the extent of low oxygen water and the intensity and location of the Angola-Benguela Front are considered to be critical components. The intense upwelling zone at Lüderitz is also important as a boundary zone separating oxygenated Atlantic Central Water originating from the Cape Basin in the south from less-oxygenated Central water moving southwards from Angola. The inshore area at 20-25 °S is important as a nursery region for recruitment of hake, horse mackerel and sardine to the northern Benguela stocks. A Marine Oceanographic Monitoring (MOM) transect at 23°S is currently monitored for oceanographic and biological variables each month, with a supplementary transect at 20 °S sampled every alternative month. A further transect at 15 °S in southern Angola covers the northern boundary of the Angola-Benguela front, but logistical problems have resulted in infrequent, irregular sampling. Continuous, underway fish egg sampling should commence in Namibia in 2005, to complement the CUFES surveys undertaken in the southern Benguela. These surveys will demarcate the spatial extent of pelagic fish spawning over extensive areas in the Benguela Current. There are plans to extend oceanographic monitoring throughout the subtropical system off Angola in the near future. For all Benguela LME sub-regions, the existing monitoring of fishing activities, and resource status, needs continuation. However, in order to assess structure, dynamics and changes at the ecosystem level, it is necessary that monitoring extend beyond abundance/biomass alone. As an example, continued monitoring of diet compositions of predators is essential for detecting and understanding changes in trophic structure (e.g. MacQueen and Griffiths 2004).

APPROPRIATE ECOSYSTEM INDICATORS AND MODELS

Because there is no general theory that can describe the whole functioning of marine ecosystems, the management decision process must be based on several different tools, analyses, models and indicators. An indicator generally is defined as a variable, pointer or index, whose fluctuation reveals key characteristics of a system. The position and trend of the indicator in relation to reference points or values indicate the present state and dynamics of that system, and in this respect, indicators can link observations on the one hand to management goals and objectives on the other (Slocombe 1999, FAO 1999). For this contribution, we use the term "ecosystem indicator" as a measurable characteristic of an ecosystem, which can provide feedback to the question of whether or not long-term ecosystem change is occurring.

Indicators are fundamental to wider objectives in the management of human activities in the ocean, as e.g., under an Ecosystem Approach to Fisheries (Sinclair and Valdimarsson 2003, FAO 2003). Because of the link to management objectives, it is important to keep in mind that the relevance of any indicator will not only depend on the specific objectives for its use, but also on the particular group of people that is to be informed by it (FAO 2003, Degnbol and Jarre 2004). Much research on properties and applicability of marine ecosystem indicators has recently been carried out by the SCOR/IOC Working Group 119 on "Quantitative ecosystem indicators for fisheries management" (www.ecosystemindicators.org), and the proceedings of a dedicated international conference have just been published (for an overview, see Cury and Christensen 2005). In this context, "ecosystem" science in the Benguela LME is at the international forefront (Cury et al. 2005a,b, Moloney et al. 2005, Fréon et al. 2005a,b, Underhill and Crawford 2005, Yemane et al. 2005, but also see the contributions in Shannon et al. 2004c).

It is often questioned whether indicators really improve our ability to detect/predict resource and ecosystem changes beyond the detection/prediction capability that single species/resource trajectories alone can offer. The danger of relying only upon single species indicators (e.g. survey or catch records) is that one misses capturing the effects of interactions between these resources, and catch data in particular may not necessarily reflect what is happening at the community or ecosystem level. Indeed, simulations carried out to formally evaluate the performance of a large suite of indicators, show that community-based indicators may hold most promise in a management context (Fulton et al. 2005), and that it is necessary to use a variety of indicators simultaneously, capturing several key functional groups.

These recent results support our general experience that the net effects of the various direct and indirect interactions in an ecosystem are often unexpected and sometimes counterintuitive. Consequently, a formal mechanism is required (and proposed below) that combines the signals from the various indicators, for use in a management context.

With respect to management, several frameworks for the use of indicators exist; here we base our discussion on the DPSIR framework as used, *inter alia*, by GOOS and the European Community (Smeet and Weterings 1999, IOC/GOOS 2003: p.87). Contributions from the natural sciences focus on the pressure (P) and state (S) categories, whereas the indicators of drivers (D), impact (I), and response (R) often would be rooted in the social sciences. Selected indicators for the Benguela are summarised in Tables 11-2 and 11-3.

What ecosystem indicators can be used to help detect change in the Benguela LME?

Indicators scrutinised by the SCOR-IOC Working Group 119 were grouped into the categories "single species and habitat", "species-based", "size-based", "trophodynamic", "spatial" and "integrated". We follow this structure to introduce some indicators for detecting change in the Benguela LME.

Habitat indicators for the Benguela are to a large extent derived from physical oceanography, and are mostly GOOS variables (IOC/GOOS 2003) or derivatives. Indicators of productivity and characteristics of the productivity chain provide an indication of the primary production of the ecosystem (Richardson et al. 2003 a,b) and its major characteristics in terms of structure, especially the short *versus* the long food chains of plankton (Demarcq et al. 2003). They can be derived from *in situ* or satellite observations (Carr 2002; Carr and Kearns 2003).

