LONG TERM ADAPTATION SCENARIOS

TOGETHER DEVELOPING ADAPTATION RESPONSES FOR FUTURE CLIMATES

MARINE FISHERIES

environmental affairs
Department:
Environmental Affairs
REPUBLIC OF SOUTH AFRICA

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Agriculture, Forestry and Fisheries
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On behalf of
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
of the Federal Republic of Germany

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LONG-TERM ADAPTATION SCENARIOS
FLAGSHIP RESEARCH PROGRAMME (LTAS)

CLIMATE CHANGE IMPLICATIONS FOR MARINE FISHERIES IN SOUTH AFRICA

LTAS Phase 1, Technical Report (no. 5 of 6)

The project is part of the International Climate Initiative (ICI), which is supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety.

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LIST OF ABBREVIATIONS

CPUE	Catch per unit effort
DAFF	Department of Agriculture, Forestry and Fisheries
DBEM	Dynamic Bioclimate Envelope Model
DEA	Department of Environmental Affairs
ENSO	El Niño southern oscillation
MLRA	Marine Living Resources Act, No, 18 1998
MPA	Marine protected areas
MSY	Maximum sustainable yield
NPP	Net primary productivity
OMP	Operational management procedure
REI	River-estuary interface
SST	Sea surface temperature
TAB	Total allowable by-catch
TAC	Total allowable catch

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THE LTAS PHASE 1

The Long-Term Adaptation Scenarios (LTAS) Flagship Research Programme (2012–2014) is a multi-sectoral research programme, mandated by the South African National Climate Change Response White Paper (NCCRP, para 8.8). The LTAS aims to develop national and sub-national adaptation scenarios for South Africa under plausible future climate conditions and development pathways. During its first Phase (completed in June 2013), fundamental climate modelling and related sector-based impacts and adaptation scoping were conducted and synthesised. This included an analysis of climate change trends and projections for South Africa that was compared with model projections for the same time period, and the development of a consensus view of scenarios for three time periods (short-, medium- and long-term). Scoping of impacts, adaptation options and future research needs, identified in the White Paper and guided by stakeholder engagement, was conducted for primary sectors namely water, agriculture and forestry, human health, **marine fisheries**, and biodiversity. This modelling and scoping will provide a basis for cross-sectoral and economic assessment work needed to develop plausible adaptation scenarios during Phase 2 (scheduled for completion in April 2014).

Six individual technical reports have been developed to summarise the findings from Phase 1, including one technical report on *climate trends and scenarios for South Africa* and five summarising the *climate change implications for primary sectors*, water, agriculture and forestry, human health, **marine fisheries**, and biodiversity. A description of the key messages emerging from LTAS phase 1 has been developed into a *summary for policy makers*; as well as into seven factsheets comprising the LTAS *Climate and Impacts Factsheet Series.*

REPORT OVERVIEW

This technical report presents the LTAS Phase I findings for the **marine fisheries** sector in South Africa. It references existing South African research combined with insights from international research and global projections to present a preliminary picture of potential impacts of future climate change on marine fisheries in the country. Specifically, it summarises the climate change impacts as well as adaptation response options and future research needs for the marine fisheries sector. This report is based on the results of relevant past and current research on extractive use and its implications for detecting and projecting climate change impacts, on historical trends in fisheries and observed management and policy responses, and on advances in projecting climate change impacts.

LTAS Phase I adopted a semi-quantitative approach to analysing the likely impacts of climate change on marine fisheries in South Africa.This report therefore provides a narrative assessment of the estuarine and inshore, and the offshore fisheries trends; and the current potential for projecting climate change impacts. A brief description of each chapter of the technical report is provided below.

Chapter 1 (Introduction) provides an overview of the South African marine environment and fisheries including estuarine and inshore fisheries, and offshore fisheries.

Chapter 2 (Climate change impacts on marine fisheries) synthesises existing research on climate variability and change and known potential impacts on marine species composition and productivity, behaviour and physiology, and the related effects on human livelihoods of coastal and offshore fishers. The chapter also provides an overview of ocean acidification linked to particular concerns for South African fisheries.

Chapter 3 (Adaptation response options) provides an overview of adaptation response options for the marine fisheries sector in South Africa.

Chapter 4 (Research requirements) provides an analysis of key research gaps in understanding the vulnerability of the marine fisheries sector to climate change.

Chapter 5 (Conclusion) concludes the report highlighting that effective management, which accounts for climate change, is critical for supporting the commercial, subsistence and recreational fishing sectors through improved environmental, resource and social resilience, maintenance of ecosystem, species, genetic and social diversity under future climate conditions.

EXECUTIVE SUMMARY

South Africa benefits from a wide range of marine resources that contribute to local, national and international food security. Commercial fisheries are concentrated on the western and southern coasts, with localised recreational and subsistence fishing spread along much of the coast. The commercial fishing industry contributes about 1% of GDP, and provides an estimated 27 000 jobs, with more than double the number of jobs in secondary industries such as fish processing, transporting fish products and boat building. Subsistence fishing is important for coastal community livelihoods. Many South African fishery resources are overexploited with more accessible coastal resources at greater risk.

Climate change is likely to affect the productivity and diversity of South Africa's fisheries by changing the distribution, abundance and size of resources, their habitat extent, condition and connectivity, their physiology and behaviour and the catchability of resource species. Changes in sea surface temperature (SST), storm frequency, freshwater flow and runoff patterns, productivity, oxygen levels and wind will all have impacts on estuarine, inshore and offshore ecosystems, affecting recruitment, fish behaviour and physiology, influencing fish size, and increasing fish mortalities. This could result in significant adverse impacts on subsistence fishing livelihoods as well as commercial and recreational industries.

Tropical species may move polewards in response to warming temperatures resulting in an expansion of the subtropical region. In contrast, temperate regions may contract, with coastal species being affected by changes in upwelling, related extremes in temperatures, reduced runoff and habitat loss, ultimately leading to a decrease in temperate species diversity and abundance. Stocks under intense exploitation pressure are likely to be more vulnerable to the effects of climate change than optimally exploited populations. Overfishing may result in reduced genetic variability, which may negatively affect the possibilities of an evolutionary response to climate change and the ability of depleted stocks to recover.

Directional shifts in the spatial distribution of several marine species, which are possibly attributable to climate change trends, have already been recorded around South Africa's shores affecting intertidal, shallow coastal and offshore species. Two projected consequences of climate change that could have significant implications for fisheries are accelerated sea level rise and increased frequency of high-intensity coastal storms and high water events. The effect of these events, such as reduced/increased freshwater flow, is a significant risk to estuarine and inshore fisheries. Reduced/increased freshwater flow, sea level rise and increased storm activity will reduce estuarine nursery habitat, and decreased rainfall may cause temporarily open/closed estuaries to close more frequently, and may even result in closure of permanently open estuaries. On a regional scale, KwaZulu-Natal and west coast estuaries are likely to be the most affected from a structural and functional perspective.

Scenarios of more extreme rainfall and dry spells, coupled with sea level rise, could cause damage to or even the loss of nursery habitats essential for prawns and estuarine fish. On the other hand, increases in summer rainfall could result in some estuaries like the St Lucia Estuary opening more frequently, with a positive impact on the abundance of shallow water prawn on the trawl grounds, as long as existing water uses in the catchments feeding these estuaries are better managed. For both estuarine and marine species, the positive impacts of increases in rainfall could be offset by seasonal shifts in rainfall that could confuse behavioural cues at critical life-history stages such as spawning or migration. Increased storm activity under a changing climate will have a significant impact on fishing activity by reducing the number of viable sea fishing days, and damaging shore-based offloading facilities and fishing vessels.

Fisheries that are successfully managed to achieve resource sustainability will be better positioned in the long term to adapt to the effects of climate change. This is because marine resources are likely to be more robust to the effects of climate change if the compounding stresses from overfishing, habitat degradation, pollution and other anthropogenic factors are reduced. Management strategies would benefit through the inclusion of sound ecosystem-based management practices that focus on rebuilding over-exploited fish resources and impacted ecosystems and improving marine habitat quality. This will result in positive gains for society and the fishing industry through more productive fish stocks, secure biodiversity and improved resilience and adaptive capacity to climate change. Maintaining genetic variability through sustainable fishing practices and appropriately zoned fishing areas including climate-resilient marine protected areas (MPAs) can secure genetic potential and enable adaptation to changing conditions. MPAs need to be effectively managed to maintain or maximise ecosystem resilience despite the effects of climate change. This can be achieved by ameliorating stressors such as overfishing, pollution, invasive species and excessive nutrient inputs, and by implementing and expanding MPAs in a way that preserves the linkages and connectivity among sites.

Adaptation measures for the communities reliant on fisheries for food and income include mechanisms and processes to balance social and economic objectives. Ensuring that policies encourage diversification of activities and income generation to enhance social resilience in the face of uncertainty and variability is also important, particularly for the most vulnerable coastal and fisher communities. The promotion of adaptation options such as education, entrepreneurial training, and training in coastal and marine tourism and sustainable aquaculture would help to prevent the potential deterioration of social conditions in fisher communities.

Projecting climate change impacts on marine fisheries is difficult because of the complex relationships between species distribution patterns, variations in their abundance, distribution and productivity, and the impacts of overfishing and other stressors. Impacts on fisheries depend on distinct oceanographic scenarios dominated either by projected changes in southerly and westerly winds, or by changes in the strength of the Agulhas Current. Effective modelling is limited by incomplete information on the functioning of the biological resources and even more critically on the physical changes in the oceans. In particular, most of the global biophysical models currently in use do not simulate fully the salient features in the oceans around South Africa. Furthermore, the effects of ocean acidification on fisheries and marine biodiversity remain a poorly quantified risk. Focused research is needed to contribute to the development of plausible scenarios of physical oceanographic and coastal habitat change. The impacts of unsustainable fishing and climate change interact in a number of ways and should not be treated as separate issues. To make progress on projecting direct impacts of climate change scenarios, additional data collection, synthesis and model development is needed.

1. INTRODUCTION

South Africa's diverse and dynamic marine environment is among the most complex in the world, with three major ocean current systems dominating this relatively small region: the cold Benguela Current on the west coast (Atlantic Ocean), the warm Agulhas Current on the east coast (Indian Ocean), and the westward flowing Circumpolar Current circulating the Southern Ocean (Sink et al., 2011). These three currents and their dynamics are key drivers of southern Africa's broader climate (Reason & Hermes, 2011). The different climatic drivers of these systems, together with variability in local oceanographic conditions, coastal topography and habitat types are likely to result in highly variable climate change effects around the coast (Rouault et al., 2010, DEA 2011). Furthermore, interactions between climate change and anthropogenic effects, specifically fishing, result in additional complexity in attributing the cause of observed changes, and make future predictions difficult (Rijnsdorp et al., 2009; Cheung et al., 2012; Heath et al., 2012).

The fisheries sector is worth an estimated six billion rand per annum and directly employs 27 000 people in the commercial sector. Thousands more, and their families, depend on marine resources for food and livelihoods and to meet basic needs (DAFF, 2012). Many of South Africa's coastal and marine resources are overexploited (DAFF, 2012; Sink et al., 2012) with the more accessible coastal and inshore resources at greater risk. Poaching and illegal harvesting and trade in marine species pose additional risks to South African fisheries and the livelihoods of legitimate fishers. South Africa has an excellent track record in marine science with substantial expertise in applied research for fisheries management. Although many resources are overexploited, management action can lead to stock recovery. Effective management, that accounts for climate change is critical to resource recovery and long term food and job security in South Africa. Key elements in securing resource sustainability in the long term include robust stock assessments, effective data management, ability to detect, understand and predict change and science-based management action grounded in the realities of resource abundance.

Specific details related to South Africa's key inshore and estuarine fisheries, and offshore fisheries are provided below.

1.1 Estuarine and inshore fisheries

South Africa's coastal ecosystems support a wide range of fisheries. Species richness is low along the west coast and increases progressively along the east coast. Most commercial fisheries are focused on the west and south coasts. Although the east coast supports smaller fisheries, the high coastal population density has resulted in intense exploitation of inshore resources and consequently many coastal resources in this region are overexploited (Griffiths et al., 2010). A key component of South Africa's coast is its estuaries (see Box 1).

Box 1. The importance of estuaries

Estuaries offer refuge for marine species from adverse conditions in the marine environment (such as lethal low-oxygen conditions). In addition, estuaries provide important nursery areas for numerous species. The Orange, Olifants and Berg estuaries, for example, are important nursery areas for exploited marine and estuarine species before they recruit into marine fisheries (Lamberth et al., 2008). Certain species are classed as being "estuarine-dependent", i.e. those with the ability to locate and secure refuge in estuaries.

River flows influence marine fish and fisheries directly and indirectly through the export of nutrients, sediment and detritus into estuaries and the ocean (Gillanders & Kingsford, 2002; Robins et al., 2005):

Nutrient supply stimulates production of phytoplankton and zooplankton and, ultimately, the larval, juvenile and adult fish that depend on them as food sources.

Sediment replenishes nearshore habitats that are continuously eroded by oceanic currents and provides a refuge for many fish by increasing turbidity.

Detritus may be broken down into useful nutrients, serve as a substrate for microorganisms or be consumed directly by detritivorous fish and invertebrates.

Recruitment and emigration of estuary-dependent fish to and from estuaries varies according to the magnitude, frequency and timing of freshwater flow and the flooding regime (Turpie et al., 2002; Taljaard et al., 2009). Reductions in freshwater flow reaching the sea translate into a weakening of recruitment cues and possible recruitment failure for the juveniles and larvae of estuary-dependent fish. As a consequence, climate projections that translate into river flows provide an important basis for projecting climate change impacts on these systems. The life-histories of estuarine-dependent fish are adapted to the natural flood regime and any deviation from it, such as a succession of atypical floods, may remove a successful recruitment from a system. From a fisheries perspective, altered freshwater flows and consequent variations in any of the above variables can cause changes in catch composition, resource base (e.g. demersal vs. pelagic fish abundance), fleet structure, the spatial and temporal distribution of effort and ultimately the economic value of the fishery concerned (Binet et al., 1995; Loneragan & Bunn, 1999).

Estuarine functioning is also strongly influenced by land management practices, particularly human management of water resources such as impoundments (i.e. affecting river flow), and ancillary impacts of water quality effects such as those resulting from agricultural management practices. For example, collapse of the west coast sole trawl fishery coincided with the establishment of most of the large dams on the Orange-Senqu catchment becoming operational in the 1970s.

South Africa's estuarine and inshore ecosystems can be broadly divided into three biogeographic regions (Van Niekerk & Turpie, 2012) separated by zones of overlap (Figure 1, described below):

- Cool-temperate (Orange River to Cape Point);
- Warm-temperate (Cape Point to Mbashe Estuary); and
- Subtropical (Mbashe Estuary to Kosi Bay).

The subtropical humid zone on the east coast is associated with the highest rainfall in the interior of all three zones (with a summer peak). The southern portion of the west coast has a predictable winter rainfall regime (Mediterranean type climate) but the northern portion is a highly arid, cool-temperate zone, with erratic rainfall. The southern coast of South Africa is a warm-temperate zone, with varying rainfall regimes that include summer, winter or bimodal peaks in rainfall (Heydorn & Tinley, 1980; Cooper, 2001). This climatic variability, which is influenced by the regional ocean temperatures, results in a variation in rainfall, river runoff and surface temperature patterns along the coastline (Cooper, 2001; Hutchings et al., 2002; Taljaard et al., 2009), which is important for estuarine functioning.

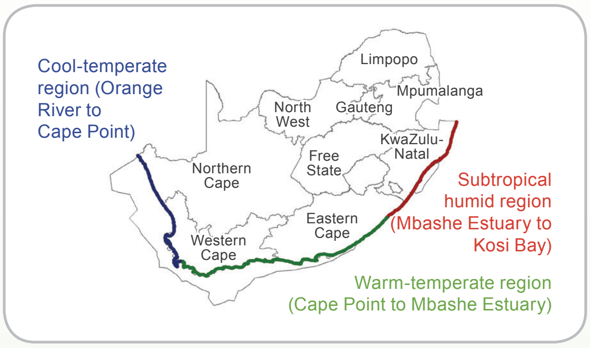

Figure 1. Biogeographic regions for South African estuaries. Red shading indicates the position of the subtropical humid zone, green shading indicates warm-temperate and blue shading indicates cool-temperate (Lamberth & Turpie, 2003). Other coastal and offshore ecoregions are shown in Figure 2.

1.1.1 Cool-temperate region

Estuarine and inshore fisheries in the cool-temperate region target a wide variety of biota including west coast rock lobster, abalone, linefish and mullet. This report focuses on the west coast rock lobster as a case study for this region.

1.1.2 Warm-temperate region

Estuarine and inshore fisheries in the warm-temperate region of the Southern and Eastern Cape) target a diversity of biota including linefish, mullet, squid and coastal invertebrates (mussels etc.). This report focuses on the chokka squid and the line fishery fisheries as case studies for this region. The squid fishery targets a short-lived species and the line fishery targets longer-lived coastal fish species that inhabitat estuarine and inshore ecosystems.

1.1.3 Subtropical region

Fisheries in the estuarine and inshore areas of the subtropical region of KwaZulu-Natal target a wide range of biota including linefish, crustaceans and coastal invertebrates. This report focuses on the prawn trawl fishery, which targets short-lived prawn species, and the KwaZulu-Natal commercial line fishery, which targets longer-lived coastal fish species, as case studies for the sub-tropical fisheries.

1.1.4 Line fishery

Recreational line fishing is the most popular form of marine usage and occurs along the entire South African coastline (Pradervand & Baird, 2002). Line fishing in estuaries is either boat or shore based, with shore angling being more popular than boat-based angling. Line fishing in estuaries is primarily recreational although there are a small number of subsistence fishers who fish in the area between Port Elizabeth and KwaZulu-Natal (Lamberth & Turpie, 2003). No commercial line fishing is permitted in estuaries or along the coast from the shore. Approximately 48 species of fish are caught in warm-temperate estuaries and of those 28 species (58%) are either partially or completely dependent on estuaries as nursery areas. Estuary-dependent species dominate the catches of recreational shore-anglers comprising 83% of the catch by number and mass (Lamberth & Turpie, 2003).

High levels of fish mortality, particularly in estuarine nursery habitats have led to the collapse of the dusky kob stock (Griffiths, 1997). Cowley et al. (2008) in an acoustic telemetry study found that 41% of tagged dusky kob (*Argyrosomus japonicas*), all juveniles, were captured in the estuarine fishery less than a year after being tagged. White steenbras (*Lithognathus lithognathus*), an important component in the catches of coastal and estuarine anglers in the Cape (Day et al., 1981; Coetzee et al., 1989; Bennett 1993a), show a similar decline. The catch rate of recreational shore anglers has declined by 90% since the mid-1970s (Bennett, 1993a). Bennett (1993b) found that the high degree of estuarine dependence, confinement of juveniles and sub-adults to the surf zone, large size at maturation, and predictable aggregation of mature individuals, make this species particularly vulnerable to estuarine degradation and overfishing.

