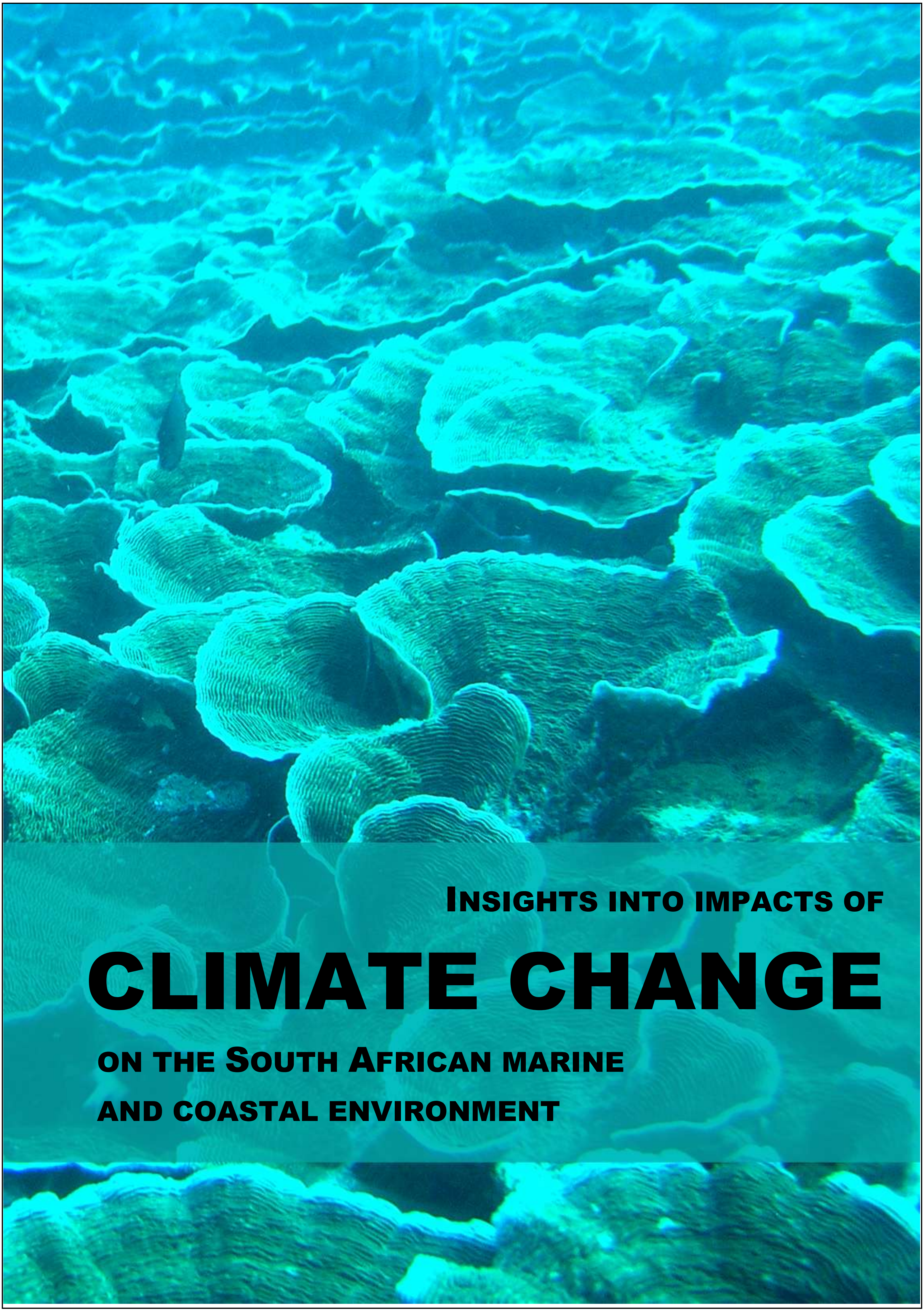

INSIGHTS INTO IMPACTS OF CLIMATE CHANGE ON THE SOUTH AFRICAN MARINE AND COASTAL ENVIRONMENT

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CONTENTS

Preface ii

Executive Summary iii

1. General Overview 1
1.1. Introduction 1

2. Key Climatic Drivers 3
2.1. Introduction 3
2.2. Mitigations and way forward 7

3. The Benguela System and South African Fisheries 9
3.1. Overview 9
3.2. Fisheries resources 18
3.3. Changes in the Benguela, based on the BCLME Climate Change Workshop, May 2007 25
3.4. Adaptation and mitigation aspects in the marine ecosystem in South Africa 25

4. The Agulhas Current System and climate change 27
4.1. Influence on local rainfall 27
4.2. Influence on global climate 28
4.3. Possible impact of climate change 29
4.4. Future research directions 29

5. Trends in Nearshore Sea Surface Temperature and Circulatory Systems 31

6. Reef Ecosystems 35
6.1. Introduction 35
6.2. Climate change findings 36
6.3. Key trends and associated vulnerabilities 41
6.4. Research and resources required to better assess possible impacts 42
6.5. Acknowledgments 43

7. Estuaries 45
7.1. Introduction 45
7.2. Climate change findings 46
7.3. Key trends and associated vulnerabilities 56
7.4. Research and resources required to better assess possible impacts 57

8. Sandy Shores 59
8.1. Introduction to South African beaches 59
8.2. Climate change findings 61
8.3. Key trends and associated vulnerabilities 65
8.4. Research and resources required to better assess possible impacts 66

9. Rocky Shores and Kelp Beds 69
9.1. Introduction 69
9.2. Climate change findings 70
9.3. Climate change findings South Africa 73
9.4. Key trends and associated vulnerabilities 75
9.5. Research and resources required to better assess possible impacts 76

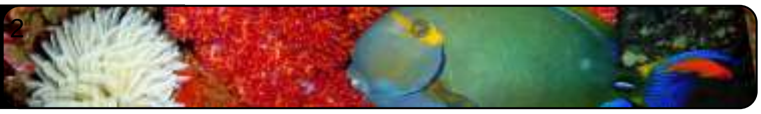
10. Subtidal Fishes 77
10.1. Introduction 77
10.2. Climate change findings 78
10.3. Key trends and associated vulnerabilities 82
10.4. Research and resources required to better assess possible impacts 82

11. Coastal Infrastructure 85
11.1. Overview of climate change effects on sea-level rise 85
11.2. The impact of sea-level rise on the South African coast 91
11.3. Options to mitigate the possible impact of sea-level rise on the South African Coast 97
11.4. Required research and resources 99
11.5. Summary 99

12. References 101

13. Appendix 127
13.1. Summary based on the BCLME climate change workshop, May 2007 127

PREFACE



The South African National Biodiversity Institute (SANBI) co-ordinated the production of *South Africa's Second National Communication* under the United Nations Framework Convention on Climate Change 2010. The second communication by design is an integrated, relatively short document that provides an overview of climate change and its implications for South Africa. The marine component of the second communication was therefore a short précis of the current understanding of climate change and its impact on the marine environment. The précis was based on this more comprehensive assessment entitled: *Insights into impacts of climate change on the South African marine and coastal environment*, which was produced by 19 authors from 12 institutions. This comprehensive assessment aims to provide the reader with the necessary detail behind the marine component in the second communication.

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EXECUTIVE SUMMARY

STRUCTURE OF THE REPORT

This report provides a synthesis of the current knowledge of climate change impacts on the South African estuarine, coastal and marine environment. The choice of chapters was driven by key coastal habitats, areas of current research and issues of socio-economic importance. There are a number of areas that will need to be expanded upon in the next version, such as benthic soft-sediment habitats and deep-water ecosystems. Climate impacts were assessed by (1) reviewing the scientific literature on climate change impacts on South African marine life and ecosystems in the context of known impacts elsewhere in the world (2) summarizing the key trends, impacts and vulnerabilities of ecosystems and marine life to climate change and (3) assessing knowledge gaps and required research and resources needed to better assess possible impacts.

This report focuses on the coastline of South Africa and the continental sections of the Atlantic and Indian oceans (that fall within the Exclusive Economic Zone [EEZ] surrounding continental South Africa). This report does not cover the 466 879 km^2 of EEZ that surrounds the Prince Edward Islands and South African territories situated in the Southern Ocean. For a thorough overview of climate change impacts on the Prince Edward Islands the reader is directed to Chown and Froneman (2008).

The report comprises separate stand-alone chapters on:

- Key climatic drivers
- The Benguela system and South African fisheries
- The Agulhas Current system and climate change
- Trends in nearshore sea-surface temperature and circulatory systems
- Reef ecosystems
- Estuaries
- Sandy shores
- Rocky shores and kelp beds
- Subtidal fishes
- Coastal infrastructure

This report is aligned to South Africa's Second National Communication under the United Nations Framework Convention on Climate Change.

KEY CLIMATIC DRIVERS

Southern Africa experiences strong ocean influences on its weather and climate patterns. In particular, South Africa is situated near the meeting place of three oceans, the South Indian Ocean on the east coast, the South Atlantic Ocean on the west coast and the Southern Ocean to the south. These three oceans play a vital role in determining southern Africa's climate and weather patterns as well as strongly influencing the global climate. The El Niño Southern Oscillation (ENSO) is the dominant type of natural variability influencing the oceans and global climate on time scales of several months to several years. In general, during the summer of a positive ENSO (El Niño) event, the tropical Indian Ocean warms, the mid-latitude Indian Ocean cools, the central South Atlantic warms, but the mid-latitude South Atlantic cools, the subtropical jet moves north and South Africa is mainly dry. Roughly the reverse pattern occurs during the cold ENSO (La Niña) event. Most severe droughts over subtropical southern Africa seem to be due either to strong El Niño events (Lindesay 1988, Mason and Jury 1997, Reason et al. 2000) or to regional anomalies over the southeast Atlantic (Mulenga et al. 2003, Tennant and Reason 2005). Unfortunately, our ability to predict the strength, the duration and the impact of ENSO events is not particularly good, and sometimes these events can coincide with other natural variability elsewhere in the global oceans, thereby confusing the signal in certain regions.

Further south, in the Southern Ocean, the Southern Annular Mode (SAM), or Antarctic Oscillation is the main form of natural variability. The relationships between the SAM, the South Atlantic and Indian oceans and South African rainfall variability have been explored, and evidence shows that, when the SAM is in its negative phase, winters over western South Africa tend to be wetter (Reason and Rouault 2005). These patterns, combined with the influence of ENSO and other modes of variability in the southern oceans point to a complex interplay of factors that can influence the weather and climate over South Africa.

Climate variability over southern Africa is complex with a multitude of forcing factors that interact (Landman and Mason 1999, Richard et al. 2000, Reason and Rouault 2002). Since a roughly two-month lag exists between wind anomalies in the tropical western Atlantic and the manifestation of sea surface temperature (SST) anomalies along the Angolan coast, some predictability of Benguela Niños and, hence, late-summer (February–April; FMA) rains over Angola and northern Namibia, may exist. Pilot Research Moored Array in the Tropical Atlantic (PIRATA, Servain et al. 1998) and Quick Scatterometer (QuikSCAT) wind data for the early–midsummer together with any equatorial subsurface anomalies evident in the PIRATA moorings could give advance warning of a developing event. Current statistical forecasting schemes used in South Africa (Landman and Mason 2001) do not capture these events, or indeed perform satisfactorily over the South Atlantic as a whole, likely because of the importance of trapped waves and other dynamics that are not well represented by statistical models of this type. In addition, the nonlinear response of SST anomalies off Angola to the remote wind forcing (Florenchie et al. 2004) emphasizes the need for further work to understand the way that different mechanisms seem to control the development of each individual event in the southeast Atlantic.

In the Indian Ocean, the Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction (RAMA) moored array is helping to understand variability in the tropics and hence improving predictability of, for example, the dipole patterns. Although work is being done with higher resolution, nested models that have been successful in resolving the Agulhas and its mesoscale features, many global ocean and coupled models are unable to resolve this intense feature. An increased understanding of the Agulhas Current is needed in order to improve its resolution in ocean models. Furthermore, given that we are yet unable to explain the cause of a Natal pulse within the system, or even categorically state how the East Madagascar Current terminates, we are far from being able to provide successful predictions of the oceanic region.

One of the biggest hurdles is the deficiency in representing the tight sea surface temperature and topographic gradients in the region. Given that the sharp topographic, vegetation, soil, and sea surface temperature gradients in the region are unlikely to be adequately represented by atmospheric general circulation models (AGCMs), it is important to consider downscaling their output to the region of interest. Either a statistical approach or nesting a regional climate model (RCM) within the AGCM output can be used to do the downscaling. Currently, application of RCMs for seasonal forecasting by southern African groups is at an early stage.

THE BENGUELA SYSTEM AND FISHERIES

The Benguela ecosystem and associated fisheries are vulnerable to changes in the frequency of harmful algal blooms, distribution of fishery resources, fishery landing points, stock levels and recruitment. The Benguela is one of the major eastern boundary upwelling systems of the world, and may be described in terms of four components (Hutchings et al. 2009): a northern subtropical region off Angola and a cool temperate upwelling region in the south, separated by the powerful Luderitz upwelling cell at 26ºS, and a warm temperate zone on the Agulhas Bank. Many organisms migrate between the cool upwelling areas and the warm temperate boundary regions, and are influenced by their dynamics. Research has shown that the system is highly productive, complex and variable, and it is extremely difficult to attribute trends to climate change as opposed to other drivers.

One of the strongest trends (~50 years length) has been a warming at the northern and southern boundaries of the Benguela system, with potential consequences for increased hypoxia on the Namibian shelf. There has also been a long-term increase in southerly winds, which induce upwelling in the southern Benguela, with modulation over decadal time scales.

Zooplankton has increased (~10-fold), caused by changes in productivity and upwelling-favourable winds. Pelagic fish stocks have been decimated, resulting in the collapse of sardines in the 1960s. This could be attributed to fishing pressure, warming trends, competition with the increased horsemackerel stocks, or suppression by predators. By contrast, southern pelagic stocks have increased, accompanied by an eastward (perhaps cyclic) shift in sardine and anchovy. Horsemackerel stocks in Namibia have recently begun to decline, while deepwater hake appear to have expanded northwards. Rock lobsters have declined in the central Benguela and shifted southwards and eastwards. Top predators have responded to the changes in fish availability in different parts of the ecosystem; seals have expanded northwards while seabirds and penguin have declined considerably in the north.

There has been persistent decadal variability in the Benguela, but it is not clear that these changes are linked exclusively to climate change, or to inherent natural long-term cycles. Nevertheless, it suggests that management of marine resources needs to adapt over similar time scales. Future research and monitoring efforts need to focus on much broader spatial and temporal scales. Not only is this important for future marine ecosystem management, but also for future seasonal and longer term weather and climate change forecasts in the region.

THE GREATER AGULHAS CURRENT

Potential changes in the Agulhas Current could have a significant impact on coastal rainfall patterns and the functioning of important coastal oceanographic features such as the Port Alfred upwelling cell. For example, changes in the timing and intensity of upwelling events, or river runoff, into the nutrient-poor east coast environment could have significant ecological ramifications for both pelagic and coastal ecosystems. Changing factors such as nutrient availability can have a knock-on effect up the food web with impacts moving from phytoplankton to zooplankton and ultimately to fisheries and bird populations. The Agulhas Current is driven by the wind stress curl over the South Indian Ocean, but is strongly influenced by perturbations. Most of our current understanding of the system is based on numerical models and remotely-sensed data. Research suggests that it is changes in the large-scale wind fields that will have a major impact on the Agulhas Current. Of great importance is how such changes will impact the Agulhas leakage into the South Atlantic and its role in the global thermohaline circulation.

Observations of the Greater Agulhas Region are very limited. Peeters et al. (2004) have shown, using sediment cores, that there was a peak in Agulhas leakage at the end of each of the last five glacial periods. Other studies (e.g., Rau et al. 2002) have indicated that although the Agulhas leakage has undergone significant changes over the past 450 thousand years, it has never ceased completely. Over geologic time, increases in salt fluxes via Agulhas leakage have coincided with increases in the intensity of the meridional overturning circulation in the Atlantic Ocean (Martínez-Méndez et al. 2010), a synchronicity which suggests a mechanistic linking between the two. Other studies (Bard and Rickaby 2009, Zahn 2009) have in turn indicated that, with a change in the latitude of the zero wind stress curl in the South Indian and South Atlantic oceans, the equatorward shift in the Subtropical Convergence will close off the inter-ocean leakage south of Africa. The Agulhas Current has a marked influence on the local atmosphere (e.g., Lee-Thorp et al. 1998), which can at times make a major difference to terrestrial synoptic systems (Rouault et al. 2002), enhancing their intensity. Apart from these very local and coastal effects, the Agulhas Current system and sea-surface temperatures in the South West Indian Ocean have been shown to influence regional atmospheric circulation patterns and attendant rainfall patterns (e.g., Reason and Godfred-Spenning 1998, Reason and Mulenga 1999, Reason 2001).

The study of the Agulhas system is still relatively immature and the interaction of the system's diverse components, its normal behaviour, its driving forces and its global impact are still not properly understood. At present, suggested scenarios under conditions of climate change for the Agulhas system are therefore mostly preliminary and largely inferential. Nevertheless, more studies of sediment cores in the region will inevitably give more reliable indications of the boundary conditions under which the Agulhas system has acted under previous climate change conditions. Numerical models with ever-increasing spatial and temporal resolution will allow more reliable experimentation with a range of climate scenarios. In most cases there will, however, not be opportunities for verification of such model products and outcomes, although a number of observational programmes exist. As more palaeoceanographic results become available, such verification will increasingly become possible (Beal et al. 2011).

TRENDS IN NEARSHORE SEA-SURFACE TEMPERATURE AND CIRCULATORY SYSTEMS

Significant large scale temporal shifts in sea surface temperatures (SST) or circulatory patterns have the potential to impact intertidal marine community structure and functioning. Rouault et al. (2009) found that since the 1980s the SST of the Agulhas Current (measured from AVHRR satellite SST data) has increased significantly (up to 0.7 ºC per decade) due to its intensification in response to changing wind patterns in the South Indian Ocean. The AVHRR data indicates that along the west coast near-shore, SST is cooling between -0.2 to -0.5 ºC per decade, with isolated small scale pockets of cooling in the region between Cape Agulhas and Cape St Francis (South Coast) of about -0.2 ºC per decade. A larger region of cooling, ranging from -0.2 ºC to -0.7 ºC was identified between East London and Port Elizabeth, centred in the Port Alfred dynamic upwelling cell. In the sub-tropical province a very thin strip of near-shore water cooling at a rate of -0.6 to -0.8 ºC per decade was identified as far as Port St Johns. North of Port St Johns, near-shore SSTs were shown to be warming.

REEF ECOSYSTEMS

Climate change findings

Coral reefs occur in South Africa within the iSimangaliso Wetland Park (iSiWP), a World Heritage Site in northern KwaZulu-Natal (or Maputaland), and have been subjected to extensive mapping for their biodiversity conservation and sustainable use (Schleyer and Celliers 2005, Ramsay et al. 2006, Celliers and Schleyer 2008). They are limited in size but provide a model for the study of many of the stresses to which these valuable ecosystems are being subjected globally (Schleyer and Celliers 2003a). The value of the South African reefs in this regard is partially attributable to their marginal nature, as their coral communities constitute the southernmost distribution of this fauna on the African coast. Their marginality is thus attributable to latitudinal and climatic parameters, making them vulnerable to climate change.

Coral bleaching associated with climate change currently constitutes the greatest threat to coral reefs, the causes and consequences of which are reviewed by Hoegh-Guldberg (1999) and Wilkinson (1999). Yet there is cause for hope in the ultimate survival of corals through resilience to bleaching (Hughes et al. 2003). While one might expect global warming to result in a pole-ward expansion in the distribution of tropical corals, Scavia et al. (2002) suggest that this will not occur due to a reduction in aragonite saturation caused by the greater solubility of CO_2 in cooler waters. These are the factors one might expect to be at play on the high-latitude coral reefs in South Africa.

Key trends – associated impacts and vulnerabilities

A long-term monitoring programme was initiated in 1993 (Schleyer et al. 2008), entailing temperature logging and image analysis of high resolution photographs of fixed quadrats on representative reefs. Sea temperatures rose by 0.15 °C p.a. at the site up to 2000, but have subsequently been decreasing by 0.07 °C p.a. Insignificant bleaching was encountered in the region during the 1998 El Niño Southern Oscillation (ENSO) event, unlike elsewhere in East Africa, but quantifiable bleaching occurred during an extended period of warming in 2000. Peak temperatures on the South African reefs thus appear to have attained the coral bleaching threshold. While this has resulted in relatively little bleaching thus far, the increased temperatures appear to have had a deleterious effect on coral recruitment success as other anthropogenic influences on the reefs are minimal. Recruitment success diminished remarkably up to 2004 but appears again to be improving. Throughout, the corals have also manifested changes in community structure, involving an increase in hard coral cover and reduction in that of soft corals, resulting in a 5.5% drop in overall coral cover. These "silent" effects of temperature increase do not appear to have been reported in the literature.

Required research and resources

Being marginal, the coral reefs provide a model for the study of many of the stresses to which these valuable systems are being subjected globally. Work on these reefs needs to continue to fully elucidate climate change impacts.

ESTUARIES

Climate change findings

Estuaries are shallow systems and are strongly influenced by rainfall (freshwater input), wind, wave action, sediment input, and water and air temperatures. Consequently, climate change is likely to produce profound modifications to the structure and functioning of estuaries (Kennedy 1990) and may have a range of implications for estuarine biota. Climate change is predicted to alter precipitation patterns, which will affect the quality, rate, magnitude and timing of freshwater delivery to estuaries and will potentially exacerbate existing human modifications of these flows (Alber 2002). Estuarine functioning is strongly influenced by the magnitude and timing of freshwater runoff reaching them (Turpie et al. 2002b). Reductions in the amount of freshwater entering estuaries in South Africa, particularly in the Western Cape, would lead to an increase in the frequency and duration of estuary mouth closure and changes in nutrient levels, suspended particulate matter, temperature, conductivity, dissolved oxygen and turbidity (Clark 2006). The reduction in pH that accompanies elevated CO_2 concentrations may have profound implications for a wide range of estuarine organisms including coralline algae, echinoderms, crustaceans and molluscs (USEPA 2009). Estuarine acidification will also influence water quality (USEPA 2009). Sea-level rise and the increased intensity of storm events, both of which are already occurring, are seen as a threat to mangrove and salt marsh ecosystems in estuaries. Migration of coastal wetlands under current and projected levels of sea-level rise may be prevented by artificial embankments and development that will cause a loss of coastal wetlands through "coastal squeeze[1]". Increased storminess, together with sea-level rise, may result in a loss of estuarine habitat which ultimately affects estuarine fish communities and will have fisheries repercussions. One of the most obvious changes associated with changing water temperatures will be shifts in the distributional patterns of estuarine species and changes in the composition of species assemblages. Changes in the distribution patterns of estuarine species are already being recorded both locally and globally, but are difficult to predict as different species respond differently to changes in temperature.

Key trends – associated impacts and vulnerabilities

The degradation of many of South Africa's estuaries, due to global change drivers, such as eutrophication, fishing and harvesting, freshwater abstraction, sedimentation and mouth manipulation, has been well documented. Documented changes that can be attributed to climate change are, however, far more limited and generally linked to range extensions of certain taxa due to changes in water temperatures, e.g., estuarine fish in the East Kleinemonde and Mngazana Estuaries.

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[1] When coastal development has been inappropriately located too close to estuaries and beaches, the normal response of systems to migrate landward in response to sea level rise is prohibited, leaving them trapped in what has been termed a "coastal squeeze".

Long term monitoring of the fishes in the warm-temperate East Kleinemonde Estuary 15 km east of Port Alfred (33°32´42˝S, 27°03´05˝E) has occurred since December 1995, with six new species of tropical fishes being recorded in the catches from 1999 onwards. Mean annual sea temperatures recorded in situ along the adjacent coast have increased at a rate of 0.09 °C per year over the past decade and may have facilitated the southward extension of tropical marine fishes into the warm-temperate biogeographic zone (James et al. 2008b). Similarly, the diversity and dominance of tropical species in the Mngazana Estuary (31º41'29"S; 29º25'24"E) have increased when compared with a similar study conducted 25 years earlier (Mbande et al. 2005).

Required research and resources

Although there are a few established long-term monitoring programmes in estuaries, more need to be initiated, particularly in estuaries that are situated at the boundary of species distributional ranges, to better assess the impacts of climate change on these systems. These programmes need to assess estuarine biota as well as establish a network of temperature, salinity and tide recorders. A range of different modelling approaches needs to be developed for South African estuaries, including climate envelope models, population, mass balance and ecosystem models. The understanding of long-term variability associated with the major estuarine abiotic drivers, such as water flow, river sediment budgets, marine long shore drift, berm formation and functioning, sedimentation and water quality, will need to be significantly improved if the implications of climate change on estuaries are to be fully elucidated.

SANDY SHORES

Climate change findings

In terms of climate change, South Africa’s sandy shores are primarily vulnerable to sea-level rise and to the increased frequency of high-intensity coastal storms in those areas where the beaches are constrained by hard structures such as sea walls, coastal infrastructure or buildings. In these developed regions of South Africa some sandy beach ecosystems are at risk of being lost through inundation and erosion as a result of coastal squeeze. Other consequences of sea-level rise for sandy beaches in South Africa may include: increased erosion, dune blowout formation; intensified flooding; and increased saline intrusion into coastal aquifers.

Storms are important in shaping beaches because they move large quantities of sand from the upper shore and deposit it in the surf zone. This sand is moved back slowly to the beach and dunes during calmer conditions (Brown and McLachlan 2002, Costas et al. 2005, Anfuso et al. 2007). Increased storm frequency will have a serious effect on beaches as time between storms will be insufficient to allow recovery from a preceding storm event. In South Africa the increased intensity and frequency of storms, coupled with sea-level rise will present a synergistic erosive force that could remove large quantities of sand off the beach face. This will exacerbate the retreat of beaches in South Africa’s unconstrained areas and impact on the availability of sandy shore habitat in the developed areas, as well as increasing the risk of damage to coastal infrastructure.

Other possible impacts of climate change on beaches include alteration of rainfall patterns that could have an effect on interactions such as groundwater flow and estuarine discharge. Changes in wind fields could also have a bearing on local wave climates and ocean currents, with implications for longshore drift of sediment and connectivity of populations that are connected by pelagic larvae. It is unlikely that temperature will have an effect on sandy beaches, with elevated temperatures possibly having only an indirect effect.

Key trends – associated impacts and vulnerabilities

Research on the effect of climate change on sandy shores in South Africa is limited to the possible impact of sea-level rise and severe storms (Harris 2008, Mather et al. 2009). A national overview of sandy beach ecosystems is currently being undertaken and should be available in the ecosystem status report of the National Biodiversity Assessment in 2011. Early indications are that sea-level rise in Kwa-Zulu Natal could result in the loss of backshore beach and upper intertidal areas due to “coastal squeeze”.

Required research and resources

A number of knowledge gaps need to be filled if possible climate change impacts are to be established. These include accurate national modelling of sea-level rise impacts (with accurate mapping of the high water mark); species distribution and biogeographic patterns; thermal tolerances/bioclimatic envelopes of species; mechanism of beach population connectivity and calculation of local sediment budgets (as an indication of resilience to erosion and storm impact recovery potential).

ROCKY INTERTIDAL ZONE AND KELP BEDS

Climate change findings

Research has shown that the unique combinations of physical stressors experienced by intertidal and kelp bed organisms result in an underlying environmental gradient that dictates the biotic interactions, behaviour and biodiversity that exist within these communities (Southward 1995, Edwards 2004). Changes in these stressors (e.g., changes in air temperatures, sea surface temperatures, storm intensity, sea-level rise and upwelling) associated with climate change make rocky intertidal and kelp bed communities vulnerable to climate change. Climate change driven species-shifts in rocky intertidal ecosystems have been detected in Europe, America, the Arctic, Australia and New Zealand. Species that are close to their thermal limits are being lost from or introduced into community assemblages, changes which are strongly linked to warming sea and air temperatures at a range of temporal scales. Within-range-shifts have resulted in the creation of ‘hotspots’, ‘coldspots’ and pocket extinctions for rocky intertidal species. Increasing sea temperatures have also negatively impacted carrying capacity, densities and size of dominant cold water kelp species. Besides changes in the horizontal distribution of species, vertical squeezing of the upper distribution limit in rocky intertidal species due to increasing air temperatures has also been recorded. Increasing wave force has been predicted to create additional physical stress on low shore communities and within kelp bed ecosystems (refer to Helmuth et al. 2006 and Mieszkowska 2009 for a review). There is also a concern that rising sea levels and increased frequencies of storm events may transport significant amounts of sediment up and down coastlines (Drinkwater et al. 2009). Larval supply, which can influence the distribution and abundance of intertidal organisms, is impacted by offshore currents, upwelling and wave action, all of which are affected by temperature regime shifts.

In South Africa, climate change impacts on rocky intertidal and kelp bed communities will differ spatially as well as temporally, due to the existence of distinct biogeographic provinces and the transition zones between them.

Key trends – associated impacts and vulnerabilities

Although South Africa has a long history of research on rocky intertidal and kelp bed ecosystems, which has resulted in a good understanding of these ecosystems, there is currently only one study being undertaken at the University of Cape Town that specifically examines climate change impacts on the rocky intertidal zone (Mead 2010). This study has shown that there have been shifts in population abundance and changes in the proportions of cold water and warm water affinity species within the community. This implies potentially significant changes in community functioning and dynamics, probably linked to cooling of near-shore SSTs in the cool-temperate region and adjacent transition zone and shifts in circulatory and upwelling patterns (Mead 2010). There have been no specific observations for kelp bed communities due to a lack of climate change specific research on this community.

Required research and resources

Although the ecology of rocky intertidal zones and kelp beds is well understood, the potential effects of climate change are not, and an extensive and well planned research programme is required. The intertidal zone is easily accessible, which will facilitate the study of the impact of both atmospheric and oceanic regime shifts. In addition to long term community and population level monitoring programs, there needs to be an emphasis on research that identifies the physiological mechanisms involved at an individual species level in response to climate change.

SUBTIDAL FISHES

Climate change findings

Potential threats to the marine coastal zone are likely to include both physical and chemical stressors, which in turn can have direct and indirect effects on subtidal fishes. Physical stressors include changes in sea temperature, sea-level rise, intensification of upwelling, changes in current strength, and changes in rainfall and consequently the amount of freshwater input to the coastal zone, while chemical stressors include a rise in CO_2 and a concomitant decrease in the ocean pH (Harley et al. 2006). Fish are thermoconformers and therefore respond to even small changes in water temperature (Clark 2006). Changes in water temperature affect physiological processes in fishes including the fluidity of membranes and the function of their organs (Hochachka and Somero 2002). Consequently, of all of the physical stressors, sea temperature is considered to be the most influential to subtidal fishes. Sea-level rise is predicted to cause an upwards shift in distribution patterns of subtidal organisms. Although this does not pose a problem to fish and most invertebrates, some slow growing corals might not be able to keep pace with sea-level rise, which would result in habitat alterations for subtidal fish on subtropical and tropical shallow reefs (Harley et al. 2006). One expected consequence of changes in wind speed and direction is a change in the frequency and strength of coastal upwelling events (Bakun 1990, Rijnsdorp et al. 2009). Depending on the affected region, upwelling events may weaken or intensify (Narayan et al. 2010).

Besides impacting the feeding and growth of subtidal species, permanent upwelling cells have been recognized as barriers to the dispersal of many fish species. Changes in the strength of ocean currents can have a major impact on the egg, larval and juvenile dispersal of subtidal fishes. Freshwater input carries nutrients, sediment and detritus into the subtidal zone and can have a direct and indirect influence on its fishes (Houde and Rutherford 1993, Gillanders and Kingsford 2002, Lamberth et al. 2009). Of all marine animals, fish appear to be the most tolerant to ocean acidification (Fabry et al. 2008). Possibly the greatest effect of acidification could be indirect, where important prey species (e.g., molluscs for some Sparid fishes) grow slower and experience shell dissolution (Fabry et al. 2008). In cases where fish are dependent on a diet of molluscs, feeding and growth may be impaired.

Key trends – associated impacts and vulnerabilities

There is currently little evidence for climate change impacts on subtidal fishes in southern Africa. Henriques et al. (in prep) have observed a southward shift in the distribution of the west coast dusky kob (*Argyrosomus coronus*) from southern Angolan into northern and central Namibian waters between 1995 and 2009. This corresponded with a 0.8–1.0 degree increase in sea surface temperature per decade during a similar period (Monteiro et al. 2008). As with many international studies, James et al. (2011), reporting on a medium term (8 year) inshore fish monitoring dataset from the Tsitstikamma National Park, showed conflicting evidence of climate change impacts. Although overall species richness and abundance maintained high levels of stability, there was correlation between the abundance of species with an affinity for warm-water and higher sea temperatures.

Required research and resources

Only a fraction of the subtidal habitat has been topographically surveyed off South Africa. Information on substrate type, depth and profile of potential fish habitats and their spatial coverage is crucial for the design of any marine coastal research programme and is of particular importance when considering the impacts of climate change. If fish react to changes in water properties by relocating, the extent and orientation of suitable, continuous habitat will determine their survival. The study of coastal oceanography of southern Africa is also still relatively immature. Consequently, our understanding of the coastal zone, its diverse components and its driving forces are poor. This makes predictions very difficult.

COASTAL INFRASTRUCTURE

Climate change findings

Consequent to a rise in sea-level, South Africa has in general very little adaptive capacity in developed coastal areas, other than relatively expensive upgrades or replacements to existing coastal infrastructures. The undeveloped areas have more adaptive capacity. For South Africa the best long-term policy in these areas appears to be to allow coastal processes to progress naturally. This strongly emphasizes the need for South Africa to set and implement measures before the damage becomes too costly to repair (Theron 2007).

Key trends – associated impacts and vulnerabilities

Sea level is rising around the South African coast (Mather et al. 2009), in agreement with current global trends, but there are regional differences. The west coast is rising by 1.87 mm yr^{-1}, the south coast by 1.47 mm yr^{-1} and the east coast by 2.74 mm yr^{-1}. The eustatic level rise is lower along the west coast (0.42 mm yr^{-1}) but higher along the south (1.57 mm yr^{-1}) and east (3.55 mm yr^{-1}) coasts. These differences are attributed to regional differences in vertical crust movements and large scale oceanographic processes off the east and west coasts (including the Agulhas and Benguela currents).

With a rise in sea-level and a possible increase in the frequency and intensity of sea storms, the South African coastline is expected to experience: increased exposure to more intense and more frequent extreme events; increased saltwater intrusion and raised groundwater tables; greater tidal influence; increased flooding, with greater extent and frequency; and increased coastal erosion (Hughes et al. 1991).

Required research and resources

Further research into the impact of, and adaptation to, sea-level rise on coastal infrastructure is required in the following areas:

- The Eastern Cape, and in particular the Port Elizabeth/Algoa Bay and East London regions.
- South Africa as a whole; most studies have concentrated on Cape Town and Durban.
- More research needs to be done on the changing marine wind and wave climate around Southern Africa.
- Coastal sediment source and sink areas need to be investigated further.

1. GENERAL OVERVIEW

Nicola James & Angus Paterson

1.1. INTRODUCTION

Climate change that is linked to the build up of greenhouse gases and aerosols in the atmosphere is now a widely accepted phenomenon that has led to increases in surface air and ocean temperatures over the last 50 years (IPCC 2007). Nelleman et al. (2008) list climate change, pollution, fragmentation and habitat loss, invasive species infestations and over-harvesting from fisheries as the top five stressors impacting on the marine environment. If climate change accelerates, the impacts on marine ecosystems from other stressors will increase and the ability of ecosystems to recover will be impaired. In addition to rising surface water temperatures, climate change incorporates changes in precipitation and evaporation rates, sea-level rise and increased frequency and intensity of storms, ocean circulation, winds and CO_2 concentrations all of which will have profound consequences for marine and coastal ecosystems (Roessig et al. 2004).

This report considers the possible influences of climate change on South Africa’s estuarine, coastal and marine environment. The South African coastline extends for approximately 3 650 km from the Orange River mouth in the west to Ponto do Ouro in the east (Lombard et al. 2004). The Exclusive Economic Zone (EEZ) surrounding continental South Africa (Figure 1.1) has an area of 1 068 659 km^2, which is only slightly less than the land area of the country which is 1 221 037 km^2 (Griffiths et al. 2010). For a region of its size, the coastal and marine environment around southern Africa is one of the most varied in the world (Shannon 1989). This is largely due to the dynamic juxtaposition of the warm boundary Agulhas Current along the Indian Ocean to the east and the cold Benguela Current along the Atlantic coast to the west (Hutchings et al. 2009). The Agulhas Current flows strongly southward along the east coast, bringing warm, nutrient-poor tropical waters southward from the equatorial region of the western Indian Ocean. Productivity on this coast is low and as a result there are few commercial fisheries, although population density is high resulting in pressure on coastal marine resources (Griffiths et al. 2010). The continental shelf is narrow on the east coast and the Agulhas Current runs close to the shelf break, except off the Tugela Banks in the Natal Bight, where the shelf is wider. Along the south coast, the Agulhas Current moves offshore along the edge of the Agulhas Bank and eventually retroflects eastwards into the western Indian Ocean (Lombard et al. 2004).

The Benguela Current flows along the west coast forming a general equatorward flow of cool water in the South Atlantic gyre, with dynamic wind-driven upwelling close inshore at certain active upwelling sites. The shelf water is nutrient rich and is characterized by dense plankton blooms that increase turbidity, productive fisheries and kelp beds (Lombard et al. 2004).

The South African coastline is generally subject to moderate (1–2 m) to strong (2–3 m) wave action. The prevailing swell direction is from the southwest, and peak roughness occurs on the southwestern Cape coastline, diminishing northwards and eastwards (DEAT 2000, Lombard et al. 2004). This results in an overall northwards drift along the shore, which transports between one and two million tons of sediment each year (DEAT 2000). The South African coastline consists of approximately 27% rocky shore, 42% sandy beach and 31% mixed shore (consisting mainly of sand on the upper shore above a wave-cut rocky platform) (Bally et al. 1984). The South African coastline also has a substantial number of estuaries (259), with the majority occurring on the east and south coasts, 121 and 129 respectively, and only 11 on the west coast (Whitfield 2000). Most estuaries (72%) along the South African coastline are relatively small and are closed off from the sea for varying periods by a sand bar that forms at the mouth (Whitfield 2000).

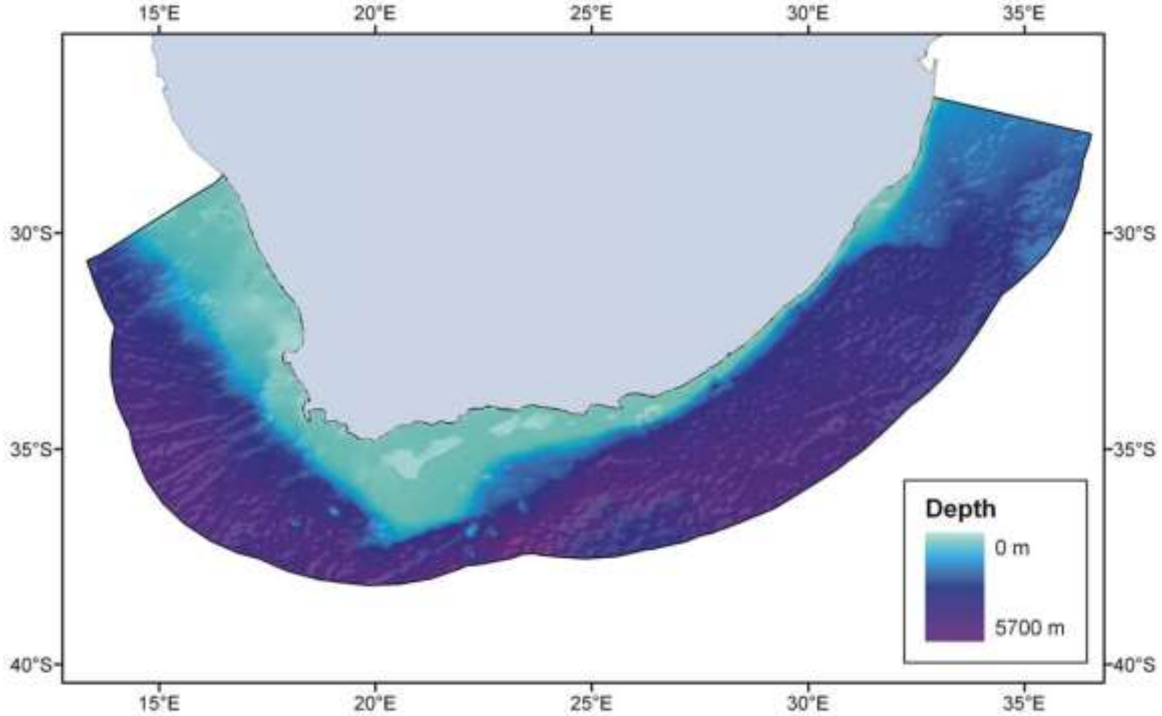


Figure 1.1 Map showing seafloor depths and the boundaries of South Africa's continental Exclusive Economic Zone (EEZ) (after Griffiths et al. 2010)

The ocean has a major influence on global climate and climate variability and is coupled to the atmosphere, such that changes in the circulation of the global atmospheric systems are linked to what happens in the ocean (Lutjeharms 1998). The ocean also directly influences the conditions of the rocky shores, sandy beaches and shallow waters adjacent to the coastline (Lutjeharms 1998). The South African coastal and marine environment is thus highly diverse with numerous habitats and bioregions and is further complicated by both marine and terrestrial forcing functions. This mixture poses a significant challenge in terms of understanding the potential impacts of climate change on our coastal and marine environments and the goods and services that they provide.

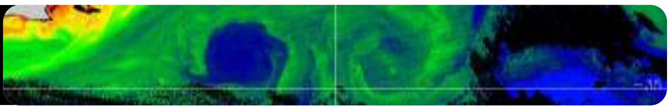
This report provides a synthesis of the current knowledge of climate change impacts on the South African estuarine, coastal and marine environment. Climate impacts were assessed by (1) reviewing the scientific literature on climate change impacts on South African marine life and ecosystems in the context of known impacts elsewhere in the world, (2) summarizing the key trends, impacts and vulnerabilities of ecosystems and marine life to climate change and (3) assessing knowledge gaps and the research and resources needed to better assess possible impacts.

This report focuses on the coastline of South Africa and the continental sections of the Atlantic and Indian Oceans (that fall within the EEZ surrounding continental South Africa). This report does not cover the 466 879 km^2 of EEZ that surround the Prince Edward Islands and South African territories situated in the Southern Ocean. For a thorough overview of climate change impacts on the Prince Edward Islands the reader is directed to Chown and Froneman (2008).

The report comprises separate stand-alone chapters on:

- Key climatic drivers
- The Benguela system and South African fisheries
- The Agulhas Current system and climate change
- Trends in nearshore sea-surface temperature and circulatory systems
- Reef ecosystems
- Estuaries
- Sandy shores
- Rocky shores and kelp beds
- Subtidal fishes
- Coastal infrastructure

2. KEY CLIMATIC DRIVERS

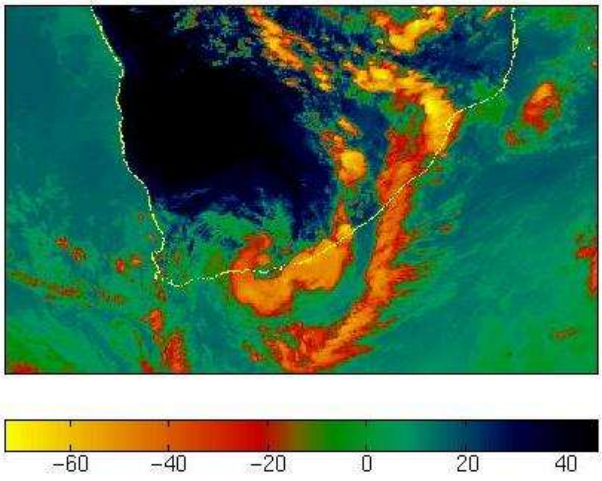


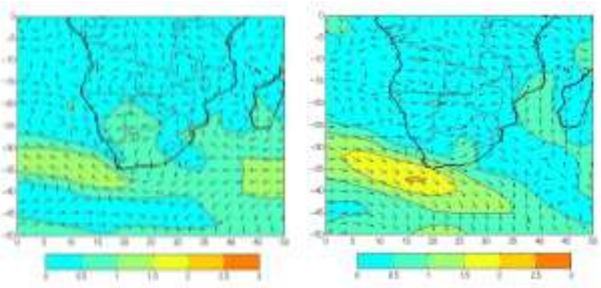
Juliet Hermes & Chris Reason

2.1. INTRODUCTION

The climate of the Earth and of any given region varies on all sorts of time scales from a few years to a few centuries and longer. These variations are collectively referred to as natural climate variability and may result from instabilities in the coupled ocean-atmosphere system (such as the El Niño Southern Oscillation), variations in solar output, volcanic eruptions and other natural processes. If the forcing is particularly strong and global in reach, such as changes in the characteristics of the orbit of the Earth around the Sun, then the resulting impacts may profoundly alter the fundamentals of the Earth's climate over many thousands of years, and then a natural climate change occurs such as an ice age or an interglacial epoch. Superimposed on such natural climate variability and change are the impacts of humans on the global climate system – together these are referred to as 'global change'. The following chapter gives an overview of the key 'natural' physical marine environment and forcings around southern Africa. Such variability can arise in the Pacific Ocean (the El Niño Southern Oscillation), the Southern Ocean (Southern Annular Mode), the Indian Ocean (tropical and subtropical dipole modes) and the Atlantic Ocean (Benguela Niños).

However, before discussing the details of these modes it is important to review what is known of the seasonal variations in the region. The position and strength of the South Atlantic and South Indian anticyclones and the Inter-tropical Convergence Zone (ITCZ) are crucial for the climates of the southern African and neighbouring oceans. In austral winter, anticyclonic conditions (and hence little rainfall) dominate most of southern Africa as the South Indian anticyclone migrates west to directly influence much of southeastern Africa, and the South Atlantic anticyclone shifts north and west, leading to strong southerly winds (and hence upwelling) along the Namibian and southern Angolan coasts. A col region (relatively low





Top: The Benguela Current Large Marine Ecosystem (BCLME) PIRATA buoy, called *Kizomba,* being deployed; *Middle:* Mandela tornado image: Brightness temperatures from infrared Meteosat imagery on 15 December (1988) at 8 am (Rouault et al. 2002); *Bottom:* NCEP Surface wind speed anomaly La Niña (left) and El Niño event (right) events in austral summer (Rouault 2007) pressure) exists over the south Western Cape and ocean areas immediately to the south and southwest; hence cold fronts bring rainfall to this region in winter and there is no upwelling. The ITCZ lies over northern Africa in winter but shifts south of the equator to lie over northern Mozambique and Malawi in summer. During this season, heat lows develop over the Northern Cape and over southern Angola/northern Namibia as the South Atlantic anticyclone shifts southeast towards the south Western Cape and the South Indian Ocean anticyclone retreats eastwards to the central part of this basin. These changes lead to the development (relaxation) of strong upwelling favourable southerly winds along the west coast of South Africa (northern Namibia/southern Angola) and better conditions for rainfall over most of southern Africa except the far west and southwest. There is less evidence for any obvious seasonality in the South West Indian Ocean since it is dominated year round by the strong Agulhas Current. However, smaller regions of coastal upwelling such as near Port Alfred or Port Elizabeth may be strengthened or weakened with seasonal shifts in the winds, which then act to oppose or enhance the main upwelling process here (divergence associated with the Agulhas Current).

Since it is a rather narrow landmass surrounded by oceans that extend from the tropics towards the mid-latitudes, southern Africa experiences strong ocean influences on its weather and climate patterns. In particular, South Africa is situated near the meeting place of three oceans, the South Indian Ocean on the east coast, the South Atlantic on the west coast and the Southern Ocean to the south. These three oceans play a vital role in determining southern Africa’s climate and weather patterns as well as strongly influencing the global climate. The main types of ocean variability that influence South Africa are shown in figures 2.1 and 2.2.

The El Niño Southern Oscillation is the dominant type of natural variability influencing the oceans and global climate on time scales of several months to several years. In general, during the summer of a positive ENSO (El Niño) event, the tropical Indian Ocean warms, the mid-latitude Indian Ocean cools, the central South Atlantic warms but the mid-latitude South Atlantic cools, the subtropical jet moves north and South Africa is mainly dry. Roughly the reverse pattern occurs during the cold ENSO (La Niña) event. Most severe droughts over subtropical southern Africa seem to either be due to strong El Niño events (Lindesay 1988, Mason and Jury 1997, Reason et al. 2000) or to regional anomalies over the southeast Atlantic (Mulenga et al. 2003, Tennant and Reason 2005). Rouault and Richard (2003, 2005) have shown that the worst drought in southern Africa happened during an El Niño and conversely the worst wet period during a La Niña. However, the interaction of this natural variability with climate change, such as the Indian Ocean warming since the 1970s, has led to drought becoming more intense and widespread during El Niños (Richard et al. 2000, 2001), highlighting the complex interactions between natural variability and climate change.

La Niña events tend to follow El Niños and the whole cycle of ENSO occurs approximately every 4–7 years. Occasionally, however, protacted ENSO events occur in which either El Niño (e.g., 1991–1995) or La Niña (e.g., 1998–2001) conditions can persist longer than typical. Unfortunately, our ability to predict the strength, the duration and the impact of ENSO events is not particularly good and sometimes these events can coincide with other natural variability elsewhere in the global oceans, thereby confusing the signal in certain regions. An example in the tropical Indian Ocean is the Indian Ocean dipole (IOD, or zonal mode), a coupled ocean-atmosphere phenomenon occurring every few years that generates in this ocean typically during June or July and dissipates by November or December (Saji et al. 1999). During ‘positive’ events, the dipole consists of cooler sea surface temperatures in the southeast tropical Indian Ocean and warmer waters in the west. These changes in the sea temperature lead to a shift in the typical atmospheric convection, with heavy rainfall over equatorial east Africa and droughts over the Indonesian region. The negative phase of the IOD brings about the opposite conditions, with warmer water and greater precipitation in the eastern tropical Indian Ocean, and cooler and drier conditions in the west (Saji et al. 1999).

