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12

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.

Ideally, real-time observation techniques would address both of those concerns, offering assemblage identification, toxicological status, biomass quantification, and spatial bloom delineation using multiple techniques at the required variety of temporal and spatial scales. In addition, HAB prediction and effective risk assessment in a physically dominated system such as the Benguela requires meteorological and hydrophysical data pertaining to the transport, maintenance and potential retention of blooms. An ideal observation network would thus 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. Products from such a network would be required at several levels: geophysical input data for use with physical, ecophysiological or probabilistic impact assessment models; and high level data products suitable for immediate use by coastal management agencies.

The specific aims of a regional operational forecasting system are also an obvious and important determinant of the structure of any real-time observational system. Given the dependence on real-time observation rather than ecophysiological modeling, effective HAB forecasting in the Benguela in the immediate future is thus likely to take two forms. The first of these is a probabilistic "ecological window" or fuzzy logic model, whereby the probability of the succession of broad taxonomic groups and HAB occurrence is determined from observations of physical, chemical and biological conditions in real-time. Such a structure allows the complexities of physical-biological couplings to be reduced to operationally attainable indices, e.g., identifying the likelihood of diatom or dinoflagellate dominance based on the expected turbulence regime and water column stratification.

The second and more important form of forecast is likely to be limited to a short term prediction of impact based on a combination of real-time bloom detection and transport prediction, likely in turn to be based on a concomitant meteorological forecast. The core product of any realisable forecasting system in the short term is therefore likely to be a prediction of HAB shoreline impact and retention, highly dependent upon observational ability, the temporal limitations of meteorological forecasts, and the dynamic circulation models needed to simulate the transportation of HABs in local flow fields. The need for appropriately configured and located coastal moorings is thus absolutely critical to all forms of HAB forecasting, as is the need for routine access to appropriate satellite derived geophysical products. Also vital to such a forecasting capability are dynamic circulation models able to integrate data from real-time observation systems. Simulation of the shoreward transport of blooms should be considered the primary aim of these sub-ecosystem circulation models. The ability to assimilate real-time physical data, and utilise real-time biological data for particle tracking and bloom dispersion is also necessary for operational forecasting. These requirements are considered here with the aim of establishing a set of prerequisites for establishing an operational circulation model for HAB forecasting.

Mechanistic forecasting of HABs in the Benguela is unlikely in the immediate future: the complex biological processes underlying HAB development are simply not well enough understood to model effectively. Nevertheless, the physical processes underlying the concentration, dispersion and advection of blooms are relatively well understood, and furthermore can be simulated using dynamic circulation models. The use of these circulation models in conjunction with real-time observation networks, and relatively simple physical-biological indices, offer the structure around which an operational HAB forecasting system in the Benguela can be developed.

PHYSICAL-BIOLOGICAL COUPLINGS UNDERLYING HABS

Harmful algal blooms of phytoplankton deserve special recognition relative to other more benign phytoplankton assemblages and blooms because of their obvious importance to humans. It is often difficult, however, to identify physical, chemical or biological characteristics of HAB species (other than toxicity) that would allow us to treat these organisms as a unique group or subset of phytoplankton. All phytoplankton by nature are intimately connected to their physical environment, since phytoplankton are by definition subject to horizontal transport by the physical environment. Therefore, any discussion of physical-biological couplings must ultimately be generally applicable to phytoplankton. This is especially true of upwelling systems such as the Benguela, where the dominant influence is wind-driven transport, both from local forcing and from the subsequent development of characteristic larger-scale forcing such as coastal jets and countercurrents.

Theoretical frameworks for HAB species succession

In identifying the important physical-biological couplings underlying HABs, it is useful to start with a theoretical framework for patterns of biological succession, with emphasis on upwelling regions. Margalef et al. (1979) described the general succession of phytoplankton functional groups based on an ecological space defined by a continuum from r-selected (diatoms) to K-selected (dinoflagellates) organisms, largely controlled by turbulence, which provides a proxy for nutrient and light availability. According to his Mandala, red-tide events of high biomass, a primary HAB event in the Benguela, were somewhat of an anomaly from the expected successional patterns, and could be treated as unusual or alternate sequences. Margalef identified these red tides as being associated with low turbulence, highly stratified waters with an excess of nutrients.

More recently, Smayda and Reynolds (2001) revisited Margalef's Mandala, and updated it based on a classification scheme which divides phytoplankton into three groups: C, or colonizing organisms, characterized by small size and motility, and an opportunistic growth strategy; S, or stable organisms, adapted to be stress-tolerant, with large, slow-growing forms dominant (Margalef's K-selected dinoflagellates); and R, or ruderal, organisms, typically disturbance and turbulence tolerant, autotrophic, with an affinity for high nutrient levels and often associated with upwelling fronts (Margalef's r-selected diatoms). Based on this scheme, Smayda (2002) further refined this for dinoflagellates, subdividing this group into nine categories based on the ecological niches they occupy as defined by preference for nutrients and tolerance to decreasing light and mixing.

Smayda (2002) also generally classified diatoms and dinoflagellates, the two main groups of bloom-forming (and HAB) organisms in coastal upwelling systems such as the Benguela, as having differing strategies for growth. Diatom blooms tend to be annual, of high species diversity, exhibit a fairly stable successional pattern as a group relative to other phytoplankton, and have adopted a "sink" strategy when faced with sub-optimal environmental conditions. Dinoflagellate blooms tend to exhibit both lower diversity and truncated succession patterns, and exhibit a "swim" strategy (detailed below). It is also important to note that dinoflagellate blooms and red tides, while relatively unpredictable in comparison to diatom blooms, are not unusual or anomalous, and are a normal part of the successional pattern occurring in upwelling systems. As noted by Pitcher and Weeks (this volume), the switch from diatom to dinoflagellate dominated algal communities can be considered succession in its simplest form, and as such the most likely succession pattern amenable to forecasting.