1.2 Hake and small pelagic fisheries (offshore fisheries)

Additional inshore and offshore ecoregions and ecozones (Figure 2) have been identified to cover variability associated with biogeographic regions (presented in Figure 1 above) and depth. Several fisheries operate in South Africa's offshore ecosystems. This report considers the demersal hake fishery and the small pelagic (sardine, anchovy and round herring) fisheries, because of their socio-economic importance, as representatives of the offshore fisheries. Both fisheries are well established (DAFF, 2012).

Offshore fishery resources depend on suitable spawning conditions on the southwest and south coasts in spring and summer, efficient transport by frontal jet currents of early life history stages to the west coast nursery grounds, and suitable nursery habitat characterised by high retention, moderate productivity and an optimal volume of low-oxygen water on the shelf.

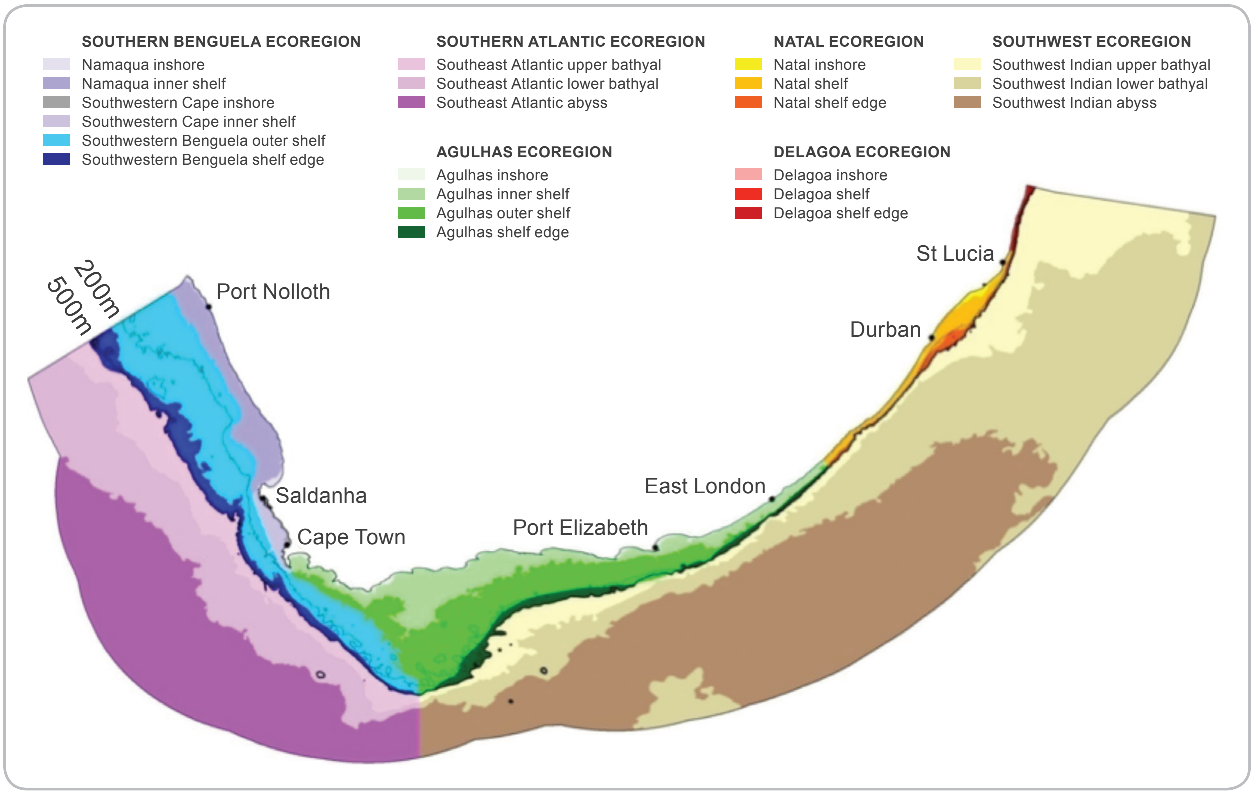

Figure 2. South Africa's coastal and marine inshore and offshore ecoregions and ecozones (Sink et al., 2012).

The small pelagic fishery initially targeted horse mackerel (*Trachurus capensis*) and sardine (*Sardinops sagax*) off South Africa's west coast, but while horse mackerel catches steadily declined during the 1950s, catches of sardine increased rapidly to peak at 410 000 t in 1962 (Figure 3). Sardine catches then declined even more rapidly following a poorly controlled increase in effort and likely overexploitation, a southward expansion of fishing, and variable recruitment (Beckley & van der Lingen, 1999), and were substantially below 100 000 t per annum from the late-1960s to the mid-1990s (with the exception of 1975). During this period, purse-seiners used smaller-meshed nets to target primarily juvenile anchovy inshore off the west coast, and this species became the mainstay of the small pelagic fishery. Annual anchovy catches were highly variable and fluctuated from close to 600 000 t in 1987 and 1988 to 40 000 t in 1996. Sardine catches steadily increased during the 1990s and early 2000s and peaked at 370 000 t in 2004 following sustained population growth. Along with good anchovy catches during the early 2000s this resulted in total annual landings by the small pelagic fishery exceeding 500 000 t for five consecutive years. Sardine catches then decreased sharply again following a rapid population decline caused by sustained poor recruitment and by the end of the 2000s were around 100 000 t, whilst anchovy catches remained around 200 000 t.

Policies that have been introduced have affected hake and small pelagic stocks both positively and negatively. Catches of Cape hakes were initially very low in the 1930s (<1 000 t) but had increased steadily by the 1950s, and the inclusion of foreign vessels from the early 1960s resulted in substantial effort and a peak catch of close to 300 000 t in 1972 (Figure 3). Multiple measures were implemented to control foreign harvesting but these had little effect, and catch rates declined until the declaration of a 200 mile exclusive economic zone in 1977. A conservative management approach that aimed at rebuilding the hake stock to the maximum sustainable yield (MSY) level was then implemented and since 1990 the demersal fishery has been managed using an operational management procedure (OMP) (Payne & Punt, 1995). This is an age-structured production model incorporating commercial catch per unit effort (CPUE) data, and indices of hake abundance derived from research surveys are used in the OMP to set total allowable catch (TAC) levels. Initially, and because of the difficulty in distinguishing between shallow water and deep water hake, the two species were assessed and managed as a single resource, but since 2006 a species-disaggregated model has been used. Hake TACs and catches increased slowly but steadily from about 115 000 t in 1983 to 160 000 t in the late-1990s, but showed a fairly rapid decline in the 2000s attributed to a reduction in the biomass of deep water hake to well below the level considered to support MSY. Recent OMPs have reduced the hake TAC in an attempt to rebuild the deep water hake stock, and the most up to date assessment has indicated a more rapid than expected recovery in deep water hake (DAFF, 2012).Currently, the stock status of shallow water hake is considered optimal (DAFF 2012).

The Sea Fisheries Act, No. 10 of 1940 generally aimed at developing the offshore fisheries. In the interest of resource conservation, however, a variety of management regulations were historically applied to the fishery for small pelagics, including limitations on vessel and processing capacity, closed seasons, mesh size restrictions and various TACs. During the 1950s, a combined sardine and horse mackerel TAC was set, and from 1971 to the early 1980s a global TAC including sardine, anchovy, horse mackerel, chub mackerel, west coast round herring and lantern fish was used. The Sea Fisheries Act, No. 58 of 1973 set the scene for increasing conservation measures

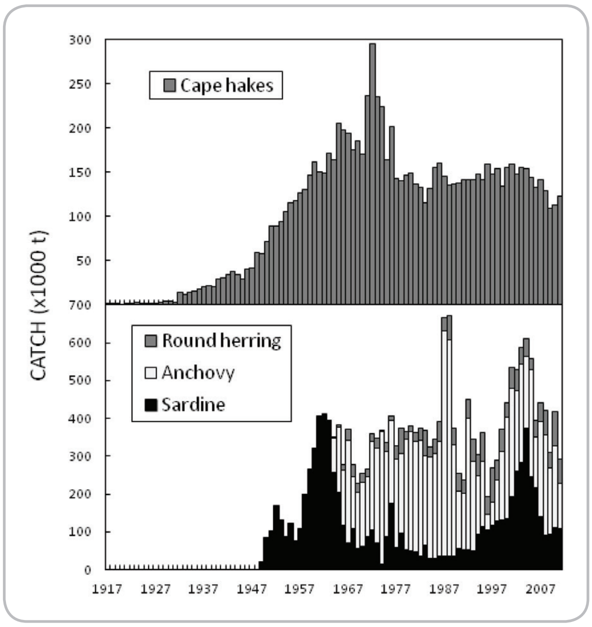

Figure 3. Annual catches of Cape hakes 1917–2011 (upper panel; both species combined) and small pelagic fish 1949–2011 (lower panel; sardine, anchovy and round herring are shown separately). Updated from DAFF (2012).

in the wake of the collapses of the South African and Namibian sardine stocks in the early and mid-1960s and early 1970s (Butterworth, 1983). Separate TACs for sardine and anchovy were applied from 1984 onwards, with a conservative management approach being adopted particularly for sardine in order to promote population recovery. The Sea Fisheries Act, No. 12 of 1988 established the Quota Board which granted access rights as opposed to just TACs (Isaacs, 2006), which were developed further under the Marine Living Resources Act, No. 18 of 1998 (MLRA) to establish long-term fishing rights granted for a 15-year period from 2006 to 2020 for both the small pelagic and hake fisheries.

An OMP for the pelagic fishery was adopted in 1994 (Beckley & van der Lingen, 1999). Management of this fishery must account for the fact that sardine and anchovy shoal together as juveniles, and because the majority (typically >70%) of anchovy caught are juveniles, large catches will result in a high by-catch of juvenile sardine that will negatively impact recruitment and subsequent population size. Hence, catches of the two species cannot be simultaneously maximised and recent OMPs have calculated a trade-off between the two that represents an overall pelagic industry preference. Annual sardine-directed and "initial" anchovy-directed TACs, and an "initial" juvenile sardine total allowable by-catch (TAB), are set at the start of each year and are based on population size estimates derived during a hydro-acoustic survey conducted at the end of the preceding year. These estimates, together with catch data, are key inputs into the population dynamics models used for assessing these resources. A "final" anchovy TAC and juvenile sardine TAB are set mid-year following a second hydro-acoustic survey conducted to estimate the recruitment strength of both species. Depending on recruitment these may be, and typically are, increased from the initial level.

Notably, the MLRA attempted to achieve a balance between marine conservation, social and economic objectives along with rectifying the historic injustices in access to resources. Some progress has been achieved with respect to the needs of critically dependent predators on small pelagics (such as the African penguin), which are currently being incorporated into the OMP. Ecological risk assessments have been conducted and reviewed, yielding a better integration of the various issues in these offshore fisheries and promoting integrated thinking in research and management (Nel et al., 2007; Petersen et al., 2010). Nevertheless, Jarre et al. (2013 accepted for publication) highlight how the process of consolidation in the offshore fishing industry that begun in the 1960s is continuing under the current legislation, and argue that this is to the detriment of social-ecological health.

1.3 Human dimensions

Research into the human social dimension of South African fisheries has gained momentum and is yielding results with relevance for people's adaptation to long-term variability and change in the fisheries sector. Although fishers acknowledge the impacts of variability on multiannual scales (in addition to seasonal and interannual variability), they contest the existence of a unidirectional trend. Nevertheless, long-term ecosystem scale changes have been documented along with tight links between the natural and human social subsystems, highlighting the need to use lessons learnt from the past to think about future major changes by means of structured scenario analyses (Jarre et al., 2013 accepted for publication).

A key conclusion from human dimension studies is that offshore and inshore subsystems should not be treated separately, because many fishers or fishing families derive their livelihoods from both inshore and offshore fisheries and social-ecological dynamics are therefore not sector specific. Of particular relevance is the observation of regional differences in involvement in fishing. Owing to the different development histories of offshore fisheries off the west and south coasts, entire families can be involved in fishing off the west coast (sometimes with gender-specific roles, men on the boats, women in the factories), whereas family income off the south coast has often been more diversified, along with a greater diversification of capital into various, typically smaller, economic sectors.

Major social restructuring has been observed as a ramification of reduced or collapsed stocks, as well as the loss of flexibility of changing resource use along with the implementation of individual rights with the MLRA. The reduced availability of sole and hake to inshore trawlers along with price incentives, for example, has resulted in inshore trawlers targeting kob, and hand-line fishers (in response to the reduced availability of kob) targeting slow-growing, overexploited redfish populations.

The fishery rights allocation process in 2005 has decreased fishers' resilience to fluctuations in resources because rights holders are typically awarded rights in a single fishery only and hence can exploit only one resource, compared to the "basketful" of species that could previously be harvested (Ragaller, 2012). Tensions between conservation and tourism on the one hand, and fishing on the other, are aggravated by a communication breakdown between stakeholders on the ground (i.e. the fishers themselves) and the management agencies (the Department of Environmental Affairs (DEA) and the Department of Agriculture, Forestry and Fisheries (DAFF)) (Ragaller, 2012). The conflict developed following a breakdown in communication and resulted in an increase in illegal, unregulated or unreported fishing (Schultz, 2010). Legislative loopholes combined with the lack of transparency in the small pelagic fisheries have made it difficult, if not impossible, for new entrants to the fishery to establish businesses independent of the established industry (Hara et al., 2013, in review).

1.3.1 Anthropogenic impacts on fisheries

Fishing is seen as the greatest threat to future fish production and affects the sustainability, resilience and ability of exploited species to adapt to climate variability and change (Brander, 2007). Fishing is also the greatest pressure on marine biodiversity and a key driver of ecosystem threat status (Sink et al. 2012). Hsieh et al. (2006) compared exploited and unexploited fish species living in the same environment and found that exploited fish populations showed higher temporal variability in their population size than unexploited populations. The distribution of fish populations under fishing pressure may shrink, reducing spatial heterogeneity, and the number of spawning individuals may decline as fishing tends to remove large individuals and thus truncate the age-size structure of exploited populations (Hsieh et al., 2008). It is also likely that the effects of fishing result in marine ecosystems being more sensitive to climate variability and change through altering the size and age structure in fish populations and hence reducing "buffering capacity" to climate-related poor year recruitment (Rijnsdorp et al., 2009; Heath et al., 2012; Cheung et al., 2012). This results ultimately in a close correlation between environmental variability and population size and length frequencies (Hsieh et al., 2006). As the impacts of fishing and climate change interact in a number of ways they cannot be treated as separate issues. Recent assessments of the status of fishery resources in South Africa found that many of South Africa's inshore marine resources are overexploited or collapsed, with few being optimally exploited (DAFF 2012). This was attributed to the accessibility of resources to a wide range of fishers and an increase in illegal harvesting or poaching (WWF, 2011, DAFF 2012). Fishing may also result in reduced genetic variability, which would negatively affect the possibilities of an evolutionary response to climate change and the ability of depleted stocks to recover (Anderson et al., 2008). This implies that fish stocks under intense exploitation are likely to be more vulnerable to the effects of climate change than stocks that have little or no fishing pressure (Rijnsdorp et al., 2009).

Fishing truncates the age structure (by removing larger individuals) and causes loss of spatial heterogeneity (distribution may shrink), which makes exploited species more vulnerable to environmental variability and to climate effects. In an eight year study of coastal fish species in the Tsitsikamma Marine Reserve, which has been protected for over 27 years, the fish assemblage was found to be relatively stable in terms of abundance, taxonomic distinctness, mean body size and species composition (James et al., 2012). Although abundance of most species was variable between years, a decrease in recruitment of Galjoen for several years did not result in a significant decrease in the abundance of this species. Populations of exploited species are likely to be more stable over time in MPAs than in fished areas because the accumulation of larger age/size classes in the protected area tends to smooth out fluctuations caused by recruitment variability (Babcock et al., 2010).

2. CLIMATE CHANGE IMPACTS ON MARINE FISHERIES

2.1 Climate change-related observations

Shifts in the spatial distribution of several marine species (including intertidal, shallow coastal and offshore species) have been recorded around South Africa's shores (Roy et al., 2007; Cockcroft et al., 2008; Coetzee et al., 2008; Griffiths et al., 2010; Mead, 2011; Lloyd et al., 2012). These shifts have largely been attributed to the effects of climate change such as increasing/decreasing SST, changes in wind patterns and upwelling, and can have concomitant effects on fisheries biodiversity ranging from mild to severe. Other examples of changes in the distribution or other characteristics of marine species off South Africa arising from climate change are rare. Shannon et al. (2010) *emphasise the necessity for considering* environmental drivers (bottom-up) as well as predation and fisheries (top-down) pressures in terms of the impact on living marine resources. The most salient global and local observations of physical and biological changes are highlighted in this section.

One of the globally measured effects of climate change on marine ecosystems is sea surface temperature (SST) over the past centuries. On a global scale, an overall warming trend in the oceans and atmosphere has been detected. Locally, in situ observations of wind and temperatures on the west and south coasts demonstrate very little trend over 30–60 year periods (Hutchings et al., 2012; Blamey et al., 2012), in contrast to satellite-derived observations (Rouault et al., 2010). In line with the highly variable nature of the South African coastline, the change in SST is not uniform and there are several areas along the west, south and southeast coasts where nearshore SSTs are cooling seasonally as a result of an increase in winds that encourage upwelling or a combination of these and an intensification of the Agulhas Current (Rouault et al., 2009 and 2010). For example, a positive trend in SST of up to 0.55°C per decade (from 1985 to 2009) in most parts of the Agulhas Current system and a negative trend in SST inshore off the west and south coasts have been reported (Rouault et al., 2010; Hutchings et al., 2009; Rouault et al., 2009). However, Hutchings et al., (2012) show little change in inshore temperatures in St Helena Bay, while instrumented records along the south coast also show little long term trend (DEA, unpublished data). Confounding the situation, in situ data (DEA unpublished data) has shown that inshore waters are not varying significantly, as increased upwelling compensates for increased heating, increasing the thermal gradient between inshore and offshore waters.

Globally, Boyce et al., (2010) reported a sustained decline in marine phytoplankton biomass over the past century which they linked to increasing SST, although this analysis is not yet widely accepted (e.g. see Mackas, 2011). A decline in marine phytoplankton has not been documented for the southern Benguela, where Demarcq et al. (2003) and Lamont (2011) showed strong interannual variability but no trend in phytoplankton abundance over the 10–15 years observed. Elsewhere, changes in fish distribution patterns (e.g. Perry, 2005; Ottersen et al., 2010) and in the phenology (the timing of life cycle events such as spawning and migration) of a variety or marine organisms (Edwards & Richardson, 2004; Koeller et al., 2009) linked to climatic variables have also been documented.

