Marine environmental monitoring programmes in South Africa: a review

L. Hutchings*, M.R. Roberts and H.M. Verheye

South Africa uniquely lies at the junction of two major currents, the Agulhas and the Benguela. The waters overlying the continental shelf exhibit exceptionally high short-, medium- and long-term (days to inter-decadal) variability compared with most other shelf areas, and strongly contrasting oceanographic conditions are observed on the east and west coasts. South Africa is rich in fisheries resources and associated environmental data collected over more than a century. The South African marine scientific community has a history of multidisciplinary studies of marine foodwebs, from the driving forces such as wind, currents and solar heating, to the top predators, with the development of kelp bed, sub-tidal reefs and estuarine ecosystem studies in the 1970s; the Benguela Ecology Programme, which ran through four successive five-year stages, focused on the pelagic marine resources. Various approaches have been used to observe the continental shelf at different time and space scales, including: macroscale but frequent satellite imagery, mesoscale environmental and fishery surveys, dedicated cross-shelf transects in key areas, measurements of dynamic processes, use of moored buoys and coastal weather stations, and integrated monitoring approaches, including modelling and simulation studies. Between 30 and 50 years of comprehensive marine data now exist, which are proving useful in the application of an ecosystem approach to fisheries monitoring and management, as decadal changes become discernible. These observations need to continue; even though the single-species stock assessment and operational management procedures have not yet formally used environmental factors for fisheries management advice, they help us to understand the factors affecting fish population fluctuations and early life histories and to identify large-scale regime shifts where marine trophic structure and functioning alter to a new state.

Key words: marine environment, indicators, fisheries, Benguela, Agulhas Bank

Introduction

Marine and Coastal Management, and its predecessors in name, the Sea Fisheries Research Institute, the Division of Sea Fisheries, and the Government Marine Biologist, has a long and proud record of collecting environmental and fisheries information since the 1900s, but particularly since 1950, when staff and ship facilities were greatly expanded. While much of the incentive for data collection and analysis has focused on sustainability as one of the goals of fisheries management, conservation of marine biodiversity and assessing decadal changes have received increased emphasis, particularly with the introduction of an ecosystem approach to fisheries management and the awareness of marked changes in climate associated with recent global warming trends. Environmental changes and their effects on resource utilisation patterns and biodiversity conservation are some of the main foci of the South African Environmental Observation Network (SAEON) programme.

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South Africa harvests wild marine resources, which require careful management because of uncertainties relating to productivity and distribution of populations. The rich fishing grounds on South Africa's continental shelf are characterised by fluid, ever-changing boundaries, driven by local forces such as solar heating, wind and currents as well as remote, large-scale forcing such as climatic shifts in weather patterns across the globe and global circulation changes.[1] The particularly dynamic juxtaposition of the warm western boundary Agulhas Current and one of the major upwelling regions of the world, the Benguela system, contributes greatly to the high variability, biodiversity and productivity of our marine resources. The sea provides unique challenges for surveying and assessment of trends in resource population sizes, which are essential to estimate the proportion which can be removed without endangering future productivity of the target population or the surrounding ecosystem. Careful monitoring of the physical driving forces, the chemical composition of the ocean, the plankton at the base of the marine food web, the target fish populations and the top predators which compete with man for food from the sea, are necessary components of a scientific approach to sustainable harvesting of marine resources in an ever-changing environment. This paper refers to the environmental components of the ecosystem monitoring programme conducted by Marine and Coastal Management. Very few of these environmental parameters are included in the formal management processes (operational management procedures) for the setting of total allowable catches. This is because many of the responses of living marine organisms to physical driving forces are non-linear and in fact change over time, varying with the size and the distribution of the population. Operating models are generally constructed to be robust to these perturbations, which are simulated by assuming the environmental influences are random over time, while natural mortality rates and growth rates are assumed to be constant. Because of non-linear or complex biological responses to physical or chemical forcing, there is inevitably considerable variance associated with the relationship between environmental parameters and the biological responses. Ecologists have so far been unable to provide the necessary precision to relationships which will result in suitably narrowly defined management recommendations. Nevertheless, the Benguela system changes markedly at interannual to decadal scales,[2] which can have profound effects on the productivity and distribution of marine resources.