In terms of growth strategy, dinoflagellates as a group are generalists, with representative genera found in all major ecosystem types. Although dinoflagellates are often associated with highly stratified, low-nutrient environments (e.g. K-selected), they do not appear to be particularly well adapted to a low-nutrient environment (i.e. they exhibit moderate to low growth rates, moderate to low affinities for nutrients, etc.). To overcome this, four strategies have developed: vertical migration, mixotrophy, allelochemical competition, and allelopathic grazing deterrents (Smayda 2002). Although dinoflagellates as a group can be considered generalists, there is considerable species- and probably sub-species level selection and adaptability, introducing a great deal of stochasticity in blooms; additionally, within a given ecosystem such as the Benguela, it is not uncommon to find three or more of Smayda's (2002) nine subdivisions of dinoflagellates simultaneously in a small spatial region.

Despite the stochasticity evident at the species-level in bloom development, there are clear successional patterns in upwelling systems. For example, in the California Current System, from year to year pennate diatoms dominate early in the year accompanying the onset of upwelling-favorable conditions, succeeded in the summer and fall by larger centric diatoms, then by dinoflagellates in the fall and early winter, and finally by a small flagellate and picoplankton community in the winter (with a substantial decrease in total biomass). What is unusual about upwelling systems compared to other regions is that, within these seasonal patterns, the biological patterns can be "reset" to some degree in response to changes in physical forcing (upwelling/downwelling), which typically occur on the order of 5-10 day timescales. It is clearly possible to identify time periods and conditions favorable for one group versus another, generally related to the physical setting. It is at the more detailed level (a particular year, or an attempt to predict particular species) that forecasting becomes difficult. This leads to a gap in predictive forecasting skill of HAB events, where it should be possible to identify and predict the formation of group- or species-specific bloom events several days in advance (on the timescale of weather forecasting), and it is possible to predict the general seasonal patterns, but it is extremely difficult to forecast events from weeks to months in advance.

Identification of physical-biological interactions

Within this larger pattern of diatoms versus dinoflagellates and seasonal succession, there are several important physical-biological interactions that influence the development or suppression of high-biomass or toxic dinoflagellate blooms. At the cellular level, the most obvious example is the ability of dinoflagellates to swim. This behavior allows them to maintain position in the water column, to seek out optimal growth conditions (e.g., to cross the nutricline in nutrient-depleted waters or to optimize their light harvesting), and to overcome or avoid the often-turbulent conditions associated with frontal systems and upwelling regions in general. Despite the importance of motility, there is no evidence that HAB-forming dinoflagellates exhibit particularly weaker or stronger swimming behavior (see the review by Smayda 2000), although chain-forming dinoflagellates such as *Alexandrium catenella*, one of several HAB species found in the Benguela, do exhibit strong swimming behavior. There is also substantial variability amongst HAB species; recent laboratory experiments conducted by Sullivan et al. (2003) showed that the dinoflagellate *Lingulodinium polyedrum* exhibits enhanced growth and decreasing cell size in response to turbulence, possibly a mechanism for coping with shear stress. At the same turbulence levels, *A. catenella* exhibits decreased growth and increased cell size, suggesting that one organism (*L. polyedrum*) might be stimulated by turbulence, while another, *A. catenella*, would likely use its swimming behavior to congregate in low-turbulence regions. Turbulence has also been shown to result in enhanced toxicity in *A. fundyense* (Juhl et al. 2001).

Turbulence-avoidance, as hypothesized for *A. catenella*, is also consistent with the observed formation of subsurface accumulations, often forming thin layers, by this and other HAB organisms. These subsurface layers may accumulate due to behavioral and/or purely physical mechanisms (Donaghay and Osborne 1997; McManus et al. 2003). Evolutionarily, a possible benefit for concentration of HAB species into thin layers may be relief from grazing pressure. Some zooplankton grazers may cease feeding and starve rather than consume toxic algae (Turner and Tester 1997), and zooplankton have also been observed to avoid layers with high concentrations of toxic phytoplankton (Fiedler 1982). Sub-surface layers of HAB organisms are of obvious importance in terms of monitoring and prediction, since these layers may serve as refugia or sources for the apparently sudden surface expression of HABs, and cannot easily be detected from the surface using methods such as remote sensing.

In addition to physical-biological interactions at the cellular level, interactions with mesoscale physical features are also of importance in upwelling systems. Some HAB dinoflagellates found in the Benguela produce cysts (e.g., *A. catenella*), and the persistence and seasonal reoccurrence of these organisms is almost certainly related to the formation of cyst beds. Many other HAB dinoflagellates do not encyst, however, and it is not clear what the source of initial seed population is, particularly in upwelling systems which are by nature highly advective. Previous work in the Benguela has identified the formation of pelagic seed banks (Pitcher and Boyd 1996, Pitcher et al. 1998, Smayda 2002); potentially leading to dinoflagellate concentration in offshore coastal fronts, and ultimately coastal impact through physically-induced onshore transport.

Potential for forecasting HAB biological characteristics

HAB organisms should be considered part of the normal successional patterns of species in upwelling ecosystems, despite the seemingly random selection at the species level among HAB organisms which occupy similar ecological niches. Although upwelling systems are unique in that successional patterns can be at least partially "reset" by the cyclic occurrence of upwelling/relaxation events, at a gross level ecological windows conducive to HAB formation should be identifiable. On larger physical-biological scales, there are several examples of HAB predictability based on statistical correlations between changes in the mean physical or environmental structure and the occurrence of HAB groups. In Hong Kong, Yin (2003) has shown that severe red tides are often associated with monsoonal wind conditions. In Galicia, the upwelling index, in combination with remotely sensed sea surface temperature and chlorophyll, has provided a robust index of *Pseudo-nitzschia* blooms (Sacau-Cuadrado et al. 2003). Along the Baja Peninsula in Mexico, Ochoa (2003) identified HAB-promoting conditions related to the ENSO index, and there is some evidence that *L. polyedrum* in the California Current System is at least loosely correlated to both ENSO and the Pacific Decadal Oscillation (Kudela, unpublished).

There is also potential for the forecasting of the initiation of high biomass HAB events from remotely sensed physiological proxies such as quantum efficiency of fluorescence. Synoptic fluorescence quantum yield data can be derived from the use of analytical reflectance algorithms with space-based ocean colour data (Bernard 2005). Preliminary indications are that such data may be used to establish algal growth phase variations (e.g., Young and Beardall 2003).