Mead (2011) detected changes in the distribution of cold- and warm-water intertidal species within rocky shore communities in False Bay that were linked to the observed declining SST and increased upwelling (Rouault et al., 2010). Whilst False Bay does not necessarily host a substantive intertidal harvesting community or fishery, changes in the intertidal species composition could result in changes in the nearshore fish community abundance and diversity being driven by prey availability. This could have potential impacts on the nearshore recreational fisheries throughout South Africa. Should similar intertidal shifts in species communities be detected, specifically along the northern KwaZulu-Natal coast, subsistence intertidal fisheries could be impacted.

Lloyd et al. (2012) reported an increase in species richness and diversity of reef fish monitored along the Natal coast from Ballito to Scottburgh between 1989 and 2007. The increase in species diversity in this study was linked to the increasing SST detected along the KwaZulu-Natal inshore region and was deduced to be as a result of species range expansions linked to ocean warming (Lloyd et al., 2012). Several studies in other parts of the world have similarly found increases in species diversity associated with changing climate conditions (Hiddink & ter Hofstede, 2008; Last et al., 2011; Cheung et al., 2012).

Blamey et al. (2012) analysed shifts in wind intensity and upwelling rates on the west and southwest Cape coast over the period 1960 to 2010 and discussed these changes in relation to changes in the rock lobster fishery. Robust shifts in winds and upwelling were detected in the early 1980s as well as the mid-1990s and possibly 2009–2010, right at the end of the data series. These indicate changes in the habitat for shelf zone species (small pelagics, rock lobster, hakes) off both the west and south coasts, with the coasts possibly reacting differently to climate drivers. From a biological perspective, observations of changes in reef fish assemblages off the east coast linked to ocean warming have been reported. These have led to a higher proportion of tropical species and a lower proportion of temperate species (Lloyd et al., 2012). An eastward expansion in the distribution of kelp in recent years, linked to cooling along the south coast, has also been documented (Bolton et al., 2012).

The southward expansion of warm-temperate/subtropical west coast water as well as a reduction in the frequency and magnitude of upwelling events in Benguela El Niño years has facilitated the expansion of west coast dusky kob into Namibian (and South African) waters at the expense of silver kob and may also have resulted in hybridisation (Potts et al., 2012). For the last 20 years, hybridisation may have existed as far south as St Helena Bay (Lamberth et al., 2010). Hybridisation is a potential response to ecological stress especially on distributional margins and may, at least partly, be due to a stress-induced breakdown in mate recognition. In fish, hybridisation is usually associated with increased resistance to disease and physiological tolerance of environmental stresses and may often allow species to expand their ranges and invade new niches. Conversely, there is molecular support for potential reduced fitness in hybridised fish under environmental stress (David et al., 2004). This may be a plausible explanation for the relatively rare occurrence of interspecies hybridisation in sympatric environments. However, the sympatric populations of the west coast dusky kob and the silver kob are both under stress from fishing, climate change, distributional shifts and an increase in inter-specific interactions. Behavioural and biological responses such as distributional shifts and hybridisation make it clear that some population thresholds have already been reached and that even minor anthropogenic drivers may precipitate further change.

2.2 Projected impacts

The potential impacts of climate change on fisheries and consequently on national economies globally has been reported in Allison et al. (2009). This was based on three variables: the predicted warming, the relative importance of fisheries to national economy and diet, and societal capacity to adapt to potential impacts and opportunities. Based on the IPCC AR4 B2 emissions scenario (which represents a lower emission trajectory than those considered most widely in the LTAS), the vulnerability of South Africa's national economy to climate-driven changes to fisheries was identified as moderate. It is likely, therefore, that higher emissions scenarios would imply a higher level of vulnerability.

2.2.1 Projecting impacts

In South Africa, projecting the impact of climate change on fisheries is complicated by the number of ecoregions found along a relatively short coastline. Currently, there are no reliable regional models of future climate scenarios for the marine areas off South Africa, and the IPCC has cautioned against downscaling from global models. One of the biggest hurdles is the deficiencies in representing the tight SST, topographic, vegetation and soil gradients in the region (Reason and Hermes, 2011). For example, global models do not include the influence of the Agulhas Current on regional heat and moisture flux for the southern Benguela. Regional models are currently being developed which realistically capture basin-scale changes in the wind field (eg Veitch et al., 2010; Loveday, 2013).

Despite a lack of projections, substantial environmental monitoring in support of fisheries research has allowed the development of several good observational data sets compared with many Southern Hemisphere countries. However, subdividing the projected time scale to look at impacts in the short (2020–25 years), medium (2050–2070 years) and long-term (2100–) is currently not possible given the status of current climate models and the overwhelming dominance of decadal variability in observational records of wind, temperature, salinity and oxygen in the Benguela system (Hutchings et al., 2009, 2012). Even with 60 or more years of observational data one is unable to anticipate decadal cycles with any degree of confidence. Cheung et al., (2009), however, presented global projections of changes in the distribution of more than 1 060 exploited marine fish species by the year 2050. The results suggest that climate change may lead to local extinctions of marine fish species in the polar regions, tropics and some enclosed seas by 2050. A follow up paper by Cheung et al., (2010) based on the same number of species suggests a global redistribution of catch with an expected 30–70% increase in catch in high latitudes and a drop of up to 40% in the tropics by 2050.

Two key projected consequences of climate change with significant implications for fisheries are accelerated sea level rise and an increase in the frequency of high-intensity coastal storms and high water events, especially through the impacts on estuarine habitats (see sections 2.2.1.2 and 2.2.1.3). Several climate models project an accelerated rate of sea level rise over the coming decades (Solomon et al., 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). Isostatic settling of the crust caused by the additional weight of water over areas with a wide continental shelf, such as the Agulhas Bank, will locally accentuate sea level rise, possibly by as much as 25% (Reddering & Rust, 1990).

The South African coastline is intermittently impacted by extreme swells associated with tropical cyclones and cut-off low pressure systems (Mather & Stretch, 2012). Extreme weather events are predicted to increase in frequency and intensity in the 21st century and appear to be on the increase globally (Solomon et al., 2007; Engelbrecht et al., 2009; 2011). Extreme rainfall events are projected to increase for South Africa and Mozambique (Davis, 2011). Increased storm frequency and intensity has been hypothesised to have the potential to indirectly change the behaviour and activity of fished species (Rijnsdorp et al., 2009; Cheung et al., 2012) and the effectiveness of trawl fishing gear (Stewart et al., 2010).

2.2.2 Fisheries species composition and productivity

Changes in SST, wind patterns and pressure systems at local scales can affect oceanographic features like upwelling and thereby influence overall marine productivity (Rijnsdorp et al., 2009, Sink et al., 2011) (see section 2.1 on Climate Change Observations (p9) for further information). Projected impacts of climate change on marine ecosystems include changes in species distribution, composition, seasonality and production (Brander, 2009). Based on the observed global scale, the general expectation for the impact of climate change on marine fauna is a decrease in species richness with increasing latitude in both hemispheres (Heath et al., 2012). These observations are correlated with warming annual average temperatures. However, this is not always the case at local scales as observed in the South African marine environment (Rouault et al., 2010, Sink et al., 2011). Marine ecosystems are characterised by large natural variability in climate and ecosystem processes and also respond in varying ways to extractive pressures (Cheung et al., 2012). This makes it difficult to measure and project changes in climate variability and its effects on ocean systems, both physical and biological (Rijnsdorp et al., 2009; DEA, 2011; Heath et al., 2012; Cheung et al., 2012).

Habitat changes in response to climatic changes are likely to have a considerable cascading effect on fish species composition associated with that habitat (Last et al., 2011). Changes could result in some habitat types becoming viable for colonisation by a suite of new species. This would, however, be dependent on several factors such as adult stock to seed new areas, successful recruitment and survival (Kennedy et al., 2002). Some species may simply contract their distribution range avoiding unfavourable parts of their former range through lowered survival, reproduction and recruitment as a result of their former habitat simply no longer supporting that species (Kennedy et al., 2002; Heath et al., 2012). Such behaviour will also result in altered diversity of fish species in a region.

Different marine resources are likely to respond to the effects of climate change differently. Rijnsdorp et al. (2009) propose that species's responses will be influenced by their habitat requirements (pelagic, demersal or deep-water), life-history characteristics (short or long-lived, specialist or generalist) and trophic positions within the ecosystem (apex predator or forage fish). Generalist species are likely to adapt to the prevailing conditions whereas specialist species are usually strongly dependent on specific prey, habitat or environmental conditions. Species that have spatially restricted or very specific habitat requirements for all or part of their life history will be more vulnerable to climate change effects. Short-lived species characterised by high reproductive rates (r-selected) are likely to be able to track the changing environment relatively rapidly while long-lived species (K-selected) would be slower, and less likely to be able to adapt (Perry et al., 2005), while pelagic and demersal species will differ in their response, a trend already observed in South African fisheries.

2.2.3 Fish behaviour and physiology

Changes in SST may also result in changes in the behaviour of resource species, including their catchability. This may be particularly relevant to species captured with baited fishing gear such as west coast rock lobster. It is hypothesised that with increasing temperatures, there is likely to be a related increase in metabolism and consumption rate in fish and invertebrates (Kennedy et al., 2002), leading to higher catch rates and potentially an increase in diversity of catch (Cheung et al., 2012). Similarly it has been suggested that an increase in temperature could result in an increase in fish swimming speed (Peck et al., 2006). Along with behavioural modifications, this may make fish more or less vulnerable to towed fishing devices like trawl nets (Rijnsdorp et al., 2009). Such behavioural modifications are likely to alter the biodiversity of fish species available to fisheries; however, further detailed studies are required in order to understand what sort of changes can be expected.

Reduced fish sizes due to ocean warming and reduced oxygen levels have also been predicted, with reductions in both assemblage-averaged and individual maximum body weight projected from 2000 to 2050 under a high emission scenario (Cheung et al., 2012). For assemblage-averaged maximum body weight, the reduction in body size is likely to be as a result of changes in distribution and abundance (invasion/increased abundance of smaller-bodied species and local extinction/decreased abundance of larger-bodied species), as well as changes in fish physiology (Cheung et al 2012). However, predicted changes in maximum body weight are more conservative than observed changes for both Atlantic cod (Sheridan & Bickford, 2011) and North Sea haddock (Baudron et al., 2011).

2.2.4 *Positive impacts*

Climate change may result in beneficial effects on some species. The change in SST, for example, may result in a limitation on the possible range of some species but may expand the optimal range available to other species. This could result in new fishing opportunities as commercially valuable species potentially enter new areas and become available for harvest (Sink et al., 2011). Cheung et al. (2012) discuss evidence of several warmer water species moving into United Kingdom and Irish seas offering new fishing opportunities in this region. A change in fish biodiversity may also occur as a result of translocation of deep-water species into the shallower shelf region resulting in these species becoming available for capture (Rijnsdorp et al., 2009). However, Hiddink and ter Hofstede (2008) caution that an increase in species diversity as a result of climate change may also have negative ecological and socio-economic effects. If large species are replaced by small species the energy flow through the ecosystem will be altered, thereby changing the dynamics of the ecosystem. Such a shift from large species to increasing abundance of smaller species is likely to decrease the value of fisheries (Hiddink & ter Hofstede, 2008). Furthermore, changes in distribution patterns could alter the combination of predators, parasites and competitors in an ecosystem ultimately resulting in altered ecosystem functioning and fishery productivity in ways that cannot be predicted with current knowledge (Kennedy et al., 2002). Some areas may also become more productive which may increase fisheries yield but increased productivity may also lead to an increase in low oxygen events that may impact negatively on some resources. Fishers are considered opportunistic and respond to environmental changed by adapting their fishing areas, target species and strategies where the management framework supports such adaptation.

2.2.5 *Human dimensions*

An increase in the global intensity and frequency of extreme weather events has been linked to the effects of climate change and such effects are similarly predicted to impact the South African coastal and marine environment (Theron, 2010). Such an increase is likely to impact on fishing activity in terms of reducing the number of viable sea fishing days, possibly affecting catch rates (Stewart et al., 2010; Cheung et al., 2012). Furthermore, increased storm intensity is likely to result in damage and destruction to shore-based offloading facilities and fishing vessels, again resulting in limitations on the catch yield.

2.3 Key impacts: Estuarine and inshore fisheries

2.3.1 *Overall impacts*

On a regional scale, KwaZulu-Natal and west coast estuaries are likely to be the most affected by climate change from a structural and functional perspective (Table 1). In KwaZulu-Natal, the major driver is increased runoff into the numerous small, perched, temporarily open/closed estuaries, which will result in more open mouth conditions, a decrease in retention time and associated loss of primary productivity and nursery function. In contrast, west coast estuaries will be negatively affected as a result of reductions in runoff, related declines in nutrient supply and an increase in sea level rise. This will increase saline intrusion in the permanently open systems and increase mouth closure in the temporarily open estuaries. Similar to KwaZulu-Natal, the west coast estuaries will display a decrease in primary production and a loss of nursery function.

Although Wild Coast, eastern and southern Cape estuaries will show some shift in mouth state, nutrient supply, salinity distribution and production, the most obvious impacts of climate change along these coastal regions will be changes in temperature (nearshore and land) driving range extensions and changes in community structure.

DRIVERS	RESPONSE	SUB-TROPICAL		WARM TEMP		COOL TEMP
		KwaZulu-Natal	Wild Coast	Eastern Cape	Southern Cape	Western Cape
Ocean circulation	Current speed	+	+	+	+-	+-
	Current position	?	?	?	?	
	Upwelling	+	+	+	+	+
Precipitation	Runoff	+	+	+	+-	-
	Mouth closure	-	-	-	+-	+
	Salinity	-	-	-	+-	+
	Nutrients fluxes	+	+	+	+-	-
	Floods & sediment	+	+	+	+-	-
	Droughts	+	+	+	+	+
	Flushing pollutants	+	+	+	+ -	-
Sea level rise	Salinity	+	+	+	+	+
	Increased tidal prism	+	+	+	+	+
	Mouth closure	-	-	-	-	-
Rising temperatures	Species range extensions	+	+	+-	+-	-
	Community composition	-	-	-	+	+
Acidification	Calcifying organisms	-	-	-	-	-
Coastal storms	Mouth closure	+	+	+	+	+
	Overwash	+	+	+	+	+
	Marine sediment	+	+	+	+	+

Table 1. Climatic drivers, key variables and intensity of response in different coastal and ishore regions within the three major marine biogeographic provinces in South Africa. Intensity ranges from high (dark shading) to low (light shading) (Van Niekerk *et al.*, 2012).

2.3.1.1 Temperature

Seasonal cooling of nearshore SSTs, associated with intensified upwelling, may have severe consequences for coastal and estuarine species along the west and south coasts of South Africa. Sudden shifts in temperature can be lethal to fish, especially if shallow water prevents them from finding a thermal refuge (Roessig et al., 2004). Although estuaries and shallow bays can provide thermal refuge for coastal species mass mortalities of coastal fish have been recorded along the south coast when upwelling causes a sudden drop in water temperature (Hanekom et al., 1989). These mortalities do not necessarily result from thermal shock but from fish aggregating in the shallows and being too weak and hypothermic to resist being stranded in the swash zone. In the short to medium term, spatial and temporal shifts in these thermal barriers may disrupt coastwise movement such as the winter spawning migration of white steenbras to subtropical waters. In the long-term, an increase in the frequency and persistence of thermal barriers may affect both temperate and tropical species and even impede the range extensions of the latter into temperate regions. Coastal cooling in some areas, associated with upwelling, may limit the ability of these species to shift their distribution poleward over long distances. It is unlikely that coastal cooling will promote the movement of more temperate taxa beyond their existing range towards the equator.

Changes in the distribution of tropical fish species have been recorded in temperate estuaries (e.g. East Kleinemonde, Mngazana and Breede) resulting in an increase in species richness in these estuaries. However, there is also the possibility of range shrinkage or a decline in the number of temperate species in temperate estuaries and along the coast. Subtle changes in temperature have already seen range expansion, stock separation and the establishment of viable populations of important exploited linefish species (Lamberth et al., 2012). Elevated estuary temperatures may allow fish to overwinter and become established in these systems. Conversely, flow reduction from west coast catchments may see partial or complete loss of the nearshore thermal refugia used as waypoints by nearshore fish migrating from Namibian to South African waters, and ultimately range shrinkage (Lamberth et al., 2008). In summary, tropical species may move polewards in response to warming temperatures resulting in an expansion of the subtropical region. Estuaries in subtropical regions will also be impacted by probable increases in rainfall, a rise in sea level and increased frequency of high intensity coastal storms. In contrast, temperate regions (Eastern and Western Cape) may contract, with estuaries and estuarine species being affected by probable upwelling related extremes in temperatures, reduced runoff and habitat loss, ultimately leading to a decrease in temperate species diversity and abundance.

2.3.1.2 Precipitation, extreme events and runoff

Schulze et al. (2005) assessed the impacts of climate change (including climate change driven alterations in rainfall patterns) on South Africa's water resources and predicted that future climate may be characterised by "hotspots" of hydrological change, one being the present winter rainfall region of the Western Cape. Another identified hotspot is the bimodal rainfall zone of the southern Cape where the frequency and magnitude of large floods as well as the duration and intensity of droughts are anticipated to increase. These systems are characterised by medium to small catchments in which bimodal rainfall ameliorates flow variability and confers a degree of stability on estuarine habitats.

Changes in precipitation, runoff and storm frequencies drive modifications in saline water intrusion in estuaries, the frequency and duration of mouth closure, nutrient fluxes, the magnitude and frequency of floods and related sediment deposition/erosion cycles and the dilution and/or flushing of pollutants (Alber, 2002). This also results in a loss of nursery function. Conversely, large storm events could trigger the premature opening of temporarily closed estuaries by introducing large volumes of seawater into the system and flattening the sandbars. Reductions in the amount of freshwater entering estuaries 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 load, temperature, conductivity, dissolved oxygen and turbidity (Clark, 2006; Van Niekerk & Turpie 2012). Overall, alterations in freshwater flow resulting from climate change into estuaries will affect recruitment and emigration of estuary-associated fish. Estuarine-dependent species are sensitive to reductions in the volume of freshwater runoff and may decline in abundance, which will have fisheries implications. Reductions in freshwater runoff will also reduce the amount of nutrients entering estuaries, with a resultant impoverishment of the biota.