Species-based indicators integrate various ecosystem signals in time and space while still having relatively fast response times. In the Benguela LME, they have principally been used for sensitive or threatened species (e.g., cormorants, gannets, penguins) or for top predators (e.g., seals, whales). Recently, however, a suite of indicators for both anchovy and sardine derived primarily from fishery-dependent data has been developed, including length at maturity, mean length of the catch, centre of gravity of catches, exploitation rate and others (Fairweather et al. in prep. a,b). Size-based indicators have the advantage of a good theoretical basis, and are relatively cheap to obtain, as size is easy and cheap to measure (Shin et al. 2005).

Trophodynamic indicators measure the interaction strength between species and help to track structural changes in the ecosystem caused by fishing or environmental forcing. Cury et al. (2005a) reviewed indicators derived from trophic models and catch records, and applied eight selected trophic indicators to the northern and southern Benguela ecosystems. They were found useful for detecting large ecosystem changes and for understanding ecosystem and fisheries dynamics. However, good understanding of trophic interactions in the system is crucial for their meaningful application (MacQueen and Griffiths 2004, Moloney et al. 2005). Both size-based and trophodynamic indicators appear conservative, and suitable reference points generally are still lacking. Their signal is relevant for strategic planning, not for management decisions on the short term.

Several spatial indicators have been developed from a GIS that covers the areas fished by three major fleets in the southern Benguela, the foraging areas of three top predators and the distribution of 15 important fish species (Fréon et al. 2005b). These spatial indicators can be used to monitor changes in the ecosystem and the effectiveness of fisheries management in an ecosystem context. Similarly, Drapeau et al. (2004) used a GIS to explore potential spatial interactions between 13 important resources (including small pelagic fish, horse mackerel, and hake) in the southern Benguela and to quantify their spatial overlap. After the incorporation of information on the diet of different species and from trophic models, the main trophic interactions between those resources were identified and mapped, complementing conventional trophic models that are not spatially resolved.

True co-operation between natural and social scientists in management of human activities in the ocean, including the detection of change relevant to the ecosystem, is still in its infancy. Indicators integrating information from both research realms are, therefore, only now starting to become available. Recent collaboration between natural and social scientists to examine stakeholder perceptions about the status of small pelagic resources off South Africa (as part of the Knowledge in Fisheries Project [EU/INCODEV KNOWFISH]) indicated convergence between resource users and natural scientists in those perceptions (Fairweather et al. in prep. c). Baseline economic and socio-economic data for South Africa's fisheries have been compiled and used to provide socio-economic indicators for each (Mather et al. 2003; Sauer et al. 2003, Table 11-3).

What threshold levels or turning points can be used to define different ecosystem states?

Specifying the threshold levels or turning point indicators that can be used to define different ecosystem states is a complex issue that requires detailed discussion, and only general considerations are presented here. Univariate analysis can be used to determine if, or when, an indicator statistically passes a threshold value that can be assigned according to the variance of the time-series examined (typically a departure of two standard deviations from the mean), but this approach is constrained by problems associated with the length of the time-series, and its distribution function. Obviously, the threshold value must be passed (above or below) for a minimum number of years before suggestions of a change in ecosystem state or a regime shift can be entertained.

Table 11-3. Social and economic indicators relevant to detecting long-term change in the BCLME.

Indicator class and type	Indicator examples
Pressure or Impact	***Social***[1] - Population density along coast (by area) - Land-use patterns along the coast - Employment in harvesting sector by area and fleet - Dependence of coastal communities on fishing (by area) - Degree of literacy in coastal population (by area) - Lifestyle value (by area) - Cultural value (by area) - Use of goods & services by sector & area, e.g., harvesting effort, beach tourism, ecotourism - Tradition and potential of using artisanal exploitation (spatialised indices as far as possible) - Reservoir of unemployed people for low-qualification fishing employment (e.g. beach seine)
	Economic[2] - Fleet structure (by gear and area) - Degree of industrialisation of fisheries (by area) - Degree of poverty in coastal population (by area) - Importance of harvests as source of nutrition for resident population: e.g., consumption of (local) marine products per capita in coastal communities; - Importance of harvests as source of income, .e.g, Mean, range and variance of per capita revenue (spatialised as far as possible) - Net economic return for fishery, profit to harvesting sector, - Governmental subside to the fishing sector - Royalties (absolute value or trend) for forein fleets - Price (absolute value or trend) of fishing products at the regional, national or global scale when relevant (e.g. fishmeal, fish oil, frozen products) - Price (absolute value or trend) of soya meal (as a substitute or complement to fishmeal) - Balance between the use of fishmeal versus soya meal in farming (poultry, pork, aquaculture) - Fraction of income generated from eco-labelled marine products and services; - Importance of non-consumptive use as source of income (e.g., leisure activities, tourism, aquaculture) - Structure of non-consumptive use modes (by activity) - Relative importance of mode of ecosystem use, by activity (e.g., generated income) - Resources (personnel & monetary) available for monitoring, control and surveillance of ecosystem use - National budgetary allocation to research (e.g, into the ability to detect change) within the BCLME (by region) - External economic inflows to research (e.g., into the ability to detect change) into the BCLME (by region)
	Measures to increase ecological sustanability of harvesting[1] - Number (and fraction) of fisheries with well-developed management plans, including indicators and references points (or directions); - Fraction of co-management arrangements (of all management arrangements) implemented and successful - Fraction of government officials involved in ocean management trained in conflict resolution and/or change management - Fraction of management arrangements that are considered legitimate among the majority of stakeholders involved in the corresponding arrangement Degree of compliance with management arrangements
Response	***Indicators derived to monitor change in*** - National policies on employment /unemployment management in the fishing sector; - National policies and allocated resources on compliance with rules of resource access and use; - National policies on aquaculture development; - National policies on access rights (open or closed); - National policies on incentives to control and modify overall fishing capacity in the different segments of the fishery (industrial, small-scale, etc.).