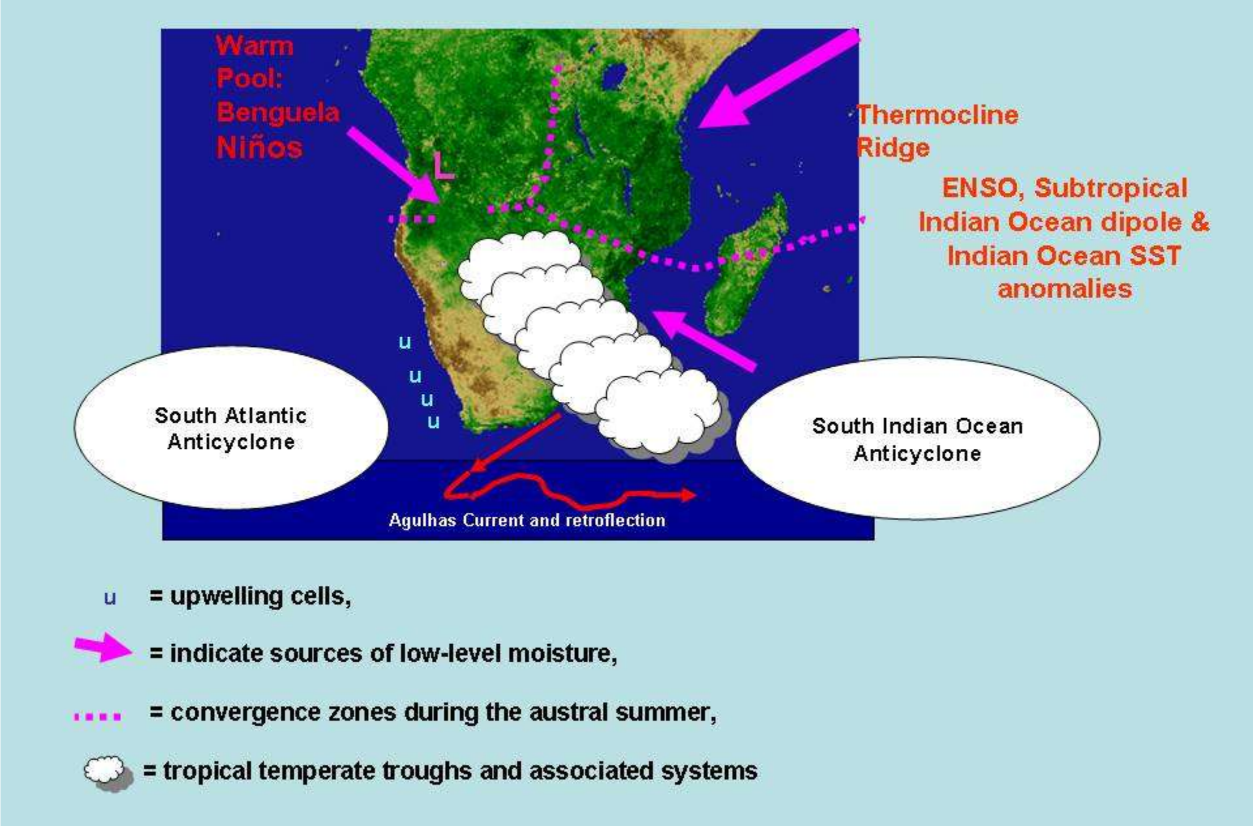


Figure 2.1 Schematic of important features during austral summer (after Reason et al. 2006)

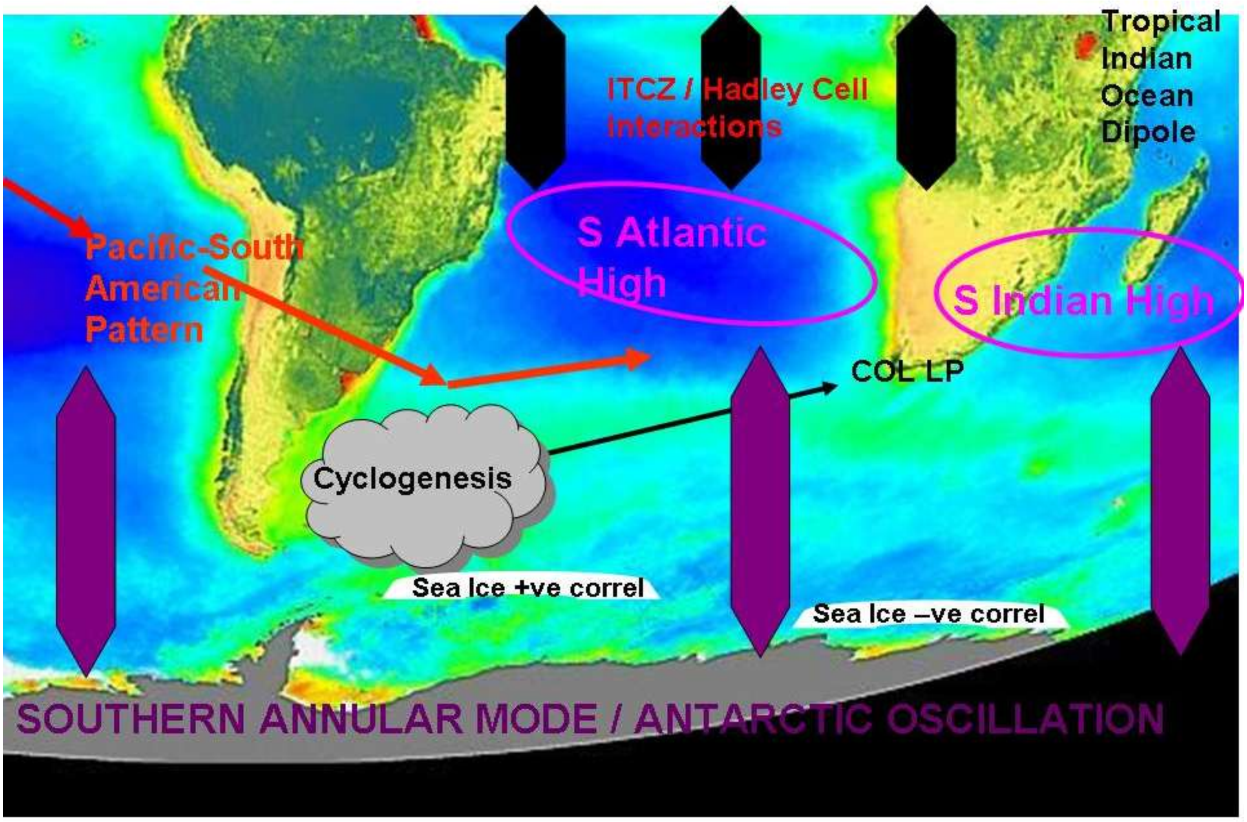


Figure 2.2 Schematic of important features for austral winter rainfall (after Reason and Rouault 2007)

At higher latitudes, dipole events in sea surface temperature can also occur every few years in the subtropics to mid-latitudes of both the South Indian and South Atlantic oceans during austral summer. Positive events consist of warmer SSTs in the NE South Indian Ocean and cooler SSTs in the SW, and similarly in the South Atlantic, resulting in reduced rainfall over southern Africa during summer (Reason 2002; Fauchereau et al. 2003, Hermes and Reason 2005). These subtropical dipole events potentially impact the major current systems, with an increase (decrease[2]) in southward heat transport in the Agulhas Current during a positive (negative) event. In the South Atlantic, a strengthening (weakening) of the southern Benguela Current occurs during the positive (negative) event, increasing (reducing) the cool water heading towards the region of the cool (warm) pole (Hermes and Reason 2005). These dipole events often coincide with ENSO events and the relationship between them is not clear. It is further evident that the characteristics of these modes of variability are changing with time; thus, the addition of anthropogenic climate change makes the situation much more difficult to disentangle and predict.

Another influential form of variability in the South Atlantic is the 'Benguela Niño' (Rouault et al. 2003, 2007), in which the usual cold upwelled water on the Angolan/northern Namibian coast near the frontal area between the southward-flowing Angola Current and the Benguela upwelling system off southwestern Africa is replaced by anomalously warm water every few years during late summer and autumn (Shannon et al. 1986). These anomalously warm events often induce significant rainfall anomalies, particularly over Angola and Namibia (Hirst and Hastenrath 1983, Rouault et al. 2003) and can drastically modify fish distributions (Boyer et al. 2001). Benguela Niños occurred in 1934, 1949, 1963, 1984 (Shannon et al. 1986), 1995 (Gammelsrød et al. 1998), and 2001. Extreme cool events in this region may be termed Benguela Niñas (Florenchie et al. 2004). Smaller warm and cool events occur more frequently along this coast and may be generated in a similar way to Benguela Niños and Niñas; however, their surface expression is weak because of other factors. How this important upwelling regime will be impacted under climate change is not clear. Due to its importance for the economies and biodiversity of South Africa, Namibia and Angola, it is essential that we are able to monitor variability and change off the west coast of southern Africa, in particular, to better understand and potentially predict natural events such as Benguela Niños and low oxygen events.

South of Africa, where the South Indian and South Atlantic oceans meet, is an extremely variable region which has been termed the 'Cape Cauldron' (Boebel et al. 2003) Here, large 'Agulhas Rings' leave the Indian Ocean, taking with them heat and salt into the Atlantic. Any changes in this region can influence not only South Africa's weather and climate pattern but also that as far afield as northern Europe (Beal et al. 2011). In fact, most of South Africa's severe flooding events have occurred due to cut-off lows strengthening over the southern Agulhas Current (Singleton and Reason 2007).

It has been suggested (Schouten et al. 2002) that Agulhas Ring shedding into the Cape Cauldron may be traced back upstream to the equatorial Indian Ocean, via the propagation of Kelvin and Rossby waves, towards the tropical South West Indian Ocean. Current work suggests that there has been a warming trend in the Agulhas Current system due to its intensification in response to changing wind patterns in the South Indian Ocean (Rouault et al. 2009). Modelling results have suggested that a southward shift in the South Indian Ocean anticyclone would lead to reduced Agulhas leakage into the South Atlantic (Hermes et al. 2007). Biastoch et al. (2009), however, found that the reverse was true in their model; hence much further work needs to be done.

Further south, in the Southern Ocean, the Southern Annular Mode or Antarctic Oscillation is the main form of natural variability. The relationships between the SAM, the South Atlantic and Indian oceans, and South African rainfall variability have been explored: evidence shows that when SAM is in its negative phase, winters over western South Africa tend to be wetter (Reason and Rouault 2005). It has also been found that reduced sea-ice extent in the Antarctic

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[2] Antonyms in brackets describe the corresponding opposites of the dipole event.

due south of South Africa, but increased sea-ice extent further west near the Antarctic Peninsula, is associated with more winter rainfall (Blamey and Reason 2007). Analysis of observations and computer model experiments have indicated that wetter or drier winters are also influenced by certain SST patterns in the subtropical to mid-latitude South Atlantic (Reason and Jagadheesha 2005). These patterns, combined with the influence of ENSO and other modes of variability in the southern oceans point to a complex interplay of factors that can influence the weather and climate over South Africa.

2.2. MITIGATIONS AND WAY FORWARD

It should be stated at the outset that climate variability over southern Africa is complex with a multitude of forcing factors that interact with each other and wax and wane in their importance through the record (Allan et al. 1996, 2003, Landman and Mason 1999, Richard et al. 2000, Reason and Rouault 2002).

Since a roughly two-month lag exists between wind anomalies in the tropical western Atlantic and the manifestation of SST anomalies along the Angolan coast, some predictability of Benguela Niños, and hence, late-summer (February–April; FMA) rains over Angola and northern Namibia, may exist. The Pilot Research Moored Array in the Tropical Atlantic (PIRATA, Servain et al. 1998) and Quick Scatterometer (QuikSCAT) wind data for the early-midsummer, together with any equatorial subsurface anomalies evident in the PIRATA moorings, could give advance warning of a developing event. Current statistical forecasting schemes used in South Africa (Landman and Mason 2001) do not capture these events, or indeed perform satisfactorily over the South Atlantic as a whole, likely because of the importance of trapped waves and other dynamics that are not well represented by statistical models of this type. In addition, the nonlinear response of SST anomalies off Angola to the remote wind forcing (Florenchie et al. 2004) emphasizes the need for further work to understand the way different mechanisms seem to control the development of each individual event in the southeast Atlantic.

In the Indian Ocean, the Research Moored Array for African–Asian–Australian Monsoon Analysis and prediction (RAMA) is helping to understand variability in the tropics, and hence improving predictability of, for example, the dipole patterns. An increased understanding of the Agulhas Current is needed in order to improve its resolution in ocean models since many global ocean and coupled models are unable to resolve this intense feature. Work being done with higher resolution, nested models, has had better success in resolving the Agulhas and its mesoscale features. However, given that we are yet unable to explain the cause of a Natal pulse within the system, or even categorically state how the East Madagascar Current terminates, we are far from being able to provide successful predictions of the oceanic region.

One of the biggest hurdles is formed by the deficiencies in representing the tight SST and topographic gradients in the region. Given that the sharp topographic, vegetation, soil and SST gradients in the southern African region are unlikely to be adequately represented by AGCMs, it is important to consider downscaling their output to the region of interest. Either a statistical approach or nesting a regional climate model (RCM) within the AGCM output can be used to do the downscaling. Currently, application of RCMs for seasonal forecasting by southern African groups is in an early stage.

Main oceanographic features:
South Atlantic
Benguela upwelling, Luderitz Upwelling, Angola–Benguela Front.
Major variability patterns: ENSO, Benguela Niños, Southern Annular Mode, Subtropical dipole, Pacific South America pattern

South Indian Ocean
Agulhas Current system (retroflection, return current and eddy shedding), Mozambique Channel eddies, Rossby waves, East Madagascar current, Natal pulses
Major variability patterns: Monsoons, ENSO, Madden–Julian Oscillation, Southern Annular Mode tropical and subtropical dipole, thermocline ridge

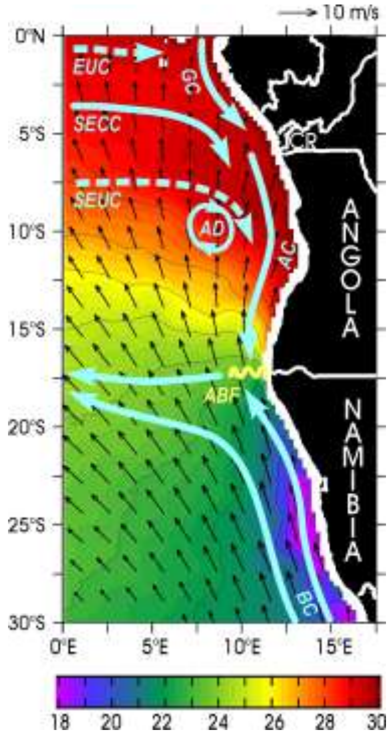
3. THE BENGUELA SYSTEM AND SOUTH AFRICAN FISHERIES

Larry Hutchings

3.1. OVERVIEW

3.1.1. THE BENGUELA SYSTEM

The Benguela system is one of the major eastern boundary upwelling systems of the world, together with the Humboldt, Canary and California current ecosystems. While all share a common feature of wind-driven divergence along the coastline, there are significant differences between them in terms of extent, seasonality, primary productivity and fisheries yield (Hutchings 1992, Ware 1992, Mackas et al. 2006). A synthesis of the Benguela region (Hutchings et al. 2009) describes the Benguela region in terms of four components: a northern subtropical region off Angola, a cool temperate upwelling region between Cape Frio (17ºS) and Cape Agulhas (35ºS), separated into northern and southern ecosystems by the powerful Luderitz upwelling cell at 26ºS, and a warm temperate zone on the Agulhas Bank along the south coast of South Africa. The Agulhas Current, running along the shelf edge, forms the southern boundary of the Benguela system in a complex mixing area south of the continent. Many biological organisms move or migrate between the cool upwelling areas and the warm temperate boundary regions, hence their inclusion in the Benguela ecosystem, even though the wind-driven upwelling system is largely confined to the west coast between 17ºS and 35ºS.



Top: Major oceanographic features in northern Benguela Current system; SST & QuikScat wind speed and direction (Rouault 2007); *Bottom:* Snoek (*Thyrsites atun*), commercially valuable species and important predator of small pelagic fish in the Benguela ecosystem (photo: Charles Griffiths)

3.1.2. LARGE SCALE FEATURES OF THE BENGUELA

Figure 3.1 indicates the major features affecting the ocean and atmosphere in the Benguela. The South Atlantic and South Indian ocean anticyclones shift seasonally, and interactions with the continental low and the complex inter-tropical convergence zone create upwelling-favourable winds along the west coast and, on the east coast, a warm poleward-flowing western boundary current, which retroflects south of the continent (Shillington et al*.* 2006, Reason et al*.* 2006). Warm water of the Atlantic and central Indian oceans influences the boundary conditions and, uniquely, feeds warm equatorial water to both the northern and southern boundaries of the Benguela. South of the continent, which ends at 35ºS, the free passage of cyclones in the westerly wind belt and the close proximity of the Southern Ocean allow strong signals to propagate into the Benguela region. Several IPCC4 models indicate a likely southward shift in the locations of the anticyclones, inducing increased southerly winds in the southern Benguela and decreased southerly winds in the northern Benguela region.

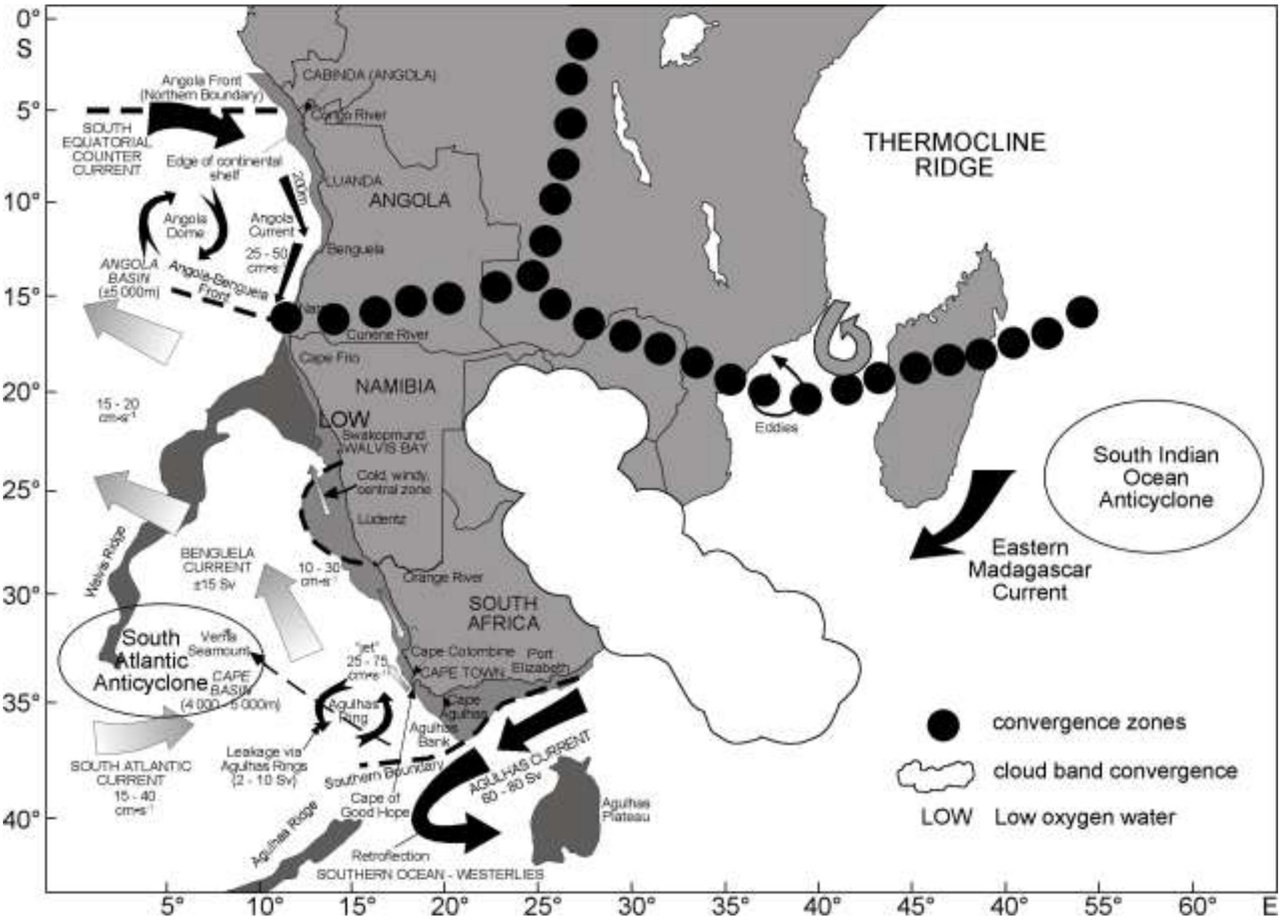


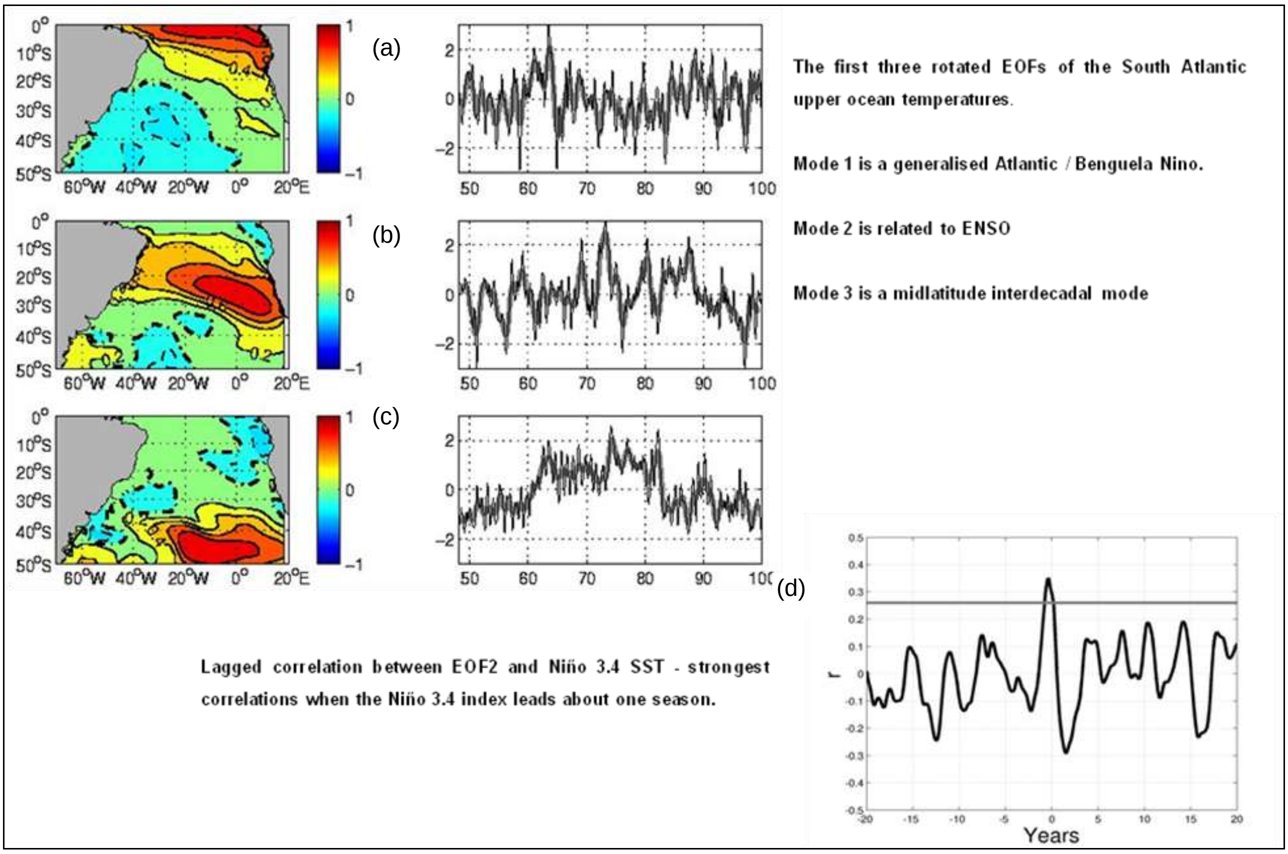
Figure 3.1 Large scale oceanic and atmospheric features impacting on the Benguela ecosystem. The anticyclone high pressure systems, the inter-tropical convergence zones over land and the west wind belt in the form of eastward moving cyclones determine the dynamic boundaries of the Benguela upwelling region (modified from Shannon 2006). Warm tropical water is advected southwards in the Angola and Agulhas currents to form intense mixing areas on the northern and southern boundaries of the Benguela.

Major modes, or patterns of variability, in near-surface waters in the South Atlantic are described by Reason et al*.* (2006) and Colberg and Reason (2007) (Figure 3.2) using rotated Empirical Orthogonal Functions (EOFs) of the upper mixed layer temperatures from the ocean model ORCA2. The first mode is in the equatorial Atlantic and links to the strength of equatorial trade winds and the occurrence of Benguela Niños (Shannon et al*.* 1986) at roughly decadal scales; the second is located approximately over the South Atlantic anticyclone and is strongly linked to ENSO events, and the third is in the midlatitudes with strong interdecadal patterns. Atmospheric forcing and latent heat exchanges between the ocean and atmosphere are thought to play a major role in the dynamics of the South Atlantic, rather than major advective transport of heat through ocean currents.

The other major influence in the southern regions is the Southern Annular Mode (SAM), or the difference in pressure between 40ºS and 65ºS, which influences the intensity and pathways of the westerly winds. No clear multidecadal-scale oscillations comparable to the North Atlantic Oscillation or the Pacific Decadal Oscillation are apparent in the South Atlantic or South Indian oceans. Strong dipole effects in both oceans also exert some influence on atmospheric forcing over the Benguela (Reason et al. 2006).

From north to south (Figure 3.1), major regional features of the Benguela system include:

- A northern thermal boundary near the Congo River plume separating the tropical Gulf of Guinea from the subtropical Angola system.
- The Angola Current, which flows southward along the narrow shelf of Angola as an extension of the south equatorial counter-current and forms a northern boundary of the wind-driven upwelling system at the conspicuous, very dynamic but relatively shallow Angola–Benguela front at 17ºS. The coastline orientation is rough N–S between Cape Frio and Cape Agulhas, but curves eastward, north from 16ºS to 12ºS, before bending westward again at Benguela in Angola.
- Three major embayments occur at Lobito (12ºS), Walvis Bay (23ºS) and St Helena Bay (32ºS). The orientation changes radically at 34ºS between Cape Point and Cape Agulhas from N–S to E–W, with the major wind-driven Benguela upwelling zone located between Cape Agulhas and Cape Frio. The very powerful upwelling at Luderitz (26ºS) with strong winds, high offshore advection and strong turbulent mixing serves to partially separate the northern and southern Benguela regions, with further subtropical boundary regions in Angola and on the Agulhas Bank. These boundary regions can be expected to shift, or the thermal gradients may become more intense or may weaken, with changing forcing functions in response to the general warming trend.



The first three rotated EOFs of the South Atlantic upper ocean temperatures.

Mode 1 is a generalised Atlantic / Benguela Nino.

Mode 2 is related to ENSO

Mode 3 is a midlatitude interdecadal mode

Lagged correlation between EOF2 and Niño 3.4 SST - strongest correlations when the Niño 3.4 index leads about one season.

Figure 3.2 (a, b, c) The first three rotated EOFs of the South Atlantic upper ocean temperatures. Mode 1 is a generalized Atlantic–Benguela Niño. Mode 2 is related to ENSO. Mode 3 is a midlatitude interdecadal mode. (d). Lagged correlation between EOF2 and Niño 3.4 SST, which shows strongest correlations when the Niño 3.4 index leads about one season. From Colberg and Reason (2007)

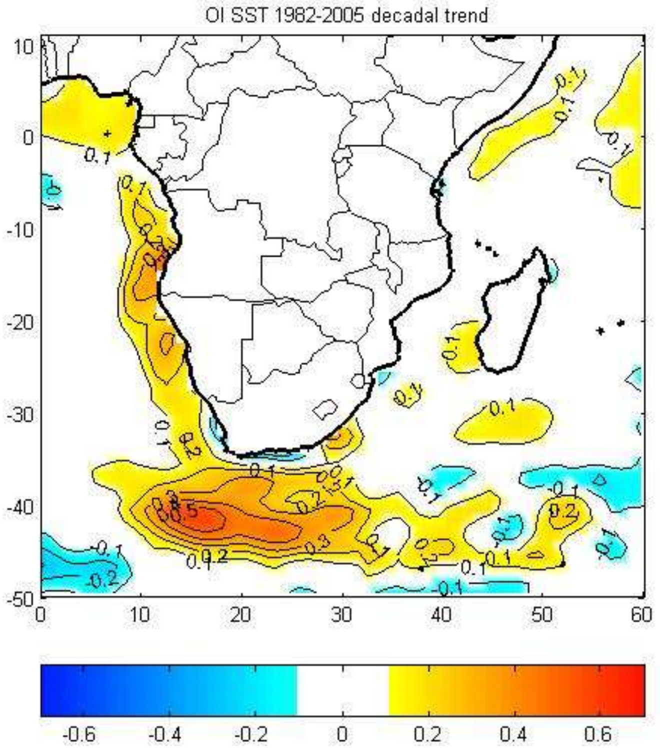


Figure 3.3. Sea surface temperature trends in ºC per decade since the start of the satellite era (1982–2005) using Reynolds SST (from Rouault 2007), showing warming in the boundary regions of the Benguela but cooling inshore in the southern Benguela and inshore southern coast

A combination of shelf width and coastal topography creates a number of discrete upwelling centres that, combined with the passage of low pressure systems south of the continent and the formation of a coastally trapped low pressure in the lower atmosphere and its southward movement against the escarpment, produce strongly pulsed, three-dimensional upwelling (Nelson and Hutchings 1983), particularly in the southern Benguela. Cool productive water occurs in a narrow band from Cape Agulhas (35ºS) to Cape Frio (17ºS), broadening at the Angola–Benguela front and on the central and eastern Agulhas Bank where the Agulhas Current diverges from the coast and where the cool ridge is manifest as a shallow doming of isotherms. At the southern boundary, the Agulhas Current flows along the shelf break of the broad Agulhas Bank towards the west and, while most of the 60–80 Sv current flow retroflects back into the South Indian Ocean, some warm saline water flows northwards into the South Atlantic in jets, filaments and large eddies, some of which impact on the shelf ecosystem.

Offshore, the broad South Atlantic gyre forms an outer boundary of the Benguela upwelling system. A noticeable feature of the Benguela has been the strong warming trend (Figure 3.3, from Rouault 2007) at the northern and southern boundaries in the period 1982–2005, while a cooling trend is detected close inshore in the southern Benguela, linked to increased coastal upwelling in response to increased southerly and easterly winds. Recently Rouault et al. (2009) have documented increased flow in the Agulhas Current itself, which should increase the divergence-driven upwelling near Port Alfred and should enhance the cold bottom waters on the Agulhas Bank itself.

Southerly winds peak in three particular locations in the Benguela (Figure 3.4), at Cape Point (34ºS), Luderitz (26ºS) and at Cape Frio (17ºS), with slightly less winds in between and a major decline in wind strength, and a change in wind direction from southerly to southwesterly in Angola. Phytoplankton biomass (Figure 3.5) is most abundant downstream of these peak upwelling locations, with perennial high concentrations on the central northern Namibian shelf, especially near Walvis Bay and off the Namaqua shelf, particularly St Helena Bay. Despite perennial upwelling off Cape Frio, the phytoplankton signal is masked by the intrusion of warm chlorophyll-*a*-poor warm waters from Angola each summer (December–March).

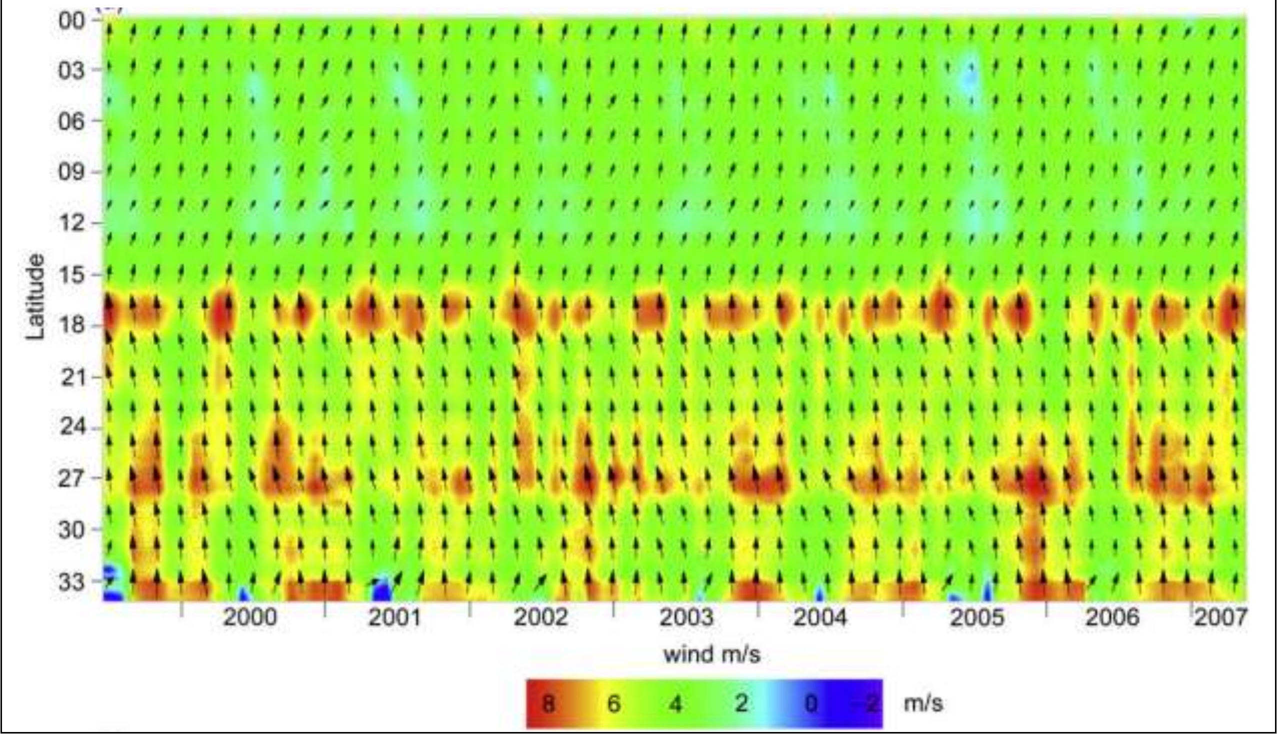


Figure 3.4 Wind patterns from Quickscat, showing high winds at 17ºS, 26ºS and 34ºS and sharply declining winds north of 16ºS.

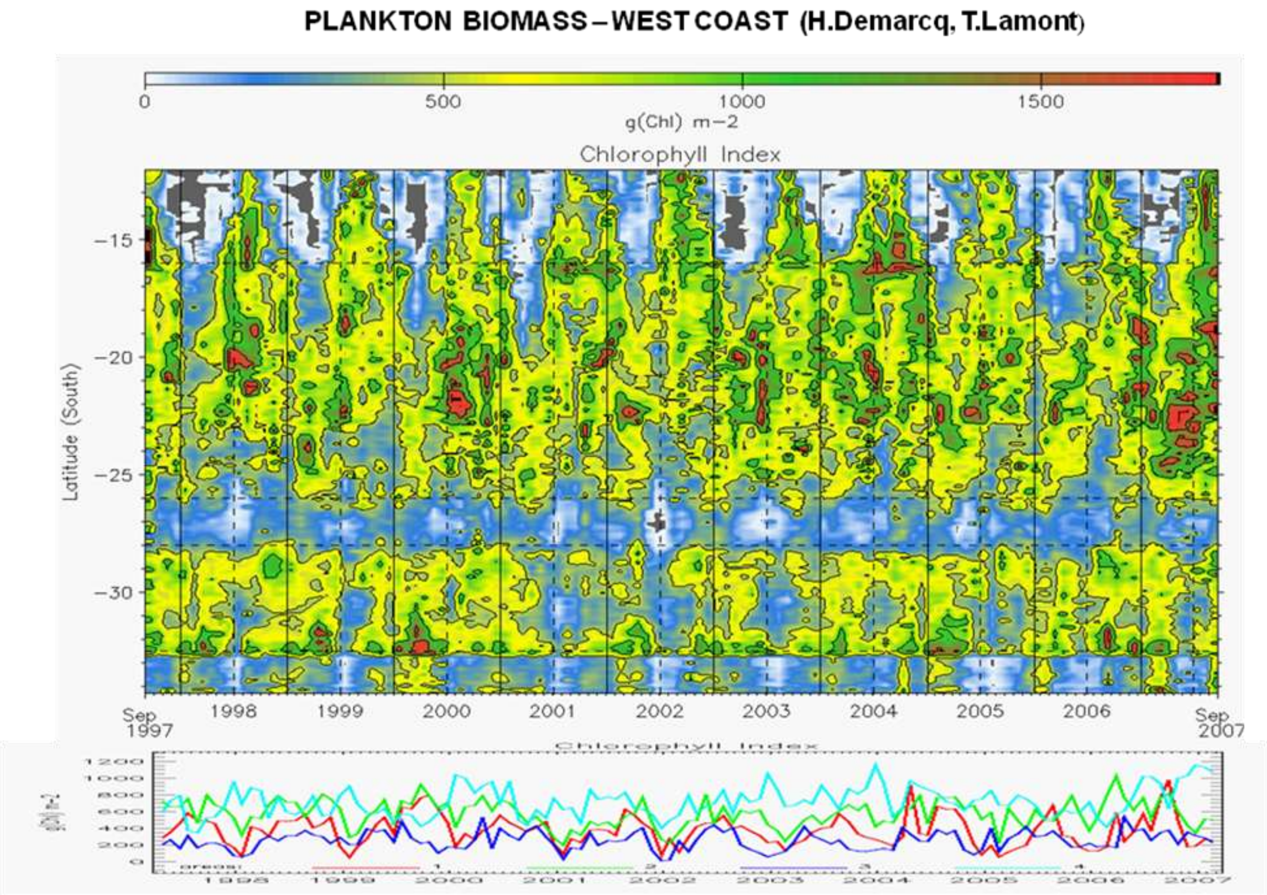


Figure 3.5 Upper panel: Patterns and indices of phytoplankton enrichment on the west coast from Angola to Cape Agulhas, based on satellite colour imagery, showing six spatially distinct zones. Patterns of surface phytoplankton abundance, updated from Demarcq et al. (2007). High phytoplankton concentrations occur downstream from strong upwelling centres. The zone just south of Lüderitz (26ºS) displays low phytoplankton concentrations.
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.

Cool, phytoplankton rich water extends northward into Angola during late winter (July–September). There is a tendency for phytoplankton and winds to peak in late winter–spring in the northern Benguela and in summer and autumn in the southern Benguela, so they show opposite seasonal signals. At Luderitz, the strong winds, narrow shelf and excessive turbulence prevent the formation of dense phytoplankton concentrations in the area between 26 and 29ºS (Hutchings et al. 2009).

3.1.3. MESOSCALE FEATURES

The Angolan subtropical zone

Sea surface height anomalies, both positive and negative, propagate southwards from the equatorial region into central Angola, indicating an equatorial Atlantic origin rather than a wind-driven ecosystem. Pronounced seasonal changes occur off the Angolan coast, with a warm season in December–March, during which strongly stratified waters overlie cooler productive water below the thermocline; the cool season extends from July to September, similar to events in the Gulf of Guinea, and only in the extreme south is wind-driven upwelling prevalent for a few months of the year.

The northern Benguela

The important features affecting this area include the Angola Current, the Angola–Benguela front, the low-oxygen water and the upwelling cells at Cape Frio and at Luderitz. The Angola–Benguela front can be defined in terms of thermal gradients and the latitudinal anomalies in the frontal position are shown in Figure 3.6 with northward (cold) anomalies in 1982/3, 1986/7, 1992/3 and 1997/8, which coincide with strong ENSO events in the Pacific and reflect the northward movement of the South Atlantic high in those periods. Southward (warm) anomalies are less frequent, with the major events occurring in 1984 and 1995 (and 1963). Less pronounced but more common warm events occurred during the 1995–2003 period, while cool events are less frequent, in line with the general warming in the northern Benguela.

Winds at Luderitz (Figure 3.7) show strong decadal variability, with southerly winds peaking in 1970–1973, 1976–1989 and 1997–1998, while lower winds occurred in 1961–1969 and again from 1990 to 2006. These coincide with SST anomalies in the northern Benguela region. However, the infrequent intense warm anomalies can only be detected with in-depth data from ship or moored instruments. Low oxygen water (LOW) on the northern Namibia shelf results from a complex interplay of (i) southerly influx of oxygen-depleted water from the Angola dome area; (ii) uplift onto the shelf at Cape Frio; (iii) local decay processes on the shelf; (iv) the influx of relatively oxygenated central water from the Cape Basin via upwelling at Luderitz; (v) stratification of the shelf waters (Monteiro and van der Plas 2006). The strength of the intrusion and the phase difference between upwelling at Cape Frio and Luderitz results in more or less intense LOW on the shelf (Figure 3.8) with an overall trend on better oxygenation over the past 8 years, with less water of <0.5 ml l^{-1} and more water of >2.5 ml l^{-1} on the monitoring transect to 120 km at 23ºS off Walvis Bay. Phytoplankton concentrations on the transect declined sharply after 2005, while mesozooplankton responded by decreasing, and the relative abundance of two important species, *Calanoides carinatus* and *Metridia lucens* altered significantly.

The Luderitz upwelling area

This area forms a partial barrier to a number of pelagic fish species, with populations to the north and south responding differently to heavy exploitation and subsequent management actions (see below under Fisheries Resources). Wind patterns at Luderitz (26ºS), Cape Columbine near St Helena Bay (33ºS) and Cape Point (34ºS) (Figure 3.7) all display the same interannual and decadal scale variability but with some lags between them, mostly in response to shifts in the position of the South Atlantic anticyclone. Mesopelagic and demersal fish assemblages and mobile predators do not perceive the area as a barrier, and only a few copepod and diatom species differ north and south of Luderitz. There is a change in upwelling source water to a less saline and more oxygenated source from the Cape basin south of Luderitz, but the major mechanism appears to be the strong turbulence, the strong offshore advection and the dearth of phytoplankton along the narrow shelf region which mostly separates pelagic fish populations into northern and southern components.

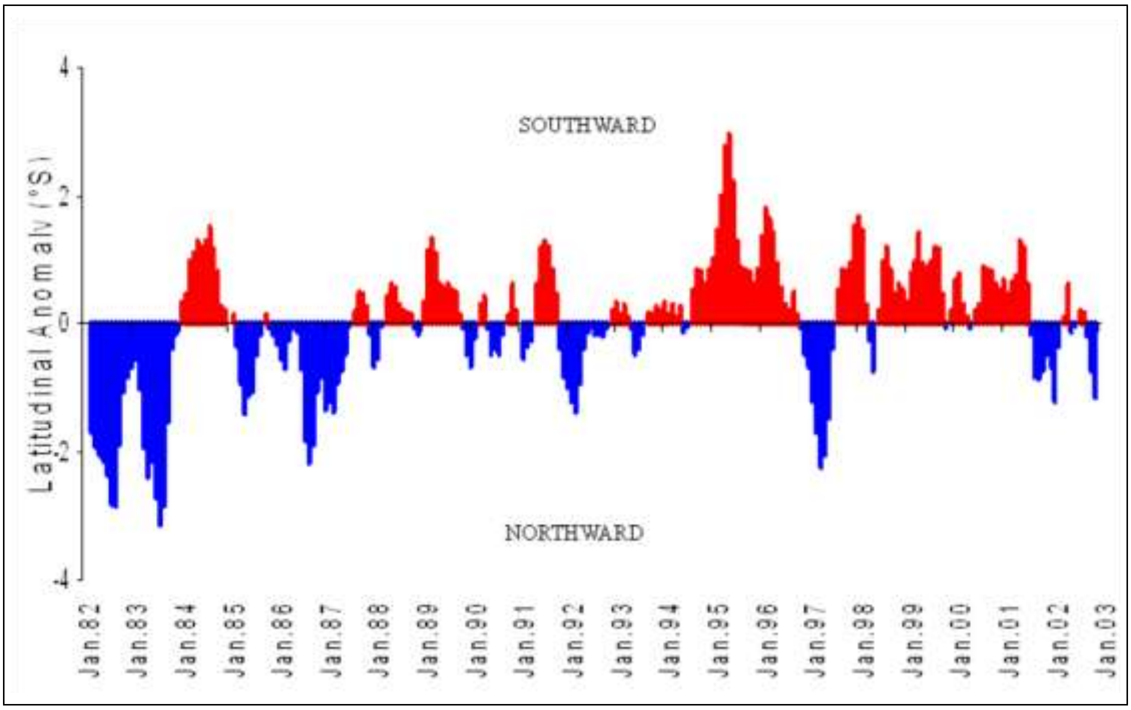


Figure 3.6 Movements of the Angola–Benguela frontal region, based on movements of the 19ºC and 23ºC isotherms, 1982–2003.

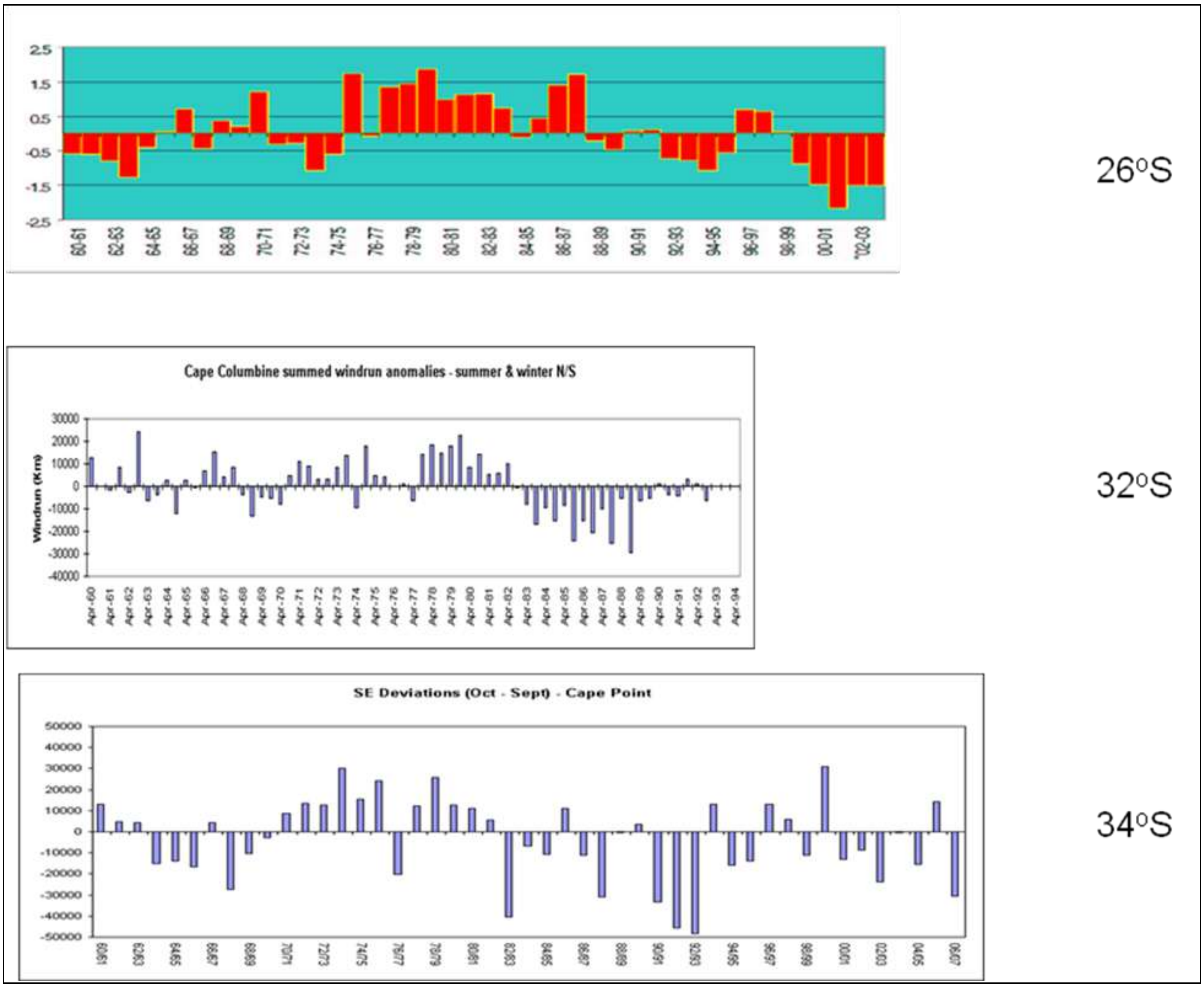


Figure 3.7 Alongshore (N–S) wind anomalies at Lüderitz (26ºS), Cape Columbine (32ºS) and Cape Point (34ºS), showing interannual and decadal variability but similar trends.