An increase in the magnitude of floods as a result of climate change will cause deeper scouring, thereby increasing tidal amplitude and exposure of subtidal habitats and communities. In large permanently open systems flow reduction may initially result in a reduction in the extent of the river-estuary interface (REI) zone, i.e. that section of an estuary with an integrated vertical salinity of approximately 10. Major reductions in river flow can result in the complete elimination of this mixed zone, so that the system functionally becomes an arm of the sea. In temporary open/closed estuaries, mouth opening and closing is directly linked to freshwater input and wave aspect, with estuaries becoming isolated from the sea by the formation of a sand berm across the mouth during periods of low or no freshwater inflow and high wave action. These systems stay closed until freshwater inflow causes their basins to fill up and their berms to breach (Whitfield et al., 2008). Reduced freshwater inflow leads to prolonged mouth closure and shorter open phases.

2.3.1.3 Sea level rise

Sea level rise will also impact on the mouths of estuaries which will interact with reductions or increases in freshwater flow as described above but these effects have not as yet been fully explored. A rise in sea level and an increase in the frequency of high-intensity coastal storms and high rainfall events may have a range of implications for estuaries and estuary-associated fish. It is anticipated that the effects of sea level rise will be exacerbated by predicted increases in the frequency of severe storms and high tides impacting the coastal platform at a higher mean sea level (Bindschadler, 2006). The upstream shift of coastal wetlands in response to sea level rise may be limited by coastal development and hinterland topography. This may ultimately result in the loss of habitat which will, in turn, affect the abundance of estuarine fish and invertebrates, and the resilience of estuarine and coastal fisheries. Coastal storms and high water events will also alter the salinity and depth of estuaries.

Sea level rise and the related increases in the size of tidal prisms will be tempered by the predominantly perched systems of KwaZulu-Natal (estuarine bays and lakes excluded) whilst it will be more evident along the extended coastal floodplains of the southern and Western Cape coast. Overall, whereas biotic change may be first discernible and more easily measurable in the biogeographic transition regions (e.g. Wild Coast and south-western Cape), the most significant structural and functional changes will be realised in the estuaries of subtropical KwaZulu-Natal and the cool temperate Western Cape.

2.3.2 Cool-temperate region

On the whole, it is anticipated that air temperatures, sea level and the frequency of storms will increase for estuarine and inshore marine habitats and fishery areas along the West Coast, whilst SST, rainfall and river flow will decrease. There will, however, be exceptions to the rule. It is likely that these changes will affect fisheries in the cool-temperate coastal region in the following ways:

- Sea level rise may reduce estuarine nursery habitat, which is essential for many species caught in estuarine and coastal fisheries.
- Decreased rainfall may cause temporarily open/closed estuaries to close more frequently and may even result in closure of permanently open estuaries all of which will have fisheries implications.
- Overall, it is expected that overexploited species (such as many of the temperate linefish species) may be more vulnerable to climate change and variability than unexploited and optimally exploited species. The likely impacts of climate variability and change on the west coast rock lobster are included in Box 2.

Box 2. The impacts of climate variability and change on the west coast rock lobster

Over the past two decades, there have been major changes in the west coast rock lobster resource linked with climatic variability. An increase in the abundance of west coast rock lobster within the eastward extent of their distribution range (south coast region, Cockcroft et al., 2008) has been observed. Catch rates of west coast rock lobster in the traditional fishing grounds along the west coast declined dramatically from 1988 to 1996, coinciding with reduced somatic growth and increased lobster walkouts, suggesting that environmental changes may have played a key role in driving distributional change (Cockcroft et al., 2008). During a similar time period (early 1990s) there was a major influx of rock lobsters into the area east of Cape Hangklip, an area not previously associated with high rock lobster abundance (Cockcroft et al., 2008). This shift in resource availability of west coast rock lobster has had serious ecological, fisheries and resource management implications. Ecological impacts include reduced densities of urchins and winkles (key prey items of rock lobsters) and increased algal cover as a result of reduced grazers (Tarr et al., 1992; Mayfield & Branch, 2000). Reduced urchin densities resulted in low abalone recruitment as juvenile abalone shelter under urchins (Day & Branch, 2000, 2002). Bank cormorants, an endangered species, feed on rock lobster and have also experienced reduced success in breeding, which has become a key conservation concern (Crawford et al., 2008). Social and economic impacts include reduced numbers of long term rights on the west coast and job losses at processing facilities (Cockcroft 2011). This spatial shift in the resource and the concomitant ecological changes are likely to cause challenges in the future management of both rock lobster and abalone resources (Cockcroft et al., 2008).

2.3.3 Warm-temperate region

It is anticipated that for estuarine and inshore ecosystems of the warm-temperate region, air temperatures, sea level and the frequency of storms will increase, while SST will decrease seasonally in some areas as a result of increased upwelling. Projections of changes in rainfall and river flow are less certain for this region. The likely impacts of climate variability and change on the chokka squid fishery are included in Box 3 below.

Box 3. The impacts of climate variability and change on the chokka squid fishery

Squid (*Loligo reynaudii*), known locally as chokka, are fished by jig fishing with effort focused on adult squid during their spawning aggregations on the warm temperate south coast. Abundance of loliginid squids has been correlated to temperature, El Niño events, turbidity and currents with fluctuations in abundance linked to environmental variability and associated biological events such as spawning distribution and survival rate of juveniles, and fishing pressure (DAFF, 2012). Changes in water temperature and upwelling may affect catches of chokka squid in the warm-temperate region but as this species is short-lived, with rapid growth and high mobility, they may be better able to adapt to changes in their environment than many other taxa (Pecl & Jackson, 2008).

Squid have extremely fast growth rates, short life spans (less than two years) and rapid population turnover. Their physiology is able to respond to changes in the environment, with temperature being a key driver (Pecl & Jackson, 2008). Oosthuizen et al., (2002) found that the optimal temperature range for normal embryonic development is between 12°C and 17°C. Bottom water temperatures recorded on the inshore spawning grounds, although more variable than those recorded offshore, are normally between 11°C and 17°C as a result of wind-driven upwelling in spring and summer (Oosthuizen et al., 2002). During El Niño conditions, with low easterly wind intensity there is less wind-driven upwelling resulting in higher bottom water temperatures. Under these conditions, spawning squid may avoid the warmer inshore spawning grounds and may spawn in the deeper mid-shelf region where bottom temperatures are cooler (Roberts, 2005).

Temperature (as an index of upwelling) affects feeding and survival of the paralarvae of chokka. The inshore spawning grounds are displaced from an area of maximum copepod abundance (which the paralarvae are feeding on) associated with a cold ridge by approximately 200 km. The cold ridge is a coastal upwelling filament frequently found off the Knysna coast during summer (Roberts, 2005). It is believed that squid use the net westward shelf currents on the eastern Agulhas Bank for movement of paralarvae to the cold ridge west of the spawning grounds (Roberts, 2005). Intense summer upwelling results in greater cold ridge stability (and thus copepod abundance) with a negative linear relationship between maximum summer SST (an index of cold ridge activity) and chokka squid biomass and catches the following autumn (Roberts, 2005).

As spawning behaviour and embryonic development and survival are directly linked to temperature and upwelling frequency and intensity, any changes in water temperature and upwelling associated with short-term climatic variability (such as ENSO events) and longer-term climate change could affect catches of chokka in the jig fishery.

Rouault et al., (2010) recorded cooling of up to 0.35°C per decade for the south coast between May and August. However, no change in temperature was recorded during summer, which is the peak spawning season for chokka (Rouault et al., 2010). It is therefore difficult to predict how changes in SSTs will affect catches of chokka squid.

Extreme weather events are predicted to increase in frequency and intensity in the 21st century which may have severe implications for the chokka squid fishery (through increased turbidity in the shallow water spawning grounds). Turbidity near the seabed also affects the spawning behaviour of adult squid, with high turbidity causing them to avoid the shallower inshore spawning grounds and move into deeper waters where they are unavailable to the inshore fishery (Roberts & Sauer, 1994). Roberts & Sauer (1994) found that severe winter storms in 1992 resulted in increased swell height, beach erosion and high turbidity on the inshore grounds and subsequently exceptionally poor squid catches in that year. Severe winter storms may be linked to El Niño conditions, which enhance severe westerly winds on the south coast (Roberts & Sauer 1994), and have also been linked to longer-term climate change.

There may be a positive relationship between squid habitat and freshwater flow. Nearshore habitat and sediment composition which is shaped by terrigenous input can change drastically and squid could move elsewhere to their preferred sediment particle size. Alternatively, changes in sediment size, texture and colour as well as in turbidity can lead to squid, eggs and young becoming more susceptible to predation. This squid response to freshwater flow, sediment and turbidity is hypothetical and needs to be tested.

2.3.4 Sub-tropical region

It is anticipated that air and sea temperatures, sea level, the frequency of storms and rainfall will increase as a result of climate change and affect subtropical estuarine and marine ecosystems The likely impacts of climate variability and change on the prawn trawl fishery are included in Box 4 and the likely impacts on the KwaZulu-Natal line fishery are included in Box 5 below.

Box 4. The impacts of climate variability and change on the prawn trawl fishery

Summer rainfall is predicted to increase along the east coast of South Africa, which may result in an increase in the frequency and duration of mouth opening of the St Lucia Estuary and in the availability of estuary nursery habitat. This may have a positive impact on the abundance of shallow-water prawns provided that mouth opening coincides with the seasonal patterns of juvenile prawn recruitment and emigration of adults to the sea. However, the anticipated increase in rainfall is likely to be in the form of more rain days and heavy/extreme precipitation events. This coupled with sea level rise, may result in the loss of nursery habitat (such as mangroves), which is essential for prawns and estuarine fish species. Coastal storms, sea level rise and high water events will also alter the salinity and depth of estuaries. Sea level rise will interact with increases in rainfall but these effects have not yet been fully explored. Changes in catchment flow volumes and sediment loads reaching the sea may alter prawn habitat on the Thukela Banks. Abundance of all three of the shallow water prawn species is dependent on a particular sediment particle size and as such species composition and abundance in catches may vary according to flow. In the long-term, reduced flows and coastal erosion are likely to reduce the extent of the fluvial fans from the Thukela and other major catchments with an overall loss of habitat across all sediment types.

Existing water uses in the catchments feeding St Lucia are already at levels that cannot be compensated for by the predicted increases in rainfall and flow. Large flow events are expected to increase but droughts remain a characteristic of the catchment and may well intensify with increased air temperatures and related massive evaporative losses from St Lucia's large surface area. Extreme drought conditions in St Lucia from 2003 resulted in a loss of estuarine nursery habitat in large areas of the system and, together with mouth closure this had a large impact on the prawn trawl fishery (Turpie & Lamberth, 2010).

Box 5. The impacts of climate variability and change on the KwaZulu-Natal line fishery

Increases in rainfall across the subtropical and tropical regions will not necessarily translate into increased fish production and improved catches. Increased rainfall will tend towards the event scale (floods), with some shifts outside the current seasonal patterns, and may be asynchronous with the life-histories of the fish that depend upon these seasonal patterns. In addition, long-term strategic planning envisages a number of future developments, ranging in magnitude from local water abstraction to large dams and inter-basin transfer schemes for most of the larger catchments in the subtropical region (DWAF, 2004). The net result will be a reduction rather than increase in flow reaching the sea. To illustrate, long-term planning for the Thukela River entails a possible 40+% reduction in runoff reaching the sea with catches of slinger (Chrysoblephus puniceus) and squaretail kob (Argyrosomus thorpei) forecast to decline by 36% and 28% respectively. These two species currently provide over 50% of the landed mass by the line fishery on the Thukela Banks (Lamberth et al., 2010)

In a 19 year study of the sub-tropical reef fish community at Ballito and Scottburgh based on recreational spearfish catches, Lloyd et al., (2012) found a general increase in the abundance of tropical species in catches as well as a change in the proportion of tropical versus temperate species represented in catches. The results from this study were consistent with a predicted poleward shift in the distributional ranges of marine fish with climate change in response to warming of the Agulhas Current.

2.4 Key impacts: Offshore fisheries

Impacts on offshore fisheries depend on distinct scenarios of change in the oceans that would be subject to changes in wind patterns and in offshore currents. Due to a limited understanding of the mechanisms involved, and an incomplete ability to model these, there is currently uncertainty over the impacts on resources. These could include significant spatial shifts in resources driven by changing offshore habitat quality. Several offshore fisheries operate in South Africa's offshore ecoregions and ecozones. The demersal hake fishery and the small pelagic (sardine, anchovy and round herring) fisheries are described below as case studies because of their socio-economic importance as representatives of the offshore fisheries.

2.4.1 Key impacts on hake

In general, the relative impact of fishing on hake population size is considered to be greater than the role played by environmental and climatic variability. This is due to the relative longevity of these fish and a resultant large number of age classes, which acts as a buffer and reduces the impacts of interannual variability in recruitment. Additionally, the deeper habitat of hake (100–800m) is subjected to less environmental variability than the upper layers. Hake prey on themselves, both cannibalistically and via predation by large shallow water hake on co-occurring small deep water hake and this can result in strong density dependence effects. Hence, hake population dynamics are likely to be significantly impacted by the removal of larger, older fish by the fishery (Punt et al., 1992). The resulting decrease in the number of year classes leads to less resilience by the surviving population to environmental variability in the medium and long-term (Brander, 2009). Hake do, on occasion, show a strong response to environmental variability. For example, the displacement offshore of juvenile hake off Namibia in 1994, which subjected them to increased predation and mortality, was caused by persistent hypoxic conditions in bottom water over much of the continental shelf (Hamukuaya et al., 1998).

Wind speed, direction and frequency are important drivers of coastal upwelling, which brings cooler, nutrient rich water to the surface. Too much upwelling results in severe hypoxia (reduced oxygen content) in near-shore waters. At present, wind speeds on the west coast are already greater than the optimal level, and any increase in these wind speeds will affect upwelling which may have adverse effects on the fisheries for hake.

2.4.2 Key impacts on small pelagic fisheries

In contrast to hake, both extraction and the environment have a high impact on the population sizes of small pelagic fish. The response to environmental variability arises from their short lifespan, low trophic level, and high relative fecundity, which result in high inter-annual, decadal and multi-decadal variability in recruitment and subsequent population strength in these species (Checkley et al., 2009). Off South Africa, the dependence of anchovy in particular on successful transport of their eggs and larvae from spawning grounds off the south coast to nursery grounds off the west coast is thought to be crucial to successful recruitment (Hutchings et al., 1998). The highest recruitment of anchovy yet observed (in 2000) over the past 28 years was attributed to a particular pattern in the prevailing wind field over the anchovy spawning period that first resulted in good transport of early larvae to the nursery grounds and then in good feeding conditions there (Roy et al., 2001). The following year also saw very high recruitment from the much larger adult population under different environmental conditions. Environmental variability also appears to impact distribution patterns of small pelagic fish, with anchovy adults showing an abrupt change in their relative distribution that occurred concurrently with a change in SST gradients over the Agulhas Bank (Roy et al., 2007). Environmental impacts notwithstanding, overfishing can obviously have serious detrimental effects on small pelagic populations, as evidenced by the collapse of, and lack of a subsequent recovery in, small pelagic fish populations, in particular sardine, off Namibia (Roux et al., 2013). Off South Africa, the inshore populations of sardine and horse mackerel that sustained the St Helena Bay fishery in the 1950s and early 1960s were likewise depleted by heavy fishing pressure (Butterworth, 1983/FAO 291), and the current lack of recovery of sardine off the west coast is hypothesised to be due to excessive fishing pressure there (Coetzee et al., 2008/IJMS).

A number of scenarios under climate change can be considered for the west coast, which functions mostly as a nursery area but partly as a spawning ground for hake and sardine; for the south coast, which is mostly a summer spawning area for anchovy and sardine; and for the area between Cape Agulhas and Cape Columbine, which is of crucial importance for the alongshore movement of juvenile stages between the spawning and nursery areas (Figure 4). The following two oceanographic impact scenarios have been selected based on robust global model projections for climate scenarios. The projections suggest that summer south-easterly winds would tend to increase in frequency and strength, and winter westerlies would tend to decrease in frequency (IPCC4), and that the Agulhas Current would continue to increase in strength (Rouault et al., 2010).

Scenario 1. Changes in wind dominate ocean dynamics and net primary productivity:

- **West coast**: there is likely to be increased upwelling along the west coast, driven by increased southeast trade winds in spring and summer, leading to sub-optimal turbulent mixing and offshore losses for pelagic plankton, while excess primary production resulting from increased nitrate supply from upwelling leads to greater hypoxia and a reduction in habitat for pelagic and benthic organisms in the inner part of the continental shelf.
- **South coast:** The strengthening of the Agulhas Current, driven by increased trade winds in the southern Indian Ocean, should result in increased temperatures offshore and increased divergence-driven upwelling and productivity, particularly at Port Alfred as well as headlands along the south coast and along the shelf edge of the Agulhas Bank. There will be stronger thermal stratification in summer and less winter mixing over the Agulhas Bank (less frequent westerlies), increasing the intensity and seasonal duration of high primary production.
- **Transport area:** there will be increased inshore–offshore temperature gradients, with stronger currents linking the Agulhas Bank spawning area to the west coast nursery area.

Based on the above, the Agulhas Bank/south coast would become more productive and the west coast less productive and the transport currents between them would become stronger. This scenario could lead to an eastward and southward shift in fish resources.

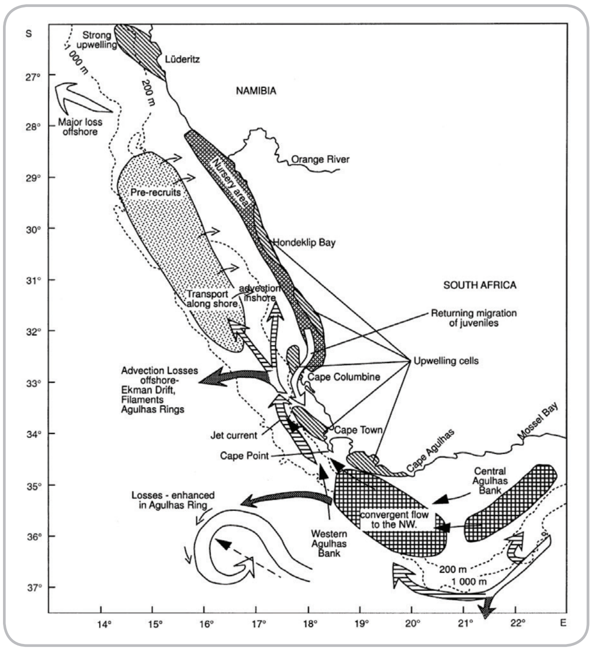

Figure 4. Schematic depicting the west coast nursery area, spawning grounds off the southwest and south coasts (cross-hatched areas) and the jet current between Cape Agulhas and Cape Columbine that connects the two. From Hutchings et al. (2002).