[1] Based on Sowman et al. (2003), Reinikainen and Molloy (2003) and FAO (2003)
[2] Based on Mather et al. (2003), and Sauer et al. (2003)

Using absolute threshold values may not be particularly useful given the high variability observed in many biological time-series for the region (e.g. small pelagics; see Figure 8-3 of van der Lingen et al., *this volume*). Because the definition of a change in ecosystem state will remain largely empirical, it is suggested that multivariate statistical tests or indices be developed, which will allow more confidence to be given to cases where several indicators coincide in their detection of a change in ecosystem state. Time-series of population descriptors of anchovy and sardine in the Benguela LME have been compiled, including data on egg distributions and the seasonal pattern of spawning, larval abundance, recruitment and stock size, condition factor, the contribution of these species to the diet of selected predators, and annual landings (Crawford et al., unpublished manuscript). However, methods to objectively detect turning points that may be indicative of ecosystem changes or regime shifts in the Benguela LME have not been applied to these time-series, which should be re-evaluated using one or more of the multivariate techniques for detecting regime shifts reviewed by Mantua (2004). For example, Hare and Mantua (2000) applied Principal Components Analysis (PCA) and the Average Standard Deviates compositing approach to empirical evidence from the North Pacific and identified regime shifts in 1977 and 1989. Whereas those authors reported relative clarity in the regime shift of 1989 as indexed by biological data, they found a lack of clear change expressed by climate indices, leading Mantua (2004) to suggest that biotic and abiotic time-series should be analyzed separately in order to isolate ecosystem behaviour from other influences such as environmental change.

Whereas PCA provides an attractive means of investigating regime shifts since it requires no *a priori* assumptions about candidate years, its major limitations include its inability to identify non-linear relationships between input variables, and the requirement for further time-series analysis using methods such as Intervention Analysis in order to identify statistically significant shifts in the principal components scores (Mantua 2004). PCA and additional time-series analysis should be applied to data from the three sub-systems of the Benguela LME in order to derive new time-series that can permit the identification of particular ecosystem states (or regimes; see above) and key state variables in each sub system, and also the identification of the time periods during which those key state variables are in transition between different quasi-stable attractors (*i.e.* regime shifts *sensu* Mantua 2004; see Table 11-1).

What models can be used to help predict ecosystem change?

It is likely that many different models will be needed to help detect and predict ecosystem change. Model development should be guided by specific objectives related to different aspects of detecting and forecasting long-term ecosystem changes. Rather than first try to reproduce the real world in a model and then use it to make predictions, appropriate models should be developed to address specific questions, and the results should be combined in a sensible way. In this section we describe different kinds of models that address different components of the ecosystem at different temporal and spatial scales.

3D hydrodynamic models forced by realistic winds, solar radiation and boundary conditions can be used for now-casting or forecasting of environmental events that might exert bottom-up controls on ecosystems, especially if they incorporate data assimilation (e.g. Chen et al. 2004). The same models forced by scenarios of long-term climatological changes, such as those predicted in relation to global warming, can be used for the "what-if" type of forecasting *sensu* Woods (*this volume*). The major challenge here is to get realistic scenarios at large temporal and spatial scales. Conflicting views can result from the use of different models (Fréon et al., *this volume*). Furthermore, it is difficult to disentangle the interactions between the recent global trend of warming and natural inter-decadal climatic oscillations. Nonetheless, these scenarios can be useful to indicate the expected ranges of magnitude in sea temperature and currents and, by elimination, exclude unlikely situations.

Marine plankton can integrate meteorological variability, and because of their environmental sensitivity, short life cycles and inability to escape their environment, they make excellent indicators of environmental change and are invaluable in the mapping of the environmental consequences of climate change in the marine environment (Reid et al. 1998). Single or multi-species plankton stage-resolved and spatially-explicit models are seldom used but could help to predict the effect of large climatic changes on the plankton community and to improve the parameterisation of biogeochemical models. However, a major difficulty is to simulate and predict behavioural changes in feeding and vertical migration. Biogeochemical models (e.g. NPZD models), especially those with enough compartments to distinguish short from long plankton trophic chains, can be used for "what-if" forecasting. The present state of the art allows satisfactory simulation of observed phytoplankton abundance and distribution but is not yet sufficiently evolved to fully reproduce the complexity of zooplankton spatial and temporal dynamics. Therefore one cannot expect too much precision in zooplankton long term forecasting.