There is a compelling and urgent need to continue to monitor and assess variability in the marine ecosystems around southern Africa in an effort to provide objective and sound scientific advice to decision makers in government and the fishing industry, who must promote sustainable fishing yet minimise harmful ecosystem effects of fishing practices. This contribution reflects the efforts of Marine and Coastal Management to contribute towards the wise use of South Africa's rich marine ecosystems for human utilisation, for biodiversity conservation, for ecosystem-based tourism and to maximise income and job creation in a sustainable manner. This is a demanding and complex task,
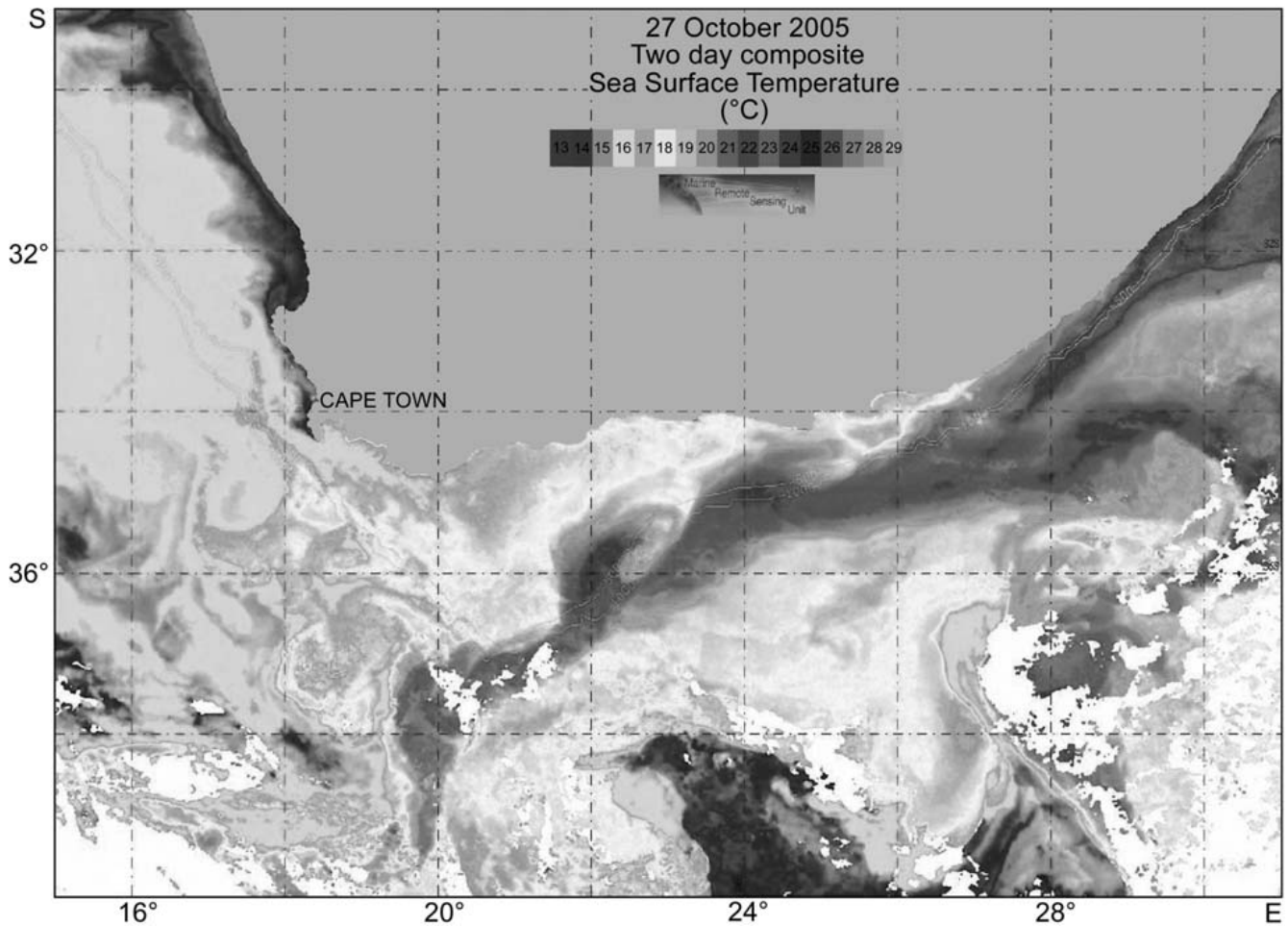
Fig. 1. Two-day composite of AVHRR infrared thermal images of the sea surface temperature on 27 October 2005, indicating the cool productive upwelling in the Benguela current and the warm nutrient-poor Agulhas current flowing swiftly down the east coast, with eddies over the Agulhas Bank and intense mixing offshore. Courtesy of Remote Sensing Unit, UCT.

given the ever-increasing human populations in coastal areas and the difficulties in distinguishing climatic variability from human influences.

Monitoring the environment at time and space intervals appropriate to the life history stages of the pelagic and demersal fish in the South African economic exclusive zone is a daunting task. Six distinct yet complementary environmental sampling schemes need to be carried out:

1. Macroscale and frequent (every 2–3 days) satellite imagery covering the entire Benguela system and its boundary conditions. On an even larger scale, the variability of the South Atlantic, South Indian and Southern Oceans plays an important role in determining events in the South African economic exclusive zone.

2. Mesoscale environmental and fishery surveys. These multidisciplinary surveys sample on spatial scales of tens to hundreds of kilometres and seasonal to annual temporal scales.

3. Regular (monthly to seasonal) ship-based transects in key areas; currently only two transects are routinely sampled in South Africa.

4. Process-orientated measurements of rates of production and consumption, following drogues or at anchor stations in key areas or in the laboratory.

5. Moored buoys (to measure currents, phytoplankton fluorescence, wind, temperature, acoustics) and coastal stations at key sites.

6. Integrated monitoring approaches.

1. Satellite imagery and indices

At present sea surface temperature and ocean colour (as a proxy for phytoplankton biomass, estimated as chlorophyll) are the most important parameters measured routinely around South Africa, with surface winds and sea surface height becoming important at coarser scales. Daily images of temperature (Fig. 1) and chlorophyll can be plotted as contour maps over time to observe changes in boundaries; they are used to derive indices of productivity and upwelling (Figs 2 and 3) over years or decades.[3] Problems arise with both technical advances in sensors and differences in instrument characteristics over long periods; each time the satellite sensor changes, a new round of ground-truthing and calibration has to be conducted. These indices have been used to run expert system models and to explain unusual events[4] and to try to explain shifts in distribution of resources.[2] However, remote sensing cannot tell us much about subsurface parameters, such as low-oxygen conditions close to the sea bed, or zooplankton organisms and fish in the water column.