Scenario 2. Changes in the Agulhas Current dominate ocean dynamics and net primary productivity:

- **West coast**: decreased nutrient enrichment occurs despite stronger winds, as stratification increases with increased flow of Agulhas Bank water to the west coast shelf area. This results in less organic loading and hypoxia and an improved habitat volume for the inshore nursery area, despite more turbulent mixing and potential offshore loss along the outer shelf.
- **South coast:** the Agulhas Current supplies more warm surface water to the upper layers, decreasing primary productivity and trapping nutrients below the deepening thermocline. This decline in productivity results in less sustained spawning on the Agulhas Bank in summer. Increased storminess due to increased large-scale thermal contrast between the tropics and polar regions mixes the upper layer even more in winter, reducing primary production and hence, its carrying capacity for marine living resources.
- **Transport area**: transport remains high or even increases as the thermal gradient between inshore upwelled water and offshore water increases, maintaining the alongshore transport function.

More effective oceanographic modelling incorporating local oceanographic processes is required to resolve which of these two scenarios, if either, is more likely.

2.5 Ocean acidification

The oceans absorb a large amount of anthropogenic CO_2 emissions from the atmosphere because of their large volume and the ability of seawater to buffer CO_2 (Doney et al., 2009). Since the beginning of the industrial era, oceans have absorbed a third of anthropogenic CO_2 emissions (approximately 127 billion tons; Feely et al., 2008). Increasing CO_2 from fossil fuels has led to a reduction in the pH levels of the oceans as well as a shift in the carbonate chemistry of oceans. Ocean acidification does not suffer from the same uncertainties that affect global temperature forecasts and, therefore, future changes in ocean chemistry can be predicted (Doney et al., 2009). Even if emissions stabilised today, the atmospheric CO_2 value will surpass double pre-industrial (280 ppmv) levels by the turn of the century (Orr et al., 2005). Surface waters in high latitudes and in upwelling regions, such as the Southern Ocean and Eastern Boundary Upwelling Systems, will absorb larger volumes of CO_2 from the atmosphere than warmer waters in lower latitudes (Riebesell et al., 2009; Gruber et al., 2012). Southern African upwelling systems have a naturally lower pH and a considerably lower carbonate saturation state (Gruber et al., 2012). The pH levels in the southern Benguela currently range from 7.60 to 8.25, depending on the season, but have an annual average pH of ~8.1 (Gregor, 2012). This system is predicted to have a pH of approximately 7.8 to 7.5 by year 2100 and an even lower pH of 7.3 to 6.7 by year 2300 (Caldiera & Wicket, 2005).

Ocean acidification affects organisms in two ways, through reduced pH and increased CO_2 (hypercapnia) (Wood et al., 2008). Research on various organisms has shown that ocean acidification causes a great diversity of responses and it is therefore difficult to generalise predictions (Vézina & Hoegh-Guldberg, 2008). Ocean acidification influences physiological processes and behaviours in many organisms by reducing gas exchange (Fabry et al., 2008; Pelejero et al., 2010), lowering metabolic rates and growth (Bibby et al., 2007; Fabry et al., 2008; Guinotte & Fabry 2008; Vézina & Hoegh-Guldberg 2008; Doney et al., 2009) and disrupting defensive responses and behaviours (Bibby et al., 2007; de la Haye et al., 2012). In addition, in some calcifiers, rates of calcification are reduced (Gazeau et al., 2010; Riebesell et al., 2000; Gazeau et al., 2007) and shells are even dissolved (Feely et al., 2004; Arnold et al., 2009; Bibby et al., 2007). Calcifiers residing in cold water habitats such as upwelling systems are at a higher risk to ocean acidification and decreased seawater carbonate saturation, as their environment is only just supersaturated with respect to the carbonate phases they excrete (Andersson et al., 2008). The extent of these potential impacts will depend on the organisms' ability to adjust their acid–base balance as well as their ability to increase their calcification rates, while the ability to withstand or adapt to these changes over long periods of time would clearly be beneficial (Fabry et al., 2008). Doney et al., (2009) predict that the effects of ocean acidification will be felt more severely in coastal waters as the combined effects of nutrient fertilisation; pollution, overfishing and climate change will make it even more difficult for organisms to adapt to or counter changes in ocean chemistry. Acidification will likely impact various life stages differently as CO_2 tolerance varies across life stages of organisms (Pörtner, 2008).

The effects of an increasingly acidic ocean are most likely to have greatest impact on those species with calcium carbonate shells and skeletons and species that prey on them (Orr et al., 2005, Fabry et al., 2008). Of particular concern in terms of South African fisheries is the impact of ocean acidification on the west coast rock lobster and abalone, species that support an important fishery and aquaculture industry, respectively. Research conducted on the European lobster showed reduced carapace mass under high carbon dioxide concentrations (Arnold et al., 2009). Studies are currently underway in South Africa to assess the effects of increasing pH on the west coast rock lobster.

There is currently limited information available on the effects of ocean acidification on fin fish, with possible proposed effects being impaired physiological functions, reduced success in development and survival of their early life stages and decreases in invertebrate food sources for fish (Cheung et al., 2012). The effects of increasing ocean pH are considered most likely to negatively impact on the development and early life stages of many invertebrate species that require delicate balances of calcium carbonate in building their structure, such as coccolithophorids, foraminifera, echinoderms and shelled molluscs

(Heath et al., 2012). Decreasing productivity of such species could have negative effects on commercially important fish that prey on them.

Ocean acidification will not only have a direct impact, but will also possibly indirectly influence the ability of organisms to deal with local phenomena, such as the lobster 'walkouts' in response to low oxygen events on the west coast (Elands Bay) (Cockcroft, 2001). Estuary-dependent species with a pelagic life-history stage will be particularly vulnerable. Slower growth and delayed metamorphosis of fish and invertebrate larvae may result in recruitment failure if these animals miss the brief recruitment window typical of most temporarily open-closed systems. In some fish species, slow development and changes in the physical and chemical structure of otoliths (and other bone structures) may alter sensory perceptions and their ability to communicate, avoid danger or detect prey. Otolith malformation led to atypical behaviour such as reliance on visual rather than sound stimuli, as well as to increased cortisol levels, stress levels and suppressed immune systems in Sciaenidae (Browning et al., 2012).

Ocean acidification research has to date focused on physiological and biological investigations with limited studies considering the population- and ecosystem-level effects (Le Quesne & Pinnegar, 2011). Indirect effects of rising pH could potentially result in greater impacts on fish and fisheries than direct effects (Heath et al., 2012). The most obvious indirect effects likely to occur are the impact of acidification on biogenic habitats like cold-water coral reefs that serve as important fish nursery grounds for a diverse range of fish species (Foley et al., 2010, Huvenne et al., 2011) or alteration in nutrient recycling and bentho-pelagic coupling (Heath et al., 2012).

3. ADAPTATION RESPONSE OPTIONS

3.1 Fisheries

Before considering adaptation in terms of fisheries management, it is important to assess the adaptive capacity of the resource or the biological system. The adaptive capacity of various species may be constrained for three main reasons:

1. Rate of future climate change is expected to be faster than natural climate change previously experienced by species;
2. Resilience of species and other components of the ecosystem is compromised by additional pressure from fishing, pollution, habitat destruction, diseases, introduced and invasive species (Sink et al. 2012); and
3. The loss of genetic diversity (Brander, 2007; Lehodey et al., 2006).

Fishery resources are likely to be more robust to the effects of climate change if the compounding stresses from overfishing, habitat degradation, pollution and other anthropogenic factors are reduced or minimised (DEA, 2011; Craig, 2012; Cheung et al., 2012). Adaptation strategies aimed at providing the best mitigation against the effects of climate change for South Africa's marine biodiversity need to include sound integrated ecosystem based management practices (DEA, 2011, Sink et al. 2012). Maintaining genetic variability through adherence to stock limits, sustainable fishing practices and spatial management can support adaptation to changing conditions (Sink et al., 2012). Fisheries that are successfully managed to achieve resource sustainability will be better positioned in the long term to adapt to the effects of climate change.

Effective spatial management, including a representative MPA network, is a key component of the strategy required to understand and cope with the impacts of climate change (Sink et al., 2012). To support ecosystem resilience to climate change, MPAs need to be adequately connected, to encompass representative habitat types and to be managed well. Observed and potential future shifts in species distributions may compromise the effectiveness of some existing closed areas and spatial fisheries management areas (Cheung et al. 2012). The boundaries and management of MPAs may need to be adaptive to account for changing favourable environmental conditions. It is likely that larger or more dynamic networks of MPAs may be necessary to ensure effective conservation of spatially shifting and/or more variable resources due to climate change.

MPAs and no-take zones in particular, have the added advantage of acting as control sites for long-term monitoring and providing research opportunities that would make it possible to identify whether observed biological responses were due to climate change or other anthropogenic impacts, such as fishing. Monitoring networks need to cover a range of ecosystems to understand and track changes across the marine environment. Other elements of ecosystem management include the implementation of integrated coastal management and an ecosystem approach to fisheries management. Managers also need to develop adaptive management capacity including enhanced management flexibility to rapidly adapt to the changing environment (Sink et al., 2012). Ensuring that policies encourage diversification of resource use and income generation to enhance social resilience in the face of uncertainty and variability is also important, particularly for the most vulnerable coastal and fisher communities.

Whilst it is unanimously agreed that the predictive accuracy of the effects of climate change on marine fisheries is poor, and even more so in the light of other anthropogenic impacts (Rijnsdorp et al., 2009; Cheung et al., 2012; Heath et al., 2012; Sink et al., 2011; DEA, 2011), South Africa can cope by securing existing fisheries and biodiversity and working towards recovery of impacted resources and ecosystems. One of the most appropriate adaptation measures is to ensure that a sufficient area of different habitat types and resources are protected from compounding anthropogenic stressors. Through management strategies focused on rebuilding over-exploited fish resources and impacted ecosystems, and improving the habitat quality, society and the fishing industry would undoubtedly gain from more productive fish stocks, higher biodiversity and improved resilience and adaptive capacity to climate change.

3.2 Human dimension

Adaptation options for the near-shore handline fisheries may benefit from consideration of mechanisms and processes to balance social and economic objectives. Several management options may be available to facilitate adaptation under climate change and prevent the potential deterioration of social conditions in fisher communities. These could include education, entrepreneurial training, and training in tourism and aquaculture, but could also include more specific adaptation strategies.

Current short- to medium-term adaptation strategies employed by local communities to cope with current variability include fishing further afield (e.g. use of towing to offshore fishing grounds and then returning to shore on own accord), legal or illegal fishing in other management areas, adapting fishing gear and equipment, downsizing or retrofitting boats (including improving fuel efficiency), switching from hand-lining to trawling in the sector, and diversifying income streams into motor servicing and boat repairs, and even into other sectors such as agriculture. Remittances from family members and networks working outside the fishing industry are also an important source of income.

4. RESEARCH REQUIREMENTS

A significant body of observational data exists for trends in biophysical conditions and biological responses for South African marine ecosystems. However, this body of information needs to be further assessed and synthesised to support more holistic analysis of past trends and future projections. Further effort is needed to separate historical fisheries impacts from climate change responses. Additional reviews and focused research on methodologies for developing plausible broad forecasts should be conducted to build the capacity of this sector to identify and assess climate change adaptation options. With respect to the linkages between the biophysical and biological aspects and human dimensions, such as economic impacts and effects on livelihoods, there have been some recent advances and this area requires focused attention, given that it lags behind current predictive capacity for biophysical and biological impacts. In this section, some key areas are highlighted to begin to inform this process of review and synthesis.

4.1 Fisheries

4.1.1 Current capacity to project climate change impacts

The projection of marine biological responses to climate change is severely limited by incomplete knowledge of a large number of parameters required for effective modelling. A significant source of uncertainty also arises from the fact that most of the biophysical models currently in use do not reproduce or simulate the salient features in the oceans around South Africa. Additional knowledge gaps remain in areas such as the adaptive capacity of the species in question. Adaptive capacity of fish species is determined by dispersal capacity to move to suitable areas, short-term physiological plasticity and the long-term evolutionary adaptation of a population to a change in the environment.

Projecting the effect of long-term changes on marine organisms requires certain criteria to be fulfilled. Hollowed et al., (2009) outlined four important steps for successful projection of the impact of climate change on fish:

1. Identify mechanisms underlying the growth, reproduction, and distribution of major fish populations.
2. Assess the feasibility of downscaling the implication of climate scenarios derived from IPCC models for regional ecosystems and select IPCC models that appear to provide valid representation of forcing for the study region.
3. Incorporate the environmental variables, extracted from climate models under a given scenario, into the population projection model.
4. Evaluate the mean, variance and trend in the production of fish and shellfish under a changing ecosystem.

Based on the outcome of the above process, the potential socio-economic consequences of changes in the production of important fish populations could be projected. Detailing the impacts of climate change on fisheries in the short, medium and long-term is not common in the biological/ecological literature largely due to the issue of reliability of such projections as noted in Brander (2007). There are a number of constraints that affect the reliability and thus confidence in the projections, including the availability of reliable environmental variables at the spatial and temporal scales which are relevant for the biological processes being modelled. Once these data are readily available, projections would be made with more confidence. However, climate change impacts on fisheries distribution patterns and resultant changes in ecosystem functioning and fishery productivity are very complex to predict in detail. Specific predictions and forecasts may not be feasible based on the current level of knowledge and models available; however, it is possible that plausible broad forecasts could be developed.

4.1.2 *Available approaches for projecting direct impacts of climate change scenarios*

A number of opportunities exist to make rapid progress on projecting direct impacts of climate change scenarios. These lie in the area of data collection, data synthesis and model development using available and newly collected data. Studies on the effect of climate change in the marine environment have historically focused on the lower trophic level. Currently, this research is being extended to the upper trophic level and generally takes three main forms:

1. Long-term retrospective data analysis where the response of populations is analysed over a long time period. These data sets provide a significant source to support the development of predictive models for climate change applications.
2. Laboratory work, mainly involving the study of the physiological response of individuals from selected populations to a gradient of change in stress factor (water temperature, ocean acidification, oxygen concentration, and others) which can then be used to project the impact of future climate change. These provide an important source of information for detailed physiological models.
3. Modelling the response of fish populations to changes in climate variables, which can be further divided into three main groups:

3.1. Species distribution modelling, usually in the form of correlative statistical models, which study the changes in species distribution and changes in biodiversity.

3.2. Complex coupled biogeochemical–hydrodynamic models (sometimes also coupled to individual based models), which study the response of species and ecosystems to both the direct and indirect effect of long-term changes in climate.

3.3. Mechanistic models, which are process based and use empirically derived relationships to model the effect of climate variables on changes in species distribution, and other vital rates that can affect the viability of a species. Three sets of models can be used to project the effect of future climate change on the productivity of fish populations (Hollowed et al., 2009):

3.3.1. Project recruitment by modifying the average recruitment by the environmental variables – no density dependent effect.

3.3.2. Models that modify the spawner-recruit relationship with the environmental variables and a random variable – No density dependent effects.

3.3.3. Models that use spawner-recruit functions that incorporate processes at multiple life-history stages. The effect of environmental variables can be incorporated and density dependent processes can be added.

The most commonly used approach to modelling changes in the distribution of fish populations and the approach with the least data and computing power requirement makes use of statistical correlative models (Option 3.1 above). There are a number of statistical models currently in use to both model current distribution and project the distribution of populations under climate change. These include: generalised additive models, generalised linear models, classification tree analysis, artificial neural network, generalised boosted regression models and random forest. Details of their application in species distribution modelling in the context of projecting climate change impact can be found in Mugo et al. (2010), Heikkinen et al. (2006), Elith (2009), Olden et al. (2002). Some of the tools that are commonly used in the modelling of species distribution include BIOMOD (Thuiller et al., 2012), and dismo (Hijmans et al., 2013).

With respect to mechanistic models (Option 3.3 above) a determination of environmental tolerance and preference ranges for the Cape hake, assuming the availability of reasonably accurate scenarios of future ocean conditions around South Africa, and coupling these, would provide new insights. Updated, spatialised ecosystem models (Option 3.2. above), for example OSMOSE (Travers et al., 2009, 2010), would complement such niche models with the necessary top-down dynamics. The hypothesised multi-stock nature of South African sardine (van der Lingen, 2011) could add further complexity to predicting climate change impacts on this population as stocks that show consistent differences in distribution, biology and life history characteristics may respond differently to environmental forcing. Recent work to develop specific assessment models for putative western and southern stocks of South African sardine has been initiated (de Moor & Butterworth, 2013), which would permit consideration of environmental drivers in terms of relative recruitment success of sardine off the west and south coasts.

While models to project climate-induced changes in the distribution of marine fishes have been developed globally, none have been specifically developed for South Africa. An example of such a modelling approach is the Dynamic Bioclimate Envelope Model (DBEM) (Cheung et al., 2008) which simulates changes in the relative abundance and spatial distribution of marine populations at global scale by accounting for an organism's ecophysiology, preferences and tolerances to environmental conditions, adult movement and larval dispersal, and population dynamics. Some data on the environmental preferences and tolerances of anchovy and sardine off South Africa are available to parameterise this model (e.g. Twatwa et al., 2005 provided environmental characterisations of their spawning habitats), and these and the relatively good understanding of small pelagic fish life histories in this region may be sufficient to enable the development of a local DBEM for these species. Similar data, but perhaps less comprehensive, exist for the Cape hake, and determination of environmental preferences and tolerances for these species is an important first step that has yet to be conducted.

With respect to indirect effects of climate change on the economics of marine fisheries in South Africa, there are a number of fishery assessment models that may be relevant (e.g. Defeo & Seijo, 1999; White et al., 2008). Few, if any, of these have been applied to assess the impact of projected climate changes, but some of the bio-economic models or their modified forms could be used to assess the potential economic consequence to the fishery of the projected changes in the production and distribution of important fish populations.

Punt et al (2013) undertook a review of studies that used the mechanistic and empirical approach to evaluate the impact of environmental variation on the performance of management strategies. Many of the studies reviewed found that modifying management strategies to include environmental factors only improves the ability to achieve management goals if the manner in which these factors drive the system is well known. The conclusion was that until stock projection models are improved, a more appropriate way to assess the robustness of management strategies is to consider the implications of plausible broad forecasts of how biological parameters may change, rather than attempting specific predictions.

4.1.3 Future research needs

Overall, South Africa needs to strengthen the information and knowledge base for the detection and projection of climate-induced changes and provide evidence-based advice to support climate change adaptation. Focused research is needed to further develop predictive capacity, support early detection of change and contribute to the development of appropriate adaptation measures (Sink et al., 2012).