Conventional single species models for fish stock assessment can provide estimates of change in abundance according to different exploitation levels, but these models do not incorporate the effects of changes in the abundance of prey and predator of the considered species, and they usually assume constancy in population parameters. Multispecies models of population dynamics incorporating trophic relationships allow for variability in population parameters, but are usually constrained by data availability and their results have increased uncertainty. Age-structured or surplus production models incorporating an environmental variable can be cautiously used for short-term prediction, especially for low trophic level species, but are currently unable to take into account interdecadal changes such as the alternation between sardine and anchovy. Because the processes driving these interdecadal changes are not understood, only empirical models can be used at present (Klyashtorin 2001; Fréon et al. 2005a).

Fishery GIS can be used to simulate changes in fish distribution and spawning area according to predictions of environmental changes and knowledge of habitat preferences (e.g. temperature). The difficulty here is to describe adequately fish habitat according to realistic proxies of forcing factors. Finally, trophic box models like EwE (Pauly et al. 2000) or dynamic and spatially-resolved individual-based models like Osmose (Shin and Cury 2001) can help to predict the effect of drastic exploitation or climate change on the structure and functioning of ecosystems (Shannon et al. 2003 a, b, Shin et al. 2004).

All these models have a role to play in understanding the dynamic processes in an ecosystem. Some of the models have an empirical statistical basis, whereas others are based on "first principles" (*sensu* Schneider 1992). The empirical statistical models depend on historical data, and can produce predictions with estimates of probability. However, the models are generally limited to predicting scenarios that have been observed in the past, or that do not depend on new processes. They are probably most useful for short-term predictions. Models that are based on first principles use equations and relationships that represent the main processes, and are well suited to *what-if* predictions. However, for these models it is difficult to validate their results, and they are probably most useful for identifying possible ecosystem states, for eliminating unlikely ones, and for identifying potential indicators of change. Ideally, we would hope to combine the results of all models in a structured and logical fashion, to make best use of available data and untested hypotheses.

In conclusion, no real ecosystem model can be used for prediction yet. There are possibilities of models being adaptable (e.g. growth rate controlled by temperature) but this often does not include all effects and interactions. The bottlenecks are our poor understanding of how systems function and how species will adapt to drastic changes in their habitat. Future advances in these fields will allow better parameterisation or changes in assumptions; modelling of long term changes must be viewed as a dynamic process. However, it is also likely that the more we learn, the more we realise we do not know! Most of the models reviewed in this section are already available for the Benguela region (Table 11-4) and form part of the "ecoscope" toolbox (Shannon et al. 2004b; *CD this volume*). At this stage we suggest that it would be productive to develop synthesis tools to make best use of the available modelling expertise, taking into account different degrees of uncertainty in the models. It is expected that conflicting outcomes will emerge from different tools, but not only does one learn from the models, one also learns from the model errors – at least as much.

DESIRED END PRODUCTS AND DATA REQUIREMENTS

Integrated data management and communication sub-systems are seen as the primary integrator of ocean observing systems, "the 'life-blood' of the system that links all of its components" (IOC/GOOS 2003: p. 102). To detect and monitor ecosystem changes in the Benguela LME region in the long term, we propose that integrating tools be developed for the Benguela LME that allow the interpretation and synthesis of different ecosystem indicators. Past experience indicates that knowledge bases (*sensu* Starfield and Louw 1986) that are formalised within "rule-based models" (Starfield and Louw 1986; Ferrar 1986; Liao 2005) are well suited to such an application. Rule-based models have been constructed to predict recruitment strength of anchovy in the southern Benguela (e.g., Korrûbel et al. 1998; Miller and Field 2002, see CD (*this volume*) for an example application of this approach using the software of Quadling and Quadling 1995). We argue that the flexibility of this approach has not been exhausted, and that it can be applied profitably to the detection of long-term change in the Benguela LME. Because a multitude of information sources needs to be considered, this approach can facilitate assessment of whether ecosystem change is taking place in a logical, defendable and transparent way.

Table 11-4. Examples of models available for sub-regions in the BCLME than can be used for scenario exploration in a comparative fashion

Class of model	Benguela implementation	Reference
Physical-Biogeochemical		
3D hydrodynamic	PLUME, RIGA and SAFE	Penven et al. (2001)
NPZ(&D)	NPZD and N2P2Z2D2	Koné et al. (submitted)
Zooplankton population models	No zooplankton models being applied yet at an ecosystem scale	Moloney (pers. comm.)
Environmental Processes / Bakun's triad	Enrichment and retention SB	Lett et al. (*in press*)
IBM	Anchovy recruitment SB Sardine recruitment SB	Mullon et al. (2002, 2003), Parada et al. (2003, *submitted*), Huggett et al. (2003) Miller et al. (*in press*)
Process-based multispecies		
Size-based ecosystem	OSMOSE	
Trophic ecosystem	EwE	Shannon et al. (2003 a,b), Shannon et al. (2004a)
Analytical empirical*		
Fish stock assessment models, single species	Bayesian assessments, age-structured production models, virtual population analyses.	Cunningham & Butterworth (2004 a,b), Johnston & Butterworth (2004), Rademeyer & Butterworth (2004).
Multispecies	Minimum realistic models	Punt & Butterworth (1995)

* In contrast to process-based multispecies and ecosystem models, analytical models do not model predator dynamics in their own right, and consequently, predation is only used as a forcing fuction for modelling prey dynamics. It is generally recognised that results such of analytical models often form the basis for algorithms and parameters used in process-based multispecies models (e.g., Whipple et al. 2000).