In summary, the difficulties of ecophysiological modeling, and the inherent stochasticity of algal succession and bloom dynamics mean that the most pragmatic current means of predicting biological HAB attributes in the Benguela is the use of real-time physical, chemical, and biological data in conjunction with a statistical "ecological window" approach. It must also be realised that high biomass HAB events in the Benguela are primarily forced by mesoscale physical factors: identification of the processes underlying these factors, and their effects on algal concentration, dispersion and advection, are critical to establishing a forecasting capability.

IDENTIFICATION OF THE PHYSICAL PROCESSES IMPORTANT TO BLOOM CONCENTRATION AND TRANSPORT

The ability to predict HABs in coastal upwelling systems depends fundamentally on understanding not only causative biological processes, but also the physical environment in which the HAB species grows. From a management perspective, it is important to be able to anticipate the movements of a HAB, particularly the intersection of an offshore HAB with the coast. Thus understanding the factors that determine the advection of a HAB will be critical elements in forecasting the impacts of HABs.

The basic aspects of the physical dynamics common to many coastal upwelling systems are amenable to real-time measurement and short-term forecasting. In particular, an understanding must be sought of the factors controlling the motions of waters containing HABs and the waters that may stimulate the formation of HABs. In the following pages models of upwelling/downwelling systems are therefore examined, with the intention of identifying important transport pathways and essential dynamics that may support the initiation, transport, or dispersal of HABs. An investigation is made of a simple 2D 2-layered upwelling system, 3D effects in upwelling systems, and 2D and 3D flows in downwelling and relaxation conditions. The investigation concentrates on identifying where water comes from, where it goes, and the forces that underlie these motions, in addition to dispersion and concentration mechanisms.

Principal physical processes and their role in shoreward bloom transport

Upwelling

A 2D model looks only at variations in two dimensions (cross shore and vertical), but ignores the alongshore changes. In Ekman's simple 2D 2-layered model of wind-driven coastal upwelling, an alongshore wind stress causes an offshore flux of surface water, the Ekman transport. This offshore flow must be replaced by an onshore flow of deeper water which drives upwelling of deep water at the coast with subsequent uplifting of the pycnocline. The assumption of two well-mixed layers obscures details of the origin and vertical structure of the deep return flow, in particular whether it originates from the interior of the water column or the bottom boundary layer. Convergent or divergent structures at the front, also obscured in a 2D structure, can only be resolved in models with vertical stratification.

Allen et al. (1995) explored a 2D primitive-equation model with a turbulence-closure mixed-layer model whose bathymetry was representative of the shelf off the coast of Oregon. The model had a gradual vertical stratification, characteristic of the water column of that region, and was forced with a steady upwelling-favorable wind. In the base case (no heating), the surface wind stress caused the formation of a surface mixed layer that deepened with time, as well as the offshore Ekman transport of surface water. The offshore surface flux was replaced by water from a thin near-bottom

Ekman layer, not waters from the interior of the domain. As the wind blew, isopycnals were pushed upward and finally broke the surface, forming a front that moved offshore. A convergence zone formed at the front, as inshore water subducted beneath it. A strong along-front jet formed at the front, and moved offshore with the front. Heating tended to reduce the surface turbulence and the depth of the surface mixed layer. Doubling the wind stress led to a doubling of the offshore surface Ekman transport, and a halving of the time taken for the frontal jet to reach a given speed. Decreasing stratification led to a decrease in the strength of the frontal jet and caused the cross-shelf flow to be distributed through a greater portion of the water column.

Austin and Lentz (2002) performed a similar modeling study, though their model was configured for a broad shelf (such as the east coast of the US), and with a sharp pycnocline at about 10 m depth. Their results were largely similar to those of Allen et al. (1995), with some interesting additional details. During upwelling, Austin and Lentz showed that as the isopycnals rose and surfaced to form the front, a vertically well-mixed region formed inshore of the front where the surface and bottom Ekman layers met. This shallow inner-shelf region extended to a depth of about 15-20 m (10 km offshore with their bathymetry). Because of the lack of vertical stratification, this inner shelf region did not support vertical shear, so onshore-offshore motions could not penetrate to the coast. Rather, the upwelling was confined to a zone near the front, and propagated offshore with the front, leaving a region with no horizontal motions inshore of the front. Tracers introduced into this model either in the bottom layer offshore, or at the coast, showed very little across-shore motion during upwelling. The tracer in the bottom layer moved slightly onshore until the front rode over it, when it became vertically well mixed and ceased to move horizontally. The tracer at the coast was almost immediately trapped within the vertically mixed inner shelf region, and showed no across-shelf movement. Thus in this scenario, delivery of a HAB to the coast would be unlikely, no matter where the HAB was in the water column.

Downwelling

During active downwelling, an alongshore wind (poleward on a west coast in the southern hemisphere) forces surface Ekman transport onshore, causing the pycnocline to bow downwards, intersecting the bottom and moving offshore at depth. This front is associated with an increasingly intense along-front jet in the direction of the wind.

Allen and Newberger (1996) used the same numerical model as Allen et al. (1995) to explore the dynamics of coastal downwelling in a 2D domain configured for the Oregon coast. In their base case (no heat flux), the isopycnals behaved as predicted by Ekman theory, bending downwards and moving offshore. A well-mixed inner shelf region formed as the front moved offshore and deeper, with an along-front jet associated with strong convergence and downwelling.

Austin and Lentz (2002) also explored downwelling-forced flows in a region with a broad shelf and a sharp pycnocline. Their results echoed those of Allen and Newberger (1996), with the formation of a strong front at the bottom that propagated offshore, associated with a strong along-front jet and a vertically mixed inner-shelf region suppressing vertical shear and horizontal circulations between the coast and the front. This was clearly demonstrated by the motions of tracers introduced into the surface layer, and at the coast in the model. The tracer in the surface layer moved slightly onshore as the wind blew, but became horizontally stationary once the front had reached and passed the patch. After the front had passed by, the patch of tracer was vertically homogeneous, and no longer moved onshore or offshore in the inner shelf. The tracer introduced at the coast remained trapped at the coast by the well-mixed inner shelf.

These results suggest that onshore transport of organisms embedded in these flows is minimal. Even a patch of tracer at the surface moved onshore only minimally under forcing from a downwelling-favorable alongshore wind. Tilburg (2003) explored this problem further by investigating the effects of across-shore (onshore) wind stresses on the transport of a tracer in the surface layer of a 2D linearly stratified model. He showed that a wind with an onshore component had a substantial effect on the onshore movement of the surface tracer and could transport it through the well-mixed inner shelf to the coast. Using these results it is possible to predict that onshore movement of a surface HAB would be driven by winds with an onshore component.