2. Mesoscale (fishery) surveys with environmental sampling

Routine monthly environmental monitoring cruises of 60–100 stations were conducted in the 1950s and 1960s, particularly in the south-west Cape, where the South African fishing industry is centred. Intermittent surveys were subsequently undertaken, but usually only for fishery survey purposes; for example, pelagic fish eggs and larvae were sampled quarterly from 1967 to 1969 and again monthly in 1977/78 during the Cape Egg and Larval Programme. Since 1988, environmental scientists have
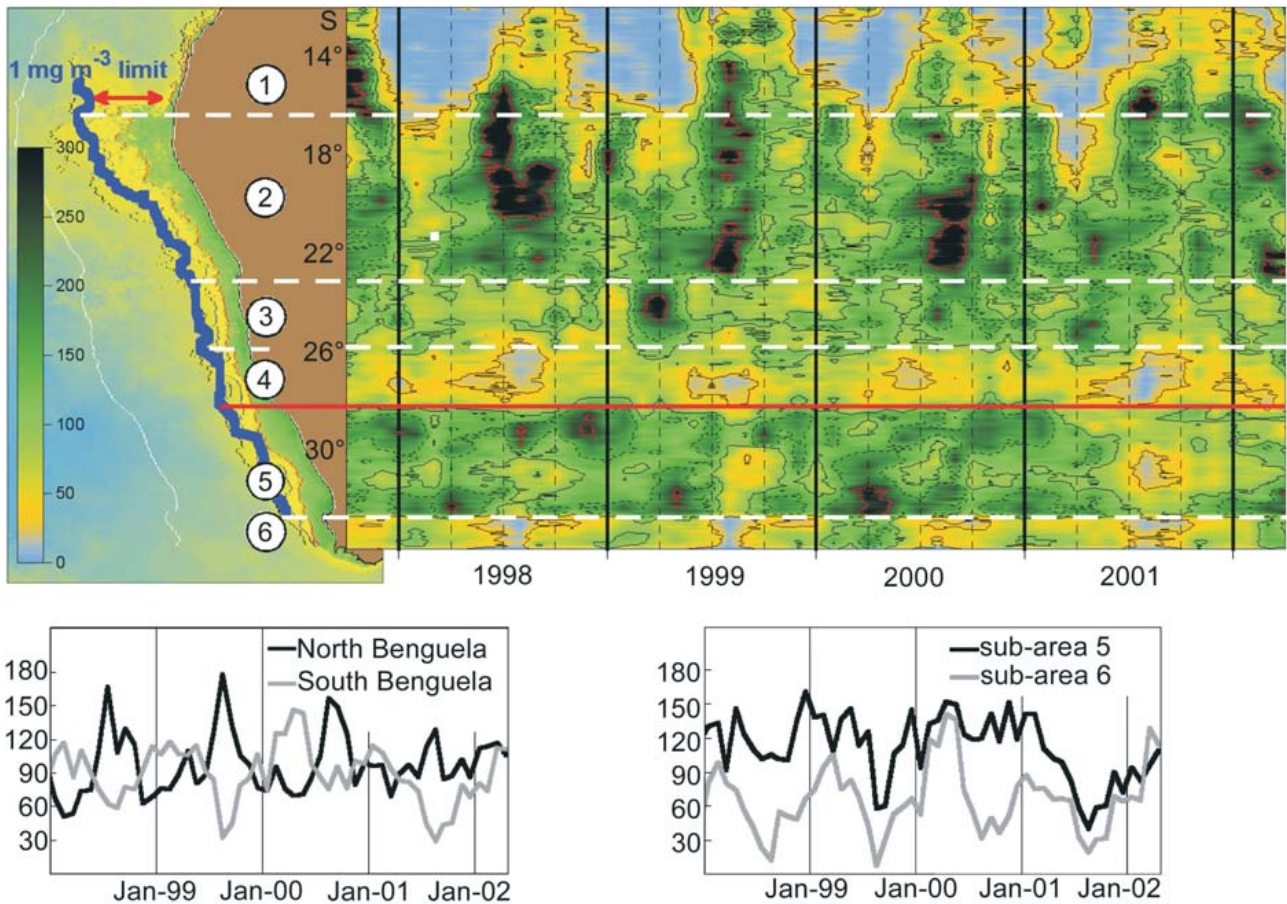
Fig. 2. Upper panel: Patterns and indices of phytoplankton enrichment on the west coast from Angola to Cape Agulhas, based on satellite colour imagery, showing six spatially distinct zones. Lower panel: Enrichment indices based on the sum of pixels between the coast and the 1 mg m^{-3} chlorophyll a isoline, to illustrate monthly and interannual variability.[3]

participated on pelagic and demersal fisheries surveys to collect information of the physical habitat (temperature, salinity, density, thermoclines, currents, light), the chemical make-up of the water column (nutrients, oxygen, phytoplankton pigments) and the phytoplankton and zooplankton species and sizes. These surveys are usually conducted two or three times per year, at the same time of year (Fig. 4). Data are used to explain unusual distributions, fish condition or feeding behaviour, to attempt to predict future trends in recruitment or to determine ecosystem effects.[4–8] Similarly for demersal surveys, environmental data such as light levels, turbidity, oxygen and temperature can potentially provide information on changes in hake catchability, or availability to both research and commercial fishing vessels. A distinct movement of hake off the near-bottom layer (where they are traditionally caught by bottom trawling) was noted during strong SE winds off the steep shelf between Cape Columbine and Cape Point, which has implications for survey design and population assessment.[9] Conductivity temperature depth casts are currently made after every trawl to determine water column properties. The environmental monitoring of squid follows an integrated approach, where turbidity and temperature are considered the most important parameters affecting squid availability and reproductive success.

3. Dedicated, long-term, regular ship-based transects in key areas

An example of this is the St Helena Bay Monitoring Line, initiated in April 2000 as part of a multinational BENEFIT (Benguela Environment and Fisheries Interactions and Training) regional project to sample three representative transects through the

Benguela Current in South Africa, Namibia and Angola. The transect (Fig. 5) covers several phases of the life cycle of a number of dominant, commercially-important species, including pelagic fish, demersal fish, rock lobster and tuna.[10] While monitoring of surface temperature and phytoplankton is better undertaken using satellite imagery, measures of dissolved oxygen, important for hake and rock lobster, and zooplankton (Fig. 6) for pelagic fish growth rates and condition, can only be determined using this approach, despite the transect being limited in space and time. The seasonal data can contribute to long-term data sets, such as the long-term changes in oxygen content at particular locations (Fig. 7) and the zooplankton changes over five
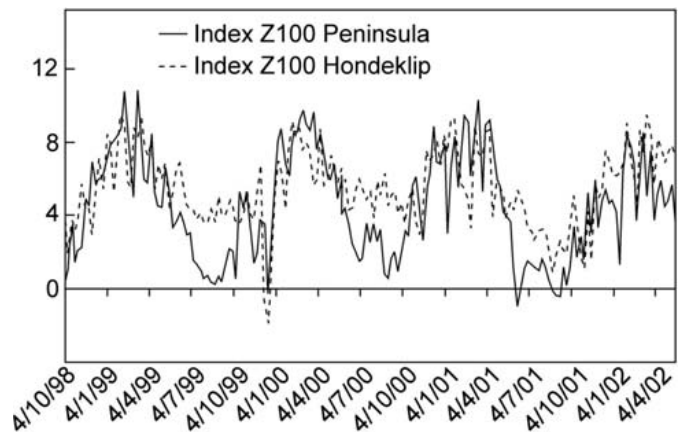

