profiles. An extensive database of this nature could be used for a variety of integrated studies, such as the chemistry and meteorology of ozone distribution, the impacts of enhanced UV on climate, oceanography, plant physiology and the occurrence of skin cancers, among others.

South Africa is, geographically, a front line state as far as the polar vortex and the ozone hole are concerned. It is important that we become familiar with our ozone layer and the effects on our environment.

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Scenarios for global-warming induced change in the open-ocean environment and selected fisheries of the west coast of Southern Africa

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Possible consequences for fisheries in the open-ocean environment off Southern Africa's west coast of four scenarios that may arise as a result of global warming are explored. The four scenarios are increased advection of warm water into the Benguela region from the north, greater input of warm water from the Agulhas Current to the southern Benguela region, altered wind stress, and warming of surface waters. Expected outcomes differ according to the scenario adopted, and there is also uncertainty concerning biological responses to environmental change. However, it is shown that global warming has the potential dramatically to affect Southern Africa's rock-lobster, purse-seine, bottom-trawl and tuna fisheries, and that there would be important consequences for the coastal fishing communities of the region.

It has been recognized that anticipated climate change may have important consequences for marine ecosystems.[1] This statement is of particular concern to developing countries such as Peru, Chile, Namibia and South Africa, where coastal fisheries provide employment for substantial numbers of people and play important roles in the economies (e.g. ref. 2). Since the late 1960s, fish catches at the western edge of the Agulhas Bank and in the Benguela upwelling system have fluctuated between two and three million tonnes.[3] Although much of this catch has been taken by foreign trawlers, the South African catch of 1988 (excluding Walvis Bay) had a wholesale value of some R900 million (approximately US$360 million). In that year the South African fishing fleet consisted of more than 600 decked vessels of various sizes and over 5 000 smaller craft, with a total replacement cost of between R2 000 million and R3 000 million. The industry provided employment for almost 26 000 people, of whom about half worked at sea and the remainder in more than 100 fish processing plants.[4] Additionally, in South Africa, more than 350 000 people are engaged in recreational angling of one form or another, supporting a considerable infrastructure.[5] Along South Africa's west coast the fishing industry provides the major source of income for entire towns, and along the Namibian coast fishing is also a major source of income and employment.[6]

There are two prerequisites for reliably predicting the impact of climate change on marine resources. It must be clear how climate change will influence the environment at a regional scale, and it must be known how the various marine resources will respond to such environmental change. At present there is inadequate information on both aspects. Even the most modern models of global climate change are far from offering reliable simulations of future regional climates.[7] There have been large changes in the dominance of species in Southern African marine ecosystems, and these changes are likely to have been influenced by the environment, although the mechanisms giving rise to them are improperly understood.[8]

Therefore, in this paper we do not attempt to predict the impact of climate change on marine resources. Rather, we endeavour to develop 'what-if' scenarios for various plausible changes to the marine environment off Southern Africa. We infer likely biological responses from past empirical observations and from studies of behavioural responses of species to environmental circumstances. For example, if a fish species consistently avoids spawning in coastal regions with strong offshore advection of surface waters (see ref. 9), we have assumed that any future region of strong offshore transport will also be unsuitable for spawning.

The present state of knowledge of environmental influences on selected elements of Southern Africa's marine biota is reviewed elsewhere in these proceedings,[8] and it is apparent that much is still to be learned. For this reason, and because the functioning of marine systems is complex and depends not only on the abiotic environment but also on biological interactions and patterns of exploitation (e.g. ref. 3), the scenarios we develop will not necessarily be correct, but at least they are plausible. Greater realism will be attained as information and understanding accumulate. Our scenarios must not be viewed as predictions. We aim instead to draw attention to some possible impacts of global warming on selected fisheries off south-western Africa. In this way we hope to facilitate planning of marine research for the coming 10-year operational phase of South Africa's contribution to the International Geosphere–Biosphere Programme.