Relaxation

An incorrect generalisation of upwelling systems is that when the wind ceases, the upwelling front propagates onshore under the influence of the across-shore pressure gradient associated with the uplifted pycnocline. In a purely 2D system, however, this will not happen, as conservation of the potential vorticity results in a geostrophic balance which maintains the position of the offshore front and the along-front jet - until the system is forced by changes in the across shore pressure gradient such as new wind events or propagating coastally trapped waves. On the other hand, it is a common observation that warm water reaches the coast during relaxation (e.g., Send 1987), and it is important to identify both the source of this warm water and the underlying transport processes.

There are several mechanisms that could lead to the appearance of warm water at the coast after an upwelling-favorable wind stops (see Figure 12-1). One process, as discussed above, is active downwelling, which can cause onshore movement of water if there is an onshore component to the wind stress. Other processes are more complex, and include the formation of eddies (baroclinic instability) and 3D dynamics associated with complex topography such as capes or canyons.

Baroclinic instabilities form when small along-front perturbations are magnified by the across-front shear and the slope of the pycnocline. As the small perturbations grow, they can roll up into eddies that can detach from the front and intersect the coast. These eddies may concentrate organisms and deliver them to inshore regions, causing the sudden appearance of warm water and HABs. These eddies are often associated with coastal topography and may impinge on the coast at predictable locations. The size and growth rate of the eddies is related to the bottom slope relative to the pycnocline slope. Steeper bottom slopes tend to reduce the formation of small eddies and increase the time taken for the eddies to form.

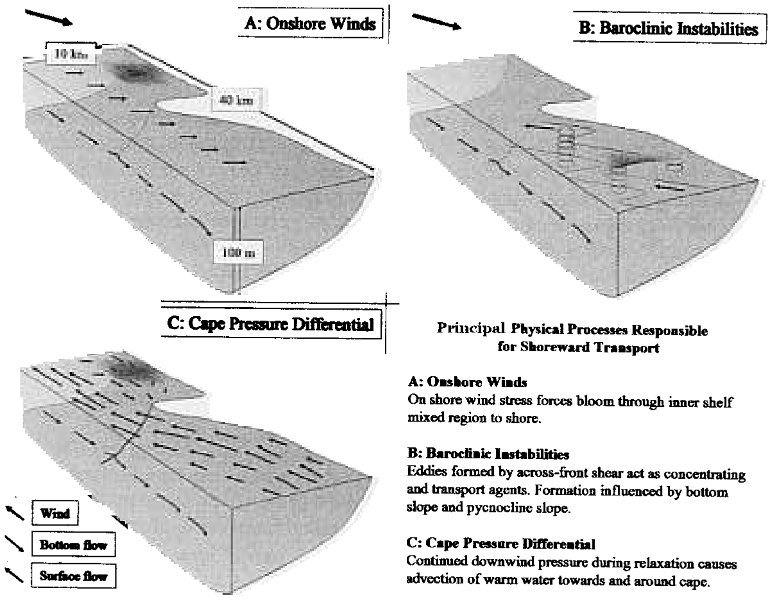
Alongshore topography has been recognized to play a role in upwelling relaxation for many years (e.g., Send 1987); however, the details of the mechanisms are still somewhat obscure. Gan and Allen (2002) explored the dynamics of flows near capes embedded in a coastal upwelling system using a 3D primitive-equation model. Their model clearly shows the appearance of warm water at the coast around a cape during upwelling relaxation and their analyses shed some light on the underlying mechanism. During upwelling, the frontal jet moves offshore, where the jet can separate from the coast and move into open waters downstream of the cape. Under steady upwelling-favorable alongshore winds, water downstream of the cape is also accelerated alongshore in the direction of the wind. Two regions of strong alongshore pressure gradients build up around the cape: on the upwind side, the pressure gradient is oriented toward the cape (i.e., in the direction of the wind), while on the downwind side of the cape the pressure gradient again points toward the cape, counter to the direction of the wind. The force balance seems to indicate that the upwind pressure gradient is balanced by a strong geostrophic onshore flow of deep, cold water, while the downwind pressure gradient is balanced by nonlinear forces associated with the movement of the jet around the cape. When the wind subsides, the upwind pressure gradient dissipates, causing no alongshore flows. The downwind pressure gradient does not dissipate, however, and forces water to move alongshore opposite to the former wind direction. This water comes from offshore due to some recirculation around the cape during upwelling, causing a warm water mass to advect toward and around the cape during relaxation, in the opposite direction of the previous upwelling jet. These dynamics may account for the appearance of warm water at the coast during relaxation and the sudden appearance of HABs in bays downwind of a cape, or along the coast upwind of a cape during relaxation.

Forcing mechanisms underlying the prediction of shoreward bloom transport

Wind stress curl

As previously discussed, the main reason for coastal upwelling is the divergence of the Ekman transport caused by the coast. Another mechanism able to generate divergence of the Ekman transport are wind stress curls, i.e., wind variation perpendicular to the wind direction. The wind stress curl is not associated with a wave guide. Thus contrary to areas close to the coast where upwelling diminishes after a while owing to coastally trapped waves, upwelling driven by the wind stress curl will not be reduced by wave processes (Fennel 1999). Whilst bands of high wind stress curls have been observed in upwelling areas (Bakun and Nelson 1991), measurements of these curls were relatively sparse.

Recent work (e.g., Chelton et al. 2004, Koracin et al. 2004) has shown that the wind stress contains a great deal of structure that is usually not measured or used to force models. Koracin et al. show that the curl of the wind stress, the aspect of wind stress that drives upwelling and downwelling, can have scales as small as a few kilometers across shore, particularly in regions of coastal topography such as mountains or capes. This has important implications for the structure of the coastal flow patterns, since the vertical flows forced by the wind will tend to have spatial scales similar to the spatial scales of the wind stress curl. Thus, we might expect multiple fronts to form, with complex patterns of transport along and among the frontal jets. This will have important implications for the transport of HAB species to nearshore locations. These esults reinforce the notion that wind-driven flows in upwelling systems are highly hree-dimensional, particularly in regions of complex coastal topography.