The following are important areas of research to aid in the accurate projection of the impact of future climate change on fish production, distribution, and conservation as well as the resultant socio-economic consequences:

1. Assess and synthesise existing observational data on trends in biophysical conditions and biological responses for South African marine ecosystems to support holistic analysis of past trends and future projections.
2. Development of plausible broad forecasts and appropriate adaptation measures until specific predictions and forecasts are more feasible, facilitated by more effective oceanographic modelling.
3. Address issues of downscaling by improving oceanographic models to simulate inter-annual and decadal variability, and effects of global climate change. This would allow more credible information to be generated for planning adaptation responses.
4. Link drivers to responses by improving observations and models of regional net primary productivity (NPP). This may involve developing new models or improving existing ones to predict how changes in NPP will cascade up the marine food web to fisheries.
5. Consider the interaction between biodiversity and important ecosystem attributes by taking into account the consequence of changes in biodiversity on the stability, resilience, and productivity of marine systems.
6. Investigate the socio-economic consequences of climate change impacts on the fisheries sector and other sectors of the economy that are dependent on fisheries.
7. Consider the interaction between aquaculture and capture fisheries and improve understanding of the consequence of future increases in aquaculture production on the production of aquatic ecosystems.

With respect to the socio-economic and ecological consequences of climate change impacts in the fisheries sector, it is important that research be dedicated towards understanding and establishing the link between the environment and distribution, growth and reproductive rates and the processes through which the changes in the environment are manifested in the biological system across the hierarchy from individual level to the whole ecosystem. Once this is established, the next step will be to project the response to climate change of the different components of the ecosystem and the socio-economic components that depend on it.

4.2 Human dimensions

4.2.1 Future research needs

Current research experience has shown that progress with respect to the human dimensions of fisheries is hindered by the mistrust and poor communication between some stakeholders. These include relationships between government officials and new entrants and/or small quota holders in the offshore fisheries, as well as members of fishing communities more generally, including crew on vessels and factory workers (van Sittert, 2003; Schultz, 2010; Ragaller, 2012; Hara in prep.). However, there is good communication between associations that represent the majority of right holders (by TAC), but communication seems to be less well developed at the fishing community level.

Immediate research needs on the human dimensions include:

- How to progress towards scenario planning with a variety of stakeholders in which mutual trust can be built.
- Research into current adaptive strategies: what works and why?
- Exploring top-down versus bottom-up approaches to fisheries management that support social-ecological resilience to the expected increase in variability.

- Methodologies for integrated intersectoral approaches to management of human activities related to the ocean (fisheries in a setup of many sectors locally/regionally).
- Trade-offs between the hake and small pelagic fishing industries under ecosystem variability and change.
- The role of international markets (exports and imports) and aquaculture in the social-ecological system.
- Social and economic challenges of threatened fisheries in a local and regional perspective.

5. CONCLUSION

Climate change is likely to affect the productivity and diversity of South Africa's fisheries by changing the distribution, abundance and size of resources, their habitat extent, condition and connectivity, their physiology and behaviour and the catchability of resource species. Changes in sea surface temperature (SST), storm frequency, freshwater flow and runoff patterns, productivity, oxygen levels and wind will all have impacts on estuarine, inshore and offshore ecosystems, affecting recruitment, fish behaviour and physiology, influencing fish size, and increasing fish mortalities. This could result in significant adverse impacts on subsistence fishing livelihoods as well as commercial and recreational industries.

Predicting climate change impacts on marine fisheries is difficult because of the complex relationships between species distribution patterns, variations in their abundance, distribution and productivity, and the impacts of overfishing and other stressors. Key modelling capacity is required to move beyond the current uncertain projections for key fisheries resources under future climate change. In particular a focused effort is required to develop plausible scenarios of physical oceanographic and coastal habitat change.

A significant body of observational data exists for trends in biophysical conditions and biological responses for South African marine ecosystems. Regular assessment and synthesis of this growing body of information would support increasingly holistic analysis of past trends and future projections. There have been some advances recently regarding linkages between the biophysical and biological aspects and human dimensions, such as economic impacts and effects on livelihoods. However, impacts on fisheries depend on distinct oceanographic scenarios that could be dominated either by projected changes in southerly and westerly winds, or by changes in the strength of the Agulhas current. Focused research is needed to contribute to the development of plausible broad forecasts, more specific local predictions and appropriate adaptation measures. The impacts of unsustainable fishing and climate change interact in a number of ways and should not be treated as separate issues. South Africa needs to invest in the information and knowledge base available for providing evidence-based guidance to support climate change adaptation.

While it is generally agreed that the predictive accuracy of the effects of climate change on marine fisheries is poor, especially in the light of other anthropogenic impacts (Rijnsdorp et al. 2009, Cheung et al. 2012, Heath et al. 2012, Sink et al. 2011, DEA 2011), this does not prevent South Africa from building greater resilience in this sector by securing existing fisheries and biodiversity and working towards recovery of impacted resources and ecosystems, including through sound integrated ecosystem based management practices. Although many resources are overexploited, management action can lead to stock recovery. Maintaining genetic variability through sustainable fishing practices and areas closed to fishing can help secure strong genetic potential that will increase resilience under changing conditions. Fisheries that are successfully managed to achieve resource sustainability will be much better positioned in the long term to adapt to the effects of climate change. Adaptive measures could also usefully include ensuring the protection of sufficient areas of different habitat types and resources from compounding anthropogenic stressors in marine protected areas. Key elements in securing resource sustainability in the long term include statistically robust stock assessments, effective data management and science-based management action. Through appropriately informed management strategies focused on rebuilding over-exploited fish resources and impacted ecosystems, and improving the habitat quality, the fishing industry would gain from more productive fish stocks, higher biodiversity and improved resilience to climate change.

Operationally, fisheries management could usefully include tactics such as improving the speed of adaptive learning cycles, decentralisation and diversification, and enhancing management flexibility to adapt to a changing environment. These could support commercial, subsistence and recreational fishing sectors through improved environmental, resource and social resilience, maintenance of ecosystem, species, genetic and social diversity and the development of adaptive capacity to climate change.

6. REFERENCES

Alber M (2002). A conceptual model of estuarine freshwater inflow management. *Estuaries* 25: 1246–1261.

Allison EH, Perry AL, Badjeck MC, Neil Adger W, Brown K, Conway D, Halls AS, Pilling GM, Reynolds JD, Andrew NL and Dulvy NK (2009). Vulnerability of national economies to the impacts of climate change on fisheries. *Fish and Fisheries*, 10(2): 173–196. ISSN 14672960. doi:10.1111/j.1467-2979.2008. 00310.x. URL http://doi.wiley.com/10.1111/j.1467-2979.2008.00310.x.

Anderson CNK, Hsieh C-H, Sandin SA, Hewitt R, Hollowed A, Beddington J, May RM and Sugihara G (2008). Why fishing magnifies fluctuations in fish abundance. *Nature*, 452: 835–839.

Andersson AJ, Mackenzie FT, Bates NR (2008). Life on the margin: implications of ocean acidification on Mg-calcite, high latitude and cold-water marine calcifiers. *Marine Ecology Progress Series*, 373: 265-–273.

Arnold KK, Findlay HS, Spicer JI, Daniels CL and Boothroyd D (2009). Effect of CO_2-related acidification on aspects of the larval development of the European lobster, *Homarus gammarus* (L.). *Biogeosciences Discussion* 6: 3087–3107.

Babcock RC, Shears NT, Alcala AC, Barrett NS, Edgar GJ, Lafferty KD, McClanahan TR, Russ GR (2010). Decadal trends in marine reserves reveal differential rates of change in direct and indirect effects. *Proceedings of the National Academy of Science* 107(43), 18256–18261.

Baudron AR, Needle CL and Marshall CT (2011). Implications of a warming North Sea for the growth of haddock *Melanogrammus aeglefinus*. *Journal of Fish Biology*, 78: 1874–1899.

Beckley LE and van der Lingen CD (1999). Biology, fishery and management of sardines *(Sardinops sagax)* in southern African waters. *Marine and Freshwater Research*, 50(8): 955–978.

Behrenfeld MJ, O'Malley RT, Siegel Da, McClain CR, Sarmiento JL, Feldman GC, Milligan AJ, Falkowski PG, Letelier RM and Boss ES (2006). Climate-driven trends in contemporary ocean productivity. *Nature*, 444(7120), 752–5. ISSN 1476–4687. doi:10.1038/nature05317.

URL http: //www.ncbi.nlm.nih.gov/pubmed/17151666.

Bennett BA (1993a). The fishery for white steenbras *Lithognathus lithognathus* off the Cape coast, South Africa, with some considerations for its management. *South African Journal of Marine Science* 13(1), 1–14.

Bennett BA (1993b). Aspects of the biology and life history of white steenbras *Lithognathus lithognathus* in southern Africa. *South African Journal of Marine Science* 13(1), 83–96

Bennett E and Zurek,M (2006). Integrating epistemologies through scenarios. Chapter 15, pp. 275–294. In WV Reid, F Berkes, TJ Wilbanks and D Capistrano (eds.) *Bridging scales and knowledge systems: concepts and applications in ecosystem assessment.* Washington, DC: Island Press,

Berkes F, Reid WV, Wilbanks TJ and Capistrano D (2006). Conclusions: bridging scales and knowledge systems. Chapter 17, pp. 315–331. In WV Reid, F Berkes, TJ Wilbanks and D Capistrano (eds.) *Bridging scales and knowledge systems: concepts and applications in ecosystem assessment.* Washington, DC: Island Press,

Bibby R, Cleall-Harding P, Rundle S, Widdicombe S and Spicer J (2007). Ocean acidification disrupts induced defences in the intertidal gastropod *Littorina littorea*. *Biology Letters* 3(6): 699–701.

Bindschadler R (2006). Hitting the ice sheets where it hurts. *Science* 311: 1720–1721.

Binet D, Le Reste L and Diouf PS (1995). The influence of runoff and fluvial outflow on the ecosystems and living resources of West African coastal waters. In: FAO Marine Resources Service, Fishery Resources Division. Effects of riverine inputs on coastal ecosytems and fisheries resources. FAO Fisheries Technical Paper, No. 349, FAO, Rome, 89-118.

Blamey LK, Howard JAE, Agenbag K and Jarre A (2012). Regime shifts in the southern Benguela shelf and inshore region. *Progress in Oceanography*, 106: 80–92.

Bolton JJ, Anderson RJ, Smit AJ and Rothman MD (2012). South African kelp moving eastwards: the discovery of *Ecklonia maxima* (Osbeck) Papenfuss at De Hoop Nature Reserve on the south coast of South Africa. *African Journal of Marine Science*, 34(1): 147–151.

Boyce DG, Lewis MR and Worm B (2010). Global phytoplankton decline over the past century. *Nature*, 466: 591–596.

Branch GM, Hauck M, Siquana-Ndulo N and Dye A (2002). Defining fishers in the South African context: subsistence, artisanal and small-scale commercial sectors. *South African Journal of Marine Science* 24: 475–487.

Brander K (2009). Predicting the effects of climate change on marine communities and the consequences for fisheries. *Journal of Marine Systems*, 79: 418–426.

Brander KM (2007). Global fish production and climate change. *Proceedings of the National Academy of Sciences*, 104(50): 19709–19714.

Brown PC, Hutchings L and Horstman D (1979). A red-water water outbreak and associated fish mortality at Gordons Bay near Cape Town. *Fisheries Bulletin of South Africa*, 11: 46–52.

Brown CJ, Fulton EA, Hobday AJ, Matear RJ, Possingham HP, Bulman C, Christensen V, Forrest RE, Gehrke PC, Gribble NA, Griffiths SP, Lozano-Montes H, Martin JM, Metcalf S, Okey TA, Watson R, Richardson AJ (2010). Effects of climate-driven primary production change on marine food webs: implications for fisheries and conservation. *Global Change Biology*, 16(4): 1194–1212. ISSN 13541013. doi:10.1111/j.1365-2486.2009.02046.x. URL http://doi.wiley.com/10.1111/j.1365-2486.2009.02046.x.

Browning ZS, Wilkes AA, Moore EJ, Lancon TW and Clubb FJ (2012). The Effect of Otolith Malformation on Behaviour and Cortisol Levels in Juvenile Red Drum Fish (*Sciaenops ocellatus*). *Comparative Medicine* 62 (4): 251–256.

Burkholder JM, Glasgow HB and Hobbs CW (1995). Fish kills linked to a toxic ambush-predator dinoflagellate: distribution and environmental conditions. *Marine Ecology Progress Series*, 124: 43–61.

Butterworth DS (1983). Assessment and management of pelagic stocks in the southern Benguela region (South Africa, Namibia): Proceedings; *FAO Fisheries Report* (FAO), no. 291, v. 2-3; Expert Consultation to Examine Changes in Abundance and Species Composition of Neritic Fish Resources, San Jose (Costa Rica), 18 Apr 1983 Sharp, G.D (ed.) Csirke, J. (ed.) Rome (Italy), FAO , 1983, p. 329–405

Buxton CD (1996) Life History Characteristics of Temperate Reef Fishes and Their Implications for Fisheries Management..In Armantrout, NB and Wolotira RJ (eds). *Condition of the World's Aquatic Habitats*. Proceedings of the First World Fisheries Congress, Theme 1. New Delhi; Oxford and IBH Publishing: 105-121.

Caldeira K and Wickett ME (2003). Anthropogenic carbon and ocean pH. *Nature* 425, 365.

Caldeira K and Wicket ME (2005). Ocean model predictions of chemistry changes from carbon dioxide emissions to the atmosphere and ocean. *Journal of Geophysical Research*, 110: 12

Checkley DM, Bakun A, Barange M, Castro LR, Freon P, Guevara-Carrasco R, Herrick SF, MacCall AD, Ommer R, Oozeki Y, Roy C, Shannon L and van der Lingen CD (2009). Synthesis and perspective. In: Checkley DM, Alheit J, Oozeki Y, Roy C. (eds.) Climate change and small pelagic fish. Cambridge: Cambridge University Press, 344-351

Cheung WWL, Lam VWY and Pauly D (2008). Modeling present and climate-shifted distribution of marine fishes and invertebrates. University of British Columbia, Canada, Fisheries Centre Research Reports Vol. 16 No. 3: 72pp, ISSN 1198–6727.

Cheung WWL, Sarmiento JL, Dunne J, Frölicher TL, Lam VWY, Palomares MLD, Watson R, Pauly D (2012). Shrinking of fishes exacerbates impacts of global ocean changes on marine ecosystems. *Nature Climate Change* September 2012: doi:10.1038/nclimate1691: 1–5.

Cheung WW, Lam VW, Sarmiento JL, Kearney K, Watson R, Pauly D (2009). Projecting global marine biodiversity impacts under climate change scenarios. *Fish and Fisheries*, 10(3), 235–251.

Cheung WWL, Lam VWY, Sarmiento JL, Kearney K, Watson R, Zeller D, Pauly D (2010). Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Global Change Biology*, 16(1), 24–35. ISSN 13541013. doi:10.1111/j.1365-2486.2009.01995.x.

URL http: //doi.wiley.com/10.1111/j.1365-2486.2009.01995.x.

Cheung WWL, Pinnegar J, Merino G, Jones MC and Barange M (2012). Review of climate change impacts on marine fisheries in the UK and Ireland. *Aquatic conservation: Marine and Freshwater Ecosystems*, 22: 368–388.

Clark BM (2006). Climate change: a looming challenge for fisheries management in southern Africa. *Marine Policy* 30: 84–95.

Cockcroft AC (2001). *Jasus lalandii* ‘walkouts’ or mass standings in South Africa during the 1990s: an overview. Marine and Freshwater Research, 52: 1085–1094.

Cockcroft AC, van Zyl D and Hutchings L (2008). Large-scale changes in the spatial distribution of South African west coast rock lobsters: an overview. *African Journal of Marine Science*, 30(1): 149–159.

Cockcroft AC (2011). Large-scale shifts in the spatial distribution of west coast rock lobster in South Africa. In: Zietsman L (ed.), *Observations on Environmental Change in South Africa*. Stellenbosch: SUN PRESS. pp. 257–260.

Coetzee PS, Baird D, Tregoning C (1989). Catch statistics and trends in the shore angling fishery of the east coast, South Africa, for the period 1959–1982. *South African Journal of Marine Science* 8: 155–171.

Coetzee JC, van der Lingen CD, Hutchings L and Fairweather TP (2008). Has the fishery contributed to a major shift in the distribution of South African sardine? *ICES Journal of Marine Science* 65: 1676–1688. doi:10.1093/icesjms/fsn184.

Colberg F and Reason CJC (2007). Diagnosis of large scale South Atlantic modes that impact on the transboundary Benguela Current large marine ecosystem: investigating the potential for improved predictability and sustainable management Final report. BCLME project EV/LS/02/06, 194 pp.

Collard SB and Lugo-Fernández A (1999). Coastal upwelling and mass mortalities of fishes and invertebrates in the northeastern Gulf of Mexico during spring and summer 1998. OCS Study MMS 99-0049. U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, La. 20 pp.

Cooper JAG (2001). Geomorphological variability among microtidal estuaries from the wave-dominated South African coast. *Geomorphology* 40(1–2), 99–122.

Cowley PD, Kerwath SE, Childs AR, Thorstad EB, Økland F, Næsje TF (2008). Estuarine habitat use by juvenile dusky kob *Argyrosomus japonicus* (Sciaenidae), with implications for management. *African Journal of Marine Science* 30: 247–253

Craig RK (2012). Marine Biodiversity, Climate Change and Governance of the oceans. *Diversity* 4: 224–238, doi:10.3390/d4020224.

Crawford RJM, Sabarros PS, Fairweather T, Underhill LG and Wolfaardt AC (2008) - Implications for seabirds off South Africa of a long-term change in the distribution of sardine. *African Journal of Marine Science*, 30(1): 177–184.

Cury P, Shannon L (2004). Regime shifts in upwelling ecosystems: observed changes and possible mechanisms in the northern and southern Benguela. *Progress in Oceanography*, 60: 223–243.

David M, Shivakumar R, Mushigeri SB and Kuri RC (2005). Blood glucose and glycogen levels as indicators of stress in the freshwater fish, *Labeo rohita* under fenvalerate intoxication. *Journal of Ecotoxicology & Environmental Monitoring*, 15: 1–5.

Davis CL (2011). *Climate risk and vulnerability: a handbook for southern Africa*. Pretoria: Council for Scientific and Industrial Research, 92 pp.

Day JH, Blaber SJM, Wallace JH (1981). Estuarine fishes. In: Day JH (ed.) *Estuarine ecology with particular reference to southern Africa*. Cape Town: Balkema, pp. 197–221

Day E and Branch GM (2000). Evidence for a positive relationship between juvenile abalone *Haliotis midae* and the sea urchin *Parechinus angulosus* in the South-Western Cape, South Africa. *South African Journal of Marine Science*, 22: 145–156.

