ECOSYSTEM EFFECTS OF BOTTOM TRAWLING IN THE BENGUELA CURRENT SYSTEM: *EXPERIMENTAL AND RETROSPECTIVE DATA ANALYSES*.

BY

SAMUEL KAKAMBI MAFWILA

Thesis Presented for the Degree of
DOCTOR OF PHILOSOPHY
In the Department of Zoology
Faculty of Science

UNIVERSITY OF CAPE TOWN

2011

SUPERVISORS:

Prof. John.G. FIELD
A/Prof. Astrid JARRE
Dr Lynne SHANNON
Marine Research (*Ma-Re*) Institute
Zoology Department
UCT

DECLARATION

The outcomes presented in this thesis are my own except those acknowledged below and in the acknowledgement section. Initial conception of the project was facilitated by Prof. John G. Field (my main PhD supervisor, *MA-RE*, UCT) and Dr Lurry Hutchings (DEA) whom I sincerely thank. All major support towards the successful completion of this thesis are either acknowledged in the acknowledgement section or cited in the text.

The work presented in this thesis either in part or in full has not been presented for any degree at this or any other University.

……………………………………………………………………………………

Samuel Kakambi Mafwila

24 November 2011

ACKNOWLEDGEMENTS

During the progress of this thesis many individuals have helped me directly of indirectly. Below is a summary of the encouragement and support from those individuals and institutions without whom this thesis would not have been completed. Initially my deepest gratitude and appreciation goes to my three supervisors (Prof. J.G. Field; Ass. Prof. A. Jarre; and Dr L. Shannon) for their mentoring, understanding, patience, critical but positive comments on my work, and kind approach towards me. Prof. J.G. Field always believed I can tell a very nice story while writing my thesis by emulating the Shakespeare's systematic writing style, with every section of a chapter flowing properly and making perfect sense. Since the inception of this thesis he has kept his doors open for any trouble I may have encountered and always willing to help. I strongly thank him for his unwavering mentorship in science. Assoc. Prof. A. Jarre has been very helpful in improving my write-up on issues pertaining to research methodology, structuring the chapter, and critical though positive comments on unexpanded facts in the thesis. Dr L. Shannon for her general outlook on my English usage and constructive comments on to ecosystem changes and the Benguela Current System. I was grateful also to having Prof. J.G. Field and Dr L. Hutching onboard the Nansen during the experimental trawl sampling, that occasion has seen the launch of the NORSA project fieldwork. I am indebted to the Captains and Crew of the *Dr Frindtjof Nansen* for the professional support during the 2007 hake survey and experimental trawl survey, as well the onboard assistance from Lara Atkinson, Annelise Fleddum, Anders Bjorgesaeter, Shaz Du Plesis, Cliffy and many more anonymous individual who were onboard with us. I thank Dr D. Yemane for his immense assistance and guidance in the use of Statistica, Primer, R, and GAM, and for sharing his knowledge on the demersal fish of South Africa and his experience on community structure work in general. You always opened your doors and had time whenever I needed your assistance. Remember how we joked on the NansClim task groups, "if we ever wanted to parallel your data analysis skills, then we need to clone you, because you are super-human". I thank Jeremy Davids for your assistance with the English language writing skills. I may have missed mentioning some of you, but I thank all.

My appreciation also goes to the research scientists at NatMIRC, Ministry of Fisheries and Marine Resources (Swakopmund): Paul Kainge; John Kathena; John Iitembu (Historical data on hake biomass surveys and commercial effort data); Anja van der Plas; and Chris Barthalomae (Environmental data), as well as the Directorate Operations (Data on hake Commercial vessels). I thank my colleagues at the Department of Fisheries and Aquatic Sciences for their support, and those who availed their teaching time slots to me whenever I needed it most to cover my teaching lord.

The Ecosystem Approach to Fisheries (EAF) working group under the South African Research Chair Initiative (SARChI) and *MA-Re* thanks you were such a wonderful team to work and interact with. Edward Hill thanks for sharing your expertise in ArcGIS v9.3, fantastic maps, and the usual daily technical support, I have learned a lot from you in terms using ArcGIS. Gilly Smith thanks for your administrative support and your prompt help to all my queries and keeping the group on toes for the chatties. Emelyn Balarin, Helen King, and Pavs Pillay, I thank you for administering the project and its funds well, and for processing requests so timeously.

Financial support for the project and my studies were provided by the co-operation between the Royal Norwegian Government and South Africa (NORSA) administered by the Marine Research Institute (*MA-RE*) at the University of Cape Town, and the Fisheries Programme in the Department of Fisheries and Aquatic Sciences, UNAM, which is co-operation between the Norwegian Ministry of Foreign Affairs (NMFA) and the University of Namibia (UNAM).

Finally yet importantly, I greatly thank my family (Dad and Mom) in Namibia for the understanding and support after those long absences from them from time to time, believing in me and encouraging me to work hard and reap the fruits of my hard-earned work. Dad, though you were taken away from us during my studies, I am sure I would have made proud once more again as your aspiration for my academic future has just come true. To my wife, “they always say save the best for last” and I am just proving it here. I cannot thank you enough for your support, taking care of family while I was away, understanding my lengthy studies for a good course one day.... i am running out words, but yes indeed thank you. To all my children, you all special in your own ways, my achievement should serve as prosperity, I love you all, and remember education is very important in life.

TABLE OF CONTENTS

ABSTRACT

Bottom-trawling is one of the most widespread sources of physical disturbance to the continental shelf substrates throughout the world. Previous studies have shown that degradation and ecosystem changes have occurred in intensively fished areas. To date it has been difficult to attribute ecosystem changes to bottom-trawling intensities at a spatial scale that is representative of commercial fishing effort. This thesis investigates ecosystem effects of bottom-trawling on demersal fish assemblages (1990 – 2006) off Namibia and their relationship to environmental variables. The study quantifies the bottom-trawl intensity using commercial data (2000 – 2006) from the Namibian hake-directed bottom-trawl fishery for the first time. The thesis further investigates short-term effects of bottom-trawling on demersal fish assemblages in heavily and lightly trawled areas experimentally. Finally, it assesses the changes in diversity, density, and structural composition of demersal fish assemblages in the northern and southern Benguela ecosystems, using the hake biomass survey data for 2007. The major research questions are answered using various approaches. Changes in the structure and composition of the demersal fish assemblages are assessed using a variety of ecosystem indicators known to capture such changes, which may be induced by bottom-trawling. They include size-based indicators such as mean length, slope and height of the size spectra and proportions of abundances by size classes; and species-based indicators such as dominance curves, dendrograms, multidimensional scaling and various diversity indices. Indicators were inferred using directions of change of the indicator in question, in relation to the expected response of the indicator to varied bottom-trawl effects and environmental variability. Bottom-trawl intensity is assessed by mapping the average number of hours trawled in a 1' latitude x 1' longitude grid square and as the average number of trawls per grid square over a seven-year period, using ArcGIS software. Effort and catch per unit effort are estimated and modelled using general linear models first, and then generalized additive models or big additive models, with longitude, latitude, depth, year, seasons, vessel type, and regions as explanatory factors. Bottom-trawling intensity varied spatially off Namibia, with the average number of trawls per grid square patchily distributed. Southern Namibia was the most heavily trawled with high fishing effort (54.18 %), followed by central Namibia (25.06 %), with northern region the least trawled (20.77 %). Most of the effort was concentrated in water depths ranging 200 to 399 meters, and freezer vessels expended more effort (71.56 %) than the wetfish vessels (28.44 %). Effort varied significantly ($p < 0.001$) both annually and seasonally with the highest effort recorded in autumn and lowest in summer. Temporal and seasonal variations affected the catch per unit effort, and wetfish vessels accounted for higher catch per unit effort (64.11 %) than the freezer vessels (35.89 %). Significant ($p < 0.05$) changes in the mean catch rates, mean catch length, heights and slopes of the size spectra are observed over the years under review, and environmental variables (Benguela Niños, low oxygen waters, sea surface temperature, Angola-Benguela Front position, upwelling favorable wind anomalies, upwelling index), and *M. capensis* recruitment index shows minimal effects on the mean catch rate, mean catch length and heights and slopes of the size spectra, thus the other effects may be partly due to direct and indirect effects of fishing. Cluster analysis and ordination by non-metric multidimensional scaling, show changes in the demersal fish community off Namibia and identified three main assemblages temporally, in 1990–1993, 1994–2000, and 2001–2006. Dominance curves suggest that the three assemblages are all moderately disturbed. Permutational multivariate analysis of variance and a distance-based linear model suggest multi-factor combined effects of regions, depth, bottom oxygen, temperature and vessels play important roles in the observed changes in demersal fish community structure. Effects of hypoxia and changing environmental conditions (bottom oxygen and bottom temperature) are more pronounced on the northern and central continental shelf and play an important role in the distribution of demersal fish species. Diversity increases with increasing latitude (towards the south) and depth, and is minimally affected by the current levels of fishing. The generalised additive model suggests that total abundance and latitude are important predictors of diversity. Demersal fish assemblages are compared between lightly and heavily trawled areas experimentally, for the first time in Benguela waters. Heavily trawled areas are characterized by low fish diversity, high abundance of small individuals and dominance by a few species. Lightly trawled areas are less dominated, exhibited high evenness and high diversity. This empirical study unravelled the immediate effects of heavy trawling activities as a partial cause of changes in the assemblage structure. Cluster analysis and multi-dimensional scaling identify three demersal fish assemblages, namely the continental shelf and slope of northern Benguela, and southern Benguela at 19 % Bray-Curtis similarity, and their *W–statistics* suggest that the northern Benguela assemblages are moderately disturbed. Fish density and diversity increase with increasing latitude and depth. The separation of the two countries' demersal assemblages, as identified by cluster analysis and multi-dimensional scaling, coincides with the boundary between the northern and southern Benguela systems. The changes in composition of demersal fish assemblages observed in this analysis are a reflection of both direct and indirect effects of bottom-trawling, complicated by varying environmental conditions, such as low oxygen water important predictors of diversity.

Key words: Benguela upwelling system, bottom-trawling, demersal fish species, fish assemblages, diversity indices

Chapter 1

INTRODUCTION

General Background

Mobile bottom-trawling gear scrapes the seafloor or digs into the seabed to a variable depth. The penetration depth into the seabed varies according to the nature of the seabed (Margetts and Bridger, 1971; Bridger, 1972; de Groot, 1972; Lindeboom and de Groot, 1998). Thus, fishing methods that damage or change ocean habitats may threaten the sustainability of some fish communities and could threaten the health of entire ocean ecosystems. Bottom trawls constitute one of the most invasive methods of fishing. Research has shown that catch composition comprises not only the target species, but also a great proportion of non-target fish and benthic invertebrate species (Andrew and Pepperell, 1992; de Groot and Lindeboom, 1994; Messieh *et al*., 1991; Rallof, 1996; Robin, 1992). Bottom-trawling has a direct impact not only on target species and bycatch, but can also impact the whole marine ecosystem (Sanchez *et al*., 2007). Heavy fishing is a major threat to the structure and function of marine ecosystems, since it affects the abundance, species diversity, size composition and life history traits of organisms (Bianchi *et al*., 2001; Yemane *et al*., 2005).

Wide nets equipped with rollers, chains and doors weighing thousands of kilograms are dragged across the ocean floor in an effort to harvest bottom-dwelling marine organisms. “Rockhopper” nets have large disks that allow the trawls to jump over and plough through rough terrain without tearing. Rock-hopper nets allow trawling in areas with high relief, such as rocky bottoms, coral reefs, and seamounts. Such gear disturbs benthic communities and damages structures such as rock piles and corals, and these environments experience continual disturbance at various scales (Hall, 1994; Lindeboom and de Groot, 1998). The combination of large size and weight designed to disturb the bottom, make mobile gear a significant threat to many benthic ecosystems. It has been demonstrated that bottom trawls and dredges can dramatically alter the ocean floor and cause major changes in biological communities (Walting and Norse, 1998; Auster and Langton, 1999; Kaizer *et al.*, 1999; National Research Council, 2002). Habitat variety and complexity are critical to supporting the abundance and diversity of marine organisms (Watling and Norse, 1998). Bottom-tending gear often disperses boulders, destroys burrows, and removes stationary organisms such as coral and sponges. Fish and other animals depend upon these structures for breeding, shelter and feeding and the loss of habitat complexity may result in reduced fish populations. Many species, particularly long-lived fish (e.g. Orange roughy *Hoplostethus atlanticus* and Alphonsino *Beryx splendens*), require several types of habitat to complete their life cycles (Maul, 1986 and 1990), some of which are particularly susceptible to damage by trawling and dredging. In addition, bottom-disturbing gear may have other less immediate, but equally harmful, impacts. It can change community structure and lead to changes in the average size of organisms; remove ecosystem engineers such as oysters, corals, and burrowing animals; alter the way that nutrients are recycled; change chemical gradients in sediments; increase an ecosystem's vulnerability to stressors and reduce habitat productivity (National Academy of Sciences, 2002).

These threats have become more pervasive with the development of methods and gear that allow fishing in areas that were previously inaccessible. Bottom trawls now reach depths of one kilometre. The potential damage caused by these fishing methods is both locally and globally significant. It is estimated that, every two years, bottom trawls drag an area of the ocean bottom equivalent to the entirety of the world's continental shelves (Watling and Norse, 1998). Fishing activity is one of the many different ways people interact with the oceans and it affects fauna across the ecological hierarchy (individual, population, community and ecosystem). The type of fishing activity varies from those that are extremely size and species selective (e.g. longline and handline) to those that are unselective (bottom-trawling), affecting the demersal fish communities by causing changes in species composition, size structure and overall biomass, as well as modifying the benthic habitat (Gislason *et al*., 2000; Bianchi *et al*., 2000, 2001; Kaizer and de Groot, 2000; Schejter *et al*., 2008). Several studies (Pauly, 1979; Gulland and Garcia, 1984; Sharp and Csirke, 1984; Greenstreet and Hall, 1996; Sainsbury *et al*., 1997; Haedrich and Barnes, 1997; Bianchi *et al*., 2000, 2001; Yemane *et al*., 2004, 2005) have documented the changes in the structure of demersal fish communities as a result of trawling.

Jennings and Kaiser (1998) reviewed the ecological effects, both direct and indirect, of current fishing practices. Among the consequences are changes in the structure of marine habitats that ultimately influence the diversity, biomass, and productivity of the associated biota (Jennings and Kaiser, 1998); removal of predators, which disrupts and truncates trophic relationships (Pauly *et al*., 1998); and endangerment of marine mammals, sea turtles, some seabirds and even some fish (National Research Council, 1994). Global research data from 800 publications, which were extracted by Alverson *et al.* (1994) has revealed that trawl fishing accounts for most of the records of by-catch (996) followed by drift nets and gill nets (232), line fisheries (150), pot (130) and purse seine (82) fisheries. Fishing can change the composition of ecological communities, which can lead to changes in the relationships among species in marine food webs. Notably also, the direct effects of fishing include differential removal of larger size classes, the most valuable species and the inevitable bycatch (Kelleher, 2005; Gislason *et al.* 2000; Gordoa *et al*., 2006; Walmsley *et al*., 2007). Thus, fishing can leave the entire community dominated by smaller individuals and smaller species. Fortunately, these trends can be predicted, both between areas exposed to different fishing intensity and through time in the same area (Jennings *et al*., 2001). The indirect effects of fishing, resulting from the direct removal of biomass and habitat destruction, are usually observed after a longer period and include changes in the size and trophic structure, genetic composition of fish populations, and community structure (Jennings and Kaiser, 1998; Jennings *et al.* 2002).

Bottom-trawl effects on demersal fish communities are mostly those associated with increasing fishing mortality; and these effects can be divided into direct and indirect mortality. Direct fishing mortality is caused by (a) encounter with fishing gear when the captured organisms die inside the gear trawled at depths greater than 200 m, (b) during handling and (c) as a result of damage caused during these processes. In most teleost fish species mortality is close to 100% due to the rapid expansion of air bladders (decompression), although it is less marked among flatfish (Millner *et al*., 1993; Russel, 1993; De Silva *et al*., 2001). Mortality caused by fishing operations is highly variable between different phyla and higher taxonomic levels, but it has been found that invertebrates have higher survival rates than fish (Lindeboom and De Groot, 1998; Bergmann and Santbrink, 2000; Jenkins *et al*., 2001; Pranovi, 2001). Indirect mortality entails organisms killed as result of contact with the fishing gear but not caught by the gear; and as a result of habitat alterations caused by fishing activities (Garcia *et al*., 2007).

World fisheries provide an important food source for many countries (Watson and Pauly, 2001). Many developing countries around the world are grappling with the mandate to reduce poverty both directly and indirectly and to improve the nutritional status of the people under Millennium Development Goals (MDG) by 2015 (United Nations, 2005). Poverty reduction projects in some developing countries, including Namibia, are financed through revenue from fish exports. This is not necessarily easy, as available natural resources such as fish may be subjected to heavier exploitation pressure in view of weak management institutions. Many countries, including Namibia, have signed and ratified international conventions, which deals with biological diversity conservation, such as the Rio Declaration 1992, Agenda 21, Chapter 17 (UN, 1992); Convention on Biological Diversity (www.cbd.int); FAO Code of Conduct for Responsible Fisheries 1995 (www.un.org/esa/resources); World Summit on Sustainable Development, Johannesburg Declaration, 2002 (www.un.org/esa/resources) ; Reykjavík Declaration 2001 (FAO, 2002). Namibia, in line with these conventions, has adopted an ecosystem approach to fisheries (EAF) in order to protect, conserve, manage and better utilize their fisheries resources without harming the habitats upon which these resources depend. Thus, fisheries management and fisheries science are progressively redirecting their attention from single species to an ecosystem approach to fisheries (EAF) (FAO, 2005), increasing the need for measuring the effects of fishing on ecosystems. This is a holistic approach with an objective to sustainable use the whole ecosystem, not only the species therein. The Benguela Current Commission (BCC) has the mandate to provide advice for EAF implementation in the Benguela Current Large Marine Ecosystem, through recently launched ECOFISH project (www.benguelacc.org).

Despite the general consensus on effects of fishing, very few studies have focused on the ecosystem effects of fishing, in particular bottom-trawling in the Benguela ecosystem. Gordoa and Duarte (1991) have looked at the size-dependent density of demersal fish off Namibia by analyzing the 40 most abundant demersal fish species. They found that the size structure of fish populations was primarily determined by fishing mortality. Macpherson and Gordoa (1992) also studied trends in the demersal fish community off Namibia from 1983 to 1990 and their multivariate analysis showed that there are several distinct assemblages separated by latitude and depth, with seasonal variation. Although the high levels of fishing effort deployed in the region have lowered the total fish biomass, yet community stability, expressed as absence of change in species assemblages, was significantly high (Macpherson and Gordoa, 1992). Bianchi *et al*., (2001) carried out the assessment of the size and species composition of the Namibian demersal fishery in the Northern Benguela. A good understanding of fishing effort is important to estimate the detailed impacts of bottom-trawling. However, data on fishing effort is often poor and sometimes can only provide crude estimates (Greenstreet *et al*., 1999). Previous studies in the North Sea and Irish Sea, have based their analysis of fishing effort on tow frequency (number of tows), tow duration (hours) and days at sea (Lindeboom and de Groot, 1998; Greenstreet *et al*., 1999; Jennings *et al*., 1999) and the use of satellite-based vessel monitoring system data (Mills *et al*., 2006). A study by Ragnarsson and Steingrímsson (2003) also looked at the spatial otter trawl effort distribution in Icelandic waters, comparing measures of effort and implications for benthic community effects of trawling activities. Wilkinson and Japp (2005) when they described and evaluated the hake-directed trawling intensity on benthic habitats off South Africa.

A study by Macpherson and Roel (1987) investigated the demersal fish community off Namibia (between the Kunene and Walvis Bay) in 50 – 650 m water depth based on distribution, abundance, and diet of 51 species, constituting 95 % of the demersal fish biomass. They found three major trophic groups , one containing species which feed on pelagic and nektonic organisms; a second dominated by predators which prey on benthic polychaetes and copepods and a third group of predators preying on benthic crabs, demersal shrimps and fish. In the study by Mas-Riera *et al*. (1990), multivariate analyses revealed that there were four distinct associations in southern Namibia, separated by latitude (ca 27 ^{o}S) and depth (ca 300 m isobaths). Demersal fish diversity decreased in areas with low bottom oxygen. In central and northern Namibia in 1994 Hamukuaya *et al*. (1998) observed a massive displacement of juvenile *M. capensis* from their inshore habitat (100 – 200 m deep) to offshore, due to transient low oxygen levels (< 0.5 ml.l^{-1}) at the bottom at that time.

Ecological responses of any community to disturbance vary with the level of disturbance and the type of organism involved. In order to detect changes caused by disturbance, Warwick (1986) proposed the abundance biomass comparison (ABC) method for monitoring disturbance to benthic invertebrate communities. Although Warwick (1986) applied the ABC to benthic invertebrates, the theory behind the relationships should apply to any group of organisms. This technique involves comparing dominance in terms of abundance and biomass. It has been successfully applied to marine benthic communities in various parts of the world, and has yielded the expected response to disturbance (Warwick *et al*., 1987; Agard *et al*., 1993; Kaiser, 2000; Schejter *et al*., 2008). Recently, the ABC curves have been applied in assessing demersal fish communities (Bianchi *et al*., 2001; Blanchard *et al*., 2004; Jouffre and Inejih, 2005; Labropoulou and Papaconstantinou, 2005; Yemane *et al.*, 2005). Bianchi *et al*. (2001) applied the ABC technique to investigate whether the Namibian demersal fish assemblages had responded to lighter fishing pressure 10 years after independence, relative to heavy pre-independence fishing by largely foreign fleets. Theoretically, ABC curves follow the evolutionary theory of r– and k– selection (Pianka, 1970). The hypothesis is that undisturbed states have a community dominated by k– selected species characterized by slow growth, large body size, and late maturation. In this state, the biomass curve lies above the abundance curve (Clarke and Warwick, 1994; Clarke and Gorley, 2006). In contrast, increased disturbance leads to communities dominated by the r- selected species, which grow fast, and by organisms that are small in size and opportunistic. In this state, the biomass curve lies below the abundance curve (Clarke and Warwick, 1994; Clarke and Gorley, 2006).

The ABC method was applied by Yemane *et al* (2004) to assess changes in the size composition and dominance structure in the Cape Region, South Africa and found (a) a decrease in the mean size of the majority of linefish species, (b) an overall change in size composition in some regions as evidenced from the changes in the slope of the size spectrum over time and (c) changes in the dominance structure. Historically, in South African waters, substantial overexploitation was reported for sardine in the 1960s, and hake in the 1960s and 1970s (Payne, 1989) and in some dominant species targeted mainly by the linefishery (Attwood and Farquhar, 1999, Griffiths, 2000).

There seem to be relatively big gaps in our existing knowledge about the ecosystem effects of bottom-trawling in both Namibian and South African waters. Thus, this study is aimed at illuminating these grey areas and attempts to clarify to a greater extent the direct and indirect effects of bottom-trawling within the Benguela upwelling system.

Demersal trawl fisheries off Namibia: an introductory overview

Namibia's long coastline of 1500 km and its proclaimed 200 nm economic exclusive zone (EEZ), characterized by centres of strong upwelling, which bring to the surface nutrient-laden cold water, supports an immensely productive system with a prolific fish population. The Namibian demersal fishery began during the Second World War (Boyer and Hampton, 2001), and the northern Benguela ecosystem was heavily exploited during the 1960s and 1970s, mainly by distant fleets (Spain, Russia, Japan to mention a few). The demersal fishery mainly targeted the shallow-water hake *Merluccius capensis* (Fig. 1.1a) and deep-water hake *M. paradoxus* (Fig. 1.1b) (Boyer and Hampton, 2001). Record landings of more than 1.1 million tons were reported in 1972 (Payne, 1989; Van der Westhuizen, 2001). Prior to Namibian Independence in 1990, there were significant changes in the total annual catches of fish off Namibia, which decreased from a peak of two million tons in 1968 to below 600 000 tons by the 1990s. The latter decline occurred together with major declines in small pelagics, particularly *Sardinops sagax* and, after Independence, in both species of hakes (*M. capensis* and *M. paradoxus*) and horse mackerel *Trachurus capensis*, due to the exclusion of non-Namibian trawlers (Boyer and Hampton, 2001). The Namibian demersal fishery currently targets hakes, monkfish, orange roughy and the deep-sea red crab, and is the most valuable fishery in Namibia.

Hake Fishery

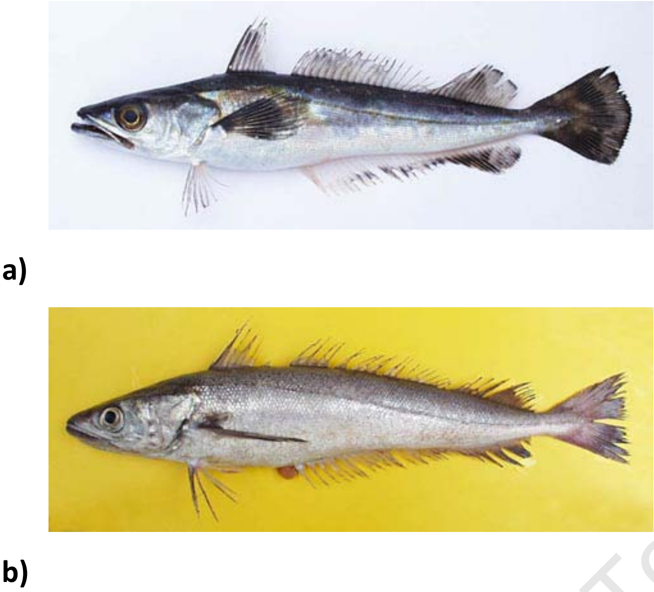


Figure 1.1: Photographs of the Cape hakes, (a) shallow-water hake *Merluccius capensis* and (b) deep-water hake *M. paradoxus*, targeted by the hake fishery off Namibia (Pictures: O. Alvheim, 2007).

Hake was one of the most depleted resources at the time of Independence, thus the Government of Namibia put in place stringent measures to control harvesting of the resource. The control measures included implementation of a 200 nm EEZ, thereby restricting access to Namibian hake by foreign fleets, and lowering of the Total Allowable Catch (TAC), in order to rebuild the stock. This resource, which is widely distributed from the north, off the Kunene River, to southern Namibia, off the Orange River, is now exploited exclusively by Namibian flagged bottom-trawlers (both wet and freezer vessels). Most of the hake resource (80%) is for the export market to EU countries, the USA and Australia. Since Independence in 1990, management of the Namibian Hake Fishery has been through the Quota System and allocation of Fishing Rights, the setting of TAC levels, the specification of mesh size (110 mm minimum) and fish size limits (>36 cm). As part of Monitoring, Control and Surveillance (MCS), independent fisheries observers have been deployed onboard fishing vessels fishing in Namibian waters. The hake TAC is based on biomass estimates (Fig. 1.2) from the bottom trawl surveys conducted by the *R/V Dr Fridtjof Nansen* (1990–1999) and the commercial trawlers (1998–2008) (Iilende *et al*., 2001; van der Westhuizen, 2001; MFMR, 2008). There has been much variability in the fishable biomass estimated from surveys from year to year (Fig. 1.2). There is also a trawling restriction in waters shallower than 200 m and, since 2006, annual closure of the fishery for the month of October during the spawning season (MFMR, 2007). Both wet and freezer vessels use otter trawl nets to harvest the resource, although the hake resource is also exploited by long-liners.

Shallow-water hake (*M. capensis*) are found throughout Namibian and South African waters, fairly evenly distributed along the entire Namibian coast, while the deep-water hake have a more southward distribution, with their highest densities in southern Namibia, extending into South Africa (Burmeister, 2000). Shallow-water hake occur in waters from tens of metres to about 380 m deep and rarely beyond, while the deep-water hake (*M. paradoxus*) occur in much deeper waters from 150 m to 800 m depth (Payne, 1989; Burmeister, 2000; Kainge *et al*., 2007a). Few larger individuals of *M. capensis* and more *M. paradoxus* occur on the continental slope and beyond (Boyer and Hampton, 2001). Both hake species are known to inhabit areas with relatively moderate dissolved oxygen levels off Namibia, but they are well adapted to hypoxic (<0.25 ml/l) conditions (Woodhead *et al*., 1996; MFMR, 2007), which occur off northern and central Namibia (Monteiro *et al*., 2004; Monteiro and van der Plas, 2005; Bartholomae and van der Plas, 2007). However, *M. capensis* are distributed in warmer waters (4 – 12^{o}C) than *M. paradoxus* (4 – 8^{o}C), in accordance with their depth distribution (Boyer and Hampton, 2001).

Cape hakes are perennial spawners (Botha, 1980; Olivar *et al.*, 1988). Shallow-water hakes spawn in Namibian waters throughout the year but mainly in between July and October, whereas deep-water hake do not spawn in Namibian waters, but in South African waters off the west coast of South Africa to Agulhas Bank (Kainge *et al*., 2007b). Thus, deep-water hake is believed to undertake spawning migrations from Namibian waters to South Africa and to return to Namibian waters where it recruits to the fishery (MFMR, 2001; Strømme *et al*. 2004, 2005, and 2006).

The feeding ecology of the hakes off Namibia is well documented. They are opportunistic feeders (Roel and Macpherson, 1988; Traut, 1996) undertaking vertical migrations to feed in the mesopelagic zone especially at night, although they are known to feed close to the bottom (Iilende *et al*., 2001; Pillar and Barange, 1998; Huse *et al*., 1998). The diet composition for adult *M. capensis* includes lightfish, myctophids, squid, some epipelagic fish and other demersal fish. Larger fish may practise cannibalism by preying on their young, and to a lesser extent they prey on small *M. paradoxus* (Punt *et al*. 1992; Macpherson and Gordoa, 1994). Cape hakes are also known to feed on horse mackerel (Roux and Shannon, 2004). Cannibalism is very common with larger *M. paradoxus* feeding on the small *M. paradoxus* (Boyer and Hampton, 2001). Young Cape hakes feed on euphausiids, pelagic goby and lanternfish (Punt *et al*., 1992, Roux and Shannon, 2004). Because hake feed on a variety of organisms, their high abundances in the Benguela make them very important predators.

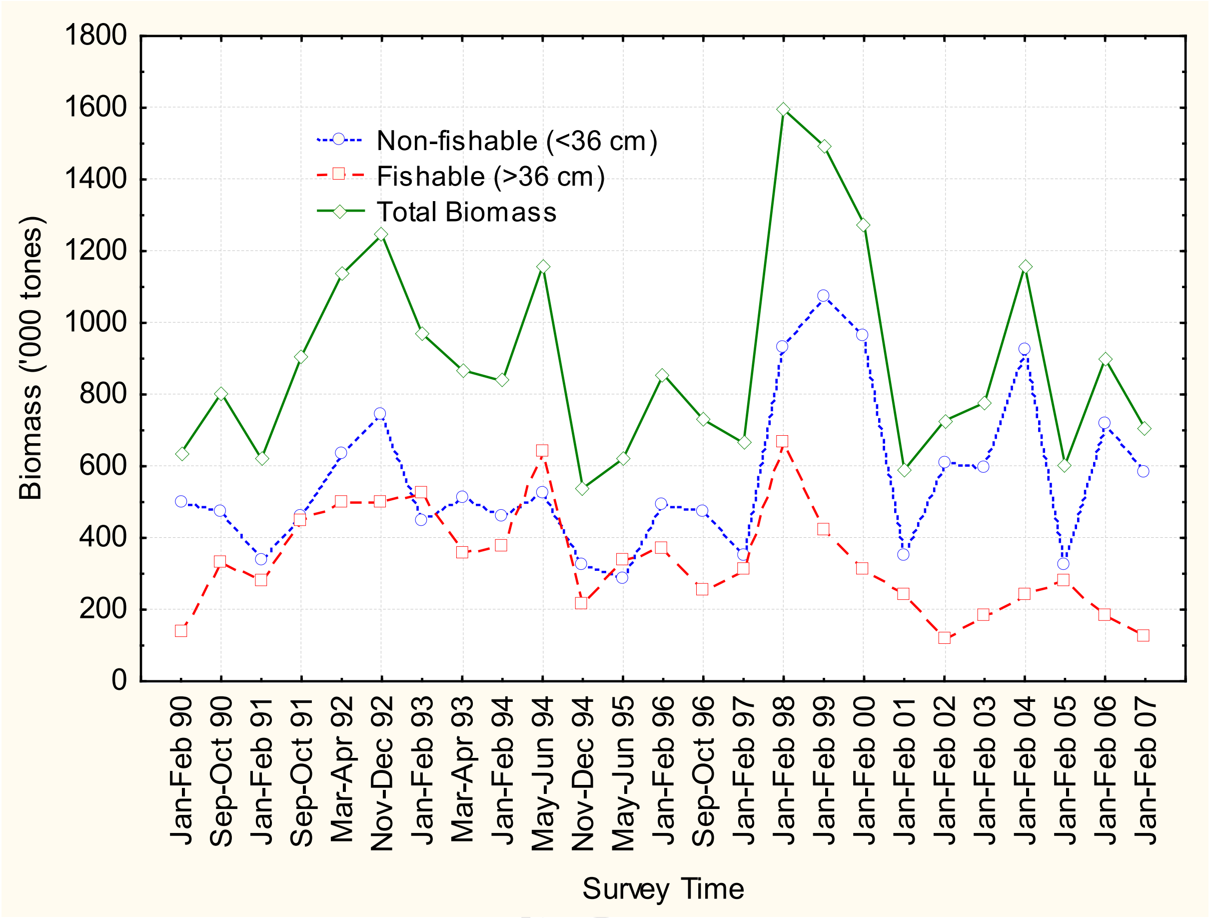


Figure 1.2: Indices of total biomass, biomass below minimum landing size and fishable biomass of hake (shallow and deep water hake combined) from annual bottom trawl surveys off Namibia since 1990 (Source: Kainge *et al*., 2007a).

Monkfish Fishery

Figure 1.3: A photograph of the monkfish *Lophius vomerinus*, targeted by the monkfish fishery off Namibia. (Picture: O. Alvheim, 2007).

Monkfish (*Lophius vomerinus* (Fig. 1.3) and *L. vaillanti*), catches date back to 1974, before Namibian Independence, where the species was caught as bycatch in the hake fishery (Maartens, 1999). Soon after Independence, the demand for the resource and the associated value, rose substantially, and thus a new fishery was established, targeting monkfish and sole (*Austroglossus microlepis*). The Namibian monkfish fishery targets *L. vomerinus*, which comprises the greater proportion of the catch, although another species *L. vaillanti* also occurs in southern African waters (Maartens and Booth, 2001). Both species of monkfish are found mainly at depths of 150–500 m, with the highest densities occurring at 300–400 m off the coast of Namibia, mainly in central areas (Maartens, 1999). The distribution of *L. vomerinus* ranges from northern Namibia to Durban (South Africa), while that of *L. vaillanti* ranges from Walvis Bay to the Gulf of Guinea (Maartens and Booth, 2001). To date, monkfish is still caught as bycatch in the hake-directed fishery (Fig. 1.4), (Maartens and Booth, 2001). However, a monfish and sole fishery was initiated by the Namibian

Government in 1994. Initially controlled by effort, through horsepower restriction (< 800 hp) and by limiting entrants into the fishery (BCLME, 2003). The management procedure was changed in 2001 from effort-controlled to quota managed fishery. The TAC is shred between the monk-directed and hake-directed fisheries (BCLME, 2003). This resource is also exported to Europe, where it fetches high prices, thus contributing to the Namibian economy (MFMR, 2007).

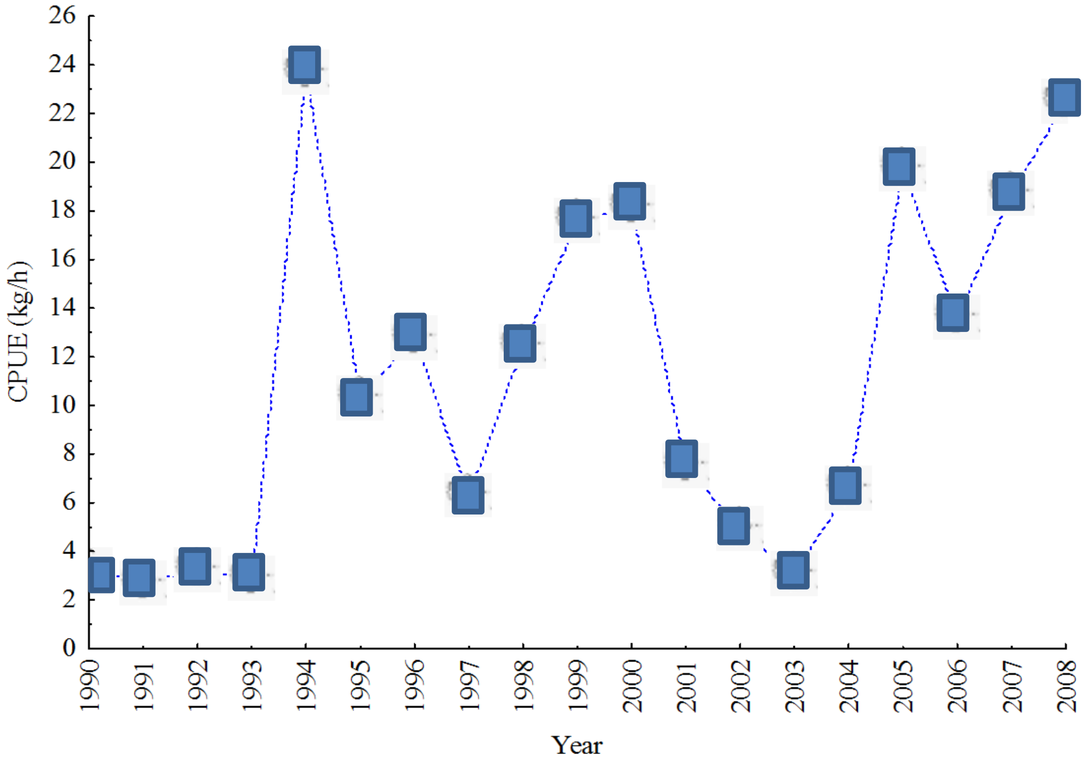


Figure 1.4 Catch per unit effort for monkfish (*Lophius vomerinus*) caught in bottom-trawls during the annual hake biomass surveys (1990 – 2008).

Monkfish spawn throughout the year (Macpherson, 1985), and they have two recruitment areas, off Walvis Bay and near the Orange River, in waters 100–300 m in depth (Leslie and Grant, 1990). Monkfish normally prey on hake and other demersal fish (Macpherson, 1985).

In addition to the overall management measures for demersal trawling as introduced above, the catching of monk as bycatch is being discouraged by charging a levy on the bycatch (MFMR, 2008), thereby leaving only rights holders and quota-allocated companies to exploit the resource. The CPUE has shown an increasing trend during 2003 – 2008, although within the range of variability observed since 1990 (Fig. 1.4).

Orange Roughy Fishery

Exploitation of orange roughy *Hoplostethus atlanticus* (Fig. 1.5) commenced in 1994, following Independence in 1990. Orange roughy is an extremely deep-living species that occurs at depths of 500 to 1500 m, and is distributed worldwide (Branch, 2001). However, in Namibia the species is found in shallower waters from 600–800 m (Boyer and Hampton, 2001). Orange roughy prefer temperatures of 3–9 °C, which are found in shallower waters off Namibia in comparison to other places in the world, and large catches were recorded at temperatures of 4.5–6.5 °C (Clark, 1997), thus making temperature important in locating the resource. The species is commercially exploited in Namibia, New Zealand and Australia (Merret and Haiderich, 1997; Horn *et al*., 1998). Seafloor topographic features such as canyons, plateaus and seamounts form havens for aggregations of orange roughy, especially when feeding and spawning (Clark *et al*., 2000; Annala *et al*. 2001; Boyer and Hampton, 2001), although the species can still be found on flat grounds. Spawning grounds were discovered off Namibia (Hotspot, Rix, Frankies and Johnies, Fig. 1.6).

Figure 1.5: A photograph of orange roughy (*Hoplostethus atlanticus*). (Source: www.marlab.ac.uk).

Orange roughy are slow growers, long-lived and late maturing, thus making them vulnerable to exploitation due to slow recovery potential (Fenton *et al*., 1991; Smith *et al*., 1995; Horn *et al*., 1998; Branch, 2001). They can attain a maximum of 75 cm total length (*TL)*, maximum weight 7 kg and the maximum reported age of 149 years (Maul, 1986). They spawn in synchrony over 2 to 3 weeks, as they form spawning aggregations (Branch, 2001). Orange roughy are opportunist-predators and feed on a variety of organisms including fish, squid, amphipods, mysids and decapod crustaceans (Bulman and Koslow, 1992; Lesch, 1995).

This resource is caught by bottom trawlers, using special gear that is much heavier than the otter trawls used by the hake fishery. Orange roughy is commercially exploited, and is highly sought after (MFMR, 2005), making it highly vulnerable to overfishing, since they grow slowly and mature late as mentioned above (Fenton *et al*., 1991; Smith *et al*., 1995; Horn *et al*., 1998; Branch, 2001). The management of the orange roughy fishery in Namibia has been difficult due to uncertainties with regard to the stock size. Experimental exploitation led to the now known orange roughy grounds, which have been sub-divided into QMAs (Fig. 1.6), where trawling is controlled, based on the annual CPUE (Boyer *et al*., 2001; Oelofsen and Staby, 2003; MFMR, 2007). The TAC allocation is based only on stock assessment data from within the QMAs, even though fishing is unlimited for areas outside the QMAs (Boyer *et al.*, 2001). Other methods of assessment were in place prior to 1997, when abundance estimation surveys were conducted using acoustic and swept-area methods (Boyer and Hampton, 2001). The TAC of 12 000 t was first allocated in 1997, and this was reduced to 900 t in 2007 (MFMR, 2007), indicating how quickly this resource could be overfished.