The southern Benguela and Agulhas Bank

Hypoxic water is also prevalent in a narrow inshore strip over the southern Benguela shelf region, but is linked solely to decay processes of phytoplankton enriched from the coastal upwelling and does not often reach the depleted levels in the northern Benguela (Monteiro and van der Plas 2006). While LOW is not as pronounced as further north, periodic mass mortalities of shellfish and rock lobsters have occurred with more frequency in the southern than the northern Benguela, usually in conjunction with the decay of dense phytoplankton blooms (Pitcher and Weeks 2006). While oxygen concentrations vary seasonally and interannually (Figure 3.8), there is a long term decline in oxygen concentrations in sub-thermocline waters since 1961 (Figure 3.9) (J Currie, UCT, pers comm), which is also reflected in the shorter term records from the St Helena Bay Monitoring Line. This decline in oxygenated water appears to have a deleterious effect on rock lobster: the frequency of walkouts has increased in the past four decades, and rock lobster distribution has shifted southwards and eastwards (Cockcroft et al. 2008) (Figure 3.17). This has led to severe economic and social problems on the largely arid west coast, where alternative livelihood prospects are limited; whereas artisanal fishers in the southern region have benefited, future trends remain uncertain. Phytoplankton concentrations from ship and satellite observations are high and variable, with a seasonal signal apparent only in smoothed data, peaking in late summer and autumn, and no obvious trend in the relatively short time series (Figure 3.5), although there is a slight upward trend in upwelling favourable winds (Figure 3.10), nutrients (Figure 3.11) and potential production over the period 1980–2007 (J Currie and M Gibberd, UCT, pers. comm.).

Mesozooplankton displayed a distinct seasonal signal, with a summer maximum for the period 2000–2003 when pelagic fish were very abundant on the west coast, but this signal declined in recent years. However a well defined 100-fold increase in zooplankton occurred between 1950 and 1995, followed by a 10-fold decline in recent years (Figure 3.12) (Verheye et al*.* 1998). The plankton increase in the southern Benguela was mirrored by a similar increase in the northern Benguela between 1970 and 2007.

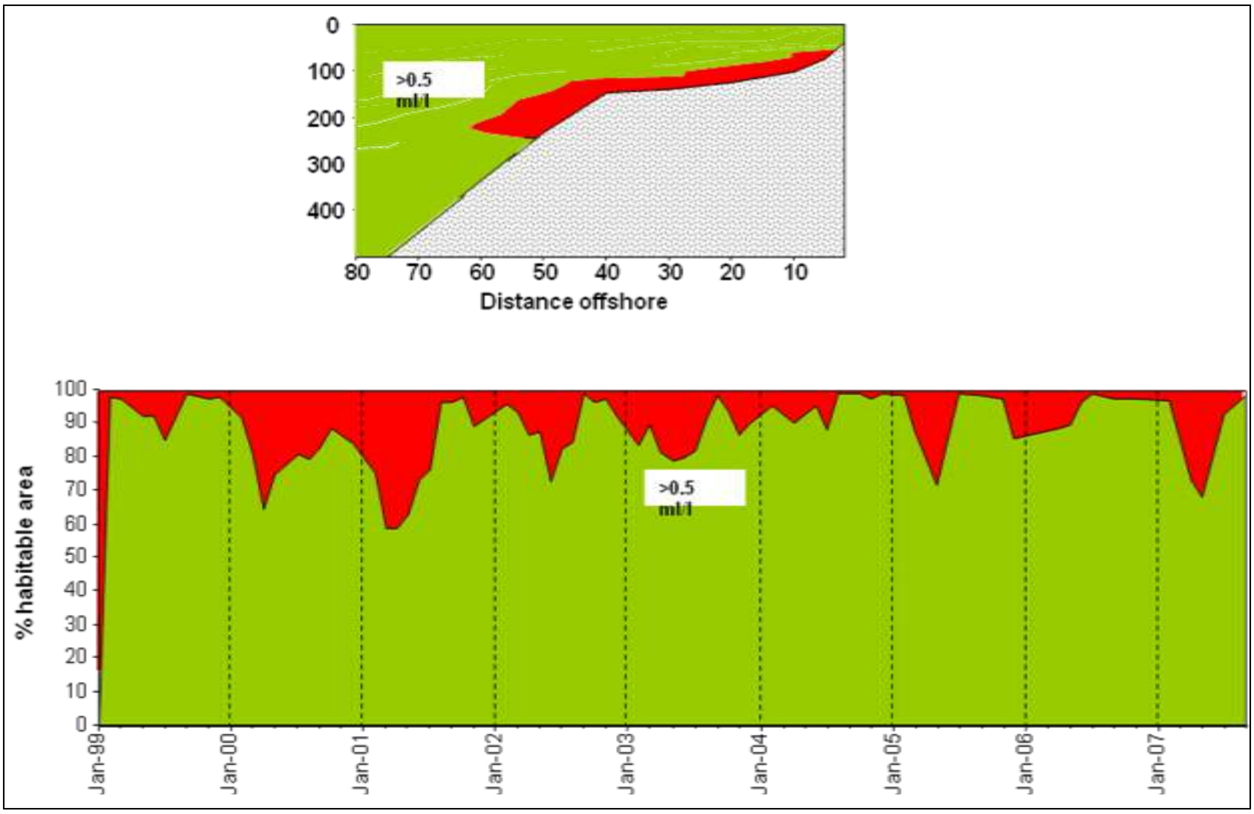


Figure 3.8 Inter annual changes in low oxygen (<0.5 ml l^{-1}) at 23ºS, 1999–2007

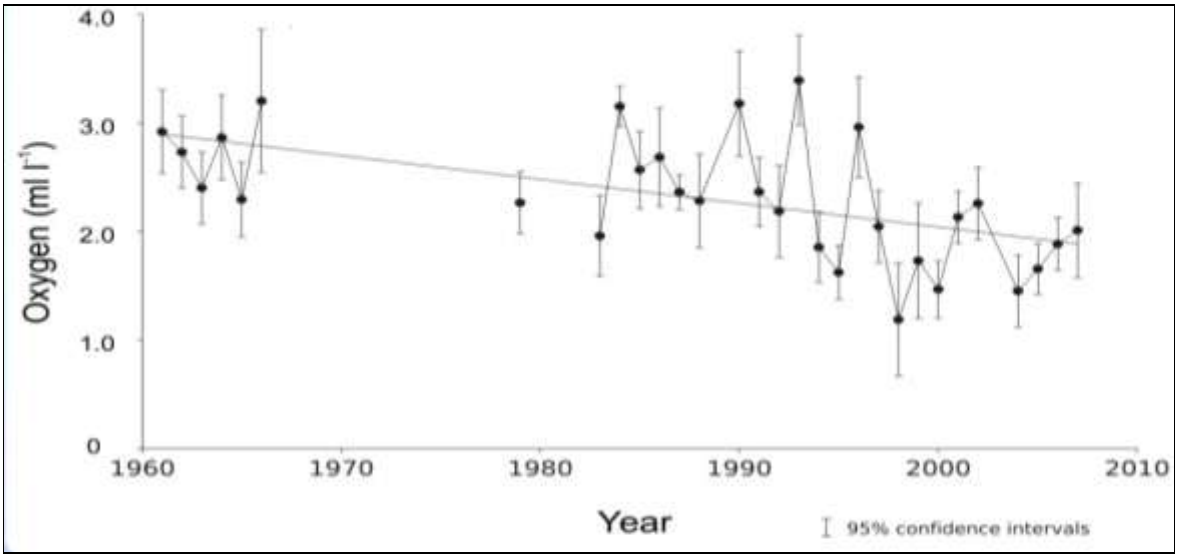


Figure 3.9 Changes in oxygen in sub-thermocline waters, St Helena Bay, 32ºS, 1960–2008.

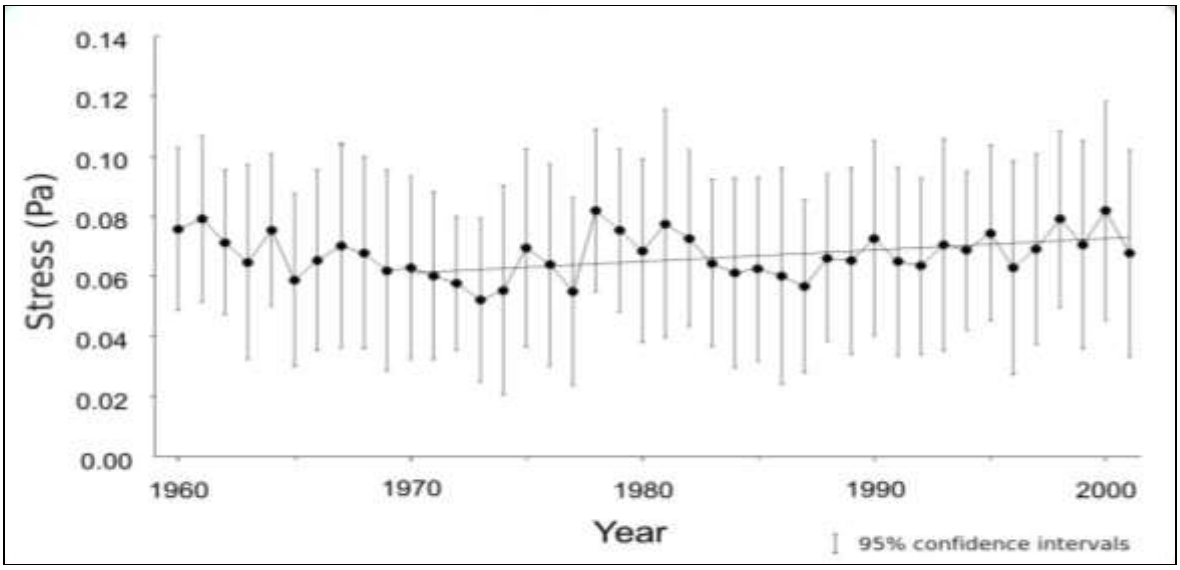


Figure 3.10 Changes in the southerly winds off the South African west coast from ERA reanalysis data winds, 1960–2004.

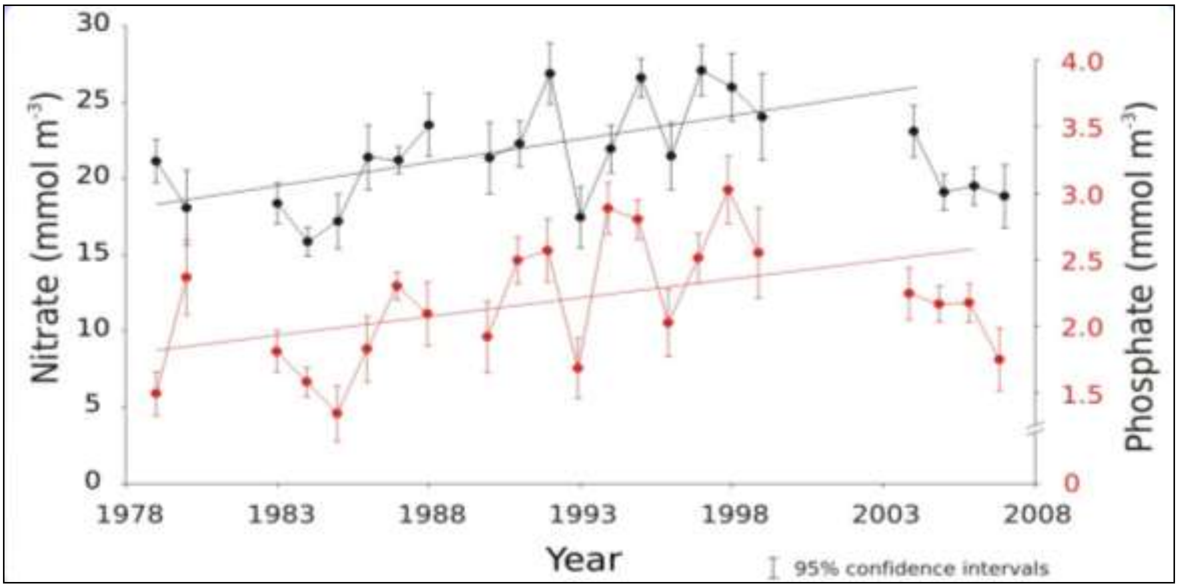


Figure 3.11 Changes in nutrients in sub-thermocline waters, St Helena Bay, 32ºS, 1978–2008.

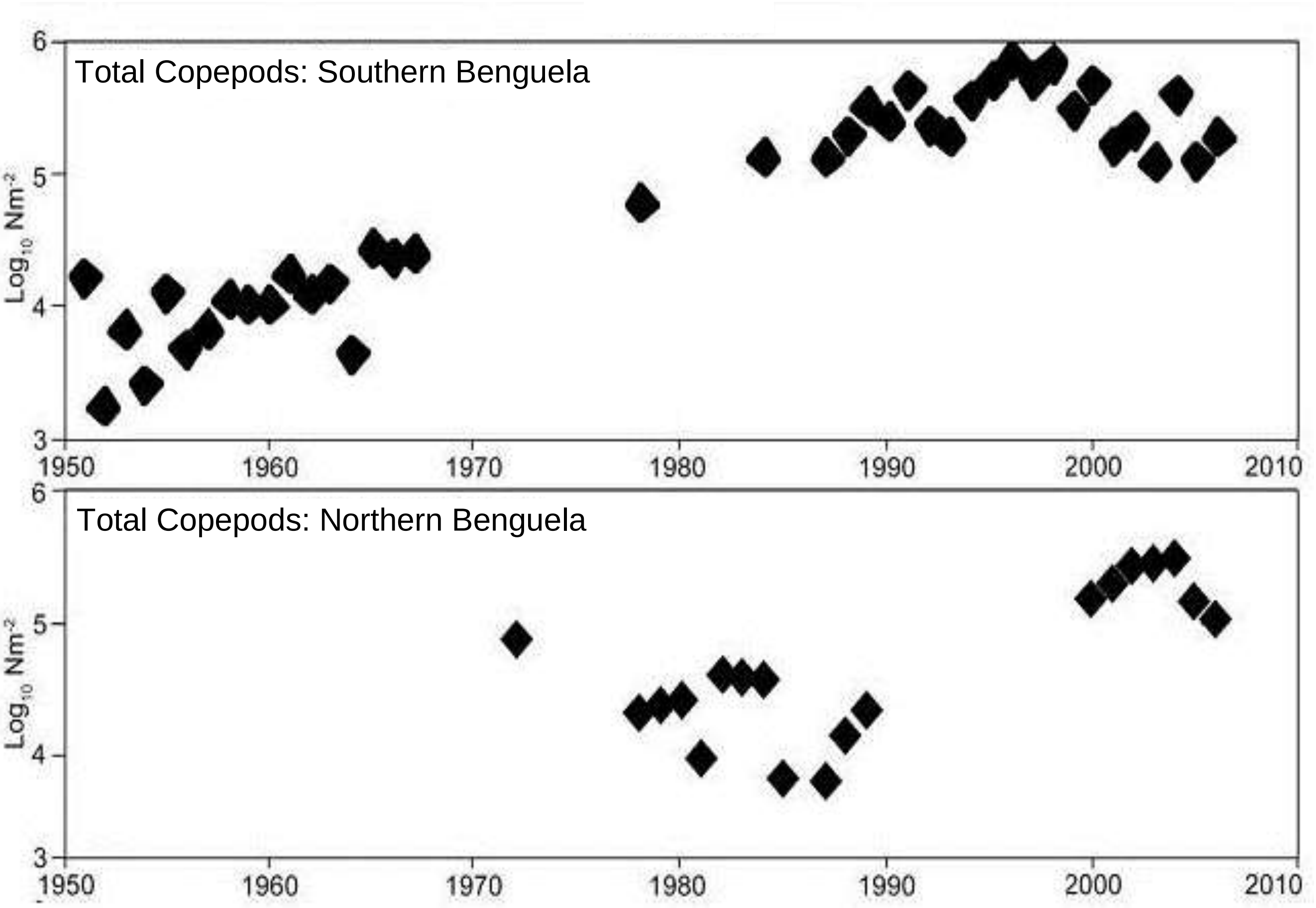


Figure 3.12 Upper: Changes in the total copepods (log$_{10}$nos.m^{-2}) in the Walvis Bay region (23ºS), 1970–2007; Lower: Changes in the total copepods (log$_{10}$nos.m^{-2}) in the St Helena Bay region (32ºS), 1950–2007 (from Verheye et al, 1998), showing 10–100 fold increase in copepods in both the northern and southern Benguela.

3.2. FISHERIES RESOURCES

The fisheries in southern Africa (Figure 3.13) comprise a diverse group of sectors, with benthic, demersal, midwater and pelagic components. Major resources include bottom-trawled Cape hake, the most valuable resource and second in volume or tonnage to the pelagic fishery, which targets principally sardine and anchovy. Other resources include rock lobster, with two species dominant on the west and south coast respectively; squid, largely on the Agulhas Bank; linefish and a midwater fishery for horse mackerel; as well as a number of minor resources. In a mature fishery such as South Africa's, most resources have been harvested over prolonged periods of time, with rock lobster harvested for more than 100 years, and most are exploited at maximal or optimal rates, although some inshore fisheries, such as abalone, linefish and rock lobster, have been overexploited. It is often difficult to distinguish fishery effects from natural variability in the time series, particularly when there is inherent high variability in recruitment rates of young fish, driven principally by environmental effects on early life history stages. In addition there are predator-prey linkages, changes in fishing effort and targeting, and changes in distribution of particular resources. Van der Lingen et al. (2006) and Hutchings et al. (2009) reviewed changes in fishery resources in South Africa and Namibia over the past decades. In contrast with South Africa, yields in the Namibian fishery have declined over recent decades (Figure 3.13), with sardines declining to low levels and remaining low, while sardines recovered in the southern Benguela in the 1990s. Hakes declined in the entire Benguela region under heavy international fishing pressure but recovered somewhat after the declaration of the EEZ, in South Africa in 1977 and in Namibia in 1990 (Figure 3.13). Hake in the southern Benguela do not indicate any major distributional shift over the period 1986–2001 but a longer data series is required.

Deep water hake appear to have moved northwards into Namibian waters as far as 17ºS in the 1990s.

Pelagic catches have remained within a relatively narrow range of 300 000 to 600 000 tons p.a. in the southern Benguela (Figure 3.13), but there have been major changes in species composition, with sardine and horse mackerel dominating in the period 1950–1964, followed by anchovy dominance from 1966 to the mid 1990s and a mixture in the 2000s.

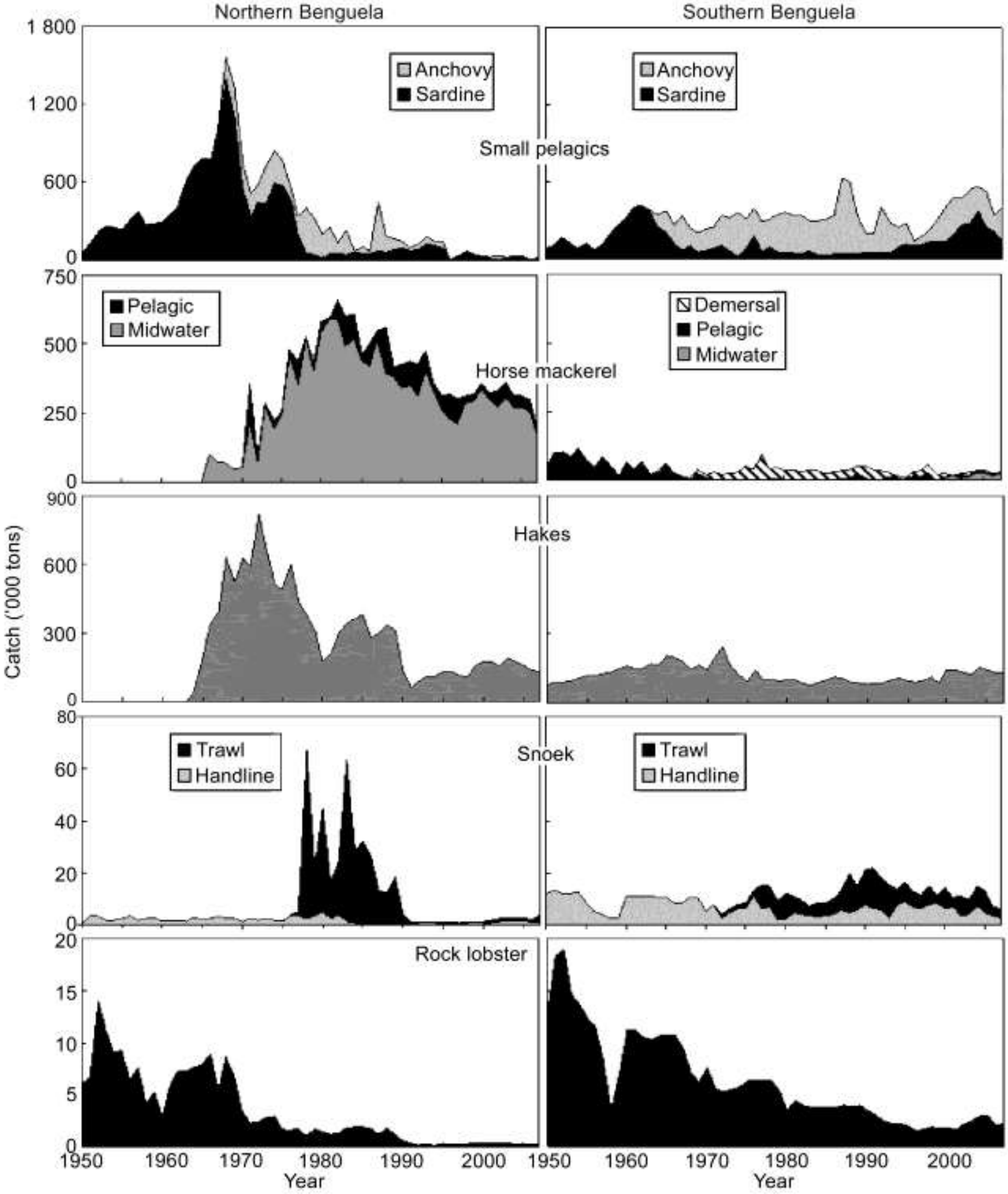


Figure 3.13 Changes in catches of major fish resources in the northern and southern Benguela, updated from van der Lingen et al. 2006. Catches are closely linked to biomass trends.

This effect was complicated by an eastward shift, past Cape Agulhas, of both sardines and anchovy during summer months (Figure 3.14). However, a sign of a westward shift of sardines is apparent from surveys in 2007 and 2008. The recruitment of anchovy, which spawn in midsummer, appears less deleteriously affected by the eastward shift than sardine, which have experienced five consecutive years of poor recruitment and have subsequently declined from more than 4 million tons in 2002 to approximately 10% of that in 2008 (Figure 3.15).

Cape rock lobster, *Jasus lalandii*, a slow-growing species, show a general decline throughout the Benguela, due to heavy, sustained fishing pressure on slow growing stocks (Figure 3.16). A change from shallow water hoopnets to traps allowed access to deeper dwelling offshore stocks, but did not halt the decline toward very low levels of abundance. Both low oxygen trends and wave action are additional important factors affecting catchability. There has been a shift in rock lobster landings from the west coast towards more southerly grounds in recent years (Figure 3.17). This can be attributed partly to the sustained heavy fishing pressure on the west coast, but also to a decline in oxygen levels on the west coast over recent decades (Figure 3.9), which would impede growth and which has also resulted in an increase in the number of mass walkouts, or strandings (Cockroft et al. 2008) that have partially depleted the breeding population on the west coast. The southerly shift in rock lobsters has resulted in decreased sea urchins and hence juvenile abalone mortality in the south as the shelter provided to abalone by the urchins vanished.

Horse mackerel appear currently to be the dominant planktivore in the northern Benguela (Figure 3.13), while the roles of jellyfish and gobies are not clear in terms of changes in biomass and distribution. Horsemackerel in the southern Benguela are currently a relatively minor fishery.

Seal pup numbers can be used as a proxy for the adult population estimation (Figure 3.18): numbers have risen in the whole Benguela region since the 1970s, with periodic mortalities and subsequent recoveries in the northern Benguela and a stable population in the southern Benguela since the 1990s. Certain coastal seabirds, such as crowned cormorant (Figure 3.19) and Hartlaubs gull, appear to have shifted their distribution eastward, possibly in response to the cooling water along the south coast of South Africa (Figure 3.19).

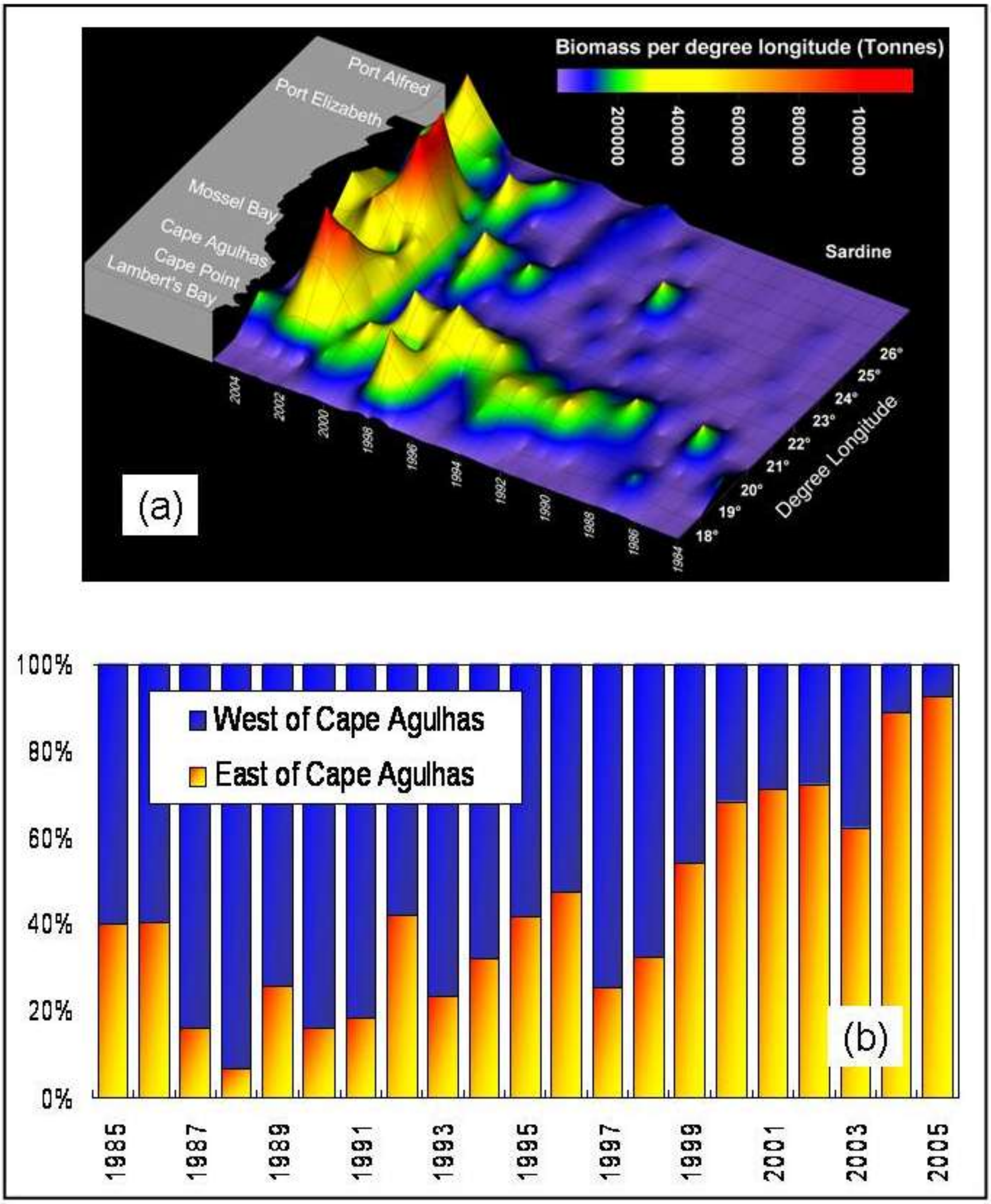


Figure 3.14 Shifts in pelagic fish distribution from west of Cape Agulhas (20ºE) to east of Cape Agulhas (from Coetzee et al. 2008)

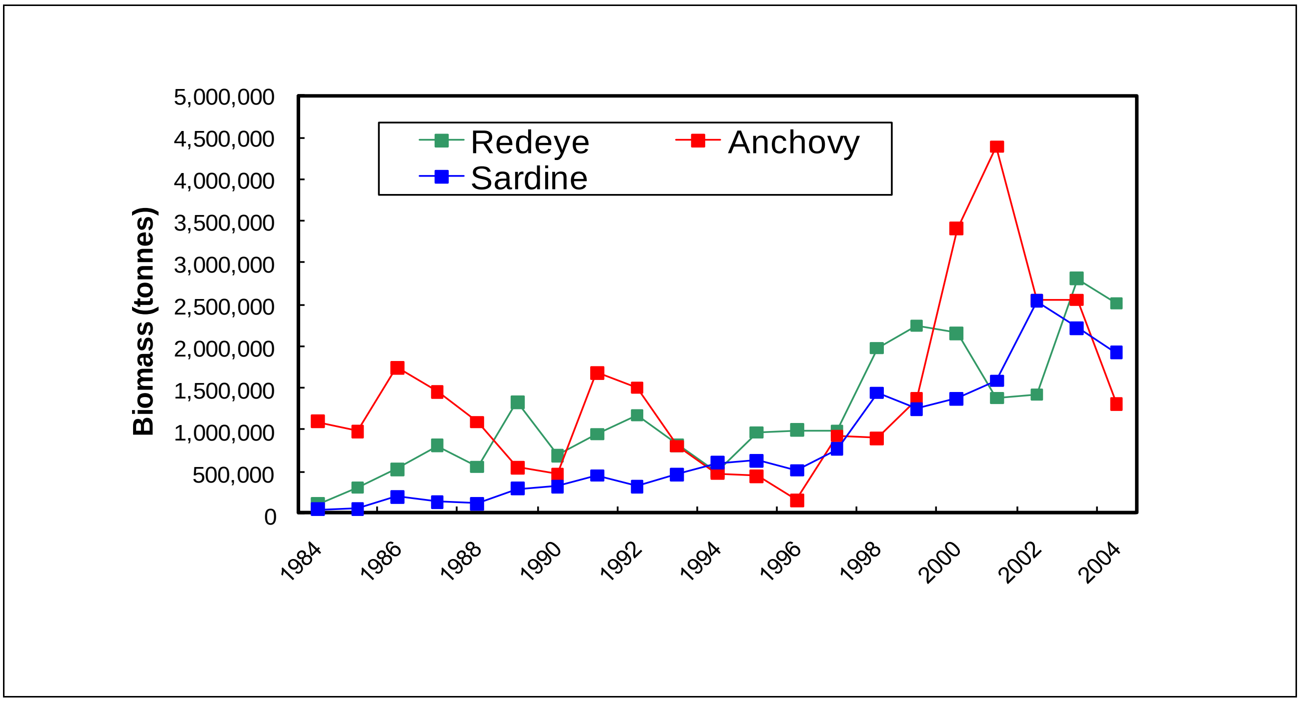


Figure 3.15 Pelagic fish biomass series from acoustic surveys, 1984–2005.

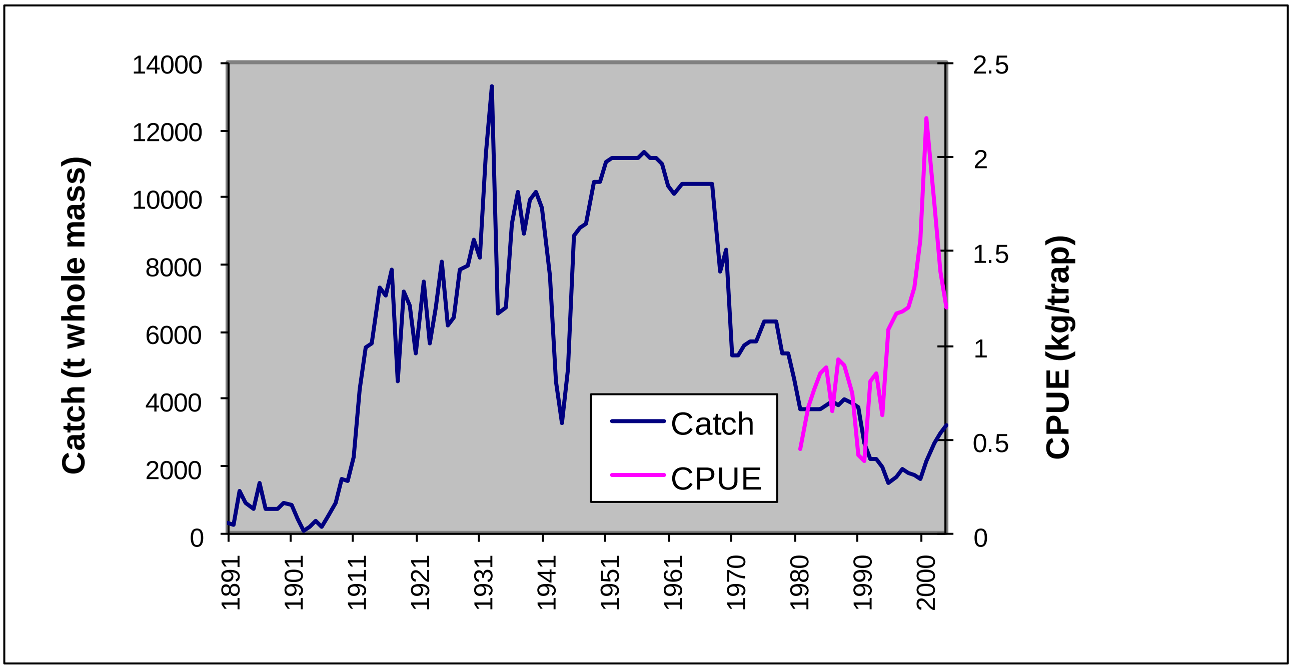


Figure 3.16 West Coast rock lobster landed catch (tons whole mass) and area-aggregated standardized trap CPUE normalized to the mean, 1891–2004.

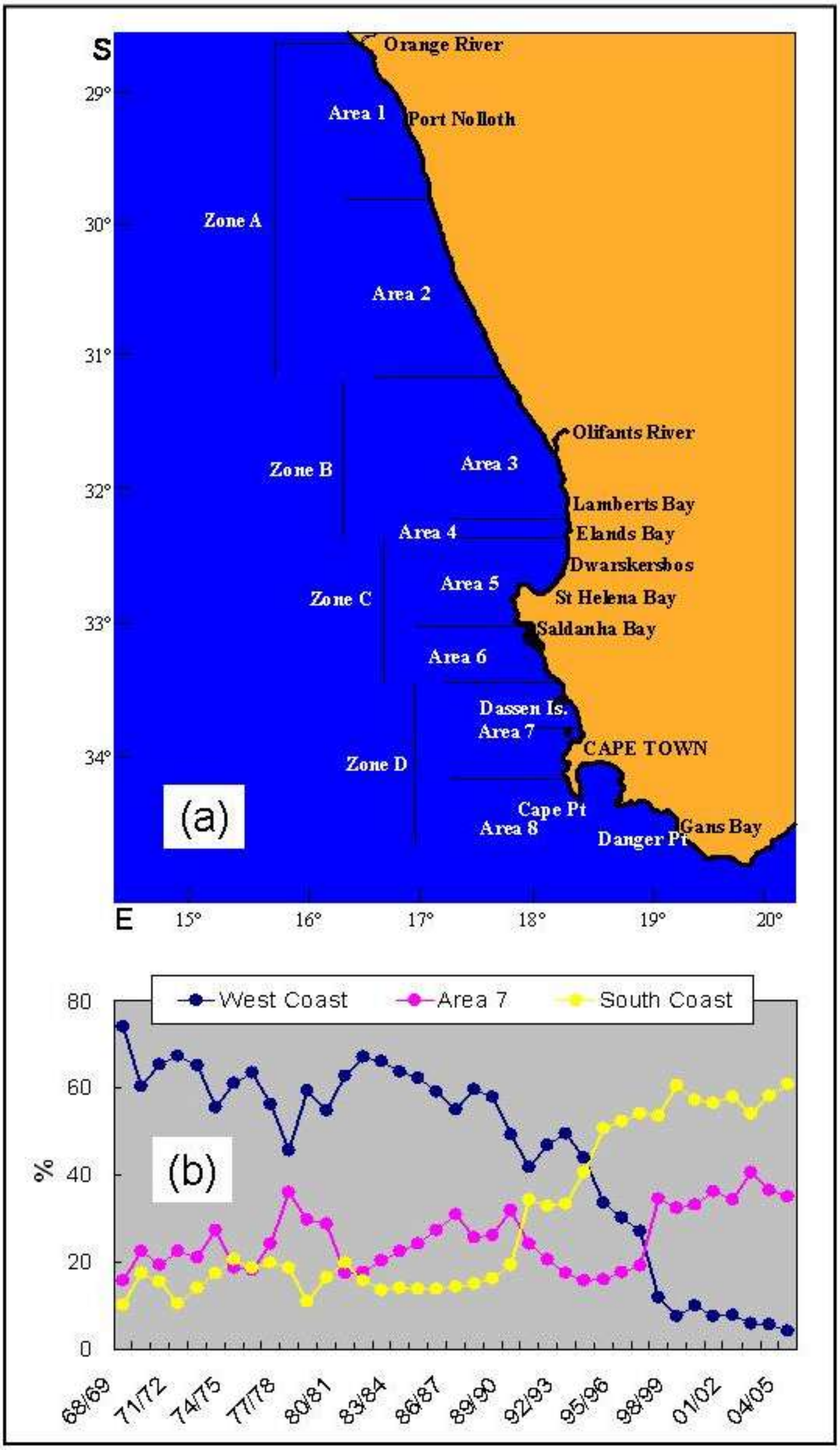


Figure 3.17 (a) Rock lobster fishing zones and areas; (b) proportion of the catches from the west coast (areas 1–6), Area 7 and the south coast (area 8), showing southwards and eastwards trends in the distribution of rock lobsters as far as Danger Point, after Cockcroft et al. 2008.

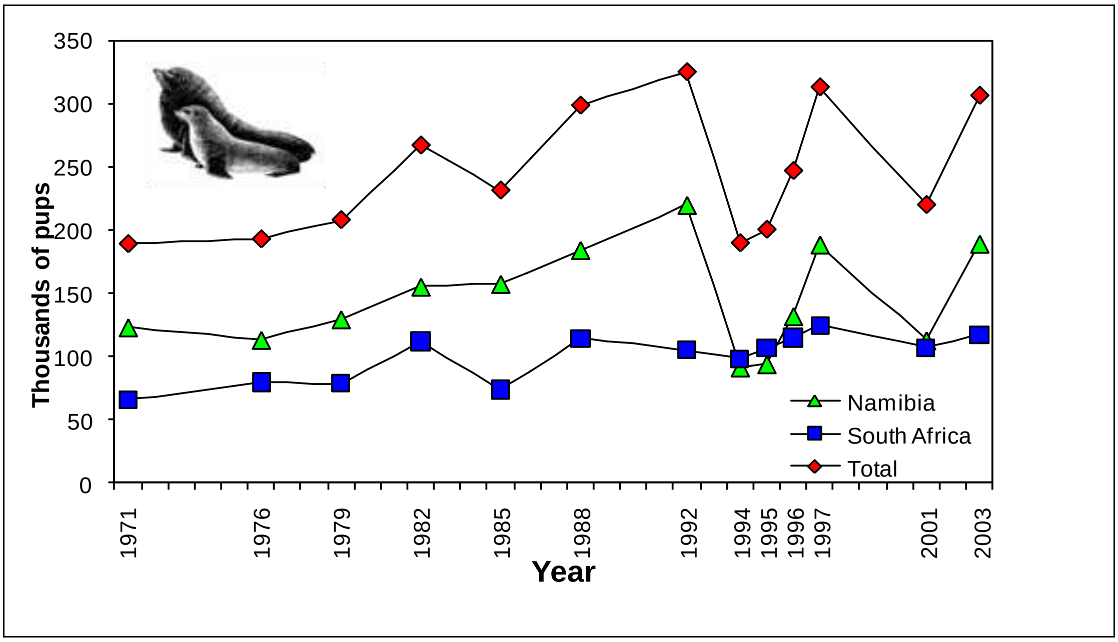


Figure 3.18 Changes in seal pup numbers, 1978–2003 (From Kirkman et al. 2007)

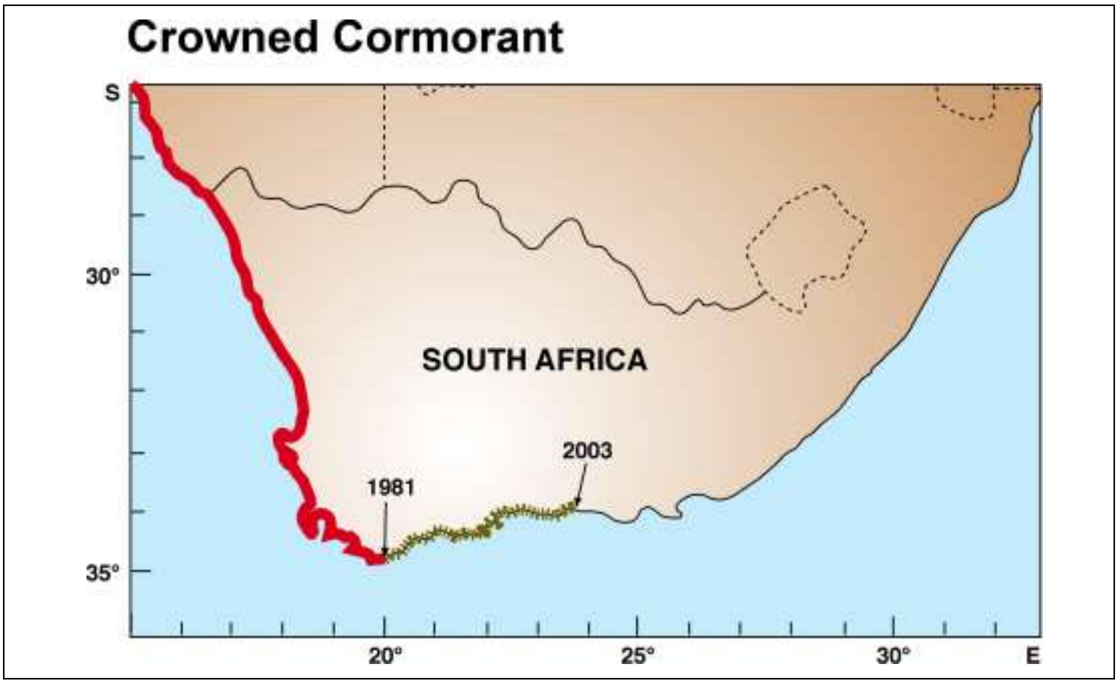


Figure 3.19 Eastward distribution shift of crowned cormorant.

Example of major factors affecting variability in the Benguela

Fishing effects

- Decline in rock lobster.
- Decline in sardines in 1960s.
- Decline and recovery in hake.

Ecosystem interactions

- The lack of recovery of sardines in Namibia (horse mackerel, predators, competitors).
- Zooplankton decline in St Helena Bay, 1995–2006, as pelagic fish biomass increases.
- Changes in gannet and penguin populations in Namibia and South Africa.

Poor indicators

- Hake distribution.
- Seal distribution.
- Satellite-derived phytoplankton distribution.
- Pelagic fish abundance.

Indicators of decadal variability

- Winds and temperature.
- Mixed layer temperatures in the South Atlantic.
- Movements of the Angola–Benguela front.

- Oxygen levels in Namibia.
- Sardine egg distribution.
- Pelagic fish distribution.

Evidence for trends, 1950–2008

- The decrease in subphotic oxygen levels in St Helena Bay.
- The increase in southerly winds.
- The increase in nitrates and phosphates.
- The increase in SST in the north and south of the region with cooling inshore.
- The increase in copepods in St Helena Bay.
- The southward distribution shift and decline of lobsters.
- The eastward shift in bird distribution.

3.3. CHANGES IN THE BENGUELA, BASED ON THE BCLME CLIMATE CHANGE WORKSHOP, MAY 2007

To address the problem of climate change in the marine environment in southern Africa, a workshop was convened under the auspices of the Benguela Current Large Marine Ecosystem (BCLME) in 2007. Forty experts gathered to discuss the changing state of the Benguela ecosystem: the patterns in long-term data sets, the possible drivers of change, the consequences for living marine resources and the prospects of adaptation or mitigation in terms of social and economic consequences. A key outcome of the meeting was that conditions in the large ocean basins surrounding southern Africa play an important role in changing not only the marine resources in the coastal regions, but also terrestrial rainfall and weather patterns over the entire region. A fuller description of the scope of the workshop is available as Appendix 1.

3.4. ADAPTATION AND MITIGATION ASPECTS IN THE MARINE ECOSYSTEM IN SOUTH AFRICA

3.4.1. INTRODUCTION

Fishing is one of the last remaining hunter-gatherer activities practised on a large scale on free-living wild organisms, albeit with a great deal of sophisticated technology. Fishing ranges from simple subsistence fishing with gill-nets, traps and hook and line through to heavily industrialized activities. The sophisticated offshore fisheries are:

- Capital-intensive ventures: where there is high investment in plant and equipment (factories, vessels, net-hauling gear).
- Fossil fuel-intensive: for large vessels that go considerable distances to locate fishable concentrations of target species, which have to be caught by trawling or purse-seining using large nets.
- Energy intensive: Once caught, the large tonnages of fish have to be chilled, frozen or transported rapidly back to port for processing and onward sale, with significant energy consumption implications.
- Labour-intensive: in that considerable effort has to be undertaken to catch and process fish and products to prepare them for market, often conducted at sea under hazardous conditions.

There is a range of intermediate fisheries where smaller vessels are used for a huge variety of activities including longlining, trap fishing, poling fish and hook and line techniques, but in all cases motorized vessels are used with significant fossil fuel consumption. In most cases, fishing produces large quantities of protein *without* using a great deal of scarce fresh water, an important consideration where rich fishing grounds are adjacent to a dry hinterland.

3.4.2. ADAPTATION

Generally, fishers are opportunistic and individualistic, and they continually adapt to changing environmental conditions using a combination of skill, experience and increasingly sophisticated electronic and mechanical technology. They are therefore “pre-conditioned” to adapt to climate change. In general, there is often too much fishing effort or power and too many fishers chasing too few fish, as the ever-increasing population creates a market demand that exceeds sustainable yields from the ocean. More than half the world’s fish stocks are fully exploited or have collapsed, and many are sustained on a subsidized basis. In South Africa the situation is a bit better than the average, in that offshore fisheries such as hake, squid, South Coast rock lobster and pelagic fish are in reasonable shape (but naturally variable), while inshore fisheries, such as rock lobster, linefish and abalone are in varying states of overexploitation, with much reduced yields relative to a few decades ago.

A number of relatively recent innovations in fisheries management have occurred, designed to mitigate some of the deleterious effects of fishing. These include the Ecosystem Approach to Fisheries, the Code of Conduct for Responsible Fisheries and individual quota rights. These measures are in addition to classic measures such as Total Allowable Catch (TAC) or global quota, fishing effort and gear limitations and closed seasons. In essence, these measures are designed to introduce sustainability in yields and resilience in both fishing companies and fish stocks to interannual and long term variations in environmental conditions. Decadal or large scale shifts in climate can alter yields and distribution of fish over prolonged periods and may improve or decrease fishing success. Climate change is therefore implicit in adaptive management of resources, where fishing rights are given for prolonged periods but interannual yields may vary with prevailing environmental conditions.

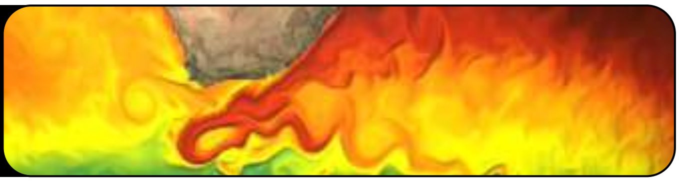
The number of rights-holders is a compromise between the total yield of any resource and the economic viability of the individual right holder, with considerable debate as to the large vs small entitlements, which are reflected in the investment needed to operate a fishing venture. The most important adaptation strategy is to limit “Olympic fishing”, whereby individuals compete to land most fish in the shortest time, and to reduce fishing effort to rational limits, which thereby restrict over-investment in vessels and processing plants.

3.4.3. MITIGATION

As fuel is a huge factor in costs, most fishing companies continually strive to reduce fuel use, using a number of techniques:

- Most vessels have changed to fuel efficient engines and electrical generators, significantly reducing consumption.
- Demersal trawling has shifted to new mesh materials and “square mesh” panels, which reduce drag and improve escapement of undersize fish.
- Vessels are fitted with governors to limit maximum speeds.
- Fishing takes place preferentially on the fish aggregations closest to the processing ports.
- Cooperative fishing takes place where a few search vessels make experimental catches and notify the bulk of the fleet when aggregations are detected.
- Some activities embrace both adaptation and mitigation, even if not always economically successful: Factories have traditionally been built on the west coast, where fish were most abundant, but the eastward shift of sardines in 2001 resulted in expensive road trucking of chilled sardines from Mossel Bay to the factories on the west coast, a distance of approximately 600 km, for a number of years. This had huge cost implications for the industry. A factory was finally erected at great expense in Mossel Bay, but the prolonged EIA process and strong local objections delayed the process for two crucial years and the sardines have not only decreased in the area but also shifted westwards again, causing serious economic stresses for the investors.
- With a sharp decrease in the South African sardine population, sardines are being sourced elsewhere, in other upwelling areas such as Morocco and potentially Mexico, transported to Thailand for canning and finally sold under a local label to preserve the brand name, which has been built up over decades and is crucially important for market retention. There is a decrease in local fishing effort and fuel directed at the sardine but this is offset by increased international transport cost as “food miles”. This is typical of many fish products globally and is an inevitable result of highly variable resources, such as sardine, from any one region.

4. THE AGULHAS CURRENT SYSTEM AND CLIMATE CHANGE



Johann Lutjeharms

The Agulhas Current is the major western boundary current of the Indian Ocean. It is unique in this current family in flowing along a continent that terminates at a relatively low latitude (Figure 4.1) thus allowing leakage from this current to penetrate the adjacent South Atlantic Ocean, and thus completing part of the global thermohaline circulation (Lutjeharms, 2006). It is unique in a number of other ways as well.

The Agulhas Current is driven by the wind stress curl over the South Indian Ocean, but is influenced by a special set of perturbations not found elsewhere. Eddies formed in the Mozambique Channel and south of Madagascar (Figure 4.1) trigger solitary meanders, called Natal Pulses, in the trajectory of the current.