Fig. 3. Upwelling indices derived from differences in sea surface temperature between the coast (<100 m depth) and a point 160 km offshore, showing seasonal, spatial and interannual patterns (C. Roy, pers comm).
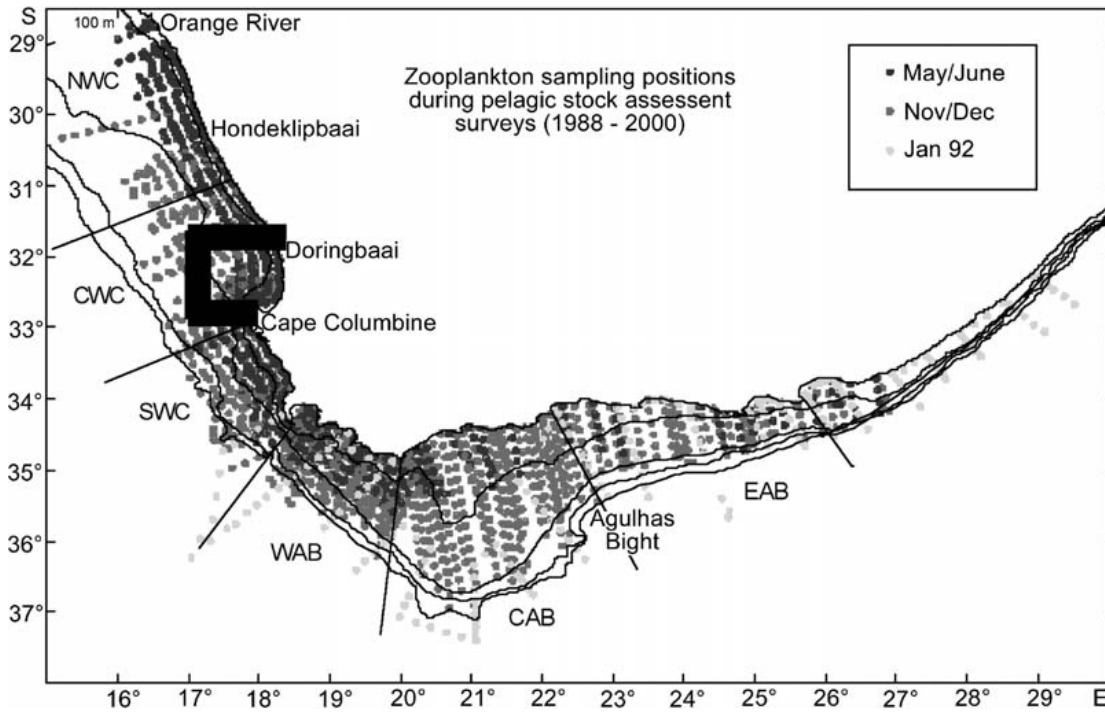
Fig. 4. Environmental sampling locations for pelagic fish surveys, 1988–2005.

decades for autumn months[11] (Fig. 8). The interannual changes have been related to changes in fish abundance and condition and wind indices in hindsight.[5,6]

Only two strategic transect lines in South Africa are currently monitored, when at least six or seven transects are required (e.g. KZN/Durban, Wild coast/Port St Johns, Port Elizabeth/St Francis Bay, Mossel Bay/central Agulhas Bank, western Agulhas Bank

and Namaqua coast). Ship's time is very expensive, however, and moored instrumentation on buoys is a complementary approach for certain key parameters, with much better temporal resolution of processes such as heating, cooling, water column mixing, currents and phytoplankton abundance.

4. Process-orientated investigations of rate processes

Usually, only static, snapshot pictures of the biomass of marine organisms can be made during monitoring cruises, which ignore the rates of processes such as growth, feeding, egg production, sinking or swimming. By combining rate measurements, made on dedicated cruises or during laboratory experiments, with biomass values obtained on monitoring cruises or fishery surveys, it is possible to estimate fish consumption relative to plankton production and to estimate the likelihood of good or poor environmental conditions affecting the recruitment process using expert systems.[6,12] These may change over short time and space scales and integration to the time and space scales pertinent to populations of marine organisms is one of the major problems facing fisheries oceanography. Modelling is an essential element of this approach.[13,14]
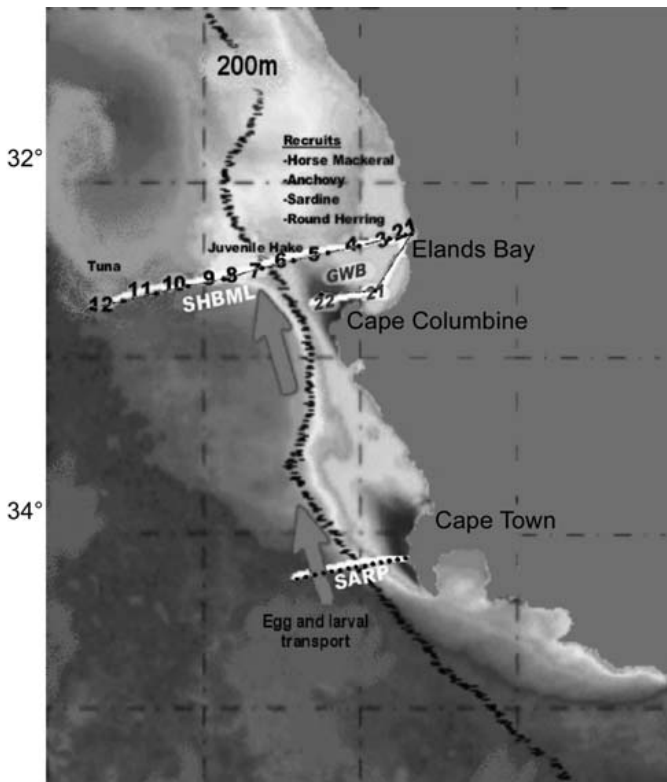

Fig. 5. St Helena Bay Monitoring Line (SHBML) and Sardine-Anchovy Recruitment Programme (SARP) lines, sampling monthly since 2000, superimposed on a typical satellite temperature image during active upwelling in summer, with pertinent biological processes.
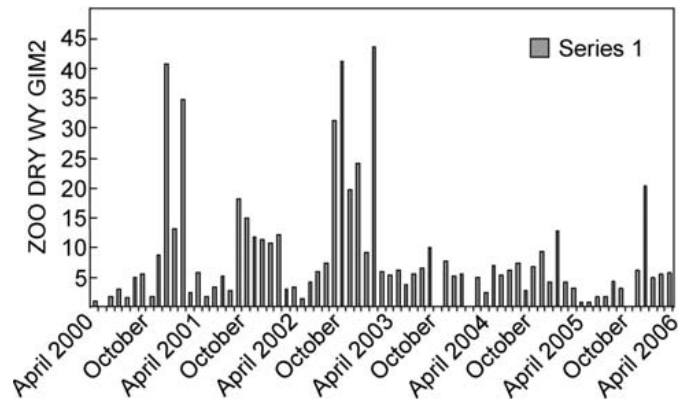