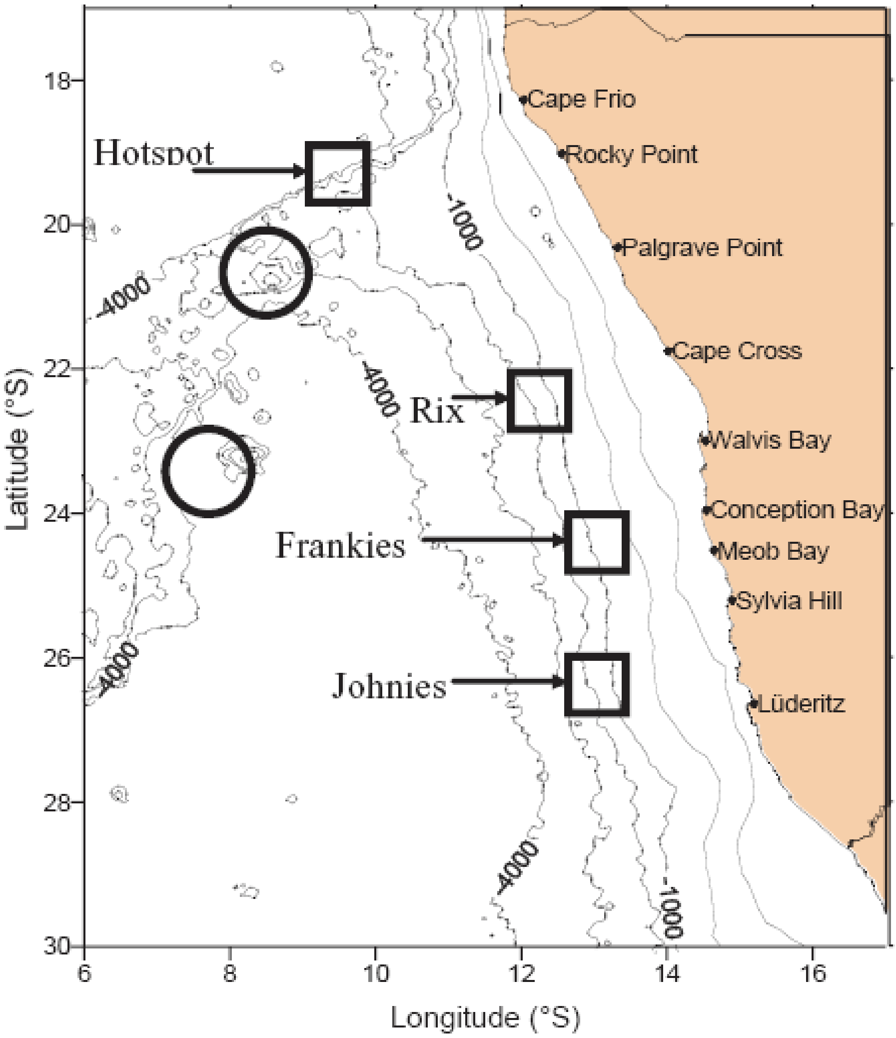


Figure 1.6: The Namibian shelf indicating orange roughy quota management areas (QMAs in squares) and areas where orange roughy has been caught outside the Namibian EEZ (circles) (Source: Oelofsen and Staby, 2003). Note that QMAs coincide with spawning areas.

Deep-sea Red Crab

The commercial exploitation of the deep-sea red crab off Namibia dates back to 1973, but following the closure of the then South West African fleet (in late 1979), only the Japanese vessels were left operating the fishery (Melville-Smith, 1988). The most common of the deep-sea red crab and commercially exploited species in Namibian waters is *Chaceon maritae* (Manning and Holthuis, 1981) (Fig. 1.7) (formerly *Geryon maritae)*, which has a wide distributional range along the west coast of Africa. There are 15 species of the genus *Chaceon* (Manning and Holthuis, 1989), of which three are widespread throughout the Atlantic Ocean and support commercial fisheries. These three are *C. quinquenderns* and *C. fenneri*, which occur on the east coast of North and South America, and *C. erythaie*, which is localized in its range, and is only found on the Walvis Ridge (Macpherson, 1984 as cited by Melville-Smith, 1988), and has been harvested since 1986.

Deep-sea red crab *C. maritae* occurs on the slope of the continental shelf from the Orange River off Namibia into Angola. This species is also caught as bycatch in the annual hake biomass survey (Fig. 1.10). The species is found at depths of 300‒900 m in Namibian waters. The Japanese vessels operating in Namibian waters still enjoy sole exploitation rights, using mostly bee-hive traps and to a lesser extent bottom-trawl (Boyer and Hampton, 2001). Records from hake biomass surveys show this species being mostly encountered at 400‒700 m water depth. Its CPUE was higher in 2005, 2006 and 2008 compared to the other years considered, while its 2007 level was also slightly above the 1990 level (Fig. 1.8). This resource forms the biggest crustacean fishery for Namibia, and the entire catch is exported to Japan. Deep-sea crab catches were close to 10 000 t in the 1980s, and decreased over the years to less than 6 000 t in the 1990s and 2000s.

Figure 1.7: The deep-sea red crab *Chaceon maritae*, found on the west coast of Africa.

Deep-sea red crab spawns throughout the year off Namibia (Le Roux, 1997) and they undertake a spawning migration into Angolan waters (Boyer and Hampton, 2001). A study conducted by Macpherson (1985) has revealed the diet of *C. maritae* to comprise carrion, mainly skates, while yet another study by the same author (1983 as cited by Boyer and Hampton, 2001) has documented the deep-sea fish *Cottuncoloides macrocephalus* and *Alepocephalus rostralus* to be part of their prey.

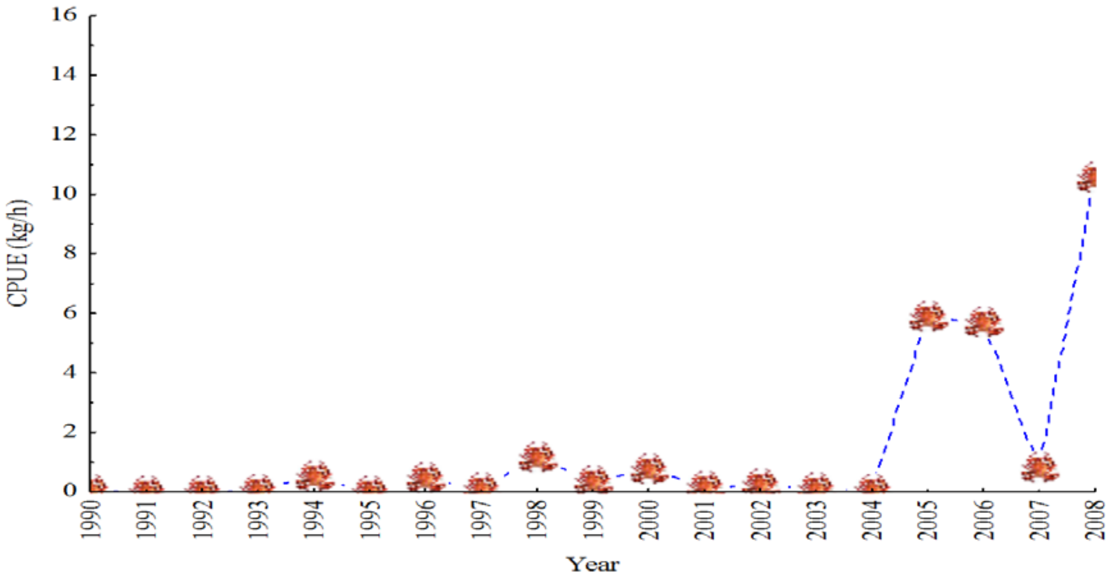


Figure 1.8. Annual catch per unit effort (CPUE) trend of *Chaceon maritae* from hake biomass survey data (1990 – 2008).

To protect the female crabs as they occupy in most cases areas shallower than 500 m, the Government of Namibia adopted a depth restriction range of 500 m in 1993, but it was later changed in the same year to 400 m. The minimum size limit of 85 mm carapace width is also used to control the catch, as opposed to pre-Independence when everything caught was processed (Melville-Smith, 1988). The stock is managed by the annual TAC, and the assessment is done using several methods, including the length-based cohort analysis and prediction models, which are based on growth rate data from tagging studies, and is in line with the growth dynamics of the species (Le Roux, 1997).

Other commercially exploited species caught incidentally in the hake bottom-trawls off Namibia

There are other species that are caught by bottom trawlers, including Alfonsino *Beryx splendens*, Kingklip *Genypterus capensis*, Snoek *Thyrsites atun,* West Coast sole *Austroglossus microlepis*, and others which are commercially important. However, most of these are caught as bycatch in the hake, monkfish and orange roughy fisheries. There has been a growing demand in the management of the world fisheries for the inclusion of by-catch information, as different countries pave the way forward towards an ecosystem approach to fisheries.

In Namibia, some of the bycatch with no economic value are discarded, and sometimes not properly recorded in the commercial trawls. This presents the management of this part of the catch with challenging aspects. However, bycatch information has been captured during the scientific surveys in Namibia since 1990. As part of the management measures to reduce bycatch, Namibia has adopted fisheries regulations whereby bycatch levies are imposed to discourage catching of the non-target species (MFMR, 2008). The following section presents catch trajectories of the different types of bycatch during the annual hake surveys.

Alphonsino

Alphonsino *Beryx splendens* inhabits waters of the outer shelf (180 m) and the slope to at least 1 300 m in depth, and it undertakes a diel vertical migration, moving off the bottom at night. Alphonsino is often found over underwater ridges (Dubocochkin and Katlyar, 1989) and seamounts (Paxton, 1999). Crustaceans and cephalopods make up its main diet (Dubocochkin and Katlyar, 1989). Its presence in the hake bottom-trawls during surveys is very rare, though it has been encountered from 22° southwards in Namibian waters at the depth range 300–600 m (Iitembu, 2008, unpublished data). Its recorded survey CPUE has been stable since 1990, but exceptionally high in 1997, 2000 and 2001 (Fig. 1.9).

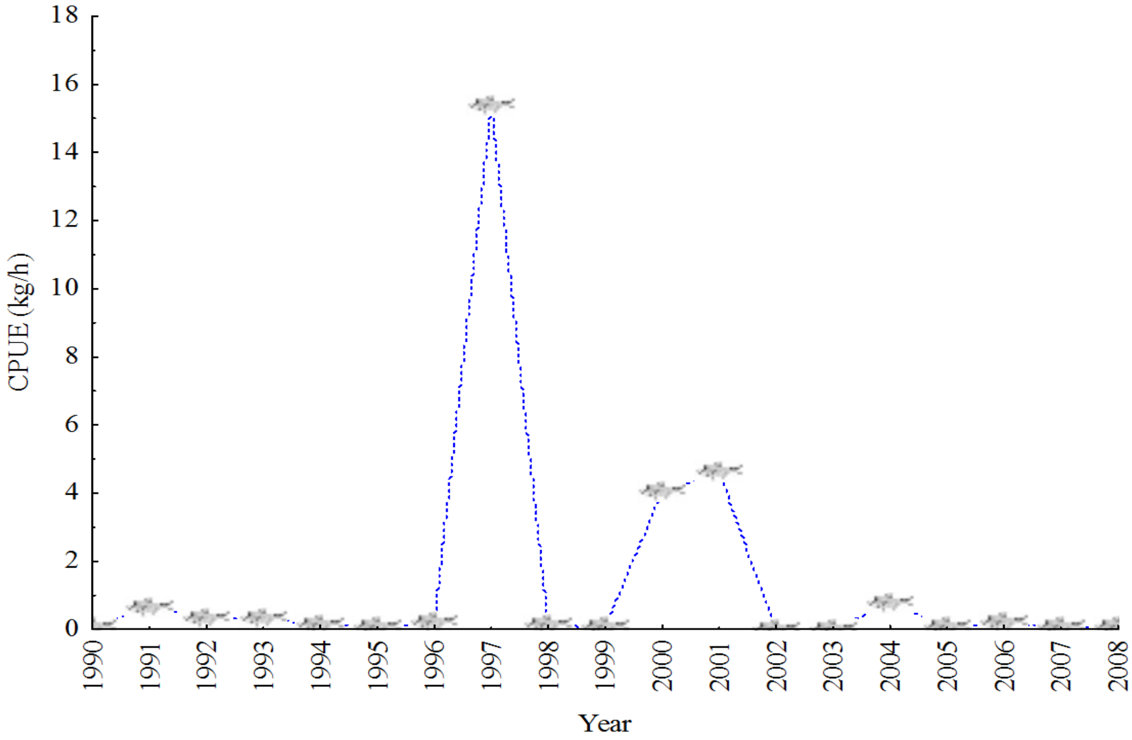


Figure 1.9. Annual catch per unit effort (CPUE) of *Beryx splendens* from hake biomass survey data (1990 – 2008).

Angelfish

Angelfish *Brama brama*, is a seasonal migrant, which comes close to shore (May and Maxwell, 1986) and forms small schools. Their movement is known to be temperature related. It is an opportunistic feeder, and its diet consists of small fish, cephalopods, amphipods and euphausiids. This species is found from 20° southward in Namibian waters at 100−500 m water depth (Iitembu, 2008, unpublished data). Its CPUE depicts no clearly defined increasing/decreasing trend for most of the years, but the highest CPUE was recorded in 2004 and lowest in 2001, while the 2007 CPUE level was slightly below the 1990 level (Fig. 1.10).

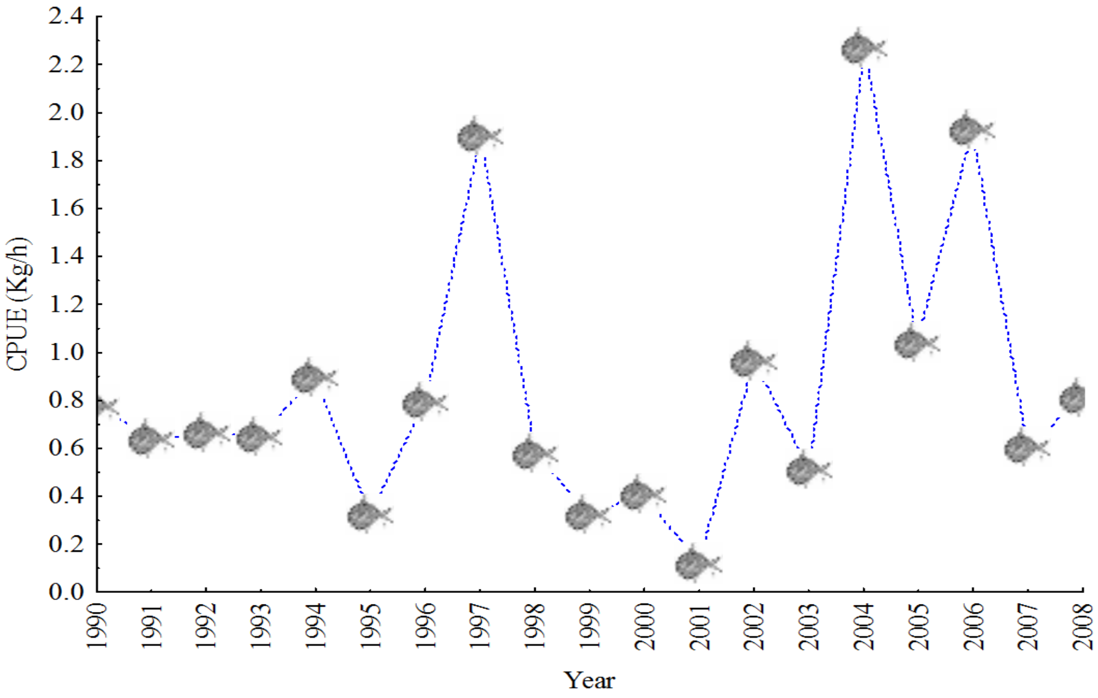


Figure 1.10. Annual catch per unit effort (CPUE) of angelfish *Brama brama* from hake biomass survey data (1990 – 2008).

Cape Gurnard

The Cape gurnard, *Chelidonichthys capensis*, is found throughout the length of the Namibian coast in waters 100–300 m in depth. It normally feeds on fish (Heemstra, 1986) and benthic crustaceans, and it is considered an excellent food fish in the northern hemisphere (Heemstra, 1986). There has been an increase in average CPUE since 1990 and the 2008 level is well above the 1990 level (Fig. 1.11).

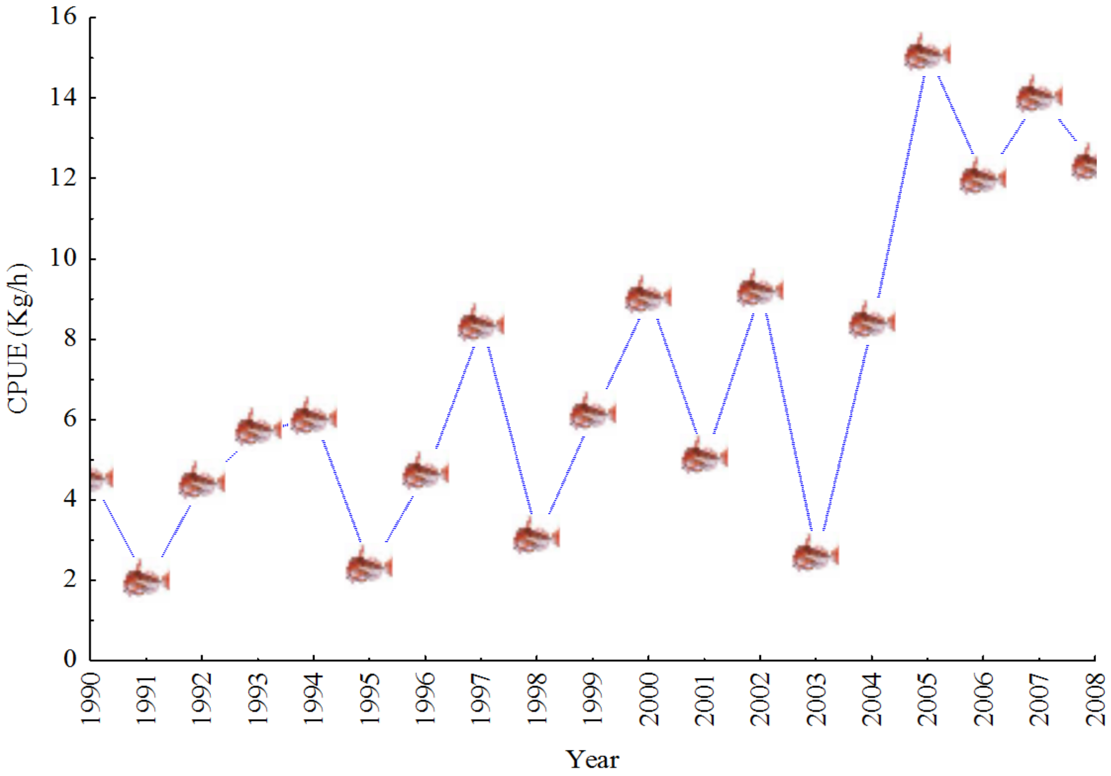


Figure 1.11. Annual catch per unit effort (CPUE) of Cape gurnard *Chelidonichthys capensis* from hake biomass survey data (1990 – 2008).

Dentex

Large-eyed dentex, *Dentex macrophthalmus*, has been encountered during the hake biomass surveys from 22° north in Namibian waters, at 100–400 m water depth (Iitembu, 2008, unpublished data). CPUE increased from 1990 to 1998 and then sharply decreased from 2002 onwards (Fig. 1.12). It has been at low levels since 2002.

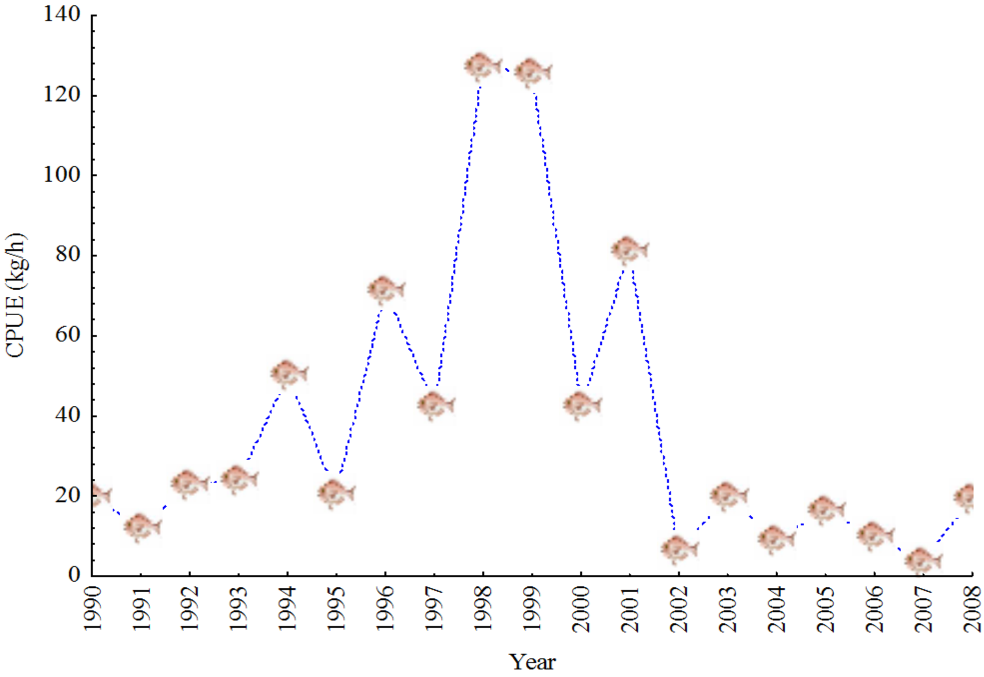


Figure 1.12. Annual catch per unit effort (CPUE) of *Dentex macrophthalmus* from hake biomass survey data (1990 – 2008).

Flying Squid

Flying squid, *Todarodes sagittatus*, is found throughout Namibian waters at a depth range between 100−700 m (Iitembu, 2008, unpublished data). The larvae are known to feed on plankton, adults feed on planktonic crustaceans, fish and other squids, since they are fast swimmers and active predators (Quetglas *et al*., 1999). Their CPUE shows an increasing trend since 1990 (Fig. 1.13).

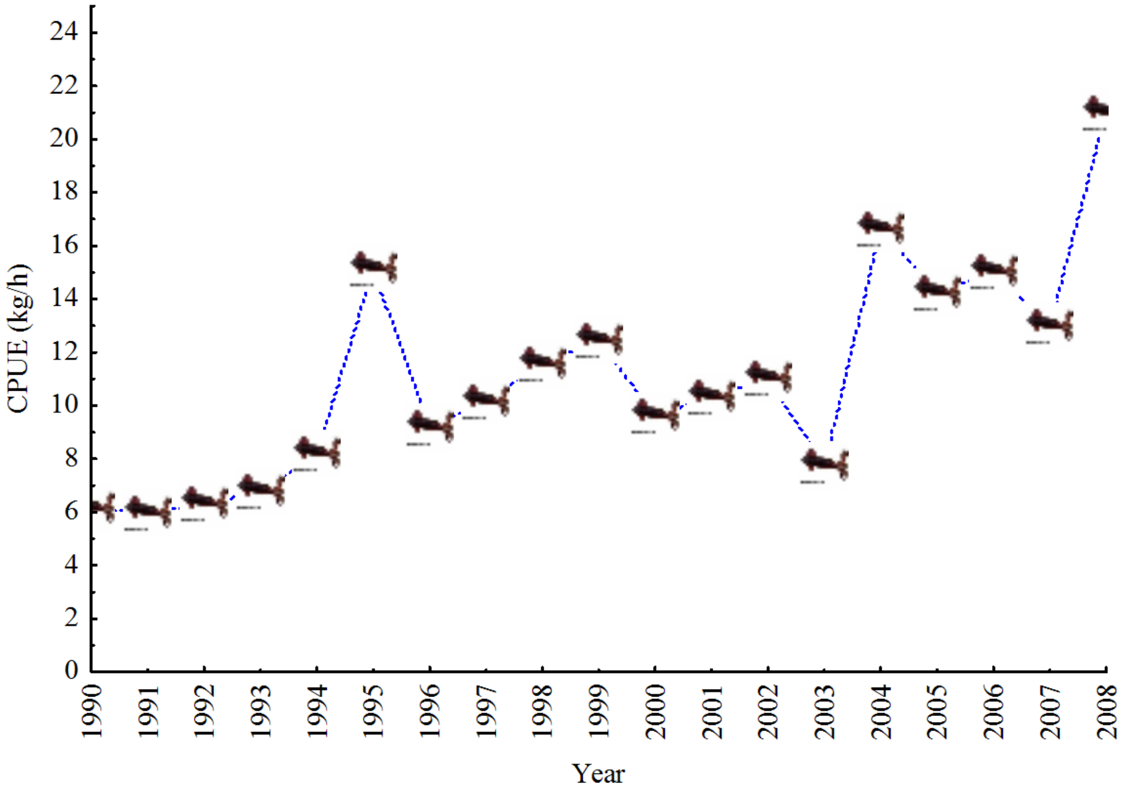


Figure 1.13 Annual catch per unit effort (CPUE) of *Todarodes sagittatus* from hake biomass survey data (1990 – 2008).

Horse Mackerel

Horse mackerel, *Trachurus capensis*, is of the abundant pelagic species found off the coast of Namibia. It is found in high abundance mostly as juveniles in the Benguela. It is important not only as bycatch but support an important midwater fishery, firstly by volume, and secondly by value. The fishery produces mainly, whole round fish, dried fish and fish-meal (Krakstad, 2001). These are exported to the Democratic Republic of Congo, Zambia, South Africa and other SADC countries (INFOSA, 2010). It is found mainly over the continental shelf, often over sandy bottoms (Bianchi *et al.*, 1993). It normally rises to feed in surface waters at night and is found close to the bottom during the day. Juveniles feed mainly on copepods while adults prey on fish and a wide range of invertebrates mainly euphausid (krill); lantern fish, and pelagic gobies to a less extent (Roux and Shannon, 2004; Bianchi *et al*., 1993 and 1999).

Horse mackerel are widely distributed along the entire Namibian coast at 100−350 m water depth (Iitembu, 2008, unpublished data). The demersal trawl survey bycatch CPUE has fluctuated from 1990 to 2008, with a highest level in 2001 and a lowest in 2002 (Fig. 1.14).

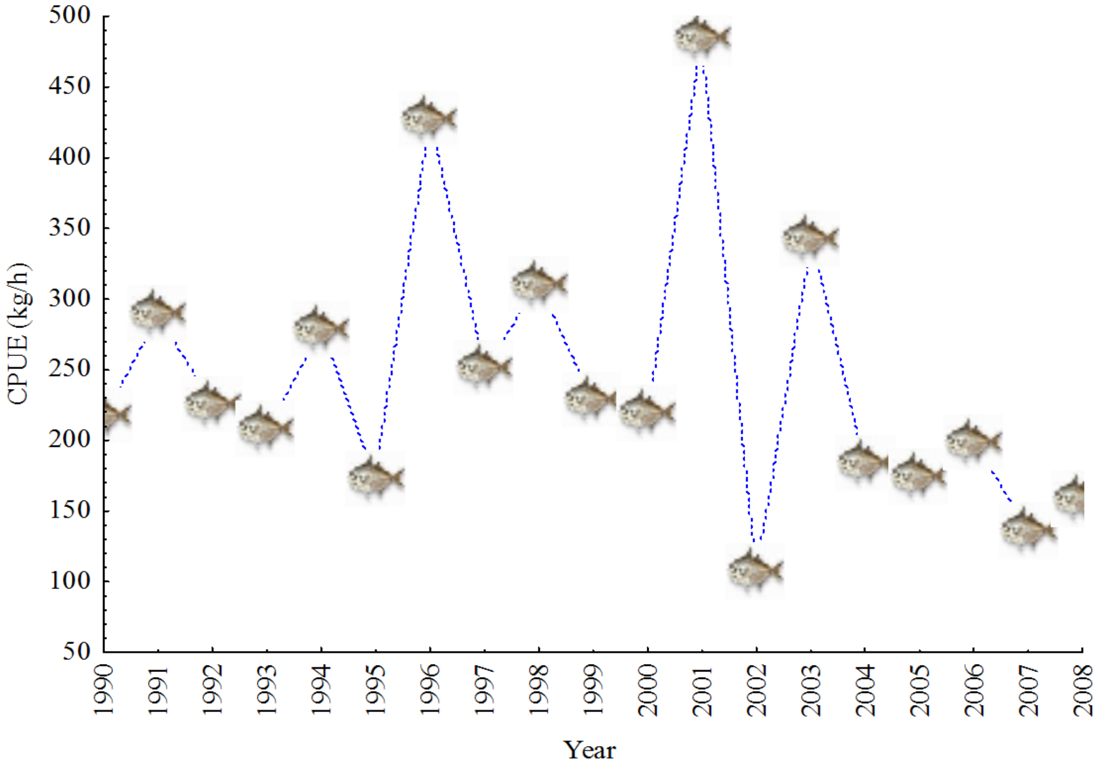


Figure 1.14. Annual catch per unit effort (CPUE) trend of *Trachurus capensis* from hake biomass survey data (1990 – 2008).

Jacopever

Jacopever, *Helicolenus dactylopterus*, is found in soft bottom areas of the continental shelf and upper slope. It feeds on both benthic and pelagic organisms (crustaceans, fish, cephalopods and echinoderms) (Hureau and Litvinenko, 1986).

From biomass surveys, this species has been found along the entire Namibian coast with the highest CPUE concentration at around 18° south, inhabiting water depths from 100−700 m (Iitembu, 2008, unpublished data). CPUE increased after 1990, but has been variable on a higher level since 2001 (Fig. 1.15).

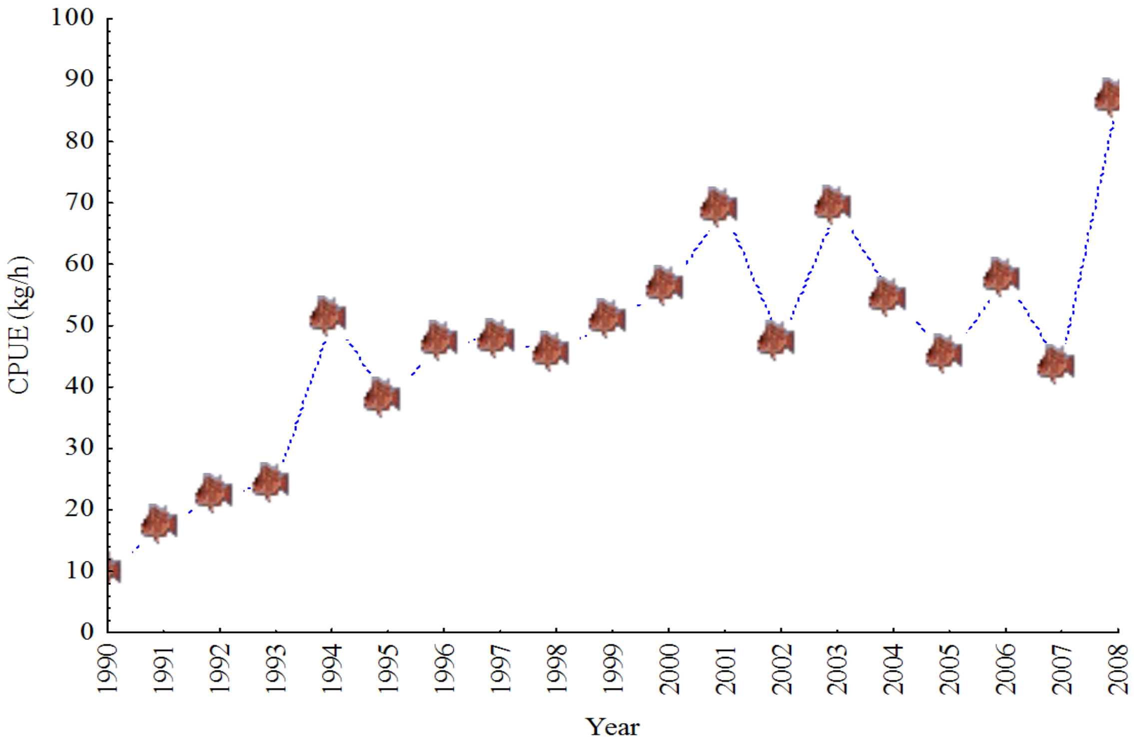


Figure 1.15. Annual catch per unit effort (CPUE) trend of *Helicolenus dactylopterus* from hake biomass survey data (1990 – 2008).

Kingklip

Kingklip, *Genypterus capensis*, is caught as by-catch from the Namibian hake fishery. It commands a high price and is retained along with the hake.

This species has been caught during hake biomass surveys mostly from around 24° southward at 100–600 m water depth (Iitembu 2006, Unpublished data). CPUE has shown an increasing trend since 1990 (Fig. 1.16).

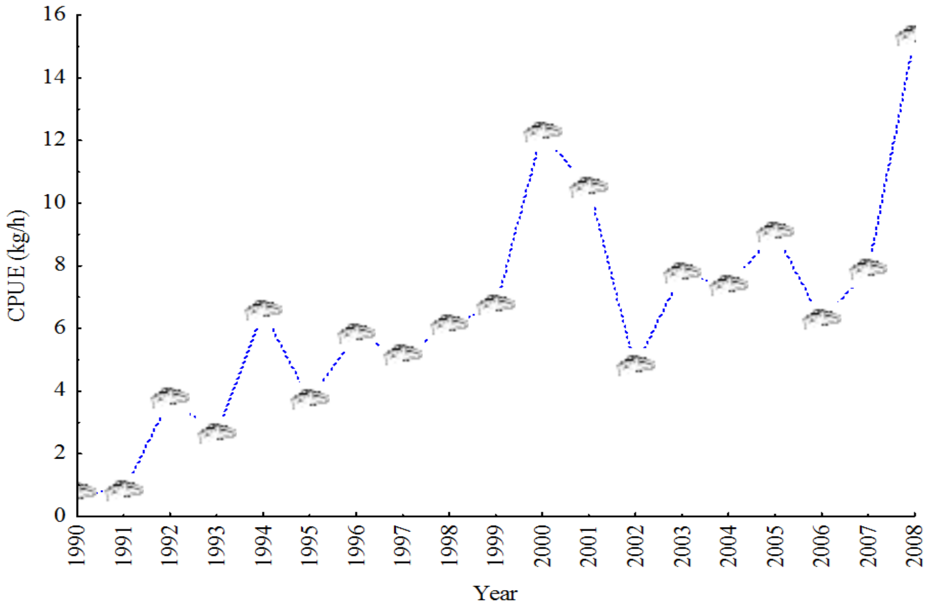


Figure 1.16. Annual catch per unit effort (CPUE) trend of *Genypterus capensis* from hake biomass surveys (1990 – 2008).

Snoek

Snoek *Thyrsites atun*, generally forms schools which are found near the bottom or mid-water, and sometimes even at the surface at night (Nakamura and Parin, 1993). It feeds on pelagic crustaceans (*Euphausia, Nyctiphanes*), cephalopods and fish (Nakamura and Parin, 1993) such as anchovy and sardine (Bianchi *et al.*, 1999). *Thyrsites atun* has been recorded from 22° southward, at 100−350 m water depth (Iitembu, 2008, unpublished data). Its erratic availability at any particular area at the coast is well documented from the southern Benguela, and very high trawl catches were made in the northern Benguela in the 1980s (Figure 18 in Hutchings *et al.* 2009). The CPUE in the research survey has been decreasing since 1990, but high CPUEs were recorded in 1994, 1996 and 2000, while its 2008 CPUE level was lower than its 1990 level (Fig. 1.17).

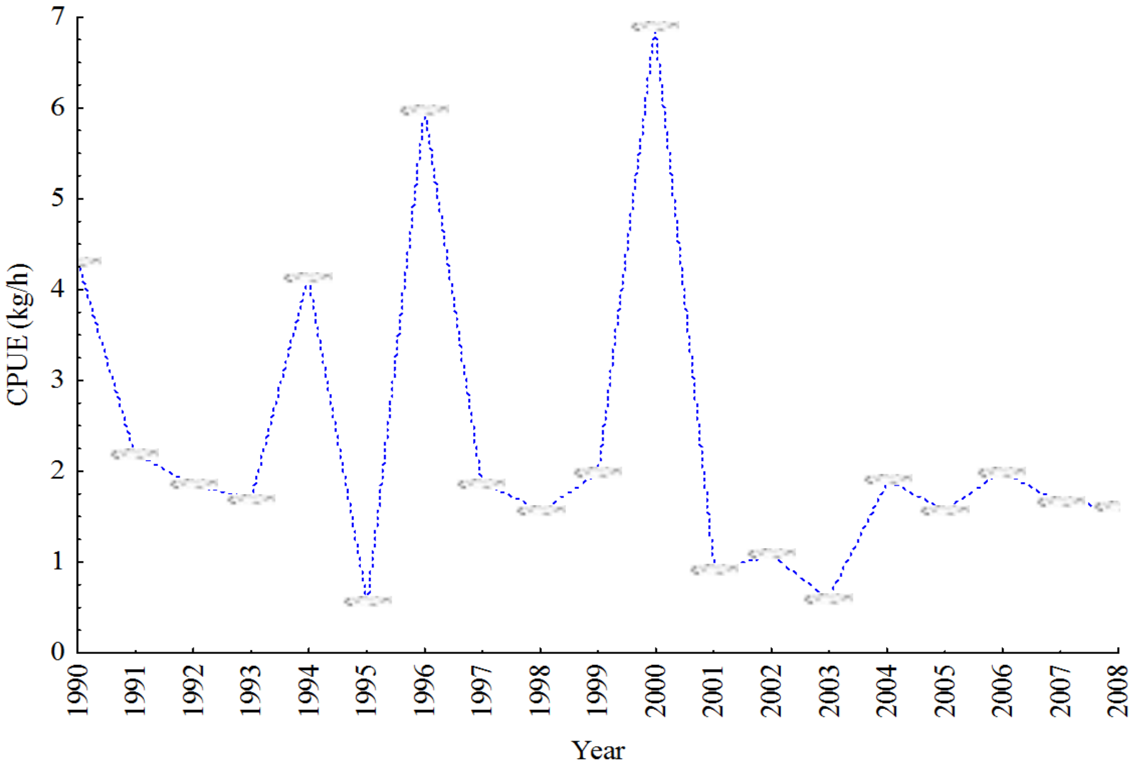


Figure 1.17 Annual catch per unit effort (CPUE) of snoek *Thyrsites atun* from hake biomass survey data (1990 – 2008).

West Coast Sole

West Coast sole *Austroglossus microlepis* is found in waters 100–400 m deep along the entire Namibian coast, and extends up to False Bay in South Africa. Both young and adult sole feed on benthic crustaceans and copepods, as well as unidentified polychaete worms, molluscs, and fish (Bianchi *et al.*, 1993 and 1999). There has been an increasing trend in annual survey CPUE since 1991. Highest CPUE was recorded in 2005 (Fig. 1.18). West coast sole is managed together with monkfish, as mentioned above.

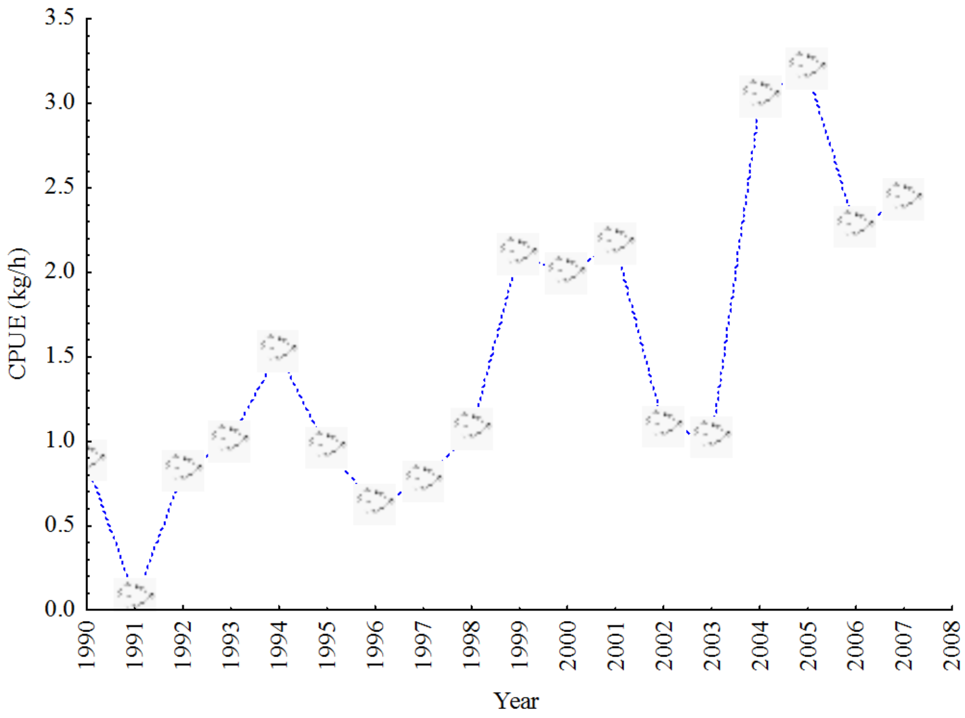


Figure 1.18. Annual catch per unit effort (CPUE) trend of west coast sole *Austroglossus microlepis* from hake biomass survey data (1990-2007, data for 2008 was not available).

THESIS STRUCTURE, GOALS AND AIMS

Thesis overview

The dissertation structure is organized into three major components: (a) analysis of the commercial effort data for the hake-directed bottom-trawl fishery of Namibia; (b) analysis of the time-series data of the Namibian hake biomass survey from 1990 to 2006; and (c) analysis of the *in situ* experimental work conducted off Namibia and South Africa, and the spatial analysis of the 2007 Benguela demersal trawl surveys conducted in northern and southern Benguela. The first chapters of the thesis are devoted to the introduction and the third to materials and methods. The first component (a) consists of Chapter 2; component (b) consists of Chapters 4 and 5; and component (c) consists of Chapters 6 and 7. The last chapter (8) is the synthesis and conclusion. Various chapters contribute to the thesis through investigations of various structural changes in fish assemblages that may be attributed to fishing and the environment. The last chapter summarizes the outcomes of the entire thesis, and how they respond to different research questions outlined through the aims of various chapters.

Chapter 1 Introduction

This chapter reviews literature on the ecosystem effects of fishing, particularly that of bottom-trawling off Namibia and elsewhere. Different assessment tools or indicators for assessing the ecosystem effects of bottom-trawling are introduced. The chapter also gives a detailed summary of the hake-directed bottom-trawl fishery and its bycatch. Lastly, it outlines the aims of the thesis, which are converted into research questions in various chapters.

Chapter 2 Bottom trawl intensity

For the first time in Namibia, this study quantifies the intensity of bottom-trawling using commercial effort data (2000 – 2006) from the hake-directed bottom-trawl fishery. The mean number of hours spent trawling and the mean number of trawls per square (1’x1’) grid, with their geographical positions are used to examine bottom-trawl intensity. The study summarizes these various trawls into light, medium, and heavy bottom-trawl intensity. Other aspects of trawl characterization are also explored in this chapter. Generalized Additive Modelling (GAM) is applied to the commercial bottom-trawl data to determine the extent to what location (latitude, longitude), depth, year, regions, seasons, and vessel type influence vessel distributions.