The scenarios we selected were increased intrusion of warm tropical water into the Benguela from the north, increased input of Agulhas Current water to the southern Benguela region, altered wind stress, and a warming of surface waters. For simplicity, we describe the scenarios separately, but it is possible, even probable, that a synergistic mixture of all scenarios will be realized.

Scenario 1 — Increased incidence and intensity of intrusion of tropical water from the north

Primary event

There is seasonal influx of warm water from the Angolan region onto the Namibian shelf. Episodically the incursion

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penetrates farther south than normal, and develops into a major, persistent warm event, a phenomenon that has been termed a Benguela Niño.[10] Previous Benguela Niños have coincided with periods of low, or sharply reduced, zonal wind stress in the western equatorial Atlantic, and consequent enhanced eastward flow of the Atlantic Equatorial Countercurrent–Undercurrent System.[11] An outcome of global warming is a change in the equator–pole temperature gradient,[7,12] leading to poleward shifts in oceanic and atmospheric systems, including the hemispheric wind belts. This could well result in an increased frequency of occurrence and intensity of Benguela Niños.

Primary effects

Benguela Niños have advected warm water to depths of at least 50 m off Namibia, and to distances at least 150 km offshore.[13] They may penetrate at least as far south as Hollams Bird Island at 25°S[10] (Fig. 1). Advection of the warm water causes greater stratification of the water column and a deepening of the thermocline, and it may lead to upwelling being only of warm tropical water deficient in nutrients. Primary production decreases by up to 70%,[14] probably as a result of reduced production by diatoms caused by limitation of nutrients, especially of dissolved silica.[15]

If diatoms are not replaced by dinoflagellates, the quantities of organic carbon produced and oxidized will decrease. This in turn could lead to a reduction in the volume and distribution of oxygen-depleted water on the shelf-bottom.[16] However, most of the water on the Namib shelf low in oxygen originates from the north.[17] Should Benguela Niños enhance advection of water deficient in oxygen onto the shelf, the volume and distribution of oxygen-depleted water could increase.

Consequences for resources

Dependent on the eventual outcome, the habitat suitable for rock lobsters *Jasus lalandii* could increase or decrease. A reduction in oxygen-deficient water should expand the habitat, with lobsters then dispersing to occupy a wider area and depth range than at present. Initially, such an expansion should not be limited by food availability, even if there were to be a reduction in the production of filterfeeding organisms such as mussels (e.g. *Aulacomya ater*) as a result of a decrease in primary production in the water column, because lobsters are capable of feeding on a wide range of food organisms.[3]

Benguela Niños bring to Namibian waters fauna of more tropical affiliation, such as *Sardinella* spp.[18] The warming may cause various scombrids, e.g. skipjack *Katsuwonus pelamis*, yellowfin tuna *Thunnus albacares* and frigate tuna *Auxis thazard*, to frequent the waters off northern Namibia more often than at present. Benguela Niños also displace species that are normally resident off northern Namibia to the south.[19,20] Hakes may be dispersed over wider areas, leading to reduced catchability, as suggested by data given by Schumacher[21] for the 1984 event. Changes in alongshore distributions of hakes are probable.

Limited empirical information, summarized in Crawford *et al.*,[8] indicates that resident fish populations may respond differently to Benguela Niños; sardine *Sardinops sagax*[22] perhaps forming good year-classes, but anchovy *Engraulis capensis* poor ones. The Benguela Niño of 1963 was preceded by a period of progressively increased influx of tropical water.[13] At that time, sardines were dominant and extended as far south as Lüderitz, where pelagic gobies *Sufflogobius bibarbatus* have since become plentiful.[23] Increased incursion of warm tropical water from the north may cause the pelagic ecosystem off central Namibia to revert to its state of the early 1960s, i.e. one dominated by sardines, with anchovies and gobies less numerous.