Principal Physical Processes Responsible for Shoreward Transport

A: Onshore Winds
On shore wind stress forces bloom through inner shelf mixed region to shore.

B: Baroclinic Instabilities
Eddies formed by across-front shear act as concentrating and transport agents. Formation influenced by bottom slope and pycnocline slope.

C: Cape Pressure Differential
Continued downwind pressure during relaxation causes advection of warm water towards and around cape.

Figure 12-1. Schematic of principal physical processes responsible for shoreward bloom transport on the southern Benguela Namaqua shelf region.

Coastally trapped waves and undercurrents

Although the basic process of coastal upwelling, the divergence of the Ekman transport near the coast, can be understood on the basis of 2D models, it is important to note that the dynamics of an upwelling system are basically three dimensional. The coastal or along-front jets are significantly stronger than the cross-shore motion. The coast is known to act as a guide for coastally trapped waves. The finite extent of the wind fields and irregularities of the coastline are the main reason for the formation of waves, in response to temporal changes of the wind fields. A model case, which can be treated analytically and provides understanding of the basic features, is a stratified coastal ocean with a straight coast and flat bottom (McCreary 1981, Fennel 1988). In this case the relevant wave processes are Kelvin waves, which propagate with the coast to the right (in the northern hemisphere) and switch the dynamical balance from linearly growing upwelling and accelerating coastal jets to a regime where the upwelling stops, and the speed of the coastal jet will be arrested. Behind the Kelvin waves an alongshore pressure gradient develops, which is driving a coastal undercurrent. The Ekman transport then no longer drives the vertical flow but is fed into the undercurrent. The Kelvin waves are the simple non-dispersive extreme case. In a more realistic consideration, the topography must be included, which makes the wave properties much more complex. The associated waves are continental shelf waves which are dispersive and can even have frequency- wavenumber combinations with vanishing group velocity. The theory of these processes is complex and cannot easily be outlined. However, some of the basic features of the Kelvin wave regime are retained with gradual modifications due to the shelf topography.

With regard to predictions of the motion of HABs the undercurrent is of obvious importance. Small upward or downward vertical migration of algal cells can change their direction of transport: from a downwind direction with the surface coastal jet to a movement in the opposite direction with the nearshore coastal undercurrent.

Whilst traditionally concerns have focused on across-shelf flows during upwelling, the along-shelf flows actually dominate the transport of organisms. The formation of an inner shelf circulation cell may substantially inhibit across-shelf transport of organisms to the coast, though this may be overcome by three-dimensional circulation patterns such as baroclinic instabilities and onshore winds.

REAL-TIME OBSERVATION OF HABS

In-situ observation technologies

Technological, logistical, and financial restraints will all impact upon the ability to construct an observational network capable of allowing the observations required for the prediction of all potential impacts of harmful algae. Technological restraints are likely to change rapidly, given the emergent nature of autonomous instrumentation in the field; and whilst some discussion must necessarily be made concerning the current nature of these restraints, it should be realised, and indeed hoped, that such discussion will rapidly lose relevance. Only techniques of potential utility for real-time autonomous operation on moorings will be discussed here, although traditional sampling and analysis methods, such as cell counts and toxin assays, will obviously continue to be extremely important for the foreseeable future.

Species identification and toxicological observations

Identification of phytoplankton to a species or genus level with remote autonomous instrumentation is a significant technological challenge, albeit one that is being rapidly surmounted. Autonomous species level identification has already been demonstrated using rRNA probes with the Environmental Sample Processor (ESP) developed at MBARI (Scholin et al. 1999) At the time of publication, a second-generation ESP system, which would be more widely available to end users, was being developed with support from the U.S. National Science Foundation. Similar molecular probe and other techniques showing promise for automated application are currently being tested and used in field studies (e.g., Scholin et al. 2003). Identification to a species or genus level is also possible using the autonomous FLOWCAM instrument, a combined flow cytometer and microscope recently made commercially available (Sieracki 1998). Recent reviews of these techniques discuss them in greater detail (Glasgow et al. 2004, Sellner et al. 2003).

Autonomous determination of cellular toxicological data is also extremely desirable, given the variability of cellular toxicity in response to environmental conditions (e.g., Bates 1998). The autonomous ESP platform has also been used for conducting toxin assays with immunological probes. While at present it appears that this is the only technology suitable for such measurements, there is potential use for in situ toxin measurements using miniaturized autonomous mass spectrometers (Langebrake 2003), while other technologies applicable to HAB monitoring are also being developed (Daly et al. 2004).

It should be realised that whilst the systems discussed above are of great potential utility, they are emergent technologies using complex, specialised, high maintenance instrumentation that is unlikely to be cost effective (or even commercially available) soon. As such, these systems are unlikely to provide routine algal monitoring data in the Benguela in the near future.

Bio-optical observations

In comparison to the systems described above, a wide variety of relatively simple, robust, and cost effective bio-optical instrumentation is commercially available that is well suited to autonomous deployment (e.g., Cullen et al. 1997). However, while such instrumentation offers data that is able to provide suitably accurate determinations of algal biomass, and in some cases a limited description of assemblage type (Roesler et al. in press), it cannot offer the level of specificity described above, i.e., species level identification or toxicity information. Nevertheless, bio-optical systems offer a currently realisable means of obtaining real-time data relating to the algal assemblage using a variety of platforms, sensor systems, and processing techniques (Cullen et al. 1997, Sellner et al. 2003) ranging from the empirical to the use of sophisticated analytical inversion algorithms (e.g., Roesler and Boss 2003) – a recent synopsis of available instrumentation and techniques can be found in *Oceanography* (Vol. 17(2):June 2004).