Chapter 3 Materials and Methods

This Chapter is devoted to a comprehensive account of the materials and methods used for data collection during the hake biomass surveys in Namibia. These are general data collection methods, sampling procedures, and processing of data onboard the research vessels *Dr Fridtjof Nansen* and contracted commercial vessels (e.g. *Blue Sea 1*), which were used as sampling platforms. These methods summarized in this chapter were used during the sampling and collection of demersal fishery data, on which most of the chapters are based, except for Chapter 2, which contains a description of specific data collection methods.

Chapter 4 Size structure

This chapter takes a holistic approach in assessing the effects of bottom-trawling on demersal fish assemblages using size-based indicators (mean catch rates, mean length of species in the catch, slope and height of the size spectra). It uses the time-series data for hake and incidental catch from the scientific surveys (1990 – 2006). Various indicators are used to infer changes in the structure of the demersal fish assemblages. The chapter investigates whether the changes in the community structure were likely to be attributable to long-term effects of bottom-trawling.

Chapter 5 Community structure and diversity indices

This chapter assesses changes in demersal fish community structure off the coast of Namibia using Abundance Biomass Comparison (ABC) curves. It uses the multivariate approach (dendrograms, multidimensional scaling, and dominance curves), permutational multivariate analysis of variance (PERMANOVA) and the distance-based linear model (DISTLM), and generalized additive modelling (GAM) for diversity analyses with their corresponding factors such as latitude, longitude, depth, and abundance. Spatial (latitude and depth) changes in the diversity pattern for demersal fish species are illustrated. Inferences are drawn in this chapter relative to temporal and spatial bounds, on the possibility of bottom-trawl impacts.

Chapter 6 Bottom trawl experiment

This chapter reports on the findings of the *in situ* experimental bottom-trawl study conducted in 2007 off southern Namibia and northern west coast of South Africa, onboard *R/V Dr Fridtjof Nansen*. As a result of no representative untrawled areas in both Namibia and South Africa' west coast, the experiment was conducted in lightly and heavily trawled areas at 4 sites each with three replicate trawls within the Benguela System. The hypothesis that heavy trawling alters the abundance, biomass, composition, and diversity of demersal fish species is investigated. Environmental variables such as depth, dissolved oxygen, bottom temperature, and salinity are included in the analyses.

Chapter 7: Regional analysis

This chapter deals with the analysis of the 2007 demersal fish data from the *Nansen* dedicated cruise which took place on the west coast of South Africa (from the Agulhas Bank to the Orange River) and the annual hake biomass survey data (from the Orange River to the Kunene River) conducted at the same period onboard *Blue Sea 1*. The chapter focuses on assessing spatial (latitude and depth) changes in diversity, density, structure and composition of the assemblages of the demersal fish species from the Kunene River to the Agulhas Bank, representing both northern and southern Benguela. Multivariate approaches are applied to assess changes in the demersal fish assemblages, in relation to bottom-trawling.

Chapter 8 Synthesis and Conclusion

This chapter links all the contributions from other chapters, and summarizes the main outcomes of the thesis according to specific research questions. Different aspects of the study on effects of bottom-trawling on demersal fish assemblages are discussed, which include issues of data, and different indices used to capture changes in community structure. Key questions addressed in different sections from different chapters, suggestions for further studies, and management needs are taken into consideration.

Chapter 2

Spatial distribution of commercial bottom-trawl effort for hake in Namibian waters between 2000 and 2006: a retrospective analysis to estimate bottom-trawl intensity

2.1 Introduction

A good understanding of fishing effort is important to estimate the impacts of bottom-trawling. However, data on fishing effort are often poor and sometimes can only provide crude estimates of fishing effort (Greenstreet *et al*., 1999). Previous studies on bottom-trawling in the North Sea and Irish Sea have based their analysis of fishing effort on tow frequency (number of tows), tow duration (hours fishing) and days at sea (Lindeboom & de Groot, 1998; Greenstreet *et al*., 1999; Jennings *et al*., 1999). Discrepancies exist in the use of these measures of effort, because they do not necessarily take into account the size of the trawl gear, and thus no information can be obtained about the size of the area disturbed by the trawl gear (Ragnarsson and Steingrímsson, 2003). However, in the absence of information on the size of the trawl gear, the available information in the form of tow frequency, tow duration, total catch, and depth can still provide useful information to determine the spatial distribution of trawl effort and its potential impact in the ecosystem.

The government of the Republic of Namibia, through its Ministry of Fisheries and Marine Resources, has put in place stringent measures to ensure the sustainable management of the hake resource within its economic exclusive zone (EEZ). Some of the measures include a ban on bottom trawling in waters shallow than 200 m depth, mesh size restriction (110 mm cod-end), and recently (since 2005), seasonal closure of the hake fishery (MFMR, 2008). Effort is controlled by the number of participants (fishing rights' holders and quota allocations) in the hake industry (MFMR, 2001). Fisheries Observers/Inspectors on each commercial trawler monitor the fishing activities onboard commercial vessels. Fisheries observers are trained personnel provided by the Fisheries Observer Agency (FOA) of Namibia, with the mandate to contribute towards sustainable utilization of marine resources within the EEZ of Namibia and international waters. They provide an efficient and transparent service to all their stakeholders through actively monitoring compliance with the marine legislation and the collection of relevant and reliable scientific data. They collect fisheries data, biological information and, with the aid of the skippers onboard commercial vessels, they collect other information such as geographical location of each trawl, trawl duration and catch weight. This information is made available to MFMR and it is reconciled (checking whether the recorded information from both the fisheries observers and the skippers is the same and accurate) with the logbook records from skippers from the two ports of Walvis Bay and Lüderitz.

Most of these bottom-trawlers land their catches at Walvis Bay, though a few fishing companies are based in Lüderitz, process their landing there, which makes it easier in principle for fisheries inspectors to record, and monitor the activities of the fishing vessels in ports. In spite of these management measures in place, which are aimed at the conservation of the target species (*M. capensis* and *M. paradoxus*), the intensity of bottom-trawling and the related impacts are not documented in northern Benguela. In the southern Benguela, Wilkinson and Japp (2007) estimated bottom-trawl intensity for the hake-directed fishery. They found that, as expected, intensely trawled grounds coincide with high density areas of hake throughout its distribution around the South African coast.

This chapter aims at quantifying bottom-trawl intensity off the coast of Namibia using the commercial effort data for the hake-directed bottom-trawl fishery. Firstly, spatial and temporal distribution patterns of (a) tow frequency and (b) tow duration are examined to estimate bottom-trawl intensity. Secondly, how fishing (bottom-trawl) effort varies between geographical areas and depth strata off Namibia is assessed. This leads to a characterization of the Namibian bottom-trawl grounds into areas that are lightly, moderately, and heavily trawled.

2.2 Material and Methods

This study covers the whole coast of Namibia, from the northern border at the Kunene River to the southern border at the Orange River, covering the bottom fishing grounds in waters deeper than 200 m, where bottom trawling is permitted (MFMR, 2001). For the purpose of this study, the coast of Namibia was divided into north (17^{o}S – $20^{o}59'59''$S), central (21^{o}S – $24^{o}59'59''$) and south (25^{o}S – $29^{o}59'59''$) subareas (Fig. 2.1). Logbook data on fishing effort for the hake-directed bottom-trawl were used for this study, provided by the National Marine Information and Research Centre (NatMIRC), Swakopmund, of MFMR. Since Namibian independence in 1990, it has been mandatory for all commercial vessels to keep logbook records on all hauls (MFMR, 2001). This is done in conjunction with the fisheries observers onboard commercial fishing vessels since the early 1990s. The logbook data are verified (checked for errors in terms of the recorded catches) by NatMIRC, and the quality of the data is considered to be appropriate for the purpose of this thesis.

The trawl intensity of the commercial bottom-trawlers from 2000 to 2006 was mapped using the GIS software *ArcGIS v9* (www.esri.com). Note that all these years pertain to the last temporal cluster identified in Chapter 5. The spatial analysis included trawl station logs (latitude and longitude), depth (metres), trawl duration (hours) and total catch (kilograms). Some additional errors in the geo-referenced commercial data were identified, in cases where the catch position was incorrectly recorded or captured, especially when the recorded position was inland or outside the area covered by fishing vessels. These errors were unusual but were found in the data during the verification process by this study. NatMIRC only verifies the catches or landings, as well as the biological information meant for the hake stock assessment. These false records (which accounted for less than five percent of the data for the period 2000 - 2006) were rejected during the data cleaning and did not form part of the analyses, leaving a total of 400 711 valid records for analysis. A total of 24 364 grid squares were trawled over the seven-year period and the surface area of the grid squares ranged from 0.866 to 0.956 nm^2 depending on latitude. The validated records had trawl durations between 0.5 – 12 hours. The average trawl duration (h) and mean number of trawl sets per grid per year were used to represent the trawl intensity for the hake bottom-trawl fishery for the period 2000 – 2006. The classification of trawl intensity was as follows: 1) average trawl duration (h), light (0.5 – 4); medium (4.1 – 6); and heavy (6.1 – 12); 2) mean number of trawl sets per grid per year, light (1 – 20); medium (20.1 – 40); and heavy (40.1 – 437). This was done after consideration of the frequency distributions of hours trawled and the number of trawls per grid.

The highest spatial and temporal resolution was used for this study using a square of area 1 square nautical mile (1' latitude x 1' longitude). The surface area for each square (Sq = square nautical mile) was then calculated using the following formula (as in Ragnarsson and Steingrímsson, 2003):

$$Sq = Cos \frac{\text{latitude} \times \pi}{180} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.1)}$$

The data were combined by year and by cell, whereby each start point of a trawl was used to represent a trawl, and was fixed to the centre of a 1' x 1' grid square. For each haul, the following data were extracted from the database at NatMIRC: coordinates at the start of tow (latitude and longitude, used to designate a tow to the centre of a square), trawling depth (m), tow duration (h) and total catch of hake, both species combined (kg). For each grid (1' x 1') square, the total number of bottom-trawls (frequency) and trawl duration (h) were averaged over the seven-year period (2000 – 2006). For the annual breakdown for number of trawl sets and trawl duration, see Table 2.1. In line with Pecquerie *et al.*, 2004, the total area covered by bottom-trawlers was calculated by summing the area of the cells where trawls took place. Latitude and distance have a constant relationship (1' latitude = 1 nautical mile = 1.852 km), whereas that of longitude varies with the cosine of latitude (Raisz, 1948), 1' longitude = 1' latitude x cos(latitude). The latitude of the centroid of a 1' x 1' square was used to calculate its area A in km^2:

$$A = 1.852 \times (1.852 \times \cos \text{latitude}) \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(2.2)}$$

The average area swept by trawling annually within each square was calculated for each year according to the following equation (Ragnarsson and Steingrímsson, 2003):

$$St_j = \frac{(\sum_{i=1}^{Nj}(D \times T \times S))}{n} \quad \text{...................} \ (2.3)$$

where St_j = area swept by otter trawl in square j (in units of nm^2)

D = door spread (metres or nautical miles, see conversion in text)

T = tow duration (hours)

S = towing speed (knots or nautical miles/hour)

n = number of years

N = the total number of hauls in a square *j*.

The duration and speed of trawls by commercial trawlers are not constant; They tend to vary in time and space and hence the need to incorporate trawl speed in the formula. The door spread for all vessels trawling off Namibia ranged from 65 – 130 m with a mean of 110 m or 0.0594 nautical miles. The towing speed ranged from 3 to 4 knots from logbook data (MFMR, 2008), with a mean of 3.5 knots, which was used in the calculations of the area swept by trawling annually. In line with Ragnarsson and Steingrímsson, (2003), fishing effort (calculated in units of hours trawled) was allocated to the centre of the (1’x1’) grid cell where the tow started. Realistically, the swept area is distributed over several squares with tows typically ranging from 10 - 20 nautical miles of distance.

The mean fishing intensity expressed as mean trawl duration (h), average number of trawl sets and the CPUE were compared regionally and bathymetrically by dividing the bottom-trawling grounds into three roughly equal regions (Fig. 2.1) and four different depth strata (200 – 399, 400 – 599, 600 – 799 and 800+ m). These depth strata are different categories to those introduced earlier. The depth categories used here are considered more appropriate for the analysis of commercial data since commercial trawlers can only legally operate deeper than 200 m and their outer limit would be the EEZ boundary, whereas the hake biomass surveys focused between the 100 m to 600 m isobaths.

Variability in the distribution of fishing effort (duration and number of trawls) for the whole coast across regions and depth strata (Fig. 2.1) was estimated using the coefficient of dispersion (C). Assuming temporal stationarity, C is calculated as the ratio between the variance and the mean, where C > 1 indicates a patchy distribution, C = 1 indicates random distribution and C < 1 uniform distribution (Elliot, 1977). C was calculated for each 1'x1' grid square fished and for the average annual trawl duration and number of trawls.

Additionally, the average number of trawls per grid was overlaid over the sediment texture map to identify which were the most popular sediment-types for trawling and what level of trawl intensity would be exerted on these sediment categories.

A univariate analysis in the simple general linear model (GLM) (McCullagh and Nelder, 1989) routine in Statistica v10 (www.statsoft.com) was used to test for the significance of the trends in effort and CPUE, after the data were log transformed to normalize their statistical distributions. The GLMs included year, season and region or depth stratum and vessel type as covariates. In both cases, all possible interaction terms were considered as well. It was not possible to use all covariates in one model because such a model design would contain missing cells, and becomes incomplete; therefore, some or even all effects may not be estimable. Thus, data were logically separated into covariates, which do not cause the similar analysis problems. Two-model runs were conducted for duration and CPUE, with sigma-restricted parameterization, and type VI (effective hypothesis decomposition) of the sums of squares, and significance level at p = 0.001.

Physical variables such as latitude, longitude, depth, year, seasons, vessel types, and regions were incorporated in the analysis of the effort (duration in hours), CPUE (kg/h), and catch data from the commercial hake bottom-trawl fishery off Namibia, using Generalized Additive Models (GAMs) (Hastie and Tibshirani, 1990) (all analysis done in *R (mgcv package)* (R Development Core Team, 2004; Wood, 200*6, 2009*), to assess their effects on these attributes of the hake-directed bottom-trawl fishery. In models like these, all the factors for input in the model should be checked for correlation, and those that are highly correlated are reviewed according to their merits in the model. For instance, one would expect depth and longitude to be often highly correlated. Correlation matrices in Statistica v10 (www.statsoft.com) were used to check for correlation between depth and longitude.

GAM is a non-parametric generalisation of multiple linear regressions that is not restricted to specific functional relationships (e.g. linearity) or underlying statistical distributions (e.g. normality) of data (Hastie and Tibshirani, 1990, Swartzman *et al.*, 1992). Thus, GAMs have been useful in examining environmental and stock relationships that are unlikely to be monotonic, linear or parametric (Maravelias and Reid, 1997). With GAMs, the dependent or response variable is modelled as the additive sum of unspecified covariate or predictor variables, whereby scatterplot smooths replace the least-squares estimates used in multiple linear regression (Hastie and Tibshirani, 1990). Therefore, the general form of GAMs is based on the assumption that the mean response (µ) is related to the predictor variables (X_1,…, Xp) by the following relationship (Eq. 2.4):

$$g(\mu) = \alpha + \sum_{j=1}^{p} fj\ (Xj) \ldots \qquad (2.4)$$

where g(µ) = the link function defining the relationship between the response and the additive predictor, α = the intercept term, f_j = the unspecified smooth function, p = parameters. However, GAM could not handle the large data set, so in this case a modified version of GAM that can handle large data sets, called big additive model (BAM), was used (Wood, 2011).

The observed response is assumed to obey some underlying statistical distribution from the exponential family (e.g. Gaussian, Poisson, Binomial or Gamma distributions) with the specified mean, μ (Hastie and Tibshirani, 1990). An additional measure of model fit was based on a pseudo-coefficient of determination (R^2), which is the fraction of the total variation accounted for by the model. This was preferred to the AIC due to the fact that we are not comparing models here. The interest lies in knowing the proportion of variance explained by the model (Equations 2.5 and 2.6):

$$R^2 = \left(1 - \frac{\text{residual deviance of full model}}{\text{null deviance}}\right) \text{x } 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(2.5)}$$

$$Partial\ R^2 = \left(1 - \frac{\text{residual deviance of full model}}{\text{residual deviance of reduced model}}\right) \text{x } 100 \quad \text{(2.6)}$$

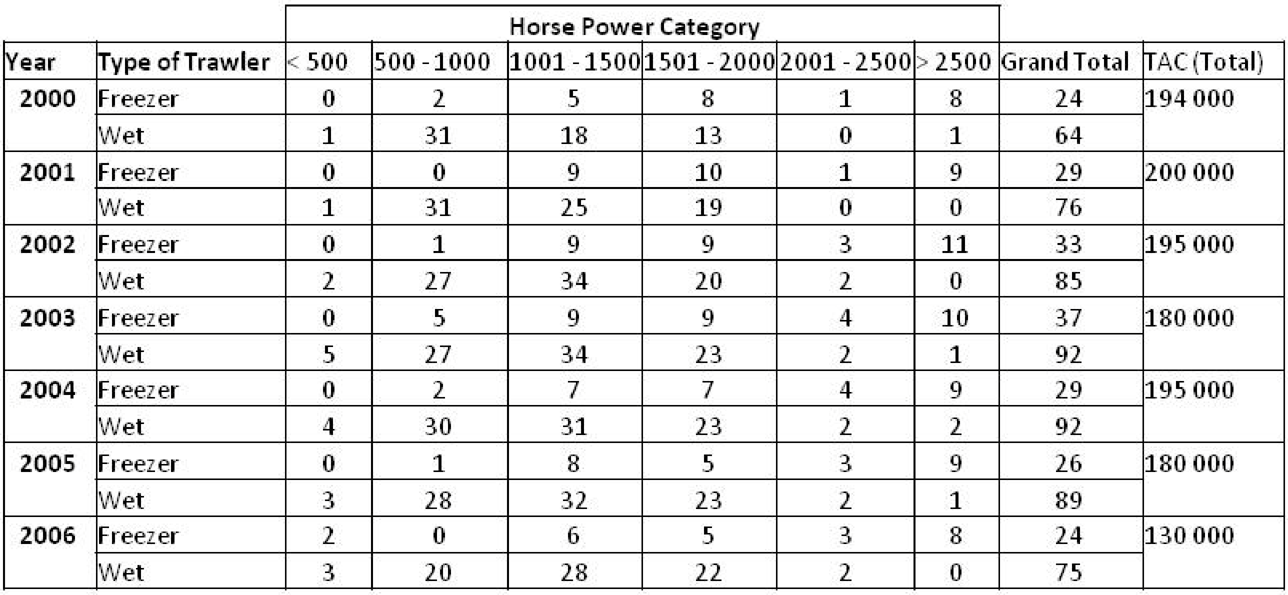
where deviance is analogous to the residual sums of squares (Swartzman *et al*., 1992, Begg and Marteinsdottir, 2002). Finally, the pseudo-partial R^2 was calculated using equation 2.6 (Swartman *et al*., 1992). Therefore, the importance of each term in the model is determined by calculating a pseudo-partial R^2, which was calculated by assessing the changes in the residual deviance when a predictor is removed from the full model. The pseudo-partial R^2 differs from the parametric partial R^2, hence the prefix pseudo. The sum of all pseudo-partial R^2 does not amount to the whole model R^2, but it does give some quantitative insight into which term is important. The model gives an opportunity to assess the effects of different predictors or explanatory terms on the fishing effort and CPUE, as opposed to looking at an individual or single effect alone.

2.3 Results

The bottom-trawl fishery for hake in Namibia had on average 110 otter trawlers over the study period, ranging from 88 in the year 2000 to a maximum of 129 trawlers in 2003, which were mostly wetfish trawlers (Table 2.1). The engine power of these vessels ranged from 150 to over 2500 horsepower (hp). The highest vessel numbers were in the category 1001 – 1500 hp (Table 2.1). Most vessels in this category operate as wetfish trawlers, meaning they go for short (4 – 5 days) fishing trips, while more powerful vessels go for longer (2-3 weeks or more) fishing trips, and freeze fish onboard.

The former have a small capacity to handle their catch, limited space for crew and low fuel capacity, whereas the latter in most cases have high fuel capacity, and adequate storage space to keep fish frozen for longer periods (Henry Ngongwe, Hangana Fishing Company Ltd, Walvis Bay, skipper *pers. comm.*). Although in this fishery there were more wetfish vessels than freezer vessels, there was a considerable increase of both vessel types from 2000 to 2003, and then the vessel numbers started to decline to the end of the review period (Table 2.1). The TAC during the years under review was at the highest level (194 000 – 200 000 t) for the first three years, then reduced slightly (180 000 – 195 000 t) during the next three years, and further reduced to 130 000 t during the final year of the study period (Table 2.1). It is currently (2011) at 180 000 t (MFMR, 2011).

Table 2.1. Characterization of the hake bottom-trawlers off Namibia and the TAC (in tons, which includes the hake bottom-trawl fishery, hake long-line, research quota, and by-catch in other fisheries) for the period 2000 to 2006. Contains year, type of trawler (freezer or wetfish), horse power category, number of vessels as grand total, and total TAC (source: Policy and Planning, MFMR).



		Horse Power Category							
Year	Type of Trawler	< 500	500 - 1000	1001 - 1500	1501 - 2000	2001 - 2500	> 2500	Grand Total	TAC (Total)
2000	Freezer	0	2	5	8	1	8	24	194 000
	Wet	1	31	18	13	0	1	64	
2001	Freezer	0	0	9	10	1	9	29	200 000
	Wet	1	31	25	19	0	0	76	
2002	Freezer	0	1	9	9	3	11	33	195 000
	Wet	2	27	34	20	2	0	85	
2003	Freezer	0	5	9	9	4	10	37	180 000
	Wet	5	27	34	23	2	1	92	
2004	Freezer	0	2	7	7	4	9	29	195 000
	Wet	4	30	31	23	2	2	92	
2005	Freezer	0	1	8	5	3	9	26	180 000
	Wet	3	28	32	23	2	1	89	
2006	Freezer	2	0	6	5	3	8	24	130 000
	Wet	3	20	28	22	2	0	75	

The bottom-trawl intensity represented by number of trawls and total trawl duration (h) has increased since 2000. It reached a peak in 2003 along with the number of vessels, but declined steadily thereafter (Table 2.2). The highest catches in 2003 correspond to the largest swept area by trawlers, and highest effort (hours fished). High catches also coincided with the highest number of trawl sets during the study period (Table 2.2), suggesting a good correspondence of total annual catches with the number of trawls and trawl duration.

Table 2.2 Namibian bottom-trawl effort for the commercial hake fishery over the period 2000 – 2006. These catches exclude catches from the hake long-liners, research catches, and bycatch by other fisheries, the estimates are based on the number of trawl sets shown below (source: MFMR).

Year	**Number of trawl sets**	**Total surface area trawled per grid square (nm^2) annually**	**Annual average area swept by trawl (nm^2)**	**Total Catch (tons)**	**Total Duration (hours)**
2000	54 513	49659	197	107 991	205037
2001	60 144	54502	230	115 443	240727
2002	60 755	55269	237	99 885	246989
2003	61 242	55840	241	134 614	251153
2004	55 730	50837	212	127 010	221308
2005	58 548	53935	227	117 781	235143
2006	49 723	45330	191	111 340	199260

The Namibian commercial bottom-trawl hake fishery legally trawls in waters deeper than 200 m to about 800 m isobaths (Figs. 2.1, and 2.2), which is not necessarily the outer limit of the EEZ, since this varies in depth. Figure 2.2 shows the distribution of all the bottom-trawls off Namibia's trawling grounds, which indicates that trawlers were active almost everywhere within the fishing grounds, except areas which are not trawlable due to obstacles (e.g. rocky ground). However, the coefficient of dispersion of both number of trawls and total duration shows an increasingly uniform distribution, while distribution per grid square over the study period was patchy (not shown). Figure 2.3 shows the average trawl set duration (h) for the entire study area.

The distribution pattern for the average trawl duration varied with latitude and depth. It had a coefficient of dispersion (C value) of 0.126, which suggests that the distribution was increasingly uniform, according to classification by Elliot (1977) over the seven-year period. However, the distribution for the average number of trawls (tow frequency) in a single grid square had a C value of 20, suggesting a patchy distribution.

The distribution of the average number of trawl sets (tow frequency) over the seven-year period for the whole coast of Namibia is shown in Figure 2.4. The average number of trawl sets sub-divided into lightly, medium, and heavily trawled areas are shown as overlays on sediment type maps (Fig. 2.6a – c). The most frequently trawled areas coincide with the heavily trawled areas from the perspective of trawl duration (Figure 2.3). The maps for the regional trawl intensity (Fig. 2.5a, b) illustrate bottom-trawl intensity as mean trawl duration (h) over the seven-year period. There were variable levels of trawl intensity across all three regions and depths and trawling extended to both sides of the border with neighbouring Angola and South Africa. However, most trawling took place in the southern region, and the least in the central region (Figs. 2.3, 2.4, 2.5). Most of the commercial trawling for hake took place on both sand-gravel and mud-sand areas off Namibia (Fig. 2.6a – c). In addition to trawl intensity maps, the annual CPUE maps for the hake bottom-trawl fishery are shown in appendix 2.1.

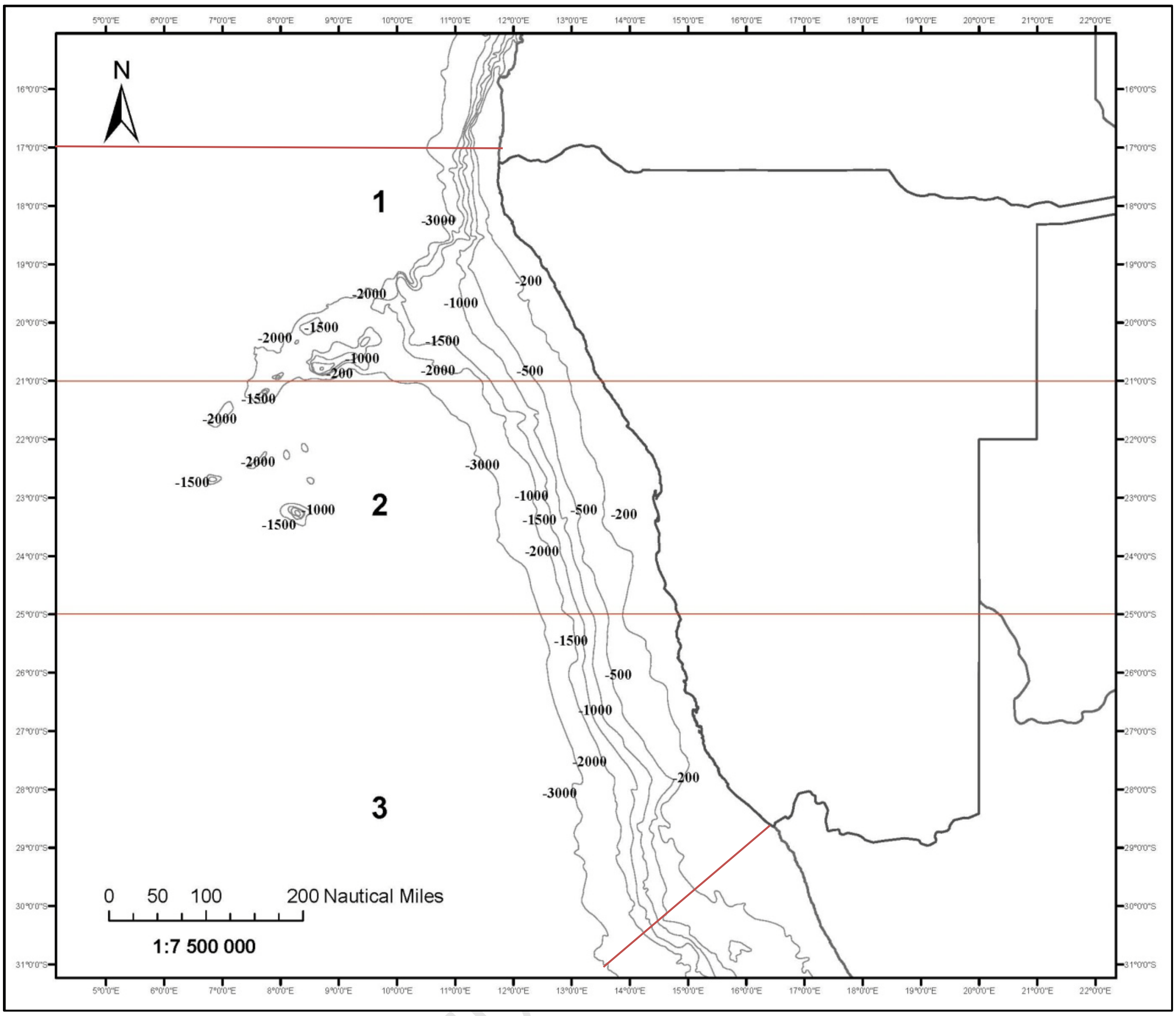


Figure 2.1 Bathymetry map of Namibia showing depth contours (m), the coast divided into regions: 1. North (17^{o}S – 20^{o}59’59”S); 2. Central (21^{o}S – 24^{o}59’59”); 3. South (25^{o}S – 29^{o}59’59”). The outer edges of the northern and southern borders are shown by the two outermost red lines.

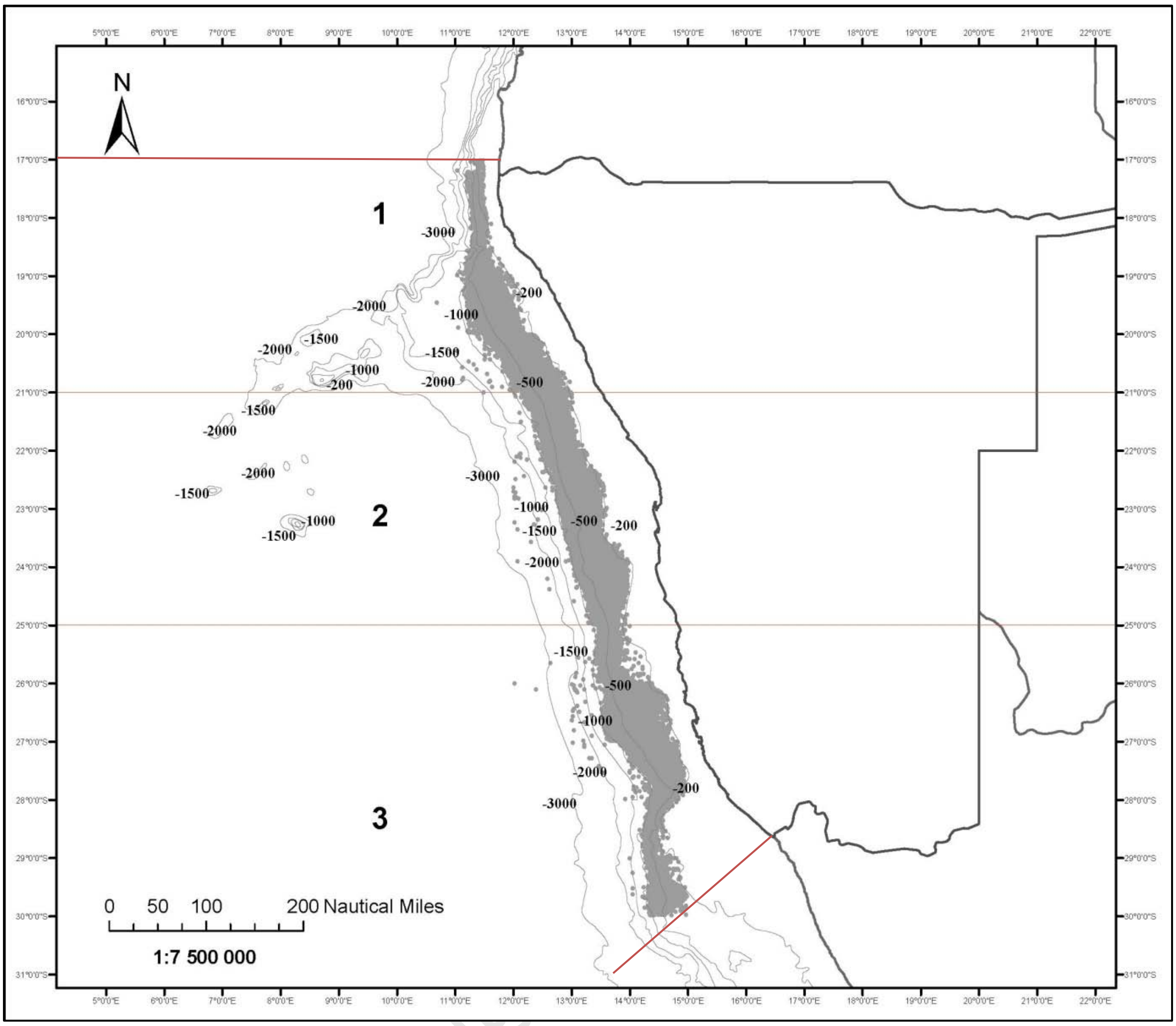


Figure 2.2 Distribution of all otter-trawl hauls over the seven-year period (2000 - 2006), carried out by the bottom-trawl fishery for hake off Namibia.

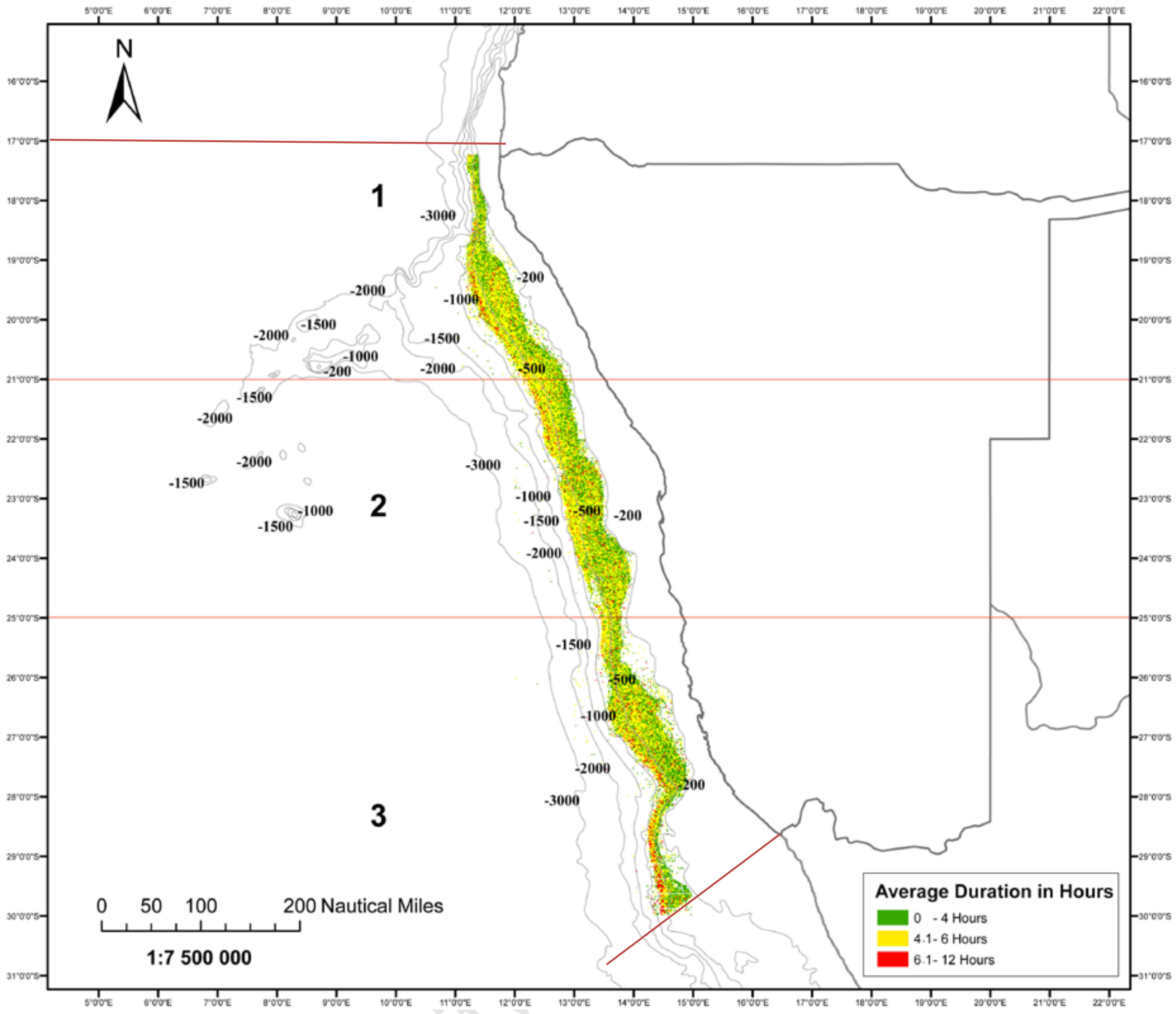


Figure 2.3 Average annual trawl duration (h) expressed as mean annual trawl intensity over the seven-year period (2000 – 2006) off the coast of Namibia.

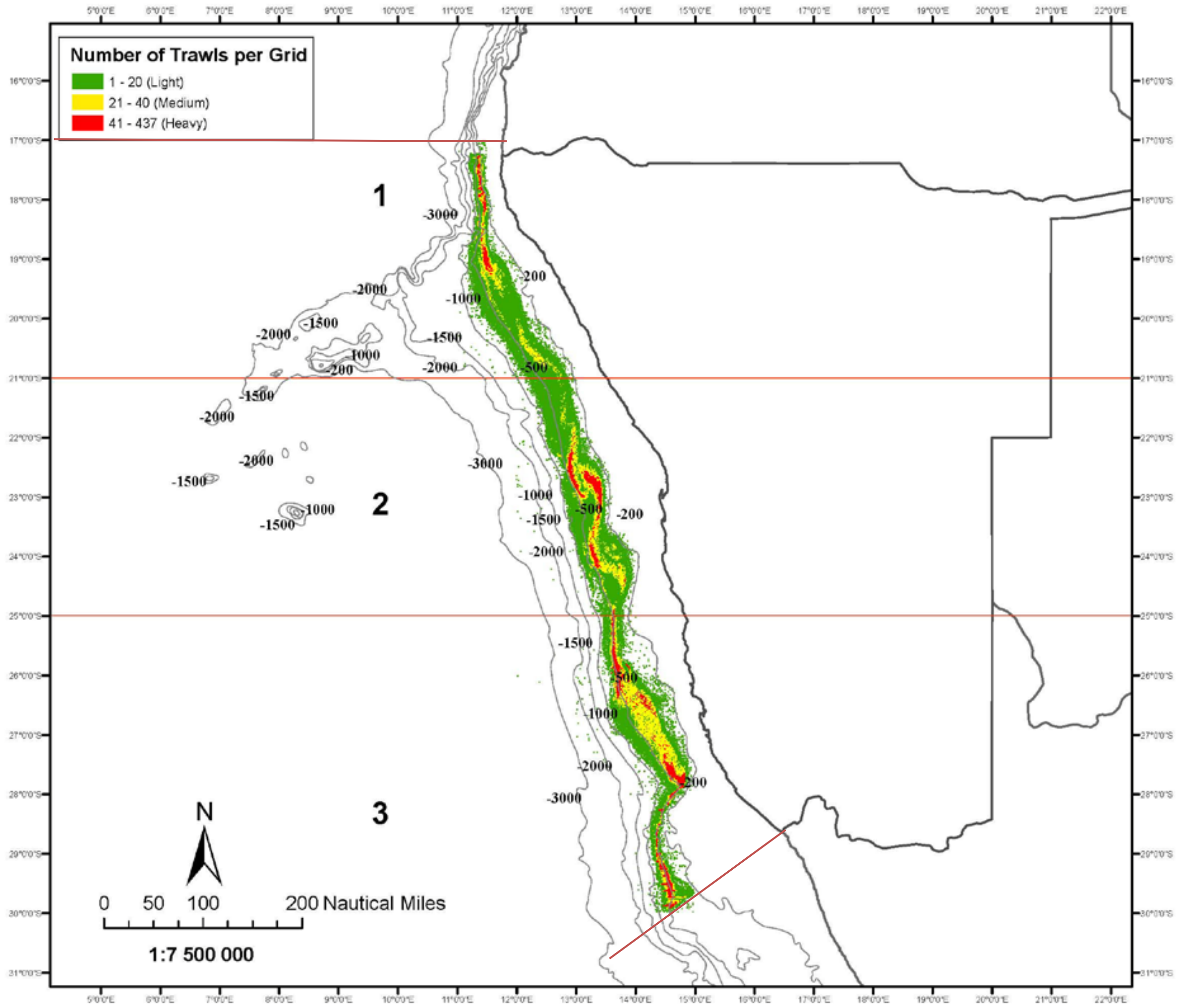


Figure 2.4 Annual average trawl frequency per grid square (1’ x 1’) for the Namibian hake bottom-trawl fishery over the seven-year period (2000 ─ 2006).