A change in the relative abundance of these planktivorous fish species is likely to influence the relative abundance of their predators. An increase in abundance of sardine at the expense of goby would increase the availability of prey in surface waters, and also the size of individual prey items. This could make prey more available to Cape gannets *Morus capensis* and less available to bank cormorants *Phalacrocorax neglectus*.[23] Hakes *Merluccius* spp. feed mainly off the bottom and, off Namibia, gobies are important in their diet (see references in Crawford *et al.*[3]). Therefore, an increase in the sardine resource, with consequent diversion of primary and

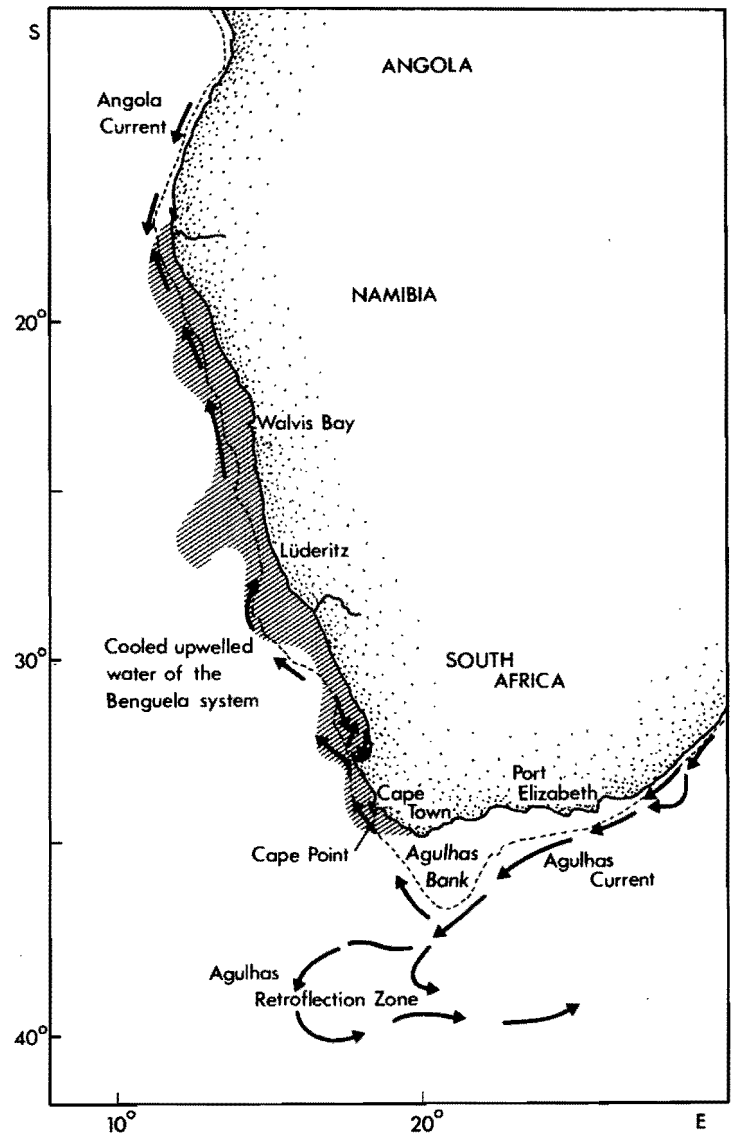

Fig. 1. The major ocean currents and upwelling system off Southern Africa's west coast.

secondary production away from gobies, may decrease the forage base for hakes and, hence, their production. Hakes are largely opportunistic predators,[24] so production may not be affected disastrously. Nevertheless, strengths of hake year-classes in the northern Benguela region have been negatively correlated with temperature.[25]

Consequences for fisheries

The consequences of an increased incidence and intensity of Benguela Niños for the rock-lobster fishery of Namibia will depend on whether the distribution of low-oxygen water on the shelf expands or contracts. Fisheries for other benthic organisms, e.g. West Coast sole *Austroglossus microlepis*, could be influenced similarly by the extent of water depleted in oxygen. The pelagic system may revert to its state of the early 1960s, i.e. sardines may increase in abundance, but anchovies, gobies and hakes decrease, and there may be a southward shift in the distribution of these species.