Expert systems typically contain a high level of expertise in a form that makes it accessible. The expert system models should provide an effective means of communication between scientists and end users (Starfield and Louw 1986), and they ave the potential to inform management groups within the region about the current nd possible future state of the ecosystem in a consistent fashion. Such knowledge vould be useful for resource management, for long term planning within different isheries sectors, and for environmental managers. In addition, because expert system nodels capture expertise from a variety of specialists, they provide an important nterdisciplinary information source for local, regional and international scientific ommunities, including academics, practitioners, decision-makers and students.

ecision support tools in general, and expert systems in particular, have evolved onsiderably during the past two decades (Guimarães-Pereira et al. 2005). The roblems of integrating disparate kinds and sources of information are encountered in nany arenas. For example, Roetter et al. (2005) describe a system for land use lanning in Asia, Power and Bahri (2005) describe an improved system for co-rdinating operational tasks in industrial plants, and Guimarães Pereira et al. (2005) how how an innovative information tool is applied to a groundwater governance issue n France. This last study emphasized that knowledge tools are useful for initiating nd informing debates, rather than simply for legitimising decisions.

Vhat is an expert system?

xpert systems capture and organise knowledge in a database (Starfield and Louw 986). They provide a formal means of synthesis, as opposed to analysis, and they rovide an operational language (IF-THEN rules) that is equivalent to mathematics as he language of analysis (Starfield and Louw 1986). In the context of ecosystem hange, rule-based models can synthesize different ecosystem indicators so that, as a roup, the indicators are interpreted effectively and consistently to identify the robability of long-term ecosystem change. A simplified draft template is shown in igure 11-3 to illustrate the approach. A variety of models and observations is used by xperts to produce ecosystem indicators. Each indicator typically and individually night suggest one of six (for example) possible states of the ecosystem:

- No indication of long-term change, current state neither identified as good or bad;
- No indication of long-term change, current state good;
- No indication of long-term change, current state bad;
- Indication of long-term change occurring, direction of change neither identified as good or bad;
- Indication of long-term change occurring, direction of change identified as good;
- Indication of long-term change occurring, direction of change identified as bad.

n identifying possible states, the assessment of whether each is good, bad or neutral equires both ecological and socio-economic criteria. The expert system therefore rovides a vehicle for multi-disciplinary integration. Individual indicators are likely to ocus only on aspects of the ecosystem. The interpretation of some indicators may be mbiguous (e.g. sardine is increasing in abundance while anchovy is decreasing), whereas others may give clear signals (e.g. jellyfish appear to have increased in abundance by two orders of magnitude). It will be necessary to garner expert opinion, on the interpretation of the indicators when viewed as a group, and at this stage the rules are constructed (Figure 11-3), and expertise is captured within the expert system. While straightforward in structure and seemingly "simple" (see also van der Lingen et al. *this volume*), expert systems in practice rapidly acquire a degree of complexity that underlines the usefulness of such a formal approach in decision support.

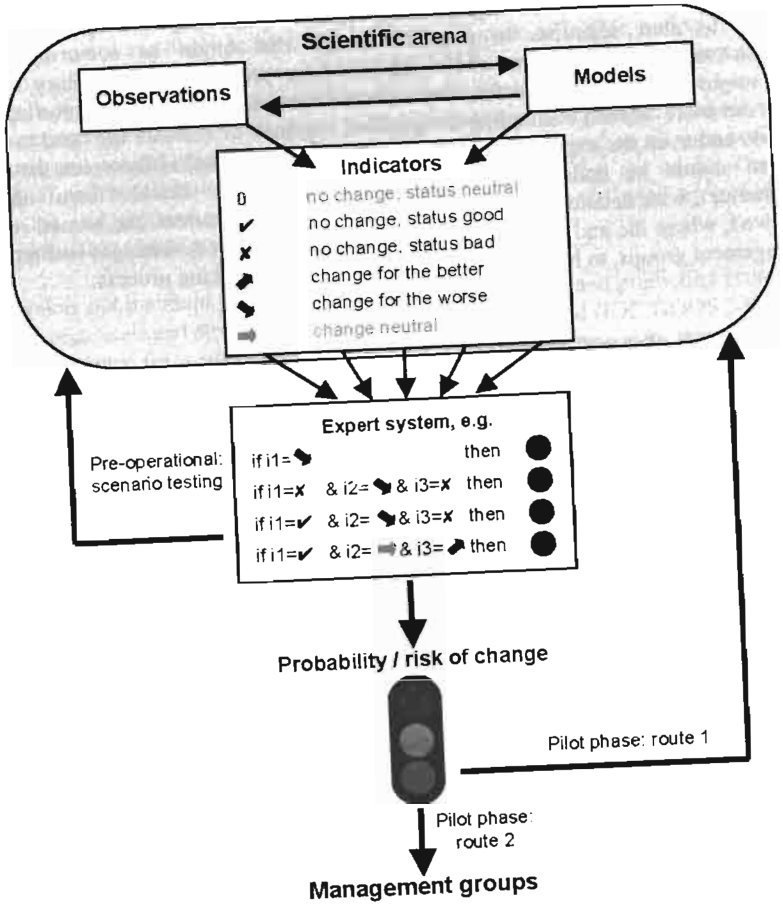

Figure 11-3. Outline of the expert system approach recommended for integrating the information of various indicators of long-term change in the entire BCLME or its sub-regions. Note that the development and calculation of indicators resides in the scientific domain only, whereas stakeholder expertise should be part of the process of definition of rules underlying the expert system model.