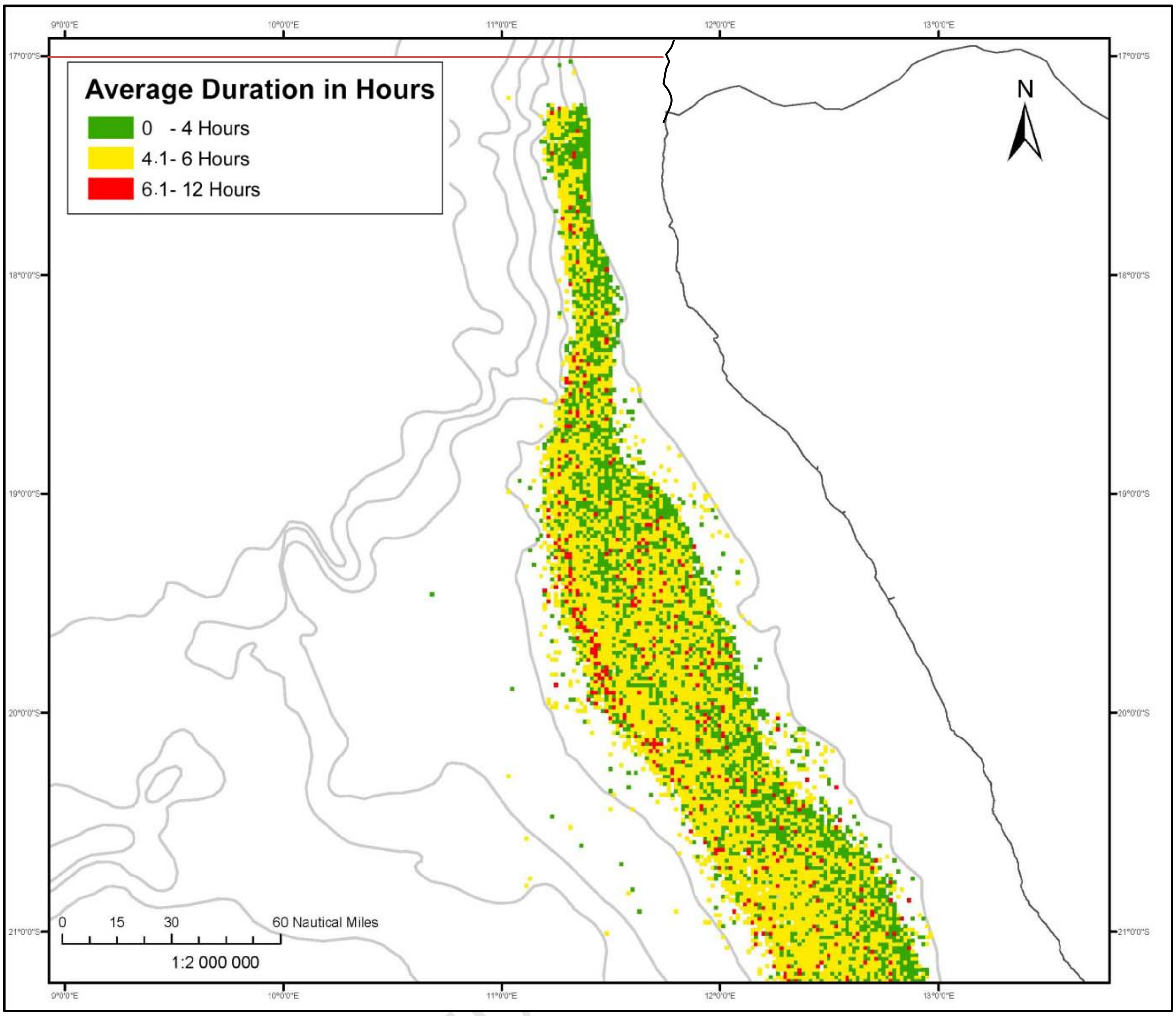


Figure 2.5a Northern region: average trawl duration per grid square (1’ x 1’) for the hake bottom-trawl fishery over the seven-year period (2000 — 2006). Isobaths are 200, 500, 1000, 1500, 2000, 3000 m.

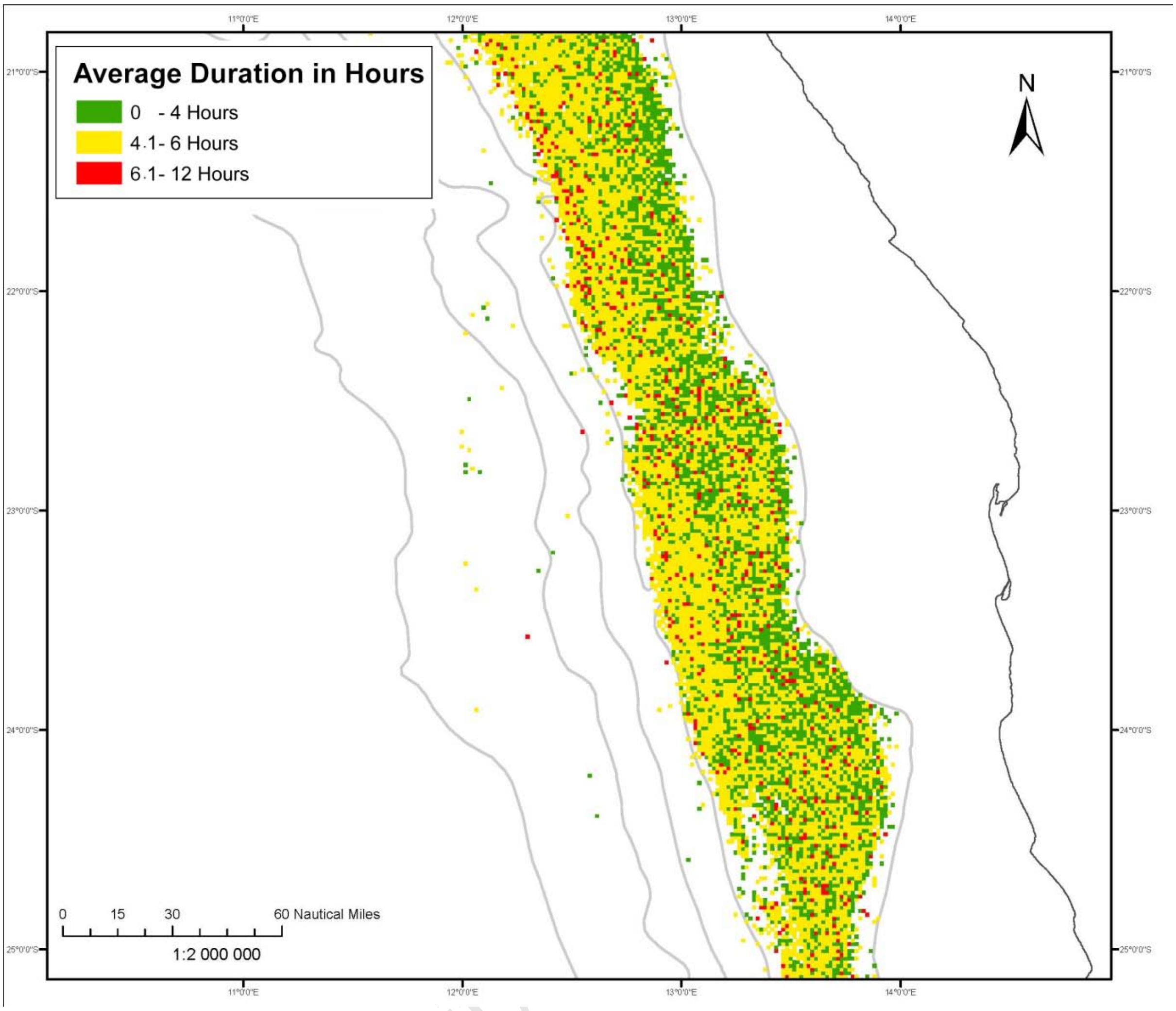


Figure 2.5b Central region: average trawl duration per grid square (1'x 1') for the hake bottom-trawl fishery over the seven-year period (2000 – 2006). Isobaths are 200, 500, 1000, 1500, 2000, 3000 m.

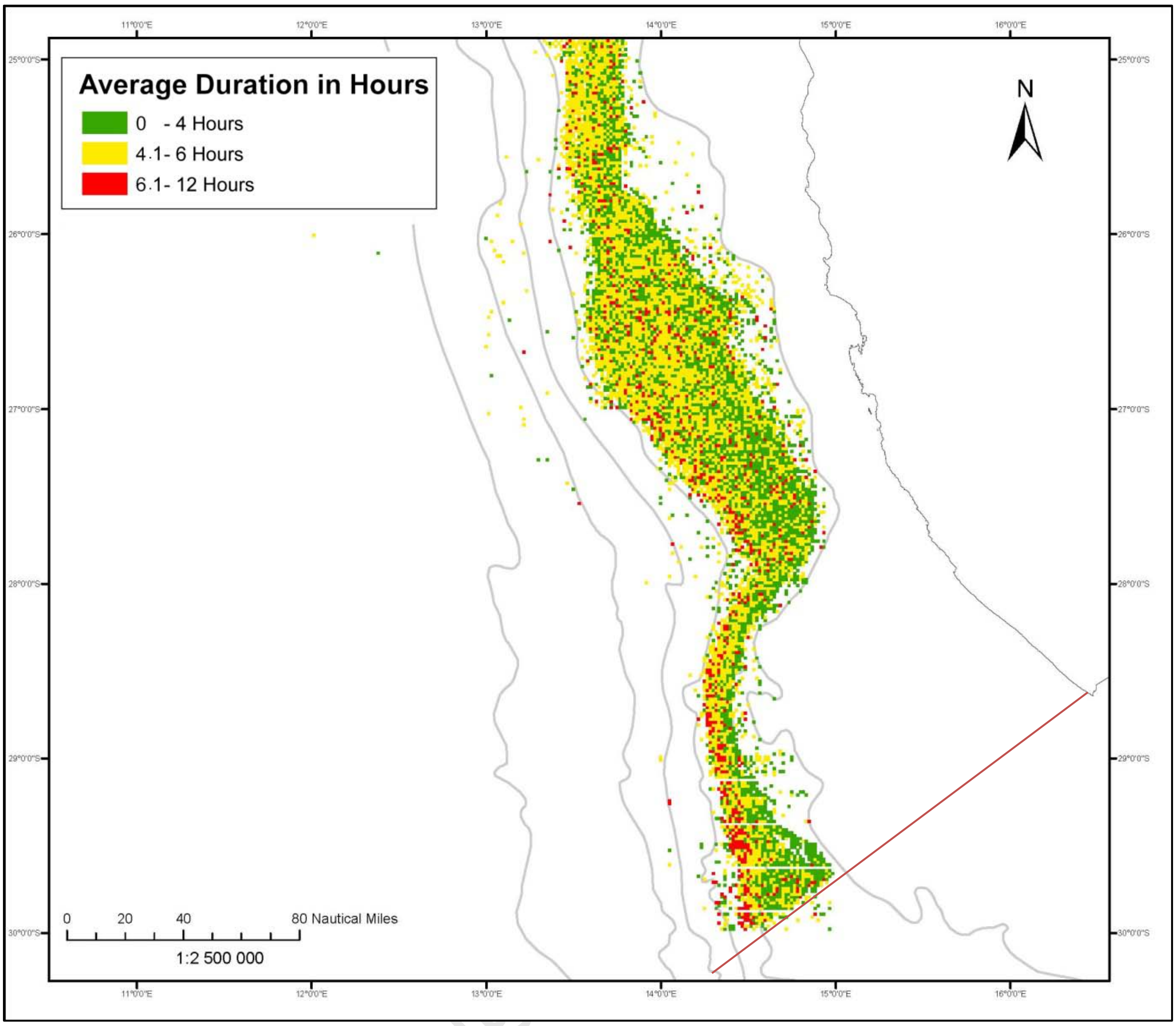


Figure 2.5c Southern region: average trawl duration per grid square (1' x1') for the hake bottom-trawl fishery over the seven-year period (2000 – 2006). Isobaths are 200, 500, 1000, 1500, 2000, 3000 m.

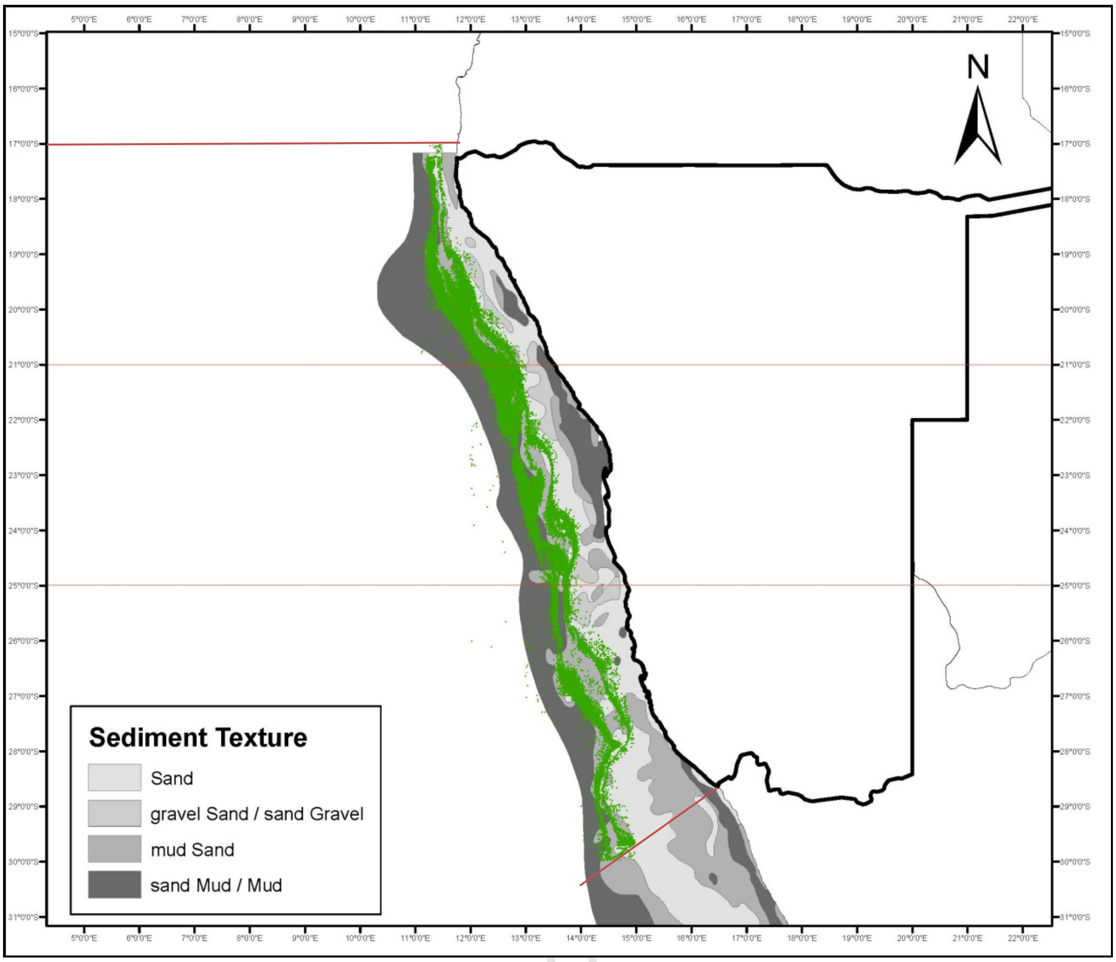


Figure 2.6a Light trawl intensity (1 – 20): average number of trawls per grid square (1' x 1') overlaid over sediment texture off Namibia for the hake bottom-trawl fishery over the seven-year period (2000 — 2006). (Sediment texture by the Council for Geoscience, Cape Town).

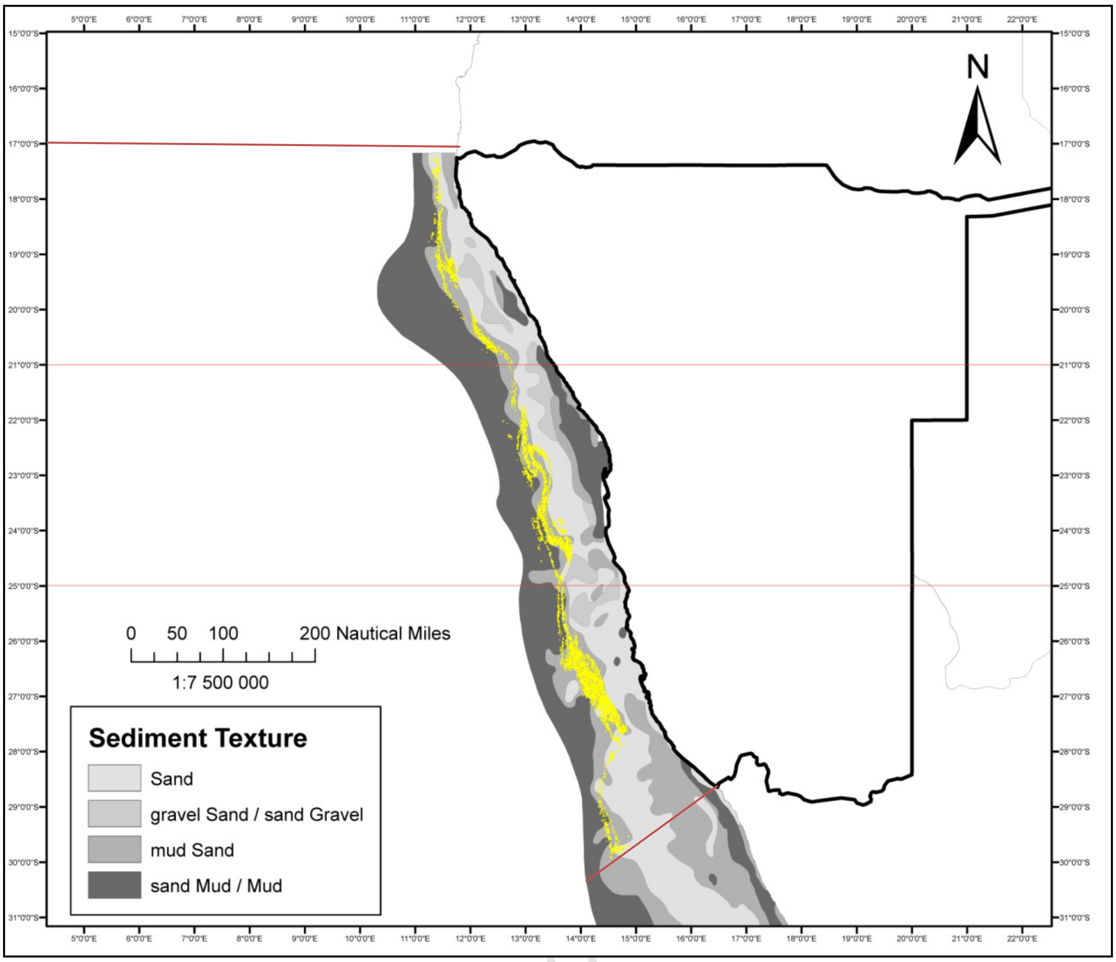


Figure 2.6b Moderate trawl intensity (21 – 40): average number of trawls per grid square (1' x 1') overlaid on sediment texture off Namibia for the hake bottom-trawl fishery over the seven-year period (2000 – 2006). (Sediment texture by the Council for Geosciences, Cape Town).

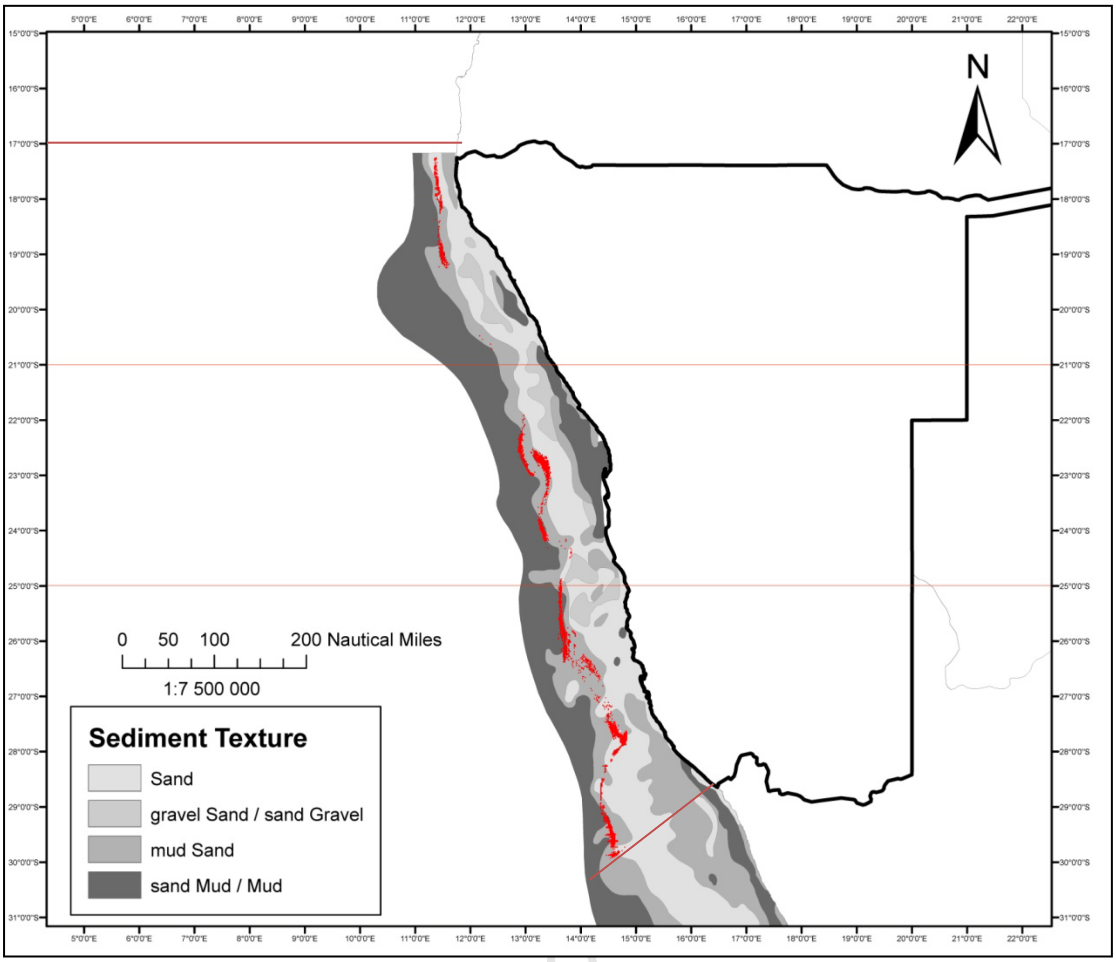


Figure 2.6c Heavy trawl intensity (41 – 437): average number of trawls per grid square (1' x 1') overlaid over sediment texture off Namibia for the hake bottom-trawl fishery over the seven-year period (2000 — 2006). (Sediment texture shapefile by the Council for Geosciences, Cape Town).

The dynamics of the fishing effort and catch per unit effort

Fishing effort

The general variability in the distribution of the commercial fishing effort for the hake-directed bottom-trawl fishery is shown in Figure 2.7a – c. The annual fractions of total fishing effort showed some increasing trend in effort from 2000 to 2003. Fishing effort then decreased in 2004, increased the year after, and decreased again in 2006 (Fig. 2.7a). The changes in the fishing effort for the entire study period were highly significant ($p < 0.001$, Table 2.3a). The interactions of covariates are provided in the table, but without figures, since the interest for this study lies in the individual covariate effects.

The duration of trawling and the number of trawls were synchronous for the whole period under review (Fig. 2.7a). Seasons affected the fishing effort, with the highest fishing effort occurring in autumn and the lowest in summer (Fig. 2.7b). Fishing effort was significantly different from season to season ($p < 0.001$, Table 2.3a). Most of the fishing effort was by the freezer vessels, with highest effort in southern Namibia, then north, and least in central Namibia. Wet-fish vessels had the lowest fishing effort over the seven-year period with their effort concentrated in central Namibia, then southern and lowest in the northern region (Fig. 2.7c). Fishing effort was greatest in the depth range 200─399 m, followed by 400─599 m (Fig.2.7d). Thus, effort declined with increasing depth. All changes in fishing effort by region, vessel type, depth, and all their interactions were significant (Table 2.3.a).

Catch per unit effort (CPUE)

The average variability in CPUE is shown in Figure 2.8a – e. Annual averages in CPUE had a declining trend in the first three years, then increased and reached a peak in 2004, a slight decline in 2005, and another increase in 2006 (Fig. 2.8a). All the changes in CPUE from year to year were significant ($p < 0.001$, Table 2.3b). The seasonal influence was greater in autumn, which had the highest CPUE. The CPUE in winter and summer was similar and it was lowest in spring (Fig. 2.8b). The seasonal effects on CPUE were significant ($p < 0.001$, Table 2.3b). The freezer vessels landed more catch than the wet-fish

Table 2.3a) EFFORT (as duration of trawls in hours) for the Namibian hake-directed bottom trawl fishery 2000 – 2006.

	Univariate Tests of Significance for log(duration) (Effort_Data_Nam) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: .2632044				
Effect	SS	Degr. of Freedom	MS	F	P <0.001
Intercept	*789458.2*	*1*	*789458.2*	*11395742*	*<0.001*
Year	*191.7*	*6*	*32.0*	*461*	*<0.001*
Season	*187.5*	*3*	*62.5*	*902*	*<0.001*
Regions	*76.8*	*2*	*38.4*	*554*	*<0.001*
Year*Season	*46.3*	*18*	*2.6*	*37*	*<0.001*
Year*Regions	*126.3*	*12*	*10.5*	*152*	*<0.001*
Season*Regions	*60.4*	*6*	*10.1*	*145*	*<0.001*
Year*Season*Regions	*134.1*	*36*	*3.7*	*54*	*<0.001*
Error	27754.1	400627	0.1		

	Univariate Tests of Significance for log(duration) (Effort_Data_Nam) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: .2573895				
Effect	SS	Degr. of Freedom	MS	F	p <0.001
Intercept	*11914.53*	*1*	*11914.53*	*179843.6*	*<0.001*
Depth Stratum	*421.13*	*3*	*140.38*	*2118.9*	*<0.001*
Vessel Type	*6.80*	*1*	*6.80*	*102.6*	*<0.001*
Depth Stratum*Vessel Type	*30.91*	*3*	*10.30*	*155.5*	*<0.001*
Error	26546.32	400703	0.07		

Table 2.3b) CPUE for the commercial hake fishery 2000 – 2006.

	Univariate Tests of Significance for log(cpue+1) (Effort_Data_Nam) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 1.046803				
Effect	SS	Degr. of Freedom	MS	F	p <0.001
Intercept	10740834	1	10740834	9801842	<0.001
Year	4764	6	794	725	<0.001
Season	2476	3	825	753	<0.001
Regions	39918	2	19959	18214	<0.001
Year*Season	1212	18	67	61	<0.001
Year*Regions	2127	12	177	162	<0.001
Season*Regions	747	6	124	114	<0.001
Year*Season*Regions	1113	36	31	28	<0.001
Error	439006	400627	1		

	Univariate Tests of Significance for log(cpue+1) (Effort_Data_Nam) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 1.079501				
Effect	SS	Degr. of Freedom	MS	F	P<0.001
Intercept	152259.4	1	152259.4	130658.6	<0.001
Depth Stratum	927.5	3	309.2	265.3	<0.001
Vessel Type	170.6	1	170.6	146.4	<0.001
Depth Stratum*Vessel Type	1613.6	3	537.9	461.5	<0.001
Error	466948.4	400703	1.2		

vessels; again, the southern region was frequented more by both vessel types, followed by the northern region, and the CPUE was lowest in the central region (Fig. 2.8c).

There was a difference in the distribution of CPUE between vessel types and among depth strata, with freezer vessels having high CPUE in the depth range 200 — 399 m, followed by 400 — 599 m, then lower in the depth range 500 — 799 m, and slightly higher in the 800+ m depth stratum (Fig. 2.8d). The wet-fish vessels had higher CPUE in the depth range 400 — 599 m, and lowest in the 600 — 799 m range. Among all depth strata, the southern region had the highest CPUE and the central region the lowest (Fig. 2.8e). The region, vessel type, depths effects as well as their interactions were all significant (Table 2.3b).

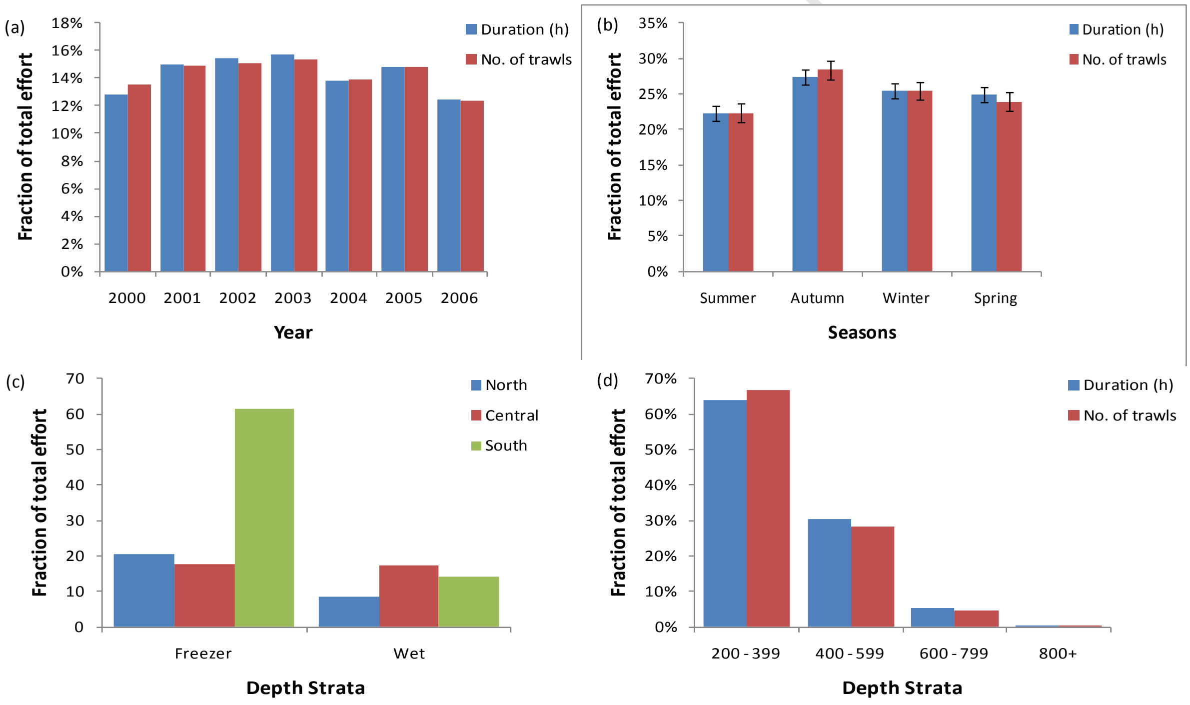


Figure 2.7 Fishing effort for commercial hake bottom-trawlers off Namibia, (a) annual fractions of the total fishing effort, (b) fishing effort by season, (c) fishing effort by vessel type, and (d) fishing effort by depth strata. Error bars are standard errors, data source: MFMR.

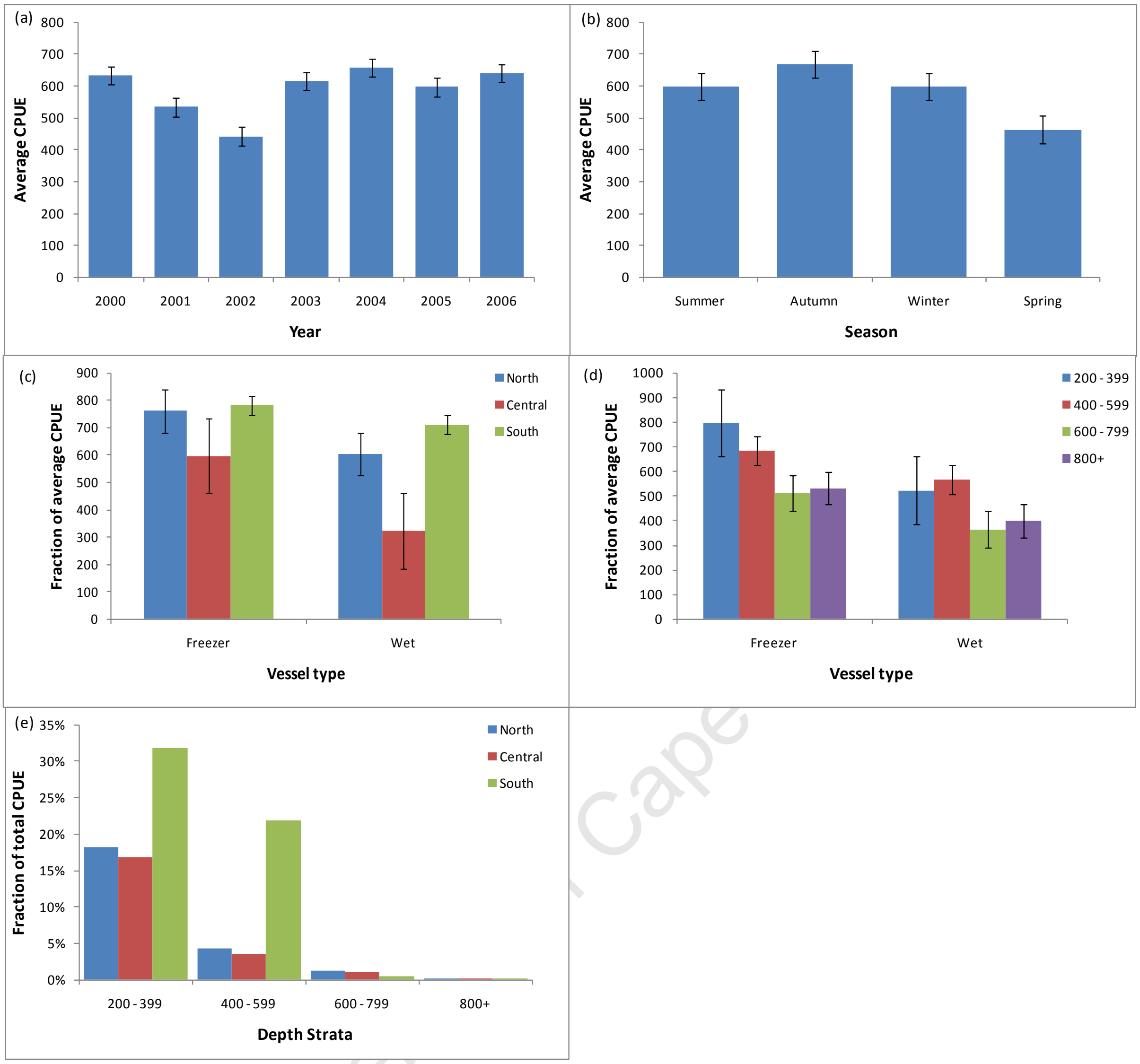


Figure 2.8 Average catch per unit effort (CPUE) for the hake bottom-trawl fishery off Namibia, (a) annual variation in average CPUE, (b) CPUE by season, (c) CPUE by vessel type and regions, (d) CPUE by vessel type split into depth strata, and (e) proportions of CPUE by depth stratum and split by regions. Error bars are standard errors, data source: MFMR.

Generalized Additive Modelling

The proportions of deviance for each term in the GAM are shown in Table 2.4. Latitude, vessel type, and longitude were the most important explanatory factors for the fishing effort, but the whole model could only explain 14.8% of the deviance in the fishing effort.

The catch per unit effort was more closely linked to latitude (12.6%), but the whole model could only explain 18% of the deviance in CPUE (Table 2.4). Interaction terms are also shown in the table, but are not explained and discussed, because the interest here is on the actual effect of each predictor only. The correlation between depth and longitude was weak at 0.0386, thus does not contradict the conditions for GAM operation (Wood, 2006, 2008).

Table 2.4 Proportions of deviance explained by each term in the model (GAM) and their interaction effects, using the commercial effort and CPUE for hake off Namibia (2000 – 2006).

	Effort		**CPUE**	
	deviance	% change deviance	deviance	% change deviance
Null model	28662.4		497428.2	
Latitude	27439.8	4.3	434777.5	12.6
Longitude	26564.3	3.2	427669.5	1.6
Depth	25915.5	2.4	423393.0	1.0
Year	25755.8	0.6	417190.4	1.5
Seasons	25664.8	0.4	415194.8	0.5
VesselType	24601.1	4.1	409621.9	1.3
Regions	24596.3	0.0	409385.8	0.1
Year:Regions	24539.2	0.2	407751.2	0.4
Year:VesselType	24467.1	0.3	406410.4	0.3
Year:Seasons	24431.4	0.1	404782.7	0.4
Whole Model		**14.8**		**18.6**

It is striking that only a minor proportion of the variability is explained by the GAMs. The following section contains a description of the effect of the various covariates, in order to highlight correspondence or discrepancies with the straight analysis in the previous section.

Figure 2.10 shows effort variation (trawl duration in hours) as a function of the latitude, longitude, depths, year, seasons, vessel type and region. Figure 2.9a – b, shows the model diagnostics, which check the distribution of the data around the mean, and whether the model assumptions are violated. The output from BAM, which considers the factors that can

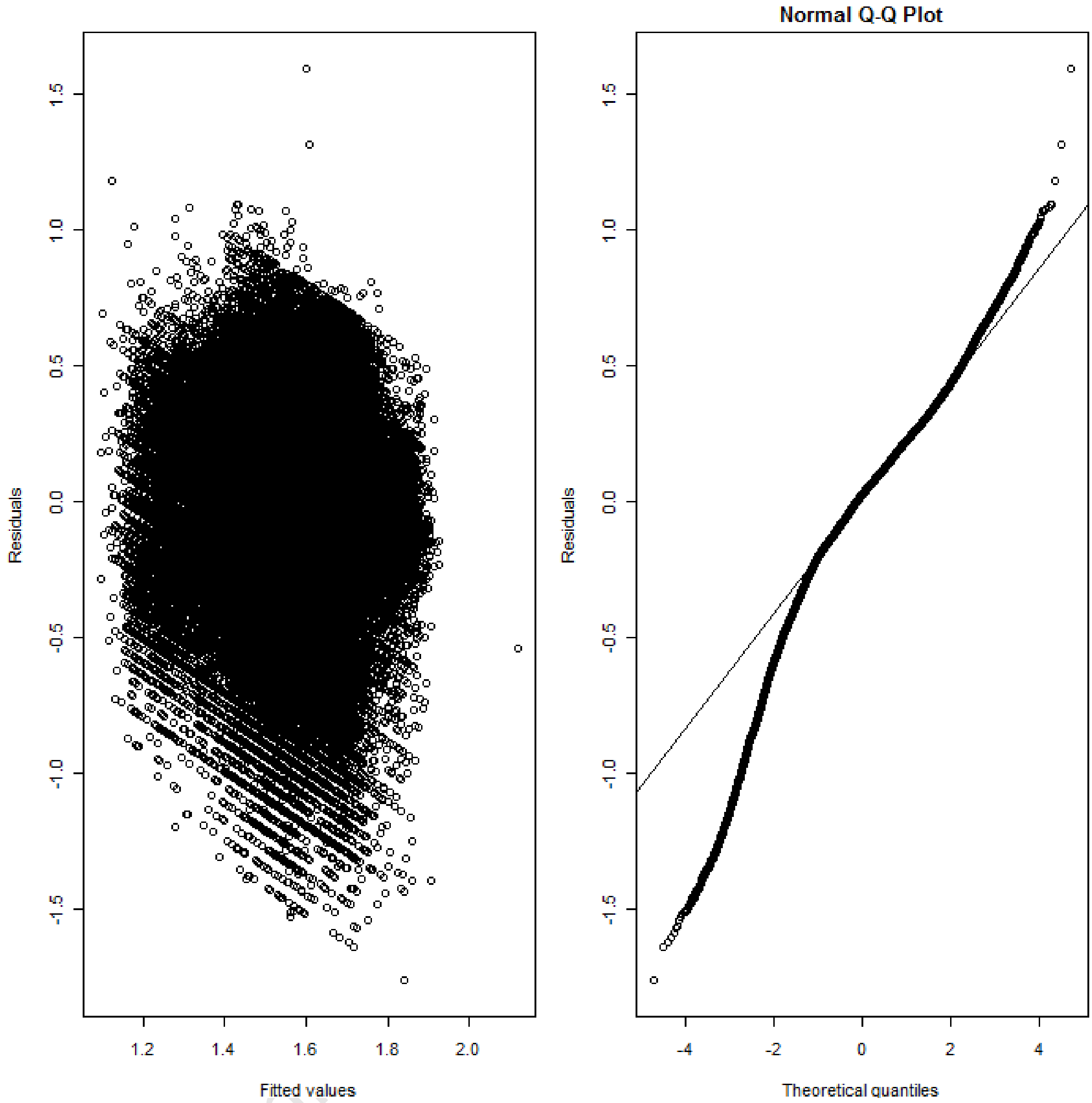


Figure 2.9a) Effort: GAM model diagnostics fitting

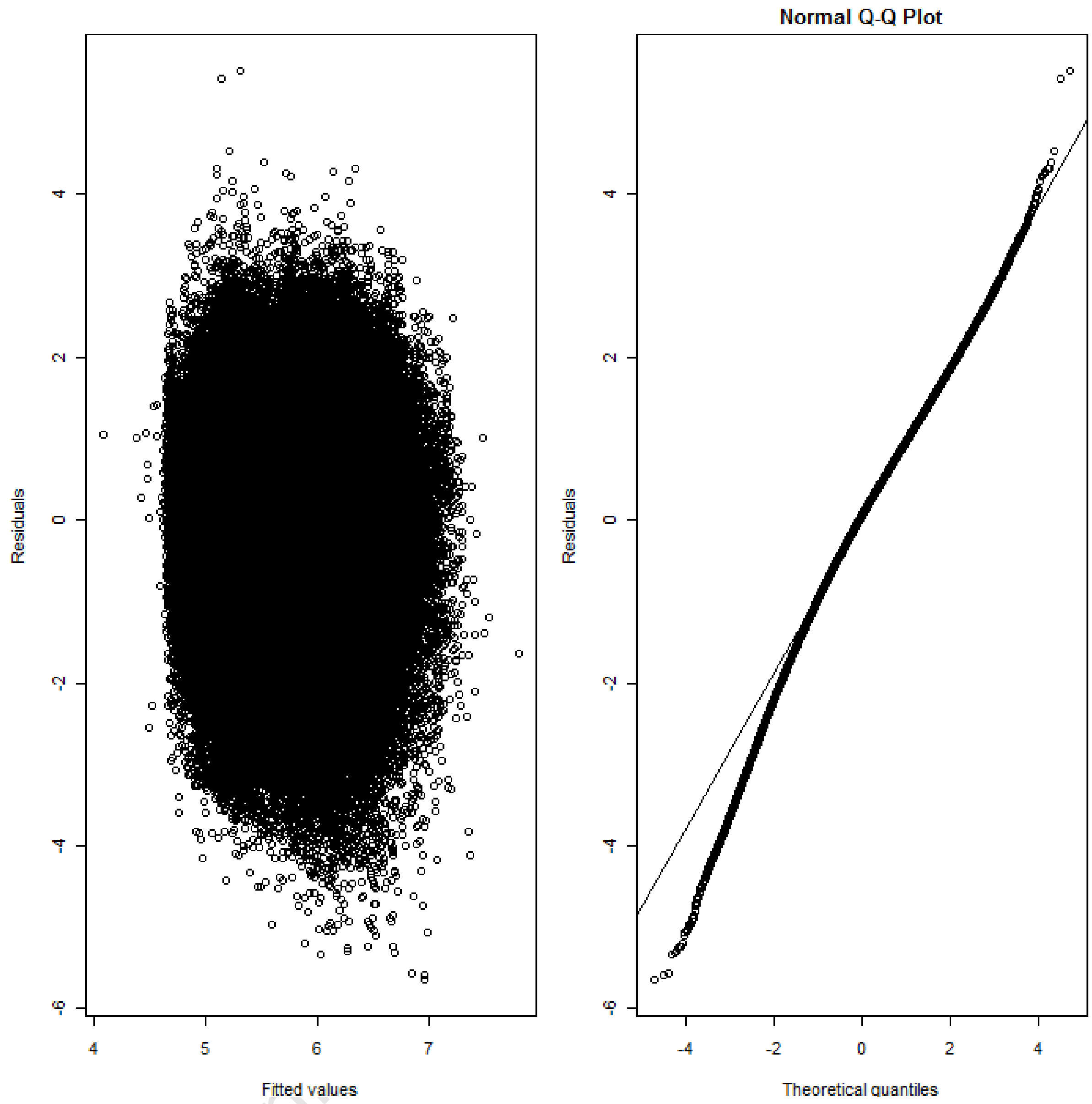


Figure 2.9b) CPUE: GAM model diagnostics fitting

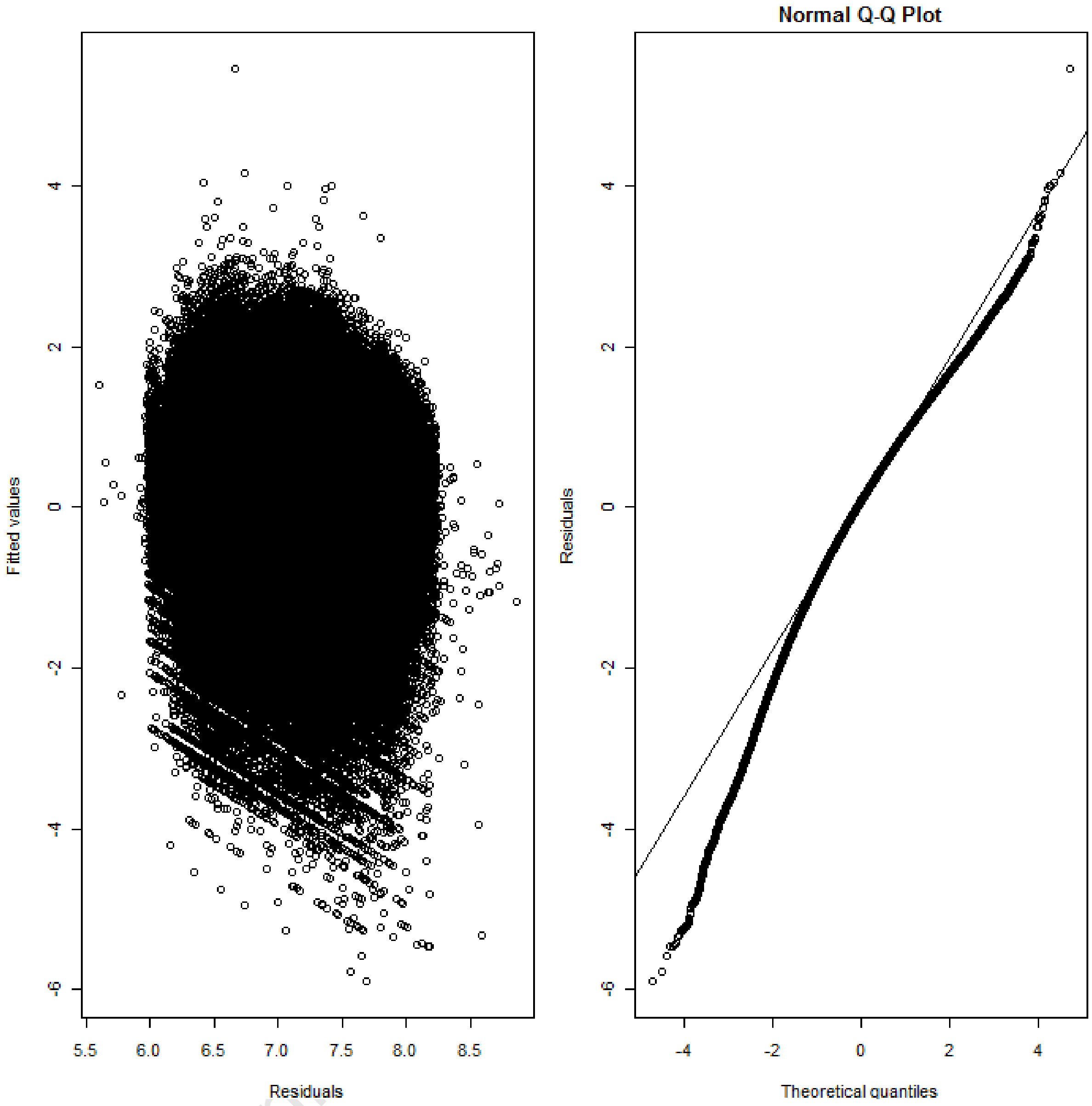


Figure 2.9c) Catch: GAM model diagnostics fitting

affect fishing effort, found high effort distribution in central Namibia between 21 to 25°S, with the highest fishing effort levels around 22°S. There was a downward trend towards the north and south of 22°S and effort reached a low at 26°S, but increased again further south of the 26°S latitude. In the northern regions, fishing effort declined almost linearly towards the northern border (Fig. 2.10).