Fig. 6. Seasonal variability of zooplankton biomass (g dry wt m^{-2}) at the inner five stations (<200 m) on the SHBML. A pronounced 5–10-fold seasonal variation is observed, dampening in recent years.
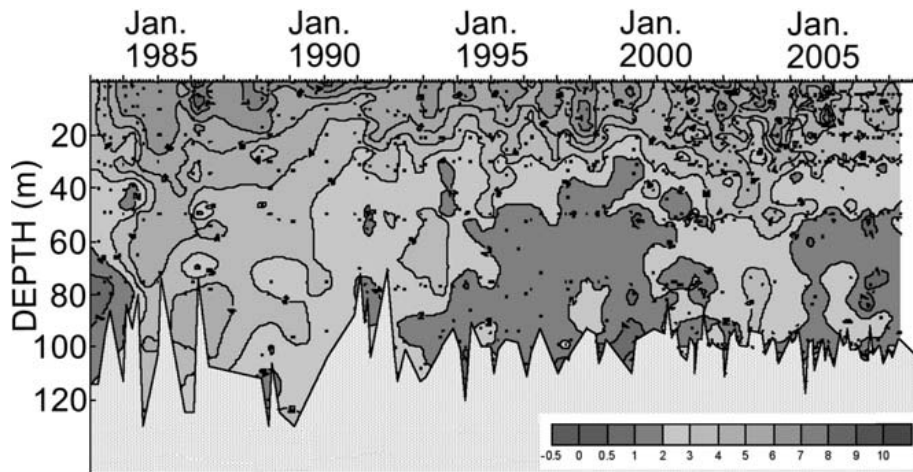
Fig. 7. Decadal changes in oxygen content of the water column at Station 22 off Cape Columbine, 1983–2006, indicating three major occurrences of low oxygen water in 1982/3, 1994–2000 and 2004/6.

5. Single fixed sites: moored instruments and coastal stations

Various initiatives have been made to collect information at key coastal locations. These include lighthouses, airports, coastal weather stations, moored temperature sensors, and multifunctional moorings. Wind strength and direction measurements are essential where coastal upwelling is an important feature, as in the seas off the south and particularly the west coast of South Africa. Coastal shipping recordings, estimates by lighthouse-keepers, anemometers, air pressure differentials and satellite scatterometer measurements have all been used to determine wind forcing in terms of pattern and persistence[15,16] (Fig. 9). Temperature measurements have been improved by installation of a network of 15 recording instruments along the entire coast of South Africa, with limits set by the logistics of servicing the instruments with technical expertise. Trends, anomalies, variability and minimum, maximum and mean values are obtainable for varying periods along the entire coast. Multifunctional moored instrumentation has been developed for a number of initiatives.

These include a buoy system for oxygen and temperature at Elandsbaai, a site of numerous rock lobster strandings and mass mortalities; a harmful algal blooms (HAB)-detection moored array in Lamberts Bay[17] (Fig. 10) coupled to satellite imagery; and an environmental monitoring and squid behaviour system in St Francis Bay (Fig. 11). These buoy systems provide poor spatial resolution but excellent fine-scale temporal resolution and are useful tools for real-time monitoring and forecasting systems.

6. Integrated monitoring systems and modelling

These utilise data and derived indices from a wide variety of sources and produce up to date environmental assessments or forecasts of likely events. Some examples of this approach include the expert system for pelagic fish recruitment[6] (Fig. 12), a rock lobster stranding expert system[8] and squid information and catches expert systems (Figs 13 and 14). A three-dimensional hydrographic model,[13] forced with monthly climatology, can effectively simulate conditions on the South African shelf for
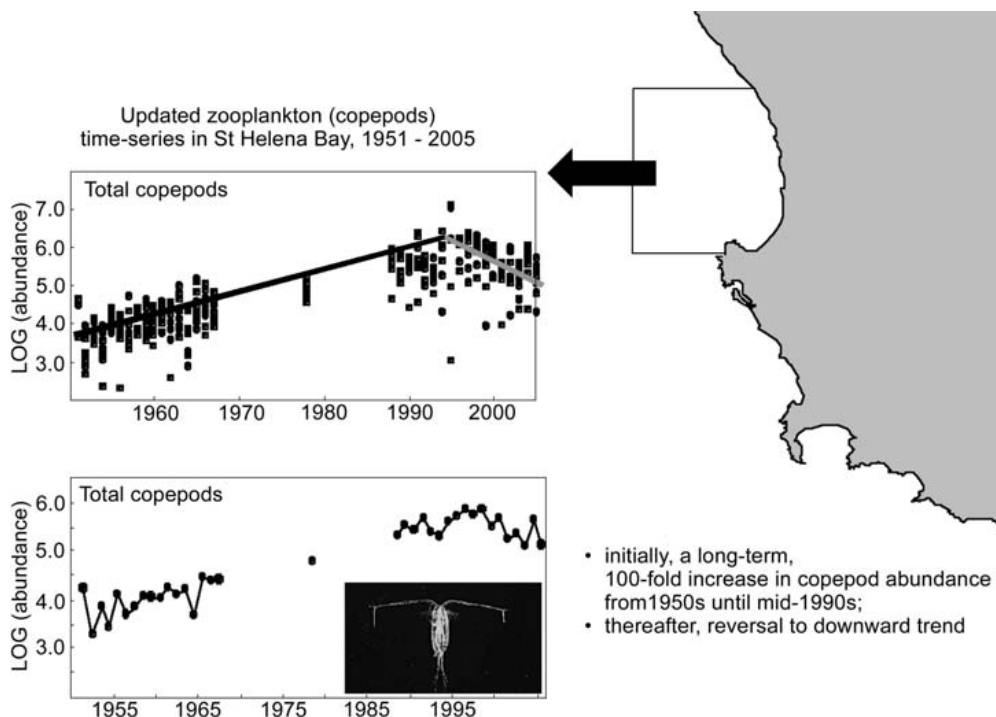