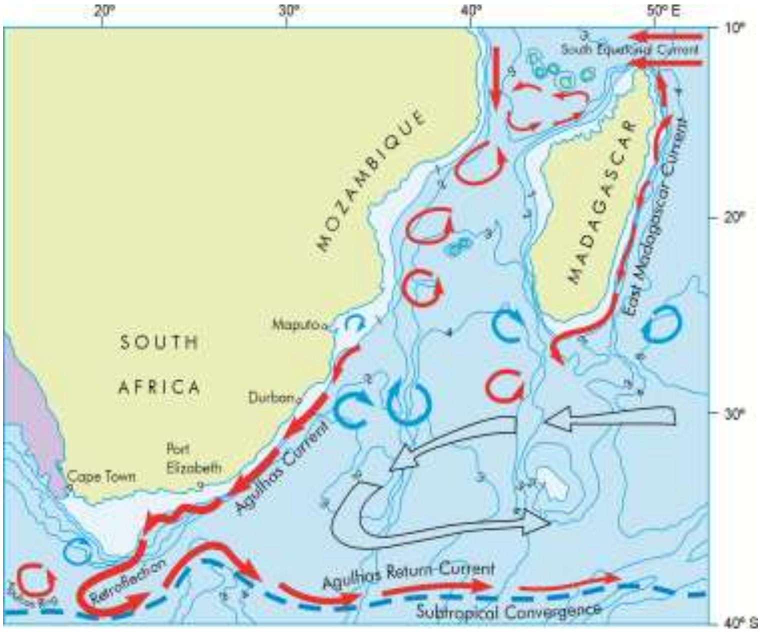


Figure 4.1 A pictorial representation of the key elements of the Agulhas Current system (after Ansorge and Lutjeharms 2007). Red arrows indicate warm currents and anticyclonic eddies. Blue arrows denote cyclonic eddies, and open arrows the average wind-driven circulation. Inflow to the Agulhas Current proper is largely due to the southwest Indian Ocean gyre; outflow is in the Agulhas Return Current along the Subtropical Convergence and in the occasional Agulhas Ring. Perturbations to the flow of the Agulhas Current are due to eddies coming from the Mozambique Channel and from south of Madagascar.

These Natal Pulses in turn trigger the occlusion of the Agulhas retroflection loop downstream, thus shedding anomalous amounts of heat and salt into the South Atlantic Ocean (Figure 4.2) through the creation of Agulhas Rings. In the southeastern Atlantic these rings are mostly destroyed by interaction with other rings and with Cape Cyclones in the Cape Basin. Those that survive the meso-scale turbulence in the Cape Basin eventually cross the Walvis Ridge and may move all the way to the coast of South America, slowly winding down and distributing their extra salt and heat across the subtropics of the South Atlantic. It has been shown that the motion of Agulhas Rings totally dominates the flow in the southeastern Atlantic Ocean with the contribution by the Benguela Current being negligible. There does not seem to be any clear evidence that Agulhas Rings directly influence the Benguela upwelling system along the coast (Figure 4.2). The Agulhas Current does, however, have an influence on local rainfall as well as on the global thermohaline circulation. With climate change these influences might well be modified.

4.1. INFLUENCE ON LOCAL RAINFALL

As might be expected from the contrast in temperature between the waters of the Agulhas Current and the overlying air, the current has a marked influence on the local atmosphere (e.g., Lee-Thorp et al. 1998). This influence can at times make a major difference to terrestrial synoptic systems (Rouault et al. 2002, Singleton and Reason

2007) enhancing their intensity. It has in fact been shown (Jury et al. 1993) that the mean distance of the Agulhas Current offshore is directly implicated in the level of coastal rainfall. Apart from these very local and coastal effects, the Agulhas Current system and sea surface temperatures in the South West Indian Ocean have been shown to influence regional atmospheric circulation patterns and attendant rainfall patterns (e.g., Reason and Godfred-Spenning 1998, Reason and Mulenga 1999, Reason 2001). Furthermore, Rouault et al. (2009) have shown that decadal warming of the Agulhas Current is entirely possible and has occurred. The question thus arises as to how the relationships between current and local rainfall will change under conditions of climate change.

A number of possibilities are obvious (e.g., Lutjeharms and de Ruijter, 1996). First, a significant warming of surface water of the Agulhas Current could lead to an increase in moisture flux to the atmosphere and therefore a bigger impact on coastal synoptic systems. Increased rainfall over this coastline could have significant ecological impacts, both terrestrial and marine, the latter through modified estuarine conditions.

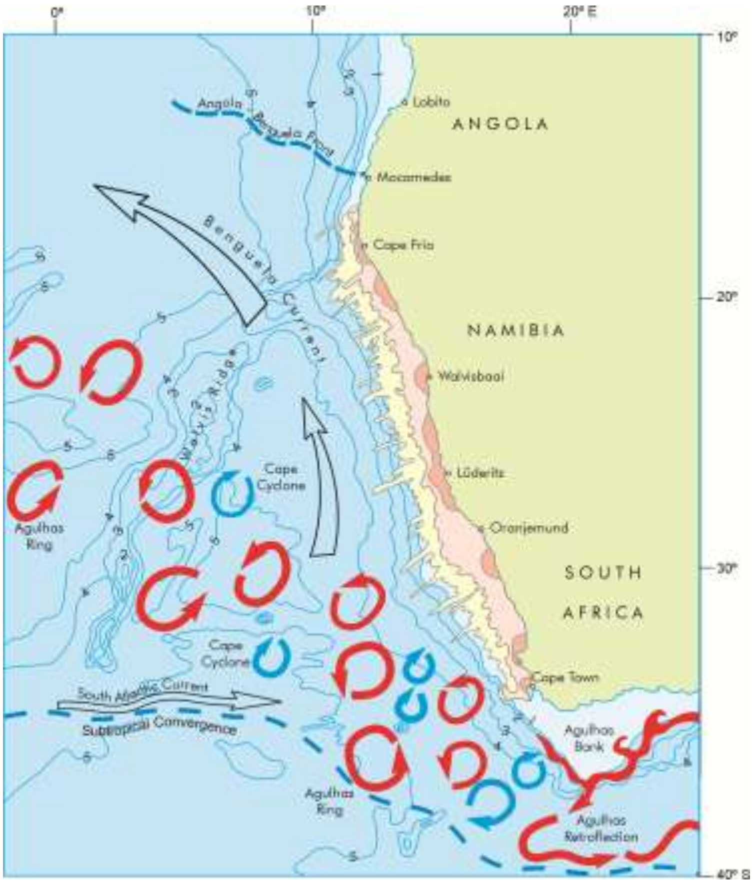


Figure 4.2 A pictorial representation of the influence of products of the Agulhas Current on the Benguela Current and environment. Red circles denote anticyclonic Agulhas Rings; blue circles cyclonic eddies, largely Cape Cyclones. Wind-driven coastal upwelling is shown from Cape Town to Cape Frio with recognised upwelling cells shown in darker pink.

Second, a change in wind stress over the South Indian Ocean could lead to an increase in the frequency of Natal Pulses. A substantial increase of this kind would imply that the average distance of the Agulhas Current offshore would be increased, leading to a decrease in the rainfall along this coastline. However, the relationship between the ocean-wide wind stress and the incidence of Natal Pulses is not understood so that these climate change scenarios have to remain entirely in the realm of speculation.

4.2. INFLUENCE ON GLOBAL CLIMATE

Of much greater importance than regional rainfall and its variability is the influence of the Agulhas system on global climate. It has been known for some time (e.g., Gordon 1986) that the Agulhas Current is a key component in the global thermohaline “conveyor belt”, as is the Agulhas leakage brought about largely by Agulhas Rings. It has been demonstrated (Weijer et al. 1999) that changes in this leakage can lead to changes in the meridional overturning circulation of the Atlantic Ocean, a recognized key climatic variable. Modelling studies by Biastoch et al. (2008a) have indicated the plausibility that the influence of the Agulhas leakage on this meridional overturning of the Atlantic Ocean is comparable to the estimated fluctuations derived from the Labrador Sea. How could such changes come about?

Various options present themselves. Based on their simulations, Van Sebille et al. (2009) have proposed that a weakening in the Agulhas Current leads to more inter-ocean leakage. By contrast Rouault et al. (2009) have indicated that a strengthening of the wind stress curl in the South Indian Ocean has led to an increase in intensity of the Agulhas Current and an increase in inter-ocean exchange. This may also be due to a poleward shift of the westerlies over the South Indian Ocean (Biastoch et al. 2009). It has furthermore been suggested that this shift in wind patterns is anthropogenically induced and already a sign of current climate change. However, there is a decided complication: it has been shown (Biastoch et al. 2008b) that it is the mesoscale perturbations in the Agulhas system, mentioned above, that control the inter-ocean exchanges south of Africa. This means that modelling the possible changes in this process due to global climate change will be considerably complex. But how important are such changes? Answers may come from palaeoceanography.

4.3. POSSIBLE IMPACT OF CLIMATE CHANGE

Peeters et al. (2004) have shown, using sediment cores, that there was a peak in Agulhas leakage at the end of each of the last five glacial periods. It is still unclear what is cause and what is effect in this case. Other studies, however, (e.g., Rau et al. 2002) have indicated that although the Agulhas leakage has undergone significant changes over the past 450 thousand years, it has never ceased completely. Martínez-Méndez et al. (2010) have in fact demonstrated that over geologic time, increases in salt fluxes via Agulhas leakage have coincided with increases in the intensity of the meridional overturning circulation in the Atlantic Ocean which suggests a mechanistic linking between the two, in line with the numerical simulations mentioned above.

Other studies (Bard and Rickaby 2009, Zahn, 2009) have in turn indicated that with a change in the latitude of the zero wind stress curl in the South Indian and South Atlantic oceans, the equatorward shift in the Subtropical Convergence will close off the inter-ocean leakage south of Africa. So where does all this leave one when planning the required research and resources, better to assess possible climate change and its impacts?

4.4. FUTURE RESEARCH DIRECTIONS

From the above it should seem abundantly clear that the study of the Agulhas system is still relatively immature and that a number of basic problems of understanding the system and the interaction of its diverse components, its normal behaviour, its driving forces and its global impact are still not properly solved. Suggesting scenarios under conditions of climate change for the Agulhas system at present are therefore mostly preliminary and largely inferential. Nevertheless, more studies of sediment cores in the region will inevitably give more reliable indications of the boundary conditions under which the Agulhas system has acted under previous climate change conditions. Numerical models with ever increasing spatial and temporal resolution will allow more reliable experimentation with a range of climate scenarios. This is already planned. However, in most cases there will not be opportunities for verification of such model products and outcomes. As more palaeoceanographic results become available, such verification will increasingly become possible.

International and regional programs have highlighted the importance of the Greater Agulhas Current and, as such, are working to provide a better understanding of the region: two key examples are the Agulhas Somali Current Large Marine Ecosystem and the SCOR (Scientific Committee for Oceanographic Research) Working Group (Beal et al. 2011).

5. TRENDS IN NEARSHORE SEA SURFACE TEMPERATURE AND CIRCULATORY SYSTEMS

Mathieu Rouault & Angela Mead

Between two and five broad coastal biogeographic provinces have been recognized around South Africa, with discrepancies regarding the naming of these areas, levels of dissimilarity between regions, region boundaries and recognition of overlap zones (Stephenson 1939, 1944, 1948, Stephenson and Stephenson 1972, Brown and Jarman 1978, Field et al. 1980, McQuaid and Branch 1984, Emanuel et al. 1992, Stegenga and Bolton 1992, Bustamante and Branch 1996, Bolton and Anderson 1997, Gibbons et al. 1999, Turpie et al. 2000, Bolton et al. 2004, Lombard 2004, Sink et al. 2005). Lombard (2004) synthesized all existing information and through extensive expert input recognized five coastal regions which have been slightly modified for the purposes of this report. The regions are defined by the oceanographic and atmospheric regimes that combine to form the climate within each province. The cool-temperate province (CTP) on the west coast and warm-temperate province (WTP) on the south coast are divided by a broad overlap zone which will be termed transition zone 1 (TZ1). On the east coast, the subtropical province (STP) merges in the north with a tropical province (TP) that extends into Mozambique. There is a second transition zone which exists between the WTP and the STP, which will be termed transition zone 2 (TZ2).

Intertidal marine communities are influenced in part by the near-shore sea surface temperatures (SST) and circulation patterns within each province. In turn, SST and circulation patterns are influenced by seasonal interactions between the cold Benguela and warmer Agulhas Current, both of which rely on regional climate regimes and larger offshore water bodies (McQuaid and Branch 1984, Shannon et al. 1991, Emanuel et al. 1992, Bustamante et al. 1997, Schumman et al. 2005, Rouault et al. 2009).

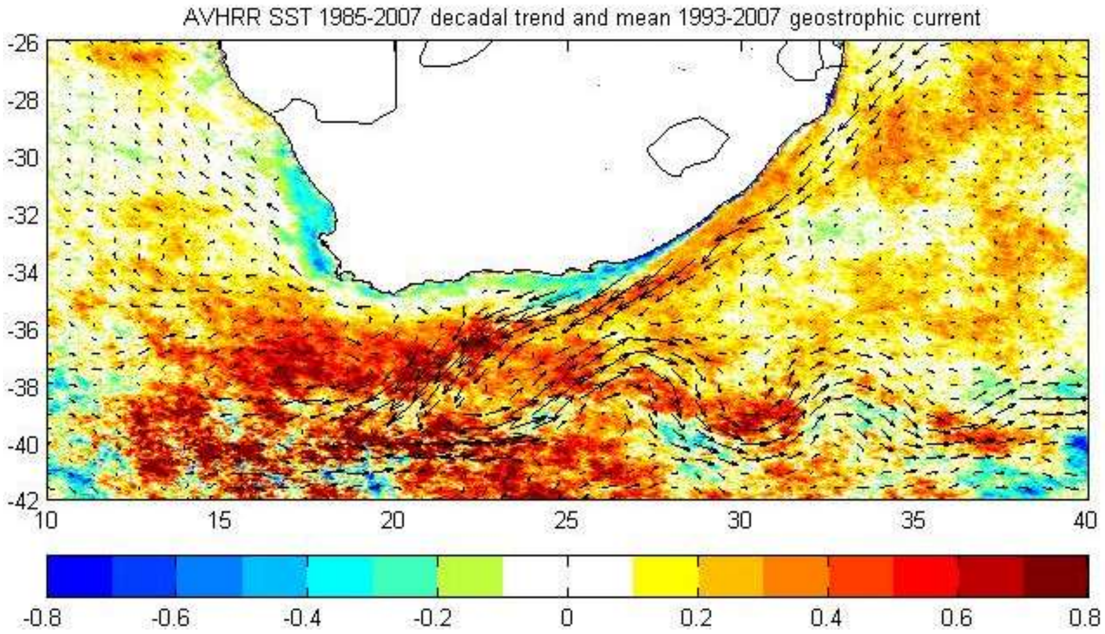


Figure 5.1 Top to bottom: linear trend of AVHRR SST from 1985 to 2007. Mean 1993–2007 absolute geostrophic velocity vectors derived from combined altimetry are superimposed (from Rouault et al. 2009).

Significant large scale temporal shifts in SST or circulatory patterns have the potential to impact intertidal marine community structure and functioning. Figure 5.1 illustrates a 4 km by 4 km resolution linear trend in AVHRR (Advanced Very High Resolution Radiometer) SST in ºC within each region, per decade, between 1985 and 2007. The major change in the region is the warming of the Agulhas Current system due to its intensification in response to changing wind patterns in the South Indian Ocean (Rouault et al. 2009).

The AVHRR data indicates that within the CTP, near-shore SST is cooling between -0.2 to -0.5 ºC per decade. TZ1 is cooling on the west side of False Bay at a rate of -0.5 ºC per decade. There are isolated small scale pockets of cooling in the region Cape Agulhas to Cape St Francis (WTP) of about -0.2 ºC per decade. A larger region of cooling, ranging from -0.2 ºC to -0.7 ºC is evident at Port Elizabeth (WTP), centred in the Port Alfred dynamic upwelling cell. At TZ2 and within the STP, a very thin strip of near-shore water is cooling at a rate of -0.6 to -0.8 ºC per decade as far as Port St Johns. North of Port St Johns, within the TP, near-shore SSTs are warming by +0.2 to +0.4 ºC. Figure 5.2 illustrates linear trends in ºC per decade for each month of the year using optimally interpolated (OI) SST (Reynolds et al. 2002) from 1982 to 2007 for the west coast (CTP), the south coast (WTP), Port Elizabeth to Port Alfred (WTP), Transkei and Durban (TZ2 and the STP). Each domain is averaged over 300 km alongshore and 100 km offshore, thus near coastal trends could actually be larger. The aim of the exercise is to find at what time of the year those changes occurred since 1982. The SST for the Agulhas Current system is also shown. Cooling is evident in both the CTP and WTP, inclusive of the Port Elizabeth/Port Alfred upwelling cell. Cooling trends within this cell appear more pronounced and occur for a longer time period, annually, compared to the remaining WTP. Warming trends are evident for Durban, the Transkei and the Agulhas Current system. Figure 5.3 represents in situ composite data (provided by South African Weather Services) which was used to obtain a monthly linear trend in ºC per decade for Muizenberg, False Bay (within TZ1). The data indicates a substantial cooling that corresponds well to the offshore cooling of the West Coast upwelling system that could have led to more intrusion of cold water into False Bay. Overall, trends evident in the AVHRR, OI and in situ composite data are in agreement with regards to cooling and warming trends within the different provinces and transition zones.

The near-shore cooling is caused by shifts in a range of components that form the overall regional climate. Bakun (1990) hypothesized that intensified alongshore winds due to warming land masses would lead to more frequent, intense seasonal upwelling events. This would bring higher volumes of cold water to the sea surface with more regularity along the eastern boundary upwelling system and explain cooling trends seen within the CTP and TZ1. Indeed, an increasing trend in upwelling intensity has been reported for the Benguela system over the last four decades (Scavia et al. 2002, Shannon et al. 1991). Kruger et al. (2004) have shown that South Africa has warmed up, but this factor alone does not explain the large scale changes in wind speed shown in Figure 5.4. Recently, significant changes to southerly and westerly wind regimes have been reported in South Africa (Reason and Rouault 2005, Rouault et al. 2009). Shifts in westerly wind patterns are a well known feature of global climate change (Trenberth et al. 2007). ERA40 (European Centre for Medium-range Weather Forecast Re-analysis) 1982–2007 linear trends in surface wind speed are shown in Figure 5.4. It is clear, from this data, that upwelling favourable winds have increased in the region. The coastal changes can therefore be explained with a combination of (i) change in wind speed and (ii) intensification of the Agulhas Current system. Both of these effects are being created by a shift of westerly wind and an intensification of the Atlantic and Indian high pressure system (Rouault et al. 2009).

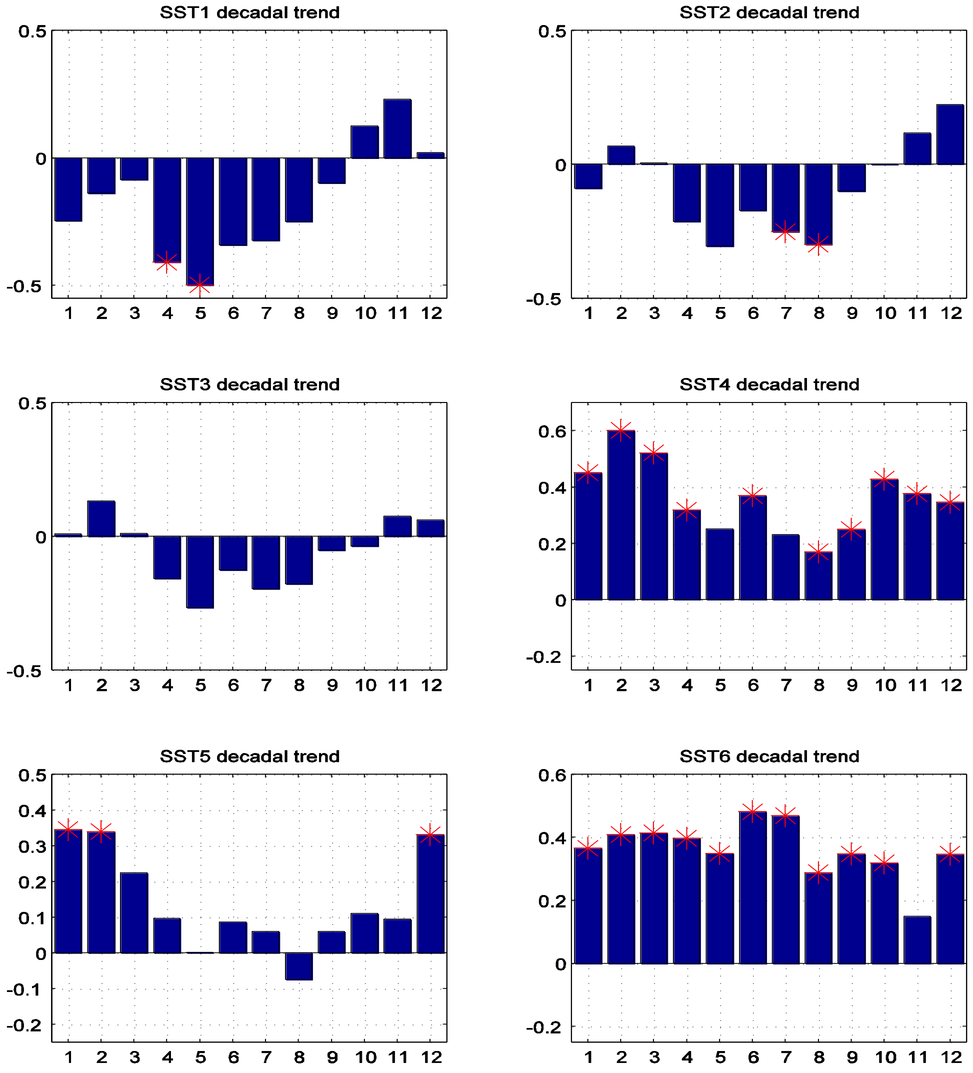


Figure 5.2 From left to right and from top to bottom: linear trend in ºC per decade for each month of the year derived using OI SST from 1982 to 2007 for domain West Coast (SST1), South Coast (SST2), Port Elizabeth/Port Alfred (SST3), Transkei (SST4), Durban (SST5) and Agulhas Current system (domain from 36ºS to 42ºS and 10ºE to 35ºE, SST6). Statistically significant trends are highlighted with a star symbol.

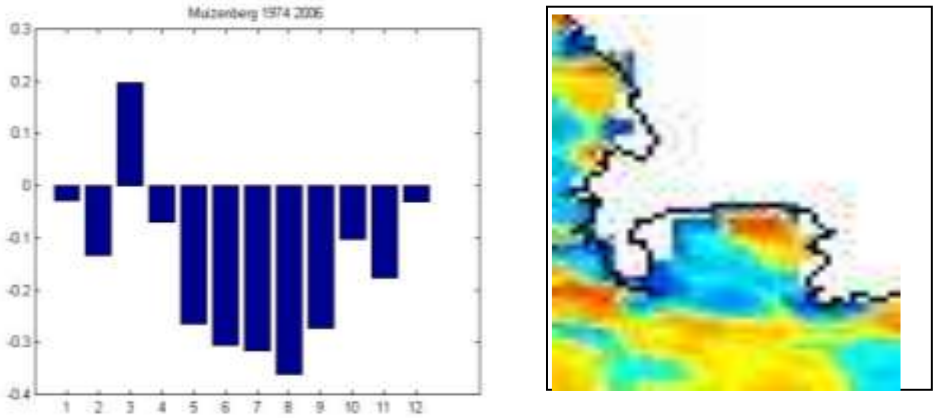


Figure 5.3 From left to right: in situ composite data (obtained from South African weather Services) in ºC per decade for Muizenberg, False Bay, 1974–2006 and corresponding AVHRR data for False Bay (4 km by 4 km resolution linear trend in AVHRR SST in ºC within each region, per decade, between 1985 and 2007)

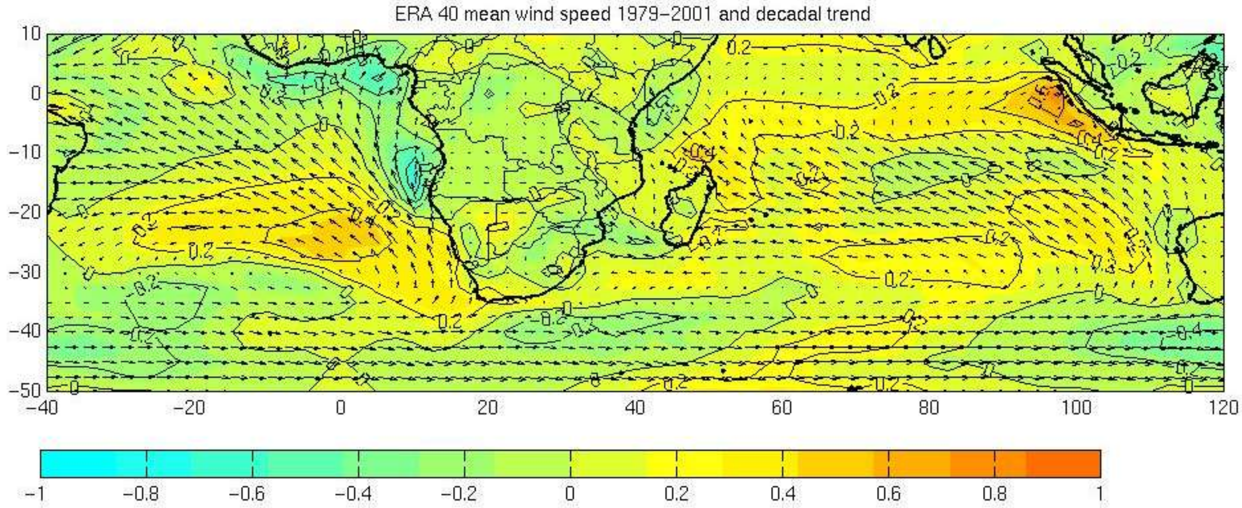


Figure 5.4 ERA 40 1982–2007 linear trends in surface wind speed. Mean wind speed and direction are superimposed (arrows).

To summarize:

- Cooling trends are evident in the CTP and TZ1, caused by an increase in the intensity and frequency of upwelling from April to August.
- Minor cooling is evident along the southeastern coast (WTP) caused by an increase in easterly winds from April to August.
- A cooling trend is evident in the Port Alfred upwelling cell (located within the WTP), caused by a combination of an intensification of the Agulhas Current and an increase in easterly winds. The minor band of coastal cooling that seems to extend as far as Port St Johns within the STP is probably due to intensification of the Agulhas Current.
- Warming in the Agulhas Current system occurs for all months of the year, and warming is evident at the near-shore, north of Port St Johns within the TP.

However, this coastal cooling trend is somewhat contradictory to the trend seen in the change in tropical species distribution, as well as data from Underwater Temperature Recorders in the region, highlighting the need for increased in situ observations and further understanding of the variability and trend in nearshore temperatures.

6. REEF ECOSYSTEMS

Michael Schleyer

6.1. INTRODUCTION

Coral reefs that occur in South Africa within the iSimangaliso Wetland Park (iSiWP), a World Heritage Site in northern KwaZulu-Natal (or Maputaland), have been subjected to extensive mapping for their biodiversity conservation and sustainable use (Schleyer and Celliers 2005, Ramsay et al. 2006, Celliers and Schleyer 2008). They are limited in size but provide a model for the study of many of the stresses to which these valuable ecosystems are being subjected globally (Schleyer and Celliers 2003a). The value of the South African reefs in this regard is partially derived from their marginal nature, as their coral communities constitute the southernmost distribution of this fauna on the African coast. Their marginality is thus attributable to latitudinal and climatic parameters, making them vulnerable to climate change.

Coral bleaching associated with climate change currently constitutes the greatest threat to coral reefs, the causes and consequences of which are reviewed by Hoegh-Guldberg (1999) and Wilkinson (1999). Yet there is cause for hope in the ultimate survival of corals through resilience to bleaching (Hughes et al. 2003). In this regard, McClanahan and Maina (2003) found that climate-related changes on Kenyan coral reefs differed between eurythermal and stenothermal corals. They noted that the former lost little reef structure but diminished in species richness, while the opposite proved true amongst the latter. While one might nevertheless expect global warming to result in a poleward expansion in the distribution of tropical corals, Scavia et al. (2002) suggest that this will not occur due to a reduction in aragonite saturation caused by the greater solubility of CO_2 in cooler waters. These are the factors one might expect to be at play on the high-latitude coral reefs in South Africa.

Impacted East African coral reefs: *Top* - tiered plates of *Montipora* sp; *Middle* - *Galaxea astreata* overun a bleached reef; *Bottom* - free-living fungiid *Halomitra pileus* on a bleached reef.

In considering the effects of climate change on these reefs, Riegl (2003) concluded that they would be minimal, but his projections concurred with those of Schleyer and Celliers (2003a), that reefs at lower latitude may undergo the reduction in reef-framework development found on the South African reefs, providing the latter with their aforementioned value as a research model.

Relevant information is available on the geology (Ramsay 1996), biodiversity (Schleyer 2000), community structure (Riegl et al. 1995, Schleyer 2000, Celliers and Schleyer 2001, Schleyer and Celliers 2005), coral recruitment (Glassom et al. 2006) and climate change effects (Celliers and Schleyer 2002, Schleyer and Celliers 2003a) on these reefs. Soft coral cover, comprising relatively few species, exceeds that of scleractinian cover over much of their surface. While not accretive, the coral communities nevertheless are rich in biodiversity at this latitude on the East African coast (Riegl 1996, Schleyer 2000, Schleyer and Celliers 2005, Celliers and Schleyer 2008).

A long-term monitoring programme was initiated in 1993 in anticipation of the effects, if any, of climate change on these high-latitude coral reefs. This entailed temperature logging and image analysis of high resolution photographs of fixed quadrats on a representative reef (Schleyer and Celliers 2003b, Schleyer et al. 2008). Results of the first 14 years of monitoring have been published by Schleyer et al. (2008), revealing important changes in community structure and population dynamics. A summary of the results is presented in the next section.

Temperate reefs are more extensive on the east coast of South Africa than those associated with coral communities, but have not been studied with respect to the effects of climate change. This is probably because their biota is not considered as vulnerable as corals to global warming. Nevertheless, fairly intensive ecosystem-related research was undertaken in past years on a near-subtidal reef near Durban (Schleyer 1981, Berry and Schleyer 1983), as well as more recent benthic reef surveys on Aliwal Shoal, a submerged rocky massif south of Durban (Schleyer 1981, Schleyer et al. 2006, Olbers et al. 2009). Finally, reefs at the southern end of the east coast were subjected to similar survey work to elaborate their benthic biodiversity and community structure (Celliers et al. 2007). Speculation on the effects of climate change on these temperate reefs, based on the aforementioned studies, follows in the next section.

6.2. CLIMATE CHANGE FINDINGS

The long-term coral monitoring site is located at 27°24'54”S; 32°43'36”E (WGS 84) on Nine-mile Reef (NMR) at Sodwana Bay. The reef is typical of the northern KwaZulu-Natal reefs in its structure and coral growth, having a thin veneer of corals on submerged late Pleistocene beach and dune rock. The morphology of NMR is also typical of many of the Maputaland reefs, consisting of shallow platforms, approximately 12 m in depth, with a few pinnacles, some of which break the surface during low spring tides, and steep drop-offs to the sea floor at 18–22 m along much of the seaward edge.

A pair of Hugrun underwater temperature recorders (UTRs), reading to a minimum accuracy of 0.02 °C, have been installed at the site at a depth of 18 m. These are set to measure temperatures to three decimals every minute but to store only hourly means of the measurements so that long-term records can be accommodated.

Mean, minimum and maximum monthly sea temperatures are presented for the site for March 1994–2006 in Figure 6.1a. A GAM smoothing curve was fitted to the mean sea temperature data (Figure 6.1b). This revealed a period of steady temperature increase up to 2000, when measurable coral bleaching occurred (Celliers and Schleyer 2002). Thereafter, a decline in temperatures became evident, again followed by an increasing trend towards the end of the study period.

For illustrative purposes, simple regressions are provided for the mean temperatures up to and after February 2000 in Figure 6.1a, revealing an increase of 0.15 °C p.a. and subsequent drop of 0.07 °C p.a. respectively. Both trends are significant.

The afore-mentioned bleaching was limited to Two-mile Reef (TMR) and NMR at Sodwana Bay and affected less than 12% of the total living cover. Hard and soft corals were affected, as well as some encrusting, zooxanthellate sponges. High maximum temperatures were measured (>29 °C). The lowest mean monthly and the mean maximum monthly temperatures at which coral bleaching occurred were 27.5 °C and 28.8 °C respectively, while the duration for which high temperatures occurred in 2000 was 67 days at ≥27.5 °C (4 days at ≥28.8 °C). Increased water clarity and radiation appeared to be a synergistic cause in the coral bleaching.

The annual photographs of the long-term, coral monitoring quadrats were merged using Analysis® and standardized using Arcview® GIS to align reference points within each transect; details of this are provided by Schleyer et al. (2008). The area of the coral colonies was measured in the calibrated images using Analysis® and the results were analysed for individual colony growth or attrition. A record was kept of the appearance of new colonies ~2 cm in size within the images, termed recruitment success because these comprised colonies that had successfully survived their early, post-settlement period. Colonies that disappeared from the images were recorded as having died in the preceding year, i.e., mortality.

Significant changes were recorded in the overall coral community structure at the monitoring site, with a slight increase in hard coral cover but a more marked reduction in soft coral cover (Figure 6.2). As a result, there has been an overall reduction in coral cover from 49.7% at the monitoring site in 1993 to 44.2% in 2006. The number of coral colonies measured from year to year (Figure 6.3) revealed a decline in the total and hard coral colonies after 2000, and a uniform decline in soft corals which appeared to reverse at the end of the study period, reflected in turn in the total coral count. Overall changes in coral mortality were not significant (Figure 6.4). However, there was a significant decline in coral recruitment success up to 2004, manifested mainly by the Scleractinia, a result considered important (Figure 6.4). This negative trend appears to have diminished since 2004.

As stated, studies on the temperate reefs have not incorporated a climate change-related focus. On the deeper reefs, they have involved recording of digital images along transects for point intercept analysis to gain information on reef biodiversity and relative cover of benthic biota. The results are nevertheless of interest as a few persistent coral species extend even to these latitudes, despite conditions not being conducive to their success. Such corals, *Stylophora pistillata* being the most conspicuous of this community, have to deal with reduced temperatures and higher turbidity. The southern reefs also share encrusting zooxanthellate sponges with the coral reefs, but they are more abundant in the south. A suite of soft corals is relatively abundant on the deeper temperate reefs and many of these are local or regional azooxanthellate endemics. Climate change-related effects on these reefs are thus unlikely to involve coral bleaching. Bleaching may occur in the zooxanthellate sponges as it did on the coral reefs when bleaching occurred in Maputaland in 2000 (Celliers and Schleyer 2002).

The near-subtidal reefs on the east coast are colonized primarily by the suspension feeders *Perna perna*, *Pyura stolonifera* and *Striostrea margariacea* (Berry 1982). These are dependent on detritus as a food source (Schleyer 1981, Berry and Schleyer 1985). It is difficult to predict what effect, if any, climate change will have on these communities. Range shifts and extensions are likely to occur in the reef communities under consideration with climate change. These have been observed in fish communities, with the gradual appearance of more tropical species on southern reefs (pers. obs. and anecdotal reports); a similar pattern will probably emerge amongst the benthos. The situation is likely to be dynamic, with a pattern of species recruitment, survival and subsequent extinction (Harriot et al. 1994); dominant species will probably remain relatively stable but rarer species will be more transient. Over a protracted time span, a large number of species might be recorded with only a subset present at any one time. Thus, with climate change, the total list of species recorded may increase slowly but the species richness less so. These effects of climate change will impact South Africa’s coral and temperate reefs alike.

A final factor merits consideration. The incidence and severity of storms are likely to increase with climate change, resulting in damage to the reefs and their biota. While local coral communities are adapted to their high energy environment (Schleyer 2000), the Maputaland coral reefs have nevertheless manifested considerable damage after recent devastating storms (pers. obs.).

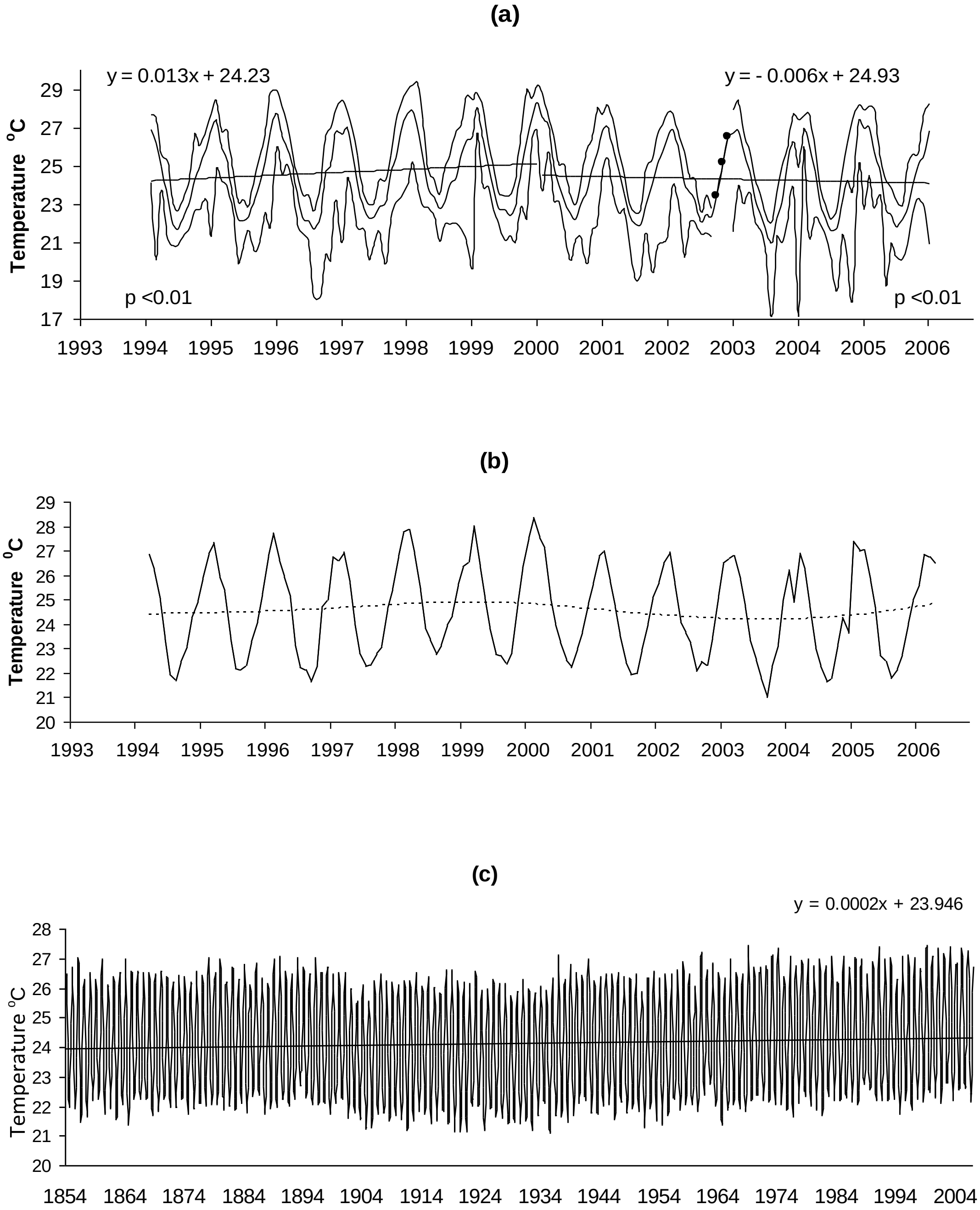


Figure 6.1 a) Mean, minimum and maximum monthly sea temperatures at a depth of 18 m at the long-term monitoring site on Nine-mile Reef, Sodwana Bay. Mean temperatures from 1° x 1° satellite data (Reynolds et al. 2002; http://ingrid.ldgo.columbia.edu/SOURCES/.IGOSS/.nmc/.Reyn_SmithOI.v2/) were used to fill a gap in data recording from November 2002 to January 2003; comparisons with UTR-recorded data on either side indicated a good fit. b) Mean data smoothed with a simple General Additive Model (GAM). c) Regional 2° x 2° ERSST data for 1854–2007 (Smith and Reynolds 2004; http://www.ncdc.noaa.gov/oa/climate/research/sst/sst.html) for 28°S; 34°E. Both sets of temperature data were downloaded from http://iridl.ldeo.columbia.edu/

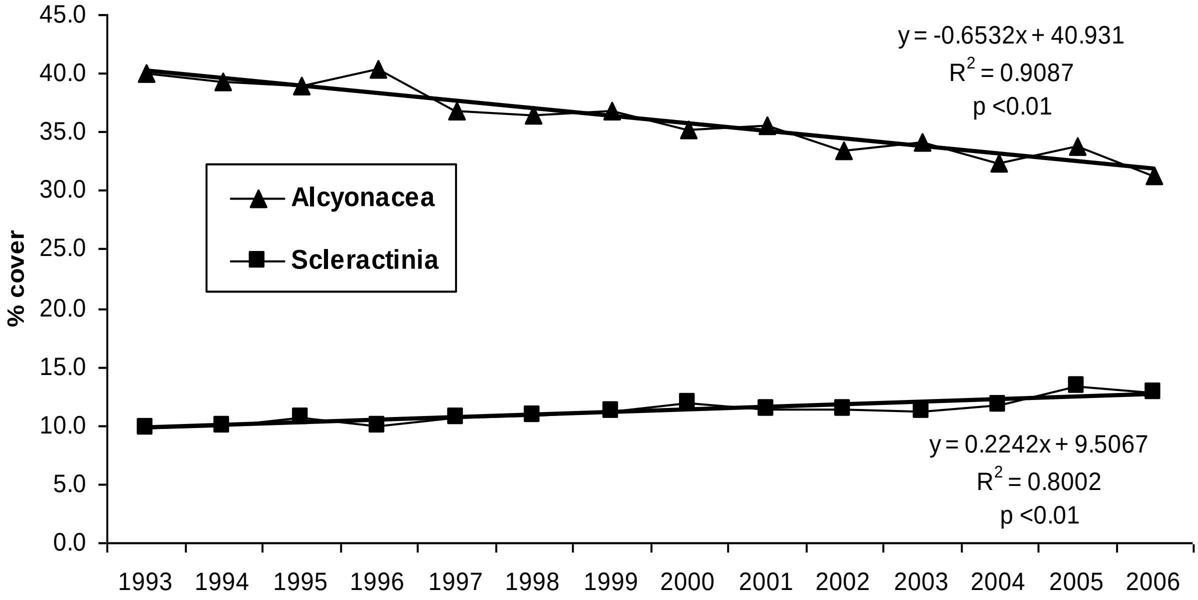


Figure 6.2 Overall changes in alcyonacean and scleractinian cover measured at the long-term monitoring site on Nine-mile Reef at Sodwana Bay from 1993–2006

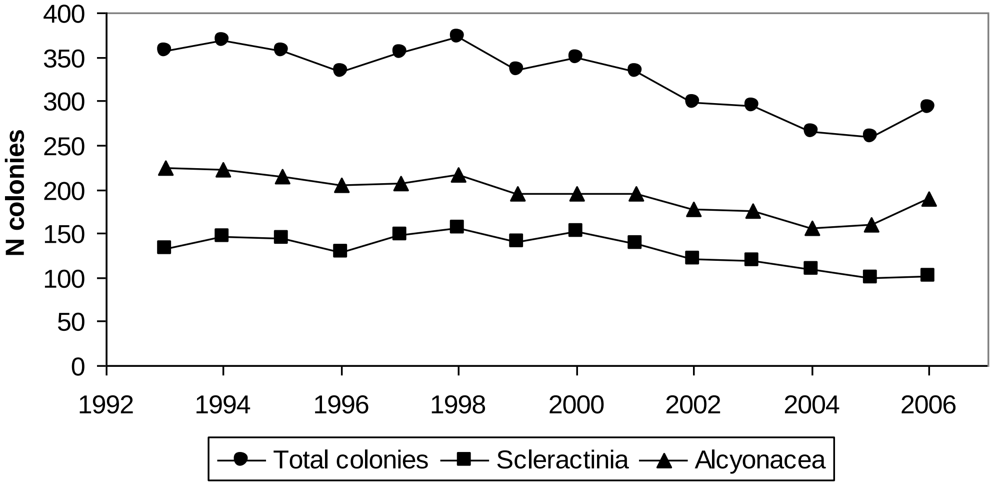


Figure 6.3 Alcyonacean, scleractinian and total number of coral colonies measured at the long-term monitoring site on Nine-mile Reef at Sodwana Bay from 1993–2006

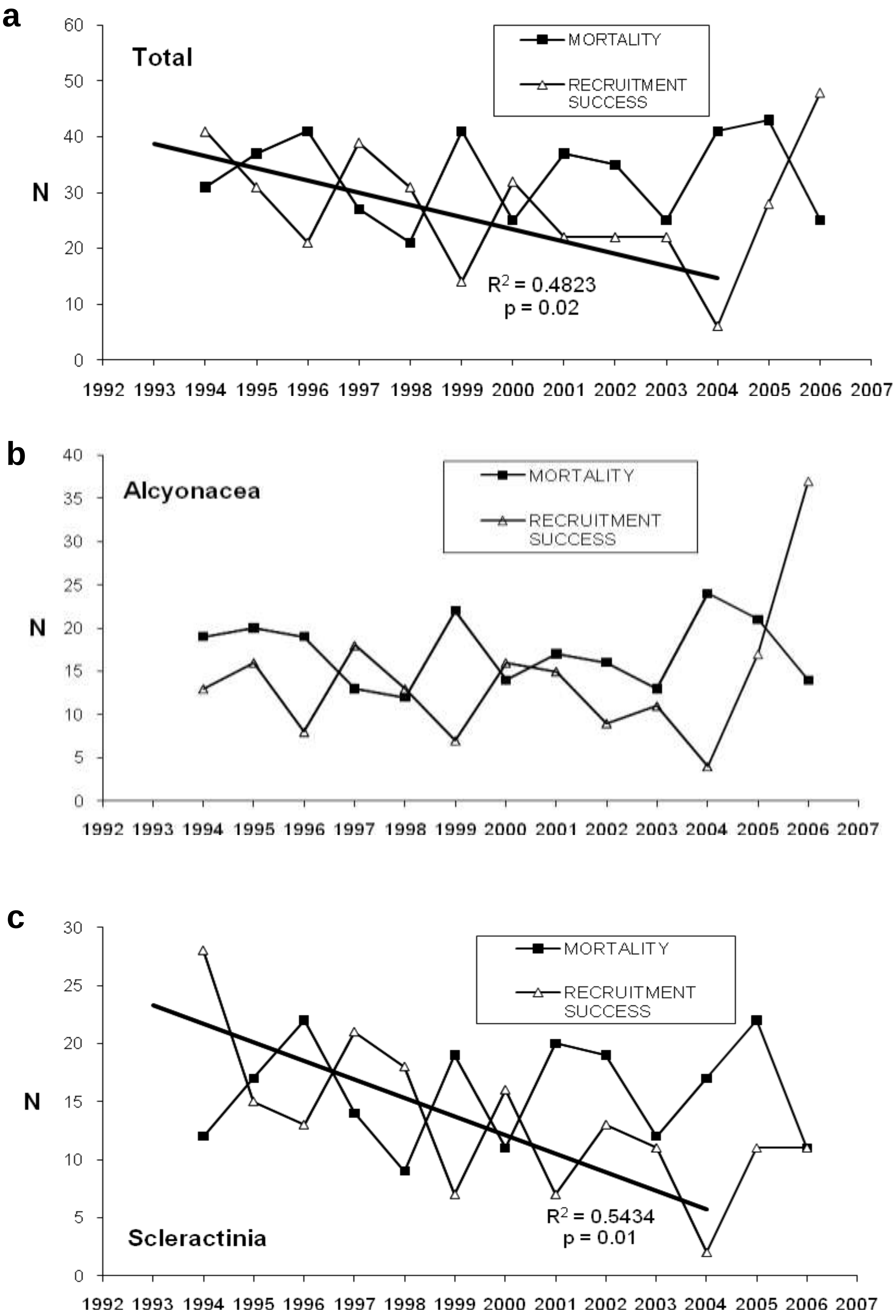


Figure 6.4 (a) Total coral mortality and recruitment success recorded at the long-term monitoring site on Nine-mile Reef at Sodwana Bay from 1993–2006, as well as mortality and recruitment success for (b) the Scleractinia and (c) the Alcyonacea. Where significant, trend lines are shown for declining recruitment success up to 2004, possibly reflecting the effects of increasing temperatures that culminated in measurable coral bleaching on the reefs (see text).

6.3. KEY TRENDS AND ASSOCIATED VULNERABILITIES

Predictions vary but remain fairly dire for coral reefs in the face of climate change, particularly in the western Indian Ocean (e.g., Hoegh-Guldbergh 1999, Kleypas et al. 1999, Sheppard 2003). Long-term monitoring of coral reefs is thus considered essential and is generally accomplished using techniques such as manta and video surveys, repeated at suitable intervals over large areas in systems like the Caribbean (Aronson et al. 1994) and Great Barrier Reef (e.g., Sweatman 1997, Sweatman et al. 2004). These methods provide good comparative data on reef state and have enabled the formulation of theories and experimental work on reef processes, particularly the interplay between reef-building organisms and algae or soft corals (Done et al. 1997). However, the long-term monitoring approach used on the South African coral reefs was initiated when climate change and global warming were becoming topical, and it was hoped that their anticipated consequences could be followed in detail. This has indeed been achieved in that individual colony recruitment, growth and mortality have been monitored over the last 14 years at Sodwana Bay.