Longitude effects on fishing effort can be misleading here due to the configuration of the Namibian coast, the continental shelf and bathymetry. The correlation between depth and latitude was less than 0.5, which is why it was included in the model. Effort increased steadily between 200 ─ 500 m, peaked at 600 m and maintained a high level between 550 ─ 800 m, then declined thereafter (Fig. 2.10). Effort varied from year to year. It increased between 2000 ─ 2003, slightly declined in 2004, then reached a peak in 2005, followed by a slight decline in 2006. Effort varied between the seasons, with highest effort in spring, followed by winter and summer. Autumn had the lowest effort. Freezer vessels were largely responsible for most effort compared to wet vessels. Most effort was devoted to southern Namibia, followed by the northern area, and least in central Namibia (Fig. 2.10).

The catch per unit effort (CPUE in kg/h) showed the opposite response to that of effort in relation to latitude and longitude (Fig. 2.11). The CPUE was initially high around 200 m with a declining trend. It began to increase at 350 m, peaked at 450m, then declined and reached a low at 600 m, and peaked again at 850 m, followed by a sharp decline thereafter (Fig. 2.11). The CPUE varied from year to year with 2001, 2002, and 2005 falling below the reference point of the first year, compared to 2003, 2004, and 2006, which were above the reference point. Seasonally, summer had the highest CPUE followed by autumn, then winter and lastly spring. The freezer vessels accounted for the high CPUE compared to the wet vessels. Across the regions, CPUE was high and at the same level in central and northern Namibia. It was lowest in the south (Fig. 2.11).

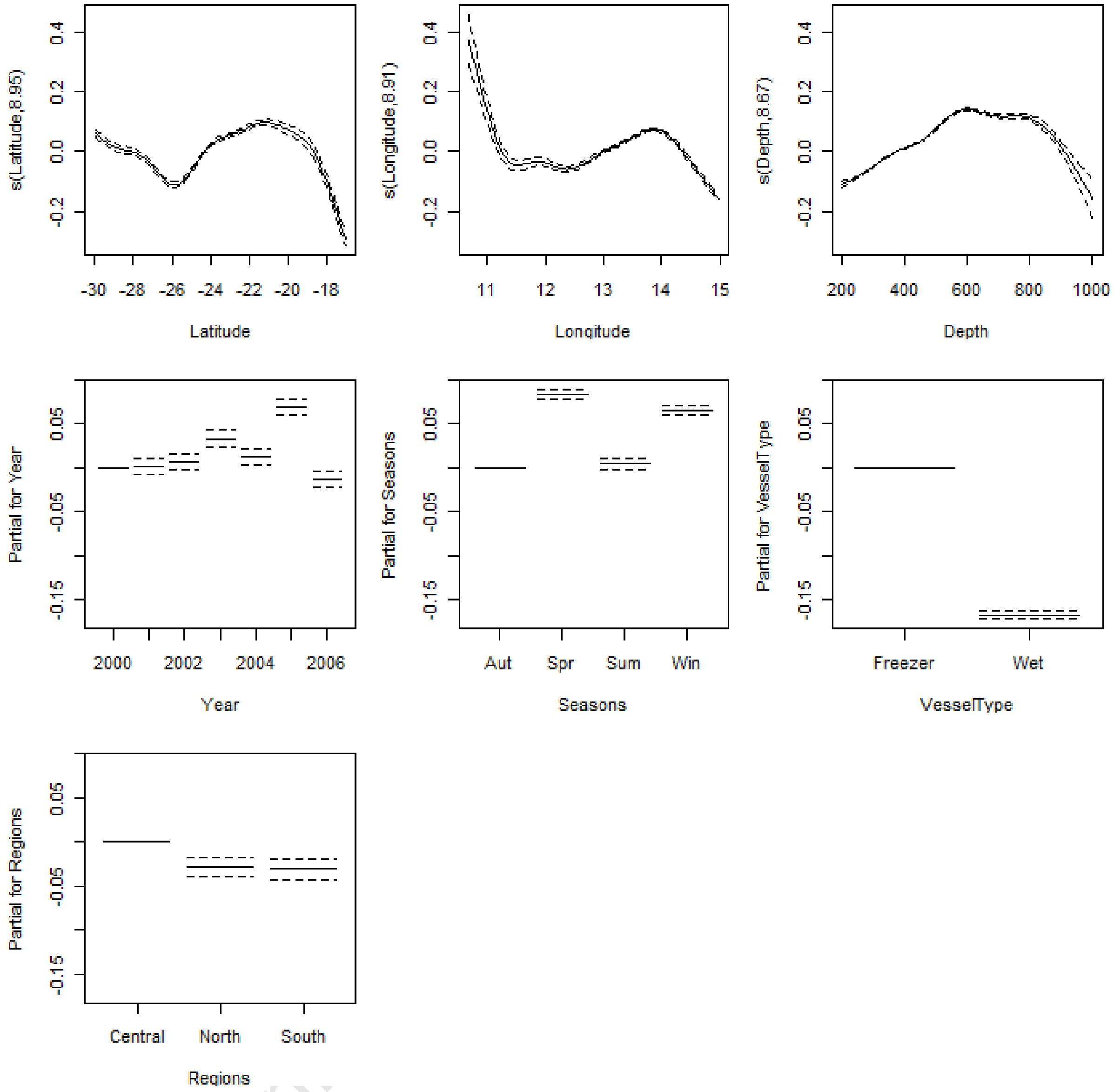


Figure 2.10 Effort variability (h trawling): Generalized Additive Model (GAM) smooths of the partial effect of latitude, longitude, depth, year, seasons, vessel type, and regions on effort. Dashed lines represent the 95 % confidence levels (Data: MFMR).

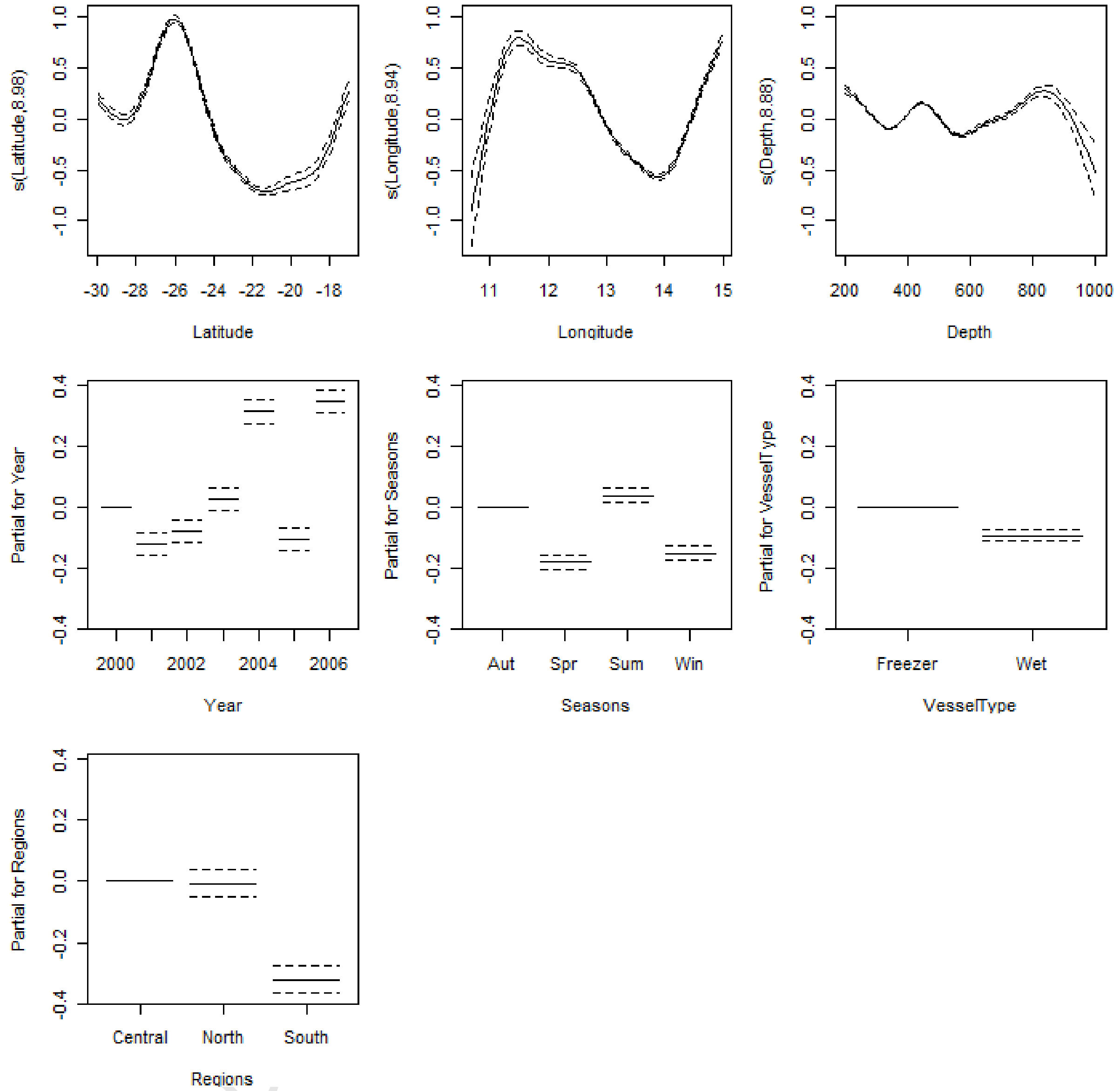


Figure 2.11 CPUE variability: Generalized Additive Model (GAM) smooths of the partial effect of latitude, longitude, depth, year, seasons, vessel type, and regions on the CPUE. Dashed lines represent 95 % confidence levels (Data source: MFMR).

2.4 Discussion

2.4.1 Fishery characterization

The demersal hake fishery is the most commercially valuable marine-capture fishery in Namibia, contributing more than half of the final fish value of all fish products (MFMR, 2001). A more detailed review of the hake fishery is provided in Chapter 1. In the effort by the national government to create jobs for Namibians, the historical quota allocation, which previously prioritised freezer vessels, was changed to allocate more quotas to the wet fish vessels. This enhanced the onshore processing of fish and the construction of new processing plants in Walvis Bay and Lüderitz, thus providing more jobs to local Namibians (Fishing Industry Handbook, 2006). Bigger freezer vessels stay longer at sea and they process their catch at sea, thus employing only a few crew members. Hence freezer vessels offer few jobs compared to shore-based processing, which employs more people (MFMR, 2006; Fishing Industry Handbook, 2006).

The TAC was steady around 180 000 tonnes, even though there was a relative increase in effort through an increase in hours trawled and number of trawl sets in 2003, coinciding with larger landed catches of hake. The increase in the number of vessels in the fishery coincided with the expansion of the trawling grounds into less accessible, previously unfished areas (Tables 2.1 and 2.2). These efforts may be facilitated by the development of new fishing gear and navigational aids (e.g. National Research Council, 1994).

2.4.2 Spatial distribution of bottom-trawl intensity

The bottom-trawl intensity as an annual mean of number of trawls (trawl frequency) within Namibian waters was patchy, with areas of high trawl intensity confined to small pockets and localised areas along the coast. The bottom-trawl intensity as an annual mean of trawl duration (time spent trawling) showed a similar pattern, but the distribution was increasingly uniform, although the areas with high trawl intensity were more localised in southern Namibia. However, this is contrary to the GAM output, which considered factors that could affect fishing effort. This indicates that at any given time during the study period, skippers maintained their average trawl duration of 4 hours per trawl, which could be related to and limited by fish quality. However, areas known to have high catches from previous experience were trawled more frequently than other areas. The observed patterns of patchiness are attributed to the fact that bottom-trawlers tend to target fishing grounds with historically high catches of the preferred size and quality of target species, (Henry Ngongwe, Hangana Fishing Company, Ltd,, Walvis Bay, skipper, *pers.comm*.) (Figs. 2.2, 2.3). This suggests that skippers would return to the same fishing grounds from year to year, and perhaps at the same time of the year, depending on their records in their logbooks.

Another factor that could contribute to patchiness is the distance to the trawl ground from the nearest landing harbour. The coast of Namibia has only two landing harbours, Walvis Bay (Central Namibia) and Lüderitz (Southern Namibia). Some fishermen prefer steaming to nearby fishing grounds to minimise fuel cost (Henry Ngongwe, Hangana Fishing Company, Ltd, Walvis Bay, skipper, *pers. comm*.). The patchy nature of otter trawl fisheries has also been noted in other regions (e.g. off Iceland, Ragnarsson & Steingrímsson 2003). Also important is the abundance or the density distribution (Kainge *et al.*, 2000, 2006) of the main target species in Namibian waters, with *M. capensis* found in high densities from the central region to the north, while *M. paradoxus* occurs in high densities in southern Namibia. The concentration of otter-trawls in deeper water (>300 m) appears to suggest they are in search of the deep-water hake, which sells well on the market, due to their quality flesh with good texture (Henry Ngongwe, Hangana Fishing Company, Ltd, Walvis Bay, *pers.comm*.). The volatility of fish market prices and exchange rates (www.economist.com.na), could also influence the observed patterns above. Fish sales fluctuate with the US dollar or euro exchange rate. Further investigations are clearly appropriate, but are beyond the scope of this thesis.

Fishermen apply their experience in search of fish; for any particular trawl set they take into account the wind speed, water temperature and colour of the water (Larie Pretorius and Henry Ngongwe, Hangana Fishing Company Ltd, Walvis Bay, *pers. comm*. and Dr. Barbara Paterson, MA-RE Institute, UCT, *pers. comm.).* The management measures for the 200 m isobaths trawl ban in Namibia (MFMR, 2001) may also have contributed to bottom-trawlers concentrating in deeper waters further offshore. The high level of trawl intensity may suggest that the concentration of trawl activity reflects the occurrence of local concentrations of target fish species, which may be affected in time due to changing environmental conditions (e.g. Benguela Niños; low oxygen water; wind stress and upwelling) and exploitation pressure. Another factor is the suitability of the seafloor for bottom-trawling, as was noted by Rijnsdorp *et al.*, (1998) for ground fish of the southern North Sea. According to the classification of trawl intensity in this study, the coast of Namibia has experienced low, moderate and heavy trawling per grid square over the period of seven years. However, there were more moderately and lightly trawled areas during this period, suggesting that heavy bottom-trawling in the fishery is quite localised.

Some studies in other parts of the world have shown that the recovery times tend to differ among marine benthic habitats with different sediment types (Churchill, 1989; Kaiser and Spencer, 1996). Hard bottom habitats, once destroyed, take longer to recover than the soft sediment habitats (National Research Council, 1994; Auster and Langton, 1999; Watling and Norse, 1998). This study revealed that bottom-trawl intensity is highest in areas covered by both soft and hard bottoms. Thus, future studies should be directed toward the assessment of the impacts of bottom-trawling on other benthic organisms in all marine habitat types off Namibia. In most cases, different ecological constraints affect the habitat selection by marine species. Environmental factors such as temperature, salinity, depth and backscattering have been shown to affect the spatial distribution of marine species (Laurs *et al.*, 1984; Castilo *et al.*, 1996; Paramo *et al.*, 2003; Taylor and Rand, 2003). Habitat selection by fish might be based on presence and absence of their prey, predators and competitors (Kramer *et al.*, 1997; Fréon and Misund, 1999, Drapeau *et al.*, 2004), and bottom dissolved oxygen, especially off Namibia.

This study has demonstrated that the intensity of bottom-trawling off Namibia ranged from light to heavy, with more than 50% of the fishing area lightly trawled, while 30% of the area experienced medium trawling and 20% experienced heavy trawling that was patchily distributed.

2.4.3 Analysis of effort and CPUE variability, 2000 – 2006

General data output

Almost all bottom-trawling for hake takes place off the shelf area, which has a surface area of 110 000 km^2 inside the 200 m depth contour from the shore, and approximately 230 000 km^2 inside the 1000 m depth contour (MFMR, 1991). More than half the total effort (in terms of both trawl duration and number of trawls) was concentrated in waters with the depth range 200 – 399 m, and most of this effort was directed towards the southern part of Namibia. The variation in annual average fishing effort reflects the changes in the annual TAC allocations and the number of participating vessels per year. Consequently, effort (number of trawls sets and total duration trawled) increased in response to increased and decreased TAC, thus suggesting TAC may have been a partial driver for effort.

Seasonal fluctuations in average fishing effort indicated that autumn had the highest fishing effort, which coincided with the end of the fishing season and the start of the new fishing season after the TAC announcement in April every year. The lowest average in fishing effort occurred in December when many industries reduce their work for Christmas and New Year holidays. It is surprising that in spring the fishing effort is almost the same as in the winter, as the fishery is closed for the month of October. Thus, the observed seasonal pattern in spring, could be an artefact of two factors. Firstly, the hake becomes scarce (low catchability) (Gordoa and Hightower, 1991; MacPherson *et al*., 1991; Voges, 2003) due to migration to spawning grounds (Gordoa *et al*., 1995; Kainge *et al*., 2007), and secondly the management measure to close the season in October, which has been in place since 2006 for (MFMR, 2005).

Although there are no reference points in terms of past trawl intensity off Namibia prior to independence, indirect measures of trawl intensity could be deduced from the size of the catches and the number of vessels, which participated in harvesting the hake resource (MFMR, 2004). It is likely, based on catches (Payne, 1989), that during those periods there were large numbers of vessels compared to more recently and high catches could translate into former high abundance., There may also have been overexploited and heavily trawled fishing grounds. The near-collapsed state of stocks in Namibian waters at independence prompted government action to reduce effort and TAC for most of the fished stocks, including hake (MFMR, 2006). Therefore, in the absence of historical numerical reference points for bottom-trawl intensity in the past (pre-independence), the bottom-trawl intensity patterns observed in this study could be those of an ecosystem recovering from a period of heavy exploitation, as indicated by the landings of hake (e.g. Payne, 1989). A system with a lower level of exploitation (after-independence), despite the expansion of ground to deeper waters, is being established. The TAC and quota-based management of the fishery after independence reduced the number of participants in the fishery thus indirectly allowing recovery of the stock.

Seasonal fluctuations in CPUE suggest changes in fishers' behaviour towards the catchability of the target species. The freezer vessels had the high CPUE, suggesting they were catching more fish since their fishing effort was higher than the wetfish vessels. Regionally and depth-wise, the CPUE pattern (Fig. 2.8) is generally similar to the fishing effort pattern (Fig. 2.7). The relationship between vessel size, gear size and distance from harbour in relation to depth may be an interesting topic for future research. One might expect larger vessels to frequent deeper waters compared to smaller ones, and their swept area could be different, depending on the gear size (Ragnarsson and Steingrímsson, 2003). However, the data for this study suggest otherwise. The larger freezer vessels operate frequently in waters 200 – 399 m deep, and their presence in deeper waters decreases with increasing depth. Trawl duration is not expected to vary greatly with size of gear or depth, since it is probably affected by the quantity of fish, the target species and gear obstructions. Thus, trawl duration alone may be regarded as an inappropriate measure of effort, since it overlooks the variations in trawl gear size (Greenstreet *et al*., 1999; Jennings *et al*., 1999). For this reason, an additional measure of trawl intensity, namely trawl frequency, was also considered and was found to depict similar trends. A previous study by Wilkinson and Japp (2007) used the counts of trawls per 20' x 20' grid square in South African waters. Although the characterization of trawl intensity was done at low resolution in their study, no other attempts are known to exist in the Benguela Ecosystem. Thus, this chapter represents the second study in the Benguela Ecosystem, and the first of its kind off Namibia.

The GLM analysis was explored first on the effort and CPUE, but the response obtained was that the data were non-linear. Therefore, it was not pursued further, and the GAMs were used for further analysis. However, the GLM was used to test for the significance of the variation in the effort and CPUE with a couple of covariates and their interaction effects. All the observed patterns in the effort and CPUE as shown above were highly significant. Thus, changes in years, depth, season, vessel type and regions had their significant contributions to the observed patterns. All interactions by the covariates indicated that they were also significant, reflecting the dynamism of the upwelling ecosystem, affecting the effort and CPUE in any year, depth stratum, season, vessel type, and region.

Generalized Additive Model (GAM) output

This sub-section illustrates the differences in the output from the data, when multi-factor effects are considered in the model exercise. However, the whole model could only explain 18 and 14 percent of the variation in fishing effort (duration in hours) and CPUE respectively. Therefore, inferences based on this model output do not give an clear answer to the dynamics of the commercial effort data. Other descriptors (e.g. actual horsepower used while trawling, distance to port, fuel consumption of vessels, and fish value) of this fishery are needed for input in the model in order to account for more variation. Thus, based on the data limitations, this aspect of this study cannot be discussed further.

2.5 Conclusion

This study has illustrated the temporal and spatial distribution of bottom-trawl intensity off Namibia for the first time.

- Bottom-trawl intensity measured as average duration of tow was uniform, and it was patchy when measured as number of trawls per grid.
- On average, the most bottom-trawling took place in southern Namibia, with some large areas heavily trawled, followed by central Namibia with pockets of heavy trawling.
- The least trawling activity occurred in the north, but there were also areas of heavy trawling.

- Bottom-trawling occurred in both soft sediments (mud-sand) and hard substratum (sand-gravel).
- Total duration and number of trawls per grid declined with increasing depth.
- Season was found to play an important role in both the mean fishing effort and CPUE, with autumn and winter having the highest fishing effort; while autumn had the highest CPUE in seven years.
- The GAMs analysis could only account for less than 20% of the variance, thus making them weaker predictive models in this case, due to the unavailable additional covariates from the data.

The hake biomass survey methodology used in Namibia since 1990

3.1 Introduction

Since Independence in 1990, the government of the Republic of Namibia has established the National Marine Information and Research Centre (NatMIRC) in Swakopmund and Lüderitz, under the auspices of the Ministry of Fisheries and Marine Resources. The personnel at these centres have a national mandate to manage sustainably and protect the nation's marine living resources and to undertake scientific research within Namibia's 200 nautical mile (nm) exclusive economic zone (EEZ). The concept of sustainable management and protection of marine resources was well received by international donors and in response to the needs of the Namibian government, the Royal Norwegian government commissioned one of their research vessels to undertake research in Namibian waters in 1990. This helping hand was not only to conduct research, but also to provide training for Namibian marine scientists at Institutions of higher education in Norway, with financial support in the form of scholarships through the Norwegian Agency for Development Cooperation (NORAD) programme.

From 1990, the *R/V Dr Fridtjof Nansen* (*Nansen*) operated in Namibian waters and annual hake biomass surveys were conducted using this vessel until 1998, when a changeover took place. Inter-calibrations between the commercial vessels and the *Nansen* were conducted every time a commercial vessel was chosen to conduct the survey for the first time, in order to have consistent comparable data series. This was done by running parallel surveys on the *Nansen* and the commercial vessel, using the same trawl gear and applying the same methods. Commercial bottom trawlers (*Oshakati,* owned by Tunarco Group and *Garoya,* owned by Northern Fishing, for the 1st and 2nd leg, parallelled with *Nansen* in 1998; *Ribadeo,* owned by NovaNam Fishing, parallelled with *Nansen* in 1999; *Frans Aupa Indongo,* owned by Cato Fishing, parallelled in 2000; *Oshakati*, parallelled in 2001 and *Blue Sea 1,* owned by Blue Sea Fishing, formerly *Garoya*, parallelled from 2002 to present) were then commissioned after the inter-calibration to the same standards as the *Nansen*. These vessels were fitted with the same gears used on the *Nansen* (Kainge *et al*., 2008). Since 1990, consistent survey methodology has been followed during all the hake biomass surveys (for more details see Strømme, 1992; Voges, 1999; Iilende *et al.,* 2000; Burmeister *et al.,* 2000, 2001; Kainge *et al*., 2003, 2004, 2005, 2006, 2007, 2008).

The annual hake biomass surveys are normally conducted in January and February each year and they cover the whole coastline of Namibia from the Kunene River in the north to the southern border off the Orange River (Figure 3.1). The surveys cover depths from 100–600 m, corresponding to the offshore distribution of the two species of hake, *M. capensis* and *M. paradoxus*. The methods used to calculate the biomass estimates were based on depth stratification, as recommended during the 2000 BENEFIT Stock Assessment Workshop (Anon, 2000).

Since Namibia took sole responsibility for conducting hake biomass surveys on commercial vessels in 2001, no acoustic measurements were recorded during the surveys. Prior to 2000, the annual hake biomass surveys included acoustics, but this has been discontinued and this thesis is based only on data derived from swept area surveys (demersal trawling). Juvenile hake (< 20 cm) are always excluded from the analysis as they have a different ecology from the rest of the adult population and are usually not available to the bottom trawl, since they spend most of their time in the pelagic zone (Iilende *et al*., 2001).

3.2 Survey design

The same survey design has been followed since 1990; a systematic transects design, with a semi-random distribution of stations along transects. Stations within transects were selected in such a way that each 100 m bottom depth category had at least one station. In the extreme south, where the shelf is very wide, stations on the shelf were about 10 nm apart. Transects ran perpendicular to the Namibian coastline and were about 20–25 nm apart, with transect lengths ranging from 20–80 nm (Figure 3.1).

Most of the hauls are done during the day in waters shallower than 450 m, generally between 06h00 and 19h00 hours local time (GMT+2) (Kainge *et al*., 2005, 2006, 2007, 2008; Johnsen and Iilende, 2007), because hake (especially *M. capensis*) is known to lift off the bottom at night (Iilende *et al*., 2001), possibly in search of prey (Kainge *et al*., 2008). Bottom lifting of hake (*M. paradoxus*) in deeper waters is considered minimal (Ingólfsson *et al*., 2005). Trawling was also conducted during the night after 19h00, but only up to 24h00 (GMT+2), and this was done to verify the commercial vessel fishing activities at night. As Johnsen and Iilende (2007) suggested the tendency of vessels to fish in deeper waters is due to the fact that they catch more *M. paradoxus*, which are bigger fish and so bigger catches. Thus this type of strategy may cause negatively biased diel amplitude estimates (Johnsen and Iilende, 2007), which may affect the biomass estimates for hake, since most hauls are conducted during the day and relatively few hauls at night during surveys. However, for the purpose of standardisation, all the hauls after 19h00 were excluded from the analyses in this thesis, especially in chapters based on the Namibian annual hake biomass surveys from 1990 to 2006. All aspects of data cleaning and confirmation are dealt with in detail in the respective chapters of this thesis, which are based on these scientific survey data.

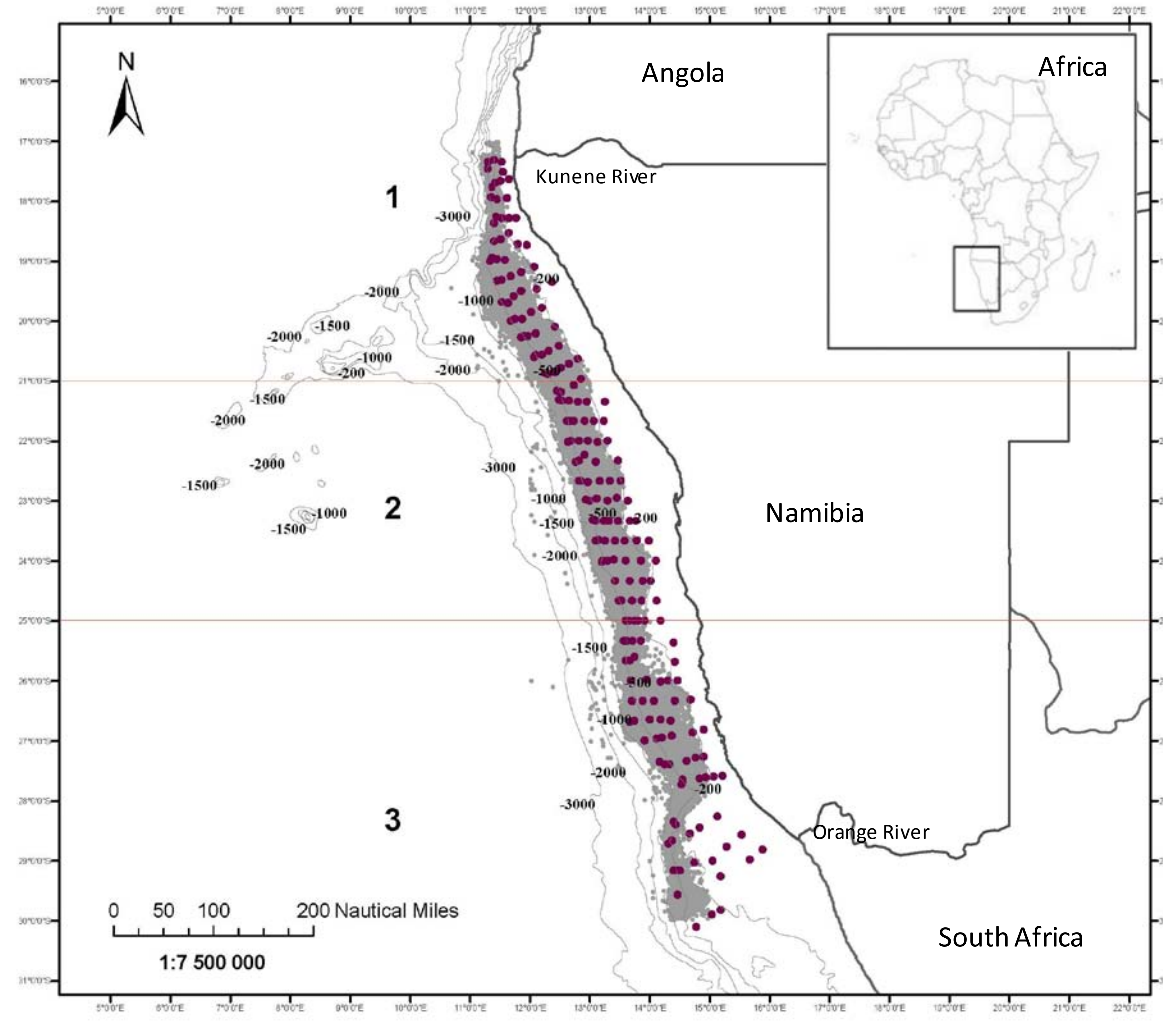


Figure 3.1-Fixed trawl stations (dots) followed during the annual hake biomass surveys overlayed on all the commercial bottom trawl stations per grid square from 2000 to 2006. The scientific surveys follow a systematic transect design. Transects ran perpendicular to the coast, covering the whole coast from the Kunene to the Orange River.

3.3 The trawl gear and vessel equipment

A Gisund Super two-panel bottom trawl with head length 31 m, footrope 47 m and the vertical net opening 4.0 to 5.5 m was used (Figure 3.2). SCANMAR trawl sensors were used to determine the trawl depth, bottom temperature, amount of catch, vertical opening of the net, clearance from the bottom and the distance between the doors during trawling for each haul. This information is not recorded but is used for controlling the trawl net by the Fishing Master. The distance between the wings during towing was about 18-21 m. The outer lining of the cod-end was 20 mm while the inner-net was 10 mm. The sweeps were 40 m long and connected the trawl to the *Steinshamn* doors, which had a total area of 6.7 m^2 and a mass of 1 800 kg.

Trawl speed was 3.0 knots on average (range 2–4 knots) and standard trawling time was usually 30 minutes (except at times when trawls are interrupted due to high densities of fish or “soft” bottoms). Thus a distance of approximately 1.5 nm was covered at each station. The length of the trawl wire (wire out) was about 3 times the bottom depth on the shelf and about 2.5 on the slope (deeper than 450 m bottom depth). The course (direction) of trawling operations was decided upon based on the bottom topography and the bottom current, but in general it was in a northerly direction. A 12 m constraining rope was attached between the warps, 150 m in front of the doors. This rope is intended to keep the distance between the doors constant at about 50 m, irrespective of trawl depth or wind direction. However, door spread, together with trawl height were not opening to intended ranges (5 and 50 m respectively), and extra floats (300 mm) were attached to the float-line to give an opening of about 5 m. In addition, the doors’ angle of attack was enlarged, as well as the swivel, which attached the sweeps to the vessels, in order to get a door spread of about 50 m.

There have been some gear changes as follows: constraining rope was introduced in 1994; a different trawl gear was introduced in 1994; trawl doors were changed in 1990 and these were used from 1990 – 1992. Different doors were used in 1993 and they were changed again in 1994 and were used from 1994 – 1997; different doors were used for the period 1998 to 2006. Non-gear changes are those of vessels as mentioned earlier, as well as vessel crew and captains (Bjorn Erik Axelsen and Espen Johnsen, IMR, Bergen, *pers.comm.*).

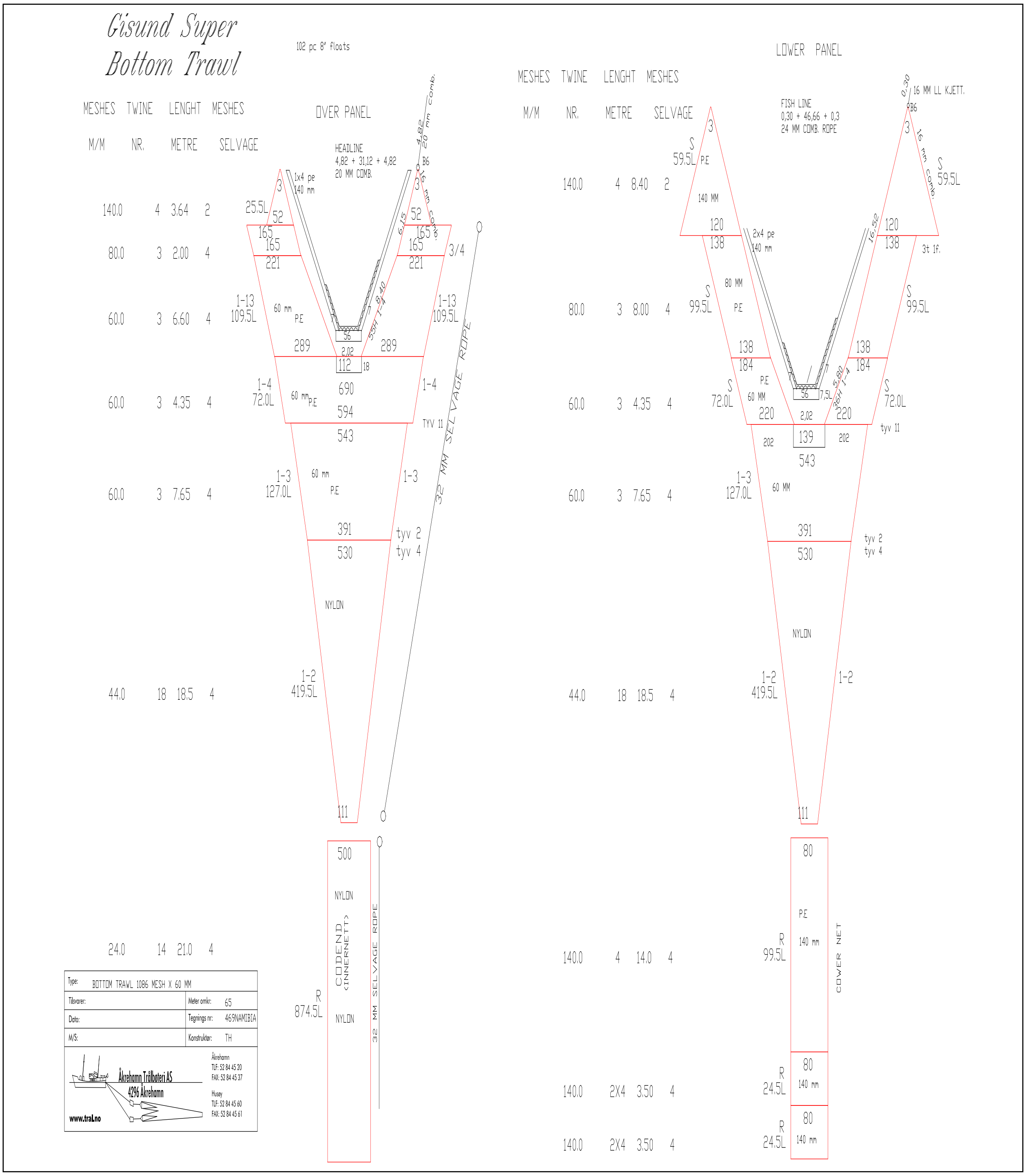


Figure 3.2 Trawl configuration for the hake biomass surveys (1990–2007). This gear has been used on both the *Nansen* and any commercial vessels which were commissioned to conduct the hake biomass survey. Adapted from the Nansen programme (Anon, 2006).

3.4 Deck Sampling Procedure

Once the trawl net is on the deck of the research vessel, the following is the consistent deck sampling procedure. This procedure varies with the size and composition of the catch, which is recorded as total catch by species in kg and number. In particular, the two species of hake (*M. capensis* and *M. paradoxus*) are enumerated separately onboard. Subsequently, the total catch is converted into catch per hour by the *Nan-Sis,* based on the duration of the haul (Strømme, 1992).

If the catch is small the whole catch is sorted by species and weighed. In the case of a big catch, several random samples are taken from the whole catch. The weight and number of the species are then raised according to the following ratio:

$$\frac{Total\ Weight\ of\ Catch}{Sample\ Weight\ of\ Catch} \quad \text{.................................} \ (3.1)$$

The two methods can also be combined. All the bigger fish species can be removed from the total catch and measured separately, while for smaller and more abundant species, a sample may be taken and the figures adjusted according to the raising factor. In the case of small and numerous species, one can even take a sub-sample from the sample to obtain a weight/number ratio, in order to avoid counting all the specimens in a sample (Strømme, 1992). Rare species are also identified to species or at least to genus level for later identification to species level (Paul Kainge, NatMIRC, MFMR, *pers comm.*), and the *Nan-Sis* database is subsequently updated.

3.5 Data Processing and Management

3.5.1 Biomass estimates

Unless otherwise stated, the procedures for the calculation of hake biomass estimates (by swept area method) that follow below were taken from Strømme (1992).