Day E and Branch GM (2002). Effects of sea urchins (*Parechinus angulosus*) on recruits and juveniles of abalone (*Haliotis midae*). *Ecological Monographs*, 72(1): 133–149.

Daw T, Adger W, Brown K and Badjeck MC (2011). Climate change and capture fisheries: potential impacts, adatation, and mitigation. In K. Cochrane, C. De Young, D. Soto and T. Bahri (eds). Climate change implications for fisheries and aquaculture: overview of current scientific knowledge. FAO Fisheries and Aquaculture Technical Paper. No. 530. Rome: FAO. pp.107–150.

De La Haye KL, Spicer JI, Widdicombe S and Briffa M (2012). Reduced pH sea water disrupts chemo-responsive behaviour in an intertidal crustacean. *Journal of Experimental Marine Biology and Ecology*, 412: 134–140.

Department of Environmental Affairs (DEA) (2011). South Africa's Second National Communication under the United Nations Framework Convention on Climate Change. Pretoria: Department of Environmental Affairs, South Africa.

Defeo O and Seijo JC (1999). Yield-mortality models: a precautionary bioeconomic approach. *Fisheries Research*, 40: 7–16.

Demarcq H, Barlow R, Shillington F (2003). Climatology and variability of sea surface temperature and surface chlorophyll in the Benguela and Agulhas ecosystems as observed by satellite imagery. *African Journal of Marine Science*, 25: 363–372.

De Moor CL and Butterworth DS (2013). Assessment of the South African sardine resource using data from 1984-2011: further results for a two stock hypothesis. Unpublished document, FISHERIES/2013/FEB/SWG-PEL/01, Pretoria: Department of Agriculture, Forestry and Fisheries, 20pp.

Department of Agriculture, Forestry and Fisheries (DAFF) (2012). Status of the South African Marine Fishery Resources 2012, Pretoria: Department of Agriculture, Forestry and Fisheries, 71pp.

Doney SC, Fabry VJ, Feely RA and Kleypas JA (2009). Ocean Acidification: The Other CO_2 Problem. *Annual Review of Marine Science*, 1:169–192.

Dulvy NK, Rogers SI, Jennings S, Stelzenmüller V, Dye SR, Skjoldal HR (2008). Climate change and deepening of the North Sea fish assemblage: a biotic indicator of warming seas. *Journal of Applied Ecology*, 45(4): 1029–1039.

Department of Water Affairs and Forestry, South Africa (DWAF) (2004). Thukela Bank: Impacts of flow scenarios on prawn and fish catch report – Reserve Determination Study – Thukela River System. DWAF Report No. PBV000-00-10310.

Edwards M, Richardson AJ (2004). Impact of climate change on marine pelagic phenology and trophic mismatch. *Nature*, 430(7002): 881–884. ISSN 1476-4687. doi:10.1038/nature02808. URL http://www. ncbi.nlm.nih.gov/pubmed/15318219.

Elith J (2009). Do they? How do they? WHY do they differ? On finding reasons for differing performances of species distribution models. (Table 1), *Ecography*, 32(1): 66–77URL http://onlinelibrary. wiley.com/doi/10.1111/j.1600-0587.2008.05505.x/full.

Emanuel BP, Bustamante RH, Branch GM, Eekhout S and Odendaal FJ (1992). A zoogeographic and functional approach to the selection of marine reserves on the west coast of South Africa. *South African Journal of Marine Science*, 12: 341–354.

Engelbrecht FA, Landman WA, Engelbrecht CJ, Landman S, Bopape MM, Roux, B, McGregor, JL and Thatcher, M (2011). Multi-scale climate modelling over southern Africa using a variable-resolution global model. *Water SA* 37: 647–658.

Engelbrecht FA, Mcgregor JL, Engelbrecht CJ (2009). Dynamics of the conformal-cubic atmospheric model projected climate-change signal over southern Africa. *International Journal of Climatology* 29: 1013–1033.

Fabry VJ, Seibel BA, Feely RA, Orr JC (2008). Impacts of ocean acidification on marine fauna and ecosystem processes. *ICES Journal of Marine Science*, 65: 414–432.

Fauchereau N, Trzaska S, Rouault M, Richard Y (2003). Rainfall variability and changes in southern Africa during the 20th century in the global warming context. *Natural Hazards*, 29(2): 139–154.

Feely RA, Sabine CL, Lee K, Berelson W, Kleypas J, Fabry VJ, Millero FJ (2004). Impact of anthropogenic CO_2 on the $CaCO_3$ system in the oceans. *Science*, 305:362–66

Feely RA, Sabine CL, Hernandez-Ayon JM, Ianson D and Hales B (2008). Evidence for upwelling of corrosive "acidified" water onto the continental shelf. In: Science, 320: 1490–1492.

Foley, N. S., Van Rensburg, T. M., and Armstrong, C. W. (2010). The ecological and economic value of cold-water coral ecosystems. *Ocean and Coastal Management*, 53: 313–326.

Forbes BP and Demetriades NT (2005). A review of the commercial, shallow water penaeid prawn resource of South Africa. Unpublished report prepared for Ezemvelo KZN Wildlife.

Gazeu F, Gattuso J, Dawber C, Pronker AE, Peene F, Peene J, Heip CHR and Middleburg JJ (2010). Effect of ocean acidification on the early life stages of the blue mussel (*Mytilus edulis*). *Biogeosciences* 7: 2051–2060.

Gazeau F, Quiblier C, Jansen JM, Gattuso JP, Middelburg JJ and Heip CHR (2007). Impact of elevated CO_2 on shellfish calcification. *Geophysical Research Letters*, 34:Lo7603, 1-5.

Gillanders BM and Kingsford MJ (2002). Impact of changes in flow of freshwater on estuarine and open coastal habitats and the associated organisms. *Oceanography and Marine Biology. An Annual Review*, 40: 233–309.

Gregor L (2012). Seasonality of the marine carbonate system in the southern Benguela: nutrient stoichiometry, alkalinity production, and CO_2 flux. MSc. University of Cape Town.

Griffiths MH (1997). Management of South African dusky kob *Argyrosomus japonicus* (Sciaenidae) based on per-recruit methods. *South African Journal of Marine Science,* 18: 213–225.

Griffiths MH (2000). Long-term trends in catch and effort of commercial linefish off South Africa's Cape Province: snapshots of the 20th century. *South African Journal of Marine Science*, 22: 81–110.

Griffiths MH and Lamberth SJ (2002). Evaluating a marine recreational fishery in South Africa. In: Pitcher TJ and Hollingworth CE, *Recreational fisheries: ecological, economic and social evaluation* Chapter 16: 227–251, Oxford: Blackwell Science, 271 pp.

Griffiths CL, Robinson TB, Lange L and Mead A (2010). Marine biodiversity in South Africa: an evaluation of current states of knowledge. *PLoS One* 5: 1–13. doi:10.371/journal.pone.0012008.

Gruber N, Hauri C, Lachkar Z, Loher D, Frölicher TL and Plattner GK (2012). Rapid Progression of Ocean Acidification in the California Current System. *Science*, 4: 1–5.

Guinotte J and Fabry V (2008). Ocean acidification and its potential effects on marine ecosystems. *Annals of the New York Academy of Sciences*, 1134: 320–342.

Hallegraeff GM (1992). Harmful algal blooms in the Australian region. *Marine Pollution Bulletin*, 25 (5-8): 186–190.

Hallegraeff GM (1995). Harmful Algal blooms: a global overview. In: Hallegraeff GM, Anderson DM, Cembella AD (eds) Manual on harmful marine microalgae. Paris: UNESCO pp. 1–22 (IOC Manuals and Guides No. 33).

Hamukuaya H, O'Toole MJ, and Woodhead PMJ (1998). Observations of severe hypoxia and offshore displacement of Cape hake over the Namibian shelf in 1994. *South African Journal of Marine Science*, 19: 57–59.

Hanekom N, Hutchings L, Joubert PA and van der Byl PCN (1989). Sea temperature variations in the Tsitsikamma Coastal National Park, South Africa, with notes on the effect of cold conditions on some fish populations. *South African Journal of Marine Science* 8: 145-153.

Hara M, Rogerson J and Raakjaer J. Fragmented participation in management of small pelagics fisheries in South Africa – inclusion of small and new rights holders is a complex matter. *African Journal of Marine Science*, in review (2013).

Hara M, Jarre A, Ragaller SM and Raakjaer J. Social-ecological resilience and adaptation in South Africa's small pelagic fishing sector through defragmentation of management. In preparation for submission to *Maritime Studies* (2013).

Harley CD, Randall Hughes A, Hultgren KM et al (2006). The impacts of climate change in coastal marine systems. *Ecology Letters* 9: 228–41

Heath MR, Neat FC, Pinnegar JK, Reid DG, Sims DW and Wright PJ (2012). Review of climate change impacts on marine fish and shellfish around the UK and Ireland. *Aquatic conservation: Marine and Freshwater Ecosystems*, 22: 337–367.

Heikkinen RK, Luoto M, Arau'jo MB,Virkkala R,Thuiller W and Thykes MT (2006). Methods and uncer tainties in bioclimatic envelope modeling under climate change. *Progress in Physical Geography*, 30: 1–27.

Hewitson BC and Crane RG (2006). Consensus between GCM climate change projections with empirical downscaling: precipitation downscaling over South Africa. *International Journal of Climatology* 26: 1315–1337.

Heydorn AEF and Tinley KL (1980). Estuaries of the Cape Part 1. Synopsis of the Cape coast. Natural features, dynamics and utilization. Stellenbosch, CSIR Research Report 380, 1–97.

Hiddink JG and ter Hofstede R (2008). Climate induced increases in species richness of marine fishes. *Global Change Biology*, 14: 453–460.

Hijmans RJ, Phillips S, Leathwick J and Elith J (2013). *dismo: Species distribution modeling.* R package version 0.8–5, URL http://cran.r-project.org/web/packages/dismo/index.html.

Hollowed AB, Bond NA, Wilderbuer TK, Stockhausen WT, Teresa ZA, Beamish RJ, Overland JE and Schirripa MJ (2009). A framework for modeling fish and shellfish responses to future climate change. *ICES Journal of Marine Science,* 66(7): 1584–1594. URL http://icesjms.oxfordjournals.org/content/ 66/7/1584.short.

Horstman DA (1981). Reported red-water outbreaks and their effects on fauna of the west and south coasts of South Africa, 1959-1980. *Fisheries Bulletin, South Africa*, 15: 71–88.

Howard JAE, Jarre A, Clark AE and Moloney CL (2007). Application of the sequential t-test algorithm for analysing regime shifts to the southern Benguela ecosystem. *African Journal of Marine Science*, 29(3): 437–451

Hsieh C-H, Reiss CS, Hewitt RP and Sugihara G (2008) Spatial analysis shows that fishing enhances the climatic sensitivity of marine fishes. *Canadian Journal of Fisheries and Aquatic Sciences,* 65: 947–961.

Hsieh C-H, Reiss CS, Hunter JR, Beddington JR, May RM and Sugihara G (2006) Fishing elevates variability in the abundance of exploited species. *Nature*, 443: 859–862.

Hutchings L, Barange M, Bloomer SF, Boyd AJ, Crawford RJM, Huggett JA, Kerstan M, Korrubel JL, de Oliveira JAA, Painting SJ, Richardson AJ, Shannon LJ, Schulein FH, van der Lingen CD and Verheye HM (1998). Multiple factors affecting South African anchovy recruitment in the spawning, transport and nursery areas. *South African Journal of Marine Science*, 19: 211–225.

Hutchings L, Beckley LE, Griffiths MH, Roberts MJ, Sundby S, van der Lingen C (2002). Spawning on the edge: spawning grounds and nursery areas around the southern African coastline. *Marine Freshwater Research*, 53: 307–308.

Hutchings L, van der Lingen CD, Shannon LJ, Crawford R, Verheye HMS, Bartholomae CH, van der Plas AK, Louw D, Kreiner A, Ostrowski M, Fidel Q, Barlow RG, Lamont T, Coetzee J, Shillington F, Veitch J, Currie J and Monteiro P (2009). The Benguela Current: an ecosystem of four components. *Progress in Oceanography*, 83: 15–32.

Hutchings L, Jarre A, Lamont T and van den Berg M (2012). St Helena Bay (southern Benguela), then and now: muted climate signals, large human impact. *African Journal of Marine Science*, 34(4): 559–583.

Hutchings K and Lamberth SJ (2003). The likely impacts of an eastward expansion of the inshore gill-net fishery in the Western Cape, South Africa: implications for management. *Marine and Freshwater Research*, 54:39–56.

Hutchings K, Clark BM and Atkinson LJ (2008). Monitoring of the line fishery in the Berg River estuary (Western Cape, South Africa), with evidence of recovery subsequent to closure of commercial gill netting. *African Journal of Marine Science*, 30(3): 507–517.

Huvenne VAI, Tyler PA, Masson DG, Fisher EH, Hauton C, Hühnerbach, Le Bas TP and Wolff GA (2011). A picture on the wall: innovative mapping reveals cold-water coral refuge in submarine canyon. PLoS ONE 6(12): e28755. doi:10.1371/journal.pone.0028755.

James NC, Götz A, Potts WM and Cowley PD (2012). Temporal variability of a temperate fish assemblage in Africa's oldest marine protected area. *African Journal of Marine Science,* 34(1): 15–26.

Jarre A, Ragaller SM and Hutchings L (2013). Long-term, ecosystem-scale changes in the southern Benguela marine pelagic social-ecological system: Interaction of natural and human drivers. *Ecology & Society*, accepted for publication (February 2013).

Kane AS, Oldach D and Reimschuessel R (1998). Fish lesions in the Chesapeake Bay: *Pfiesteria*-like dinofagellates and other etiologies. MMJ 47, 106–112.

Kennedy VS, Twilley RR, Kleypas JA, Cowan JH Jr, and Hare SR (2002). Coastal and marine ecosystems and global climate change: Potential effects on U.S. resources. Report prepared for the Pew Center on Global Climate Change pp. 51.

Koeller P, Fuentes-Yaco C, Platt T et al. (2009). Basin-scale coherence in phenology of shrimps and phytoplankton in the North Atlantic Ocean. Science, 324: 791–793.

Kruger AC (2006). Observed trends in daily precipitation indices in South Africa: 1910–2004. *International Journal of Climatology*, 26: 2275–2286.

Kruger AC and Shongwe S (2004). Temperature trends in South Africa: 1960–2003. *International Journal of Climatology* 24, 1929–1945.

Lamberth SJ, Branch GM and Clark BM (2010). Estuarine refugia and fish responses to a large anoxic, hydrogen sulphide, "black tide" event in the adjacent marine environment. *Estuarine, Coastal and Shelf Science*, 86: 203–215.

Lamberth SJ, Drapeau L and Branch GM (2009). The effects of altered freshwater inflows on catch rates of non-estuarine-dependent fish in a multispecies nearshore line-fishery. *Estuarine, Coastal and Shelf Science*. 84: 527–538

Lamberth SJ, James N, van Niekerk L and Whitfield AK (2012). The effects of climate change on fish and fisheries in the cool/warm temperate and warm temperate/subtropical biogeographical region transition zones. *COP 17* Climate Change and Fisheries presentation.

Lamberth SJ, van Niekerk L and Hutchings K (2008). Comparison of, and the effects of altered freshwater inflow on, fish assemblages of two contrasting South African estuaries: the cool-temperate Olifants and the warm-temperate Breede. *African Journal of Marine Science*, 30(2): 311–336.

Lamberth SL and Turpie JK (2003). The role of estuaries in South African fisheries: economic importance and management implications. *African Journal of Marine Science* 25(1), 131–157.

Lamont T (2011) Bio-optical investigation of phytoplankton production in the southern Benguela ecosystem. PhD thesis, Department of Oceanography, University of Cape Town.

Last PR, White WT, Gledhill DC, Hobday AJ, Brown R, Edgar GJ and Pecl G (2011). Long-term shifts in abundance and distribution of a temperate fish fauna: a response to climate change and fishing practices. *Global Ecology and Biogeography*, 20: 58–72.

Le Quesne WJF and Pinnegar JK (2011). The potential impacts of ocean acidification: scaling from physiology to fisheries. *Fish and Fisheries*. doi: 10.1111/j.1467-2979.2011.00423.x

Le Quesne WJF and Pinnegar JK (2012). The potential impacts of ocean acidification: scaling from physiology to fisheries. *Fish and Fisheries,* 13:333–344. doi: 10.1111/j.1467–2979.2011.00423.x.

Lehodey P, Alheit J, Barange M, Baumgartner T, Beaugrand G, Drinkwater K, Fromentin JM, Hare SR, Ottersen G, Perry RI, Roy C, van der Lingen CD and Werner F (2006). Climate variability, fish, and fisheries. *Journal of Climate*, 19(20): 5009–5030. ISSN 0894-8755. doi:10.1175/JCLI3898.1. URL http://journals.ametsoc.org/doi/abs/10.1175/JCLI3898.1.

Lloyd P, Plaganyi EE, Weeks SJ, Magno-Canto M and Plaganyi G (2012). Ocean warming alters species abundance patterns and increases species diversity in an African sub-tropical reef-fish community. *Fisheries Oceanography*, 21: 78–94

Loneragan NR and Bunn SE (1999). River flows and estuarine ecosystems: implications for coastal fisheries from a review and a case study of the Logan River, southeast Queensland. *Australian Journal of Ecology*, 24: 431–440.

Loveday B (2013). PhD thesis, in prep Department of Oceanography, University of Cape Town.

Lumsden TG, Schulze RE and Hewitson BC (2009). Evaluation of potential changes in hydrologically relevant statistics of rainfall in southern Africa under conditions of climate change. *Water SA* 35: 649–656.

Mackas DL (2011). Does blending of chlorophyll data bias temporal trend? *Nature* 472: doi: 10.1038/nature09951.

Mann BQ and Pradervand P (2007). Declining catch per unit effort of an estuarine-dependent fish, *Rhabdosargus sarba* (Teleostei: Sparidae), in the marine environment following closure of the St Lucia estuarine system, South Africa. *African Journal of Aquatic Science* 32: 133–138

Mather AA, Garland GG and Stretch DD (2009). Southern African sea levels: corrections, influences and trends. *African Journal of Marine Science,* 31: 145–156.

Mather AA and Stretch DD (2012). A perspective on sea level rise and coastal storm surge from southern and eastern Africa: a case study near Durban, South Africa. *Water SA* 4: 237–259.

Mayfield S and Branch GM (2000). Interrelations among rock lobsters, sea urchins, and juvenile abalone: implications for community management. *Canadian Journal of Fisheries and Aquatic Science*, 57: 2175–2185.