The equilibrium yield of the Namibian sardine resource prior to its collapse was estimated at about 500 000 tonnes,[26] so the annual catch could well increase to this level from the present average of about 50 000 tonnes.[3] Equally, the anchovy catch could decrease from its present level of around 200 000 tonnes to nearly zero. The overall increase in the purse-seine catch of some 250 000 tonnes would have a 1988 wholesale value of about R80 million. The southward shift in fish distributions would make the sardine resource more accessible to boats operating out of Walvis Bay and Lüderitz, and therefore there could be both a decrease in operating costs and an increase in the quality of the landed catch. In Southern Africa, sardines are considerably more valuable than anchovies because they are utilized for human consumption rather than animal feed.[27] This would further increase the profitability of the industry. Fish canning is more labour-intensive than the reduction of fish to meal and oil, because fish must be selected which are suitable for canning.[28] Therefore, a switch from anchovy to sardine could be expected greatly to increase both earnings and employment opportunities in the Namibian coastal region. However, there would be an initial cost, because purse-seine nets aimed at anchovy would need to be replaced by nets with a larger mesh, in order to catch sardine at an optimal size.

The extent to which the yields of hakes may decrease is uncertain, because, although the hake fisheries off Namibia commenced only in the late 1960s,[3] catch rates and stocks are already greatly reduced.[29] Further potential decreases can only be speculated on, but should the warmer conditions disperse hakes, catch rates could be reduced even more, making bottom-trawling even less of an economic proposition. Most of the Namibian hake catch was, until the demise of the International Commission for the Southeast Atlantic Fisheries (ICSEAF) in 1990, taken by fleets from countries in the northern hemisphere.[30]

The likely incursions of tropical species would create an opportunity for their exploitation off northern Namibia. *Sardinella* spp. would become accessible to the purse-seine fleet, although boats would probably need to travel well north of Walvis Bay, i.e. operating costs would be higher than for the sardine fishery. Exploitation of the scombrids would require the establishment of a new fishery. Yields of seabird guano would be likely to decrease on account of losses to the sea, because of increased coastal rainfall.[8]

Scenario 2 — Increased input of Agulhas Current water to the southern Benguela region

Primary event and effects

In some years, substantial volumes of water from the Agulhas Current may intrude the southern Benguela region, and penetrate as far north as Lüderitz.[31] The intrusions appear to be remotely forced by small changes in the large-scale wind field in the Indian Ocean and to the south of Africa.[11] Climate warming may displace wind systems polewards. It is then likely that the position of zero wind-stress curl south of Africa would shift polewards, and that the volume of water transported by the Agulhas Current would decrease, because boundary currents such as the Agulhas are the result of integrated wind-stress curl over the adjacent ocean basin — in this instance the Indian Ocean. A probable outcome is increased leakage of water from the Agulhas Current into the South Atlantic, and dependent on the trajectory this leakage assumes, the southern Benguela region could be impacted. If it is, the coastal water should become warmer, less turbulent and better stratified, and offshore advection should decrease. If the warm water reaches the coast, the upwelling of cold, nutrient-rich water could decrease, and hence primary production and the production of filter-feeders, e.g. mussels, could decrease.

Consequences for resources

Warm-water organisms may move into the southern Benguela, among them some predatory reef-fish, such as red steenbras *Petrus rupestris* and roman *Chrysoblephus laticeps*, that are likely to prey on juvenile rock lobsters. Lower densities of rock lobsters might result from increased predation, but the overall production of the resource should be little affected. This is because reduced densities are likely to cause faster growth rates of juveniles, an increase in mean size at maturity of females, and an increase in *per capita* egg production.[32] If the warmer conditions lead to increased activity by rock lobsters, catch rates may improve, despite lower densities.