Developing and maintaining an expert system for detecting and predicting ecosystem change will be a dynamic process. In the initial, pre-operational stages of development, the focus will be in the scientific arena (Figure 11-3), where the system is tested using *what-if* scenarios and modified. Guimarães-Pereira et al. (2005) pointed out that broad participation of all stakeholders in designing and exercising the knowledge-based system corresponded to a peer-review process, providing elements of quality assurance. The system can then be moved into a pilot phase, where two sequential routes for the end-product (the "traffic light" signal) are suggested (Figure 11-3). The first route is from the "traffic light" to the research community. The purpose of this step is to alert scientists to possible change that might be occurring, or to inconsistencies in the results, where indicators are providing contradictory signals. This might provide guidance for future short-term research and/or monitoring (e.g. carry out more intensive sampling in specified regions), or indicate the need to check models and even the expert system as necessary. If the signal is incorrect, the expert system should be updated and refined (expert systems should "learn" through experience), with detailed documentation. If the signal is correct, the second route is followed, where the end product (an indication of change or no-change) is directed at management groups, to help inform them in the decision-making process.

Requirements of expert systems

At present, many research groups within the Benguela LME are producing indicators as part of their normal activities. For the medium term, we can probably assume that existing data will continue to be needed and will also be available in the future. However, there are currently some important data gaps, and these should be discussed and prioritized in the short term. Some examples of data gaps include comprehensive measurements of sub-surface variables (e.g. changes in depth of the thermocline), primary production (from field measurements and remote sensing), and integrative variables (over large spatial areas, from remote sensing and towed undulator technology).

For an expert system to be developed and tested, time series of indicators are required. Because these time series are likely to be short relative to the time scale being considered, it would be useful also to use a comparative approach, where data are standardized across sub-systems and scales, allowing comparisons among different sub-systems within the Benguela LME region, and other LMEs.

The major inputs to the expert system are the various indicators. At present, many of these are produced without qualifiers or errors. The outputs of the expert system will depend on a weighted assessment of the inputs (the indicators), and this assessment should be informed by the skill of the indicators in providing reliable values. For some indicators the skills level can be represented by confidence intervals and error estimates, whereas others might require more qualitative reliability scores. This is an area of research that needs to be tackled in the short term.

What are the appropriate time and space scales for data and predictions?

The expert system will serve as an early warning system for long-term changes including, but not restricted to, regime shifts. The key characteristic of a regime shift is that the time-scale for the change between states is much shorter than the time within alternate states. This pragmatic definition can be applied, or tested, by measuring the rate of change of time-series (de Young et al 2004), and this will provide guidance for the interpretation of different indicators in developing the expert system. For the end-products of the expert system, the time-scales for depicting ecosystem states are likely to be of the order of a decade or longer, and spatial scales probably also will be large (*sensu* IOC/GOOS 2003), probably incorporating all three main sub-systems (off South Africa, Namibia and Angola). Other levels of ecosystem organisation might also be considered, such as benthos versus pelagial, inshore versus offshore, and coastal gradients. In general, data will be required on all time scales up to annual and possibly longer, depending on the indicators that are used. The time scales for end products should be annual, although this would need to include the recognition that trends are being analysed.

To develop and maintain an operational system for detecting and predicting ecosystem change, organisational structure and infrastructure are required (IOC/GOOS 2003). Of great importance for a sustainable system is the need to improve data management in the Benguela LME region, including systems for quality assurance and quality control, and good communication (IOC/GOOS 2003). Previous experience in the North Atlantic is that an optimum staff complement is needed to ensure effective database design and maintenance, and for timely provision and analysis of national and regional data (e.g., ICES 1999, OSPAR 2000). There is an urgent short-term need to address data management and communication issues within the Benguela LME region, and to foster strong institutional partnerships that will facilitate this.

SCHEDULE FOR IMPLEMENTATION

Environmental changes related to regime shifts are not yet taken into account in fishery management (Sinclair and Valdimarsson 2003, ICES 2004, Rothschild and Shannon 2004). Detecting and predicting changes and finding ways of incorporating this information into fishery management advice are highly desirable, particularly in the light of the "Reykjavik Declaration on Responsible Fisheries in the Marine Ecosystem", to which Angola, Namibia and South Africa are signatory and thus obliged to ensure that the declaration is upheld and fully considered in the work of their fisheries scientists, in the functioning of their fishing industries and in their respective fisheries management approaches. Further, the targets agreed upon at the World Summit for Sustainable Development (WSSD), held in Johannesburg in 2002, include the following undertakings:

- "Encourage the application by 2010 of the ecosystem approach, noting the Reykjavik Declaration on Responsible Fisheries in the Marine Ecosystem and decision 5/6 of the Conference of Parties to the Convention on Biological Diversity" (WSSD Chapter 4, paragraph 29 d)

- "Develop and facilitate the use of diverse approaches and tools, including the ecosystem approach, the elimination of destructive fishing practices, the establishment of marine protected areas .... and time/area closures for the protection of nursery grounds and periods..." (WSSD Chapter 4, paragraph 31 c)

What are the priorities for detecting and forecasting change?