McGrath MD, Horner CCM, Brouwer SL, Lamberth SJ, Mann BQ, Sauer WHH, and Erasmus C (1997). An economic valuation of the South African line fishery. *South African Journal of Marine Science* 18: 203–211.

Mead A (2011). The rocky intertidal: are marine introduced species and climate change forcing significant spatial and temporal community assemblage shifts in South Africa? PhD Thesis, University of Cape Town, South Africa.

Melville-Smith R, van Sittert L (2005). Historical commercial west coast rock lobster *Jasus lalandii* landings in South African waters. *African Journal of Marine Science*, 27: 33–44.

Morrison JA, Gamble JC and Napier IR (1991). Mass mortality of herring eggs associated with a sedimenting diatom bloom. *ICES Journal of Marine Science*, 48(2): 237–245.

Mugo R, Saitoh SI, Nihira A and Kuroyama T (2010). Habitat characteristics of skipjack tuna (*Katsuwonus pelamis*) in the western North Pacific: a remote sensing perspective. *Fisheries Oceanography*, 19(5): 382–396. ISSN 10546006. doi:10.1111/j.1365-2419.2010.00552.x. URL http://doi.wiley.com/10. 1111/j.1365-2419.2010.00552.x.

Nel DC, Cochrane K, Petersen SL, Shannon LJ, van Zyl B, Honig M.B (Editors) (2007). Ecological risk assessment: a tool for implementing an ecosystem approach for southern African fisheries. WWF South Africa Report Series – 2007/Marine/002, 203pp.

Ottersen G, Kim S, Huse G, Polovina JJ, and Stenseth NC (2010). Major pathways by which climate may force marine fish populations. *Journal of Marine Systems*, 79: 343–360.

Olden JD, Jackson DA and Peres-Neto PR (2002). Predictive models of fish species distributions: a note on proper validation and chance predictions. *Transactions of the American Fisheries Society*, 131: 329–336.

Oosthuizen A, Roberts MJ, Sauer WHH (2002). Temperature effects on the embryonic development and hatching success of the squid *Loligo vulgaris reynaudii*. *Bulletin of Marine Science*, 71: 619–632

Orr JC, Fabry VJ, Aumont O, Bopp L, Doney SC, Feely RA, Gnanadesikan A, Gruber N, Ishida A, Joos F, Key RM, Lindsay K, Maier-Reimer E, Matear R, Monfray P, Mouchet RG, Naijar RG, Plattner GK, Rodgers KB, Sabine CL, Sarmiento JL, Schlitzer R, Slater RD, Totterdell IJ, Weirig MF, Yamanaka Y and Yool A (2005). Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, 437: 681–686.

Payne AIL and Punt AE (1995). Biology and fisheries of Cape hakes (*M. capensis* and *M. paradoxus*). In: Alheit J, Pitcher TJ (eds.). Hake. Fisheries, ecology and markets. London: Chapman and Hall, pp.15–47.

Peck MA, Buckley LJ and Bengtson DA (2006). Effects of temperature and body size on the swimming velocity of larval and juvenile Atlantic cod (*Gadus mohua*): implications for individual-based modeling. *Environmental Biology of Fishes*, 75: 419–429.

Pecl GT and Jackson GD (2008) The potential impacts of climate change on inshore squid: biology, ecology and fisheries. *Reviews in Fish Biology and Fisheries*, 18: 373–385.

Pelejero C, Calvo E and Hoegh-Guldberg O (2010). Paleo-perspectives on ocean acidification. *Trends in Ecology and Evolution*, 25(6): 332–344.

Penny AJ, Pulfrich A, Rogers J, Steffani N, and Mabille V (2008). Project: BEHP/CEA/03/02: Data gathering and gap analysis for assessment of cumulative effects of marine diamond mining activities on the BCLME region. Final Report to the BCLME mining and petroleum activities task group. March 2008. 410pp.

Perry AL, Low PJ, Ellis JR, and Reynolds JD (2005). Climate change and distribution shifts in marine fishes. *Science*, 308: 1912–1915.

Petersen SL, Paterson B, Basson J, Moroff N, Roux J-P, Augustyhn J, D'Almeida G (eds.) (2010). Tracking the implementation of an ecosystem approach to fisheries in southern Africa. WWF South Africa Report Series – 2010/Marine/001.

Punt AE, Leslie RW, Du Plessis SE (1992). Estimation of the annual consumption of food by Cape hake *Merluccius capensis* and *M. paradoxus* off the South African west coast. *South African Journal of Marine Science* 12: 611–634.

Punt AE, A'mar T, Bond NA, Butterworth DS, de Moor CL, De Oliveira JAA, Haltuch MA, Hollowed AB, Szuwalski C (2013). Fisheries management under climate and environmental uncertainty: control rules and performance simulation. *ICES Journal of Marine Science*; doi:10.1093/icesjms/fst057 http://icesjms.oxfordjournals.org/

Pitcher GC and Calder D (2000). Harmful algal blooms of the southern Benguela Current: A review and appraisal of monitoring from 1989 to 1997. *South African Journal of Marine Science*, 22: 255–271.

Pörtner H (2008) Ecosystem effects of ocean acidification in times of ocean warming: a physiologist's view. *Marine Ecology Progress Series*, 373: 203–217

Potts WM, Heriques R, Sauer WHH, Santos CV and Shaw P (2012). Are changing water temperatures in the Benguela about to alter the evolutionary history of our *Argyrosomus* fishes? Proceedings of the 4th South African Marine Linefish Symposium, in press.

Pradervand P and Baird D (2002). Assessment of the recreational line fishery in selected Eastern Cape estuaries: trends in catches and effort. *South African Journal of Marine Science*, 24: 87–101.

Ragaller SM (2012). Misunderstandings in fisheries: An ethnography of regulative categories and communication around Gansbaai and Dyer Island. M. Soc. Sci. thesis, Department of Social Anthropology, University of Cape Town.

Reason CJC, Florenchie P, Roualt M and Veitch J (2006). Influences of large scale climate models and Agulhas System variability on the BCLME Region. In: Shannon V, Hempel G, Malanotte-Rizzoli P, Moloney CL, Woods J. (eds.) *Benguela: Predicting a Large Marine Ecosystem*. Amsterdam: Large Marine Ecosystems Sereies 14 Elsevier, 223–238.

Reason CJC and Hermes JC (2011). Climate change and variability in southern Africa and regional ocean influences. In: Zietsman L (ed.). *Observations on Environmental Change in South Africa*. Stellenbosch: SUN PRESS. pp 270–273.

Reddering JSV and Rust IC (1990). Historical changes and sedimentary characteristics of southern African estuaries. *South African Journal of Science*, 86: 425–428.

Richardson AJ and Schoeman DS (2004). Climate impact on plankton ecosystems in the Northeast Atlantic. *Science*, 305(5690): 1609–1612. doi:10.1126/science.1100958. URL http://www.ncbi.nlm.nih.gov/pubmed/15361622.

Riebesell U, Körtzinger A and Oschlies A (2009). Sensitivities of marine carbon fluxes to ocean change. *Proceedings of the National Academy of Sciences of the United States of America*, 106(49): 20602–20609.

Riebesell U, Zondervan I, Rost B, Tortell PD, Zeebe RE and Morel FMM (2000). Reduced calcification of marine plankton in response to increased atmospheric CO_2. *Nature*, 407: 364–367.

Rijnsdorp AD, Peck MA, Engelhard GH, Möllmann C, and Pinnegar JK (2009). Resolving the effect of climate change on fish populations. *International Council for the Exploration of the Sea Journal of Marine Science*, 66:1570–1583.

Roberts M (2005). Chokka squid (*Loligo vulgaris reynaudii*) abundance linked to changes in South Africa's Agulhas Bank ecosystem during spawning and the early life cycle. *ICES Journal of Marine Science*, 62: 33–55.

Roberts MJ, Sauer WHH (1994). Environment: the key to understanding the South African chokka squid (*Loligo vulgaris reynaudii*) life-cycle and fishery. *Antarctic Science*, 6: 249–258.

Robins JB, Halliday IA, Staunton Smith J, Mayer DG and Sellin MJ (2005). Freshwater-flow requirements of estuarine fisheries in tropical Australia: a review of the state of knowledge and application of a suggested approach. *Marine and Freshwater Research*, 56: 343–360.

Roessig JM, Woodley CM, Cech JJ, Hansen LJ (2004). Effects of global climate change on marine and estuarine fishes and fisheries. *Reviews in Fish Biology and Fisheries*, 14: 251–275.

Rouault M, Pohl B, and Penven P (2010). Coastal oceanic climate change and variability from 1982 to 2009 around South Africa. *African Journal of Marine Science*, 32(2): 237–246.

Rouault M, Penven P, and Pohl B (2009). Warming of the Agulhas Current system since the 1980's. *Geophysical Research Letters*, 36(12) L12602, doi:10.1029/2009GL037989.

Roux JP, van der Lingen CD, Gibbons MJ, Moroff NE, Shannon LJ, Smith ADM, Cury PM (2013). Jellyfication of marine ecosystems as a likely consequence of overfishing small pelagic fishes: lessons from the Benguela. , 89: 249–284.

Roy C, van der Lingen CD, Coetzee JC, and Lutjeharms JRE (2007). Abrupt environmental shift associated with changes in the distribution of Cape anchovy *Engraulis encrasicolus* spawners in the southern Benguela. *African Journal of Marine Science*, 29: 309–319.

Roy C, Weeks S, Rouault M, Nelson G, Barlow R, and van der Lingen C (2001). Extreme oceanographic events recorded in the southern Benguela during the 1999–2000 summer season. *South African Journal of Science*, 97: 465–471.

Roy C, van der Lingen CD, Coetzee JC, and Lutjeharms JRE (2007). Abrupt environmental shift associated with changes in the distribution of anchovy spawners in the southern Benguela. *African Journal of Marine Science*, 29: 309–319.

Royal Society (2005). Ocean acidification due to increasing atmospheric carbon dioxide. London: The Royal Society.

Sauer WHH, Hecht T, Britz PJ, Mather D (2003). An economic and sectoral study of the South African fishing industry. Volume 2. Fishery profiles. Unpublished report prepared for Marine and Coastal Management by Envirofish Africa, Rhodes University.

Schulze RE, Lumsden TG, Horan MJC, Warbuton M, Maharaj M (2005). An assessment of impacts of climate change on agrohydrological responses over southern Africa. In: Schulze RE (ed.) Climate change and water resources in southern Africa: Studies on scenarios, impacts, vulnerabilities and adaptation. WRC Report 1430/1/05, pp. 141–189. Pretoria: Water Research Commission.

Schultz O (2010). Belonging on the West Coast: An Ethnography of St Helena Bay in the context of marine resource scarcity . M. Soc. Sci thesis, Department of Social Anthropology, Humanities Faculty, University of Cape Town.

Shannon L J, Coll M, Yemane D, Jouffre D, Neira S, Bertrand A, Diaz E, and Shin, Y-J (2010). Comparing data-based indicators across upwelling and comparable systems for communicating ecosystem states and trends. *ICES Journal of Marine Science*, 67: 807–832.

Shannon LJ, Jarre A, and Petersen S (2011). Developing a science base for an ecosystem approach to fisheries in the Benguela. *Progress in Oceanography*, 87: 289–303.

Sheridan JA and Bickford D (2011). Shrinking body size as an ecological response to climate change. *Nature Climate Change*, 1: 401–406.

Sink KJ, Branch GM, and Harris JM (2006). Biogeographic patterns in rocky intertidal communities in KwaZulu-Natal, South Africa. *African Journal of Marine Science*, 27(1): 81–96.

Sink K, Holness S, Harris L, Majiedt P, Atkinson L, Robinson T, Kirkman S, Hutchings L, Leslie R, Lamberth S, Kerwath S, von der Heyden S, Lombard A, Attwood C, Branch G, Fairweather T, Taljaard S, Weerts S, Cowley P, Awad A, Halpern B, Grantham H, and Wolf T (2012). National Biodiversity Assessment 2011: Technical Report. Volume 4: Marine and Coastal Component. Pretoria: South African National Biodiversity Institute, pp. 325.

Solomon S, Qin D, Manning M et al. (2007) Technical Summary. In: Climate change 2007: the physical science basis. Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change (Editors Solomon S, Qin D, Manning M, Chen Z, Marquis M, Avery KB, Tignor M, Miller HL), pp. 21–91. Cambridge: Cambridge University Press.

Stewart IJ, Keller AA, Fruh EL, Simon VH, and Horness BH (2010). Throwing in the towel: When do adverse conditions dictate a weather day during a bottom trawl survey? *Fisheries Research*, 102: 130–140.

Stock CA, Alexander MA, Bond NA et al (2011). On the use of IPCC-class models to assess the impact of climate on living marine resources. *Progress in Oceanography*, 88: 1–27.

Taljaard S, van Niekerk L, Joubert W (2009). Extension of a qualitative model on nutrient cycling and transformation to include microtidal estuaries on wave-dominated coasts: southern hemisphere perspective. *Estuarine, Coastal and Shelf Science*, 85: 407–421.

Tarr RJQ, Williams PVG, and MacKenzie L (1992). Abalone, sea urchins and rock lobster: implications for community management. *Canadian Journal of Fisheries Aquatic Science*, 57: 2175–2185.

Theron AK (2011). Climate change, sea level rise and the southern African coastal zone. In: Zietsman L (ed.), *Observations on Environmental Change in South Africa*. Stellenbosch: SUN PRESS. pp 212-217.

Thuiller W, Georges D, and Engler R (2012). BIOMOD: Ensemble platform for species distribution modeling. R package version 1.1-7.04/r480, URL http://R-Forge.R-project.org/projects/biomod/.

Travers M, Shin Y-J., Jennings S, Machu E, Huggett JA, Field JG and Cury PM (2009). Two-way coupling versus one-way forcing of plankton and fish models to predict ecosystem changes in the Benguela. *Ecological Modeling*, 220: 3089–3099

Travers M, Watermeyer K, Shannon LJ, Shin Y-J (2010). Changes in food web structure under scenarios of overfishing in the southern Benguela: Comparison of the Ecosim and OSMOSE modeling approaches. *Journal of Marine Systems*, 79(1–2):101–111

Turpie JK, Lamberth SL (2010). Characteristics and value of the Thukela Banks crustacean and linefish fisheries, and the potential impacts of changes in river flow. *African Journal of Marine Science*, 32: 613–624.

Turpie JK, Adams JB, Joubert AR, Harrison T, Colloty B, Maree R, Whitfield AK, Wooldridge T, Lamberth SJ, Taljaard S and van Niekerk L (2002). Assessment of the conservation priority status of South African estuaries for use in management and water allocation. *Water SA*, 28: 191–206.

Twatwa NM, van der Lingen CD, Drapeau L, Moloney CL, and Field JG (2005). Characterising and comparing the spawning habitats of anchovy *Engraulis encrasicolus* and sardine *Sardinops sagax* in the southern Benguela upwelling ecosystem. *African Journal of Marine Science*, 27(2): 487–499.

Tyson PD (1986). *Climatic Change and Variability in Southern Africa*. Oxford: Oxford University Press.

Van Niekerk L and Turpie JK (Editors) (2012). South African National Biodiversity Assessment 2011: Technical Report. Volume 3: Estuary Component. CSIR Report Number CSIR/NRE/ECOS/ER/2011/0045/B. Stellenbosch: Council for Scientific and Industrial Research.

Van Niekerk L, Engelbrecht F, James N, Lamberth SJ, Meyer A, and Theron AK (2012). How vulnerable are South Africa's estuaries to climate change? National Conference on Global Change, 26 – 28 November 2012, Department of Science and Technology and National Research Foundation.

Van der Lingen CD (2011). The biological basis for hypothesizing multiple stocks in South African sardine *Sardinops sagax*. DAFF unpublished document, MARAM IWS/DEC2011/P/OMP/P7, 10pp.

Van der Lingen CD, Coetzee J, Hutchings LF (2011). Causes and effects of changes in the distribution of anchovy and sardine in shelf waters off South Africa In Zietzman L (ed.), Observations on Environmental Change in South Africa, pp. 252–257. Stellenbosch: Sun Press.

Van Sittert L (2003). The tyranny of the past: why local histories matter in South African fisheries. *Ocean and Coastal Management*, 46: 199–219.

Van der Lingen CD, Fréon P, Hutchings L, Roy C, Bailey GW, Bartholomae C, Cockcroft AC, Field JG, Peard KR and van der Plas AK (2006). Forecasting shelf processes of relevance to living marine resources in the BCLME. In Shannon V., Hempel G, Malanotte-Rizzoli P, Maloney C and Woods J (eds), *Benguela: Predicting a Large Marine Ecosystem. Large Marine Ecosystems, Vol.* 14. Amsterdam: Elsevier, 309–347.

Veitch J, Penven P, and Shillington F (2010). Modeling Equilibrium Dynamics of the Benguela Current System. *Journal of Physical Oceanography*, 40: 1942–1964.

Verheye H, Richardson A, Hutchings L, Marska G, Gianakouras D (1998). Long-term trends in the abundance and community structure of coastal zooplankton in the southern Benguela system, 1951–1996. *South African Journal of Marine Science*, 19(1): 317–332.

Verheye HM, Richardson AJ (1998). Long-term increase in crustacean zooplankton abundance in the southern Benguela upwelling region (1951–1996): bottom-up or top-down control? *ICES Journal of Marine Science*, 55(4): 803–807.

Vézina A and Hoegh-Guldberg O (2008). Effects of ocean acidification on marine ecosystems. *Marine Ecology Progress Series*, 373: 199–201.

White C, Kendall BE, Gaines S, Siegel Da and Costello C (2008). Marine reserve effects on fishery profit. *Ecology Letters*, 11(4): 370–379. ISSN 1461-0248. doi:10.1111/j.1461-0248.2007. 01151.x. URL http://www.pubmedcentral.nih.gov/articlerender. artid=2268951&tool=pmcentrez&rendertype=abstract.

Whitfield AK, Adams JB, Bate GC, Bezuidenhouts K, Bornman TG, Cowley PD, Froneman PW, Gama PT, James NC, MacKenzie B, Riddin T, Snow GC, Strydom NA, Taljaard S, Terorde AI, Theron AK, Turpie JK, van Niekerk L, Vorwerk PD. and Wooldridge TH (2008). A multidisciplinary study of a small, temporarily open/closed South African estuary, with particular emphasis on the influence of mouth state on the ecology of the system. *African Journal of Marine Science*, 30(3): 453–473.

Wood HL, Spicer JI, and Widdicombe S (2008). Ocean acidification may increase calcification rates, but at a cost. *Proceedings of the Royal Society B: Biological Sciences*, 275(1644): 1767–73.

World Wildlife Fund (WWF) (2011) *Fisheries: Facts and Trends South Africa.* Cape Town: WWF.

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