One particular approach will be focused on here, the use of passive radiometric sensors in conjunction with analytical reflectance inversion algorithms. While offering a robust, cost effective moored system allowing the derivation of algal biomass, size and accessory pigment descriptors (Bernard 2005), the reflectance algorithm approach also offers the ability to derive concentrations of other water constituents, such as algal degradation products, which may be of utility in assessing bloom growth phase. The approach also offers a significant advantage in that it allows the derivation of equivalent geophysical products from both in situ, airborne, or space-based sensors. This offers the ability to use analogous multi-platform derived data measured on a

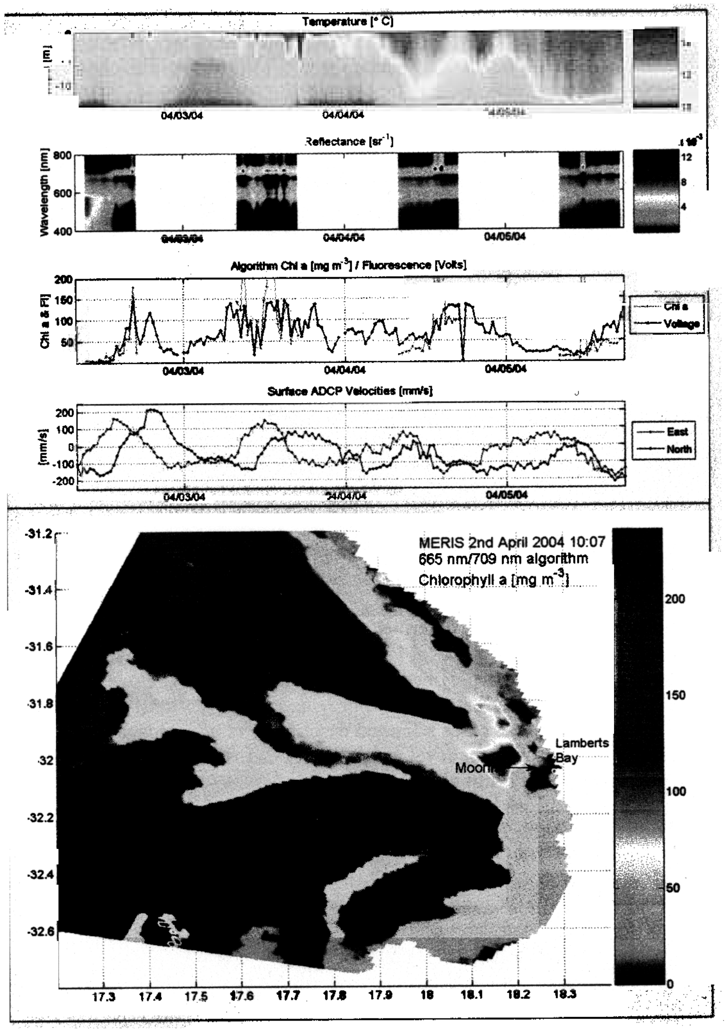


Figure 12-2. Mooring time series data and MERIS chlorophyll *a* data showing the detection and wide spatial extent of a bloom of the small dinoflagellate *Prorocentrum triestinum* from 2 to 5 April 2004, in the Namaqua shelf region. The bloom appears at the mooring ~ 4 hours after the satellite overpass, as warm high biomass bloom waters are advected shoreward in the easterly surface flow. Satellite chlorophyll *a* data, derived through an experimental red band algorithm designed for high biomass application, show the widespread and complex distribution pattern of the bloom. Data such as these are likely to form the basis of a southern Benguela HAB observation system.

variety of temporal and spatial scales, i.e., Eulerian high frequency mooring-derived data and daily synoptic satellite-derived data.

Physical and chemical observations

The dominance of physical forcing mechanisms in the Benguela, the critical role of bloom transport in HAB forecasting, and the desire to use data assimilation techniques in hydrodynamic models underline the need to gather physical in conjunction with biological data. The importance of spatial variability in wind stress as an influence on shelf transport processes emphasises the need for wind measurements in as many across– and along-shelf locations as is feasible. Temperature profiles, indicative of both potential ecological niches and the stratification changes likely to lead to conditions favouring dinoflagellate blooms, are also desirable. Surface currents or current profiles offer both a Eulerian indication of immediate bloom transport and data suitable for assimilation into hydrodynamic models. In this regard, there would be obvious advantages to synoptic surface current data from a coastal high frequency radar system, e.g., CODAR (Glenn et al. 2004), to greatly improve predictions of surface bloom transport. Additional sensors offering the capability of indicating the onset of wind reversals leading to HAB favourable conditions, owing to longshore bloom transport, are paired pressure sensors installed around capes, as discussed here on p. 276. Such sensor pairs also represent a low-cost, low-maintenance forecasting tool, which may be more easily achievable than installation and maintenance of an HF radar system.

Chemical parameters of advantage that may be measured autonomously are the inorganic nutrients nitrate, silicate, phosphate, and ammonium: the immediate utility of such data would be as input to a probabilistic "ecological window" prediction model. While strictly falling under the remit of other chapters in this volume, real-time bottom oxygen data is of great importance to the short term prediction of high biomass bloom impact in critical locations such as Elands Bay in the southern Benguela. Real-time bottom water oxygen sensors can be considered the single most important segment of an operational network for forecasting the locally devastating impact of HABs on organisms vulnerable to hypoxic events.

Satellite based observations

A variety of satellite derived data, allowing description of both biological and physical variables, is required for HAB forecasting. Ocean colour-based sensors offer the most immediately useful HAB-specific data, providing synoptic maps of surface algal biomass on a near real-time basis. In addition to traditional empirically derived chlorophyll *a* products, the use of satellite ocean colour data in conjunction with reflectance inversion algorithms offer experimental geophysical products that are specifically designed for HAB monitoring application. These include more accurate estimates of algal biomass in high biomass waters and products that allow some form of assemblage description independent to biomass. These include assemblage size descriptors such as the cellular effective diameter and a fluorescence quantum yield product of potential utility as a physiological proxy (Bernard 2005). While these and other ocean colour products offer tremendous potential for incorporation into an operational HAB forecasting system, several logistical and scientific hurdles will need to be overcome for routine operational use. These include enabling routine access to full spectral data from sufficient sensors to ensure daily coverage for the region (e.g., MERIS and MODIS) and development of optimal flagging and processing routines for application in the high biomass waters of the Benguela, a system complex with regard to both in-water bio-optics and atmospheric correction.