In the Benguela LME region as a whole, high priority for detecting changes will be given to issues that require immediate management attention. In addition, due to the fact that this is a developing region, issues with social and economic implications (e.g. food supply and employment) generally will be given first priority.

Several marine taxa endemic or migrating to the Benguela LME region are vulnerable or endangered and could be affected drastically by ecosystem changes. Many species of seabirds and some cetaceans are highly sensitive to changes in abundance and distribution of their prey (small pelagic fish in particular) as well as being affected by industrial fisheries through incidental catches. In order to comply with international agreements, countries in the region might have to implement immediate remedial actions to improve and maintain the conservation status of those species.

Due to different ecological and socio-economic contexts, it is expected that priorities will differ between the different sub-regions of the Benguela LME. In the southern Benguela, large fluctuations in abundance, species alternations and shifts in distributions of small pelagics (sardine and anchovy) have had significant economic impacts on the fisheries sector as well as important ecological implications (Cury and Shannon 2004, Shannon et al. 2003b) and constitute probably the highest priority there. Ecosystem changes in the inshore communities involving abalone, kelp, west coast rock lobster and sea urchins (Cochrane et al. 2004) are also of high priority due to the high market value of the products of the fisheries involved and their impacts on the local communities.

In the northern Benguela, the collapse of the small pelagic stocks (sardine in particular) in the early 1970s and mid 1990s has had profound ecological (e.g., Cury and Shannon 2004) and economic (Armstrong and Thomas 1995) implications. The reasons for the lack of recovery of the sardine stock are still not completely understood (van der Lingen et al. *this volume*) and warrant the highest priority in Namibia in order to attempt rebuilding this stock and restoring the degraded pelagic ecosystem. Forecasting environmental anomalies (Benguela Niño and low oxygen events) and detecting longer term ecological changes are important as they may have long term impacts on the whole ecosystem and the fisheries and require timely management mitigating actions (Roux 2003, Roux and Shannon 2004, van der Plas et al. *this volume*).

In Angola, the ecosystem effects of habitat degradation (effect of fishing gear on benthic habitats and degradation of mangroves in particular) have been highlighted as a priority due to their potential impacts on some key commercial resources (shrimps) as well as the sustainability of the multispecies demersal fishery important for local food supply (Cochrane 2004). Ecosystem considerations linked to the horse mackerel industrial fishery and the depletion of the stock, as well as changes in abundance and distribution of *Sardinella sp.* are also important both in their ecological and socio-economic implications.

What practical steps can be taken? What are realistic time frames for implementation?

Short term (1-3 years)

There is a need for improved understanding of current ecosystem states in the sub-regions of the Benguela LME, and evaluation of the extent to which they are ecologically, economically and socially desirable. The capability to predict (or hypothesize) whether and how long-term changes occur would be a giant leap forward in being able to manage fisheries in an ecosystem context. A necessary step would be adaptation and development of multivariate statistical tools for the analysis of available time series (catch, spawner biomass, recruitment, egg and larval abundances, fish condition factor, proportion of pelagic fish in predators' diets, etc.), and this is seen as an important area of study. A proposed starting point is the time series collated and examined during a workshop to identify "turning points" in the Benguela ecosystem (Alheit et al. 2001, Crawford et al. unpublished MS). We recommend that these data be revisited with preliminary statistical analyses of catch and biomass series, and with an analysis using a methodology that has been developed more recently (see above section, "What threshold levels and turning points can be used to define different ecosystem states?").

Generic indicators for detecting and monitoring ecosystem changes can be indentified through a comparative approach to establish which indicators are likely to be the most sensitive to detecting ecosystem changes across a range of possible ecosystem states and driving forces. By comparison with other ecosystems, an attempt to identify indicators or early warning signals of ecosystem change would be valuable. For example, early warning indicators of small pelagic fish stock collapses have been proposed as a high priority for management of the South African pelagic fisheries. Single species indicators should be examined in conjunction with ecosystem/integrated indicators and environmental indicators, and the most appropriate set of indicators should be selected for each fishery. It would be important to ensure that these indicator sets are regularly updated to inform management and to be used by the proposed expert system (see medium-term actions below).

Establishing reliable, taxon-specific, spatially extensive and area-explicit estimates of primary production for developing long time series are important short-term targets for understanding ecosystem changes in the Benguela LME region. Backward projections of existing time-series (likely to extend into medium-term activities) enable quantification of variability of bottom-up forcing over short periods (years, e.g., Carr

2002, Demarcq et al. 2002). Trophic models can be used to estimate what should have been required to generate the observed dynamic fluctuations within the southern and northern Benguela ecosystems (e.g. Shannon et al. 2004a), but quantitative estimates of primary production over the whole Benguela LME region (including off Angola) still require refinement and ground-truthing, and longer time-series are needed.

Another major "gap" would be filled by estimates of the biomass of gelatinous zooplankton in the northern Benguela. Trophic impacts of gelatinous zooplankton on predators and prey need quantification to assess the trophic roles of gelatinous zooplankton in the northern versus southern Benguela ecosystems. Results might be expected in the short term, with refinements in the medium term.