The swept area (SA) of a haul during a survey in nm^2 is calculated by:

$$SA_i = (d_i * b) \qquad (3.2)$$

where d_i is the log or trawl distance (in nm) at station i. It can be converted to metres (m), since it is the product of trawl speed and trawl duration. It may also be calculated as the distance between start and end position (GPS). b is the effective gear width (usually measured in m but can be converted to nm), measured as the distance between the wings of the trawl, in this case assumed to be constant at 18.5 m. This can be converted to the swept area per hour at station i, SA_i from the equation:

$$SA_i = d_i * \left(b \middle/ t_i \right), \qquad (3.3)$$

where

d was the log or trawl distance (in nm can be converted to m), which is the product of trawl speed and trawl duration or as the distance between start and end position (GPS).

b was the effective gear width (usually measured in m but can be converted to nm), measured as a distance between the wings of the trawl, assumed to be constant at 18.5 m; and

t_i was the duration of the trawl (minutes).

The basic assumption behind the swept area analysis is that the density of species (t/nm^2 or kg/m^2) in the sea is proportional to the mean catch rate (kg/hour) by the research vessel (Strømme, 1992). For conversion of catch rates to fish densities, $d*b$ is assumed to be equal to the effective fishing area and the catchability factor (q) is assumed to be constant and equal to 1, assuming (for simplification) that all fish in the area swept by the trawl were caught by the net. Which q to use is subject to discussion, although most studies apply a q value between 0.5 and 1 (Doubleday and Rivard, 1981). The *Nan-Sis* uses a default q = 1, and this produces the minimum estimate of biomass in the range.

Since *b* is in metres (1852 m = 1 nm) and *t* in minutes (60 min = 1 hour), swept area becomes:

$$SA_i = d_i * \left(\frac{b/1852}{t_i/60} \right) nm^2 / hour \quad \text{................ (3.4)}$$

The surveyed area (100–600 m bottom depth) was subdivided into 100 m depth strata (Table 3.1).

Table 3.1. Areas in square nautical miles for 100 m strata as used in the stratified calculation for the swept area during the hake biomass surveys

Depth zone (metres)	Area in square nautical miles
101 – 200	20921
201 – 300	9942
301 – 400	8518
401 – 500	3387
501 - 600	2283

Density of fish (in t/nm^2 or kg/m^2) in the trawl *i* was calculated using the following relationship:

$$Y_i = \frac{Catch_i}{Swept\ Area_i} \quad \text{............................ (3.5)}$$

For each of these 100 m depth strata the mean density was calculated and the total biomass, variance and co-efficient of variance (CV) were also calculated.

The stratum mean density ($\overline{Y_i}$) was calculated from the following formula:

$$\overline{Y_i} = \frac{\sum_{j=1}^{n_i} Y_{ij}}{n_i} \quad \text{.........................} \ (3.6)$$

where Y_{ij} represents the individual densities in stratum *i* and n_i the number of individual densities in stratum *i* (Cochran 1977).

The stratified mean density ($\overline{Y_{str}}$) was calculated by:

$$\overline{Y_{str}} = \frac{\sum_{i=1}^{L} A_i \overline{Y_i}}{A} \quad \text{.......................} \ (3.7)$$

where L was number of strata, A the total area, A_i the area of the stratum *i*, and *i* the individual strata (Cochran 1977). The total biomass index was thus calculated by:

$$B = \overline{Y_{str}} \, A \quad \text{..............................} \ (3.8)$$

The variances of biomass index and standard error (*SE*) of the stratified mean were also calculated and the precision for the estimates/coefficient of variation (*CV*) (Zar, 1999) was calculated by:

$$CV = \frac{SE}{Biomass} \quad \text{......................} \ (3.10)$$

The calculation of the total biomass indices was based on depth stratification and this stratification was chosen as both species have a depth-related distribution (Macpherson and Duarte, 1991; Burmeister, 2001) and survey sampling covered the main depth ranges of the main target species.

3.5.2 Data recording

The data collected during each trawl station (station and operation information, catch composition by weight and number, total length and weight of all commercially important species and some bycatch, as well as some biological data, i.e. sex and gonad maturity of the target species) were stored in the *Nan-Sis* database. This database is still managed by the Nansen programme, and all the data collected after the *Nansen* left Namibia were sent to the database for inclusion in the *Nan-Sis*. However, the Ministry of Fisheries and Marine Resources still has full ownership and control over the use of the data. The data are carefully cleaned and verified by the scientists at NatMIRC before they are entered into the database.

3.6 Environmental Data

Collection of environmental data (temperature, oxygen and salinity) is also done during the surveys for a selected number of stations on some transects. This is mainly done by deploying a Seabird SBE 19plus CTD instrument and a battery operated *Hydrobios Slimline* rosette was used to collect water samples at pre-determined depths. The water samples are used for titration of dissolved oxygen by the Winkler method, and for analysis of nutrients and salinity. Environmental data collected during the annual hake biomass survey do not correspond with the number of stations sampled over the years under review. Thus, there are many gaps in the data which cannot be used for numerical analysis in determining the influence of the environment on the observed patterns in the biology. However, existing data were made available with permission from the Ministry of Fisheries and Marine Resources in some published and unpublished reports and are properly cited as such. The end-product graphs and composite maps were available for use in this study to help with qualitative analysis and explanation of some of the observed results in various chapters of this thesis.

The effects of bottom trawling on the demersal fish communities off Namibia: assessing changes in size structure

4.1 Introduction

Studies around the world, both empirical and theoretical, have demonstrated that the size composition of fish communities is affected by fishing pressure (Rice and Gislason, 1996; Haedrich and Barnes, 1997; Gislason and Rice, 1998; Bianchi *et al*., 2000, 2001; Shin and Curry, 2004; Yemane *et al*., 2006). Fishing is known to be size selective, and this is one way of many in which fisheries interact with the structural and functional organization of the marine ecosystem. Continuous removal of large fish, which are more valuable, modifies the size structure and the functioning of the fish assemblage, which may result in low productivity and lowered resilience of some stocks (Shin *et al*., 2005). Essentially, size-based indicators may provide a lead towards integration of the effects of fishing on fish communities and processes (Shin *et al*., 2005) into the concept of an ecosystem approach to fisheries (EAF) (Garcia *et al*., 2003).

A range of indicators has been developed to capture the effects of fishing on fish community size structure, such as average size of fish in the community, modal length, mean weight and size spectra (Rice, 2000; Rochet and Trenkel, 2003; Shin *et al*., 2005). The application of these indicators depends entirely on the type of data available, structural and functional aspects of the community or ecosystem being studied, and whether or not the indicator possesses the desired attributes expected of an ecosystem indicator, such as sensitivity to fishing, meaningfulness to the objective of the investigation, easily understandable and readily measurable (Rochet and Trenkel, 2003; Degnbol and Jarre, 2004). The size spectra technique is currently one of the most promising sources of indicators and is still under development (Rochet and Trenkel, 2003; Shin *et al*., 2005, 2010; Yemane *et al*., 2005, 2008). Mean community weight or length, mean maximum length and proportion of abundance by size class have also been shown to capture changes in the size structure of fish communities (Daan *et al.,* 2005, Yemane *et al.*, 2005; Shin *et al*., 2010).

The community structure of demersal fish off Namibia was assessed by Bianchi *et al*. (2001) from 1990 to 2000. The authors found different communities inhabiting the lower shelf (100–300 m) and the upper slope (300–600 m), with no clear trend in the abundance and biomass comparison (ABC) curves. The use of the ABC method is explored fully in Chapter 5 of this thesis. This chapter incorporates an additional six years of data and revisits the size structure of demersal fish communities to assess changes over 17 years (1990–2006), also including assessment of changes in mean catch rate and mean catch length of demersal fish communities off Namibia that can possibly be attributed to bottom-trawling.

Figure 4.1 Map of Namibia showing the three marine regions, North, Central and South. The outer extent marks the limit (200 nautical miles) of the EEZ. The horizontal lines at 21^{o}S and 25^{o}S mark the border for north and central, and central and south regions respectively.

4.2 Materials and methods

The study area covers the whole 200 nm EEZ of Namibia stretching from the Kunene River mouth in the north to the Orange River mouth in the south, covering a distance of approximately 1500 km. The data used were collected during the annual hake biomass surveys from 1990 to 2006 for the first quarter of each year, since surveys were conducted bi-annually in the early 1990s, but only annually thereafter. For details of sampling and data collection methods see Chapter 3. For the purpose of this thesis the Namibian coast was divided into depth stratum (shelf and slope), then three regions: north (17^o – 20^{o}59’59’’S), central (21^o – 24^{o}59’59’’) and south (25^o – 29^{o}59’59’’) (Fig. 4.1) and each region further sub-divided into sub-regions (slope and shelf). For the purpose of this thesis the continental shelf refers to an area within the depth zone 100–300 m and the continental slope to an area within the depth zone 301–600 m. All these divisions were done in ArcGIS v9.3 (ESRI software for mapping, www.esri.com).

The usage of the terms ‘communities’ and ‘assemblages’ in this thesis should be viewed as specific; the communities are merely a collection of species occurring in the same place (boundaries defined) at the same time and these species are not restricted by phylogeny or resource use, whereas assemblages are phylogenetically related groups of organisms within a community (for review see Fauth *et al*., 1996).

4.2.1 Catch rate by size class

All pelagic families such as the Carangidae and Clupeidae (see Chapter 1, under hake fishery) were excluded from the analysis because the emphasis is on demersal fish (teleosts and chondrichthyes) species in this study. Given species *i* and haul *j*, the mean individual weight was calculated by dividing the catch in weight (W_{ij}) by the number of individuals caught (N_{ij}). Therefore, for a given trawl over the study period (1990–2006), the mean individual weights (g) were derived from the available total weights (kg) and numbers for each species caught, which were subsequently converted to mean length per species, using the theoretical length-weight relationship ($W = 0.01L^3$). The use of a theoretical length-weight relationship introduces the assumption that growth is isometric (Bianchi *et al.*, 2001; Yemane *et al.*, 2004). Although this might introduce some errors, it is still a reliable method used to calculate length in the absence of length-frequency data (Bianchi *et al.*, 2000, 2001).

The whole coast was sub-divided into the following sub-regions: northern shelf; northern slope; central shelf; central slope; southern shelf; southern slope. Although these sub-divisions are arbitrary, they experience varied fishing pressure, with the southern region experiencing the greatest fishing pressure and the northern region the least (details are given in Chapter 2). This provides the opportunity to assess the temporal changes in size structure that might possibly be attributed to different fishing intensities. The mean catch rates by 20 cm size class (<20, 21–40, 41–60, 61–80, > 80 cm) in each year for the whole coast and across the sub-regions adopted for this study were calculated according to equations (1) by stratum, (2) by year, and (3) by sub-region, below.

$$\overline{CatchRate_{ijk}} = \frac{\sum CatchRate_{ijk}}{n_{jk}} \quad . \quad . \quad . \quad . \quad . \qquad (1)$$

$$\overline{CatchRate_{ik}} = \frac{\overline{CatchRate_{ijk}} * Area_j}{\sum_{j=1}^{N} Area_j} \quad . \quad . \quad . \quad . \quad . \qquad (2)$$

$$\overline{CatchRate_{irk}} = \frac{\sum CatchRate_{irk}}{n_{irk}} \quad . \quad . \quad . \quad . \quad . \qquad (3)$$

Where $\overline{CatchRate_{ijk}}$ is the mean catch rate per size category *i*, for *i* = 1 to 5 (<20, 21–40, 41–60, 61–80, > 80 cm) in the stratum *j* for *j* = 1 to 2 (shelf and slope) in year *k* for *k* = 1990 to 2006, n_j is the number of trawls in stratum *j*; $\overline{CatchRate_{ik}}$ is the mean catch rate per size category *i*, for *i* = 1 to 5 for the whole coast in $year_k$ for *k* = 1990 to 2006, $Area_j$ is the area of stratum *j*, *N* is the total number of strata; $\overline{CatchRate_{irk}}$ is the mean catch rate by size class *i* in sub-region *r* for *r* = 1 to 6 (northern shelf and slope; central shelf and slope; southern shelf and slope), and year *k*, $CatchRate_{irk}$ is the catch rate in size class *i* sub-region *r* and year *k*.

The mean catch rate by size class, for each stratum and sub-region, was calculated by dividing the total catch rate (numbers per 30 minutes trawled) in a size class by the total number of trawls conducted in the strata or sub-regions concerned. The mean catch rate by size class for the whole coast was calculated as a weighted mean of the continental shelf and slope mean catch rate – using the area of the continental shelf and slope (see appendix 4.1) as a weight. The significance of a temporal trend in the mean catch rate by size class was assessed by fitting linear regressions, and the significance of the slopes of the linear regression was determined using Student's t-test (Zar, 1999).

4.2.2 Mean length

The length frequency data, which were prepared based on mean length calculated from mean weight per species, for the construction of size spectra, were used to calculate mean length of the community. Mean length of the community corresponding to the stratum, whole coast, and sub-region was calculated according to equations 4, 5, and 6 respectively. The significance of the temporal trend in the mean length was assessed by fitting a linear regression to the mean length versus survey year. The significance of the slope of the linear regression was determined using Student's t-test (Zar, 1999).

$$Mean\_length_{jk} = \frac{\sum class\_mark_{cjk} * abundance_{cjk}}{\sum abundance_{cjk}} \quad . \quad . \quad . \qquad (4)$$

$$Mean\_length_{k} = \frac{\sum Mean\_length_{jk} * Area_{j}}{\sum_{j=1}^{N} Area_{j}} \quad . \quad . \quad . \quad . \qquad (5)$$

$$Mean\_length_{rk} = \frac{\sum class\_mark_{crk} * abundance_{crk}}{\sum abundance_{crk}} \quad . \quad . \quad . \qquad (6)$$

Where $Mean\_length_{jk}$ is the mean length of the community in stratum *j* for *j* = 1 to 2 (shelf and slope); $class\_mark_{cjk}$ is the class mark *c* (the mid-point of the interval) of the length frequency in stratum *j* in year *k* for *k* = 1990 to 2006; $abundance_{cjk}$ is the abundance of the class mark *c* in stratum *k* in year *j*; and $Mean\_length_{k}$ is the mean community length of the whole coast in year *k*; $Area_{j}$ is the area of stratum *j*; *N* is the total number of strata for *N* = 2; $Mean\_length_{rk}$ is the mean length of the community in region *r* for *r* = 1 to 6 in year *k*; $class\_mark_{crk}$ is the class mark *c* of the length frequency in region *r* and year *k*; $abundance_{crk}$ is the abundance of the class mark *c* in region *r* and year *k*.

4.2.3 Construction of size spectra and temporal trends in the slope and height

The size spectra using mean length were constructed by using the existing weights and numbers for each species in each haul, because not all species caught in each haul had their length recorded during sampling. To generate size spectra, size classes were determined to correspond to 5 cm length intervals, using the size range 21 – 80 cm as that part of the descending limb of the size spectra. The number of individuals in each size category k (N_k) was then calculated by distributing all the N_{ij} over the length classes according to their mean length. The natural logarithm of abundance (N_k) was then plotted against the logarithm of the mid-point of each size class. The parameters (slopes and heights) of size spectra were estimated using linear regression for the descending limb of the size-frequency distribution (Bianchi *et al*., 2000, 2001; Yemane *et al*., 2004, 2005). The heights were estimated as in Daan *et al*. (2005) at the mean of the independent variable to avoid its correlation with the slope. Intercepts and slopes of the size spectra are strongly correlated; thus, Daan *et al*. (2005) supported the use of heights of the size spectra, instead of the intercept, to avoid statistical correlation, thus trends tracked by the heights of the size spectra capture biological information. The changes in the slopes of the size spectra are interpreted to represent changes in relative abundances of small versus large fish, whereas changes in the heights suggest changes in the overall abundance of the fish assemblage (Daan *et al*., 2005; Yemane *et al*., 2005).

Separate size spectra were constructed at a broad spatial scale (whole coast) and at a small spatial scale for the northern, central and southern regions for both the shelf and slope. Temporally size spectra were constructed for the period 1990 – 2006. Temporal patterns in the slope and height of the size spectra were assessed to deduce the changes in size structure.

4.3 Ancillary Information

This section contains information collated from both published and unpublished materials, which is cited as such. In addition, the SST anomalies, upwelling index, and the position of the Angola-Benguela-Front (ABF) data were supplied with anomalies and indices already calculated by scientists at MFMR (Nadine Moroff, NatMIRC, MFMR, *pers. comm*.), and were plotted on graphs for the purpose of this study. This information is believed to be helpful in the interpretation of the size structure of demersal fish species.

4.3.1 Hake recruitment index

The recruitment index for *M. capensis* was estimated from the proportion of this species of hake in the diet of seals (from otoliths in seal scats) in the Lüderitz area for the previous winter and using the empirical relationship established during the first seven years (hake in seal diet in year 1 versus number of recruits estimated in *Nansen* survey in year 2, log-log relation) (Jean-Paul Roux, MFMR, *pers. comm*.).

4.3.2 Environmental variables

NatMIRC, MFMR in Swakopmund, supplied all environmental data used in this Chapter. The upwelling favourable wind anomalies and upwelling index were calculated from the monthly averages (1990 – 2006) of the wind records at Lüderitz. The SST for central Namibia is based on annual average (1990 – 2006) records of SST from a monitoring line at 23^{o}S off Walvis Bay. The position of the Angola-Benguela-Front (ABF) is based on the latitudinal annual averages for the monthly position of the frontal system captured via satellite using the 17^{o}C isotherm. The data SST anomalies, ABF and Upwelling index were supplied by Nadine Moroff, NatMIRC, MFMR, *pers. comm*., (NatMIRC, MFMR, Swakopmund, Namibia).

4.4 Results

4.4.1 Long-term spatio-temporal trends in the catch for the whole coast

The long-term spatio-temporal trends in the catch rates of demersal fish were investigated for the whole coast (mainly the continental shelf and slope components at 100–600 m depth) off Namibia. Temporal trends in the mean catch rate (abundance. 30 minutes tow^{-1}) per size class for the whole coast for the period 1990–2006 show little or no change at all size ranges of demersal fish communities (Fig. 4.2). Relatively high mean catch rates are evident in the smaller size groups (< 20 cm size class), and catch rates are lowest in the bigger size groups (> 80 cm size class) (Fig. 4.2). Regression analysis for the mean catch rate revealed no significant trends over years under review in any of the size classes considered together across all depths (Table 4.1). Nonetheless, a negative slope was estimated in the following size classes: < 20; 41–60; 61–80 cm and a positive slope in the size classes: 21–40 and > 80 cm (Table 4.1).

4.4.2 Long-term spatio-temporal trends in the catch for the continental shelf and slope

A similar trend was observed when the coast was divided into two bathymetric divisions (continental shelf and slope). There are some observed temporal variations in terms of mean catch rate from year to year for both the shelf and slope, but the most evident consistent pattern was the decline in the overall mean catch rate with increase in size class (from the smallest <40 cm to the largest >80 cm) (Fig. 4.2). On the continental shelf, the result of linear regression showed that there was a significant ($t = -2.73$, $n = 17$, $p < 0.05$) decline in mean catch rate in the size class 41–60 cm over the study period (Table 4.1), while all other size classes had no significant changes. The continental slope region experienced a significant increase in the mean catch rate in the following size classes: < 20 cm ($t = 3.94$, $n = 17$, $p < 0.05$); and 21–40 cm ($t = 3$, $n = 17$, $p < 0.05$) over the study period (Fig. 4.2 & Table 4.1). Other apparent trends were not significant.

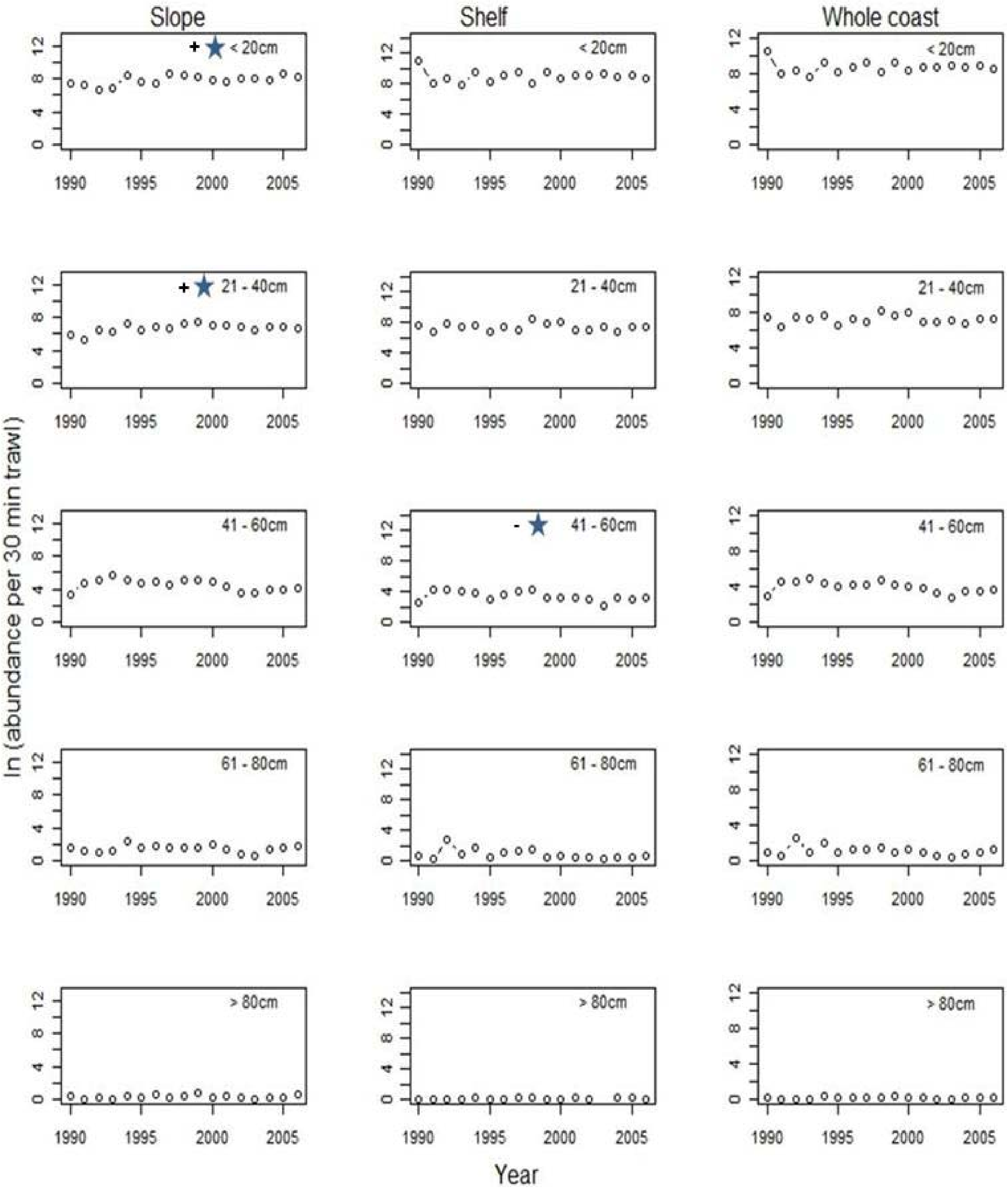


Figure 4.2 Mean catch rate for demersal fish off Namibia, expressed as the natural logarithm of abundance per 30 minutes tow, for the continental slope (300 – 600 m deep); continental shelf (100 – 300 m deep); and the whole coast (100 – 600 m deep, pooled data) for the following size classes (< 20; 21 – 40; 41 – 60; 61 – 80; > 80 cm), over the period of 17 years, based on hake survey data. The star indicates significant

(at 5% level) trend (+ for positive trend, and – for negative trend) for the slopes in the mean catch rate, see Table 4.1 for details.

Table 4.1 Results of linear regression fitting mean catch rate per size class as a function of survey year, at 5% level. (The * in the p-value column denotes significantly different trends from zero, $p < 0.05$) (i.e. significant change over time). Est. Slope is estimated slope (positive and negative trends); Std. Error is standard error.

	Whole Coast (all depths)			
Size Class (cm)	**Est. Slope**	**Std. Error**	**t - value**	**P - value**
< 20	0.00	0.03	-0.14	0.89
21 - 40	0.00	0.02	0.12	0.91
41 - 60	-0.04	0.03	-1.21	0.24
61 - 80	0.00	0.04	-0.01	0.99
> 80	0.05	0.04	1.24	0.24
	Shelf (100 - 300 m)			
< 20	-0.03	0.04	-0.82	0.42
21 - 40	-0.03	0.02	-1.17	0.26
41 - 60	-0.08	0.03	-2.73	0.02*
61 - 80	-0.09	0.05	-1.74	0.10
> 80	0.03	0.03	0.90	0.39
	Slope (300 - 600 m)			
< 20	0.01	0.03	3.91	0.00*
21 - 40	0.09	0.03	3.00	0.01*
41 - 60	-0.23	0.03	-0.67	0.51
61 - 80	0.03	0.03	0.96	0.36
> 80	0.07	0.05	1.38	0.19

4.4.3 Spatio-temporal trends in the mean catch rate per size class by region

4.4.3.1 Continental shelf sub-regions

Temporal trends in the mean catch rate (abundance per 30 minutes tow) for each of the 20 cm size classes were additionally assessed by sub-region over the 17 years (1990 - 2006). Figure 4.3 shows the spatio-temporal trends in the mean catch rate for the shelf region (100 – 300 m deep) sub-divided into sub-regions: north, central and south. At this finer scale, the mean catch rate for the northern shelf sub-region for the size class: 41 – 60 cm (slope = -0.19, t = -2.68, n = 17, $p < 0.05$) has significantly declined over the years under review (Fig. 4.3 and Table 4.2). In the same sub-region other size classes have not shown any significant changes. On the central continental shelf, there was a significant increase (slope = 0.06, t = 2.20, $p < 0.05$) in the mean catch rate for the size class < 20 cm, while no other size classes showed any significant changes over the study period (Fig. 4.3 and Table 4.2). On the southern continental shelf, the mean catch rates for all the size classes did not show significant trends.

4.4.3.2 Continental slope sub-region

For the continental slope region, general fluctuations in the mean catch rate over different size classes and sub-regions were observed over the 17-year period (Fig. 4.4). There was a significant increase in the mean catch rate in size class < 20 cm in the northern slope sub-region (slope = 0.06, t = 2.35, $p < 0.05$); and a significant decline in the mean catch rate for the size class 41 – 60 cm (slope = -0.08, t = -2. 15, $p < 0.05$) (Fig. 4.4 and Table 4.2). On the central continental slope, significant increases in the mean catch rates for the smaller size groups, viz < 20 cm and 21 – 40 cm (slope = 0.11, t = 3.02, $p < 0.05$ and slope = 0.08, t = 2.74, $p < 0.05$ respectively) were estimated (Table 4.2). The southern continental slope sub-region had a significant increase in the size class > 81 cm (slope = 0.03, t = 2.58, $p < 0.05$) (Table 4.2). All other mean catch rates showed no significant temporal trends (Table 4.2).

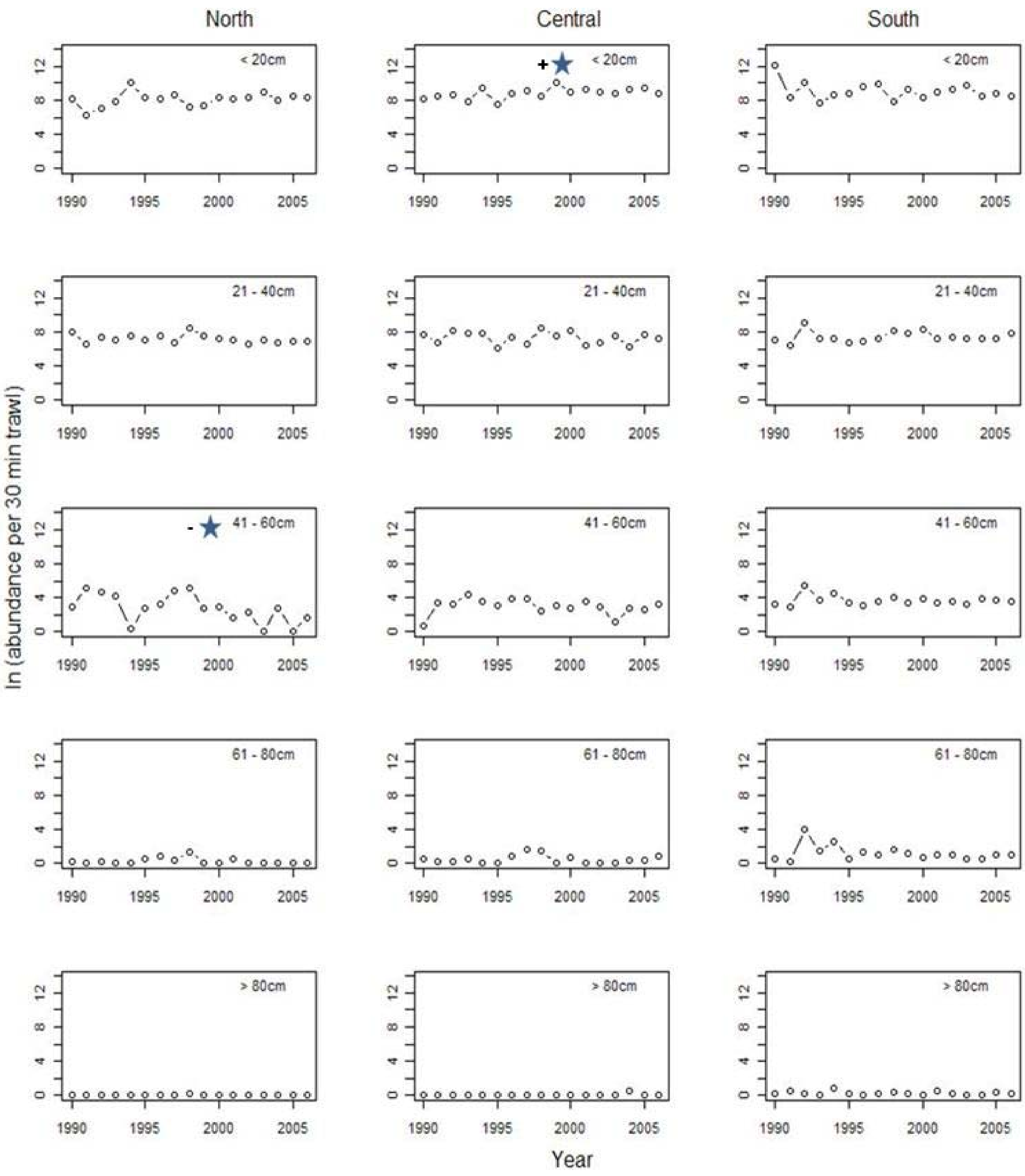


Figure 4.3 Continental shelf region (100 – 300 m): Temporal trends in the mean catch rate (as the natural logarithm of the abundance) for demersal fish (all species combined) per size class per sub-region during the annual hake surveys off Namibia from 1990 to 2006. The star denotes significant ($p < 0.05$) trend (+ for positive trend, and – for negative trend) for the slopes in the mean catch rate, i.e significant change over time.

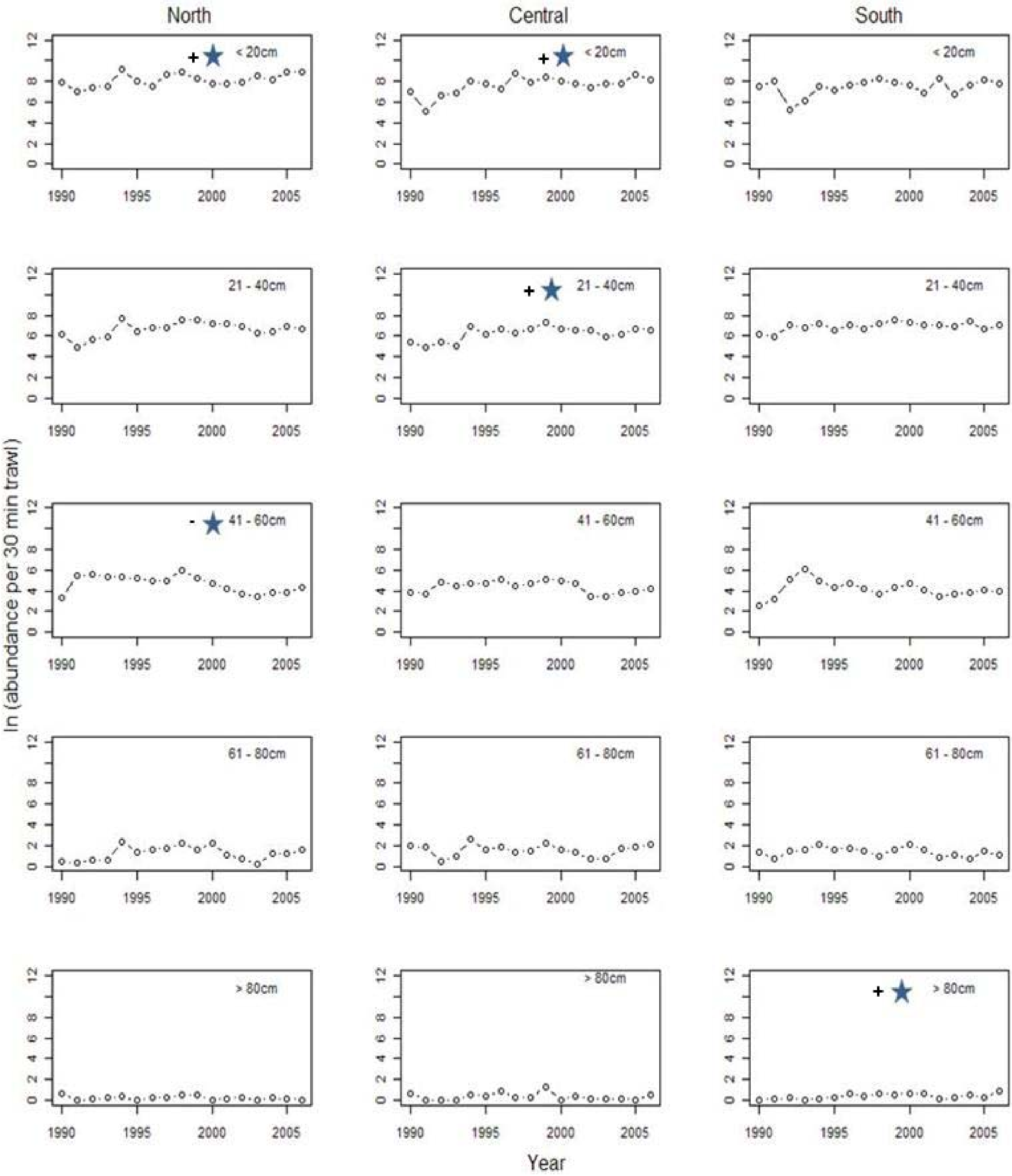


Figure 4.4 Continental slope (300 – 600 m deep): Temporal trends in the mean catch rate (as the natural logarithm of the abundance) for demersal fish (all species combined) per size class per sub-region during the annual hake surveys off Namibia from 1990 to 2006. The star denotes significant ($p < 0.05$) trends (+ for positive trend, and – for negative trend) in the slopes of the mean catch rates over the years.

Table 4.2 Mean catch rate per size class by sub-region: results from the linear regressions tests for significant differences (at 5% level) in the slopes of the catch rates over time, the star (*) next to p-values denotes significant (p < 0.05) trends, i.e. significant change over time.

	Northern Shelf (100 - 300 m)					**Northern Slope (300 - 600 m)**			
Size Class (cm)	Est. Slope	Std. Error	t - value	p - value	Size Class (cm)	Est. Slope	Std. Error	t - value	p - value
< 20	0.04848	0.0405	1.197	0.25	< 20	0.06197	0.0264	2.347	0.0330*
21 - 40	-0.03734	0.02357	-1.585	0.134	21 - 40	0.06169	0.03413	1.807	0.0908
41 - 60	-0.18744	0.06974	-2.688	0.0169*	41 - 60	-0.08004	0.03717	-2.153	0.0480*
61 - 80	-0.01239	0.01849	-0.67	0.513	61 - 80	0.02511	0.03473	0.723	0.481
> 81	0.001127	0.002775	0.406	0.69	> 81	-0.010585	0.009702	-1.091	0.292
	Central Shelf (100 - 300 m)					**Central Slope (300 - 600 m)**			
< 20	0.06232	0.02837	2.196	0.0442*	< 20	0.10669	0.03536	3.018	0.00866*
21 - 40	-0.02687	0.03643	-0.738	0.4721	21 - 40	0.07733	0.02822	2.74	0.0152*
41 - 60	-0.01768	0.04671	-0.378	0.71	41 - 60	-0.0289	0.02771	-1.043	0.313
61 - 80	-0.00172	0.025641	-0.067	0.947	61 - 80	-0.003694	0.029617	-0.125	0.902
> 81	0.00674	0.006773	0.995	0.335	> 81	-0.007935	0.01742	-0.455	0.655
	Southern Shelf (100 - 300 m)					**Southern Slope (300 - 600 m)**			
< 20	-0.05952	0.05018	-1.186	0.254	< 20	0.05445	0.03873	1.406	0.18
21 - 40	0.01295	0.03295	0.393	0.7	21 - 40	0.03896	0.01871	2.082	0.0549
41 - 60	-0.01445	0.03113	-0.464	0.649	41 - 60	-0.02298	0.04183	-0.549	0.591
61 - 80	-0.05691	0.04525	-1.258	0.228	61 - 80	-0.02081	0.02113	-0.985	0.34
> 81	-0.00343	0.010681	-0.0322	0.752	> 81	0.02782	0.01077	2.582	0.0208*

4.4.4 Spatio-temporal trends in mean catch length

The mean catch length for the whole coast, continental shelf and slope showed some fluctuations from year to year with slight decreasing trend observed only for the slope region during 1992 – 2006 (Fig. 4.5).

4.4.4.1 Whole coast

The whole coast (pooled depth) showed the lowest mean catch length of less than 10 cm in 1990 and then a steady increase reaching a relatively higher mean catch length close to 20 cm in 1993, after which it varied inter-annually with no clear trend (Fig. 4.5). The overall temporal trend in the mean catch length is positive, but was not significant (Table 4.3).

4.4.4.2 Continental shelf

The mean catch length for the continental shelf region varied inter-annually, but was relatively lower throughout the time series compared to the continental slope, except for 1998. The lowest and highest mean catch lengths were estimated in 1990 and 1998 respectively (Fig. 4.5).

4.4.4.3 Continental slope

The continental slope region experienced similar fluctuations in the mean catch length, although it was relatively higher compared to the shelf region (Fig. 4.5). The mean catch length had an upward trend from 1990 and reached its peak of 26 cm in 1992, after which it declined consistently, though characterized by inter-annual fluctuations (Fig. 4.5). Although the temporal trends on the continental slope were those of continuous decline, they were not significant (Table 4.3).

Table 4.3 Regression tests for significant difference from zero (at 5% level) for the mean catch length, i.e. significant change over time.

	Est. slope	*Std. error*	*t – value*	*p - value*
Shelf	0.01	0.13	0.06	0.95
Slope	-0.26	0.15	-1.80	0.09
Whole coast	0.02	0.12	0.20	0.84

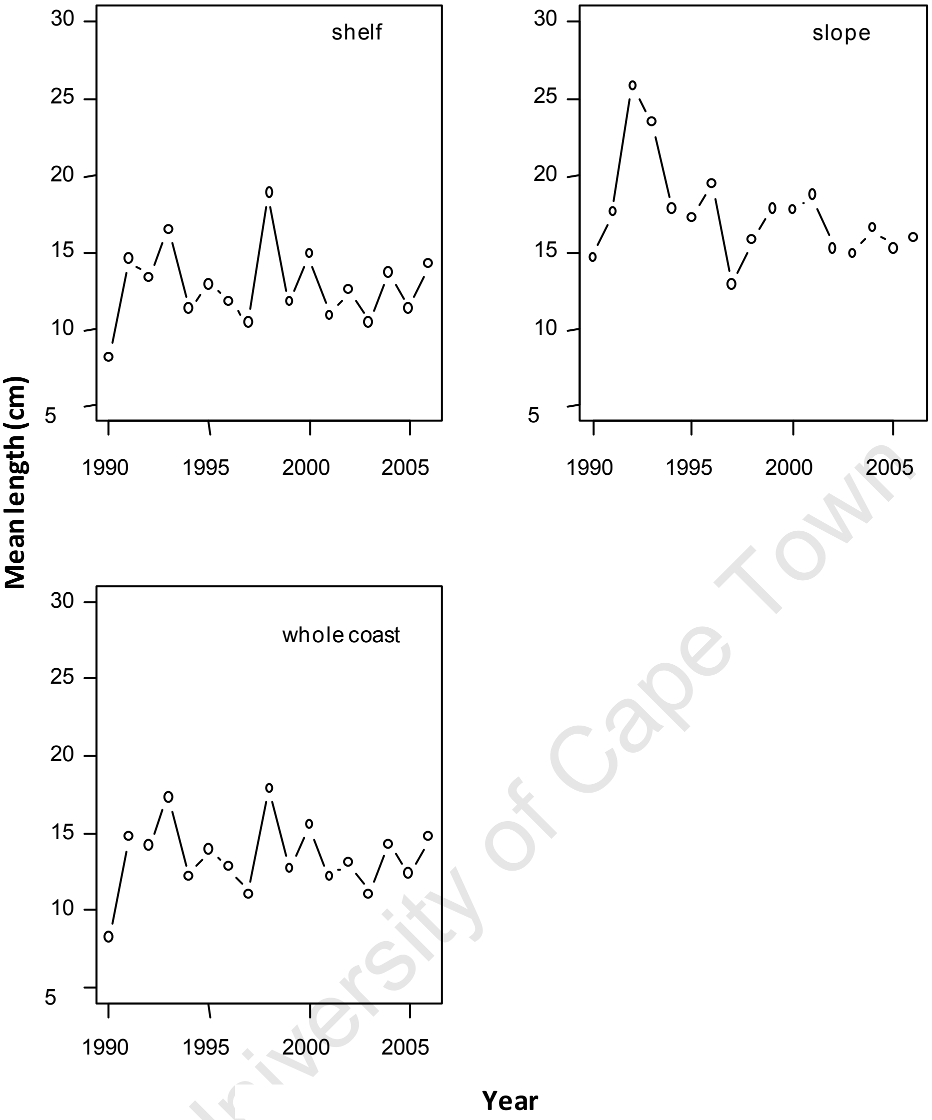


Figure 4.5 Spatio-temporal trends in the mean catch length (cm) of demersal fish assemblages on the shelf (100 – 300 m); slope (300 – 600 m); and the whole coast (pooled depth) off Namibia, for the period 1990 – 2006. Data derived from the annual hake surveys for summer. See Table 4.3 for significance tests of the slopes in mean catch length over the years.