Spawning by sardines and anchovies off South Africa may assume a more westerly distribution, because of the warmer temperatures and reduced offshore advection in the west. The distance from spawning grounds to the nursery grounds, which are situated along the West Coast,[33] would decrease, with a likely increased survival of ichthyoplankton. There is empirical evidence that the production of both species increases in relatively warm conditions.[25] In a former period of intensive spawning off the West Coast, sardine dominated the pelagic ecosystem.[3] If this sceriario is repeated, anchovy could perhaps become less abundant than in the 1980s.

The best year-classes of hakes in the southern Benguela have been formed in cool periods.[25] Therefore, productivity of the hake resource would be expected to decrease with warming. This may be compounded if epipelagic fish take a greater share of primary and secondary production, leaving less to follow the pathway to organisms feeding in mid-water. Nevertheless, young hake are mainly crustacean (predominantly euphausiid) predators[24] and, because the food supply for those organisms is clearly more than sufficient, the impact on the hake resource may not necessarily be catastrophic.

Consequences for fisheries

If hake catches were to decrease, there could be severe ramifications for the South African fishing industry as a whole, because the bottom-trawl catch contributes about half the wholesale value of the industry, even in years of a higher than normal purse-seine catch.[34]

The fishery for rock lobster is expected to be little influenced by increased input from the Agulhas Current to the southern Benguela. If there is to be a change in production, it is uncertain what direction it might take.

South African purse-seine catches were relatively stable from the early 1960s until the mid 1980s at a level of

about 400 000 tonnes.[3] If the production of epipelagic fish species increases, the average yield may increase, but the extent of that increase is indeterminable. A more westerly distribution of the fish shoals would increase their availability to the purse-seiners, most of which operate from ports northwest of Cape Point.[27] Fish would then also be transported over shorter distances, leading to an improved quality and a higher value of the landed catch. If sardine became dominant, the value of the catch would further increase.

Longfin tuna *Thunnus alalunga* tend to be associated with water of 16–17°C off Southern Africa,[35] so warming of the southern Benguela may increase their availability there, and in so doing decrease variability in catches of the tuna fishery off South Africa's western Cape Province.

Scenario 3 — altered wind stress

Primary event

The long-term effect of global warming may be reduced upwelling, because of a slackening of trade-wind intensities on a global scale as a result of diminution in the thermal gradient between equatorial and polar regions. This is the reverse effect of that known to prevail during glacial periods, when trade winds strengthen and upwelling is greatly increased.[36,37] However, Bakun[38] suggests that alongshore, equatorward wind stress on the ocean surface of coastal upwelling regions could be increased by global warming, leading to an acceleration of upwelling. The stronger winds are expected to result from intensification of thermal lows adjacent to the upwelling regions, because of inhibition of night-time cooling and enhanced daytime heating of the land. Bakun's scenario may be an intermediate phase, because later warming of the ocean surface could decrease subsidence over the ocean and reduce onshore–offshore pressure gradients. It is also possible that trade winds may shift to the south as a result of changed latitudinal thermal gradients. Thus, a number of scenarios for future wind stress are possible.

Primary effects

If we adopt Bakun's prediction, and assume also that there will be a southward shift in the zone of maximum wind stress, primary production should be enhanced, but offshore advection and turbulence may increase. In upwelling areas, epipelagic fish species benefit from winds that are neither too strong nor too weak, but of intermediate strength.[39] However, empirical information on wind speeds that are optimal for sardines and anchovies in the Benguela region is lacking, so we are unable to speculate as to whether production of these species would be increased or decreased. Indeed, the fate of any increased primary production is uncertain, and there is no guarantee that it would be channelled to trophic components valued by society.[38] Should biogenic sedimentation increase, there could be further depletion of oxygen in bottom waters, restricting habitat for species such as rock lobsters, enhancing density-dependent effects, and decreasing their yields.