Fig. 8. Decadal changes in planktonic copepods in St Helena Bay in autumn months (April–June), 1951–2005, showing a 100-fold increase until 1995, followed by a downward trend in recent years.
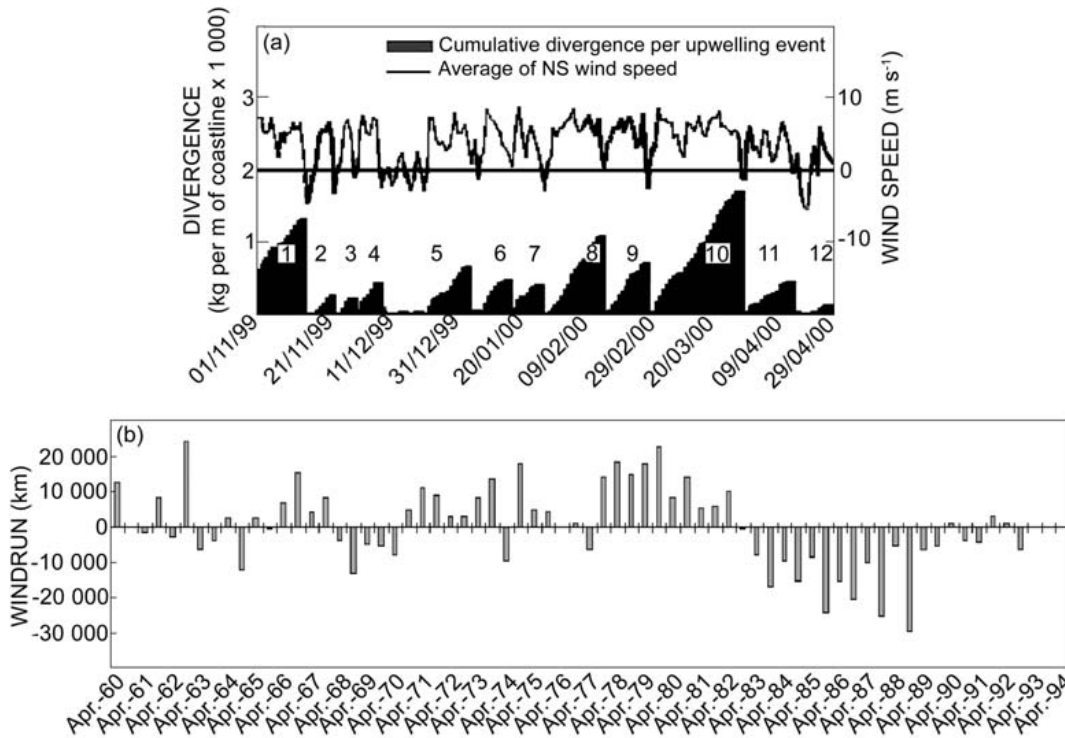
Fig. 9. Upwelling indices based on winds, in the short term over six months to show upwelling pulses, and anomalies from the mean over 33 years, 1960–1994, for Cape Columbine.

examining retention, transport and survival of fish eggs and larvae, future climate change scenarios of global warming and hydrodynamic influences on features such as the Natal sardine run. Expert systems, while lacking the statistical rigor of formal stock assessment and operational management procedures,

do provide useful early warning signs of impending changes. However, they, like the assessment models, are subject to assumptions underlying their construction; for instance, the recruitment expert system of Korrubel *et al.*,[6] which worked well in hindcast mode, assumed that the major anchovy spawning
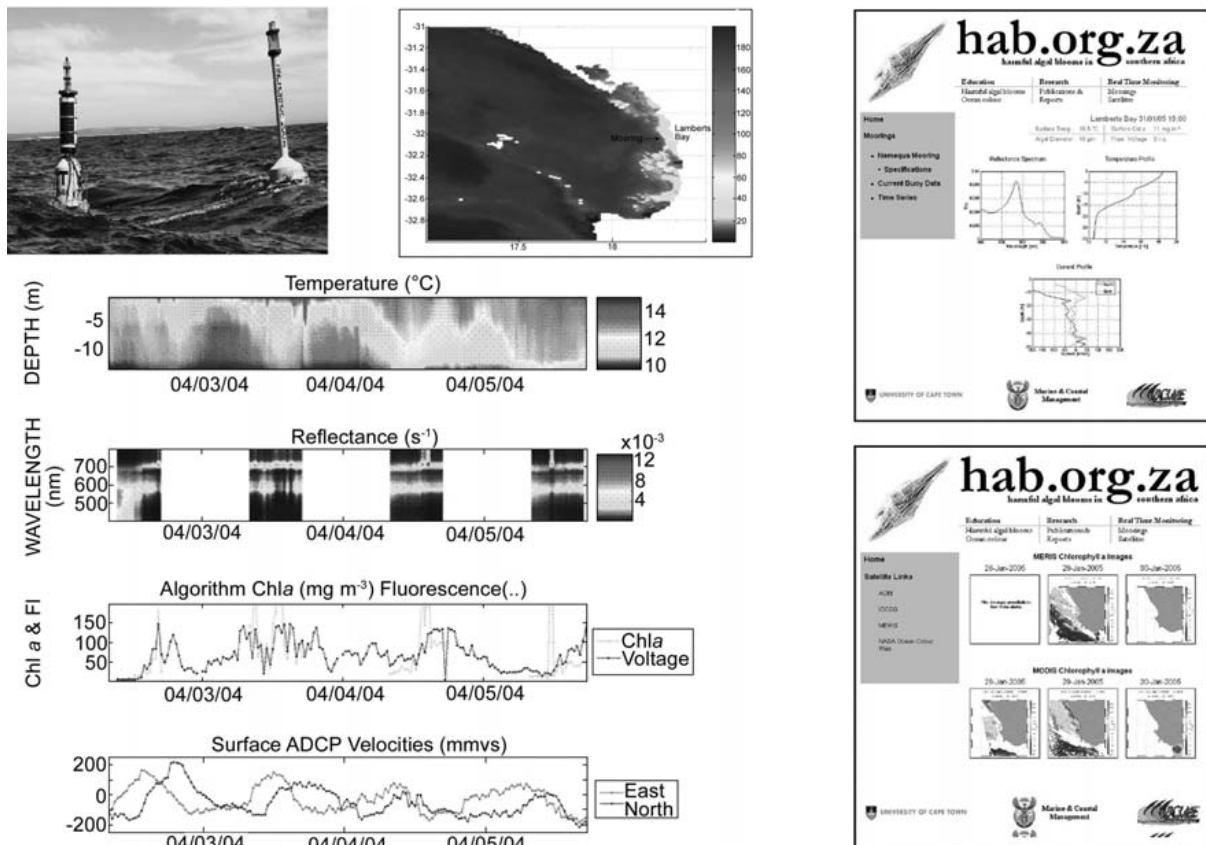