HAB forecasting in the Benguela necessitates that satellite data pertaining to the dominant physical forcing mechanisms are also routinely available. Such data are essential to determining bloom pre-conditioning, transport, and longevity and are likely to play an important role in any probabilistic forecasting model in addition to potential assimilation into hydrodynamic models. Sea surface temperature (SST) and the surface wind field are considered the most important variables and are available from a range of space based platforms. These include the NOAA AVHRR and NASA MODIS missions for SST data (daily, ~ 1 km spatial resolution) and the NASA QuikSCAT mission for surface winds (daily, ~ 25 km spatial resolution, no coverage within 50 km from coast). The availability of new or improved remotely sensed products is also to be expected. For example, a mission that has the potential to provide valuable high frequency SST data is the ESA MeteoSat Second Generation (MSG) mission (15 minutes sampling frequency, 3 km spatial resolution).

Platforms and observation systems

The establishment of permanent multi-sensor moorings, providing the biological and physical data necessary for bloom detection and transport prediction, is critical to establishing a HAB forecasting capability in the Benguela. Mooring platform payloads have been discussed above; an additional and important consideration is the location of the mooring(s). In the southern Benguela, HAB formation and retention is in response to generally well defined physical processes (Probyn et al. 2000, Pitcher and Weeks, this volume) and mooring location should be dictated primarily by the shelf circulation patterns associated with the various stages of bloom development, maintenance, and decay. A potential complementary approach to the use of fixed platforms is the use of autonomous underwater vehicles (AUVs), sampling platforms that are becoming increasingly more effective as instrument systems are miniaturized, deployment times are extended, and costs are lowered. These platforms, in particular low power gliders, have the capability to provide high frequency spatial data pertaining to HAB detection. However, whilst the effectiveness of such platforms has been demonstrated elsewhere (Glenn et al. 2004), logistical demands in their use are still considered too high for operational use in the Benguela in the near future.

Current HAB related efforts in the southern Benguela have focused on the provision of a lightweight multi-sensor platform servicing the Namaqua shelf, carrying paired hyperspectral radiometers, a fluorometer, thermistor chain, and an Acoustic Doppler Current Profiler (ADCP). The system is designed as a lightweight, low cost, multiple buoy mooring employing GSM telemetry and designed to be serviceable from small boats. An example of the effectiveness of the approach relative to bloom detection is presented in Figure 12-2, detailing the detection of a bloom dominated by the dinoflagellate *Prorocentrum triestinum*, observed in data derived from both a prototype mooring and the Medium Resolution Imaging Sensor (MERIS) ocean colour sensor.

An operational observation network in the southern Benguela, effective for the prediction of HABS in the Greater St. Helena Bay region (see Pitcher and Weeks, this volume), can be briefly considered as an example. The network is considered to consist of a minimum of three moorings in combination with the satellite data discussed above. Two inshore moorings, configured in a similar manner to the example platform discussed above, should be located in ~50 m water depth offshore from the Olifants river mouth and Lamberts Bay, allowing the early detection of surface blooms moving in a typical southerly direction during quiescent periods (Probyn et al. 2000). A third midshelf mooring located at mid-latitude relative to the inshore moorings is intended to provide meteorological and physical data for ecological window assessment, data assimilation, and modeling validation studies. A schematic of the system can be seen in Figure 12-3. Finally, it must be realised that there is still a great deal of uncertainty regarding the mechanisms underlying HAB formation: the research value of an effective coastal observation network providing multi-sensor data across a wide range of spatial and temporal scales cannot be understated.

NUMERICAL MODELLING AND PREDICTION OF HAB DYNAMICS

The availability of appropriately configured and validated circulation models, specific to each sub-ecosystem region of impact, are vital to establishing an operational HAB forecasting capability. Accurate simulation of the processes responsible for shoreward bloom transport and coastal retention are the most important criteria for establishing model efficacy. These processes can be summarised as the response to onshore winds, baroclinic instabilities, poleward pressure driven flows, and non-linear internal waves.

Preliminary modelling efforts in the region have focussed on the southern Benguela, employing a 3D numerical hydrodynamic model using Delft3D-FLOW (Pitcher et al. in press; WL|Delft Hydraulics, 2003a) for the Greater St. Helena Bay region. Initial validation studies appear to show that the temporal and spatial characteristics of physical variability in the St. Helena Bay – Namaqua system can be simulated with uncertainties approximating 20%. While demonstrating the feasibility of simulating the primary circulation characteristics of the system, the study also reveals the complex dynamical characteristics of circulation and stratification and aids in establishing model requirements for operational forecasting.

Current modelling efforts require improvement through the use of dynamic boundary conditions, e.g., the nested ROMS (Regional Ocean Model System, Song and Haidvogel 1994) model approach and more extensive validation data from both a

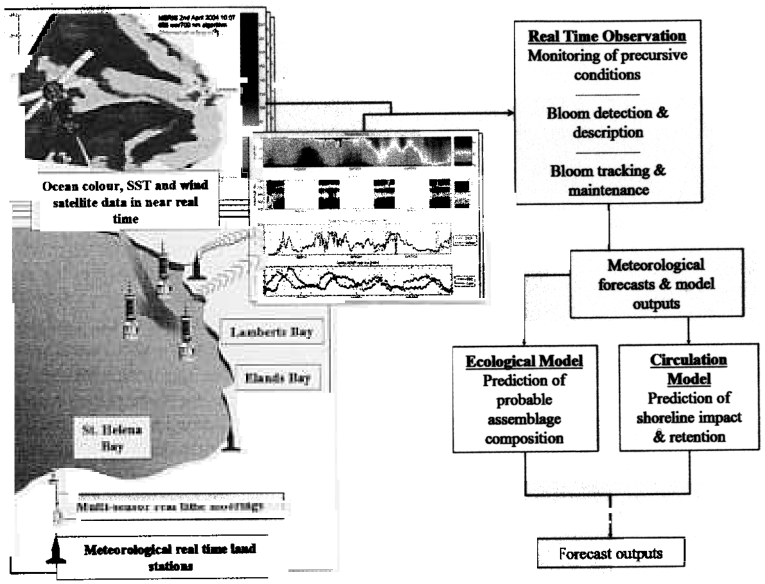


Figure 12-3. Schematic of proposed HAB forecasting system for the southern Benguela.

temporal and spatial perspective. Validation data should not be restricted to surface fields and should include data from throughout the water column. Simulation and process oriented studies should be conducted with validated models to identify the dominant dynamics underlying the initiation and transport of HABs.