If we accept that atmospheric and oceanographic systems will shift polewards as warming continues, it follows that an Angolan-type climate will shift south to Namibia. Together with reduced longshore winds, increased precipitation will cause now-dry Namibian rivers to flow once again. Increased river run-off, and input of terrigenous muds and silts into the shelf marine environment, will help to dilute and bury the almost pure biogenic deposits (e.g. the diatomaceous mud-belt) which currently characterize the sediments of the inner shelf.[40] The latter sediments are, at present, at the centre of processes of nutrient-recycling, deposition and decay of organic material. Dilution of these biogenic sediments (rich in silica and organic carbon) by terrigenous material will disrupt the nutrient-recycling processes, which appear to be responsible for the present enhanced rates of primary production off the Namib desert coast. There, concentrations of dissolved silicate in upwelled waters are remarkably high.[41] Reduced nutrient-recycling may greatly alter the level of primary production, whether wind stress alters or not. If primary production decreases in most of the world's arid upwelling regions, there is bound to be a reduction in the rate of sequestration of organic carbon into the shelf sediments. This will accelerate the rate of accumulation of atmospheric carbon dioxide, thereby inducing a positive feedback for further global warming.

Consequences for resources and fisheries

Areas of strong offshore advection and high turbulence are unfavourable spawning grounds for sardine and anchovy.[9] A southward movement of the zone of maximum wind stress may expand the spawning area for these species off Namibia to the south, but make South Africa's west coast less favourable for spawning. However, upwelling along South Africa's south coast may increase, expanding the distribution of sardines and anchovies to the east. Because of these shifts in distribution, the two species may become more available to boats operating from Walvis Bay and Lüderitz, but less available to those fishing along South Africa's west coast. An increase in upwelling would increase mesoscale frontal activity and hence the number of longfin tuna that have been shown to be associated with these events.[42] It would also intensify biological activity at these fronts leading to increased biotic diversity and prey abundance and enhanced productivity of the Benguela ecosystem. The generally cooler conditions in the entire Benguela region may increase productivity of hakes,[25] leading to better catches by bottom trawlers. It should be stressed, though, that increased upwelling, if it occurs, may be just a transient, intermediate phase.

Scenario 4 — warming of surface waters

It has been predicted that global warming will increase sea surface temperatures off Southern Africa, irrespective of any changed advective processes.[43] Surface warming is likely to influence the distribution of epipelagic organisms around Southern Africa, with warmer-water organisms tending to impinge on the Benguela system from both the north and the south-east. In general the distributional changes resulting from warming should be similar to those described under scenarios 1 and 2. The impacts of the altered distributions on the ecology and fisheries of the Benguela region should also be similar to those described for the advection of warm water into the Benguela system.

Conclusions

The various scenarios all involve global warming, but the postulated impacts on the marine resources and fisheries of Southern Africa's west coast differ. Most resources could be benefited or disadvantaged, depending on which environmental signal is most important and on the biological responses to environmental change. The scenarios we have developed suggest some key environmental parameters to monitor, e.g. input from the Agulhas Current to the southern Benguela. An area of particular biological uncertainty is the path that organic primary production might take under different environmental conditions. Because of the complex structure of the ecosystems, the farther one removes from

a primary response to change, the more difficult it becomes to predict the eventual outcome.

Simulation models could be constructed to explore the sensitivity of ecosystems to various forcing functions but, as long as the models have inherent structural uncertainties, little confidence can be placed in their predictions. Greater insight into the trophic functioning of the ecosystems is likely to arise from comparative studies of trophic pathways in other ecosystems that have similar species assemblages. In the interim, the most credible predictions will be those of primary biological responses to environmental change, although these are not necessarily of greatest interest to society.

There may be uncertainty concerning the eventual outcome of global warming on the ecosystems, resources and fisheries of south-western Africa, but there can be no doubt that the impacts are potentially dramatic (cf. Bakun[38]). However, until there is greater clarity as to the nature change may take, it will be difficult to plan strategies of response. The Benguela ecosystem is bounded at both its northern and southern extremities by warm water,[44] and it may therefore respond differently to global warming from other upwelling systems at the eastern boundaries of oceans.

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