Fig. 10. A moored buoy for early detection of harmful algal blooms (HAB) off Lamberts Bay, with web-based outputs for near-real-time monitoring.[17]
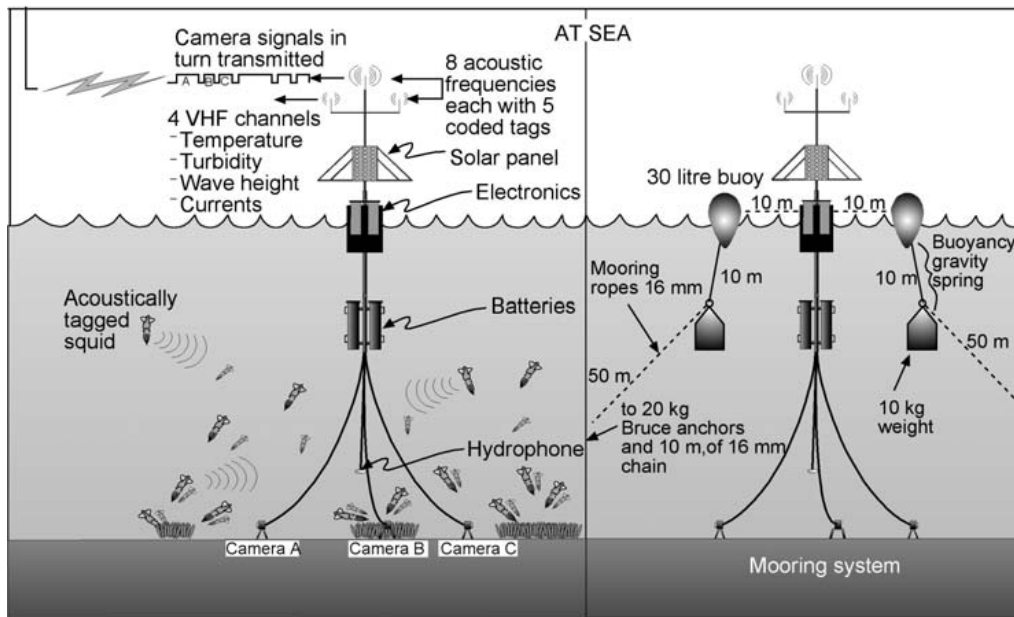
Fig. 11. A buoy monitoring system in St Francis Bay to monitor squid spawning behaviour and environmental parameters such as temperature and turbidity.

ground was centred on the western Agulhas Bank. An eastward shift in the spawning to the east of Cape Agulhas[2] rendered the parameters used in the expert system untenable. The major problem common to the use of empirical correlation coefficients, expert systems and stock assessment techniques to estimate future fish yields is the strong interdecadal variability[1] in the forcing functions or dominance regimes which characterise South African and other marine areas. Generating enough data points to ensure statistical rigor is not possible with annual data before major changes in the ecosystem have occurred. Building operational management systems which are robust to uncertainty allows one to make pragmatic forecasts of future productivity, but renders them insensitive to environmental change. When environmental thresholds are reached, more adaptable

techniques, such as expert systems, are required to anticipate future scenarios. For instance, the operational management procedure for sardines, devised after a prolonged period of better than average recruitment from 1983 to 2002, failed to prevent the rapid depletion of the stock as recruitment failed for three years in a row in 2003 to 2006. In addition, sardines and anchovies, long considered to have similar early life histories, diverged in their recruitment success following an eastward shift in the adult populations, with anchovies still maintaining strong recruitment and sardines sharply declining. Unless one initiates novel approaches to pelagic fish recruitment and variations in natural mortality, stock assessment will be locked into environmental insensitivity stasis in perpetuity.

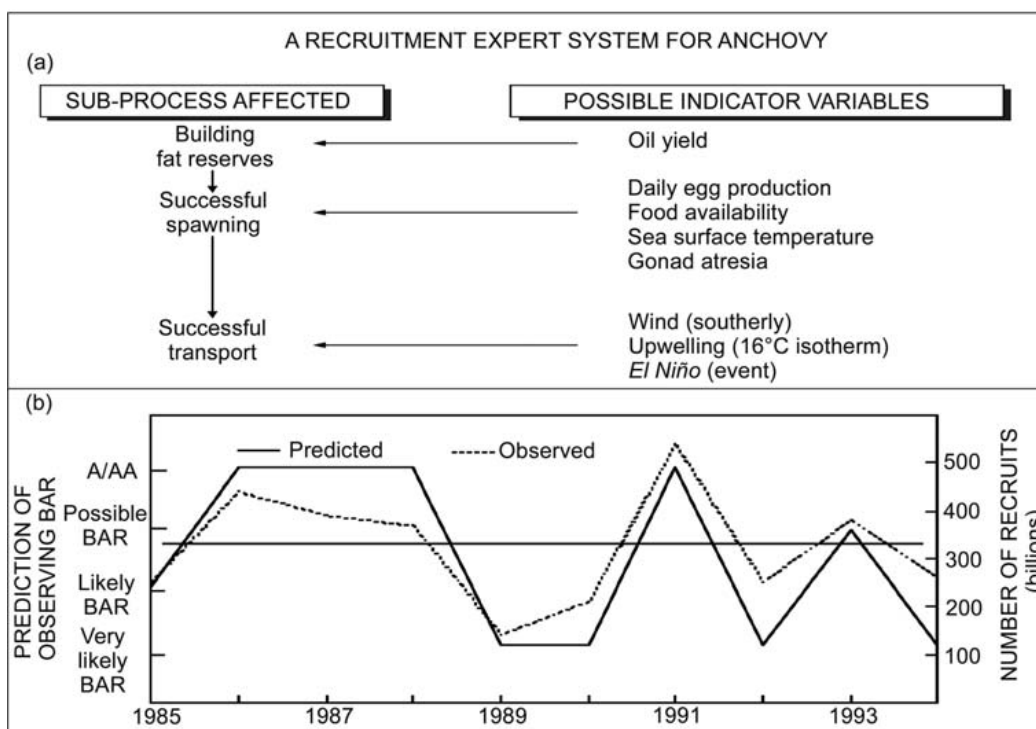Incorporation of large-scale forcing into regional climate