Effective data assimilation requires the establishment of critical thresholds in observation; achieving such a critical threshold is likely to require considerable additional investment in observation network structure in order to provide data with a high enough spatial density. However, the first aim of a simple operational model is to provide a prediction of bloom shoreline impact and retention through a bloom tracking approach, given initial offshore bloom magnitude and delineation from near real-time buoy and satellite data. This capability, where real-time observations are utilised to determine initial model conditions for a bloom tracking simulation, should be distinguished from a true data assimilation capability, which is considerably more complex and observationally resource intensive. Further modelling studies should therefore include particle and bloom tracking studies, supported by similar efforts in the field.

It is recommended that platform-related sources of uncertainty identified in initial southern Benguela modelling studies be addressed by transferring to the ROMS platform, where the required boundary condition resolution can be achieved through nesting. There is also much to gain by considering several model structures, ranging in complexity from the simple 2D to complex 3D formulations. A simple alternative to the use of complex 3D models running in real-time is the use of a pre-generated offline catalog of circulation scenarios; such a facility used in conjunction with available real-time data would offer a simple and robust first approximation of potential shoreline impact.

CONCLUSIONS

The substantial complexity of the biological response amongst HAB organisms (e.g., variability in swimming, growth, mortality, nutrient and light acquisition, etc.) and the inherent stochasticity of species selection and bloom events means that it is unlikely that realistic predictions of species-level bloom formation can be achieved in the near future. The forecasting scheme outlined here provides an alternative approach by utilising real-time observation systems to replace the need to model biological aspects of HAB development. It appears that that the most pragmatic means for the prediction of biological HAB attributes in the Benguela at this time is a statistical "ecological window" approach, whereby physical, chemical, and biological real-time data are used to predict broad taxonomic groups (e.g., diatom versus dinoflagellate dominance, based on turbulence criteria). The future availability of species-targeting real-time observation techniques would substantially improve the ability to identify and predict taxonomic HAB aspects. Until such time, routine identification of toxic HAB blooms will require traditional sampling methods (direct cell counts and toxin assays), since these HAB events fall into the category of species-level forecasting.

The principal considerations with regard to the effects of physical processes on HAB forecasting can be summarised as follows. Three dimensional coastal morphology, and the spatial and temporal structure of the wind field, are the principal determinants of initial physical conditions. Shoreline impact of HABs, a key forecasting parameter, is determined principally by baroclinic instabilities, onshore winds associated with wind reversals, and southerly alongshore transport near capes during relaxation. With regard to surface transport in upwelling systems, alongshore transport dominates across-shore transport. Consideration must be made of variability in both local and remote forcing, e.g., coastally trapped waves, and the impact of these on HAB transport in local flow fields. New sets of observations are also required, most importantly high spatial resolution wind stress, and the deployment of pressure sensors around capes, given the importance of wind reversals in the vicinity of these features. Finally, it can be concluded that while bloom and retention are amenable to prediction, the processes underlying precondition and formation are unlikely to be sufficiently characterised to enable prediction in the near future.

An operational, real-time observation network is critical to the success of regional HAB forecasting schemes and a combination of multi-sensor coastal moorings and satellite data are required. Offering both biological and physical data, dedicated HAB moorings should provide hyperspectral reflectance data allowing the derivation of algal assemblage and physiological descriptors, surface fluorometer-derived algal biomass, and profiles of temperature and currents from thermistor chains and ADCPs. Bottom oxygen sensors are important in locations prone to hypoxic events. Additional chemical and meteorological sensors would be highly beneficial, as would be pressure sensors in the vicinity of capes, and the availability of high frequency coastal radar. Greater continuity and greater spatial coverage are also needed. At present there are a maximum of two moorings in the entire Benguela providing real-time HAB related data. Routine availability of appropriately processed satellite data is essential and should consist of multi-sensor ocean colour, SST and wind data. Species-targeting real-time observation techniques, needed for the prediction of toxin related impacts, are unlikely to be routinely available within the next few years.

The establishment of appropriately configured and validated circulation models, specific to each sub-ecosystem region of impact, is vital to any HAB forecasting capability. The first aim of a simple operational model is to provide a prediction of bloom shoreline impact and retention through a bloom tracking approach, given initial offshore bloom magnitude and delineation from near real-time buoy and satellite data. Simple offline circulation catalogs can be used to provide initial first approximation predictions of shoreline impact. Ultimately, it would be hoped to establish a forecasting structure operating in near real-time, utilising probabilistic ecological models and complex nested 3D physical models in conjunction with data from a variety of multi-sensor observation platforms.

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Low Oxygen Water (LOW) Forcing Scales Amenable to Forecasting in the Benguela Ecosystem

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INTRODUCTION

Episodic Low Oxygen Water (LOW) events (day – seasonal time scales) in the Benguela system impact on ecosystem properties such as habitat suitability for the different life cycle stages of economically important marine resources (Monteiro et al. 2004; van der Lingen et al. Chapters 8 and 14 *this volume*). The timing, persistence and spatial extent of such events in the recent past have led to major mortality and shifts in distribution of economically important living marine resources (hake in Namibia 1992-1994; rock lobster in South African west coast: 1990s) which impacted on fisheries yields and continue to be a source of uncertainty in forecasting fisheries total allowable catches (TACs).

Stock assessment models, used to forecast fishery TAC and the potential future economic yields from a fishery, incorporate the effects of environmental uncertainty such as LOW as a random contribution to mortality. This may have been justified while there was a weak understanding of the actual scales of LOW variability and how they are governed by complex interacting processes. Recent work on long term data sets indicates that LOW variability is not a random effect but can be characterised by specific frequency, persistence and intensity scales (Monteiro et al. 2004). The incidence of event scale (days) seasonal LOW variability (weeks to months duration) and its ecosystem impacts responds to longer time scales (decadal) of remote forcing. Moreover, improved understanding of the key processes and their linkages and response to short and long term forcing scales is beginning to improve the feasibility of reliable forecasting (Monteiro et al. 2004; Monteiro and van der Plas, Chapter 5 *this volume*).

A requirement for forecasting LOW variability and its impact on the economic value of ecosystem services and living marine resources is an ability to deal with the extreme range of scales involved. Thus, while basin scales govern shelf boundary conditions on seasonal to decadal time scales, local event scales modulate the variability by