Mean sea temperatures rose at the long-term coral monitoring site at the remarkable rate of 0.15 °C p.a. over the six year period up to 2000. This increase far exceeded what could be expected from global warming and clearly included elements of a local, macro-cyclical phenomenon (Celliers and Schleyer 2002, Schleyer and Celliers 2003a). This is borne out by the fact that regional NOAA National Climate Data Centre (NCDC) Extended Reconstructed Global SST (ERSST) data for 1854–2007 (Smith and Reynolds 2004) (Figure 6.2c) manifested a more typical temperature increase of <0.01 °C p.a., and a simple linear regression of sea temperatures at the site decreased by 0.07 °C p.a. after 2000. Insignificant bleaching was encountered in the region during the 1998 ENSO event, unlike elsewhere in East Africa, but quantifiable bleaching occurred on various Sodwana reefs, excluding the monitoring site, during an extended period of warming in 2000 (Celliers and Schleyer 2002). Peak temperatures on the South African reefs thus appear to have attained the local coral bleaching threshold (4 days at ≥28.8 °C; Celliers and Schleyer 2002) and, while this has resulted in relatively little bleaching thus far, the increase in temperature appears to have had the effects discussed below.

Throughout the study period, the monitoring site has undergone changes in community structure, involving an increase in hard coral cover and a reduction in the more abundant soft corals (Figure 6.2), resulting in a 5.5% drop in overall coral cover. The abundance of soft corals at the monitoring site is characteristic of the South African reefs (Schleyer 2000, Schleyer and Celliers 2003a, 2003b), but the reduction in soft coral cover was greater for the less abundant of the two principal genera (*Lobophytum vs Sinularia*; Schleyer et al. 2008). The number of soft coral colonies measured in the transects also diminished for most of the study period, increasing again at the end (Figure 6.2). The number of scleractinian colonies declined as well (Figure 6.3), but only after 2000, the year regional bleaching occurred; the increase in their cover would thus be attributable to individual colony growth. Trends amongst the most abundant of the hard coral genera fluctuated and were unpredictable (Schleyer et al. 2008), and are probably attributable to interactions within the community in view of its diversity. Notwithstanding these elements of detail, the overall trends in community structure remain those illustrated in Figure 6.2.

The trend in recruitment success was, however, most remarkable (Figure 6.4). This diminished significantly up to 2004 but appears again to be improving, resulting in the upturn in the total and alcyonacean colony counts at the end of the study period (Figure 6.3). The decline in recruitment success seems surprising as normal larval settlement, particularly of pocilloporids, was recorded on settlement plates between November 1999 and November 2002 (Glassom et al. 2006). Coral spawning, which was recorded in January (*Pocillopora verrucosa*) and March (four Alcyoniidae) in earlier studies (Schleyer et al. 1997), thus did not appear impaired by the elevated summer temperatures when they were at their highest. Coral recruits take some years to grow to a diameter of >2 cm, when they can be visually detected in the monitoring photographs, and it would take a new recruit roughly four years to reach this size (e.g., Glassom and Chadwick 2006). The decline in their number, peaking in 2004, probably signified a reduction in the grow-out of recruits, resulting from the hardships and stress associated with increasing temperatures, and the protracted peak temperatures and bleaching that followed in 2000 (Celliers and Schleyer 2002).

The monitoring site is little used for recreational diving and fishing (Schleyer and Tomalin 2000) and is not subjected to turbidity and pollution from rivers (Schleyer 2000). Other anthropogenic influences on the reefs are thus minimal, and elevated sea temperatures remain the strongest candidate for the observed changes. These trends in coral recruitment success and changes in coral cover and number appear to be “silent” effects of the earlier increases in sea temperature, as both recruitment success and colony survival have improved in more recent years (figures 6.3 and 6.4).

Schleyer and Celliers (2003a) proposed that increasing temperatures may encourage more scleractinian growth on South African reefs, until other atmospheric, climatic and physico-chemical factors, as suggested by Kleypas et al. (1999) and Scavia et al. (2002), become inhibiting (Table 6.1), causing a global reduction in corals.

Table 6.1 Simple model of the effects of climate change on South African coral reefs (from Schleyer and Celliers 2003a). Increased temperatures resulting from the atmospheric build-up in greenhouse gases are likely to stimulate coral growth at high latitude until the coral bleaching threshold is attained, or until a reduction in aragonite saturation impairs accretion**.**

	Physico-chemical effects	***Effects on coral growth and reef formation***
CO_2 increase	Temperature ↑	Could increase up to bleaching threshold
	Aragonite saturation state ↓	Will decrease

If the increase in Scleractinia on the South African reefs continues for some time, it is conceivable that it may result in subtle changes in other components of the reef biota, particularly the fish, for example, as more hard corals become available for obligate corallivores. Examples of such changes have been recorded in fish populations subjected to varying levels of protection within marine protected areas (MPAs) in East Africa, resulting in concomitant habitat improvement (McClanahan and Arthur 2001).

In the meantime, however, the fixed site monitoring on the marginal coral reefs of South Africa has yielded some surprising results, including potential effects of extended increases in temperature on reef processes beyond mere changes in reef community structure.

Coral numbers and the total and alcyonacean coral cover have decreased but the scleractinian cover has increased. Rising sea temperatures appear to have hindered reef function with regard to coral recruitment success, and this effect was manifested after or protracted beyond the point that temperatures began dropping. These are “silent” effects of temperature increase, which may be related to climate change. The results corroborate the earlier suggestion by Schleyer and Celliers (2003a) that changes on South Africa’s high-latitude reefs could precede those on more typical, tropical reefs. Their study and monitoring could yield results that may provide an insight into the global future of corals.

6.4. RESEARCH AND RESOURCES REQUIRED TO BETTER ASSESS POSSIBLE IMPACTS

It is clear from the above that efforts were initiated at an early stage to monitor climate change-related effects on a climatically sensitive ecosystem in South Africa, viz. its coral reefs (Schleyer et al. 2008). While this is considered an ongoing project, it is jeopardized by a lack of funding. Monitoring is not perceived to be a priority in South African marine science, a problem shared with other Cinderella disciplines such as taxonomy. The cost of this study has thus been partially met in past years by a variety of donors, but it is fully self-funded at present by the South African Association for Marine Biological Research because of funding cuts. This is clearly an unsatisfactory situation.

The need for protection of the reefs in the face of climate change merits expansion of the study to incorporate other disciplines. An examination of genetic resilience to coral bleaching will be of particular importance in this regard. Studies on the cladal composition of the coral zooxanthellae have thus been undertaken (Starzack 2007) and have revealed that South African corals are entirely dependent on clades of *Symbiodinium* belonging to clade C. Several of these were new and, since C clades of *Symbiodinium* tend to be more bleaching-susceptible, they warrant further study. The genetics of the coral host tissue are also under study (Macdonald in prep.). The combined results of this research are expected to provide information on local coral resilience and the extent of genetic exchange by corals between the reefs. This will facilitate improved conservation and management of the reefs to provide better protection of resilient coral communities.

Limited oceanographic studies have been undertaken in the vicinity of the coral reefs at Sodwana Bay (Morris 2009), providing some information on the physical dynamics of water movement on and between the reefs. These studies could likewise be expanded to elucidate the oceanographic effects of climate change within the greater Maputaland region, using data gained from selectively deployed oceanographic instrumentation and remote sensing.

Another area that warrants monitoring is the expansion of the distributional range of various biotic components, especially fish. Since the South African east coast constitutes a subtraction zone between tropical and temperate waters, it has a high level of endemism (Schleyer 2000). Range shifts have been noted amongst various fish species (see above) and these are likely to provide further evidence of climate change.

Finally, similar research is needed on the temperate reefs on the east coast. As stated earlier, less is known of the likely effects of climate change on such reefs but they will probably be less severe. Nevertheless, they also merit monitoring according to the above principles.

6.5. ACKNOWLEDGMENTS

We are grateful for financial support for this work from the Marine Living Resources Fund, the National Research Foundation and the South African Association for Marine Biological Research. Ezemvelo KwaZulu-Natal Wildlife provided accommodation for much of the fieldwork and assisted in the procurement of the funds. We are also grateful to staff of the Oceanographic Research Institute for their support in the field and in the laboratory. BP (Southern Africa) sponsored the research craft, and the Mazda Wildlife Fund, a 4 x 4 vehicle. Finally, our thanks to Professor Y Benayahu of the Tel Aviv University in Israel, who encouraged us to commence reef monitoring of this nature at an early stage of the Oceanographic Research Institute’s Coral Reef Programme, and Dr P de Bruyn who assisted with the statistical analyses.

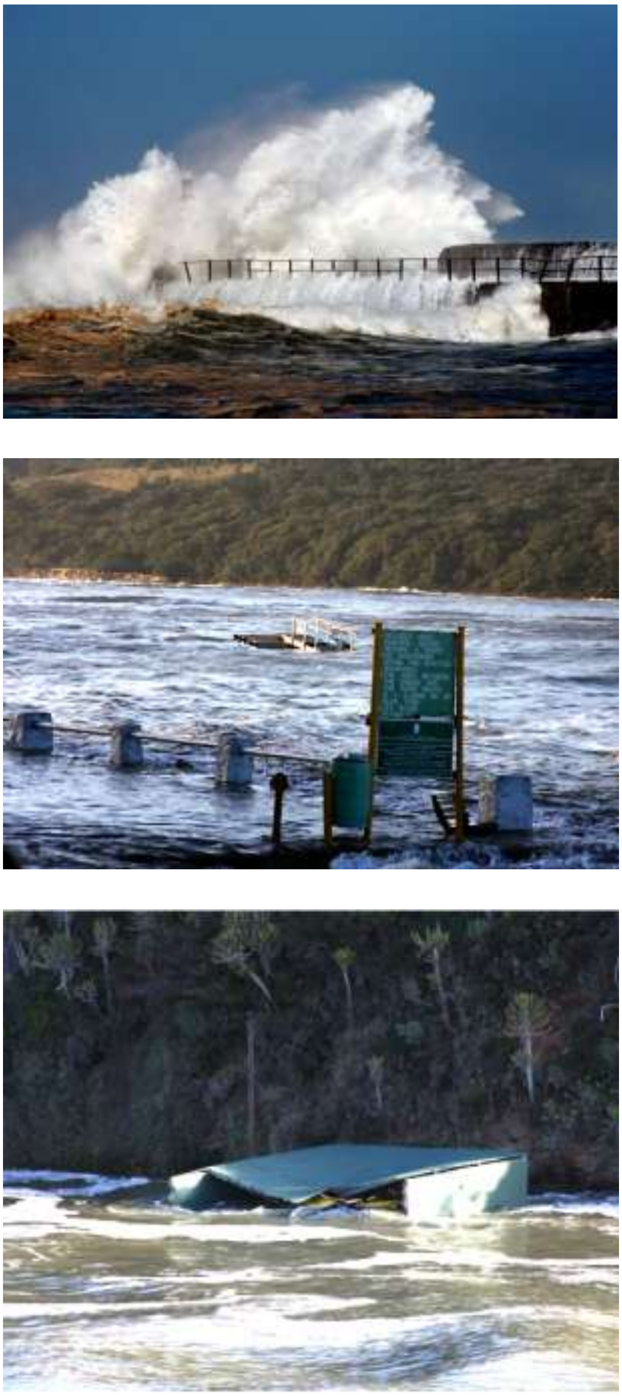
7. ESTUARIES

Nicola James & Lara van Niekerk

7.1. INTRODUCTION

Estuaries are the meeting place of freshwater from rivers and saltwater from the sea and, as such, are dynamic environments characterized by large fluctuations in environmental conditions. There are approximately 250 estuaries (with a total area of 600 km^2) along the 3000 km coastline of South Africa (Whitfield 2000). Whitfield (1992) identified five estuary types based on the dominant phase prevailing in each estuary: permanently open estuaries, temporarily open/closed estuaries, river mouths, estuarine lakes and estuarine bays. The majority of estuaries along the coast of southern Africa are relatively small and are closed off from the sea for varying periods by a sand bar which forms at the mouth (Potter et al. 1990, Whitfield 1998).

Although estuaries are amongst the most fluctuating aquatic environments on earth (Day et al. 1989), they are important nursery areas for numerous fish and invertebrate species (Dando 1984, Wallace et al. 1984) and are known to be more productive than adjacent freshwater and marine environments (Woodwell et al. 1973, Haedrich and Hall 1976). Numerous species of fish and invertebrates (more than 100) use estuaries as nurseries and/or feeding grounds. Species dependent on estuaries as nursery areas often spawn or breed at sea. Egg and larval development takes place at sea and this is followed by the mass migration of larvae and juveniles into estuaries, where higher temperatures and a rich food supply favour rapid growth. Juveniles typically remain in estuaries until the onset of maturity and then migrate back to sea (Wallace et al. 1984). Estuaries also perform other important ecological functions such as providing conduits for species that migrate between the sea and rivers (such as eels), and many bird species also depend on estuaries at different stages of their life cycle. Many coastal communities rely on estuarine resources for subsistence, and estuaries



Storm surges in the Eastern Cape, September 2008: *Top:* Heavy seas washing over Port Alfred Pier, Kowie Estuary; *Middle & bottom:* High seawater engulfing jetties and boat houses up the Kariega Estuary (photos, Dr Angus Paterson).

are important areas for recreational activities such as fishing, swimming and tourism. Despite the importance of estuaries, they are amongst the most threatened habitats in the country (Turpie et al. 2002a).

Changes in environmental conditions within an estuary may be fairly predictable, or they may be caused by short and/or long-term unpredictable climatic fluctuations, all of which have large effects on the abundance and distribution of estuarine fish and invertebrate stocks (Flint 1985, Kupschus and Tremain 2001, Desmond et al. 2002). In most parts of the world, estuaries are shallow and strongly influenced by wind, wave action, rainfall, and water and air temperatures. Consequently, climate change is likely to produce profound modifications to the structure and functioning of estuaries (Kennedy 1990) and may have a range of implications for estuarine biota.

7.2. CLIMATE CHANGE FINDINGS

Climate change that is linked to the build up of greenhouse gases and aerosols in the atmosphere is now a widely accepted phenomenon, with the International Panel on Climate Change stating with very high confidence (90%) that the net effect of human activities since 1750 has been one of warming (IPCC 2007). Change in climate incorporates change in temperature, precipitation and evaporation rates, sea-level rise and increased storminess, ocean circulation, winds and CO_2 concentrations, all of which will have profound consequences for estuarine and coastal ecosystems (Roessig et al. 2004).

7.2.1. TEMPERATURE

Greenhouse gases and aerosols released by humans have led to an increase in global air and ocean temperatures over the last 50 years. Estimates of average global temperature rise in the surface atmosphere range from a low scenario of 1.1–2.9 ºC to a high scenario of 2.4–6.4 ºC by 2100 (IPCC 2007). As a result, the water in the world's rivers and estuaries and the sea is also heating up. Ocean temperatures will follow increases in air temperatures, although to a lesser extent owing to the high heat storage capacity of water masses (Rijnsdorp et al. 2009).

A time series analysis of ocean heat content showed that the global trend is one of warming, with an increase of 0.1 ºC estimated for the 0–700 m layer of the ocean for the period 1961–2003 (IPCC 2007). However, significant decadal variations were observed in the global time series, and there are large regions where the oceans are cooling (Figure 7.1).

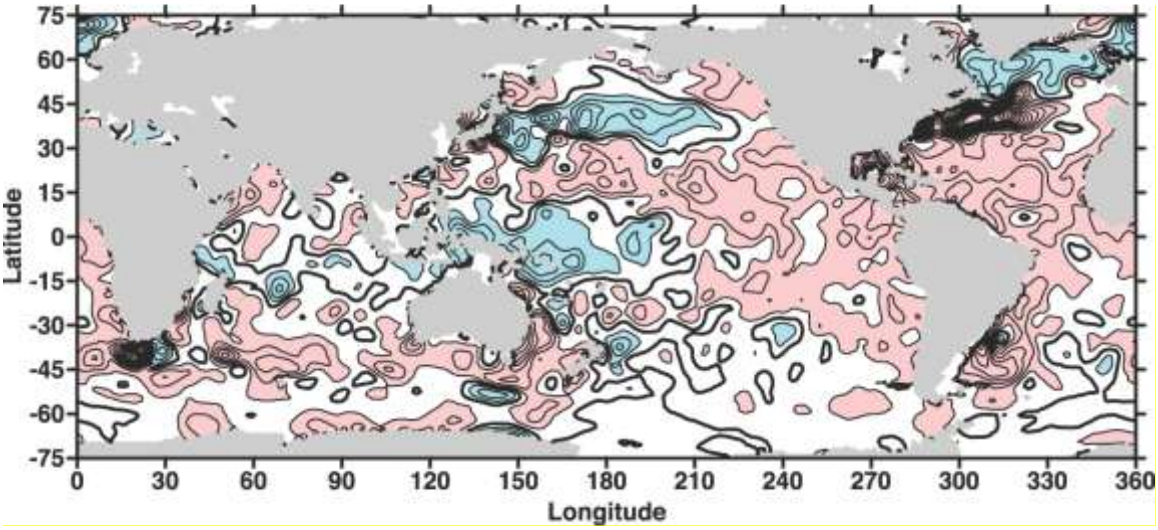


Figure 7.1 Linear trends (1955–2003) of change in ocean heat content per unit surface area (W m^{-2}) for the 0 to 700 m layer, based on the work of Levitus et al. (2005). The linear trend is computed at each grid point using a least squares fit to the time series at each grid point. The contour interval is 0.25 W m^{-2}. Red shading indicates values equal to or greater than 0.25 W m^{-2} and blue shading indicates values equal to or less than –0.25 W m^{-2}. (After IPCC 2007)

The Atlantic has warmed south of 45°N, with warming penetrating deeper in the Atlantic Ocean Basin than in the Pacific, Indian and Southern oceans. The Indian Ocean has warmed since 1955, with the exception of the 5°S to 20°S latitude belt, where cooling occurs at sub-surface depths (centered at 12°S at 150m depth) (Figure 7.1). Analyses of sea surface temperatures (temperature in the uppermost few metres) showed that 1998 was the warmest year globally, with the five warmest years all occurring after 1995 (IPCC 2007). The Indian Ocean shows fairly steady warming in recent years (IPCC 2007).

Analysis of sea surface temperatures (SST) from satellite data gives slightly contrasting results. Monteiro et al. (2008), using optimally interpolated (OI) SST data, recorded a rise in SST in the coastal and offshore areas of the west coast of, on average, approximately 1 °C between 1920 and 1990, which was accompanied by an increasing trend in southerly winds. High resolution SST records from 1982 indicate: an increase of 0.13 °C for the South Atlantic as a whole; an increase of 0.8–1.0 °C in the northern Benguela in the vicinity of the Angola–Benguela Front across the boundary of the upwelling system (near the Angola–Namibia geopolitical border); a corresponding increase of approximately 1.0 °C in the Agulhas Retroflection area just south of the Agulhas Bank; and a SST decrease of 0.2–0.3 °C near the coast along the west and south coast (see Figure 7.2).

Rouault et al. (2009) found that since the 1980s the SST of the Agulhas Current (measured from AVHRR satellite SST data) has increased significantly (up to 0.7 °C per decade). Their analysis produced similar results to that of Monteiro et al. (2008) (Figure 7.3) for the west and south coasts; they indicated that along the west coast near-shore SST is cooling between -0.2 and -0.5 °C per decade, with isolated small scale pockets of cooling in the region between Cape Agulhas and Cape St Francis (South Coast) of about -0.2 °C per decade. In contrast to the results of Monteiro et al. (2008), a larger region of cooling, ranging from -0.2 °C to -0.7 °C was identified between East London and Port Elizabeth centered in the Port Alfred dynamic upwelling cell. In the sub-tropical province a very thin strip of near-shore water cooling at a rate of -0.6 to -0.8 °C per decade was identified as far as Port St Johns.

Sea surface temperatures measured over a 25 year period in situ off Port Elizabeth on the south-east coast of South Africa have been increasing by ±0.25 °C per decade for the past four decades (Schumann et al. 1995). Similarly, despite considerable variation between years, there has been a positive increase ($r^2 = 0.19$; $P>0.05$) in mean annual sea temperature measured in situ at the mouth of the Kowie Estuary at Port Alfred between 1996 and 2006 (James et al. 2008a). The maximum temperature recorded was 25.3 °C in February 2003. Mean monthly sea temperatures were warmer by 0.2–0.6 °C from June to August (winter) during 2000–2005 compared to 1996–1999, and minimum summer temperatures, when many fish and invertebrate species are recruiting into South African estuaries, have increased significantly between 1996 and 2006 ($r^2 = 0.56$; $P<0.01$) (James et al. 2008a, data courtesy Oceans and Coasts, Department of Environmental Affairs).

Shallow areas, such as estuaries, are predicted to exhibit greater increases in temperature than deeper waters (Rijinsdorp et al. 2009). Furthermore, increasing air temperatures may also have a greater impact on temporarily open/closed estuaries than permanently open estuaries, as these systems are cut off from the effect of sea temperatures for long periods and therefore respond to a greater degree to prevailing land, air and river water temperatures (James et al. 2008a).

Although 1–2 °C changes in temperature may seem insignificant to animals that thermoregulate, many aquatic organisms are thermo-conformers and, therefore, respond rapidly to changes in ambient temperature (Clark 2006). The estuaries along the coast of South Africa, and their associated biological communities, can be grouped according to biological, physical and geographical criteria (Maree et al. 2000) with the coast of South Africa having three distinct biogeographic zones, a subtropical zone, a warm-temperate zone and a cool-temperate zone (Figure 7.4).

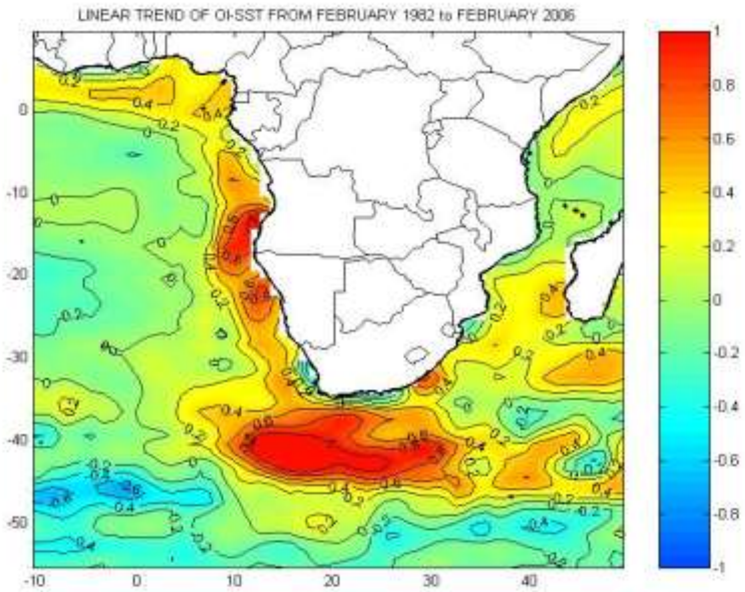


Figure 7.2 Linear trend of OI-SST from February 1982 to February 2006 in the southeastern Atlantic Ocean (after Monteiro et al. 2008)

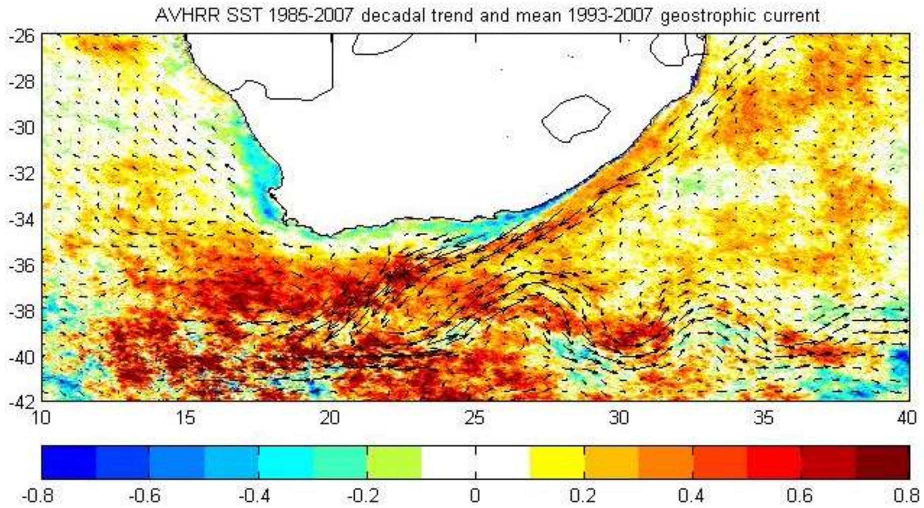


Figure 7.3 From top to bottom: linear trend of AVHRR SST from 1985 to 2007. Mean 1993–2007 absolute geostrophic velocity vectors derived from combined altimetry is superimposed (after Rouault et al. 2009).

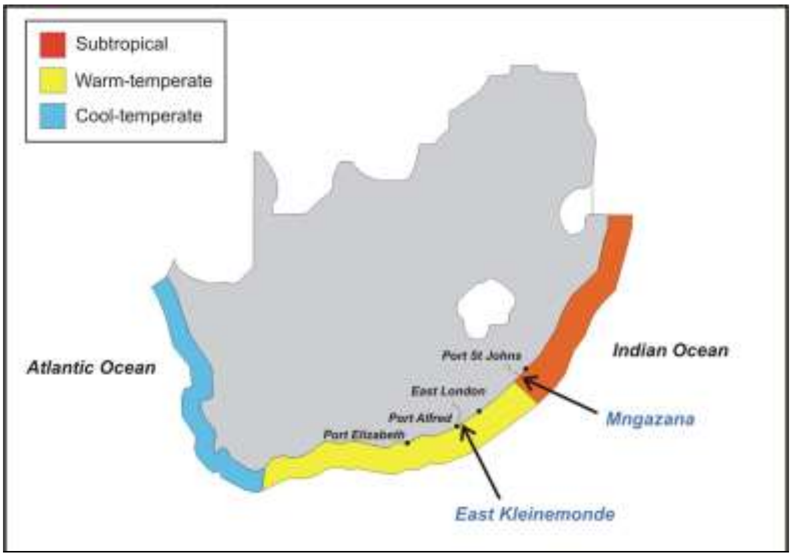


Figure 7.4 Map of South Africa indicating the three biogeographic provinces, based on estuarine fish communities (after Harrison 2005), and showing the location of estuaries referred to in the text.

Few species occur in all southern African estuaries and many species only occur within specific biogeographic zones. Harrison (2005) recorded differences in estuarine fish communities around the South African coastline, with a gradual decrease in the number of species recorded in estuaries from east to west, mainly as a result of the decreasing number of tropical marine species recorded. Cool- and warm-temperate estuaries are mainly dominated by species that occur only in southern Africa and not by tropical species. Temperature and salinity were found to be the primary determinants influencing the biogeography of fishes, particularly tropical species, in South African estuaries (Harrison and Whitfield 2006). According to Elliot (2002), climate change has the potential to affect the major aspects of fish physiology, such as their salinity and temperature tolerances, and thus to influence their ability to use estuarine habitats, which will in turn affect the distribution of species, including the migrations of locally rare and endangered species (illustrated below, Figure 7.5). Many organisms are more stressed near their species range boundaries (Sorte and Hoffman 2004), and the distributions of these species can be expected to shift as environmental conditions change.

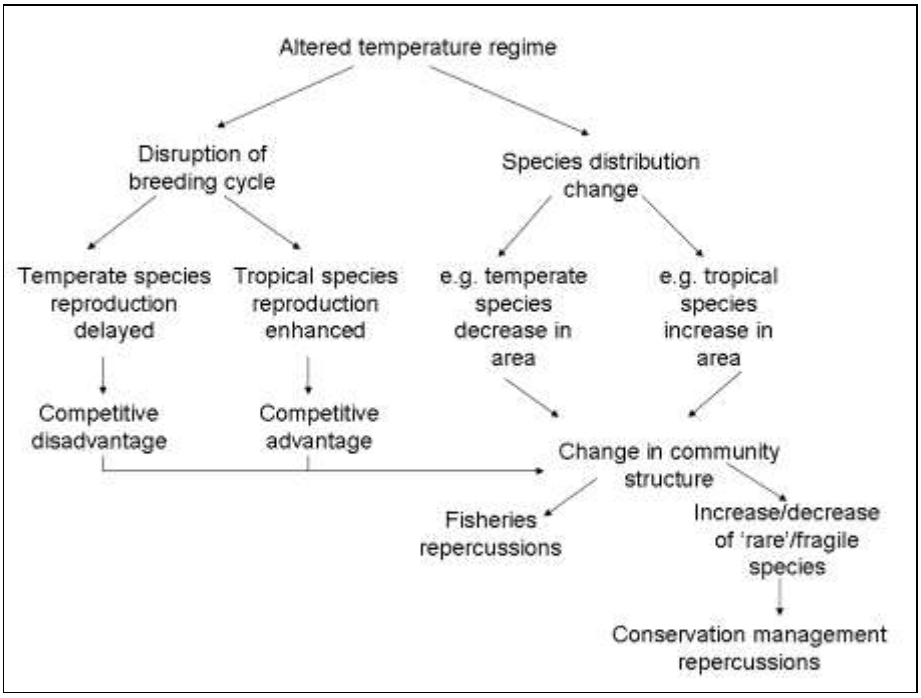


Figure 7.5 The effects of an altered temperature regime on estuarine fish and fisheries – conceptual model (After Elliot 2002)

Clark (2006) predicts that the most obvious changes associated with increasing sea surface temperatures around South Africa will be shifts in the distributional patterns of species and changes in the composition of species assemblages. Changes in the distributional patterns of estuarine and coastal species have been recorded both locally and globally.

In the northern hemisphere, Cabral et al. (2001) recorded significant increases in water temperature in the Tagus Estuary, Portugal, between surveys conducted during 1980–1983 and 1995–1996 and noted that fish species richness also increased between the two periods. Climatic variability was found to have a principal controlling influence on the structure of the Thames Estuary fish assemblage, the growth of resident juveniles and the abundance of many species (Attrill and Power 2002). Stebbing et al. (2002) correlated warming of the North Atlantic with the northward extension of warm water fish into coastal waters off the Cornish coast of the United Kingdom. Similarly, Henderson (2007) recorded a continuous increase in fish species richness during a 25 year study of the temperate Bristol Channel, correlated with increased average seawater temperatures. The increase in species richness was attributed to more frequent capture of warmer water species without a corresponding loss of temperate members of the fish community. Temperate species close to the southern edge of their range became less abundant but were not lost. Perry et al. (2005) in a study of 20 benthic fish species at the southern/northern limit of their range in the North Sea found that the boundaries of half the species had moved significantly with warming at a mean rate of 2.2 km per year. Although marine species generally face fewer constraints to their movement than terrestrial species, climate change may pose a greater threat to species when their dispersal capabilities are limited or suitable habitat is unavailable (Perry et al. 2005). Different species were also found to respond differently to climate change according to their rates of population turnover; for example, fish species with a more rapid turnover of generations were found to respond more rapidly to climate change, resulting in stronger distributional responses. Similarly, shifting species were found to have smaller body sizes, faster maturation and smaller sizes at maturity (Perry et al. 2005). These findings have important implications for fisheries as species with slower life histories are often already more vulnerable to overexploitation (Perry et al. 2005).

As part of an ongoing long-term study, the changing fish assemblages in the East Kleinemonde Estuary, a warm-temperate system on the southeast coast of South Africa (Figure 7.4), have been studied since December 1995. This estuary is a small (3 km in length) temporarily open/closed system that is closed off from the sea for most of the year by a sand bar that forms across the mouth and which usually only opens after river flooding in the catchment. A total of 38 species of fish were recorded in the East Kleinemonde Estuary between December 1995 and July 2006 (James et al. 2008b). Indicative of warming waters, six new tropical species: longarm mullet (*Valamugil cunnesius*), robust mullet (*Valamugil robustus*), diamond mullet (*Liza alata*), largescale mullet (*Liza macrolepis*), tank goby (*Glossogobius giuris*) and thornfish (*Terapon jarbua*) have been recorded in the catches since 1999. The four tropical mullet species (longarm mullet, robust mullet, diamond mullet and largescale mullet) and thornfish normally occur in the tropical and subtropical estuaries of southern and eastern Africa (common in the subtropical estuaries along the KwaZulu-Natal coast), although stragglers have occasionally been recorded in the warm-temperate estuaries of the south-eastern coast (Smith and Heemstra 1990). The tank goby is a tropical and subtropical species that has only previously been recorded as far south as the Mngazana Estuary on the east coast (Figure 7.4). Of the six species, longarm mullet and largescale mullet were recorded almost every year after 2002, and were found in both the summer and winter samples, which means that they were not just stragglers straying into the estuary with the warm current but rather that water temperatures were continually within the tolerance range of these species. As a result of the increased occurrence of tropical species, the number of species recorded in the estuary between 1996 and 2006 has increased steadily (Figure 7.6, James et al. 2008a).

The effects of climate change on fish distributions have also been recorded further north in the Mngazana Estuary. In a study of the fish community of the Mngazana Estuary undertaken in 1975 (Branch and Grindley 1979), the proportion of tropical species recorded was found to be lower during winter than summer, while temperate species increased during winter (Figure 7.7). This was attributed to tropical species extending their ranges southwards during summer and temperate species extending their ranges northwards during winter (Branch and Grindley 1979). In a similar study conducted 25 years later, the proportion of tropical species recorded in the estuary was high in both summer and winter (Mbande et al. 2005). The increase in the overall proportion of tropical species during winter, from 1975 to 2002, may be an effect of global warming. Higher average temperatures would favour tropical species during winter, while limiting the northward penetration of certain temperate species (Mbande et al. 2005).

Both the Kleinemonde and Mngazana studies have highlighted the increased occurrence of tropical fish species in estuaries along the east coast of South Africa. Although changes in the abundance of fish species have not been reported in these two estuaries, climate change may eventually result in marked changes in the composition of coastal fish communities. It is important to keep in mind that each species responds differently to warming, and communities do not shift their distribution as a unit. Climate warming is therefore likely to create new mixes of foundation species, predators, prey, and competitors, thus making it very difficult to predict how communities will change in response to climate change (USEPA 2009). Studies conducted off the eastern United States have shown that fishes with the most temperature sensitive distributions included key prey species of non-shifting predators (Perry et al. 2005).

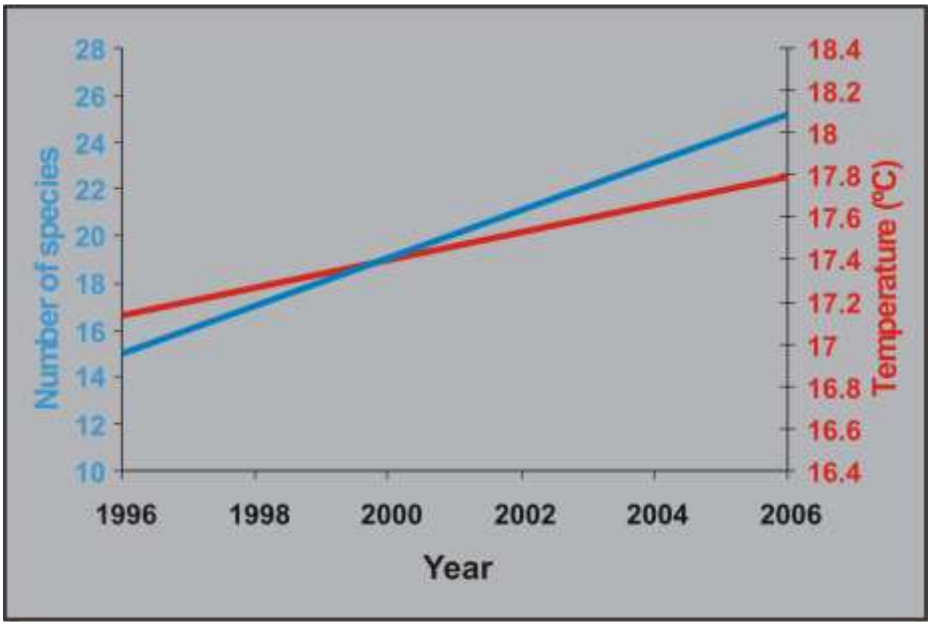


Figure 7.6 The total number of fish species recorded in the East Kleinemonde Estuary and mean annual sea temperatures (ºC) recorded at Port Alfred between 1996 and 2006 (after James et al. 2008a; temperature data courtesy Oceans and Coasts, Department of Environmental Affairs)

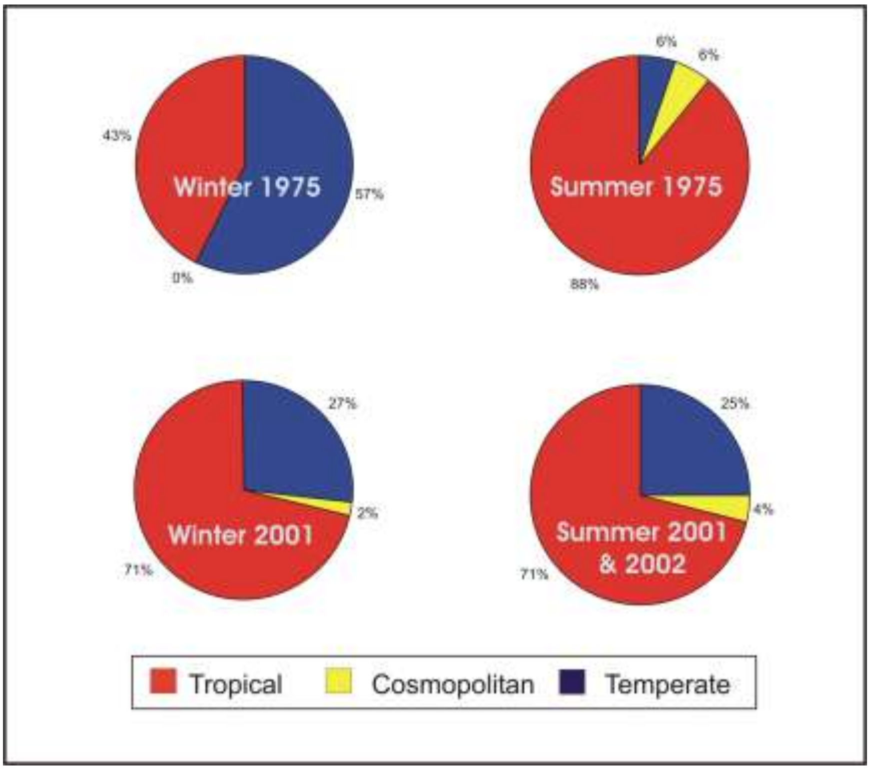


Figure 7.7 Trends in fish species composition in the Mngazana Estuary (after Branch and Grindley 1979, and Mbande et al. 2005)

Although biotic range shifts are expected in South African waters, they have not been modelled as yet because anticipated shifts are closely associated with ocean currents, and changes in the movements of currents have not been accurately predicted (Turpie et al. 2002b). If climate change weakens alongshore advection, marine biogeographical barriers that prevent range expansions could be broken down (Harley et al. 2006). If estuary warming occurs then temperature dependent processes such as growth, maturity and feeding rates may also accelerate (Murawski 1993).

Increased surface temperatures are also expected to affect estuarine and coastal wetlands such as mangroves and saltmarsh. Saltmarshes are coastal ecosystems that develop mainly in temperate areas exposed to low-energy wave action and that are characterized by a suite of herbaceous or low woody vascular plants and by zonation of species from high, mid to low marsh (Adam 2002). Although saltmarshes are found in tropical areas the number of species in the tropics is very low (Adam 2002). In South Africa saltmarshes occur only in certain estuaries and embayments. North of the Kei River the subtropical conditions favour the development of mangrove swamps (Adams et al. 1999). Mangroves are coastal ecosystems that are characterized by primarily tree or shrub species that develop in tropical/subtropical areas (US Geological Survey, USGS 2004). Mangroves usually occur between mean sea level and mean high water spring tide level. Temperature is regarded as the most important factor governing the distribution of mangroves. In South Africa mangroves are restricted to bays and estuaries along the southeastern coastline from East London northwards (Steinke 1999).

Changing temperatures will affect mangroves by changing species composition, changing phenological patterns (such as the timing of flowering and fruiting), increasing productivity where temperature does not exceed an upper threshold, and expanding ranges of mangroves to higher latitudes (Gilman et al. 2008). As the distribution of saltmarsh reflects climate, increasing temperatures are also likely to affect individual saltmarsh species, communities and marsh types and may favour the invasion of saltmarsh by mangrove species (Adam 2002).

7.2.2. SEA-LEVEL RISE AND STORM DISTURBANCE

Two significant consequences of climate change are accelerated sea-level rise and increased frequency of high-intensity coastal storms and high water events (Figure 7.8). Several climate models project an accelerated rate of rise over the coming decades (IPCC 2007). Projections of sea-level rise from 1980–1999 to the end of the 21st century (2090–2099) range from a low projection of 0.18–0.38 m to a high projection of 0.26–0.59 m. The projections do not, however, take into account the effects of melting of the Greenland and Antarctic ice shelves and could be a serious underestimate (IPCC 2007). An assessment of sea-level rise in South Africa, using available tide gauge data for the last 50 years, shows a 1.87 mm y^{-1} rise on the west coast, a 1.48 mm y^{-1} rise on the south coast, and a 2.74 mm y^{-1} rise on the east coast (Mather et al. 2009). Of all climate induced changes, sea-level rise is seen as the greatest threat to mangrove and salt marsh ecosystems in estuaries (Adam 2002, Gilman et al. 2008). Over the last 6000 years coastal wetlands expanded inland as low lying areas became submerged, retaining a constant position relative to the shifting tidal frame, to keep pace with the slow rate of sea-level rise (Scavia et al. 2002). Migration of coastal wetlands under current and projected levels of sea-level rise may be prevented by artificial embankments and development which will cause a loss of coastal wetlands through “coastal squeeze” (illustrated in figures 7.8 and 7.9). Furthermore, some mangrove and saltmarsh systems may not be able to keep pace with current more rapid levels of sea-level rise when rates of subsidence (the sinking of the land) and sea-level rise (eustacy caused by thermal expansion of water and melting of the polar ice caps and glaciers) are not balanced by accretion (sediment accumulation) (USGS 1997). Upward movement of mangrove at the expense of saltmarsh in subtropical areas is also predicted as an early response to rising sea level (Adam 2002). In southern Australia substantial invasion of saltmarsh by mangrove species has occurred over the past 50 years (Adam 2002).

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change predicts, with a high level of confidence, an increasing frequency and intensity of extreme weather events in the 21st Century (IPCC 2007). The frequency and magnitude of severe weather events such as tropical cyclones, hailstorms, droughts and floods appears to be on the increase globally (IPCC 2007). In South Africa, increases in either intensity or frequency, or changes in seasonal storm intensity have been recorded at a local scale (Guastella and Rossouw 2009). Sea-level rise and the increased frequency of high-intensity storms alter the hydrogeomorphology of coastal ecosystems (Figure 7.8). Furthermore, human alterations to these ecosystems determine the extent to which they are affected (USEPA 2009). The intense storms (e.g., hurricanes Katrina and Rita) that hit the coastline of the Gulf of Mexico resulted in the loss of wetlands and sharp alterations in wetland community structure. The severity of the impacts was linked to historical wetland loss and damaged conditions (USEPA 2009). Sea-level rise and erosion, caused by intense storms, also caused estuarine islands to disappear and led to significant changes in shorelines. Sea-level rise and increased frequency of intense storms will influence saltmarsh and other wetland habitats by erosion and salt water intrusion (USEPA 2009). Hughes et al. (1993) modelled the impacts of a 1 m rise in sea level on the Diep Estuary in Cape Town. The Diep Estuary comprises a temporarily open/closed estuary (Milnerton Lagoon) and wetland system (Rietvlei). The model predicts that with a 1 m rise in sea level the wetland area will effectively become a large shallow body of seawater connected to the sea via a long narrow channel (Hughes et al. 1993). Increased storminess, together with sea-level rise, may result in a loss of estuarine habitat which ultimately affects estuarine fish communities and will have fisheries repercussions (Figure 7.9).

Figure 7.8 Global warming in a South African context may result in sea-level rise and, together with the more frequent occurrence of extreme weather conditions, could have implications for estuarine ecosystems. Pictured here are (a) a flooded caravan site on the banks of the Great Fish River and (b) storm surf conditions resulting in a major overwash event in the temporarily open/closed East and West Kleinmonde Estuaries, Eastern Cape, September 2008 (Photos, Dr Paul Cowley, SAIAB)

7.2.3. RAINFALL

Climate change is predicted to alter precipitation patterns which will affect the quality, rate, magnitude and timing of freshwater delivery to estuaries and will potentially exacerbate existing human modifications of these flows (Alber 2002, USEPA 2009). Estuarine functioning is strongly influenced by the magnitude and timing of freshwater inflows (Turpie et al. 2002b). Downscaled regional climate models (RCMs) derived from three global climate models (GCMs) indicate the likelihood of increased summer rainfall over the eastern part of South Africa, the interior and the Drakensberg Mountains, and a slight decrease in wintertime frontal rainfall in the later half of winter in the Western Cape (Hewitson and Crane 2006). The increased rainfall projected for the east coast would be in the form of more raindays and an increase in heavy/extreme precipitation events in the summer (Hewitson and Crane 2006). If these scenarios are correct, the combination of wetter antecedent conditions and heavy precipitation events would result in more runoff being generated. The decrease in rainfall along the west coast and adjacent interior, with the possibility of a slight increase in inter-annual variability, would result in a decrease in flows and an increase in flow variability, as changes in precipitation are amplified in the hydrological cycle (Lumsden et al. 2009, Hewitson and Crane 2006). The models also show an increase in raindays for much of the country, excepting possibly the extreme west/southwest (Hewitson et al. 2005). Schultze et el. (2005) assessed the impacts of climate change (including rainfall) on water resources in South Africa and found changes in a future climate may result in "hotspots" of hydrological change, one being the present winter rainfall region in the Western Cape.

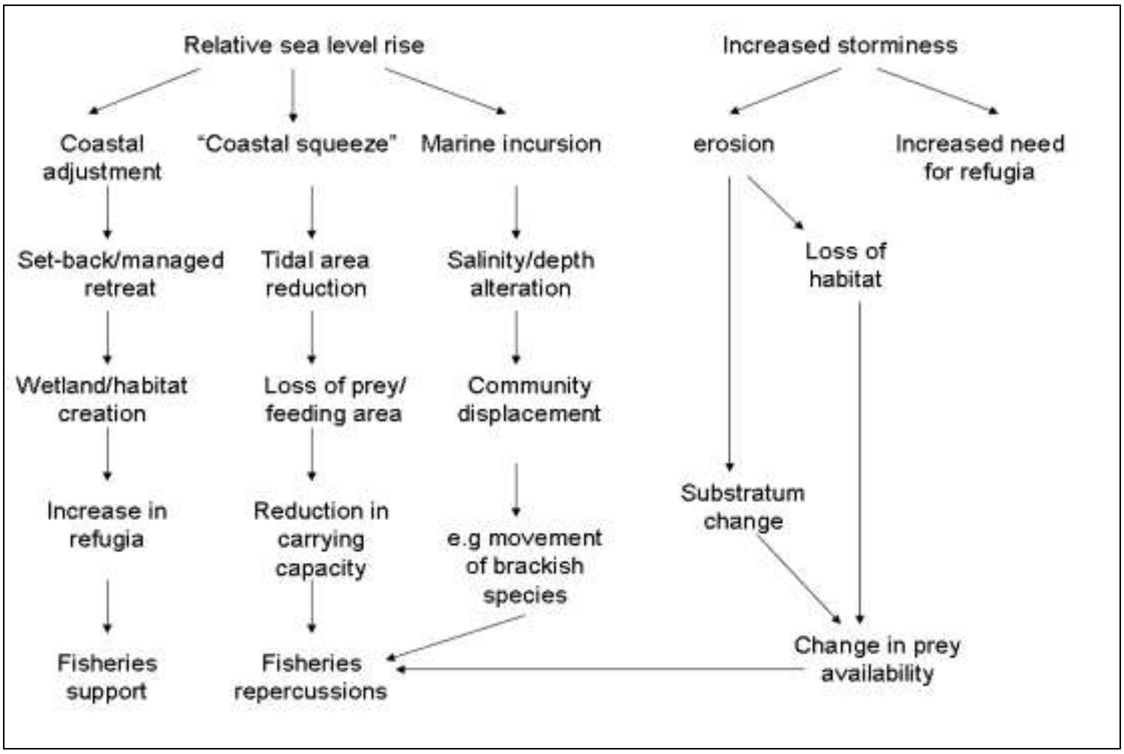


Figure 7.9 Climate change (relative sea-level rise and increased storminess): effects on estuarine fish and fisheries – conceptual model (after Elliot 2002)

Reductions in the amount of freshwater entering estuaries in South Africa, particularly in the Western Cape, would lead to an increase in the frequency and duration of estuary mouth closure and changes in the extent of seawater intrusion, nutrient levels, suspended particulate matter, temperature, conductivity, dissolved oxygen and turbidity (Clark 2006, van Niekerk et al. in prep). The degree to which seawater will enter an estuary is dependent on river inflow and the bathymetry of the system, i.e., seawater penetration into the more constricted upper reaches is often constrained by river inflow, with relatively easy penetration into the deeper middle reaches; and with the lower reaches generally dominated by tidal flows. Often, it is thus the middle reaches of an estuary that show the most sensitivity to changes in flow (river and tidal) (van Niekerk et al., in prep). In large permanently open systems, flow reduction may initially result in a reduction in the extent of the estuarine mixed zone, i.e., that section of an estuary with salinity between 20 ppt and 10 ppt. Further reduction in stream flow can result in the complete elimination of this mixed zone so that, effectively, the system becomes an arm of the sea, e.g., the Kromme Estuary (Bate and Adams 2000, Scharler and Baird 2000, Snow et al. 2000, Strydom and Whitfield 2000, Wooldridge and Callahan 2000). If there is no inflow at all, a reverse salinity gradient may develop, in which the salinity at the head of the estuary may exceed that of seawater, e.g., the Kariega Estuary (Bate et al. 2002, Whitfield and Paterson 2003). In contrast, reduction in stream flow in small temporarily open/closed estuaries (TOCEs) may lead to a reduction in salinity (van Niekerk et al., in prep).