4.4.4.4 Sub-regions

The continental shelf and slope sub-regions were further subdivided into the north, central, and south sub-regions. The results for the mean catch lengths are shown in Figure 4.6 and results of the tests of the significance of the slope of the linear regressions in Table 4.4. The northern and central continental shelf sub-regions showed negatively declining mean catch lengths, although these would be significant only at $p < 0.10$, they may be biologically important to note (Table 4.6). The northern and central continental slope sub-regions showed significant overall declining temporal trends in the mean catch length (Fig. 4.6, Table 4.4). In the south, a decline is indicated for the period 1992 – 2006, but not during the period 1990 – 2006.

Table 4.4 Tests for significance of the linear trend in mean catch length for all the demersal fish species off Namibia by regions. The star (*) denotes significant ($p < 0.05$) trends, i.e. significant decline over time.

Region		*Est. Slope*	*Std. error*	*t - value*	*p - value*
Shelf	North	-0.20	0.10	-1.96	0.07
	Central	-0.39	0.19	-2.03	0.06
	South	0.16	0.15	1.04	0.31
Slope	North	-0.33	0.14	-2.31	0.04*
	Central	-0.19	0.09	-2.23	0.04*
	South	-0.23	0.26	-0.87	0.40

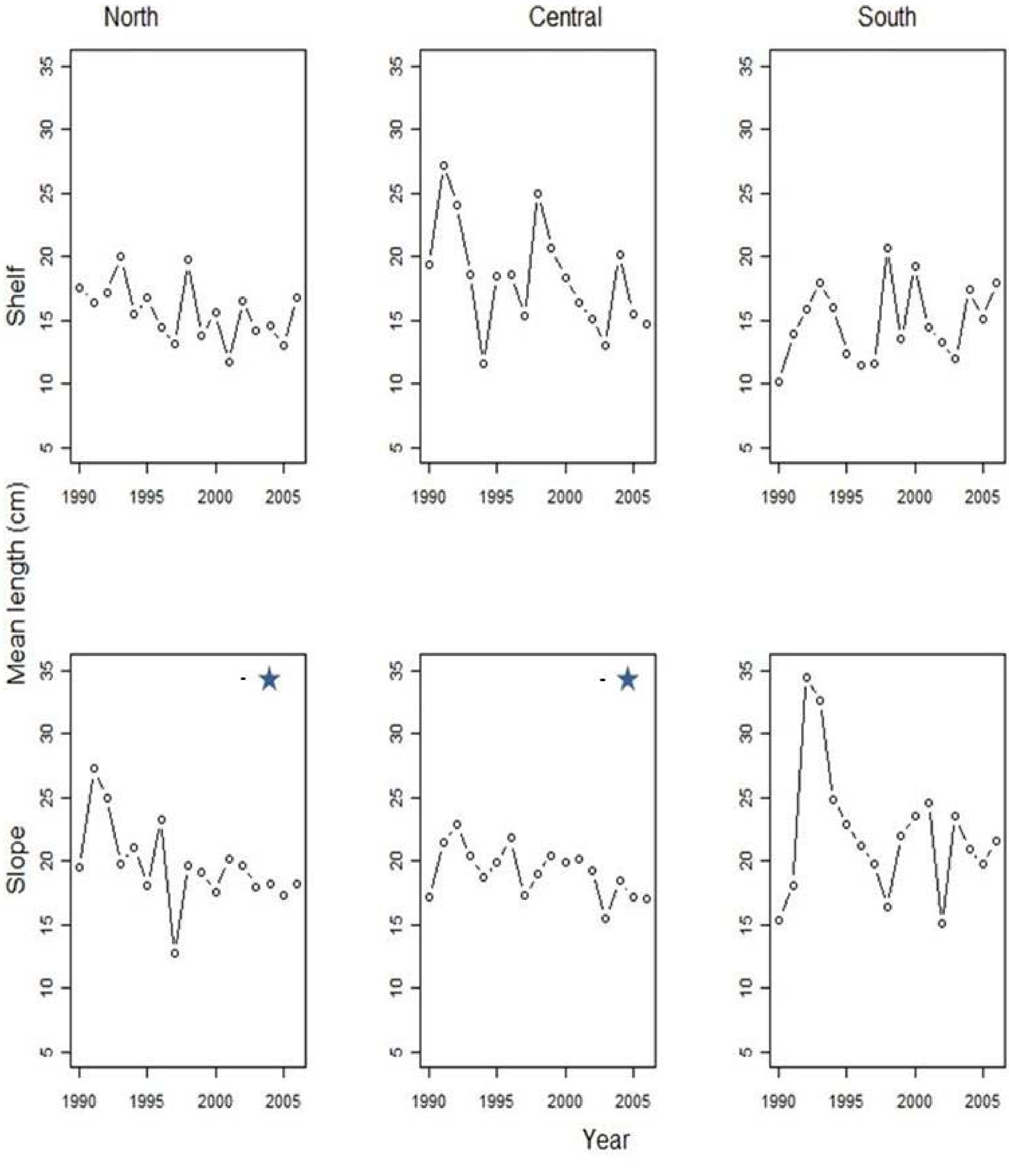


Figure 4.6 Regional: Spatio-temporal trends in the mean catch length (cm) for all the demersal fish species in the annual hake surveys for the Namibian shelf (100 – 300 m depth) and the continental slope (300 – 600 m depth) from 1990 to 2006. Data derived from the annual hake surveys for summer. The star denotes significant ($p < 0.05$) trend (+ for positive trend, and – for negative trend) in slopes of the mean catch length over the years, see Table 4.4 for details.

4.4.5 Temporal trends in the size spectra of the demersal fish communities based on mean length

4.4.5.1 Whole coast size spectra

Fig. 4.7 shows the size spectra for demersal fish (all species combined) per year surveyed for the whole coast (100 – 600 m depth) off Namibia. The size spectra for the whole coast show the ideal characteristics of an exploited fish community, with more small and fewer large fish being caught. The long-term trends of the height of the size spectra for the whole coast of Namibia remained relatively stable up to 2000, after which they declined until 2003 and increased again afterwards (Fig. 4.8a). The slopes (Fig. 4.8b) of the size spectra for the whole coast of Namibia show some upward trend from 1991 to 1994, then remained at that relatively high level until 1997, declined in 1998, and showed a slight increase a year after and maintained the same level until 2002. Another decline in slope of the size spectra was evident in 2003, which was followed by a steady increase in slope until 2006 (Fig. 4.8b). Slight declines in both the heights and slopes of the size spectra in 1995 coincided with the Benguela Niño and low oxygen waters. The same declines are evident from 2000 to 2002, which were years experiencing low oxygen water especially on the shelf (see Chapter 5). This pattern was found in all regions and sub-regions as shown below in Figures 4.10, 4.12 and 4.14.

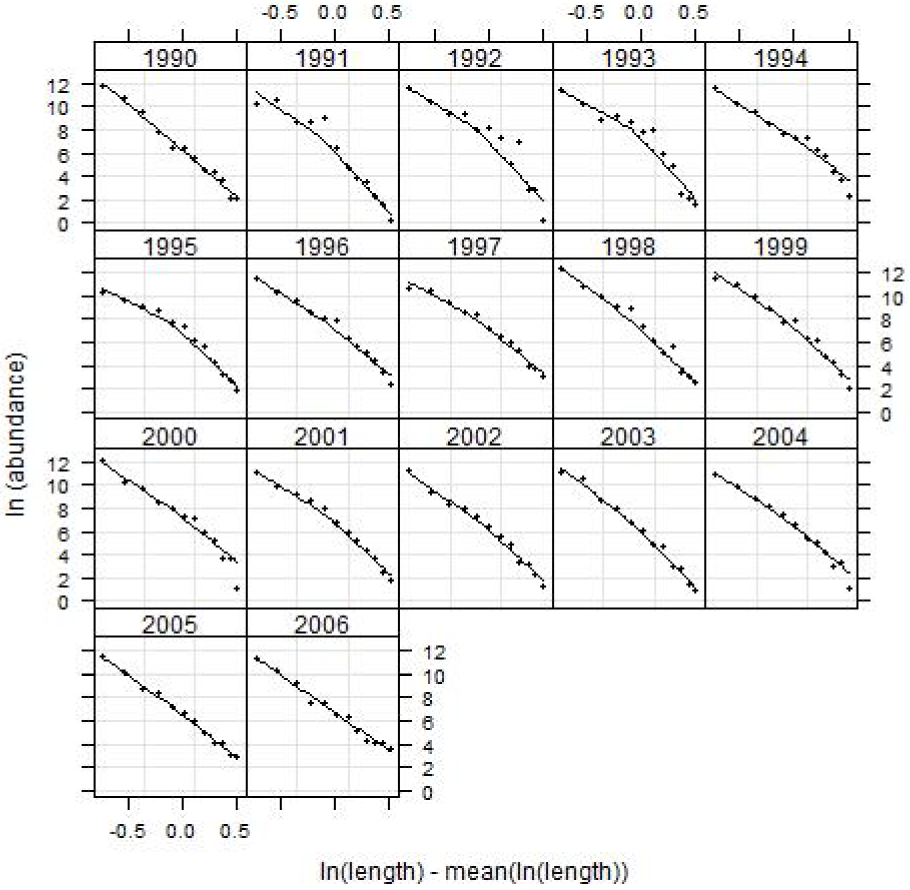


Figure 4.7 Whole coast (100 – 600 m deep): The size spectra for demersal fish (all species combined) for the study period 1990 – 2006. Each graph plots the log abundance against log length (cm). The trend lines are Loess smoothed.

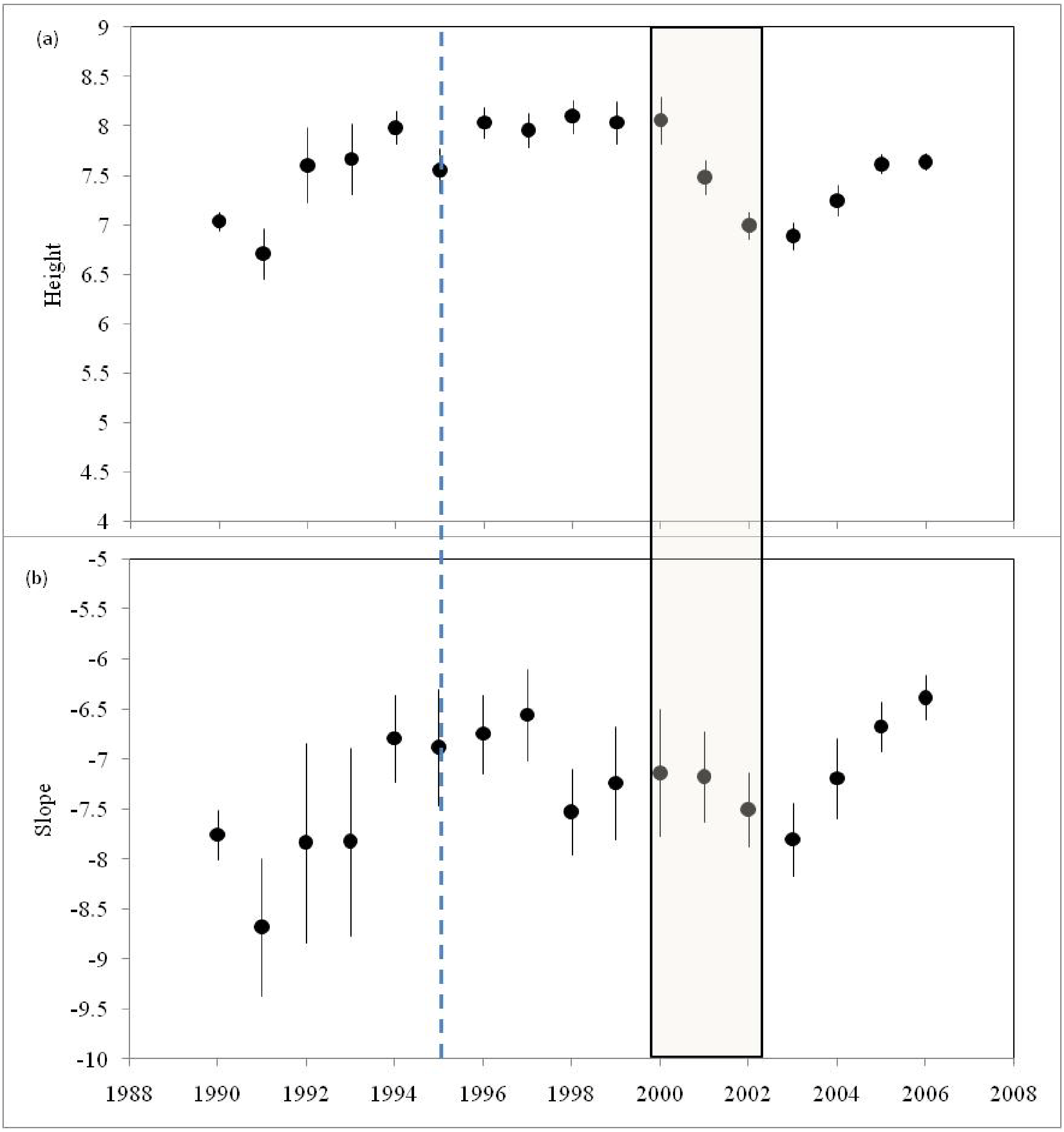


Figure 4.8 Whole coast (100 – 600 m deep): Long-term trends of the heights (a) and slopes (b) of the size spectra of demersal fish species (all species combined) off Namibia, over the study period 1990–2006. Error bars denote ± 2 SE. The heights and slopes of the size spectra are calculated by linear regression, with the height at the mean length standardized to zero. The vertical dashed line indicates the Benguela Niño year coupled with low oxygen water (LOW), and the vertical block represents years with persistent LOW.

4.4.5.2 Continental shelf and slope

The size spectra for demersal fish (all species combined) are shown in Fig. 4.9a & b, for both the continental shelf and slope respectively. They depict a size spectrum of fish communities, whereby high abundances are found in the smaller-sized fish classes, but there is a steady decline in abundance as fish size increases within the annual samples. Temporal trends in the heights and slopes of the size spectra for demersal fish on the continental shelf (Fig. 4.10a & b) and slope (Fig. 4.10c & d) again depict the regularities in the size spectra of marine ecosystems. The temporal trends in heights of the size spectra for the shelf showed variable changes from 1990 to 1995, then an increase in height from 1996 to 1997, then a steady decrease in height from 1998 to 2003, then an increasing trend again from 2004 to 2006 (Fig. 4.10a). The slopes of the size spectra for the shelf showed relatively high variability with no clear pattern over the years (1990 to 2006) (Fig. 4.10b).

For the continental slope assemblage, the heights of the size spectra again showed a clear temporal pattern with a marked steady increase in heights from 1991 to 1994, a slight decrease in 1995, then an increase in 1996, and maintained a relative stability from 1996 to 2000, then a decreasing trend in 2001 to 2003, then a slight recovery is observed from 2004 to 2006 (Fig. 4.10c). This temporal pattern on the slope was opposite to the pattern obtained for the continental shelf region. There was a systematic decline up to 2003, after which the slope started to increase to reach the level of the early 1990s (Fig. 4.10d).

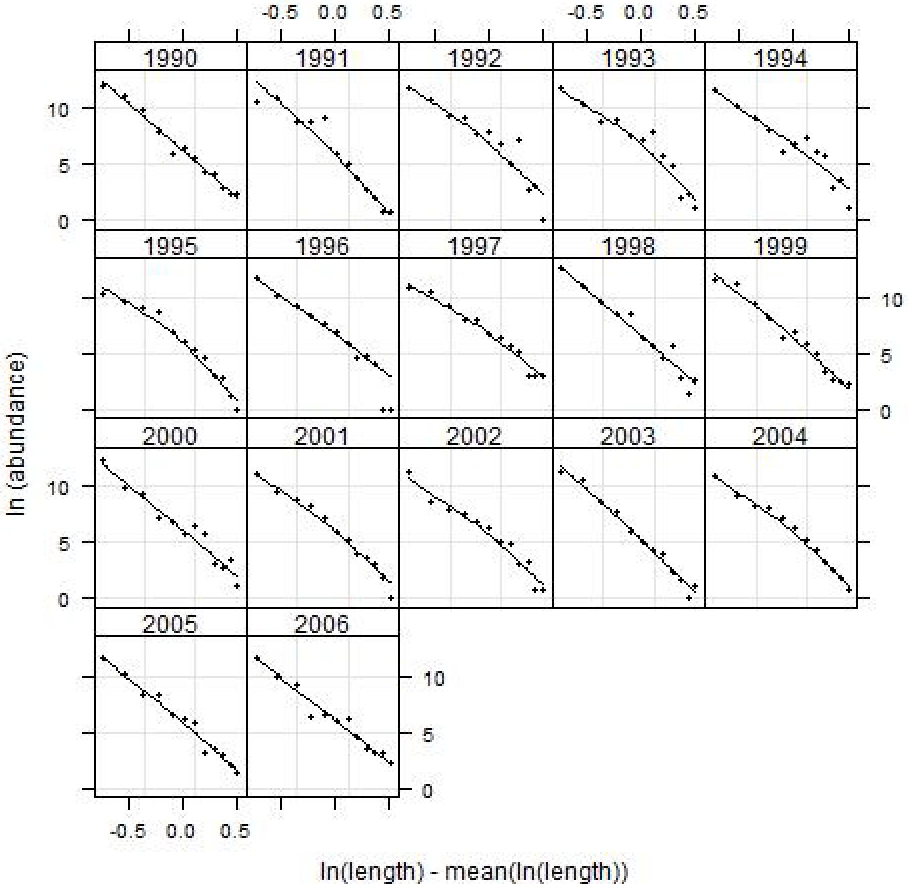


Figure 4.9a Continental shelf (100-300 m deep): The size spectra for the demersal fish (all species combined) off the coast of Namibia. Each graph plots the log abundance against log length (cm). The trend lines are Loess smoothed.

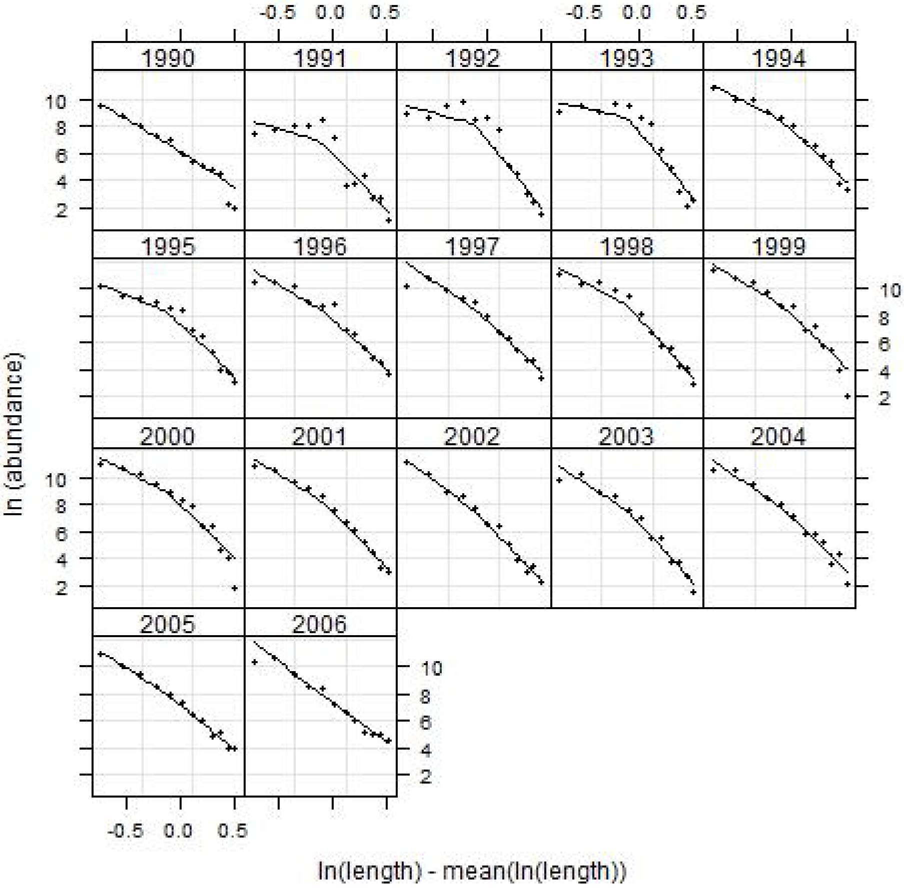


Figure 4.9b Continental slope (300 – 600 m): The size spectra for demersal fish (all species combined) off the coast of Namibia. Each graph plots the log abundance against log length (cm). The trend lines are Loess smoothed.

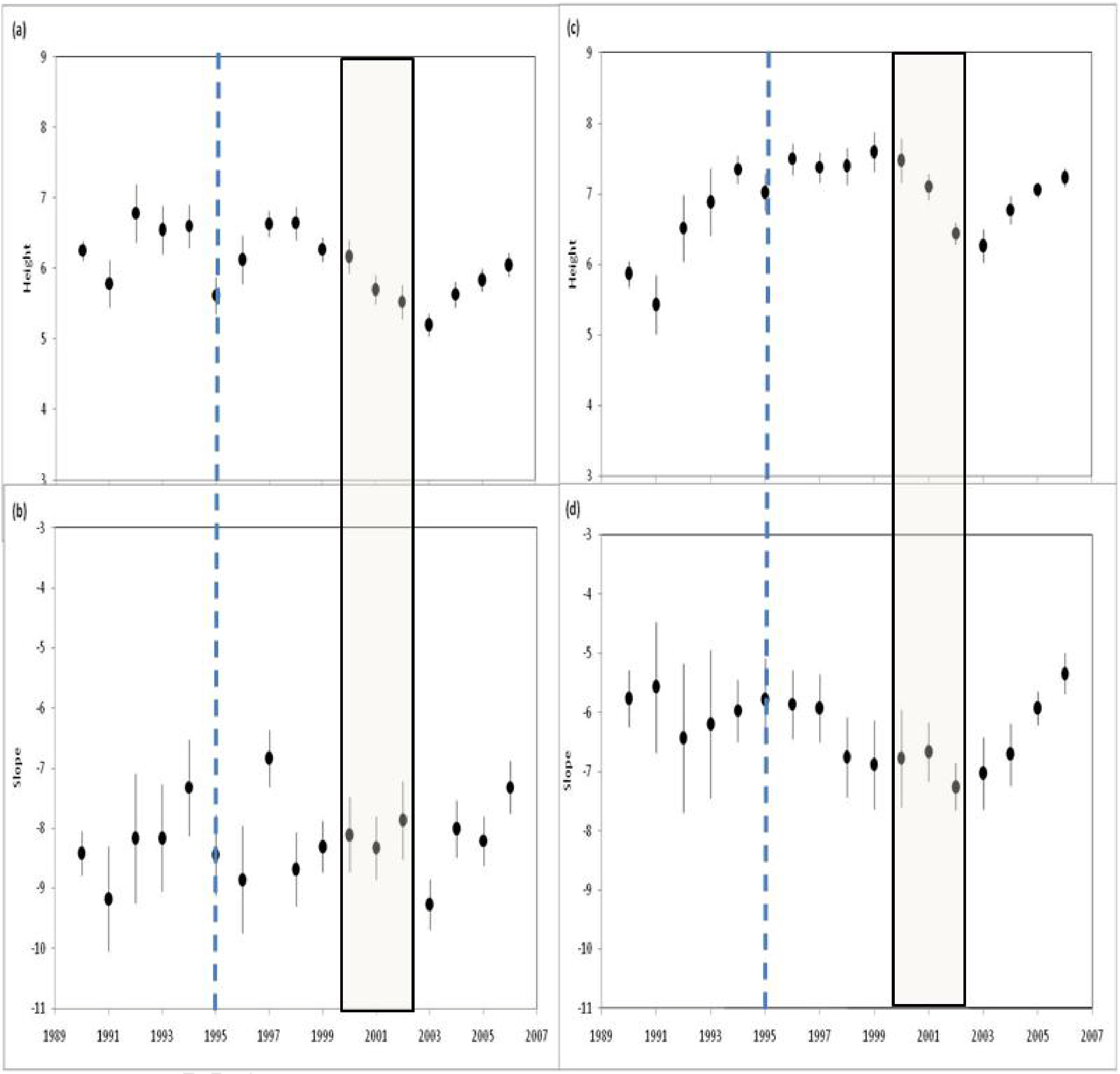


Figure 4.10 Temporal trends in the heights (top panel) and slopes (bottom panel) of the size spectra of the continental shelf (100 – 300 m) assemblage (a, b), and the continental slope (300 – 600 m) assemblage (c, d) off Namibia based on mean length. The heights and slopes of the size spectra are calculated by linear regression, with the height at the mean length standardized to zero. The vertical dashed line indicates the Benguela Niño year coupled with low oxygen water (LOW), and the vertical block represent years with persistent LOW.

4.4.6 *Regional trends in size spectra for demersal fish assemblages*

The size spectra of demersal fish communities for the sub-regions showed a similar pattern as observed earlier in the size spectra of demersal fish (all species combined) for the continental shelf and slope regions (Figs. 4.11a - c & 4.13a - c). Figures 4.12 & 4.14 show results of the temporal trends in the heights and slopes of size spectra of demersal fish assemblages arranged by sub-regions (north, central and south) and by region depth stratum (continental shelf and slope). These figures enable a closer look at the trends of size spectra in each of these regions over time. In some cases, a few non-linear trends are noticeable in the size spectra, especially in 1992 and 1993, and again in 2003.

4.4.6.1 Continental shelf sub-regions

The heights of the size spectra for the northern, central and southern continental shelf showed a consistent declining trend over the 17-year period (Fig. 4.12). This suggests a decline in overall abundance of demersal fish over the continental shelf off Namibia. The slopes of the size spectra for the continental shelf region remained relatively stable in the central and southern shelf, whereas there was a gradual decline over time on the northern shelf (Fig. 4.12).

4.4.6.2 Continental slope sub-regions

The heights of the size spectra for all sub-regions of the continental slope (300 – 600 m deep) showed consistent increase over the study period (Fig. 4.14), suggesting an increase in overall abundance over time. The slopes of the size spectra were steeper (more negative) in the northern and central sub-region and to some extent in the southern sub-region over the study period (Fig. 4.14). These declines in the slopes of the size spectra for the continental slope sub-regions suggest a long-term shift in the size composition towards smaller fish.

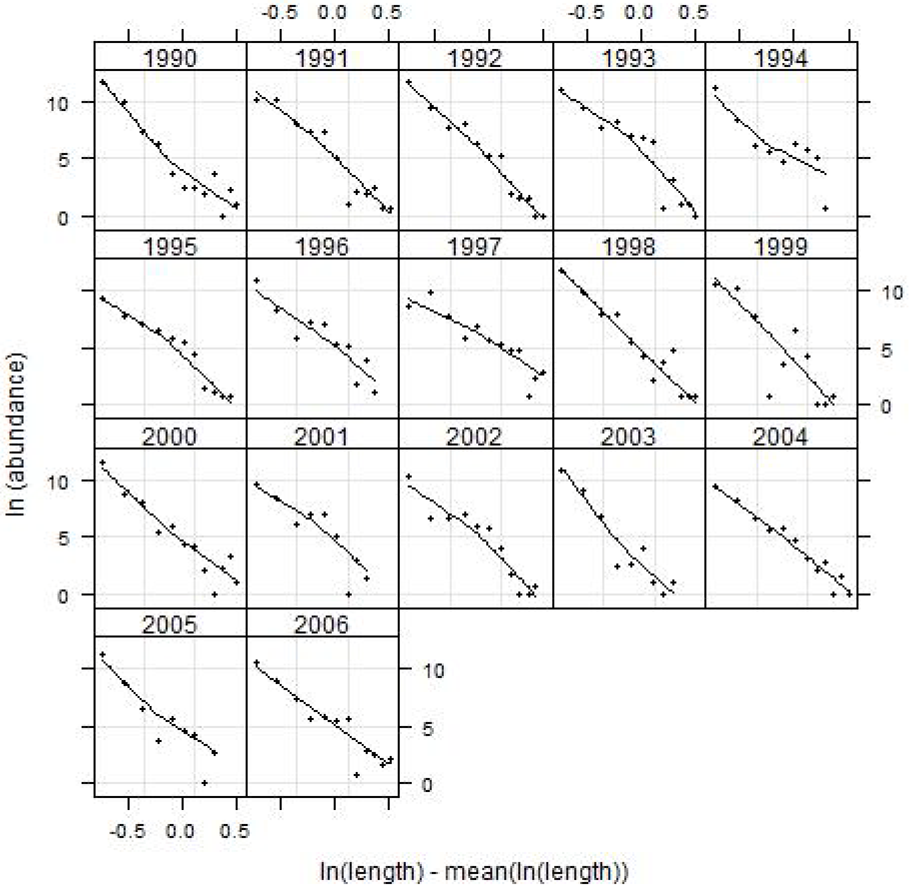


Figure 4.11a Northern continental shelf sub-region (100 – 300 m depth): The size spectra for demersal fish (all species combined) off the coast of Namibia. Each graph plots the log abundance against log length (cm). The trend lines are Loess smoothed.

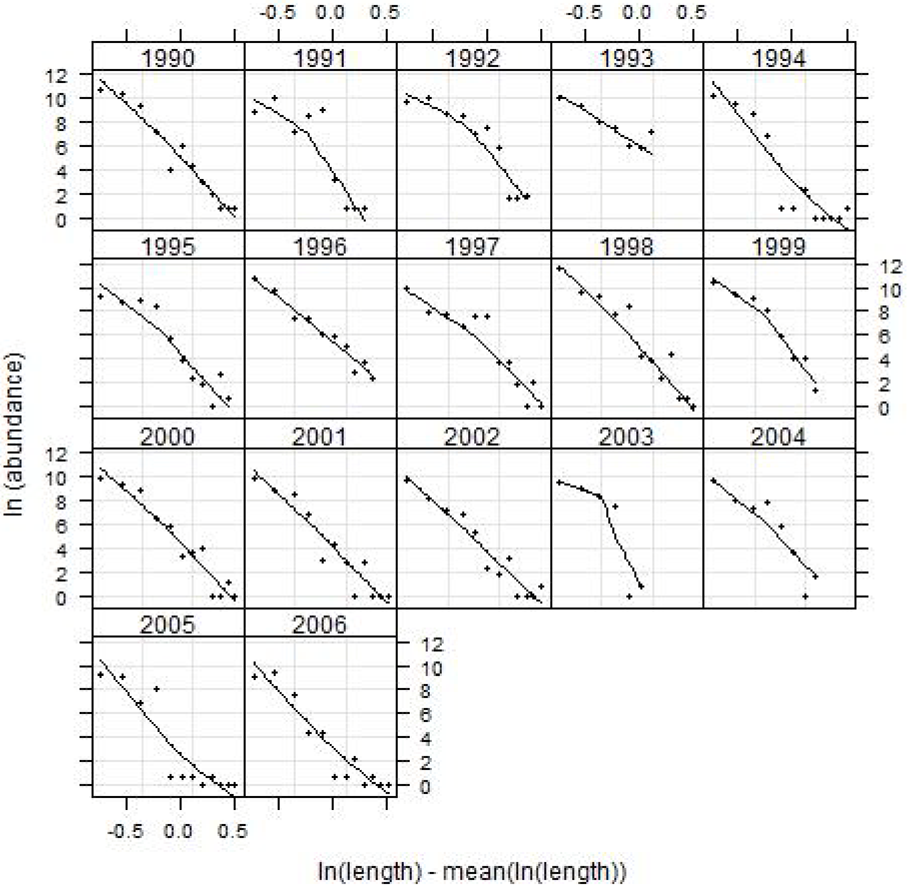


Figure 4.11b Central continental shelf sub-region (100 – 300 m depth): The size spectra for demersal fish (all species combined) off the coast of Namibia. Each graph plots the log abundance against log length (cm). The trend lines are Loess smoothed.

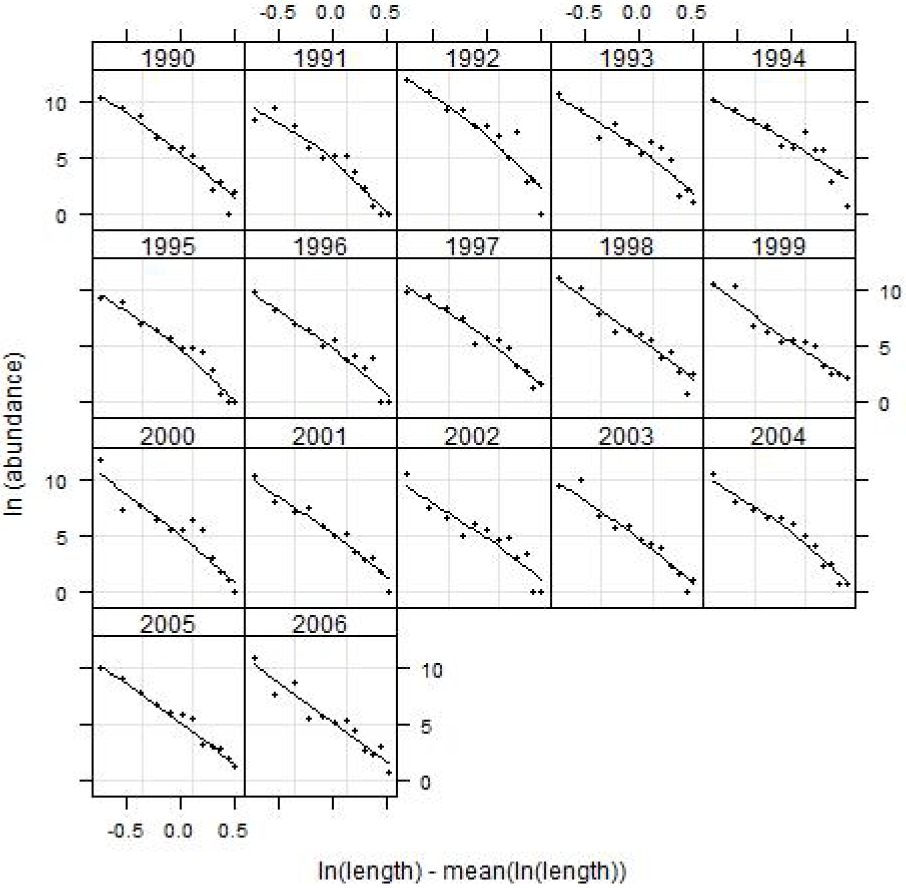


Figure 4.11c Southern continental shelf sub-region (100 – 300 m depth): The size spectra for demersal fish (all species combined) off the coast of Namibia. Each graph plots the log abundance against log length (cm). The trend lines are Loess smoothed.

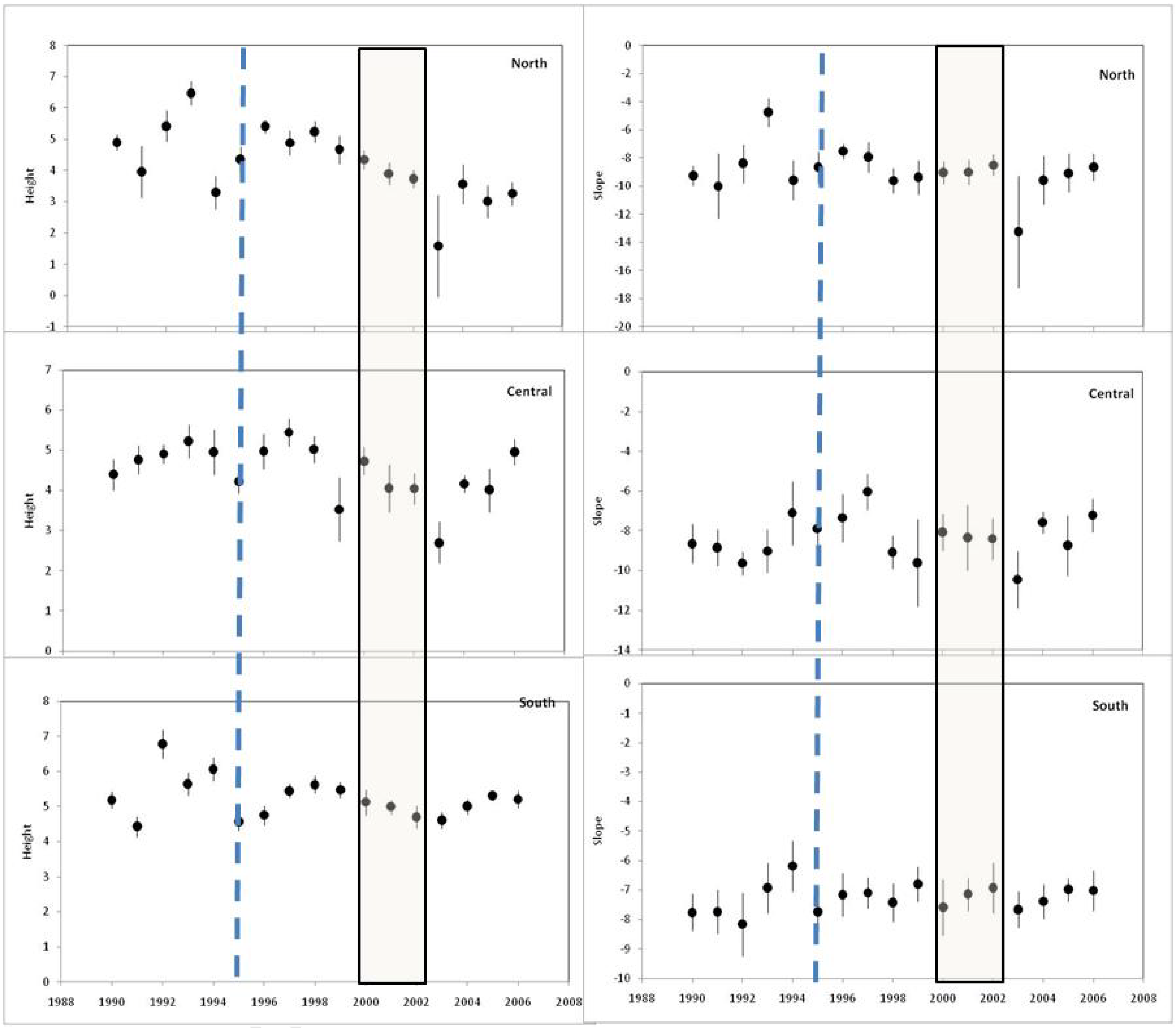


Figure 4.12 Sub-regional size spectra for the continental shelf (100 – 300 m depth): Spatio-temporal trends in the heights (left panel) and slopes (right panel) of size spectra of all the demersal fish species off Namibia, from 1990 to 2006, according to three sub-regions: north, central and south. The heights and slopes of the size spectra are calculated by linear regression, with the height at the mean length standardized to zero. The vertical dashed line indicates the Benguela Niño year coupled with low oxygen water (LOW), and the vertical block represent years with persistent LOW.

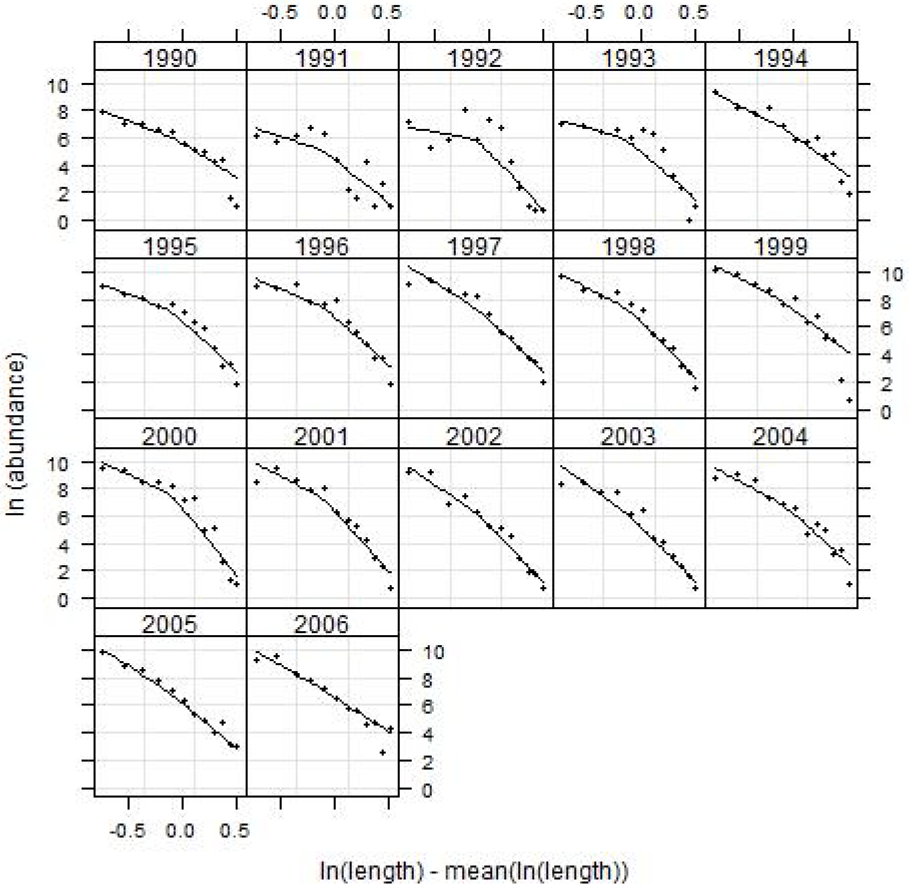


Figure 4.13a Northen continental slope sub-region (300 – 600 m deep): The size spectra for demersal fish (all species combined) off the coast of Namibia. Each graph plots the log abundance against log length (cm). The trend lines are Loess smoothed.