Fig. 12. An expert system, designed to predict anchovy recruitment six months ahead of the recruitment survey, demonstrated in hindcast mode.[6]
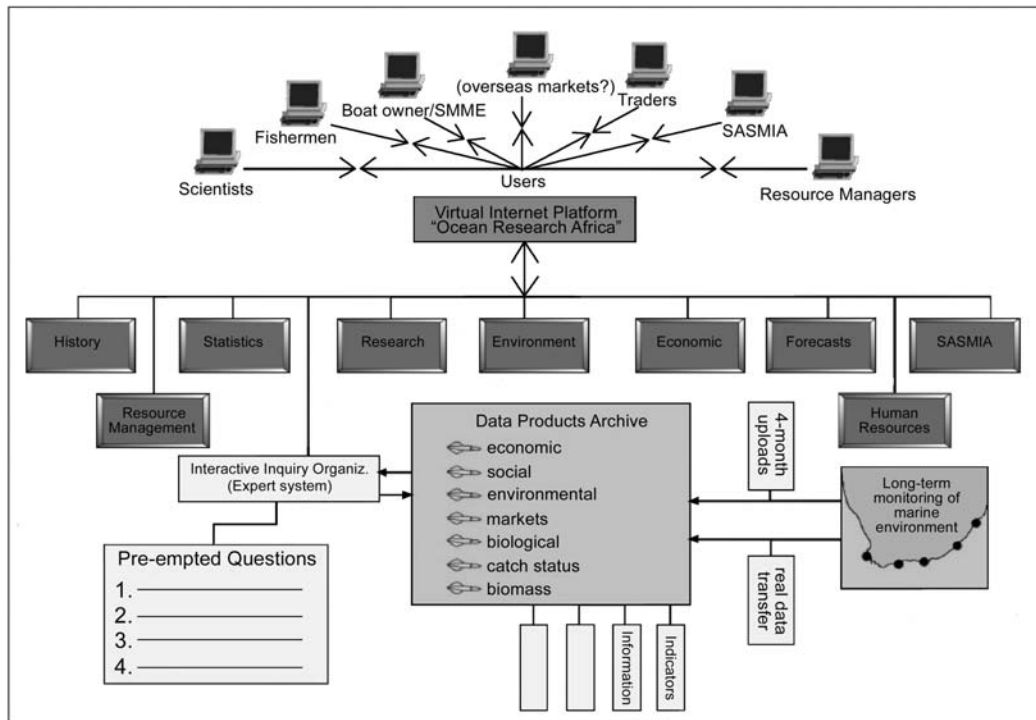
Fig. 13. An interactive, decision-making/information tool for the squid industry.

change models is an important process for scenario planning in the future. Modes of variability in the Indian and the South Atlantic Oceans are crucially important drivers of rainfall on land and marine productivity and regime shifts in the exclusive economic zone as most organisms are adapted to the "normal" range of variability but cannot cope with prolonged, large-scale changes. Much research is currently directed at the exchange of heat and salt between the Atlantic and Indian Oceans as part of the global conveyor belt, while the variability of the larger cur-

rent and wind systems and their links to changes in circulation patterns on the shelf biota remain a task for the future. Despite decades of concerted research and monitoring efforts, the understanding of the causative links and processes between oceanographic parameters and fish productivity and distribution remain poor.[18] It is in fact an extremely complex process, with both positive and negative feedbacks, but is beleaguered by relatively poor understanding of basic processes such as early life history of valuable resources, when environmental factors
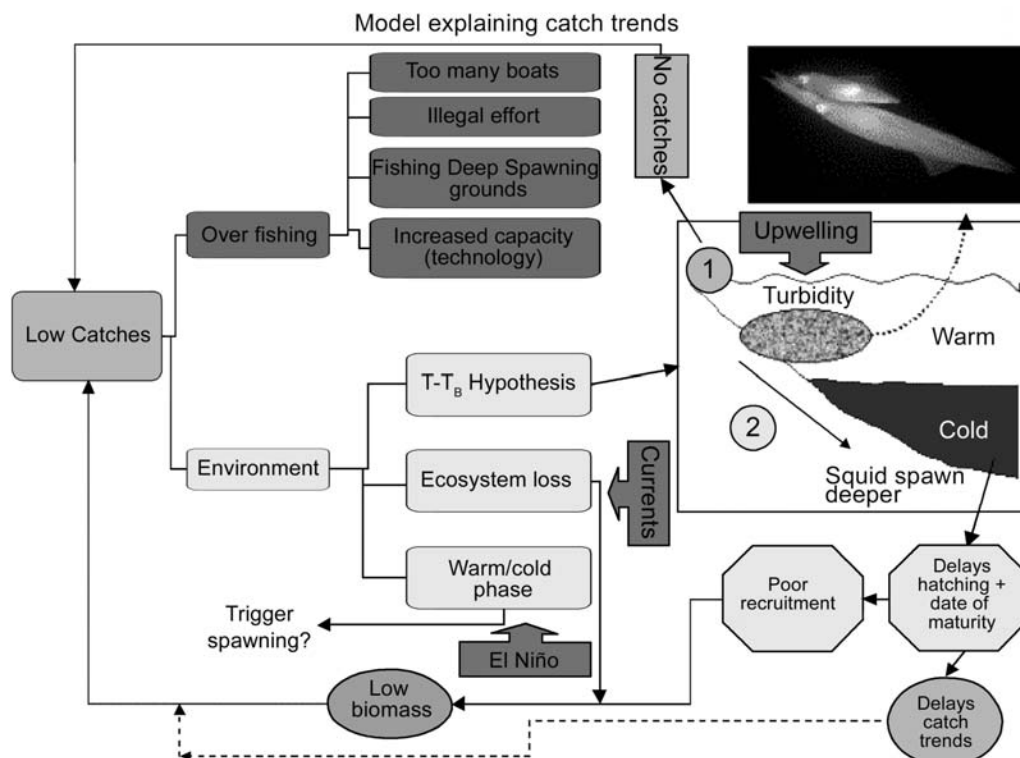

Fig. 14. A conceptual model to explain catch trends in the squid industry: fishing or the environment.

are thought to be important. Another reason is the high fecundity of most fish—each female produces hundreds of thousands to millions of eggs each year, of which, on average, only two need survive to replenish the population. The potential for exceptional survival and recruitment is always there, but is seldom realised. Most fish species also produce batches of eggs in serial spawning mode, which is thought to be an adaptation to overcome short-term variability. The capability for extreme variation is inherent in the broadcast spawning reproductive strategy. Small scale processes affect the microscopic eggs and larvae and these have to be integrated over space (hundreds of kilometres) and time scales (several months) appropriate to the particular life history. Computing capacity is only now beginning to have the capabilities to simulate these early life conditions.

Future prospects for offshore marine monitoring for SAEON

Reconciling the assumptions of a randomly-varying environment with only moderate effects on fish populations with the reality of erratic strong environmental influence, particularly during the early life history stages when recruitment strength is determined,[18] remains one of the major challenges for fisheries oceanography and management. Changes in distribution, productivity and natural mortality of fish populations are also difficult to estimate and parameterise for management procedures of wide-ranging wild resources such as fish. Time series of appropriate parameters need to be methodically collected over a range of time scales, from daily to decadal, to provide reality checks on numerical models of the ocean, ranging from primary productivity through zooplankton, the recruitment process and fish behaviour and migration.

In addition to providing background information pertinent to the management of wild fish resources, the data become useful for climate-related research, biodiversity conservation and for coastal developments.

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