Temporarily open/closed estuaries become isolated from the sea by the formation of a sand berm across the mouth during periods of low or no freshwater inflow; TOCEs stay closed until their basins fill up and their berms are breached by increased freshwater inflow. A major consequence of reduced freshwater inflow is, therefore, a change in the frequency and duration of estuary mouth closure in TOCEs. In extreme cases freshwater reduction can cause permanent mouth closure (van Niekerk et al., in prep). Changes in marine fish community structure in a small South African estuary were found to be primarily driven by mouth state (James et al. 2008b), and consequently changes in the frequency of mouth closure may have a profound effect on the fish communities of this and other estuaries. One of the most important values of estuarine systems is their contribution to fisheries (Turpie et al. 2002b). Meynecke et al. (2006) identified clear links between estuarine fish catches and rainfall in Queensland, Australia, because many estuarine-dependent species are sensitive to freshwater runoff. Similarly, estuarine fish catches in South Africa are strongly linked to geographical location, size and mouth conditions of estuaries (Lamberth and Turpie 2001). The consequences of these physical changes for the invertebrate fauna can be severe. For example, the mudprawn *Upogebia africana* has an obligatory marine phase of larval development. Estuary mouth closure, particularly for extended periods (e.g., >1 yr), disrupts the life cycle and could result in local extinction of the mudprawn (Wooldridge and Loubser 1996).

A change in river flow regimes also affects the nutrient loads entering estuaries. Freshwater inflow into estuaries is an important source of nutrients, both dissolved and particulate. Dissolved nutrients include nitrates, phosphates, silica and trace metals essential for primary production. Particulates such as organic detritus derived from riparian vegetation may also be an important source of carbon for the estuarine food web. Reduction in freshwater inflow (as a consequence of dam development or climate change) will reduce the quantity of nutrients entering the estuary, with resultant impoverishment of the biota. In particular, primary producers such as phytoplankton and benthic diatoms will be adversely affected with a consequent “knock-on” effect through the entire food chain (Allanson and Read 1987). Increased freshwater inflow will conversely increase the quantity of nutrients entering the estuary. The biological response will depend on residence time, or the time between breaching events. The shallow estuaries of KwaZulu-Natal are “perched” at elevations above mean sea level; tidal prisms are usually small and there is a rapid drop in water level when the estuary breaches. In these systems, residence time decreases with increased freshwater inflow often resulting in a decrease in production.

Floods in estuaries scour sediment deposited during periods of low flow. This accumulated sediment is both catchment derived and brought in from the sea by flood tides. Soil erosion in catchments poses a major threat to estuaries, particularly those in KwaZulu-Natal and those in the former Ciskei and Transkei regions of the Eastern Cape Province (Morant and Quinn 1999). The potential denuding of vegetation in arid catchments (i.e., increasing the erodibility of soils) coupled with an increase in the frequency of high intensity rain events due to climate change would lead to a significant increase in the deposition of sediment in estuaries.

The potential water shortage, especially in the Western Cape, would lead to the need to build more dams to secure water supplies to urban areas and agriculture. Major dams may have the effect of capturing minor (annual) flood peaks entirely and attenuating major flood peaks. The degree to which this will occur depends on the ratio of dam volume to the mean annual runoff (MAR), the level in the dam preceding the flood, and the size of the flood. Therefore, if floods are reduced in intensity and frequency, sediment deposition and accumulation occurs and the estuaries are reduced in water volume and surface area. Numerous small farm dams, as well as barrages and weirs, collectively may also have a major impact on the variability and duration of stream flow and consequently on estuaries. Instead of being available as stream flow the water is stored and subjected to consumption and losses, including evaporation and seepage. It is estimated that as little as 8% of the total annual runoff reaches the coastal zone (Department of Water Affairs 1986).

7.2.4. CO_2 AND PH CHANGE

Relative to pre-industrial times, the atmospheric concentration of CO_2 has risen by 35% in 2005 (IPCC 2007). Elevated atmospheric CO_2 concentrations may increase productivity of some mangrove and saltmarsh (C_3) species, but the effect of enhanced CO_2 on saltmarsh and mangroves is poorly understood (Adam 2002, Gilman et al. 2008) (Figure 7.10). Furthermore, with the exception of seagrasses, most marine plants are carbon saturated and enhanced growth is not anticipated (Harley et al. 2006). The reduction in pH that accompanies elevated CO_2 concentrations may have severe implications for coastal ecosystems (Harley et al. 2006). It is estimated that the pH of surface waters will decrease by 0.3–0.4 units by 2100 as atmospheric CO_2 levels continue to increase (Caldeira and Wickett 2003). The resulting decrease in pH will affect all calcifying organisms because structures made of calcium carbonate will start to dissolve and, as carbonate becomes undersaturated, it requires more metabolic energy for an organism to deposit calcium carbonate. A wide range of estuarine organisms will be affected, including coralline algae, echinoderms, crustaceans and molluscs (USEPA 2009). Estuarine acidification will also influence water quality (USEPA 2009).

Figure 4.10 Changes in CO_2 as a result of global warming may enhance the growth of mangroves (White Mangroves, *Avicennia marina*, Richards Bay)

7.3. KEY TRENDS AND ASSOCIATED VULNERABILITIES

Although *sea surface temperatures* have been increasing around South Africa, by up to 0.25°C per decade, there is evidence from satellite data that coastal water temperatures have been decreasing in certain areas (such as the western and southern Cape coasts).

Increasing sea surface and estuarine temperatures (particularly in closed estuaries) are predicted to result in:

- Shifts in species distributions, with tropical species moving south and temperate species moving north; this has already been recorded in some estuaries.

- Areas of cooling may, however, limit the ability of species to shift their distribution resulting in a decrease in the range of certain species in South Africa.
- Shifts in species distributions and changes in reproduction will ultimately result in changes to the community composition within estuaries, but this is difficult to predict as different species will respond differently to increasing temperatures.
- Species less able to respond to changes in climate may decrease in abundance and this may ultimately result in localized extinctions.

Species with slow growth rates may be less adapted to climate change and, as these species are often already overexploited, climate change may have serious implications for coastal and estuarine fisheries.

Accelerated *sea-level rise* and increased frequency of *high-intensity coastal storms* and high water events may have a range of implications for estuaries and their associated biota.

- Coastal squeeze will limit the ability of coastal wetlands to expand inland in response to sea-level rise, ultimately resulting in a loss of habitat which will in turn affect the abundance of estuarine fish (and thus have fisheries implications).
- Marine incursion into estuaries will cause changes to the salinity and depth of estuarine habitat which will in turn affect the biota.
- Increased storminess, exacerbated by sea-level rise, will lead to erosion and loss of estuarine habitat, which will in turn have fisheries repercussions.

Sea-level rise will also impact on the mouth status of estuaries (open or closed), which will interact with reductions or increases in freshwater flow (from rainfall), but these effects have not as yet been modelled.

Reductions in *rainfall* along the west coast of South Africa may result in:

- A reduction in the amount of freshwater entering estuaries, particularly along the west coast, may cause estuaries to close more frequently and permanently open estuaries to close.

Estuarine fish species are known to be sensitive to freshwater runoff and this may reduce the abundance of estuarine species, which will also have fisheries implications.

Changes in *CO_2* and *pH* may result in:

- Enhanced growth of certain mangrove and saltmarsh species.
- Growth deficiencies of certain estuarine organisms.

7.4. RESEARCH AND RESOURCES REQUIRED TO BETTER ASSESS POSSIBLE IMPACTS

7.4.1. REQUIRED RESEARCH

- Long-term monitoring programmes need to be initiated in estuaries, particularly estuaries that are situated at the boundary of species distributional ranges, to better assess the impacts of climate change on these systems.
- These programmes need to assess estuarine biota as well as to establish a network of temperature recorders in estuaries and the coastal environment around the country. These gauges can then be used to ground-truth readings from satellite data.
- Aerial surveys of South African estuaries should be undertaken every 5–10 years, and after episodic events.
- Changes in the wave climate also need to be assessed, as changes in wave climate will impact on the mouth conditions of estuaries.
- GIS maps of all estuarine vegetation types and habitat (mudbanks, sandbanks, open water area, etc.) for all the estuaries in the country using the most recent satellite images are needed to establish a baseline. GIS maps using historic aerial photographs are also required to quantify changes that have taken place over time.
- The sediment accretionary dynamics (vertical accretion, short-term sedimentation, shallow subsidence, soil vertical elevation change and horizontal shoreline change) of most estuaries need to be determined. Precise measurements (within 1.5 mm) of sediment elevation in the salt marsh must be made relative to a fixed subsurface datum using a Sediment Elevation

Table (SET). A pilot study involving the Swartkops, Kromme and Knysna estuaries are currently underway.

- Accurate elevation maps (digital terrain models) need to be created of most estuaries to identify risk areas related to sea-level rise.
- Salt marsh community structure and diversity along elevation gradients need to be investigated, and soil physico-chemical attributes (electrical conductivity, sediment particle size, redox potential, soil moisture, soil organic content and nutrients) determined that are responsible for the zonation over time.

7.4.2. REQUIRED RESOURCES

- Tide gauges or water level recorders in most estuaries (including temporarily open/closed estuaries).
- Temperature and salinity recorders in most estuaries (including temporarily open/closed estuaries) and the coastal zone.
- Flow gauges in all rivers. Flow gauges should be located as close as possible to the head of the estuary.
- Satellite or aerial images of all the estuaries (covering entire estuary from the mouth to the head and up to the 5 m contour) taken at least every 2–5 years during neap low tide.
- Rods for Sediment Elevation Tables inserted in the lower, middle and upper reaches of most estuaries.
- Construction of more than one Sediment Elevation Table for use in the different provinces.

8. SANDY SHORES

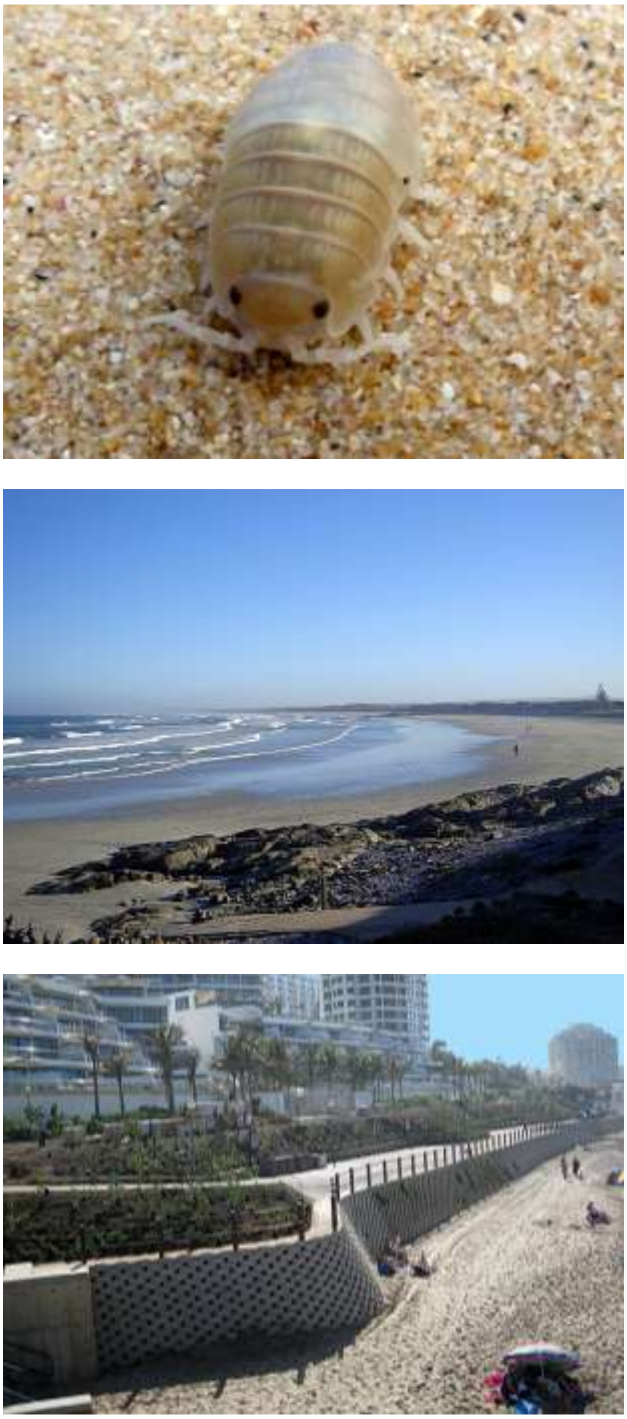
Linda Harris, Eileen Campbell & Ronel Nel

8.1. INTRODUCTION TO SOUTH AFRICAN BEACHES

The South African coastline extends for approximately 3100 km between the Orange River mouth and Ponto d'Ouro. Sandy beaches make up more than a third of the coastline (~39%) and represent the dominant coastal type (Harris et al. 2010). The beaches are microtidal, wave-dominated and generally exposed to oncoming swell from the open ocean. The prevailing beach morphodynamic types are dissipative-intermediate (50%) and intermediate (30%) (Short and Wright 1983, Wright and Short 1984), with lesser representation by the dissipative (12%) and reflective (8%) extremes (Harris et al. 2010). However, conditions are far from similar around the coastline.

The South African coastline can be divided into three bioregions: the cold-temperate west coast (Benguela); the warm-temperate south coast (Agulhas); and the sub-tropical east coast (Natal; e.g., McLachlan et al. 1981, Hockey et al. 1983, Turpie et al. 2000, Harris et al. 2010). Along the west coast, the shoreline is relatively straight north of St Helena Bay, but is rugged south of that, with prominent coastal features such as Saldanha Bay, Langebaan Lagoon, Cape Peninsula and False Bay. Coastal productivity in the Benguela region is boosted by upwelling (Nelson and Hutchings 1983, Bate and Campbell 1990), kelp-wrack and particulate organic matter derived from reefs and kelp (Dugan et al. 2003). The kelp is often washed up onto the beach whole, providing an important food source for the supra-littoral fauna.

The warm-temperate south coast has numerous log-spiral bays, e.g., Mossel Bay, Plettenberg Bay, St Francis Bay and Algoa Bay, with sheltered, reflective-like beaches to the west of each bay, and exposed dissipative-like beaches to the east. Mobile dunes generally form a headland bypass system across each of rocky points at the tip of the bays, parallel to prevailing winds. However, these active dunefields have generally been stabilized; sand



Top: Tylos capensis – a beach isopod that is probably the most threatened/vulnerable macrofaunal species (genus) in South Africa; *Middle:* Yserfontein: dissipative beach along the west coast*; Bottom*: Umhlanga Rocks – inappropriate (too close to the beach) coastal development is taking out the primary dunes and breaking down the links in the littoral active zone.

movement has been retarded, and thus beaches inside the bays are eroding, e.g., St Francis Bay (La Cock and Burkinshaw 1996). The log-spiral bays are generally interspersed with cliffs or rocky stretches of coastline, e.g., Tsitsikamma. There is occasional upwelling along the warm-temperate south coast, which together with high biomass of surf diatoms in well-developed surf zones enhances coastal productivity (Campbell and Bate 1991b, 1997). The Alexandria dune field near Port Elizabeth is a prominent feature because it is one of the largest active coastal dunefields in the world (McLachlan et al. 1982). It is 50 km long and 2.1 km wide, with dunes as high as 150 m (McLachlan et al. 1982).

The southern half of the east coast is exceptionally rocky, with small pocket and embayed beaches that are almost always associated with estuaries. The shoreline in southern KwaZulu-Natal comprises rocky, mixed and sandy shores, with the latter tending to be reflective or intermediate. These morphodynamic types extend up the rest of the province, although several dissipative-intermediate beaches are present north of Richards Bay, and estuaries become sparser. In northern KwaZulu-Natal, the iSimangaliso Wetland Park is the longest stretch (~200 km) of continuous shoreline in the country that falls within a marine protected area. Only localized upwelling occurs along the subtropical east coast (Lutjeharms et al. 2000, Meyer et al. 2002). However, there are no surf diatoms in this region, which limits productivity on sandy beaches (Campbell and Bate 1991c, 1997).

Sandy shores harbour a unique suite of flora and fauna. In terms of the former, the majority of beaches have a benthic microflora (epipelic and epipsammic microalgae) with a transient oceanic-based phytoplankton community (Campbell 1987, Talbot et al. 1990). At beaches with appropriate topography, suitable morphodynamics and sufficient turbulence, augmented by nutrients primarily from groundwater discharge, surf diatoms accumulate into dense masses (Campbell and Bate 1988a, 1988b, 1991a, 1996, 1997, Du Preez 1996) that occasionally can be observed as brown patches in surf foam. Such accumulations raise the primary productivity of sandy beaches, by an order of magnitude, to 100 kg C running m^{-1} y^{-1}, which is similar to the productivity of enriched upwelling coastal areas (Campbell 1987, Campbell and Bate 1988a). With rich phytoplankton communities, sandy beaches can be completely self-sustaining and not require any imported nutrients to support the higher trophic levels (Campbell 1987, 1996).

Primary production by phytoplankton and microphytobenthos, supplemented by carrion, wrack (Koop and Lucas 1983, Dugan et al. 2003) and nutrient exchanges with dunes (McLachlan et al. 1996, McLachlan and Brown 2006), jointly support the discrete interstitial and macroscopic food webs. The former is made up of the least studied and described biotic components of sandy beaches: microbes; benthic protists; and meiofauna. Phytoplankton exudates and other forms of dissolved organic carbon are also utilized by micro-zooplankton in the microbial loop (McLachlan and Romer 1990, McGwynne 1991, Heymans and McLachlan 1996). Micro-organisms play an essential role in many of the ecosystem services provided by sandy beaches, chiefly water filtration, water purification and nutrient cycling (McLachlan 1979, McLachlan 1982, McLachlan et al. 1985, McLachlan 1989, McGwynne 1991, Heymans and McLachlan 1996).

The macroscopic food web comprises zooplankton, macrofauna and top predators. To date, almost 100 macrofaunal species have been recorded from 150 sampled sites in South Africa. The dominant fauna are: crustaceans (isopods, amphipods, ghost crabs, mole crabs and surf-zone mysids), polychaetes and molluscs. Insects and arachnids are often also present, but these are usually opportunistic terrestrial species that come down from the dunes during low tide. Macrofauna species richness on a local sandy shore depends largely on beach morphodynamics with the number of species increasing from reflective to dissipative conditions (Noy-Meier 1979, McLachlan et al. 1993). Macrofaunal communities, particularly on dissipative beaches, provide an important source of prey items for larger fauna.

The top predators in the macroscopic food webs include surf zone fish, birds and some small mammals. Surf zone fish can be exceptionally diverse, with up to 160 species recorded off a single beach, although usually only 1–5 species are true residents (McLachlan and Brown 2006). There are a number of coastal bird species that use sandy beaches as feeding and/or nesting grounds. Opportunistic, migrant mammals, such as jackals, brown hyenas and dune-rodents, scavenge on carrion; honey badgers are known to dig up sea turtle eggs; and Cape clawless otters occasionally hunt along the south coast. All of these top-predator species provide important export linkages between sandy shores and the adjacent marine and terrestrial systems.

It is estimated that the global coastal and marine ecosystem goods and services are worth US$ 21 trillion per annum (Krelling et al. 2008). In South Africa, coast-related products contribute 35% of the country's Gross Domestic Product (DEAT 2000). Goods provided by sandy beaches include: food; salt, mineral and oil resources; construction materials; and biodiversity, including a genetic stock that could have applications in medicine and bioprospecting (Martínez et al. 2007). The primary ecosystem services are: sediment storage and transport; wave dissipation and associated buffering against extreme wave energy from large storms; dynamic response to sea-level rise (within limits); breakdown of organic materials and pollutants; water filtration and purification; nutrient mineralization and recycling; water storage in dune aquifers and groundwater discharge through beaches; protection from harmful algal blooms; maintenance of biodiversity and genetic resources; nursery areas for juvenile fishes; nesting sites for turtles (loggerheads, *Caretta caretta,* and leatherbacks, *Dermochelys coriacea*) and shorebirds, and rookeries for pinnipeds (South African fur seal, *Arctocephalus pusillus pusillus*); prey resources for birds and terrestrial wildlife; provision of scenic vistas and recreational opportunities, particularly supporting tourism; supply of bait and food organisms; and functional links between terrestrial and marine environments in the coastal zone (Campbell and Bate 1997, Schlacher et al. 2008, Defeo et al. 2009). Sandy beaches are therefore exceptionally valuable ecosystems, deserving of far more conservation priority than they have previously been afforded.

This chapter documents the known and unknown physical and biological impacts of climate change on sandy beach ecosystems in South Africa. It also measures the state of knowledge of these pressures acting along our coast against that which is known for beaches globally.

8.2. CLIMATE CHANGE FINDINGS

Sea-level rise and extreme storms represent the most critical climate induced threats because they relate specifically to the key drivers of sandy beaches. Globally, sandy beaches are already threatened by a number of pressures (e.g., Brown and McLachlan 2002, Schlacher et al*.* 2006, Schlacher et al*.* 2007, Schlacher et al. 2008, Defeo et al*.* 2009) and thus impacts of climate change threaten to be synergistically superimposed on an already stressed system, with a compromised resilience. Most threats are human-related, and include: disruption of sand transport; pollution; trampling; recreational activities, including use of off-road vehicles; litter; beach cleaning; mining; groundwater abstraction and pollution; bait collecting; and fishing pressures. This has led to the overexploitation of resources and modification of the coastline to the extent that these unsustainable practices have reduced the resilience of affected ecosystems to natural disturbances (Klein 2001), and have impacted beach faunal communities (e.g., Thomas et al*.* 2001, Dugan et al*.* 2008, Veloso et al. 2008). In South Africa, the pill bug *Tylos* on the west coast appears to be sensitive to human disturbance and is showing signs of potentially disappearing from our shoreline.

International trends show that coastal human populations are expanding more rapidly than inland populations (Small and Nicholls 2003, Schlacher et al*.* 2008). As our population increases, the more difficult it is to attain sustainability in natural ecosystems (Halpern et al. 2008). Some reports even suggest that the socio-economic scenario is of greater consequence than the climate change scenario when looking at the predicted effects for the next century (e.g., Nicholls 2004, Jollands et al*.* 2007).

This means that, in most developed areas along the coastline, there is currently limited adaptation capacity. The most ecologically suitable solution would be a gradual retreat or “coastal realignment”, and expropriation of the inappropriately located buildings. Given the high economic and tourism priorities in some of the coastal urban areas, however, it is unlikely that ecological priorities will take precedence. In these cases, a combined response of hard defence coupled with soft engineering (beach nourishment) will be the likely way forward – at least in the medium term.

8.2.1. SEA-LEVEL RISE

Sea-level rise (reviewed more extensively in Chapter 11) is caused primarily by the thermal expansion of the ocean (Chemane et al. 1997, Cabanes et al. 2001, California Coastal Commission 2001, Edwards 2005) in response to global surface temperature increases (IPCC 2007), melting of polar ice caps and other subsidiary sources (e.g., Munk 2003). Currently, global rates of sea-level rise are accelerating and following the upper limits predicted by the IPCC (Church 2001, Church and White 2006, Rahmstorf 2007, Rahmstorf et al. 2007). The latest sea-level rise predictions by the IPCC are 18–59 cm by 2100 (IPCC 2007). Rahmstorf (2007) suggests that, given the current observational data, these predictions may be too conservative and that it is reasonable to expect a one-meter rise in sea level by 2100. This is a global average prediction, with acknowledgement that some areas will experience more or less sea-level rise depending on local tectonic movements and/or barometric pressure differences.

Sea-level rise is one of the greatest threats to developed sandy shores. Here, beaches lie trapped in a coastal squeeze between inappropriately-located development in the littoral active zone, and rising sea levels. This phenomenon ultimately leads to loss of habitat, fauna and ecosystem services – most notably the loss of nesting grounds for endangered sea turtles (Fish et al. 2008, Rizkalla and Savage 2011) and shore birds. Thus, while sea-level rise itself will not affect the highly adaptable, mobile beach species, the loss of habitat that it causes will (Brown and McLachlan 2002, Dugan et al. 2008). Further consequences of sea-level rise for sandy beaches include: increased beach erosion, dune blowout formation and ultimately, landward beach retreat where the beach is not constrained by development (Hesp 2002); intensified flooding; and increased saline intrusion into groundwater (Gambolati et al. 2002). What is important to stress is that the implications of sea-level rise (coastal squeeze) for beaches are not at a species, assemblage or community scale, but at an ecosystem scale. Furthermore, the extent of this threat is largely determined by the management of the shoreline (Chust et al. 2009).

The implications of sea-level rise for South African beaches and coastal infrastructure have been the focus of recent investigations. This research includes a national assessment of sea-level rise, using all available tide gauge data over approximately the last 50 years (Mather et al. 2009). These calculations show a 1.87 mm y^{-1} rise on the west coast, a 1.48 mm y^{-1} rise on the south coast, and a 2.74 mm y^{-1} rise on the east coast. Harris (2008) did coarse-scale modelling of sea-level rise for KwaZulu-Natal, based on the Bruun Rule (Bruun 1962, 1983, 1988). Model results showed that the backshore (sandy area between the high water mark and dune base) and the upper intertidal were at a high risk of being lost through coastal squeeze. In contrast, where the littoral active zone was intact, no beach loss was predicted as the shoreline migrated landwards. The beaches at risk of coastal squeeze (as a function of being backed by development) have been mapped nationally. These outputs will appear in the ecosystem status report of the National Biodiversity Assessment in 2011.

8.2.2. EXTREME STORMS

There is much debate about whether or not there is an increase in the intensity and frequency of extreme storms or tropical cyclones, with arguments both for (e.g., Knutson et al. 1998, Hoyos et al. 2006, Landsea et al. 2006) and against (e.g., Bijl et al. 1999). The IPCC (2007), however, has predicted an increase in the frequency (decrease in the return period) and intensity of extreme storms.

Storms are important in shaping beaches because they move large quantities of sand from the upper shore and deposit it in the surf zone. This sand is moved back slowly to the beach and dunes during calmer conditions (Brown and McLachlan 2002, Costas et al. 2005, Anfuso et al. 2007). Consequently, many coastlines display erosion-accretion cycles (Anfuso et al. 2007), particularly those that have strong monsoon seasons (Mburu et al. 2009). Depending on the intensity of the erosion event and the local wave energy, recovery of beaches from storms can take up to a decade (Anfuso et al. 2007), and some beach profiles may not fully recover (Costas et al. 2006, Anfuso et al. 2007). During storms, dunes are an important store of sand (Leatherman 1979, Morton et al. 1994), and it is only on beaches backed by dunes that full profile recovery takes place (Morton et al. 1994).

Studies on intertidal beach fauna have shown that storms have little impact on intertidal communities, in spite of changes in habitat morphology (Crocker 1968, Saloman and Naughton 1977). However, the intensity of impact for macrofaunal communities depends on factors such as: intensity of the storm and hence amount of erosion; the frequency of the storms; depth of the underlying bed rock; and the exposure to (or shelter from) the storm, particularly in relation to the angle of wave attack. This could result in extreme localized impacts, with other areas being minimally affected. If the return period of extreme storms decreases as is predicted (IPCC 2007) and insufficient time is available for recovery from a preceding storm event, there could be severe implications for beaches. This would be of particular concern for those beaches that are currently sediment starved and already in a critical state of erosion.

Research on storm-impacts for South African beaches follows international trends, with the focus being primarily on the physical aspects. Numerous publications have detailed the physical impacts of an extreme storm that hit the South African east coast in March 2007 (Smith et al. 2007a, 2007b, Smith et al. 2010). These studies showed that extreme storms move substantial quantities of sand off the beach face. There has only been one South African study examining storm trends, which concluded that there is no clear national trend for increased frequency and intensity of storms (Guastella and Rossouw 2009). Locally, however, there appear to be increases in either intensity or frequency, or changes in seasonal storm intensity (Guastella and Rossouw 2009). There has also been only one study from South Africa that has considered the ecological implications of extreme storms for sandy beaches (Harris 2008). This study showed that macrofauna are able to persist through storms, and that beaches with intact dune cordons are more resilient. Since most studies have focussed on a small spatial and short temporal scale, greater research is required to fully appreciate the extent of the threat that storms pose to sandy beaches.

8.2.3. RAINFALL

As the air warms as a result of increased concentrations of greenhouse gases in the atmosphere, its capacity to hold water vapour increases. There has thus been an increase in the atmospheric water vapour content since the 1980s (IPCC 2007). Consequently, specific humidity is expected to increase approximately exponentially with increasing temperature according to the Claisius–Claperyon relation, whereby a 1 °C increase in temperature leads to a 3.4% increase in precipitation (Huntington 2006). The global increase in precipitation, however, is not spatially or temporally uniform. The IPCC (2007) indicates that some areas are increasing significantly in precipitation, e.g., eastern parts of the Americas, northern Europe and central and northern Asia, while other areas are drying, e.g., Sahel, Mediterranean, parts of southern Africa and parts of southern Asia. As with temperature, it is the extremes that are also changing. Since the 1970s, it has been observed that droughts are longer, more intense and occur over a greater area, particularly in the tropics and sub-tropics (IPCC 2007). In some areas, an increase in precipitation is expected, but this will be as a result of fewer, but intense, precipitation events and longer periods of no rain (Naidu et al. 2006).

The western half of South Africa currently receives less than 500 mm rainfall per annum, which by international standards is arid. Regional climate change predictions indicate decreased rainfall in this western half, and increased rainfall along the eastern escarpment (Naidu et al. 2006). This implies that living conditions along the east coast will be more favourable than in the west and thus, it is predicted that the future east coast population will increase (Naidu et al., 2006). Increasing populations threaten to put strain on already limited resources, and have serious implications for land use change. In KwaZulu-Natal (KZN), the last 12 years have already seen a 22% increase in coastal urbanization in the 100-m strip inland of the high water mark (Celliers, pers. comm.). Maps of the conservation status of vegetation types in KZN show a band, approximately 50 km from the coast (excluding the northern third of the province), that has mostly been transformed from endangered to critically endangered in the last five years (Kohler 2005). In addition to rapid development, this province is associated with the greatest rate of sea-level rise in the country (Mather et al. 2009). Unless managed appropriately, KZN will be particularly at risk of losing its beaches to coastal squeeze, along with the associated biodiversity, ecosystem goods and ecosystem services.

Additional consequences of changes in rainfall patterns, particularly prolonged periods of drought, are that the amount of sediment and nutrients reaching the coast from estuaries will be reduced owing to reduced run-off and river flow. This will exacerbate the problem of sediment starvation on beaches, reducing their resilience to pulse disturbances such as storms. In contrast, heavy rainfall events will flood down estuaries and through storm water pipes, promoting erosion on beaches. Periods of excessive rainfall can also destroy turtle nests (Ragotzkie 1959, Kraemer and Bell 1980). The threatened (*Caretta caretta*) and endangered (*Dermochelys coriacea*) turtles that nest in South Africa haul out on the east coast (in northern KwaZulu-Natal), where rainfall is likely to increase (Naidu et al. 2006). A final, but subtle consequence of changes in rainfall include potential alterations in groundwater dynamics. The flow of water through these aquifers is critical for the formation of highly productive surf diatom accumulations, and thus for food web dynamics on sandy beaches.

8.2.4. WIND FIELDS AND CURRENTS

The mid-latitude westerly winds have strengthened since the 1960s, in both the northern and southern hemispheres (IPCC 2007). There is very little published information on wind fields and currents that relates specifically to beaches, either globally or in South Africa. One can surmise that changes in the strength and direction of local wind fields could lead to: accretion/erosion of beaches; changes in dune structure and mobility; and promotion or retardation of aeolian sand transport through headland bypass systems. Changes in wind fields could also have a bearing on local wave climates and ocean currents, with implications for alongshore drift of sediment (Theron and Rossouw 2008), upwelling (Rouault et al. 2010), and connectivity of macrofaunal populations that may be/are connected by pelagic larvae. Knock-on effects include the spread of marine invasive species whose larvae are dispersed (partly) by wind-driven currents (McQuaid and Phillips 2000).

Theron and Rossouw (2008) describe the potential implications of changes in wind regimes and currents for the drivers that shape the South African shoreline. They estimate that a wind speed increase of 10% could cause: a 26% increase in wave height; an 80% increase in wave power; and a 40–100% increase in the rate of across-shore sediment transport. If the volume of sand eroded off beaches increases by 50%, this could result in approximately a 50% increase in the across shore distance of shoreline erosion (Theron and Rossouw 2008). Beaches globally are mostly in a state of erosion (Bird, 2000). Between altered sediment budgets, sea-level rise and ever-expanding coastal development, beaches are exceptionally vulnerable to coastal squeeze (see section 5.2.1). The predicted increase in erosion through changes in wind-regimes (Theron and Rossouw 2008) is thus likely to exacerbate an already significant threat to sandy shores.

Changes in winds may also influence upwelling cells, which could alter nutrient delivery to beaches. Mote and Mantua (2002) considered two models that both predicted no changes in upwelling. The authors concluded that climate models are not sufficiently developed to accurately model this phenomenon. More recently, however, Rouault et al. (2010) were able to show that measured changes in sea surface temperature around South Africa for the last two decades can be linked to altered wind regimes. Increases in easterly and southeasterly winds that promote upwelling are significantly correlated with cooling in the southern

Benguela and the southeastern coast seas (Rouault et al. 2010). Since southeasterly and easterly winds are stronger during La Niña and weaker during El Niño, these events are also likely to play a role in modulating local nutrient regimes by respectively promoting and retarding upwelling (Rouault et al. 2010). In contrast, the poleward shift of the westerly winds and the increase in trade winds in the South Indian Ocean have contributed to intensification of the Agulhas Current, which in turn has caused a warming of the seas along the South African east coast (Rouault et al. 2010). Thus, while largely unexplored, the ecological implications of changes in wind and current regimes for sandy shore biota appear to be significant, and potentially dramatic.

8.2.5. TEMPERATURE

There is evidence of localized cooling (west coast) and warming (east coast) of the coastal oceans around South Africa (Rouault et al. 2009, 2010). However, it is unlikely that changes in temperature will have an effect on sandy beaches from a faunal/community point of view, because few beach species live at their upper thermal limits, and they can burrow if surface conditions become too harsh (Brown and McLachlan 2002). Other drivers of species distributions are far stronger, such as sand grain size and beach morphodynamic type. Given that there are three bioregions that cover large sections of the South African coastline, it is unlikely that any of these will disappear completely. It is more likely that the bioregional boundaries will shift. Since species distributions are broadly linked to temperature, it is possible that there will be localized modifications of species assemblages, particularly around the biogeographic breaks. Any other implications of altered sea-surface and ambient temperatures for sandy beaches are more likely to be indirect. For example, it has been shown that warmer weather is associated with an increase in the number of beach visitors (Moreno et al. 2008, Coombers et al. 2009), which will heighten trampling and disturbance pressures on biota (Coombers et al. 2008).

One of the only direct effects of changes in temperature will relate to the sex ratios of sea turtles. During the middle-third of the incubation period of the eggs, the temperature of the beach sand around the nest determines the sex of the hatchlings, and consequently the ratio of males to females in the population. The pivotal temperature (for a 1:1 ratio), measured in South Africa, is approximately 28 ºC (Maxwell et al. 1988). Elevated temperature thus has the potential to cause a female-bias in turtle populations.

8.3. KEY TRENDS AND ASSOCIATED VULNERABILITIES

8.3.1. SUMMARY OF PREDICTIONS AND VULNERABILITIES FOR SANDY BEACHES IN SOUTH AFRICA

Inundation, Erosion and Coastal Squeeze

- Beaches that are constrained by hard structures, such as sea walls, coastal infrastructure or buildings, or cliffs will be trapped in a coastal squeeze. The backshore beach area will be inundated and the upper intertidal zones will be compressed. In a worst case scenario, the whole beach (locally) will be inundated, biota lost and ecosystem services halted.
- The increased intensity and frequency of storms, coupled with sea-level rise, will present a synergistic erosive force that could remove large quantities of sand off the beach face. This will exacerbate the retreat tendency of beaches in unconstrained areas, and will increase the risk of damage to coastal infrastructure in developed areas.
- Reduced rainfall in the western half of the country and increased rainfall along the east coast will likely make the latter a more favourable place to live. This will likely lead to increased development in the coastal zone, which will exacerbate the effects of coastal squeeze in this area.
- Pulse rainfall events will promote erosion on beaches, particularly where there are estuaries and/or storm water outlets.
- Increased wind speeds can raise local sea level by wind setup, thereby increasing beach inundation.

- Wind-related increase in wave height and wave energy will promote erosion of sandy shores. In addition, a change in wind regimes could alter the sediment-movement dynamics through mobile coastal dunefields.
- Saline intrusion into groundwater and altered groundwater flow can be expected.

Impacts to biota

- Changes in sediment composition and beach slope/close shore bathymetry from continued erosion could alter the local beach morphodynamics of the system, and hence cause shifts in the local assemblages of infauna.
- Inundation due to sea-level rise of some beaches will increase the isolation of adjacent beach faunal populations by increasing the distance to the next beach (of the same kind).
- If the frequency and intensity of extreme storms increases, beaches will erode and will not have sufficient time between events to recover to pre-storm morphology. If the erosion is significant enough to remove all the sand off the shallow-lying bedrock, it will cause a local, likely temporal extirpation of the biota.
- Increased storm activity could increase the amount of pollution and wrack on sandy beaches.
- Salinization or alteration of groundwater flow will result in reduced biomass of surf diatoms. This could result in replacement of surf diatom accumulations with harmful algal blooms at the extreme, or cause a switch in beach function from being an exporting to a depauperate system, with knock-on implications for coastal processes at a large scale (e.g., nursery function).
- It is possible that elevated temperatures could cause shifts in species distributions. This may have implications for subsistence and commercial harvesting of beach-associated resources. These effects may be limited, however, given the fairly small scale of these fisheries in South Africa (Clark et al. 2002).

Impacts to turtle and shorebird nesting grounds

- It is unlikely that the turtle nesting beaches will be lost, because they are currently backed by sand dunes and the beaches are unconstrained. This translates into a high resilience and adaptive capacity of the local ecosystem. It will be imperative that these beaches remain undeveloped to allow for natural shoreline retreat. Nesting grounds of shorebirds, that are currently developed, will be at risk in the future.
- Extreme wave conditions from storms could destroy sea turtle nests in northern KwaZulu-Natal, and shorebird nests elsewhere in South Africa.
- Excessive rainfall periods could kill the developing turtle eggs in northern KwaZulu-Natal.
- Elevated temperatures may increase the number of female turtle hatchlings produced relative to the number of males.

8.4. RESEARCH AND RESOURCES REQUIRED TO BETTER ASSESS POSSIBLE IMPACTS

8.4.1. WAY FORWARD

There are a number of gaps in our understanding of climate change impacts for sandy beaches. This is largely a consequence of a currently limited understanding of certain aspects of the ecosystem functioning and processes. For example, it is difficult to determine the effect that shifts in current patterns will present for sandy beach connectivity, when the mechanism and process of beach connectivity is currently not understood. There is a need for more research that takes an ecosystem approach at a national scale, to fill the following gaps:

- Accurate modelling of sea-level rise impacts nationally.
- Species distributions and biogeographic patterns, and thermal tolerances / bioclimatic envelopes of species.
- Mechanism of beach population connectivity.
- Calculation of local sediment budgets (as an indication of resilience to erosion and storm impact recovery potential).

8.4.2. SCOPE FOR BEACH CONSERVATION

Sandy beach conservation in South Africa is particularly well legislated. The White Paper on Sustainable Coastal Development of 2000 (DEAT, 2000) and the recently enacted Integrated Coastal Management Act (RSA, 2009) can be applied to managing the coastline and regulating coastal development into the future. There has been a national ban of off-road vehicle (ORV) driving on sandy beaches, except at boat launch sites and for permitted activities, e.g., access for disabled persons (DEAT, 2001). Thus, in spite of the poor public awareness and general lack of understanding of sandy beaches as ecosystems by most people, there is some recognition of the importance of conserving beaches, even if this is motivated largely by human interests along the coast.

9. ROCKY SHORES AND KELP BEDS

Angela Mead & Tamara Robinson

9.1. INTRODUCTION

Rocky shores and kelp beds are ocean margin ecosystems that co-exist in close association across a range of temperate and polar regions. Rocky shores are intertidal ecosystems located between the high and low tide lines of coastal regions.They are divided up into high, mid and low-intertidal zones based on the dominant physical and biological processes that form a gradient across the shore. The sublittoral fringe, located at the seaward edge of the rocky intertidal zone, marks the upper limit of kelp bed ecosystems which extend into the sea to depths that can exceed twenty metres. Both ecosystems are considered amongst the most physiologically and physically stressful for the organisms that survive there (Dayton et al. 1998, Helmuth and Hoffman 2001, Scavia et al. 2002, Przeslawski et al. 2005). Natural physical stressors experienced by organisms in both ecosystems include changes in sea and air temperatures over a variety of temporal scales, fluctuating nutrient and light levels, circulatory patterns, and upwelling and wave action (e.g., Dayton et al. 1998, Witman and Smith 2003, Kitzes and Denny 2005, Leslie et al. 2005, Wernberg and Goldberg 2008).

Within the rocky intertidal, a large diversity of faunal and algal taxa are found, the majority of which have pelagic larval life stages but live as sessile or sedentary juveniles and adults. Dominant taxa include foliose and crustose algae, crustaceans, molluscs, polychaetes, echinoderms and ascidians. Different species assemblages are found within high, mid and low-intertidal zones, and the structure of species assemblages is influenced by competitively dominant species. While rocky intertidal organisms are ectotherms, with their evolutionary roots in marine habitats, they must contend with the challenges posed by exposure to both oceanic and atmospheric conditions.

The changing face of rocky shores. Top & middle: On the west coast in particular, three major invaders dominate the species assemblages: *Balanus glandula*, *Mytilus galloprovincialis* and *Semimytilus algosus*. *Bottom:* remnant *Perna perna* population in False Bay; a small population of adults left behind following a range edge recession over the past 20 years. (Photos by Charles Griffiths)

Dominant kelp species contribute most of the structure and productivity within kelp ecosystems, forming dense forests that create habitat and provide nutrition for numerous species (Dayton 1985, Foster and Schiel 1985). Vertical zonation with increasing depth exists in kelp beds, possibly linked to the relationship between light penetration, sea temperature and nitrate concentrations (Dayton et al. 1984, 1992). Physical stressors impact the survival and fecundity of adult kelp plants, as well as sporophyte germination and growth rates. This leads to variability in the distribution and abundance of kelp canopy cover, which ultimately impacts community structure (North et al. 1993, Dayton et al. 1998, Tegner et al. 1996). In addition, a series of cascading biotic relationships that control community structure have been identified within kelp bed communities, the most well known of which is the feeding relationship between otters, urchins and kelp in Californian and Alaskan systems (Foster and Schiel 1988, Foster, 1990).

The two ecosystems are intricately linked. Along the west coast of South Africa, rocky intertidal ecosystems rely on kelp beds to provide nutrients in the form of particulate organic matter (POM) from kelp drift and for direct grazing (Bustamante et al. 1995, Bustamante and Branch 1996). The presence of kelp within the water column influences localized flow patterns (currents and waves) and therefore transportation and recruitment of pelagic larvae into both the kelp bed and rocky intertidal systems (Dayton et al. 1998).

9.2. CLIMATE CHANGE FINDINGS

Several key drivers of climate change have been implicated in altering the long-term climatic regimes that drive physical processes in ocean margin regions (Scavia et al. 2002, Helmuth et al. 2006, IPCC 2007). Shifting trends in regional temperatures have direct impacts on organisms within ocean margin ecosystems. However, temperature change also drives change in other climatic parameters, such as atmospheric pressure, wind, precipitation and circulatory patterns (e.g., Rouault et al. 2009). This translates, indirectly, into changes in the range of physical stressors experienced by the organisms within these systems. Examples of indirect impacts include regional changes in nitrate concentration, the frequency and intensity of coastal storms, sediment transportation, wave action, upwelling processes and sea-level rise.

9.2.1. TEMPERATURE

Shifts in environmental gradients are cascaded down to individuals at various life stages through altering physiological, morphological and behavioural responses. In turn, impacts on individuals can scale back up to population level responses (for example, shifts in abundance and distribution). In the case of a key structural or functional species, this can significantly alter the composition and dynamics of overall species assemblages (e.g., Hawkins and Hartnoll 1983, Sagarin et al. 1999, Edwards, 2004, Simkanin et al. 2005, Harley et al. 2006). On this basis, it is generally agreed that an integrated approach is required in order to understand climate change impacts on ocean margin ecosystems. Temporal and spatial changes in the underlying environmental gradient must be linked to the physiological and ecological responses of individuals and communities within these ecosystems (Helmuth et al. 2006, Mieszkowska 2009).

Based on a ‘climate envelope’ model, long-term change in underlying environmental gradients could fall within or outside the physiological tolerance range of a species living within rocky intertidal or kelp bed ecosystems (Pearson and Dawson 2003). If the shift is significant or fast enough to favour population level increases or decreases over species acclimation or genetic adaptation, then the result would be range extensions or contractions respectively (Walther et al. 2002). However, range extensions would depend on species interactions within the community assemblage, habitat type or connectivity and larval dispersal mechanisms in order for niche realization to occur (Helmuth et al. 2002, Mieszkowska 2009).

Within rocky intertidal ecosystems, climate change driven species shifts have been detected across several regions, including Europe, America, the Arctic, Australia and New Zealand (Helmuth et al. 2006, Mieszkowska 2009). Species which are close to their thermal limits are being lost from or introduced into community assemblages, and this has been strongly linked to regional warming of both sea and air temperatures (Helmuth et al. 2006, Mieszkowska 2009). In temporal regions, the overall effect has been poleward shifts in the biogeographic ranges of intertidal species at rates of up to 50 km per decade. The resultant contractions in the distributional range of cold-water adapted species have led to population loss from lower latitude assemblages and increased abundances at poleward range limits (Barry et al. 1995, Kendall et al. 2004, Shinen and Morgan 2009). Conversely, both native and non-native warm-water adapted species have extended their ranges into new regions, thus representing new influxes of species into assemblages (species creep).

In addition, Sagarin et al. (2006) documented within-range-shifts that result in pocket extinctions along the biogeographic range of intertidal species. Also, decreased abundances of cold-water adapted species relative to warm-water adapted species have been detected and demonstrated, through in-field experimentation, to significantly impact biotic interactions (Southward et al. 1995, Moore et al. 2007, Hawkins et al. 2008). Besides changes in the horizontal distribution of species, vertical squeezing of the upper limit in rocky intertidal species, due to increasing air temperatures, has been recorded (Harley 2003).

Range-edge and within-range shifts in direct response to temperature change are evident in kelp bed ecosystems located in the northeastern Pacific. Although it has been difficult to tease long-term responses apart from fisheries activity and the short term impacts of extreme weather events, increasing water temperatures have negatively impacted carrying capacity, densities and size of dominant cold water kelp species (Tegner et al. 1996, 1997, Dayton et al. 1998). This is thought to be due to nitrate concentrations decreasing as water temperature increases, which limits growth. Conversely, biomass of the warm water kelp, *Ecklonia radiata*, is positively correlated with increasing sea temperature (Wernberg and Goldberg 2008). Sea and air temperatures are also known to influence reproductive and recruitment success in both ecosystems (Mieszkowska et al. 2006, Broitman et al. 2008).

In order to accurately predict the rate and extent of biogeographic shifts, an understanding of why a population-level response has occurred is pivotal. Species ranges are defined by a combination of physical and ecological factors which act on important physiological processes such as reproduction, dispersal, recruitment and mortality (Lindquist 1986, Mieszkowska 2009). Both molecular and bio-indicator technologies have advanced rapidly over the last decade. Hence, underlying mechanisms are being effectively elucidated in both the laboratory and field.

One such technique is the use of a group of molecular chaperones, the ‘heat shock’ or ‘stress’ proteins in detecting the thermal responses of organisms to heat stress. Families of stress protein, such as HSP70, contain inducible forms that express at threshold temperatures representing extremes of the physiological temperature range tolerated by the intertidal organisms studied. Thus, they can be used as a measure of thermo-tolerance within species (e.g., Hofmann and Somero 1996, Chapple et al. 1998, Buckley et al. 2001, Sagarin and Somero 2006). Inducible expression is related to the role of stress protein in refolding or preventing aggregations of thermally denatured cell proteins (Parsell and Lindquist 1993, Feder and Hofmann 1999). HSP70 has been demonstrated to be effective at detecting thermal stress over a variety of spatial and temporal scales and has proven effective when used for mussels belonging to the *Mytilus* genus (Halpin et al. 2002). Recent advances in the use and application of bio-indicators includes monitoring heart rate response up to lethal levels in response to thermal fluctuation and the use of protein labelling using ‘gene chips’ to detect impacts of temperature on different metabolic pathways (Dahlhoff et al. 2002, Braby and Somero 2006a, 2006b, Field et al. 2006).

9.2.2. SEA-LEVEL RISE, WAVE FORCE, EXTREME WEATHER EVENTS AND UPWELLING

Increasing wave force, which will add physical stress to both rocky and kelp bed ecosystems, is due to an increase in storm frequency and rising sea levels. Within both systems, an increase in disturbance events will clear species from large areas, promoting patchiness. Therefore increased storm frequency may favour short lived, faster growing species in both systems as succession periods will be significantly reduced (Roughgarden et al. 1987, Dayton et al. 1998, Menge and Olson 1990, Edwards 2004). Sea level along the South African coast is predicted to increase between 0.5 and 1.4 m above 1990 levels by 2010 (Rahmstorf 2007, Theron and Rossouw 2008). On rocky shores, this may alter the lower vertical limits of a species, due to increasing submergence periods.

There is a concern that rising sea level and increased frequencies of storm events may transport significant amounts of sediment up and down coastlines (Drinkwater et al*.* 2009). In the northeastern Pacific, significant amounts of substrate which stabilize kelp beds have been removed and scouring of kelp has led to reduced canopy cover which impacts community structure (Dayton et al. 1998). Additional sediment loading in the water column impacts light penetration and has reduced biomass and canopy cover of the kelp, *Ecklonia radiata* (Wernberg and Goldberg 2008). In rocky intertidal systems, sand inundation due to storm driven sediment transportation is predicted to impact community structure. Some algal turfs appear to survive better when buried by sand (Norris 1983) and sand tolerant species have been found to dominate over sand intolerant species which are sensitive to smothering and scouring (Bally et al. 1984).