Medium term (4-7 years)

An important medium-term target is the development of methodology to quantify uncertainty related to both inputs and outputs of ecosystem models (e.g., confidence intervals). Other practical steps should include completion of (or new) analyses of sediment deposits (fish scales, plankton) and linkage of these records to historical ocean climate, and possibly investigation of the potential value of ecosystem modifications (importantly, with necessary caveats: see discussion at the end of section "What changes in the ecosystem might be caused by fishing, pollution, environment, or climate?").

There is also a need for evaluation of the usefulness of Marine Protected Areas (MPAs) as control systems for purposes of comparison with fished/uncontrolled ecosystems subject to the same environmental effects. This could assist in distinguishing the effects and/or driving forces for ecosystem change exerted by anthropogenic versus natural (environmental, biological) processes. In addition, MPAs provide opportunities for the validation of community indicators (Trenkel and Rochet 2003), so that the some of the sets of ecosystem indicators identified (see short-term activities) could be validated and their effectiveness at capturing ecosystem changes tested.

A high-priority, over-riding activity would be the development and implementation of the proposed expert system of ecosystem indicators to monitor ecosystem state, identify ecosystem changes, evaluate the effectiveness of adopted management strategies and their underlying strategic objectives and, where appropriate, identify/recommend actions to be taken.

CONCLUSIONS

1. The detection and prediction of ecosystem states and changes is central to ocean observation programmes globally, and one of the key policy actions of the BCLME Programme.

2. We highlight a suite of approaches to detect and monitor change in the long-term in one of several of the Benguela LME sub-regions. We elaborate on the many ways in which ecosystem changes may be measured and modelled. Suites of composite indicators, rather than single variables, appear to be the most useful for depicting ecosystem-level attributes.

3. We suggest an expert system of ecosystem indicators as a general and feasible methodology (i) to synthesize the results of these different approaches, (ii) that should be applicable to any sub-system of the Bengulea LME region, and (iii) which will support long-term ecosystem considerations in the management of human activities in the Benguela LME.

4. Priorities for detecting and predicting long-term ecosystem change need to be given to issues that require immediate management attention in the different sub-regions of the Benguela LME. These issues include fluctuations in the abundance and shifts in the distributions of small pelagic species (South Africa and Namibia), rebuilding of collapsed stocks (Namibia), effects of habitat degradation (Angola), ecosystem change in marine inshore communities (South Africa), and population sizes of vulnerable and endangered species (South Africa and Namibia).

5. Important practical steps towards a basis for detecting and predicting long-term ecosystem changes are highlighted. In the short term (1-3 years), important steps are the re-analysis of existing time series with up-to-date multivariate tools, the identification of early warning indicators, the improved understanding of patterns of and fluctuations in primary production in the region, and the improved understanding of the abundance and ecological role of gelatinous zooplankton.

6. Important practical steps in the medium term (4-7 years) include the development of methodology to quantify uncertainty related to inputs and outputs of ecosystem models, analyses of sediment deposits and linkage of these to historic ocean climate, and the evaluation of the usefulness of Marine Protected Areas. The development and implementation of the proposed expert system of ecosystem indicators is seen to be a pratical step to be awarded high priority.

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The Requirements for Forecasting Harmful Algal Blooms in the Benguela

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INTRODUCTION

The Benguela system suffers from the frequent occurrence of a variety of harmful algal blooms (HABs) (Pitcher and Calder 2000). These blooms can have severe negative impacts on local marine ecosystems and communities, in addition to commercial marine concerns such as rock lobster and aquaculture operations. Harmful impacts of HABs are associated with either the toxigenicity of some species, or the high biomass such blooms can achieve. Collapse of high biomass blooms through natural causes such as nutrient exhaustion can lead to low oxygen events, which in extreme cases result in hypoxia and the production of hydrogen sulphide, frequently causing dramatic mortalities of marine organisms. Effective coastal management requires the characterisation of HABs as ecologically prominent phenomena, the means of monitoring critical ecosystem locations in real-time and, ultimately, the operational forecasting of both HABs and their impacts. This document outlines the feasibility and requirements for establishing an operational HAB monitoring and forecasting system in the southern Benguela based on the current state of understanding of the variability of HABs within the region (Pitcher and Weeks, this volume).

HAB forecasts are likely be derived primarily from the output of sub-ecosystem models. The structure of a potential forecasting system is thus dictated to a large degree by the effectiveness of coupled physical-biological models. There is a high degree of uncertainty associated with the biological components of such models, particularly any species level aspect of prediction, as discussed in greater detail below. A central tenet of any regional forecasting system is thus the use of real-time observations to effectively replace the need to model biological processes associated with HAB development. Algal blooms classified as potentially harmful in the Benguela additionally have a highly variable taxonomic composition (see Pitcher and Weeks, this volume), and for the purposes of forecasting are best characterized by their impacts. Distinct in their nature, these impacts are associated with either the toxicity of some species present in the assemblage, or hypoxia resulting from the shoreline retention and collapse of high biomass blooms. The requirements for the forecasting of HABs in the Benguela are dictated primarily by these two modes of impact, which both require prediction of shoreline impact and retention.

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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.

A list of recent publications in this series appears at the end of this volume.

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