The impacts of extreme weather events are evident in both rocky and kelp bed ecosystems. As these events are infrequent and operate over short temporal scales, they are set apart from community responses to longer-term temperature regime shifts. For example, the occurrence of sub-zero temperatures in Britain in 1962 and 1963 impacted northern range limits of rocky intertidal species, although recovery has since been observed. Other species have experienced large scale mortalities in response to heatwave events but exhibit no significant abundance shifts or mortalities in response to less severe increases in air temperature (Crisp 1964, Sandford 2002, Edwards 2004).

Kelp bed ecosystems in the northeastern Pacific have been impacted both by the unpredictable and low frequency El Niño Southern Oscillation (ENSO) and severe storm events. Short-term increases in sea temperatures associated with ENSO resulted in reduced available nitrates that are used by the kelp during growth. The reduction in canopy cover was evident over scales of a few metres to over 1000 km. However, full recovery was evident within 6–12 months (Tegner et al. 1996, 1997, Edwards 2004). In addition, sand scour and wave action due to storms removed large areas of canopy cover, understory and drift kelp, which in turn led to increased feeding of urchins on live kelp (Tegner and Dayton 1991, Dayton et al. 1998).

Differences in larval supply influence the distribution and abundance of intertidal organisms (Roughgarden et al. 1988, Menge et al. 1999). In turn, larval supply is impacted by local offshore currents, upwelling patterns and levels of wave action, all of which are being affected by climate change. Thus, shifts in temperature and oceanographic regimes are predicted to impact recruitment success in species such as barnacles and mussels (Roughgarden et al. 1988).

9.2.3. CLIMATE CHANGE AND MARINE INTRODUCTIONS

Climate change driven disturbance may increase the vulnerability of natural communities to marine introductions (Carlton 1996). Should range recessions and within-range impacts, in response to shifting climate regimes, open resource niches and reduce biodiversity through the removal of indigenous species, they could be open to an influx of marine introduced species (Kennedy et al. 2002, Stachowicz and Byrnes 2006, Occhipinti-Ambrogi 2007). Shifts in atmospheric CO_2 are changing the chemistry of sea water by decreasing oceanic pH (Occhipinti-Ambrogi 2007). As a result, the levels of minerals essential to calcifying organisms are changing, and calcification rates of intertidal organisms, such as coralline algae, are decreasing (Feely et al. 2004). Such disturbances may also increase the vulnerability of natural communities to marine introductions (Carlton 1996). Following the establishment of introductions, alterations in the structure and functioning of native communities and ecosystems can be expected (Occhipinti-Ambrogi 2007). Just as changes in temperature and oceanographic regimes have been shown to result in the range expansion of indigenous species (Firth et al. 2009, Ling et al. 2009), they have also been implicated in the spread of introduced species (Bachelet et al. 2004). Once established these non-native organisms may alter productivity, nutrient retention and cycling, habitat structure, biodiversity and community stability (Grosholz 2002, Castilla et al. 2004, Ruesink et al. 2006, Robinson et al. 2007).

It is known that temperature regimes may cause the delay or complete failure of recruitment of indigenous species (Philippart et al. 2003). This may favour the recruitment success of marine introduced species, such as the establishment of introduced populations of the Japanese oyster *Crassostrea gigas* that has been attributed to unprecedented increases in water temperature (Shatkin et al. 1997). Additionally, changes in circulation patterns or local oceanographic features such as upwelling may alter dispersion routes of larvae (Zacherl et al. 2003), again potentially facilitating the recruitment of introduced organisms.

9.3. CLIMATE CHANGE FINDINGS SOUTH AFRICA

In South Africa, the biogeographical ranges of both cool-water and warm-water adapted macrofauna and algae within each system are relatively well known, and coastal biogeographic regions have been defined, albeit with discrepancies in number, naming, and boundary definition (e.g., Emanuel et al. 1992, Stegenga and Bolton 1992, Bustamante and Branch 1996, Bolton et al. 2004, Lombard 2004, Sink and Branch 2005). For the purposes of this report, the biogeographic regions, as defined by Lombard (2004) and Sink and Branch (2005), have been slightly modified. There are four main biogeographic regions with two transition zones located between provinces (Figure 9.1). They are defined as the cool-temperate province of the west coast (CTP), the False Bay transition zone (TZ1), the warm-temperate province of the southeast coast (WTP), the East London transition zone (TZ2), the sub-tropical province of the east coast (STP) and the tropical province of the northeast coast (TP).

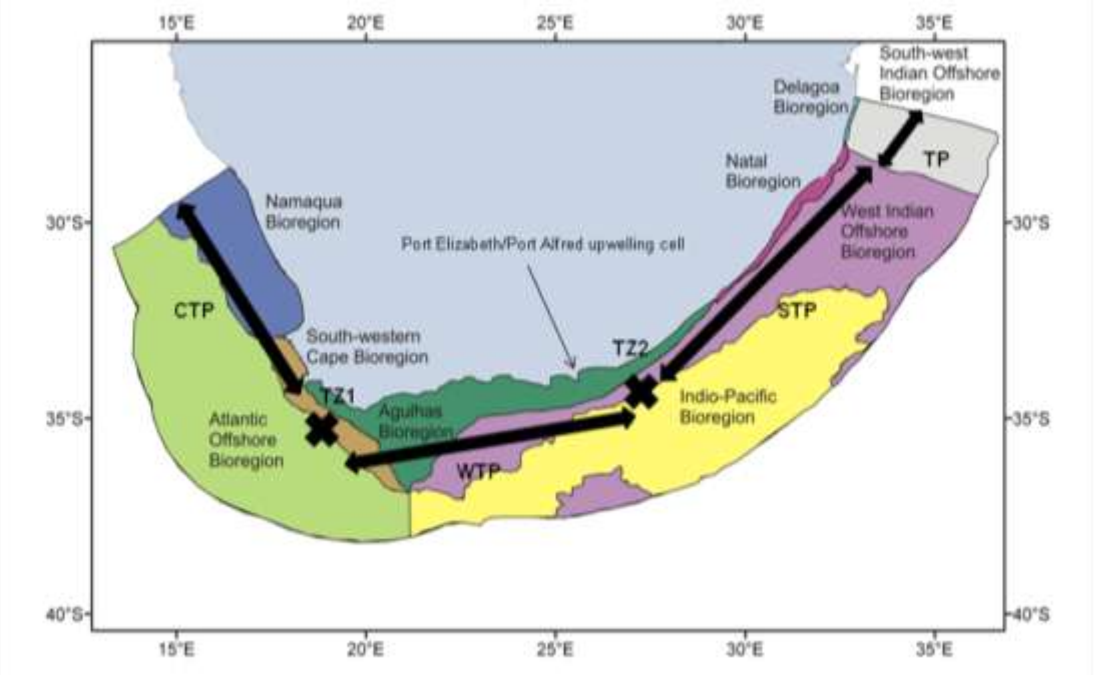


Figure 9.1 Biogeographic provinces of the South African coast. Note: CTP = cool-temperate province, TZ1 = transition zone 1, WTP = warm-temperate province, TZ2 = transition zone 2, STP = sub-tropical province and TP = tropical province

Two major gradients have been established horizontally across South African rocky shores. Productivity and biomass decrease from the west to east coast, whereas biodiversity increases. This has been linked to wave action and temperature (McQuaid and Branch 1984, Bustamante and Branch 1996, Bustamante et al. 1997). McQuaid and Branch (1985) and Bustamante et al. (1995)

have established that the dominance of a functional feeding group within a rocky shore community is linked to wave exposure. In addition, recruitment patterns of both introduced and indigenous mussels have been studied comprehensively (McQuaid and Phillips 2000, 2006, Porri et al. 2006, Nicastro et al. 2008). Several studies have focused on community and species level interactions and their mediation by physical stressors (Bownes and McQuaid 2006, Ruis and McQuaid 2006, Xavier et al. 2007, Zardi et al. 2006, 2007). Pollock and Shannon (1987) described the influx of lobsters into shallow kelp bed systems in response to low oxygen events which were potentially linked to shifts in upwelling and sea surface temperatures. Kelp beds were surveyed from the west to the southeast coast, establishing a southern gradient in the dominant species within communities (Field et al. 1980). Following on from this research, links were established between South African cold and warm water kelp species, associated communities and physical stressors such as upwelling, storms, temperature and wave exposure (Bolton 1986, Bolton and Anderson 1987, Bolton and Anderson 1997).

Branch (1984) considered the impacts of an extreme weather pattern anomaly that resulted in a short term significant increase in temperature along the coast as far as East London. This study used both quantitative and qualitative data as a benchmark and detected mass mortalities for the indigenous black mussel, *Choromytilus meridionalis*. However, in the case of the warm water gastropod, *Oxystele tabularis,* and the limpet, *Scutellastra longicosta,* a southwesterly range extension was observed. Recruitment patterns shifted for the limpet, *Scutellastra oculus,* and a recruitment failure at the range edge of the limpet, *Scutellastra granatina,* was noted in False Bay.

Mead (2011) compared long-term intertidal species data from 1930–1990, with recent sampling undertaken between 2007 and 2009. Results indicated that the numbers of cool-water species have increased, whereas warm-water adapted species have decreased on the west and south-east coast; this has been linked to cooling of near-shore temperatures within these same regions (Rouault et al. 2009).

A finer scale re-survey within False Bay (Mead et al. 2011a) has indicated that the indigenous warm-water mussel, *Perna perna,* has undergone a significant range contraction toward the northeast post 1987 (Figure 9.2). In parallel, the cool-water kelp, *Ecklonia maxima,* and the marine introduced Mediterranean mussel, *Mytilus galloprovincialis*, now dominate along the west and southeast coast (Figure 9.2).

Figure 9.2 *Perna perna* (brown indigenous mussel) and *Mytilus galloprovincialis* (introduced mussel) abundance at the same site in False Bay: (a) 1990 and (b) 2009. Climate change has been proposed as one of the forcing factors behind distribution shifts in these two species.

Mytilus galloprovincialis is considered a relatively cool-water adapted species on South African shores. Shifting temperature regimes and competition have been proposed as the most probable factors behind the shifts observed, further supported by differences in the physiological thermal responses of the two species (Mead et al. 2011a). In South Africa several studies have experimentally quantified the impacts of temperature on the energetics of both indigenous and introduced mussel species within the lab (Hockey and van Erkom Schurink 1992, van Erkom Schurink and Griffiths, 1991, 1992, 1993). The outcome of the thermal response study offers further insight into the response of these organisms to reducing sea surface temperatures and how that may feed back into the quality of reproductive output, population levels, responses and species level interactions (Mead 2011).

It is highly probable that marine introductions took place in South Africa over the first 400 years of European colonial history, as the region lies along major shipping routes, and shipping is a well-documented vector of marine introductions (Occhipinti-Ambrogi and Savini 2003, Wonham et al. 2000, Wonham and Carlton 2005). Given this fact, it is interesting that both the introduced mussel, *M. galloprovincialis*, and introduced barnacle, *B. glandula*, did not establish populations on South African coasts until 1979 and 1992 respectively (Griffiths et al. 2009, Mead et al. 2011b). The temporal signal for their successful introduction has not been established to date but could be linked to climate change (Occhipinti-Ambrogi 2007). Several publications have attempted to progressively quantify numbers of introduced and cryptogenic species within South Africa (Griffiths et al. 1992, Griffiths 2000, Robinson et al. 2005, Griffiths et al. 2009). However, a recent effort, which involved the expansion of methods used to detect introductions and cryptogenics revealed the presence of 85 and 40 species respectively (Mead et al. 2011b).

There are no studies specifically looking at climate change driven range shifts within South African kelp beds to date or investigating vertical zonation shifts in response to changes in air temperature and sea-level rise. However, baseline studies into species diversity within kelp beds do exist. In addition, the questions of within-range impacts and the impact of oceanographic and intertidal regime shifts on larval recruitment processes have yet to be investigated within a climate change context.

To summarize, South Africa has a rich body of both historic and contemporary research that can form baselines for temporal comparisons, act as a ‘springboard’ for developing future climate change research themes and testable hypotheses, and be used to facilitate interpretation of the measured results arising from future climate change focused research. This is true for both rocky intertidal and kelp bed systems.

9.4. KEY TRENDS AND ASSOCIATED VULNERABILITIES

The forecasts presented within this section are based on measured shifts in climate change regimes and community to species level responses predicted or observed in both the international and South African literature. Testable hypotheses for both rocky intertidal and kelp bed ecosystems have been formulated under two broad research themes that are appropriate for the region:
(i) Biogeographical impacts and (ii) Marine introductions.

9.4.1. BIOGEOGRAPHICAL IMPACTS

- If near-shore temperatures continue to cool along the west and southeast coast, further range edge and within-range impacts will be evident.
- If near-shore temperatures continue to warm along the east coast, southern creep of non-native tropical species from Mozambique will occur, and native tropical species will extend their range southward, as far as Port St Johns.
- In response to continued rising air temperatures, vertical shifts will occur in the rocky intertidal. Species located high on the shore in regions where they are at their thermal limits will experience upper limit squeeze and may be forced downshore or be lost from species assemblages.
- If sea-level rise continues and wind pattern, rainfall and pressure system shifts favour increasing storm intensity and frequency, vertical

shifts will occur in the rocky intertidal. Species located on the low shore will experience prolonged immersion periods, altering their lower and upper distributional limits.

- Increased storm intensity and frequency will lead to reduced canopy cover and patchiness in kelp bed systems in response to wave force and sand scouring. Rocky intertidal systems will experience community change where sand inundation occurs and increased spatial heterogeneity due to reduced succession periods.
- The strengthening Agulhas Current and increased upwelling intensity and frequency will impact larval dispersal and recruitment success which will lead to range impacts around the coast.
- Range impacts expected for kelp bed ecosystems are likely to significantly influence fisheries (for example the lobster fishery) and may affect the abalone industry which relies on kelp as a major food source.

9.4.2. MARINE INTRODUCTIONS AND CLIMATE CHANGE

- Accelerated rates of establishment and spread of marine introduced species with both cool and warm-water affinities will occur in response to long-term shifts in sea and air temperatures.
- Shifts in the underlying regional environmental gradient in response to climate change will lead to significant measurable differences in the biological interactions between introduced and indigenous species.

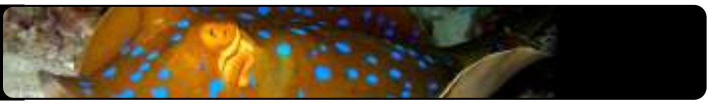
9.5. RESEARCH AND RESOURCES REQUIRED TO BETTER ASSESS POSSIBLE IMPACTS

In order to test the hypotheses above with confidence, several key areas of research are required:

- Ongoing quantitative monitoring programs over a variety of temporal and spatial scales are required for both rocky intertidal and kelp bed ecosystems. They must be carefully planned to ensure that they are statistically sound in order to make spatio-temporal comparisons with confidence. Both of these ecosystems are easily accessible and do not require complex specialist equipment. Therefore surveys of this nature are relatively simple and cost effective.
- In order to continue to detect both historic and new marine introductions, rapid surveys across all marine habitats are required which combine the expertise of global and South African taxonomic specialists. In addition, there is a need to make an in-depth study of all historical documentation pertaining to marine introduced species.
- Physiological field and laboratory studies need to continue and expand focus in order to further mechanistic understanding of why population-level range responses are occurring. Laboratory based experiments do require specialist equipment and chemicals, as well as large-scale functioning aquaria, and this currently represents a major gap in climate change based research within South Africa.

If climate change research within ocean margin systems is to be developed as detailed above, appropriate local and international funding is vital and collaborations between institutes should be encouraged. The availability and retention of well qualified researchers is paramount for the success of long-term monitoring programs and effective co-ordination of ocean margin system climate change research. There are research opportunities described above that will produce results over relatively short periods of time. Thus, the potential for capacity building through training is massive.

10. SUBTIDAL FISHES



Warren Potts & Albrecht Götz

10.1. INTRODUCTION

The subtidal zone is the marine habitat between the low tide mark and the continental shelf and is also referred to as the marine coastal zone. Although this zone represents only 7.6% of the world’s ocean habitat (Yool and Fasham 2001), it is considered to be one of the most socio-economically and ecologically important ecosystems on the planet (Harley et al. 2006). The subtidal zone provides essential ecosystem services such as habitat and food for both resident and migratory animals, and both recreational and commercial opportunities for human populations. Globally, Costanza et al. (1997) estimated the value of the goods and services provided by the marine coastal zone at over USD 14 trillion. When compared with the offshore environment, coastal areas are characterized by high levels of productivity and biodiversity as a result of their shallow nature and more diverse range of habitats. It is therefore unsurprising that the majority of marine taxa occur in this ocean zone (Ray 1991). The marine coastal zone supports subsistence, small scale, artisanal, recreational and commercial fishing activities. These fisheries are not only significant in terms of local livelihoods (Béné 2003, Stobutzki et al. 2006, Glavovic and Boonzaier 2007), but also provide significant benefits to local and national economies (McGrath et al. 1997, Costanza et al. 1999, Glavovic and Boonzaier 2007, Potts et al. 2009).

The South African subtidal zone is no exception. In terms of biodiversity, Turpie et al. (2000) estimated the number of coastal fish species in South African waters at approximately 1 239, with a progressive decrease in the number of species from the Mozambican border via Cape Point to the Namibian border. Based on this distribution, Turpie et al. (2000) divided the South African coast into a west coast zone (from Cape Point to the Namibian border), a south coast zone (west from Cape Point to the KwaZulu-Natal border) and an east coast zone (between the KwaZulu-Natal border in the

Top & middle: Juvenile *Chrysoblephus laticeps* (Roman seabream) feed in shallow-water beds of seaweed where they are vulnerable to climate induced changes (photos, A Götz). *Bottom:* Sport fishing boats. Part of a highly organized multi-billion Rand industry (photo, Charles Griffiths) south and the Mozambican border). Besides having enormous biodiversity value, the marine coastal zone provides fish resources for approximately 24 700 commercial, 750 000 recreational and 29 000 subsistence line fishers as well as approximately 2000 small scale gillnet and seine net fishers (McGrath et al. 1997, Branch and Clark 2006). The value of the commercial line fishery was estimated to be R336 million p.a. in 1995/1996 (McGrath et al. 1997). In 1996, the revenue generated by recreational fishers in the coastal zone was estimated to be R750 million p.a. (Branch and Clark 2006). The contribution of gillnet and seine net fisheries to the Western Cape economy was at least 15 million p.a. (Hutchings et al. 2002). In contrast, the subsistence fishery has a low economic value but is critical for the livelihood of its participants (Branch and Clark 2006).

With strong scientific agreement that coastal ecosystems are under threat as a result of anthropogenic global climate change (IPCC 2001), prediction of these threats is key to the successful mitigation and adaptation required to conserve our coastal marine fish species and maintain sustainable fisheries. Potential threats to the marine coastal zone are likely to include both physical and chemical stressors, which in turn can have direct and indirect effects on subtidal fishes. Physical stressors include changes in sea temperature, sea-level rise, intensification of upwelling, changes in current strength and changes in rainfall and consequently the amount of freshwater input to the coastal zone, while chemical stressors include a rise in CO_2 and a concomitant decrease in the ocean pH (Harley et al. 2006). The aim of this chapter is to review the global understanding of climate related stressors to subtidal fish communities, to identify the greatest vulnerabilities of fish biodiversity and fisheries in the South African marine coastal zone, to highlight the areas where research is needed, and to identify the resources required to predict the potential impacts.

10.2. CLIMATE CHANGE FINDINGS

10.2.1. TEMPERATURE

Fish are thermoconformers and therefore respond to even small changes in water temperature (Clark 2006). Changes in water temperature affect physiological processes in fishes including the fluidity of membranes and the function of their organs (Hochachka and Somero 2002). Consequently, of all the physical stressors, sea temperature is considered to have the most influence on subtidal fishes. While an altered temperature regime will ultimately result in changes in the subtidal fish assemblages, there are a number of drivers facilitating these changes. These drivers affect fish differently depending on life history and movement characteristics of the fish.

The first driver is simply thermal preference. Fish species have generally evolved to function optimally within a narrow range of temperatures. With climate change it is likely that some individuals, particularly those on the boundary of their distribution, will find themselves outside their thermal optimum and will respond by moving to areas with favorable temperatures. Species, whose distribution is limited by water temperature, might be able to extend their range under a changing temperature regime. For example, Figuera and Booth (2010) established a link between overwinter survival of tropical fishes transported to temperate latitudes and water temperature off the Australian coast. They found that southward distributional shifts by tropical species were limited by a specific minimum threshold temperature. If the sea temperature remained above that threshold temperature throughout winter, post larval settlement of several tropical species occurred south of their normal distribution.

The second driver linked to changing water temperature is a change in reproductive success. Water temperature can influence fish reproduction from egg production right through to larval survival and distribution. Egg production in fishes is thought to be regulated by temperature (e.g., Pauly and Pullin 1988) and is generally maximized within a narrow thermal range. Temperature is also considered to be an important cue for reproduction in many temperate marine teleosts (Bye 1990). Changes in the timing of cues can have a major impact on reproductive success as the rate of development will be negatively influenced by suboptimal conditions and most often, there will be a mismatch between larvae and their food supply or a convergence between larvae and their predators (Blaxter 1991). After hatching, the conversion of yolk may also be less efficient at temperatures outside the fish's thermal preference (Sund and Falk-Peterson 2005), causing fry to be less competitive at their first exogenous feeding (Cavalli et al. 1997). Elevated or reduced temperatures also generally change the metabolic rate of the early life history stages. This can influence their tolerance to low oxygen habitats and their rate of development (Munro 1990). Besides a negative impact on their ability to feed, this can also increase their susceptibility to predation.

A third driver is an alteration to the life history parameters of fishes. The growth of fishes, in particular, is considered to be closely related to temperature and usually has a thermal maximum (Munday et al. 2008). This is not restricted to a particular life history stage because evidence of a relationship between environmental temperature and fish growth has been observed at the larval (Meekan et al. 2003, Jenkins and King 2006), juvenile (Thresher et al. 2007) and adult stages (Pauly 1979). Besides the obvious correlation with fish production, fish growth has also been correlated with natural mortality (Pauly 1980), changes in the size and age at sexual maturity (Godø and Haug 1993, Charnov and Gillooly 2004) and age specific fecundity (Thresher et al. 2007). Generally, most fish species can adapt certain life history traits to cope with temperature changes. However, these responses only counteract a shift from the thermal optimum below species specific thresholds after which complex and detrimental changes are expected.

A fourth driver is a change to the burst swimming speed of fishes. The burst swimming speed of fishes is considered to be closely linked to water temperature and is an important strategy used by larval (Batty and Blaxter 1992, Hunt von Herbing 2002), juvenile and adult fishes to avoid predation and to capture prey (Claireaux et al. 2006, Figueira et al. 2009). Generally, the burst speed of a species is maximized within the fish's optimal thermal range. For example, elevated water temperature prompted an increase in the burst speed of a tropical reef fish (*Abudefduf vaigiensis*), but had no effect on the sub-tropical confamilial damselfish (*Parma microlepis*) (Figueira et al. 2009).

The warmer sea temperatures predicted worldwide should cause a latitudinal shift in the distribution of species towards the cooler waters of the poles. This shift has been predicted by many authors (Fields et al. 1993, Lubchenco et al. 1993, Clark 2006, Harley et al. 2006) and evidence for this has been observed in many regions, including the North Atlantic (Stebbing et al. 2002), North Sea (Perry et al. 2005), Sea of Japan (Masuda 2008) and off the coast of Tasmania (Last et al. 2009). However, several medium and long-term monitoring studies, such as those of Holbrook et al. (1994) and Malcolm et al. (2007) have also indicated that the compositions of many subtidal fish assemblages have remained stable. There is currently little evidence for latitudinal shifts in subtidal fish species in southern Africa. Henriques et al. (in prep) have observed a southward shift in the distribution of the west coast dusky kob (*Argyrosomus coronus*) from southern Angolan into northern and central Namibian waters between 1995 and 2009. This corresponded with a 0.8–1.0 degree increase in sea surface temperature per decade during a similar period (Monteiro et al. 2008). As with many international studies, James et al. (2011), reporting on a medium term (8 year) inshore fish monitoring dataset from the Tsitsikamma National Park, showed conflicting evidence of climate change impacts. Although overall species richness and abundance maintained high levels of stability, there was correlation between the abundance of species with an affinity for warm-water and higher sea temperatures.

10.2.2. SEA-LEVEL RISE

The direct effect of sea-level rise is an upwards shift in distribution patterns of subtidal organisms. Although this does not pose a problem to fish and most invertebrates, some slow growing corals might not be able to keep pace with sea-level rise which would result in habitat alterations for subtidal fish on subtropical and tropical shallow reefs (Harley et al. 2006).

The latest low projections of sea-level rise by the IPCC (2007) are 0.18–0.59 m from 1980–1999 to

2100 (IPCC 2007). An assessment of sea-level rise in South Africa, using available tide gauge data for the last 50 years, shows a 1.87 mm y^{-1} rise on the west coast, a 1.48 mm y^{-1} rise on the south coast, and a 2.74 mm y^{-1} rise on the east coast (Mather et al. 2009). Pethick (1993) using examples from the southeast coast of Britain assessed the direct impact of sea-level rise on the physiological and biological processes of estuarine and coastal systems. He concluded that future changes in the intertidal profiles were likely and that this would result in increased wave energy and erosion in the upper tidal profile in coastal areas. Shallow intertidal areas will be lost in what is known as “coastal squeeze” with a concomitant reduction in prey organisms in both the rocky and sandy intertidal zone (chapters 8 and 9). This is likely to have a negative impact on subtidal fish species that utilize this zone for feeding or as nursery areas. Fish that utilize the intertidal zone are likely to move into areas that are less impacted by coastal squeeze and erosion.

Changes in estuarine profiles will directly influence coastal fish and fisheries through their impact on estuarine-associated fish species (Chapter 7). This may cause significant reductions in South African coastal fisheries as 83% (in number and mass) of the recreational shore-angler and commercial gill- and seine-net catch is composed of estuarine-associated species (Lamberth and Turpie 2003). Changes in estuarine profiles will also have an indirect impact on coastal fish and fisheries through an expected reduction in the organic nutrient loading and food availability for fishes in the coastal environments adjacent to estuaries (Pethick 1993). The consequences of reduced organic nutrient loading are described in section 10.2.5 (rainfall)

10.2.3. UPWELLING

One of the expected consequences of changes in wind speed and direction is a change in the frequency and strength of coastal upwelling events (Bakun 1990, Rijnsdorp et al. 2009). Depending on the affected region, upwelling events may weaken or intensify (Narayan et al. 2010). The consequence of coastal upwelling is the arrival of cool nutrient rich waters in the inshore zone. Areas with large upwelling cells generally have a high phytoplankton biomass and productive fisheries. Strengthened upwelling may have positive consequences for fisheries due to the increase in primary and secondary production. However, lower water temperatures may have a negative influence on the growth rate of some fishes (Section 10.2.1). In South Africa, Rouault et al. (2010) attributed decreasing trends in annual surface temperatures along the west and south coasts to an increase in upwelling favorable winds. The increased productivity and decreased temperatures expected in these areas are likely to have an influence on subtidal fish and fisheries (Section 10.2.1).

Besides having an impact on the feeding and growth of subtidal species, permanent upwelling cells have also been recognized as barriers to the dispersal of many fish species. Consequently, these cells can act as phylogenetic barriers for many fish species (Floeter et al. 2005). However, if changes in climate result in the weakening of the driving forces of the permanent upwelling cells, these barriers may break down (Harley et al. 2006), with significant consequences for fisheries productivity, species distribution and geneflow between regional fish populations. For example, on the west coast of southern Africa, the Luderitz upwelling cell is known to be a barrier to the dispersal of many fish species. However, with the increasing intensity of the southward displacement of the Angola–Benguela front and consequent warm water intrusions associated with Benguela Niño’s (Shannon et al. 1986, Boyer et al. 2000), it is possible that this barrier will be temporarily broken and that allopatric species such as the dusky (*Argyrosomus japonicus*) and west coast dusky kob (*Argyrosomus coronus*) will again occupy the same environment, with potential evolutionary consequences for both species.

10.2.4. CURRENTS

Changes in the strength of ocean currents can have a major impact on the egg, larval and juvenile dispersal of subtidal fishes. For example, the recruitment strength of the Australian salmon (*Arripis trutta*) has been directly related to Leeuwin current flow, especially the southern Australian stock which is at the edge of its distribution (Lenanton et al. 1991, Lenanton et al. 2009).

Changes in ocean current flow can also significantly influence the catchability of some fishery species. The catchability of fishes in the south coast fishery in Australia has been directly related to the flow rate of the Leeuwin Current (Lenanton et al. 1991, Caputi et al. 1996).

In South Africa, the circulation features of the coastal zone are markedly influenced, and to a large extent determined by, the two large scale ocean currents on either side of South Africa, i.e., the Agulhas Current along the east and south coasts and the Benguela Current along the west coast. Lutjeharms and de Ruijter (1996) showed that the Agulhas Current will exhibit increased meso-scale meandering which will force the current on average further offshore from its contemporary mean position. In the present global climate regime, the Agulhas Current is located 77% of the time within 15 km from the shore along the east coast of South Africa. However, perturbations in the form of large-amplitude intermittent meanders (Natal Pulse) can force the current’s core up to 300 km offshore. Lutjeharms and de Ruijter (1996) suggest that Natal Pulses will increase in frequency due to global warming and that the current will be located on average further from the shore. Any change in the average position and intensity of the Agulhas Current may impact on coastal zone currents. Many of South Africa’s important subtidal fishery species are thought to spawn in the waters of Kwa-Zulu Natal, after which their pelagic eggs and larvae are transported with the southwesterly coastal zone currents (Beckley and Connel 1996). A change in temperature or speed of the coastal zone currents may affect the southern advection of the eggs and larvae of these species, with consequences for larval survival due to suboptimal pelagic larval durations and temperature regimes. Surviving larvae might change the spatial pattern of juvenile recruitment along the coast thereby influencing biogeographic patterns with unknown consequences for fishery productivity and biodiversity.

10.2.5. RAINFALL

Freshwater input carries nutrients, sediment and detritus into the subtidal zone and can have a direct and indirect influence on its fishes (Houde and Rutherford 1993, Gillanders and Kingsford 2002, Lamberth et al. 2009). Nutrients are assimilated by phytoplankton, which are eaten by zooplankton, which in turn provide an important food source for many larval, juvenile and adult fish (Morgan et al. 2005, Lamberth et al. 2009). The low visibility conditions created by suspended sediments in the subtidal zone provide refuge for fishes (Cyrus and Blaber 1992). However they can also increase the catchability of subtidal fishes (Lamberth et al. 2009). Detrital input is normally subject to microbial colonization which renders it highly nutritious for detritivorous fish and invertebrates (Mann 1988, Whitfield 1998). Freshwater inputs also provide estuarine-associated fishes with important cues used to locate and utilize estuarine environments (Whitfield 1994, James et al. 2007).

Downscaled regional climate models (RCMs) derived from three global climate models (GCMs) indicate the likelihood of increased summer rainfall over the eastern part of South Africa, the interior and the Drakensberg Mountains, and a slight decrease in wintertime frontal rainfall in the latter half of winter in the Western Cape (Hewitson and Crane 2006). Decreased and increased rainfall may result in alterations in the abundance of fishes in the subtidal zone, particularly in those areas adjacent to large estuaries. For example, Lamberth et al. (2009) identified significant relationships between freshwater flow and the commercial and recreational catches of 14 subtidal species on the Thukela Banks. Under a scenario of a 44% reduction in flow from the Thukela River (due to freshwater abstraction), they forecast a 36% and 28% decline in the catch of slinger (*Chrysoblephus puniceus*) and squaretail kob (*Argyrosomus thorpei*), respectively.

10.2.6. OCEAN ACIDIFICATION

In a review of the impacts of ocean acidification, Fabry et al. (2008) concluded that of all marine animals, fish appeared to be the most tolerant to ocean acidification. Ishimatsu et al. (2004) attributed this to a high capacity for internal ion and acid–base regulation, which is afforded through direct proton excretion and an intracellular respiratory protein that allows a high oxygen carrying capacity. However, decreases in pH have been found to reduce the metabolic capacity and food intake of gilt-head bream (*Sparus aurata*) (Michaelidis et al. 2007) and seabass (*Dicentrarchus labrax*) (Cecchini et al. 2001), respectively. A review by Truchot (1987) indicated that the ventilation of dogfish (*Scyliorhinus canicula*) increased with a decrease in pH. Larval behaviour may also be modified during dispersal as a reduction in pH has been shown to affect chemical cueing (Munday et al. 2009). Possibly the greatest effect of acidification could be indirect, by which important prey species (e.g., molluscs for some Sparid fishes) grow more slowly and experience shell dissolution (Fabry et al. 2008). In cases where fish are dependent on a diet of molluscs, feeding and growth may be impaired.

10.3. KEY TRENDS AND ASSOCIATED VULNERABILITIES

Although biotic range shifts are expected in South African waters, they have not been modelled, primarily because anticipated shifts are closely associated with ocean currents, and changes in the movements of currents have not been accurately predicted (Turpie et al. 2002b). However, based on the summary of expected environmental changes in chapters 2 and 5 and the climate change findings summarized in this chapter, the associated impacts of climate change and vulnerabilities of fish species in the South African marine coastal zone should vary depending on the biogeographic zone and are summarized below.

South African West Coast Zone

- A poleward movement of fishes from the West African tropical region is unlikely due to the expected intensification of the Benguela upwelling cells (Chapter 5) which function as a significant biogeographical barrier for fishes.
- The intensification of upwelling events is likely to result in a reduction in average annual sea surface temperature and an increase in nutrient load. Migratory species that are not cold water tolerant may move southward around Cape Point, while migratory species that are tolerant to cold water environments are likely to become more abundant due to the higher food availability.
- Resident fishes are likely to remain in the area. The lower water temperatures may inhibit fish growth; however, this may be mitigated somewhat by an increase in food availability.

South African South Coast Zone

- The intensification of upwelling cells is expected to reduce average annual sea surface temperatures. Migratory species that are not tolerant of colder water temperatures are likely to move in an eastward direction, while the abundance of cold water tolerant species is expected to increase due to increased food availability and the migration of fishes from the west coast zone.
- As for the west coast zone, resident fishes are likely to remain in the area. The lower water temperatures may inhibit fish growth; however, this may be mitigated somewhat by an increase in food availability.

South African East Coast Zone

- Unlike the west coast zone, the poleward movement of tropical species is expected. The increase in sea temperature is expected to allow tropical juvenile recruits to survive the cooler winter season and colonize this region.
- With warming ocean temperatures expected in this region, the growth rates of resident species are likely to increase. If, however, temperatures exceed the thermal tolerance of species, these fishes may migrate to cooler, deeper waters.
- The southerly advection of fish eggs and larvae is expected to be impacted. Cooling in the south coast zone may inhibit the survival of eggs, larvae and juveniles, particularly during times of upwelling.

10.4. RESEARCH AND RESOURCES REQUIRED TO BETTER ASSESS POSSIBLE IMPACTS

Required research

- Only a fraction of the subtidal habitat has been topographically surveyed off South Africa. Information on substrate type, depth and profile of potential fish habitats and their spatial coverage is crucial for the design of any marine coastal research programme and is of particular importance when considering the impacts of climate change. If fish react to changes in water properties by moving, the extent and orientation of suitable, continuous habitat will determine their survival.

- The study of coastal oceanography of southern Africa is still relatively immature. Consequently, our understanding of this zone, its diverse components and its driving forces are poor. This makes predictions very difficult. Moored instruments, including Acoustic Doppler Current Profilers (ADCPs) and thermistor arrays, should be deployed in a variety of habitats at depths of between 10 and 30 m in the coastal waters of southern Africa. These can be serviced using small craft, and this information should be supplemented with profile information from Conductivity, Temperature and Depth sensors (CTDs) collected during routine small craft surveys.
- Long-term studies should monitor the relative abundance of subtidal fishes and the stability and resilience of subtidal fish assemblages. Underwater video camera systems such as remotely operated vehicles (ROVs) and baited remote underwater video (BRUV) stations provide a permanent record of fish abundance free of observer bias and can be analyzed comparatively and accurately (in the lab) across the entire subtidal depth range and infinite time intervals. These results should be related to oceanographic data to assess the impacts of climate change. Currently there are at least two long-term monitoring projects in both the south and east coast zones. These should be continued, and at least one long-term monitoring project should be initiated in the west coast zone to monitor changes in the subtidal fish community.
- An understanding of the proximate and ultimate factors determining fish reproduction is required. This can be achieved using a combination of laboratory experiments and in situ data collection. By understanding these factors, predictions on the impact of environmental changes on reproductive activity can be made.
- Information on the relationship between ocean currents and the rates of the egg and larval dispersal of subtidal fishes is required. Combined larval and environmental sampling trips should be undertaken along the coastal zone to gain an understanding of egg and larval dispersal. A co-ordinated research programme along the entire coast would have more value than specific projects. This type of information could be used to model patterns of larval dispersal under a range of climate change scenarios and in relation to marine protected area placement (connectivity).
- Information on the threshold temperatures of juvenile fishes is required. This should include determining the minimum and maximum threshold temperatures by comparing feeding, growth and burst swimming ability under a range of temperature regimes in a laboratory environment. This will provide information on the potential colonization capacity of species when their dispersal characteristics are altered.
- Studies to determine trends in changes in fish growth with climate change are required.
- Our understanding of the response of fish to elevated CO_2 and acidification is poor. Laboratory studies should be used to evaluate the affect of elevated levels of CO_2 and decreased pH on fish growth, feeding, metabolic activity, respiration, olfactory ability and survival.
- Fish movement studies (biotelemetry and conventional tagging methods) should focus on the relationship between oceanographic factors and the timing and extent of fish migrations. This information could then be modelled to predict migration patterns under various climate change scenarios.
- With the likely increase in intensity of upwelling events in the west and south coast zones, fish are likely to be exposed to more rapid fluctuations in temperature. The tolerance of subtidal fishes to rapid temperature fluctuations should be investigated to inform us of the response of these fishes to intense upwelling events.
- Certain species may be also more adaptable than others. In order to predict the climate driven changes to fish assemblages, future studies should include determining the adaptability or

inherent phenotypic plasticity of subtidal fish species.

Required resources

- Multi beam and sidescan sonars for use on small craft are necessary to compile crucial information on subtidal habitat types and their spatial extent off South Africa.
- ADCPs, UTRs, CTDs and possibly small craft to service the instruments.
- Underwater video camera systems such as ROVs and BRUVs are required to monitor fish assemblages in a standardized manner throughout all subtidal depth ranges.
- State of the art environmental control marine laboratory facilities are required for experimental work.
- A range of standardized plankton nets for a co-ordinated larval sampling program along the coast.
- Continued and additional support for long-term monitoring studies.
- Continued and additional support for fish movement studies.

11. COASTAL INFRASTRUCTURE

Wayne Goschen, Andrew A. Mather & Andre K. Theron

11.1. OVERVIEW OF CLIMATE CHANGE EFFECTS ON SEA-LEVEL RISE

11.1.1. GLOBAL

Recent advances in the use of satellites to calculate mass and energy budgets on a global scale, and the improvement of altimetry-based measurements, have led to more accurate measurements of sea-level height and provide increased confidence in the results derived for global sea-level rise (Cazenave 2009). Comparisons between corrected and verified altimetry-based observations of sea-level, upper ocean steric sea-level measurements from Agro floats, ocean mass calculations from GRACE gravity observations and tide gauge measurements are in agreement with a total sea rise of between 2.4 mm yr^{-1} ± 1.1 mm yr^{-1} (Jasen-1) and 2.7 mm yr^{-1} ± 1.5 mm yr^{-1} (Envisat) within a 95% confidence interval (Leuliette and Miller 2009). Previous studies, using data from tide gauges, estimated that global mean sea-level had been rising at an average rate of about 1.7 mm yr^{-1} ± 0.3 mm yr^{-1} during the 20th century (Church and White 2006, Jevrejeva et al. 2008a), although the exact figure varies between different authors. Moreover, altimetry has confirmed that global, regional and coastal sea-levels are rising at the same rate (Prandi et al. 2009), whereas it was previously thought that coastal sea-levels were rising faster than global sea-levels (Holgate and Woodworth 2004).

Models have been used in an attempt to predict future sea-level rise, such as the Coupled Global Climate Models (Horton et al. 2008) and Ocean General Circulation Models (Thompson et al. 2008). However, these models are likely to underestimate the observed sea-level rise if recent trends in the polar region accelerate (Horton et al. 2008). A sudden rise in sea-level could happen if, for example, the West Antarctic ice sheet collapsed (Tol et al. 2006, Keller et al. 2008). These scenarios are unverified, but nevertheless are being

Damage from the March 2007 storm in KwaZulu Natal by high sea-levels and large waves; Top: Beach facilities on the lower South Coast; *Middle*: Flooding of George Hulett Place, Salt Rock; *Bottom:* Inundation of North Beach Pier, Durban addressed by coastal nations under threat, such as the Netherlands, where the impact of a 5 m rise over 100 years has been investigated (Olsthoorn et al. 2008).

Global sea-level rise is mainly the result of an increase in volume of the oceans caused by thermal expansion of the seas due to warming, melt-water entering the ocean from glaciers, ice caps (Bahr et al. 2009) and other ice at low altitude (Oerlemans 2007, Steffen et al. 2008), and melt-water from polar ice-sheets, especially from Greenland (Krabill et al. 2004, Box et al. 2006) and West Antarctica (Shepherd and Wingham 2007, Rignot et al. 2008, Willmes et al. 2009). The contribution of each to the total sea-level rise is currently under debate. Jevrejeva et al. (2008a) provide evidence that the primary role is being played by the melting glaciers and ice sheets (47%) as opposed to thermal expansion due to increasing heat content (25%). However, about quarter of the rise is still unaccounted for, possibly due to underestimated melting, climate driven changes in terrestrial storage components and decadal timescale variability in global water cycle (Jevrejeva et al. 2008a). Since the rise in sea level is equal on a global scale, the rise will affect all nations with an ocean boundary. On a local scale, the measured sea-level rise could be affected by the adjustment of the land-masses (rise or fall), local coastal and deep-sea ocean dynamics, and other regional/local phenomena. Wind and wave regimes, barometric pressure, currents and storm surges contribute to short-term variability of local and regional sea water levels and will have progressively worsening impacts due to the background long-term rise in sea level.

Solomon et al. (2009) argue that climate change is largely irreversible for at least 1 000 years after anthropogenic CO_2 emissions potentially stop, because the loss of heat by the oceans will be slow, causing atmospheric temperatures to decrease slowly. A more optimistic Washington et al. (2009) suggest that if green house gas emissions are reduced by 70% by 2100 then roughly half the change in temperature and precipitation would occur, preserving considerable sea ice and glaciers and slowing sea-level rise. Whatever the outcome of the different scenarios, there is general agreement that the level of the sea will continue to rise into the next millennium. In fact, it has been found that sea-level has been rising, at different rates, for at least the last 20 000 years (Fairbanks 1989, Harvey and Nicholls 2008), but that anthropogenic influences are suspected to be causing the sea-level rise rate to accelerate (Church and White 2006, Jevrejeva et al. 2008b, Woodworth et al. 2009). Jevrejeva et al. (2008b) provide observational evidence that sea-level rise has been accelerating at about 0.01 mm yr^{-2} from the end of the 18th century, although this rate of acceleration remains under debate as White et al. (2004) and Ablain et al. (2009) have found a reduction in mean sea-level rise rate.

Coastal environments and habitats around the world are especially vulnerable to sea-level rise and variability (Church et al. 2008a, FitzGerald et al. 2008, Harvey and Nicholls 2008), and efforts have been made to forecast the effect of sea-level rise on coastal ecosystems (Hopkinson 2008). Bioregions that are especially exposed, such as estuaries and salt marshes, are being assessed for vulnerability to sea-level rise (for example, Mudd et al. 2009). Efforts have been made in many countries and states to combat the impacts of sea-level rise, for example, USA (Hopkinson et al. 2008, Cayan et al. 2008), Australia (Church et al. 2008b, Hunter 2008), Portugal (Andrade et al. 2007) and, in Africa, Tanzania (Sallema and Mtui 2008). Storm surges influencing developing countries have been investigated by Dasgupta et al. (2009). Nicholls and Tol (2006) argued that the socio-economic status of a country, rather than the magnitude of sea-level rise, will determine how vulnerable the country is to sea-level rise.

11.1.2. SOUTH AFRICA

Climate variability and climate change have had an effect on the large scale physical processes of the oceans around southern Africa; in particular, there is evidence of a poleward shift of westerly wind in the southern hemisphere (Reason et al. 2006). The discovery by Rouault et al. (2009) that the temperature of the Agulhas Current has been increasing since the 1980s, caused by an increase in wind stress curl in the South Indian Ocean due to the shift of westerly winds, could have a profound effect on local ecosystems and the physical environment off South Africa, although as yet unstudied. These results are supported by local measurements made along the coastline of South Africa; for example, Schumann (1992) found, from an analysis of 38 years of data, that the wind direction at three coastal sites around South Africa shifted by up to 30º to a more northerly direction after an El Niño Southern Oscillation event in 1982/1983, although there was a difference in the effect between the east and south coasts. Temperature extremes show patterns consistent with warming over most of the regions of southern and western Africa (New et al. 2006), while substantial increases in coastal sea surface temperature of about 0.25 ºC per decade and even greater increases in coastal air temperature of 0.36 ºC per decade have been found by Schumann et al. (1995). These results for the southern African region support the global trend in climate change and sea-level variability.

Limited historical sea-level rise research has been conducted in South Africa. Sea-level records in South Africa data back to the 1950s and are of variable quality with much noise and many gaps (Merry 1990, Brundrit 1995). An early study by Merry (1982), working with data from between 1960 and 1975, concluded that there were no trends in sea-level around the coast of South Africa. However, later studies on monthly variability in mean sea-level dataset by Brundrit (1984), using a larger dataset, revealed the long-term interannual structure from the west coast of southern Africa. The dataset was further extended by Brundrit et al. (1987), who found that high sea-level events propagated polewards from the equatorial Atlantic, and found years that had anomalously high sea-levels. This was confirmed by De Cuevas et al. (1986), who used sea-level records to study coastal trapped waves and who concluded that there was a high synoptic-scale correlation along the west and south coasts of southern Africa, from Walvis Bay (Namibia) to Port Elizabeth.

An index was derived by Hughes and Brundrit (1992) to assess South Africa's vulnerability to sea-level rise using variables that identified risk in the relief, rock types, landform, vertical movement of land, shoreline displacement, tidal range and wave height to identify high-risk and low-risk locations. They applied their index to the Western Cape south coast, between Witsand and Plettenberg Bay (Figure 11.1), and found that the greatest hazards were from extreme storm and flood events. (These are actually short term events, but are likely to be exacerbated by longer term climate change effects.) Hughes and Brundrit (1992) also noted that the most vulnerable coastal infrastructure was that of private housing, which suggests that damage costs would be borne by individuals and not the nation as a whole. Extending the area coverage, Brundrit (1995) examined and derived trends from tide gauge data further north in Namibia, at Lüderitz and Port Nolloth, and also at Simon's Town and Mossel Bay in South Africa. Brundrit (1995) suggested a rise of 1.2 mm yr^{-1} ± 0.4 mm yr^{-1} on the west coast of southern Africa, but no trend on the south coast of South Africa (data from Mossel Bay). The results of Brundrit (1995) agreed with the known global trend at that time. Searson and Brundrit (1995) investigated the occurrence of extreme high sea-levels around the coast of South Africa, suggesting that sea-level extremes are tidally dominated. Hughes (1992) and Cooper (1991, 1995a, b) used scenarios of sea-level change to assess coastal impacts along the South African coast.

From 1995 to 2007, little sea-level rise research was undertaken in South Africa, but the necessity for coastal city authorities to understand the impacts of sea-level rise on public and private structures has caused a renewed interest. Mather (2007) examined tide gauge records located at Durban and found several anomalies and errors with the gauge data. He was able to correct some of these problems but had to eliminate sections of the data as unreliable. After some manipulation of the data, analysis of the Durban records by Mather (2007) yielded a rate of sea-level rise of 2.7 mm yr^{-1} ± 0.05 mm yr^{-1} for the monthly mean and 2.4 mm yr^{-1} ± 0.29 mm yr^{-1} for the yearly mean.

Following on from this, a comprehensive analysis of the southern African tide gauges was undertaken by Mather et al. (2009). Data problems were experienced at all gauge sites and resulted in the use of the Permanent Service for Mean Sea Level (PSMSL) data in determining sea-level trends, rather than the original South African Navy data, as these data are independently reassessed. The results show that, generally, sea-level is rising around the South African coast in agreement with current global trends derived by Leuliette and Miller (2009), but there are regional differences in the estimated rate of sea-level rise. Mather et al. (2009) reported that sea-level on the west coast of South Africa was rising by +1.87 mm yr^{-1}, on the south coast by +1.47 mm yr^{-1} and on the east coast by +2.74 mm yr^{-1}. The eustatic (true) level rise was found to be lower along the west coast (+0.42 mm yr^{-1}) but higher along the south (+1.57 mm yr^{-1}) and (+3.55 mm yr^{-1}) east coasts. These differences were attributed, by Mather et al. (2009), to the difference in vertical crust movements between the east and west coasts of South Africa, and to the different oceanographic processes occurring along the east and west coasts. On the east coast, the warm Agulhas Current is driving the increase in sea water temperatures and providing a strong thermal expansion component (Rouault et al. 2009), while on the west coast, colder water upwelling from the Benguela Current is less affected by global temperature increases, as shown by a comparison between the global thermal expansion coefficient and that of the Bengeula Current by Mather et al. (2009) and described by Hutchings et al. (2009). The results are shown in Figure 11.2 and summarized in tables 11.1 and 11.2.

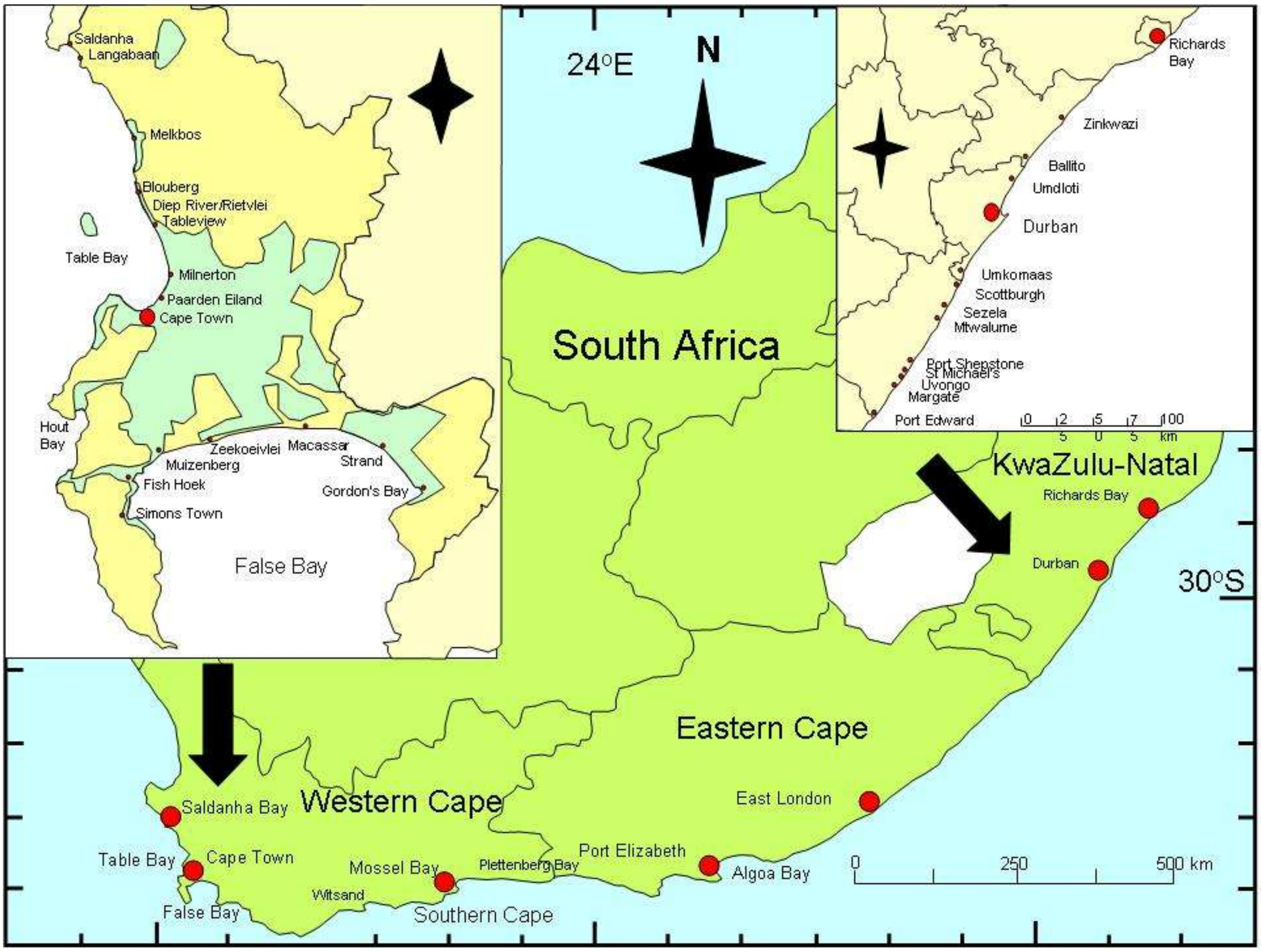


Figure 11.1 Map of South Africa showing the various damage locations in KwaZulu-Natal after the March 2007 extreme event (after Smith et al. 2007b). The insert on the left of the main map shows the vulnerable areas in the Municipality of Cape Town (after Hughes and Brundrit 1991, Hughes et al. 1993; Cartwright 2008) and the region of the Southern Cape area (after Hughes and Brundrit 1992). The major ports of South Africa are marked along the coastline of the South African map (after Rossouw and Theron 2009).

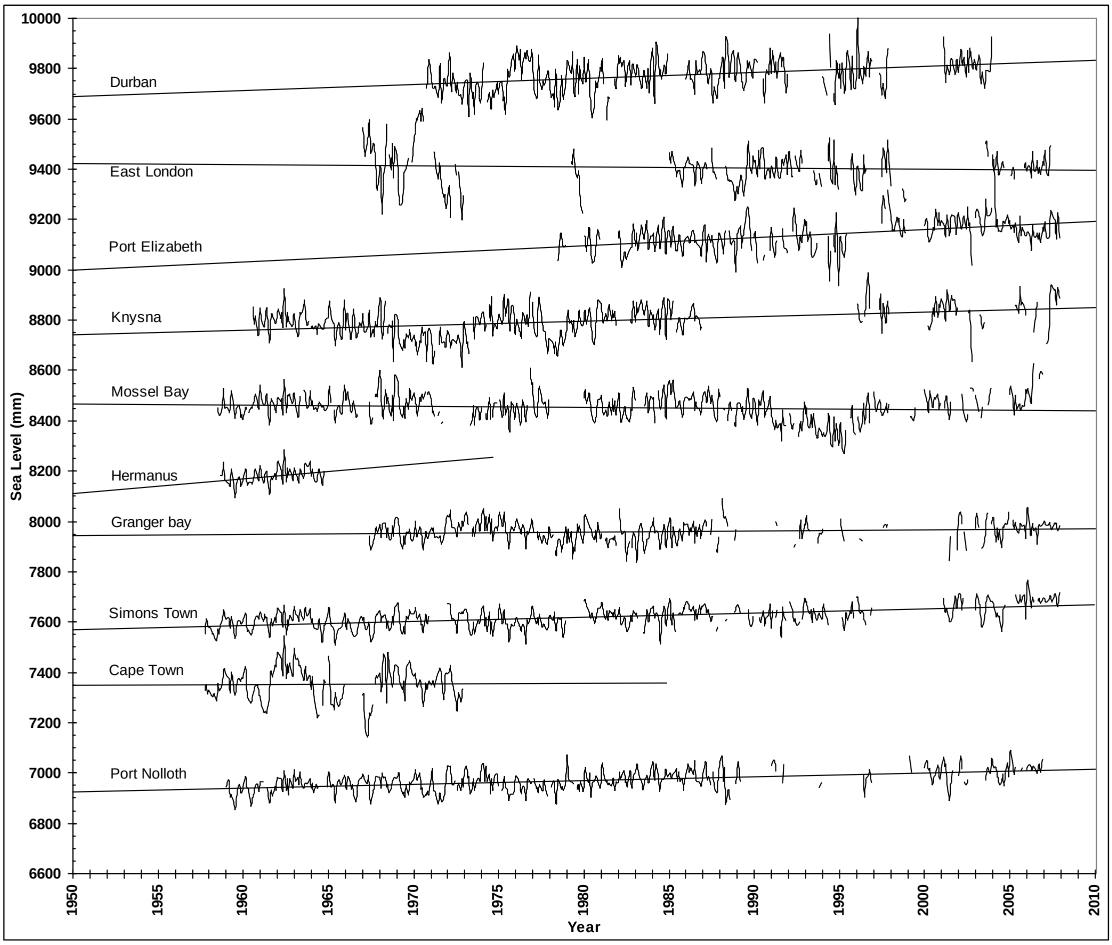


Figure 11.2 South African tide gauge time series from the PSMSL database, 1959–2006. All time series contain an arbitrary vertical datum offset (Mather et al. 2009).

Table 11.1 South African and Namibian relative sea-level trends. All stations are from the Permanent Service for Mean Sea Level (PSMSL) data holdings, except Durban (Mather 2007, Mather et al. 2009).

Tide station	***Period of Record***	***Years of record***	***Completeness of record*** (%)	***Observed annual sea-level trend using monthly data*** (mm yr^{-1})	***Observed annual sea-level trend using annual data*** (mm yr^{-1})
Walvis	1958–1998	41	58	+0.38 ± 0.33	+0.67 ± 1.06
Luderitz	1958–1998	41	78	+2.73 ± 0.81	+2.40 ± 1.64
Port Nolloth	1959–2007	49	75	+1.25 ± 0.23	+1.11 ± 0.41
Table Bay	1957–1972	16	Insufficient data		
Simons Town	1957–2007	51	78	+1.58 ± 0.22	+1.14 ± 0.51
Granger Bay	1967–2007	41	77	+0.08 ± 0.20	+0.44 ± 0.53
Hermanus	1958–1964	7	Insufficient data		
Mossel Bay	1958–2007	50	77	-0.40 ± 0.19	-0.66 ± 0.56
Knynsa	1960–2007	48	64	+1.27 ± 0.50	+1.95 ± 1.62
Port Elizabeth	1978–2007	30	76	+2.97 ± 1.38	+2.89 ± 2.05
East London	1967–2007	41	50	+0.17 ± 0.05	-2.03 ± 1.86
Durban	1970–2003	34	79	+2.70 ± 0.05	+2.40 ± 0.29
Richards Bay	1990–2000	11	Insufficient data		

Table 11.2 Regional relative sea-level trends. Equal weighting was given to each location in the calculation of regional sea-level trends in each region (Mather et al. 2009).

Region	***Port***	***Observed annual sea-level trend using monthly data*** (mm yr^{-1})	***Observed annual sea-level trend using annual data*** (mm yr^{-1})	***Regional relative sea-level trends based on the average of annual and monthly trends*** (mm yr^{-1})
Western	Luderitz	+2.73 ± 0.81	+2.40 ± 1.64	+1.87
	Port Nolloth	+1.25 ± 0.23	+1.11 ± 0.41	
Southern	Simons Town	+1.58 ± 0.22	+1.14 ± 0.51	+0.68 (+1.48, excluding Granger and Mossel bays)
	Granger Bay	+0.08 ± 0.22	+0.44 ± 0.53	
	Mossel Bay	-0.40 ± 0.19	-0.66 ± 0.56	
	Knynsa	+1.27 ± 0.50	+1.95 ± 1.62	
Eastern	Port Elizabeth	+2.97 ± 1.38	+2.89 ± 2.05	+2.74
	Durban	+2.70 ± 0.05	+2.40 ± 0.29	

In addition to an increase in sea-level, other factors work to increase the instantaneous level of the sea surface along the coastline, at times together. For South Africa, Theron and Rossouw (2008) list these parameters as spring high tide, Highest Astronomical Tide (HAT), wind set-up, hydrostatic set-up and wave set-up (Table 11.3), while the influence of potentially more extreme weather events (due to climate change) have not been quantified. The effect of wave run-up is often the biggest risk factor, but this short-term impact is very site specific.

Table 11.3 Parameters and estimated maximum effects on still-water levels for the South African coast (Theron and Rossouw 2009).

Parameters and effects	***Elevations*** (m to mean sea level) ***and setup*** (+ m)
Mean high water spring tide	1
Highest Astronomical Tide (HAT)	1.4
Severe wind set-up	+0.5
Maximum hydrostatic set-up	+0.35
Wave set-up	+1
100 year sea-level rise (IPCC, 2007)	+0.2 to +0.6 (say 0.4)

A particularly extreme event occurred on the KwaZulu-Natal coastline in 2007 when some of these factors coincided, resulting in extreme levels of erosion and associated property damage (Smith et al. 2007b, Mather 2008a, b, Phelp et al. 2008). The storm during March 2007 coincided with HAT, allowing run-up levels near Durban of about 10 m above mean sea-level (MSL), causing over a billion rand in damage (Smith et al. 2007b). Although the probability of a severe storm and HAT occurring simultaneously in the future is estimated at 1-in-500 years, the increase in sea-level and a possible increase in the frequency of storms lower this probability (Theron and Rossouw 2008). The most significant factor of the 2007 storm event was, however, the magnitude of the storm waves. In terms of wave height, the return period was between 1-in-10 and 1-in-30 years.

The quantification of sea-level trends around the coast of South Africa led Theron (2007) and Theron and Rossouw (2008) to consider the physical coastal zone impacts due to climate change, sea-level rise and an increase in wave heights around the coast of southern Africa. They also provided some mitigating response options. Their study coincided with several publications on the storm damage and rehabilitation of coastal structure on the east coast of South Africa caused during the extreme wave and sea-level event of 19–20 March 2007 (Smith et al. 2007b, Mather 2008a, b, Phelp et al. 2008). Vulnerable locations along the KwaZulu-Natal coastline, some identified by Department of Agriculture and Environmental Affairs (DAEA, 2008), were confirmed when the brunt of the storm of March 2007 struck the KwaZulu-Natal coastline. Its effects were observed from the Eastern Cape Province to Mozambique, with KwaZulu-Natal receiving the brunt of the storm. In KwaZulu-Natal many coastal towns between Port Edward and Richards Bay were affected (Figure 11.1), with roads damaged at Margate, Uvongo, St Michael's-on-Sea, Port Shepstone, Umkomaas, Durban, Umdloti, Ballito and Zinkwazi. The KwaZulu-Natal south coast railway-line experienced severe damage at Mtwalume and Sezela. Private property along the coast was also damaged due to flooding and wave action and inundation (Mather 2008a, b). South Africa's largest coastal cities, Cape Town and Durban, have recently began to take notice of the implications of climate change and sea-level rise and commissioned studies to assess the risk (Midgley et al. 2005, Mukheibir and Ziervogel 2007, Breetzke et al. 2008, Brundrit 2008, Cartwright 2008, DAEA 2008, Mather 2009a, b). At an early stage, harbours and ports were identified as vulnerable infrastructure, leading Rossouw and Theron (2009) to assess the potential climate change impacts on ports and maritime operations around the southern African coast.

11.2. THE IMPACT OF SEA-LEVEL RISE ON THE SOUTH AFRICAN COAST

The coastline of South Africa can be classified as a high energy environment due to significant wave energy reaching our shoreline (Gründlingh 1993, 1994, Queffeulou and Croizé-Fillon 2007). The most severe wave conditions occur on the South African southwest and south coasts, decreasing in magnitude northwards (MacHutchon 2006, Joubert 2008). The waves originate predominantly from the southwest, in the Southern Ocean, but significant waves are occasionally generated in tropical cyclones of the South Indian Ocean that impact the east coast of South Africa, and also by cut-off low systems that migrate along the southern to eastern coastline of Southern Africa (Preston-Whyte and Tyson 1988).

With a rise in sea level and increases in the frequency and intensity of sea storms, and in wave heights, Hughes et al. 1991 expect the South African coastline to experience:

- Increased exposure to more intense and more frequent extreme events.
- Increased saltwater intrusion and raised groundwater tables.
- Greater tidal influence.
- Increased flooding, with greater extent and frequency.
- Increased coastal erosion.

11.2.1. NATURAL ENVIRONMENT

Hard shores and cliffs

Rocky shorelines are well represented along the South African coastline (Lombard et al. 2004). By their very nature these shorelines are relatively stable and are not subject to catastrophic erosion. In some cases there is expected to be no noticeable erosion of the hard shores, although the high-water mark will likely move landward according to the shoreline slope. Cliffs exist along the South African coast but are generally formed from hard rock that is weather and wave resistant and will erode at a slow pace. Cliffs consisting of soft material that is prone to weather and wave erosion are often found to be already undergoing slow long-term erosion, such as the weathered limestone cliffs at Swartklip in northern False Bay (Waldron 2008). The KwaZulu-Natal storm of March 2007 showed that sandy and rocky coastal sections were generally more resilient, but mixed coastlines of rock and sand, especially pocket beaches, were severely impacted. Many low-lying built structures that failed were next to or on rocky headlands, or within bays encompassed by rock shelves where wave energies converged (Brundrit 2008).

Ancient Primary Dunes

There are several large primary dune systems that dominate sections of the coast of South Africa (Rust 1991). An example is the Berea Red formation in KwaZulu-Natal, which exists along the coast from south of Durban to beyond Maputo, Mozambique, and forms the Bluff Headland at Durban (Truswell 1977). Sea-level rise will result in slips along the steep seaward facing slopes of the Bluff, potentially causing structures located at the top and sides to slide down. Infrastructure located seaward of the Bluff (such as sewage pipelines) will also be endangered. Figure 11.3c illustrates the situation at the base of the Bluff in Durban, showing progressive retreat inland on the High Water Mark for 300 mm, 600 mm and 1 000 mm sea-level rise scenarios.

Mildly sloped sandy shores

Mildly sloped sandy shores could potentially be subject to the greatest landward migration of the shoreline due to sea-level rise (Brown and McLachlan 2002). Small increases in sea-level potentially result in significant regression of the high water mark. Typically these areas were inundated in previous high stands of sea-level (Ramsay and Cooper 2002). The Cape Flats, located outside Cape Town, exemplifies this type of coastline and has been examined in studies by Brundrit (2008) and Cartwright (2008). Inundation of the Cape Town coastline under conditions of 2.5 m, 4.5 m and 6.5 m sea-level rise events is illustrated in Figure 11.4. Although wave runup (a short-term storm related occurrence) could well attain such levels, sea-level rise and longer term inundation levels of 2.5 m to 6.5 m by 2100 are extremely unlikely.

Sandy Beaches

The South African coastline includes many sandy areas that are fully or almost fully exposed to incident wave attack (Lombard et al. 2004). Where the wave regime is high, the shoreline is exposed to a high potential for erosion. Sandy beaches form an integral part of the tourism product of South African coastal cities; for example, Durban’s beaches constitute the KwaZulu-Natal province’s most important tourist attraction, with 73% of domestic tourists visiting them (Tourism KZN 2007). Rising sea-levels will erode these beaches, reducing their surface area, while increasing storm intensity will require more coastal defence systems. These two factors contribute adversely to beaches and in turn to the local tourism industry, which favours wide sandy beaches. Figure 11.3a shows the effect of sea-level rise at Durban’s north beaches under scenarios of 300, 600 and 1 000 mm.

Undeveloped natural sandy shorelines

Similar to the rocky shores, this location type is least likely to present a hazard to human settlements simply because they are undeveloped. However, they are vulnerable to the impacts of sea-level rise and will not go unaffected. Generally there is sufficient land for the sea to retreat naturally, as along parts of the coast of KwaZulu-Natal (Harris 2008). From an adaptation point of view, these areas need to be allowed to naturally respond to rising sea-levels, and perhaps the only management interventions should be to actively prevent new settlement in the potential erosion zone. Key information would be the extent of this likely retreat under the various sea-level rise scenarios as well as a development of set back lines which would need to be demarcated to prevent additional development in areas of high risk. The development set back lines must be at sufficient distance from the existing shoreline to cover the risk zone. From previous experience in the region, developments are often not set back sufficiently far from the sea, and buffer zones are of insufficient width to retain natural functioning of dune systems. These deficiencies will lead to problems with development sited too close to the coast in the future (Harris 2008). However, if development set back lines are determined properly, risk will be reduced sufficiently so that any economic activities undertaken in the developments are fully realized before the developments are lost or have to be relocated.

Estuaries

Estuaries fulfil important environmental, economic, and cultural functions. Lamberth and Turpie (2003) estimated the total value of estuarine and estuary-dependent fisheries to be equivalent to R1.251 billion in 2002. Increase in sea-level, increased storminess and change in the sand budget will affect estuary mouth dynamics, resulting in changes in the open/closed mouth status of estuaries. The occurrence of mouth closure could increase, and more sand could be deposited in the lower reaches of an estuary. Combined with the potential increase in salinity that may exceed a given threshold for the ecological function of an estuary, these would affect the vital nursery area for a number of marine fish and shellfish. Altered freshwater inflows (due to climate change or anthropogenic impacts) and sea conditions (waves, water-levels, sedimentation) could (further) reduce environmental function of some estuaries (with knock on impacts on fisheries etc.). Some estuaries of South Africa function as small-craft harbours and have been developed as marinas with near-shore housing estates, which will be severely impacted by sea-level rise. An example is the Kowie River estuary at Port Alfred, which is already experiencing sedimentation problems (Schumann et al. 2001).

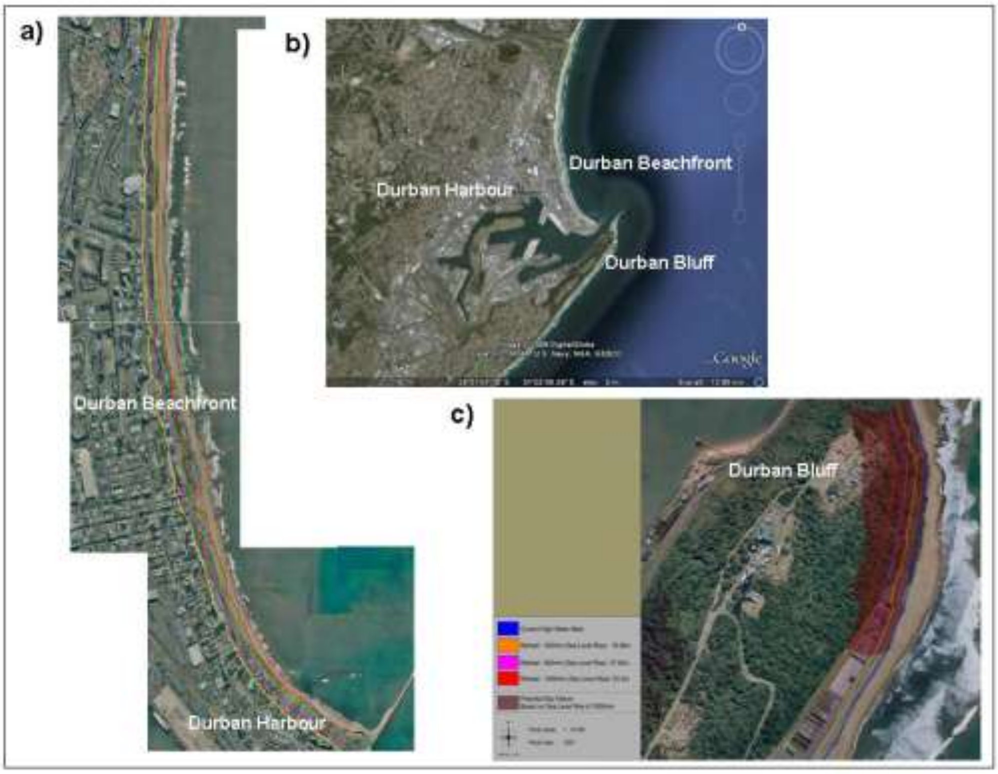


Figure 11.3 Potential impacts of sea-level rise scenarios around Durban. The progressive retreat inland of the High Water Mark (here defined in accordance with DEAT 2008) for 300 mm, 600 mm and 1 000 mm sea-level rise scenarios are shown for a) the area north of Durban Harbour (b) and c) the Durban Harbour Bluff. The red shaded area in c) shows the extent of slip failure of the Bluff's historic dune under 1 m sea-level rise (Mather 2009a).

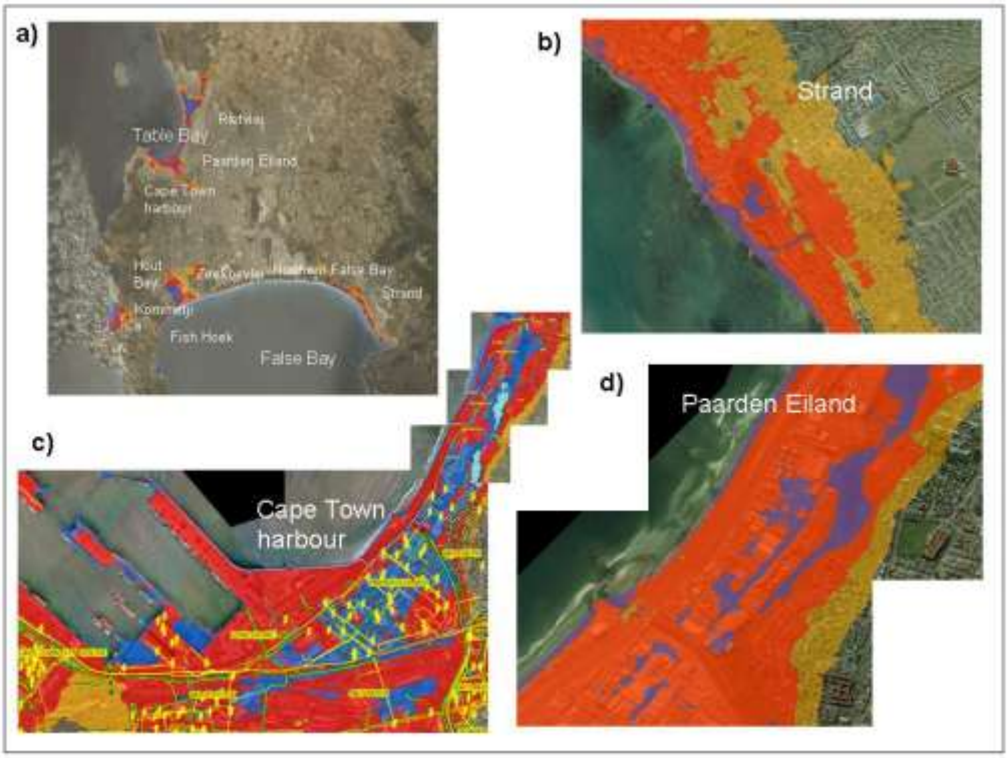


Figure 11.4 a) Aerial photograph of the coastline of the Municipality of Cape Town showing the inundation that would be caused by 3 scenarios of a 2.5 m (blue), 4.5 m (red) and a 6.5 m (orange) sea-level rise event. The other images show the simulated impact of scenario 1 (blue), scenario 2 (red) and scenario 3 (orange) sea-level rise, and the associated impact on the b) Strand coast, c) Cape Town Harbour and d) Paarden Eiland (from Brundrit 2008, Brundrit et al. 2008, Cartwright 2008), showing the potential for loss of the beach amenity and damage to infrastructure.

Wetlands

South Africa has a number of coastal lakes, and natural and artificial wetlands situated along the coastline (Hart 1995). According to Tol (2004), by 2100 South Africa could potentially lose some 11% of its wetlands if full coastal protection measures and structures were to be erected to mitigate sea-level rise impacts, making South Africa potentially the 5th most vulnerable country worldwide by 2100 with respect to wetland losses resulting from sea-level rise.

11.2.2. COASTAL SETTLEMENTS AND INFRASTRUCTURE

Flooding and inundation of coastal settlements

In terms of South African national vulnerability to the impacts of sea-level rise, several high-risk areas/regions stand out (Table 11.4):

- Greater Cape Town, including northern False Bay, Table Bay and Saldana Bay areas (Hughes and Brundrit 1991, Hughes et al. 1993, Midgley et al. 2005, Brundrit 2008; Cartwright 2008). Table 11.4 shows some of the most vulnerable areas in the Western Cape (after Midgley et al. 2005). An estimation of risk to the Cape Town coastline under three assumed scenarios is given by Cartwright (2008) in Table 11.5.
- The south Cape coast centred on Mossel Bay, from Witsand to Plettenberg Bay (Hughes and Brundrit 1992).
- Port Elizabeth (discussed briefly by Klages 2008).
- KwaZulu-Natal coast from Port Edward to Richards Bay, as demonstrated by the March 2007 extreme event (Smith et al. 2007b, Mather 2008a, b, Phelp et al. 2008). Figure 11.1 shows some of the vulnerable towns in KwaZulu-Natal.

Within these areas/regions the greatest and most immediate risk is considered to be a combination of rising sea-levels and extreme storm events.

Impacts on livelihoods

Examples of potential impacts on livelihoods within various socio-economic sectors in the vulnerable areas of South Africa are as follows (Theron 2007):

Industrial

- Hindered shipping access to ports (e.g., due to increased sediment transport).
- Reduced navigability.
- Increased cost of maintenance to infrastructure due to increased storminess.

Commercial

- Reduced fair weather fishing time.
- Increased safety risks due to increased occurrence, duration and magnitude of sea-storms, leading to less appealing and adverse working conditions.
- Loss of income from the shoreline and estuarine fisheries and nursery function.

Farming

- Low-lying farming areas adjacent to the shoreline will suffer from salt water intrusion, resulting in loss of crops and livestock, and hence lower earning potential.
- Aquaculture, which is generally located in protected bays, may need to be re-located.

Residential

- Coastal and estuarine suburbs may lose properties including houses, hotels, guesthouses, etc., and their associated employment opportunities.
- Undeveloped residential land could be lost.

Recreational areas

- Loss of space and appeal, through erosion and water intrusion, and therefore fewer visitors leading to reduced economic activity.

Waste water outflows and dredging dump sites

- Sewage and waste water pipe outlets may be damaged with sea-level rise and increased sea storms, but water circulation and dispersal of waste matter from these outflows could be enhanced, which would have a beneficial effect.
- Present dredge dumpsites may be less suitable and require relocation.

Mining

- Mining of the coastal dune fields or coastal diamond mining may be disrupted, leading to loss of income and employment.

Transport

- Major, minor and secondary roads.
- Railways.
- Rail and road bridges.

Table 11.4 Identification of some of the most vulnerable areas in the Western Cape Province where the impacts will potentially be the most severe (after Midgley et al. 2005).

Specific area/location	***Impact***	***Extent***
Nature's Valley	Inundation & flooding of low-lying areas adjacent to estuary, mainly residential & holiday homes	Small area, few properties.
Plettenberg Bay – Keurbooms	Shoreline erosion & under-scouring of houses and access roads due to more wave energy penetration through mouth.	Small area, few properties.
Knysna Lagoon	Inundation & flooding of low-lying areas adjacent to estuary, residential & holiday homes, commercial property.	Small area, few properties.
Victoria Bay	Increased damage to historical "visvywers" (archaeological heritage sites) due to increased wave impacts through deeper water & increased storminess.	Small area, few properties.
Still Bay & Skipskop/Rys Punt	Increased damage to historical "visvywers" (archaeological heritage sites) due to increased wave impacts through deeper water & increased storminess.	Small areas, but important
Bredasdorp Plain	Higher seawater levels into the Heuningnes Estuary may cause increased saltwater intrusion and raised groundwater tables in agricultural areas where farming occurs directly adjacent to the estuary & shoreline.	Relatively large land area, but actual impact very uncertain.
Danger Point (Gansbaai)	Damage to mariculture (perlemoen) infrastructure (intakes, pipes, pumps, buildings) due to increased wave impacts through higher water levels & increased storminess.	Localized – individual operators.
Strand	The coastal road here is very close to the high-water mark. Thus, the low wall on the pavement is overtopped even if only a moderate storm occurs during spring high tides. This results in temporary road safety problems and necessitates regular maintenance. Both sea-level rise and increased storminess will increase the number of occurrences and the scale of the impact.	Small area
Northern False Bay	Baden Powell Drive, parking areas and ablution facilities have been located within the littoral zone. The continuous influx of windblown sand off the beach has resulted in a costly, ongoing sand clearing exercise that peaks during the summer period when the southeasterly and southerly winds prevail. More mechanical effort will be required to clear the road. From Cementery Beach to Strandfontein Point the road itself and any structures seawards of the road are often inundated and are considered to be vulnerable to storm damage.	Relatively longer stretch of coastline, but mainly limited to impacts to the road
Table Bay (Diep River mouth – Milnerton – Blaauwberg)	Existing problems with shoreline erosion, aeolian sand transport and stormwater drain outlets on the beach will be aggravated; due to sea-level rise, as well as increased storminess.	Relatively longer stretch of coastline, but incremental impact still small?
Table Bay	Koeberg Nuclear Power Station seawater intakes could potentially be affected.	The relatively small rise in seawater level is highly unlikely to have any significant impact.
Langebaan Point (Paradise Beach & Blouwaterbaai; Saldanha Bay area)	Shoreline erosion & under-scouring of house foundations, retaining walls and access roads; due to sea-level rise, as well as increased storminess.	Small area, few properties.

Table 11.5 Summary of assumptions and estimated risk to the Cape Town coastline (after Cartwright 2008).

	Assumed probability of occurring in the next 25 years (%)	***Value of real estate at risk*** (R billion)	***Value of tourism revenue at risk*** (R billion)	***Value of public infrastructure at risk*** (R billion)			***Total potential cost to Cape Town*** (R billion)	***Value of the risk to Cape Town*** (R billion)
				Storm-water	Roads	Elec		
Scenario 1 (2.5 m rise)	0.95	R3 255	R750	R167.3	R900	R94.8	R5 167	R4 908
Scenario 2 (4.5 m rise)	0.85	R19 459	R1.44	R408.25	R2 197	R230.2	R23 734	R20 174
Scenario 3 (6.5 m rise)	0.20	R44 460	R3.60	R635.80	R5 702	R358.6	R54 756	R10 951

Urban settlements

Urban settlements have expanded rapidly over the last thirty years, especially in developing countries, making more people and infrastructure vulnerable to this risk (Rakodi and Treloar 1997). The South African coastline, about 3 000 km in length, is not densely inhabited, although the rate of coastal development has become a concern in recent times. For example, transformation of the coastal strip (100 m wide) in KwaZulu-Natal has experienced a rapid rate of urban development (Cilliers and Groenewald 2002). In South Africa, beachfronts are significant economic generators, and it is this area where the largest impacts are expected. They are frequently utilized with significant back-of-beach amenities and infrastructure that cannot be re-located. Some beachfronts have sea defence walls or revetments in place protecting infrastructure, and it is often this infrastructure that is damaged by heavy seas. Ordinarily, managed retreat would be the preferred international best practice action in these cases (Breetzke et al. 2008). Unfortunately, for many urban beachfronts in South Africa there is no longer any room to manoeuvre; development is so intense that the option for retreat is highly problematic. This situation then creates the need for a multi layered approach to the problem of coastal erosion. The adaptation response must be tailored to suit each location and its respective circumstances. For example, the erosion of the beachfront at Durban, South Africa (shown in Figure 11.3) could result in the loss of significant development and infrastructure, ranging from Ushaka Marine World (valued at R750 million, this was the fifth largest aquarium in the world when it was completed in 2003) to roads, coastal structures, buildings and tourism amenities, unless adaptation measures are implemented.

Harbours/Ports

The South African coastline is exposed with very few natural harbours. The three main ports in South Africa are at Richards Bay (largest coal export terminal in the southern hemisphere exporting 85 mega-tonnes per annum), Durban (the largest container port in Africa, with import/export at 42 mega-tonnes per annum) and Saldana Bay (exports of 43 mega-tonnes per annum of iron ore) (Rossouw and Theron 2009). Other major ports serving as import/export hubs for the southern African region are Cape Town, Mossel Bay, Port Elizabeth and East London (Figure 11.1), as well as Walvis Bay, Luanda, Maputo and Beira in neighbouring countries. In a survey of port cities world-wide, Nicholls et al. (2008) rank Cape Town port at 107/135 and Durban port at 93/135 for exposure of population and assets to risk of sea-level rise. Almost all South Africa's harbours are engineered with substantial harbour entrance works built seaward of the shoreline. These structures interrupt the natural longshore transport processes, which can cause severe erosion on the down drift side of harbours. Such impacts are sometimes mitigated by sand pumping schemes, as at Durban (Nijhoff 1935, Smith 1941, Kinmont 1955, Barnett 1982, 1999). Durban plans to double its container port capacity over the next few years (Mather et al. 2006), and planning needs to take into account the rise in sea-level and the potential change in alongshore sediment transport due to increased wave action suggested by Theron (2007).

Armoured or fortified coastlines

Shorelines that have previously been fortified using sea walls or other defence systems will not be immune from attack. Increases in water depth as a result of sea-level rise will allow increased wave energy to penetrate closer inshore. This increased wave energy could exceed the original design condition; if so, the structure could be subjected to more wave energy than it is capable of withstanding resulting in partial or full failure of the structure. Adaptation to increased sea-level rise would be to check the design parameters of existing critical infrastructure where failure could result in severe financial, social and environmental costs. New infrastructure adaptation is easier as these additional wave forces can be designed into the structure at the initial stage. South African coastal engineers are currently investigating structural design criteria that will match the predicted sea-level rise.

11.3. OPTIONS TO MITIGATE THE POSSIBLE IMPACT OF SEA-LEVEL RISE ON THE SOUTH AFRICAN COAST

In South Africa little research has been done on, or effort put into, ways to mitigate possible impacts of climate change, sea-level rise and increased storminess on the South African coastline, although there are many general publications on the subject (e.g., Sorensen et al. 1984). The discussion below is based on guidelines discussed by Theron (2007) and Theron and Rossouw (2008), and those of Midgley et al. (2005) for the Western Cape.

11.3.1. SAND BUDGET

A crucial factor that determines how severely climate change and sea-level rise will impact erosion of the coast is the amount of available sediment. Already, anthropogenic reduction of sediment supply to the coast has resulted in serious coastal erosion in South Africa, and in California, some large dams are being removed in an attempt to rectify such actions of the past. In water scarce developing countries, such as South Africa, particularly frugal and wise management of the water resources is imperative. South Africa’s natural environments along the coast have some inherent adaptive capacity, but only where there is a surplus of sediment. Quantification of sediment transports and budgets is tremendously complex, even more so in attempts to understand the relevant effects of climate change on nearshore dynamics. Coastal sediment source and sink areas in South Africa have not been comprehensively investigated, and more study needs to be done in this area.

In the short-term, it is possible to maintain the shore-line by providing additional sand from offshore dredge sites to replace and offset the increased erosion and beach reduction caused by sea-level rise. The economic costs of this option will determine when this intervention is no longer viable. In the medium-term, the decision to defend might need to be taken, as retreat may not be practically possible. The nature of the coastline could change permanently with, for example, sea walls replacing the once sandy beaches, as were observed along the KwaZulu-Natal coastline after the March 2007 storm (Phelp et al. 2008). Other beachfronts may not be so fortunate and may find that the renourishment option is too expensive and may need to move directly to a defend position. On a positive side, some smaller regional and local beachfronts might be less developed and it may be possible to retreat some distance inland, effectively putting off the defend option.

11.3.2. DUNE MANAGEMENT

Primary dunes provide protection to coastal infrastructure against wave attack and erosion (Pye et al. 2007). In some South African areas it appears that maintenance and management of the coastal dune fields is the most sensible approach to take.

11.3.3. DECISION-SUPPORT TOOLS

South Africa needs to develop decision-support tools such as a geographic information system (GIS) database, with maps and reports for use by the coastal management community. This will lead to a coastal vulnerability classification scheme, whereby realistic scenarios of future coastal conditions can be used to support adaptive management and the development of coastal policy. There is a clear and urgent need for improved understanding of and especially predictive capabilities regarding these issues. This will eventually enable South Africa to achieve wider goals such as:

- To integrate physical processes at different spatial and temporal scales into regional models to improve predictions of regional responses to global change.
- To understand the increased vulnerabilities of coastal biodiversity and ecosystem services to the cumulative effects of climate change (rainfall, temperature, sea conditions, ocean water levels), human agency (water allocation, water quality, development in the coastal zone and catchments) and natural processes (hydrology, wind regime, sea currents, wave regime, coastal processes, underlying geology, sediment transport).
- To understand and identify thresholds and risks in order to predict system state transitions.
- To inform, aid and promote wise policy, management and governance of the southern African coastal zone from a holistic and integrative perspective.

11.3.4. COASTAL MANAGEMENT STRATEGY PLANS

The limited research, done on the mitigation and adaptation options available to South Africa, is considerably different from first world approaches and is still largely undefined. Knowledge gained from this research still has to be incorporated into specific coastal management strategies. When provincial state of coasts reports are initiated in the form of strategic environmental assessments and strategic development plans, the coastal development set-back lines (Collier et al. 1977, Cambers 1997, FEMA 2000, Nichol 2003) need to be accurately determined for each particular stretch of coastline under study. The development setback lines need to take into account:

- The increase in duration and magnitude of sea storms due to climate change (or any other such impacts other than sea-level rise).
- The increase in maximum natural short-term shoreline variability (due to higher storm waves resulting from climate change).
- The increase in progressive shoreline retreat rates (due to climate change, for example, resulting in a greater gradient in alongshore transport) where this phenomenon is occurring.

Sufficient physical environmental data should already be available for most locations along the South African coastline to draw up a point rating system whereby the vulnerability of sites can be evaluated objectively on a relative scale in terms of the main potential impacts.

11.3.5. DEVELOPMENT

The most vulnerable areas along the coast of South Africa will almost invariably be located where problems are already being experienced at present. In most cases these are areas where development has encroached too close to the high-water line, or too near the mean sea-level. When provincial state of coasts reports are initiated and strategic development planning is conducted for South Africa, coastal development set-back lines need to be determined accurately for the particular stretch of coastline under study. Appropriate coastal development needs to take into account proper planning, knowledge of local and remote coastal processes (including climate change effects, sea-level rise and sea-storm impacts), and environmental assessments. This is particularly relevant considering that about 90% of the world's coastline is already affected by erosion, which is likely to be exacerbated significantly by sea-level rise and increased sea storminess. Coastal real estate, tourism and recreation along South Africa's coastline have enormous socio-economic value, assets that should be protected and wisely governed. The importance of sustainable development of these resources has been recognized by national government as reflected in, for example, the South African National Environmental Management: Integrated Coastal Management Bill (2007), now Act, which inter alia calls for coastal management plans that include climate change effects and impacts. Many of the problems in coastal areas relate to escalating conflicts between development and the environmental protection and management of natural resources. The White Paper for Sustainable Coastal Development in South Africa (DEAT 2000) aims to “achieve sustainable coastal development through a dedicated and integrated management approach”. If the current rapid development along the South African coast is to occur in a communally beneficial and sustainable manner, it is vital that planning takes place based on scientific knowledge of present and expected future conditions.

11.4. REQUIRED RESEARCH AND RESOURCES

Further research into the impact of, and adaptation to, sea-level rise on coastal infrastructure is required in the following areas:

- The Eastern Cape, and in particular the Port Elizabeth/Algoa Bay and East London regions.
- South Africa as a whole; most studies have concentrated on Cape Town and Durban.
- More research needs to be done on the changing marine wind and wave climate around southern Africa.
- Coastal sediment source and sink areas need to be investigated further.

A recent workshop dedicated to storm surges was instigated by the Department of Environmental Affairs and was aimed at communications between regional government, town planners and researchers. It is hoped that this is the first of many workshops aimed at identifying and addressing the impact of storm surges on South Africa’s coastline.

11.5. SUMMARY

In general, South Africa has very little adaptive capacity in developed coastal areas, other than relatively expensive upgrades or replacements to existing coastal infrastructures. The undeveloped areas have more adaptive capacity. For South Africa, the best policy in the long term in these areas appears to be to allow coastal processes to progress naturally. If left undisturbed, the natural ecosystem is expected to have good adaptive capacity in many instances. South Africa’s ability to halt the coastal impacts of climate change on a large scale is virtually nonexistent, and the climate change effects on the coast may well lead to other detrimental impacts if the problem is misunderstood or underestimated by authorities. Tol (2004) predicts that adaptation would reduce impacts by a factor of 10 to 100 (globally) and that adaptation would come at a minor cost compared to the damage done without adaptation. This strongly emphasizes the need for South Africa to set and implement measures before the damage becomes too costly to repair. Each vulnerable stretch of coastline should be studied in terms of aspects such as wave energy, sand budgets, future sea-levels and potential storm erosion setback lines. It is important to consider all environmental impacts during the life of a project so that the real costs and functionality can be estimated. Sea-level rise will affect both the built and natural environment. At the very least, coastal zone managers, coastal engineers and planners need to remain informed on the probable future impacts of global weather changes.

Midgley et al. (2005), Theron (2007) and Theron and Rossouw (2008) suggest that, for South Africa, the best approach appears to lie in planning and research related activities, such as:

- Instigate and maintain a measurement program utilizing high resolution aerial photographic/ satellite mapping, accompanied by a study of hydraulic conditions and surveys of coastal erosion/evolution and sediment transports/ budgets. The purpose of the measurements is also to confirm the predicted sea-level rise and increased storminess, and to quantify the many impacts.
- Identify important thresholds of dangerous change and include sensitivity analyses.
- Develop a GIS based operational system that highlights the vulnerable areas and places of

potential impacts, and identifies hotspots and hazardous areas of change.

- Determine coastal erosion and development setback lines, allowing for at least a Bruun-type erosional response (Brunn 1983, 1988), as well as expanded profile envelopes.
- Draw up Shoreline Management Plans which could advocate responses of the type: “Do nothing”, “Hold the existing line”, and “Advance the existing line” or “Retreat”. In terms of developments and infrastructure, this will provide the strategic framework in which all coastal structures and sea defences are evaluated. Specialist studies and monitoring of the shoreline are essential components of ongoing Shoreline Management Plans (Midgley et al. 2005).
- Design coastal protection /developments /structures specifically to compensate for effects of climate change.

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13. APPENDIX

Larry Hutchings

13.1. SUMMARY BASED ON THE BCLME CLIMATE CHANGE WORKSHOP, MAY 2007

The Benguela Ecosystem is an inherently highly productive, complex and variable ecosystem. In a system such as this, it is extremely difficult to separate the climate change “signal” from “noise”. Other large ocean basins such as the North Atlantic and the North Pacific have well defined interdecadal changes or cycles. The Benguela has a higher degree of variability than its counterparts elsewhere (the Humboldt, Canary and California currents) and this has to be taken into consideration when managing the Benguela Current ecosystem and its response to climate change. It is at the confluence of three major ocean systems, (the Atlantic, Indian and Antarctic oceans) and is subject to influence from the tropical Atlantic, the subtropical high pressure systems in the South Indian and South Atlantic oceans and the midlatitude pressure systems in the Atlantic and the Southern oceans. We have comprehensive data sets stretching back about 50 years and long-term trends and cycles are beginning to emerge from data and models.

Major findings include:

- One of the strongest trends in the data has been a warming at the northern and southern boundaries of the Benguela system. The northern warming has occurred across the boundary, while the southern boundary has warmed just south of the Agulhas Bank, with cooling in the inshore areas of the Agulhas Bank and southern Benguela, increasing the gradients across the southern boundary region.
- There has been an increased frequency of “warm events” at the Angola–Namibia border in the past decade or so. There has been a persistent change in the onset of seasonal warming in the north, which has potential consequences for increased hypoxia (low oxygen water) on the Namibian shelf. In this respect, it is thought that a major low oxygen event off Namibia in the 1990s had a severe and longlasting impact on the hake stocks, which have not recovered despite conservative management actions.
- There has been a long-term increase in southerly winds that induce upwelling in the southern Benguela with modulation over decadal time scales. In the northern Benguela, winds also follow a decadal cycle and are currently in a low wind phase.
- Sea level has risen at approximately the same rate as the rest of the world, but is not regarded as a serious problem in the BCLME region, which has relatively few low-lying developments.
- Zooplankton has increased by approximately 10-fold over the past five decades in the Benguela region, caused by changes in productivity and the upwelling-favourable wind field, but moderated by the pelagic fish boom in the southern Benguela in 2000–2003.
- Pelagic fish trends in the northern and southern Benguela have been dominated by heavy fishing pressure, resulting in collapse of sardine stocks in the 1960s. Despite a steep decrease in fishing pressure in Namibia in the 1990s, the sardines have failed to recover to their former levels. This could be attributed to the warming trend, competition with the increased horsemackerel stocks, or suppression by predators.
- By contrast, southern pelagic stocks have increased, accompanied by an eastward shift in sardine and anchovy. These eastward and westward shifts appear to be cyclical, but are currently causing economic problems for the industry and foraging problems for penguins. The 40–60 year cycles are characteristic of sardine and anchovy worldwide and have been

occurring since before industrial fishing began, judging by scale deposits.

- Horsemackerel stocks in Namibia increased after the demise of sardines but have recently begun to decline. Another horsemackerel species in Angola has also declined, and there is currently a ban on catching horsemackerel, resulting in a need to import fish for local consumption in that country.
- There is no evidence of changes in hake distribution in the southern Benguela, but deepwater hake appear to have expanded northwards in Namibia in response to improved oxygen levels on the Namibian shelf in the late 1990s.
- Rock lobsters have declined in the central Benguela and shifted southwards and eastwards in the southern region. This could be a result of heavy sustained fishing pressure, which has been exacerbated by the increase in low oxygen waters in the inshore waters of the southern region. This has lead to an increased frequency of mass walkouts in the 1990s and a depleted population on the west coast. Employment has dropped on the west coast and increased in the Walker Bay area.
- Top predators have responded to the changes in fish availability in different parts of the ecosystem. Seals, which are generalized feeders, have expanded northwards into southern and central Angola and stabilized in the central Benguela region. Seabirds, however, have declined considerably in the northern Benguela. The eastward shift in pelagic fish in the southern Benguela has lead to recent steep declines in penguin and gannet populations on the west coast. Several other seabirds, which do not depend on fish as food, have expanded their range eastwards in recent decades. There have also been increased outbreaks of avian flu and cholera, symptomatic of stressed populations.
- Viewing the system as a whole, where there has been persistent decadal variability in the BCLME, it is not clear if these changes are linked exclusively to climate change, or to inherent natural long-term cycles. There appears to be a resource shift to the northern and eastern extremes of the Benguela region from the central parts along the west coast, creating economic hardships for communities in the core of the Benguela Current region.
- The inherent high decadal (5–15 year) variability in driving forces in the BCLME and the South Atlantic suggests that the management of marine resources needs to adapt over similar time scales.
- Future research and monitoring efforts need to focus on a much broader approach in space and time, including global changes and palaeo-oceanographic time scales. Not only is this important for future marine ecosystem management, but it is likely to underpin future seasonal and longer term weather and climate change forecasts in the region.
- Clearly this will require improved collaboration between the oceanic and atmospheric institutions in southern Africa and a global perspective. The newly established Benguela Current Commission can play an important role in furthering this goal.

NRF National Research Foundation | SAIAB South African Institute for Aquatic Biodiversity

NRF National Research Foundation | SAEON South African Environment Observation Network

SOUTH AFRICAN national biodiversity institute SANBI

University of Cape Town · iYunivesithi yaseKapa · Universiteit van Kaapstad

Oceanographic Research Institute ORI

CSIR our future through science

Nelson Mandela Metropolitan University for tomorrow

Rhodes University Where leaders learn

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