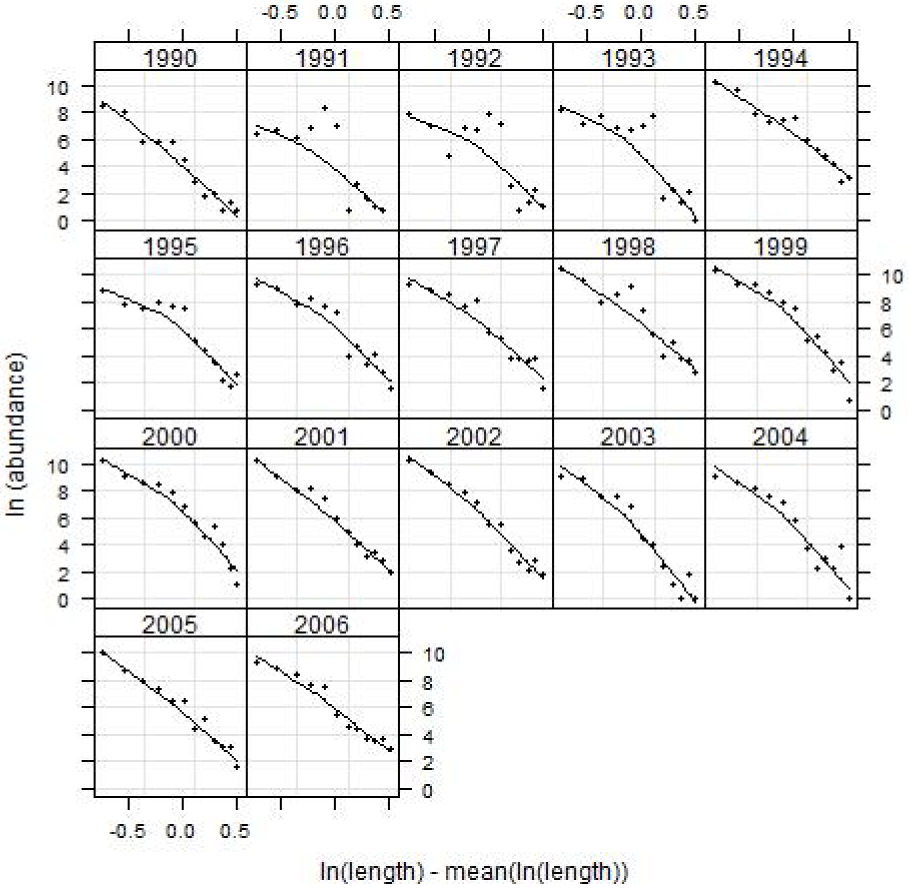


Figure 4.13b Central continental slope sub-region (300 – 600 m deep): The size spectra for demersal fish (all species combined) off the coast of Namibia. Each graph plots the log abundance against log length (cm). The heights and slopes of the size spectra are calculated by linear regression, with the height at the mean length standardized to zero. The trend lines are Loess smoothed.

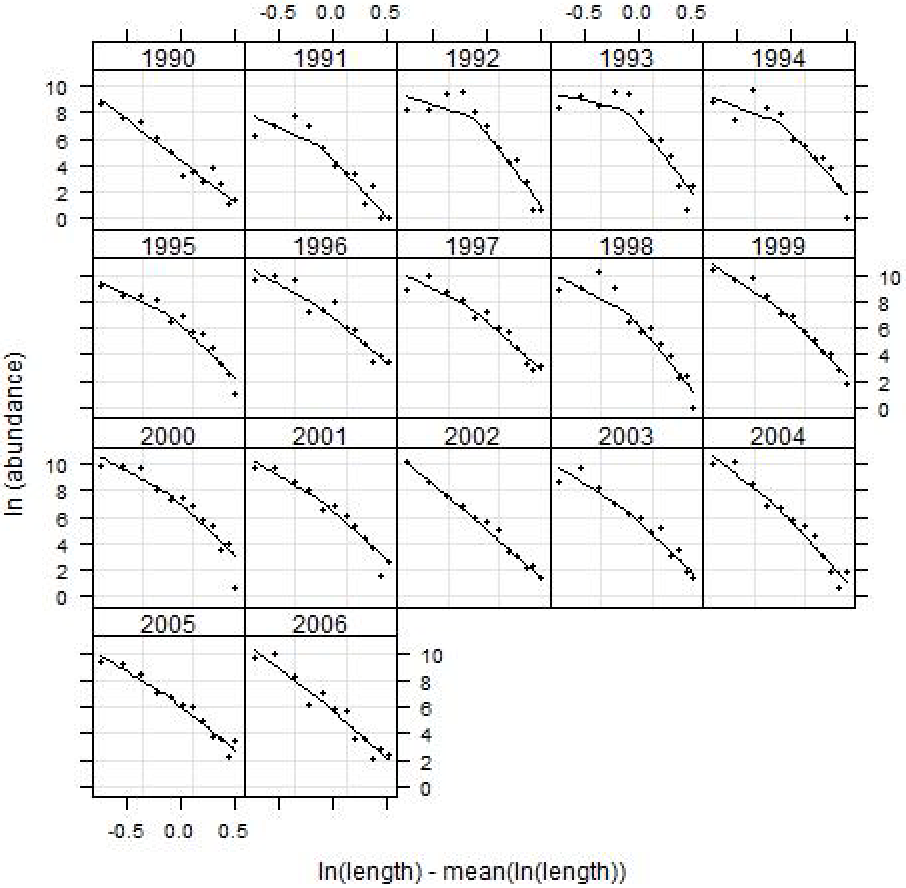


Figure 4.13c Southern continental slope sub-region (300 – 600 m depth): The size spectra for demersal fish (all species combined) off the coast of Namibia. Each graph plots the log abundance against log length (cm). The trend lines are Loess smoothed.

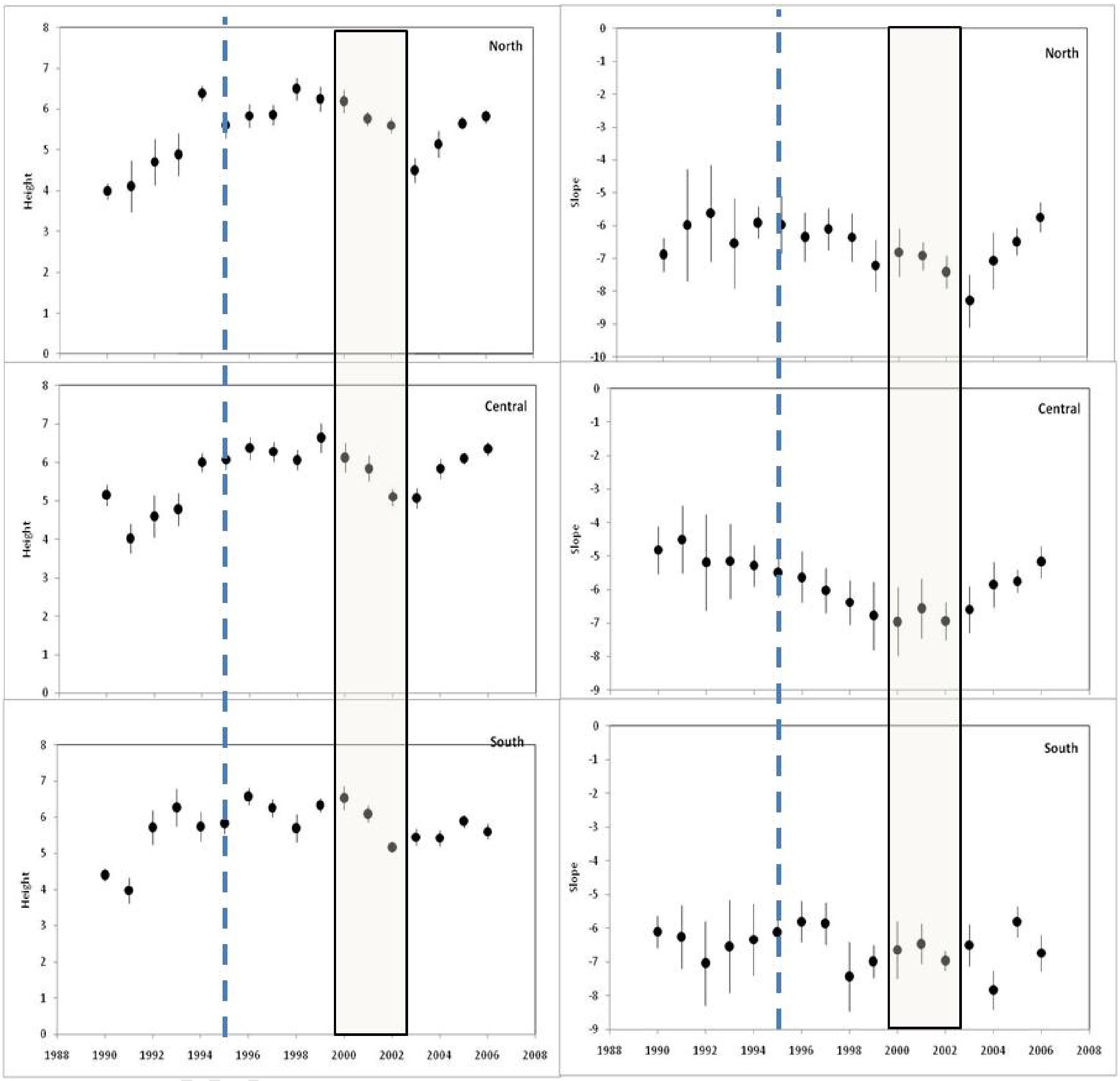


Figure 4.14 Regional size spectra for the continental slope (300 – 600 m depth): Spatio-temporal trend in the heights (left panel) and slopes (right panel) of size spectra of all demersal fish species off Namibia, from 1990 to 2006, according to three sub-regions: north, central and south. The heights and slopes of the size spectra are calculated by linear regression, with the height at the mean length standardized to zero. The vertical dashed line indicates the Benguela Niño year coupled with low oxygen water (LOW), and the vertical block represent years with persistent LOW.

4.5 Ancillary information to aid the interpretation of the changes in size structure: an environmental perspective

4.5.1 Recruitment index for M. capensis off Namibia

The recruitment index (1993 – 2005) of the Cape hakes *(M. capensis)* is shown in Fig. 4.15. It shows a downward trend from 1993 to 1995, where 1995 had a very low recruitment index, which coincided with the presence of the Benguela Niño (Shannon, 1985) off the coast of Namibia. In 1996 the cohort strength estimate was second highest after that of 2002 for the period under review. Cohort strength was estimated to have been lowest in 2001 (Fig. 4.15).

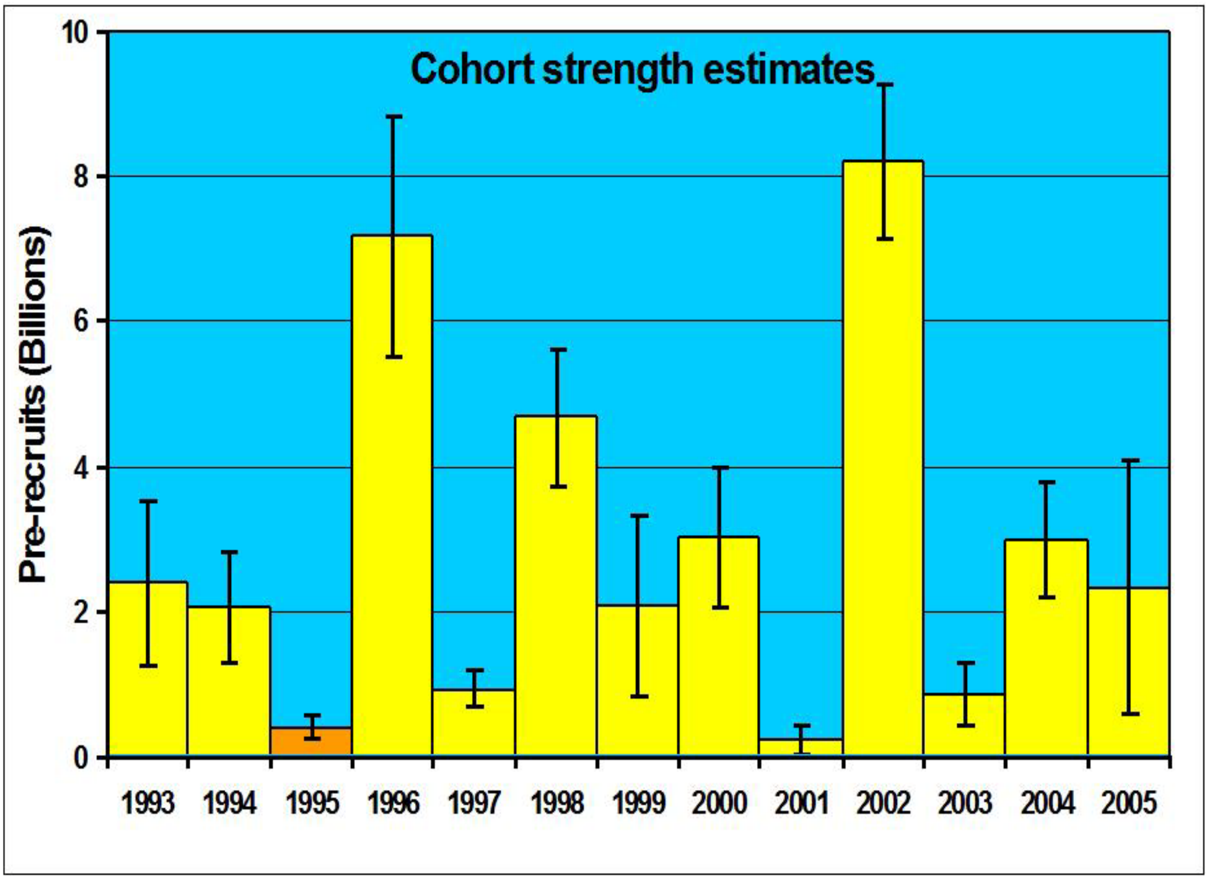


Figure 4.15 Cape hake recruitment index in Namibia. The Y-axis is the number of fish aged 2.5 years, and the X-axis is the year in which the recruits were spawned. The two-sided standard error is shown on each bar. (Source: J-P Roux *pers. comm.*, NatMIRC, MFMR, Presentation at the Symposium on "Celebrating a decade of

collaboration in the Benguela region", the outcomes of the BENEFIT and BCLME Programmes and the establishment of the Benguela Current Commission, Swakopmund, Namibia, 19-21 Nov 2007).

4.5.2 Environmental variability

The Benguela system is a wind-driven upwelling system. The upwelling favourable winds (north/south anomalies) are shown in Fig. 4.16, and have been measured since 1961 off Lüderitz, which is the strongest upwelling cell in the region (Shannon, 1985). The upwelling favourable winds showed decadal, annual and inter-annual variability, with the most recent period dominated by southerly winds (Fig. 4.16). During the years under review depicted in the box, there was a positive change from more southerly wind to more northerly wind anomalies from 1990 to 1998, and reversal thereafter.

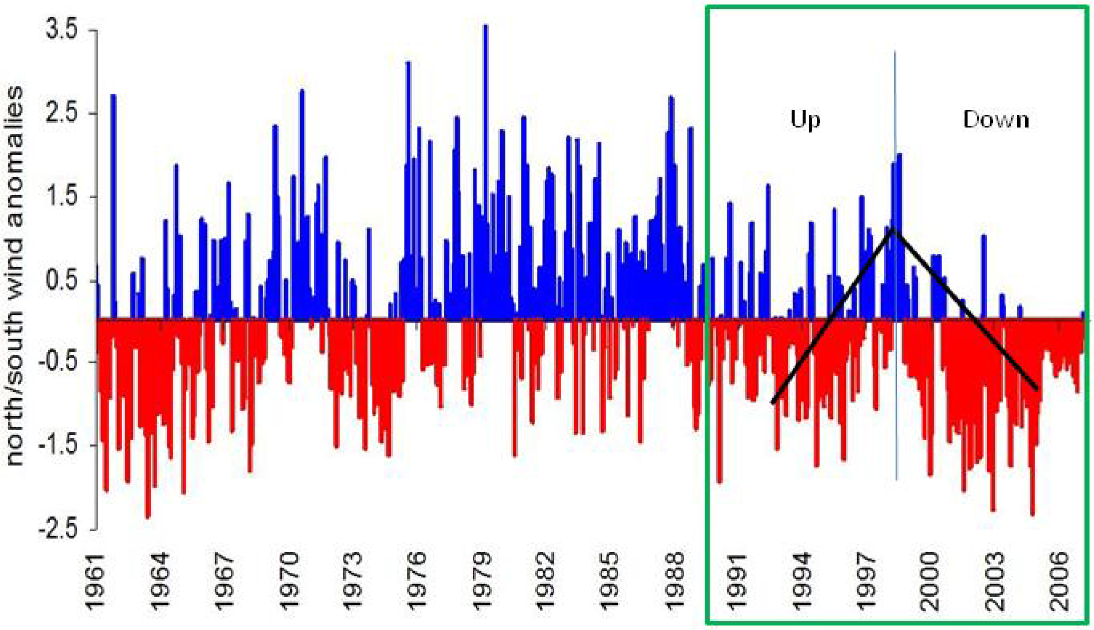


Figure 4.16 Lüderitz upwelling favourable wind anomalies from 1961 to 2006. Blue histograms show the southerly wind anomalies and red histograms show the northerly wind anomalies; these were calculated from monthly means. The rectangle shows years under review in this study, and the inverted V-shape is the direction of change in the wind anomalies. Modified from *A. van der Plas, pers. comm., NatMIRC, Swakopmund, Environmental monitoring in the Benguela current region. BENEFIT/BCLME project, a presentation reported in Swakopmund, Namibia, 19-22 Nov 2007).*

The trend in annual upwelling index off Lüderitz showed some annual variation with the lowest upwelling index in 1993, 1998 and 2001; while the highest annual upwelling index was reported in 2002 (Fig. 4.17). Variability in annual upwelling index coincides with the presence of upwelling favourable winds in Fig. 4.16 although the former is for a shorter period (1990 – 2006).

The annual average Sea Surface Temperature (SST) for central Namibia is shown in Figure 4.18 for the years under review. The lowest average SST anomalies were recorded for years 1992, 1997 and 2004. The highest average SST anomalies were recorded in 1995, 1996 and 2000 in decreasing order (Fig. 4.18). The observed trend in average SST anomalies coincides with the movement and position of the Angola-Benguela-Front (ABF) in Figure 4.19. The ABF was further north (Fig. 4.19) during the cooler periods off the coast of Namibia in Figure 4.19, and moved further south during the warmer period.

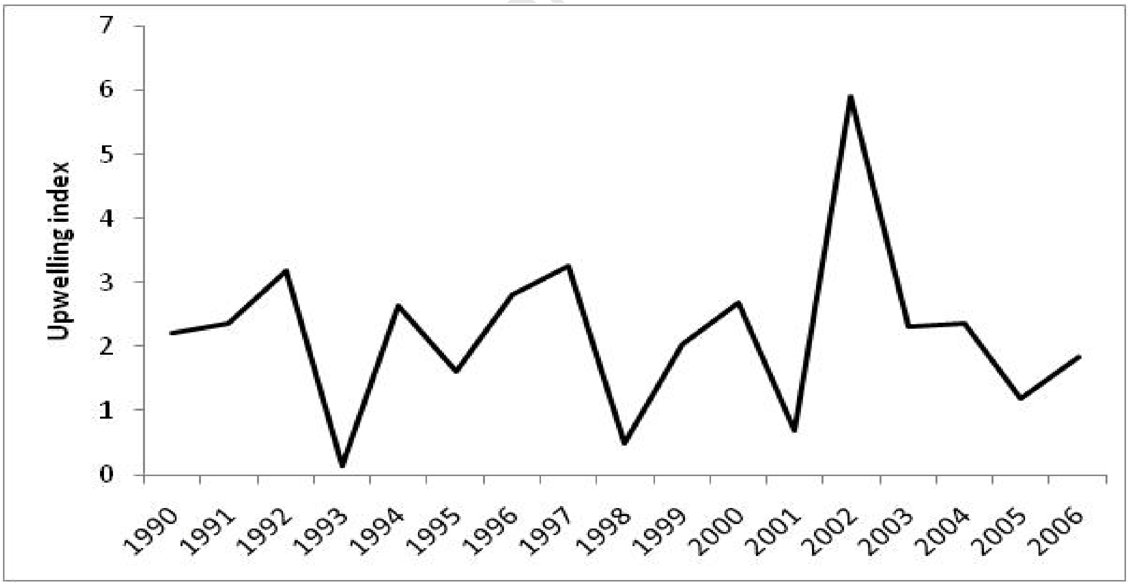


Figure 4.17 Trend in the upwelling index off Lüderitz from 1990 to 2006. (Data source: Nadine Moroff, *pers. comm*., NatMIRC, MFMR, Swakopmund).

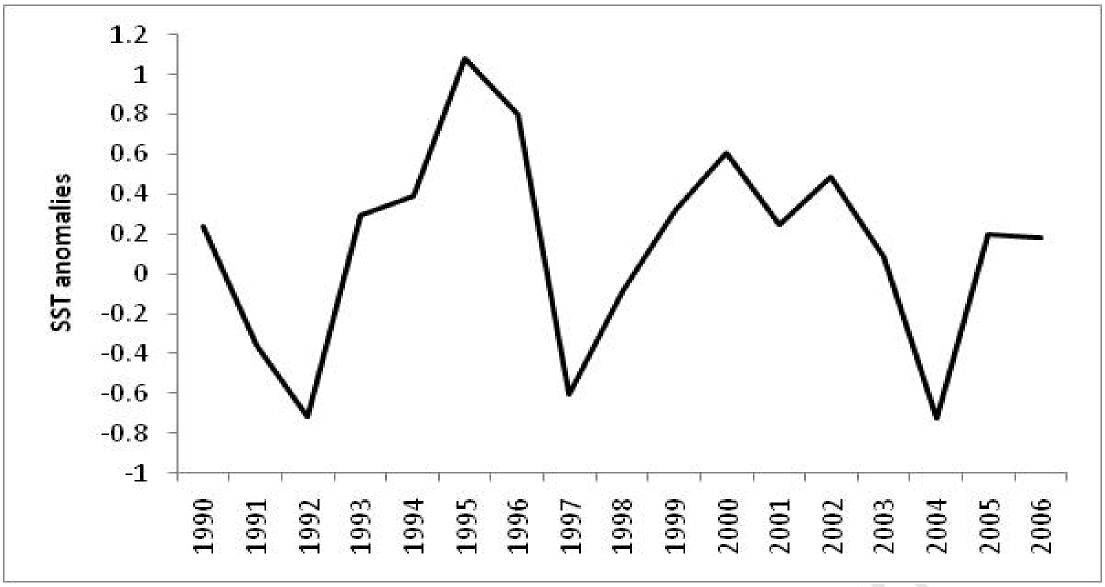


Figure 4.18 Trend in Sea Surface Temperature (SST) anomalies for central Namibia calculated from annual means. Data source: Nadine Moroff, *pers. comm.,* NatMIRC, MFMR, Swakopmund, Namibia).

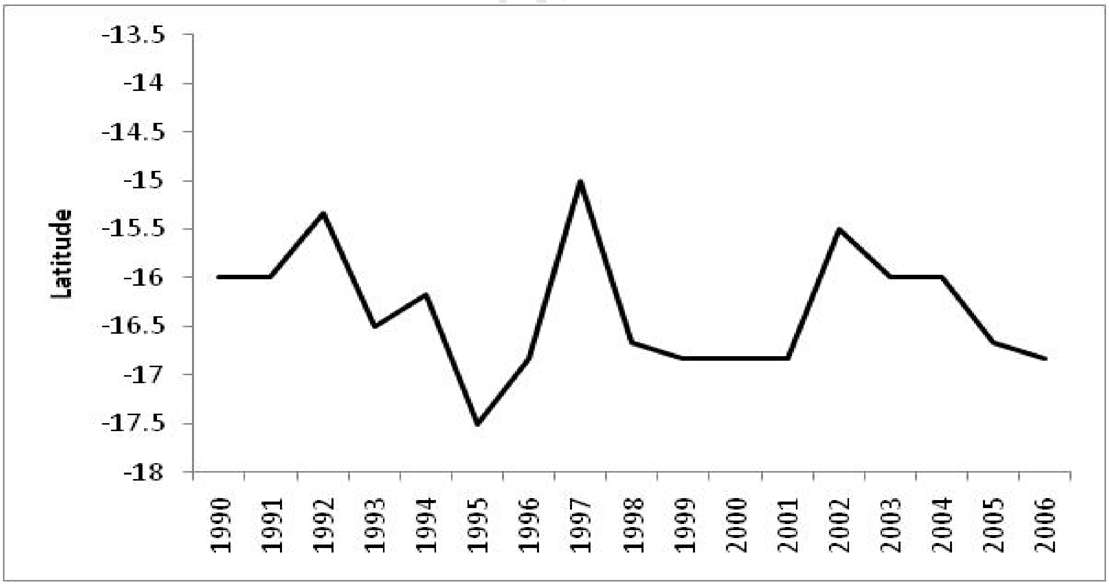


Figure 4.19 Latitudinal position of the Angola-Benguela-Front (ABF) from 1990 to 2006. Data source: Nadine Moroff, *pers. comm,* NatMIRC, MFMR, Swakopmund, Namibia.

4.6 Discussion

Bottom-trawl data from the annual biomass surveys need consistent and systematic assessment over the years to analyse the effects of fishing (Rochet and Trenkel, 2003). Changes in the size structure of demersal fish communities off Namibia were assessed systematically at a broad spatial level for the whole coast (100 – 600 m depth) and also divided into continental shelf (100 – 300 m) and continental slope (300 – 600 m) sub-regions. Additionally, the coast of Namibia was further sub-divided into three sub-regions: north, central and south to assess changes in the size structure at a finer scale.

4.6.1 Trends in mean catch for the whole coast

The temporal trend in mean catch rate per size class for the demersal fish communities for the whole coast did not show any significant changes at a broad scale. However, slight declines in overall abundances were observed in the size classes < 20, 41 – 60 and 61 – 80 cm. The observed changes in the size class < 20 cm could be attributed to the fact that the bottom gear used in these surveys was not designed to sample these small fish (larvae and juveniles) due to net escapement. Further, fish in the smallest size categories are mostly not available to bottom trawls, since they spend most of the time in the pelagic zone (Iilende *et al*, 2001). The negative changes or decline in relative abundances in the size classes 41 – 60 and 61 – 80 cm can be attributed to fishing due to the selective nature of the trawl nets targeting bigger fish, although other factors such as migration cannot be excluded; however, there is lack of information on this. Although not statistically significant, this is indicative of the exertion of fishing pressure and most probably also due to other causes of fish mortality (Murawski and Iodine, 1992; Haedrich and Barnes, 1997; Hall, 1999).

4.6.2 Mean catch for continental shelf

The results for the mean catch rate for the continental shelf (100 – 300 m) show that there was a significant decrease in the abundance of fish in the size class 41 – 60 cm, which forms part of the prime target size (legal minimum sizelimit: 36 cm for hake) (see Chapter 1) for hake off Namibia (MFMR, 2006). This suggests heavy fishing pressure for this size class over the 17 year study period (see Chapter 2). Additionally, all other size classes on the continental shelf were generally showing a non-significant declining trend, except the > 80 cm size class. Indications are that it has become increasingly difficult in recent years to catch demersal fish species in large numbers on the shelf. The mean catch rate showed both on a small spatial scale (continental sub-regions, continental shelf and slope) and large spatial scale (whole coast) that the system reflected the typical characteristic of an exploited fish community – namely more small fish and fewer large fish being caught (Fig. 4.2). The influence of *M. capensis* recruitment on the mean catch rate of demersal fish is neither pronounced in the < 20 cm nor bigger size classes, since there are no synchronous patterns between recruitment and mean catch rate. It is expected that years of good recruitment would influence the mean catch rate with high abundance of juvenile fish (< 20 cm) (Fig. 4.2 and 4.15). However, the recruitment index used here only refers to *M. capensis* from otoliths in seal scats in the Lüderitz area and it may be relevant for the entire stock, although it is not representative of the full distributional extent of the species off Namibia.

4.6.3 Mean catch rate for continental slope

The continental slope region (300 – 600 m) has experienced a significant increase in abundance in size classes below 40 cm. The increase in abundance does not coincide with the low troughs and high peaks in the recruitment index for *M. capensis*, simply because *M. capensis* recruits mostly on the shelf, suggesting other causes could be at play. This may reflect the inshore-offshore movement of the major demersal fish species, since there was a decline in terms of abundance of these size classes on the shelf, indicating that they could be migrating into deeper waters. Hypoxic and low oxygen waters (LOW), as well as warm water intrusion from the southward flowing equatorial current on the continental shelf (Hamukuaya *et al.*, 2002; Monteiro and van der Plas, 2006; Bartholomae and van der Plas, 2007) may be contributing factors for this migration into deeper water on the continental slope. However, a non-significant decline in abundance for the size class 41 – 60 cm was observed on the continental slope, which may suggest that the impacts of selective fishing on this preferred size class could be increasing.

Regional separation in the temporal trends of the size spectra for the continental shelf and slope also depicted a clear pattern with high catches for small size classes and very few large fish caught in the trawls (Figs. 4.3 & 4.4). This is a typical pattern for an exploited fishery, due to gear selectivity and natural abundances. Table 4.2 enables us to determine where the observed changes in Table 4.1 occur, when the coast is sub-divided into sub-regions. The negative slope for the continental shelf in size class 41 – 60 cm falls in the northern shelf (Fig. 4.3 & Table 4.2), and the lowest mean catch rates in this size class were in 1995, 2003, and 2005. The low mean catch rate in the year 1995 (and very low *M. capensis* recruitment in this year, Fig. 4.15) coincided with the Benguela Niño, with very high SST anomalies, while the ABF reached the southernmost extent (Figs. 4.15 – 4.18), and there was a presence of low oxygen waters (LOW) on the northern and central continental shelf. This was also coupled with the stronger northerly wind anomalies causing the relaxation in southerly wind, which drives the upwelling, thus resulting in a relatively low upwelling index (Figs. 4.16 and 4.17). During 2003 and 2005 there was a period without any LOW or any adverse environmental conditions in the system. This may be attributed to declining stocks, which is an indirect effect of fishing.

The central continental shelf and slope, including the northern slope appear to be very good retention areas for the small size classes <20 and 21 – 40 cm, where they showed an increase in abundance and mean catch rate over the years (Figs. 4.3 & 4.4; Table 4.2). This could be attributed to less predation by large fish, good spawning and recruitment success, especially for the main dominant species caught in bottom-trawls in these regions over the years, and to favourable environmental conditions in some years (Figs. 4.16 – 4.18). Good spawning in *M. capensis* may result from the widespread presence of warm water during the spawning period (September – March) and the reduction in upwelling during the following May – September; the eggs spawned are retained in favourable nursery areas and may lead to potentially strong recruitment (Voges *et al*., 2002). This is consistent with the results in Figure 4.17, showing the low upwelling index in 1995 and 2001, and the positive SST anomalies in 1995 and 2001 (Fig. 4.18), which may have potentially contributed to the strong recruitment for *M. capensis* in 1996 and 2002 (Fig. 4.15).

The episodic environmental effects could have some kind of lag effects as explained above, which may only be noticed in the biology afterwards. This is noticeable in the annual variability of the size spectra. It can also be attributed to an indirect effect of fishing where direct removal of larger individuals/species results in reduction of predation (J-P Roux, *pers. comm*.) and/or competitive interaction and hence increase in abundance of smaller size individuals. The northern continental slope sub-region seems to have been significantly depleted of demersal fish in the size class 41 – 60 cm over the years. Environmental variables such as dissolved oxygen, as shown by Hamukuaya *et al*. (2001), (low oxygen waters in the central and northern continental shelf have contributed to mass mortalities of juvenile hake off Namibia), and bottom temperature have played a role in changing the community structure (see Chapter 5). The northern continental slope sub-region is one of the favourite “hot-spots” for freezer vessels fishing for hake, as they concentrate in large numbers on a good trawl ground with high catches (Chapter 2). Thus, heavy exploitation of demersal fish cannot be ruled out in this case.

4.6.4 Mean catch length

Although there were some inter-annual fluctuations in the mean catch length for demersal fish species at a larger spatial scale (whole coast, continental shelf and slope), the regression tests for their trends were all non-significant. The fluctuation in the mean catch length coincided with the presence of low and high recruitment for *M. capensis* (as was shown in Figs 4.7 and 4.15), which is one of the main target species in the hake demersal trawls. However, at a smaller spatial scale (sub-regions), the annual mean catch length of demersal fish assemblages significantly decreased with time on the northern and central continental slope (Fig. 4.6 and Table 4.4). Although the recruitment index for *M. capensis* at this spatial scale is fairly reflected in the annual mean catch length, yet 1996 had a high recruitment and high annual mean catch length and 1997 had a low recruitment index with low mean catch length for both the central and northern slope. These results are contrary to expected results for the recruitment and mean catch length relationship. Low recruitment is usually associated with high mean catch length and vice versa, since there will be more large fish in the system than small fish recruits. Other results of this sub-regional scale also suggest that recruitment showed opposite trends to that of the mean catch length for most years. The 1998 peak in *M. capensis* recruitment index and the low recruitment years 1997, 2001, and 2003 were well depicted in the annual means for mean catch length, except for 1995 that had a very low recruitment index, but high mean catch length. It seems that there may have been some kind of lag effect for recruitment versus mean catch length.

The occurrence of high *M. capensis* recruitment and the high mean catch length suggest that *M. paradoxus* fishable sizes (and possibly other species) are present in greater abundances in the fishing areas, thus affecting the mean catch length. The negative SST anomalies and the northern position of the ABF coincide with the years of bad recruitment for shallow-water hake (Figs. 4.15, 4.18, and 4.19. However, there seems to be a shift in terms of the mean catch length from a system dominated by larger sized fish to one dominated by small fish on the slope over the 17 year study period. This is an indication that bottom-trawling targets bigger fish from these communities, leaving small fish, which in turn changes the size structure of the fish community. This is in agreement with other related studies that have shown that a decrease in mean length in the population is expected and has been observed under the effects of fishing (Haedrich and Barnes, 1997; Babcock *et al.*, 1999; Shin *et al.*, 2005; Yemane *et al.*, 2005).

4.6.5 Size spectra

Another means of determining fishing effects is the size spectra, the characteristics of which may vary among ecosystems. Fishing should affect them through removal of large fish, possibly enhancing small fish as a result of predator release (Pope and Knights, 1982; Murawski and Iodine, 1992). Decreasing linear functions has been described for most length-based size spectra from around the world (Rice and Gislason, 1996; Bianchi *et al* 2000, Yemane *et al* 2005). This is in line with the observed results on size spectra in this study, except in some instances where non-linear trends were evident. These irregularities have been described (Duplisea *et al*., 1997; Bianch *et al*., 2000) as common in small-sized classes causing curvature in the size spectrum. It is not known whether this is caused by sampling bias or predation mortality of small fish or both (Shin *et al*., 2005). However, small sized fish (< 20 cm) were excluded during the construction of the size spectra in this study, but there are still signals of non-linear trends. The long-term temporal trend in the heights of the size spectra (Fig. 4.8a) for the demersal fish communities for the whole coast of Namibia suggests there was a subtle recovery in the overall abundance of demersal fish from early 1990s to 1994 (Fig. 4.8a), after which abundance declined in 1995 with the occurrence of the Benguela Niño, then stabilized from 1996. Another decrease in overall abundance took place in 2003 coinciding with poor recruitment index for *M. capensis* (Fig. 4.15) and increased again afterwards up to 2006. Some cooling (Fig. 4.18) took place in the system in 2004. In spite of all these unfavourable environmental conditions, the recovery in demersal fish abundance may be attributed to the stringent management measures undertaken by the government to reduce the TAC for all stocks at Independence in 1990, to allow for stock recovery (MFMR, 2006).

However, it is rare to find good recruitment in all species at the same time and for a long period. Correspondingly, the long-term temporal trends in the slopes of the size spectra are systematically shallower (less negative) along the whole coast for the study period (Fig. 4.8b). There was no need to apply a step-wise linear regression to the data, since the three periods in the temporal trend of the slopes are clear, e.g.

1990 – 1997, 1998 – 2002 and 2003 – 2006 (Fig. 4.8b). Considering the trend from 1990 – 1997, the slope becomes shallower indicating that the fish community has more large-sized fish. The latter coincided with the occurrence of the Benguela Niño in 1995 (Figs. 4.18 and 4.19, see also Chapter 5, and references therein), and there were cooler periods (1992, Fig. 4.18) prior to this event. The upwelling favourable winds and upwelling index off Lüderitz were all favourable for most of the period, except for 1993. Another explanatory factor could be a change in fishing practice such as an increase in mesh size, since there was a change in gear in 1994 (Bjørn Erik Axelsen, IMR, *pers. comm*.). There was no clear temporal trend between 1998 – 2003 and after 2003 the slopes linearly increased again, which corresponds to the explanations of the environmental variables given above. Consequently, both the heights and slopes of the size spectra for the whole coast (Fig. 4.8a & b) suggested that, after 2003, the size composition of the demersal fish was changing towards a community with greater relative abundance of larger individuals (or larger species), which is not a common trend in an exploited community.

Some studies (Rice and Gislason, 1996; Bianchi *et al*., 2000) have discussed the expected response of the slope of the size spectra to over-exploitation, especially in the North Sea and Scotian Shelf. In both cases the slopes smoothly declined over time, which is what would be expected if there were differential exploitation of different size classes. But as reported in the study by Bianchi *et al.,* (2000), in some systems, especially tropical and warm temperate systems, the slopes of the size spectra do not change over time or they vary inter-annually without any consistent trend. MacPherson and Gordoa (1996) showed that, from 1987-1990, biomass size spectra in the northern Benguela System differed for areas with different productivity and did not differ between areas experiencing different levels of fishing pressure. This emphasizes that inferences based on the characteristics of the size spectra should be treated with caution and when possible be assessed in the light of the underlying ecological dynamics of the system under focus, as has been attempted in this chapter. Furthermore, in line with the general understanding that a suite of indicators is needed to describe state and trends in communities (e.g. Shin *et* *al*., 2005, 2010), the result of the size spectra analysis should be interpreted in conjunction with results from other chapters of this thesis.

4.6.6 Heights and Slopes of the size spectra

The observed bathymetric and temporal trends in the heights and slopes of the size spectra for the continental shelf and slope (Fig. 4.10a - d) indicated no consistent trend over a long period, but at short temporal scales there was some consistency, which may have contributed towards the overall abundance and the size composition of the demersal fish community observed for the whole coast (Fig. 4.8a & b). Thus, much of the increase in overall abundance for the whole coast was more on the continental slope (300 – 600 m) (Figs. 4.4 & 4.10c), while the changes in the size composition were accounted for by the continental shelf region (100 – 300 m) (Fig. 4.10b). However, the increase in temporal trends in overall abundance for the whole coast was dominated by small individuals in the size classes < 20 and 21 – 40 cm, and the current data points to the continental slope as the main source (Tables 4.1 & 4.2). The continental slope is where most bottom-trawling is taking place (Chapter 2), thus continued exploitation of the demersal fish species by bottom-trawling, and most likely by long-lining, may have led to the greater abundance of smaller fish, because larger fish have been targeted. The contribution of different species to the observed trends in abundance and size structure are documented in Chapter 5 of this thesis. Most of these demersal fish species are migratory (Chapter 1), meaning they could be migrating to different parts of the EEZ, depending on several factors which include disturbance from fishing (as shown in Chapter 2, with three levels of fishing: light, medium and heavy bottom-trawling), predation (from seals, see Fig. 4.15; cannibalism; other top predators), food availability, reproductive status (spawners and non-spawners) and changing environmental variables (dissolved oxygen, water temperature etc).

The spatio-temporal trend in the heights of the size spectra for the three sub-regions over the shelf confirms the same trend as above (Fig. 4.12). However, the slopes of the size spectra point to the origin of the increase in larger-sized individuals, which originate from the central and southern continental shelf (Fig. 4.12). The spatio-temporal trend in the heights of the size spectra for the three sub-regions of the slope (300 – 600 m) re-affirms the contributions of all the three sub-regions to the overall abundance of the demersal fish communities. A systematic steepening of the slopes of the size spectra for the three sub-regions suggests increasing abundance of small versus large individuals in the community, with reduced abundance of larger individuals in the 1990s especially for the north and central continental slope (Fig. 4.14). The observed increase over time in the abundance of individuals in the smaller size classes may be attributed to the indirect effect of fishing, because size selective fishing pressure differentially removes larger size classes, which reduces predation on individuals in the smaller size classes. This results in an increase in the abundance of smaller size individuals/species. This type of response has been reported in other studies and similar cases were attributed to the indirect effect of fishing (Bianchi *et al*., 2000, 2001; Shin *et al*., 2005; Yemane *et al*., 2004, 2005).

4.6.7 Conclusion

This chapter highlights the dynamics of the community size structure of the demersal fish species in the Benguela ecosystem off Namibia. An essential feature of this study was the decision to assess attributes of the ecosystem/communities at two spatial scales. Firstly, at the larger spatial scale (at the level of the whole coast) the demersal fish community appears to have remained the same over time, although the typical inter-annual variability that characterizes ecological systems was noted. Secondly, at a smaller spatial scale (at the level of sub-regions), the real effects of fishing have been documented. It is at the smaller spatial scale that this study reveals for the first time that, within the size class 41 – 60 cm, there were significant declines in mean catch rates of demersal fish species, over the study period, on the northern continental shelf and slope. This was in contrast to the finding of significant increases in mean catch rates within the small size class < 20 cm on the central continental shelf; central and northern slopes. Mean catch rates in both size classes 21 – 40 cm and > 80 cm were also found to have increased significantly on the central and southern continental slopes respectively.

The size composition of the demersal fish community off Namibia is also changing, with significant declines in the mean catch length for mainly the northern and central continental slopes. A general trend was found in the slopes of the size spectra for all sub-regions, whereby there was an increase in overall abundance of smaller fish and reduced abundance of larger fish. These declines in the slopes of the size spectra for the continental slope sub-regions are evidence for a long-term shift in the size composition towards smaller fish. All these changes are attributed to the effects of bottom-trawling, and to some extent the changing environmental conditions, which may support either good or poor spawning and recruitment, thus contributing to the changes in the size structure of demersal fish species over time. These results should be viewed together with the results in Chapter 5 on ABC curves and diversity indices, which look at the status of demersal fish assemblages in relation to physical parameters and environmental variables over temporal and spatial scales. Changes in the mean catch rates, mean catch length and the heights and slopes of the size spectra were analysed over the years covered by this study. Environmental variables (such as Benguela Niños, LOW, SST, ABF position, upwelling favourable wind anomalies, upwelling index, and *M. capensis* recruitment index) have shown minimal effects on the observed changes, and thus these changes are mainly attributed to the direct and indirect effects of fishing.

Assessing the effects of bottom-trawling on the demersal fish community structure off the coast of Namibia using multivariate and univariate techniques

5.1 Introduction

Traditionally, the management of demersal trawl fisheries focused on target species only, though some studies have reviewed the effects of fishing on non-target species and habitats (Jennings and Kaiser, 1998; Kaiser and de Groot, 2000). Fishing has been shown to exert both direct and indirect effects on the fish community structures for both target species and the bycatch. Some research into the effects fishing have revealed indirect effects of fishing (Fogarty and Murawski, 1998; Pauly *et al*., 1998; Daan *et al*., 2005) and Fogarty and Murawski, 1998 have shown major collapses of some fisheries due to direct effects of fishing. Recently, efforts are being made to study, understand and measure the wider effects of fishing through size-based indicators in South Africa (Yemane *et al*., 2005). A suite of size-based indicators and a suite of indicators for fisheries management have been developed internationally, in order to measure these effects (Rice, 2000, 2003; Rochet and Trenkel, 2003; Rice and Rochet, 2005; Shin *et al*., 2005).

Warwick (1986) proposed the Abundance Biomass Comparison (ABC) method for monitoring disturbance of benthic invertebrate communities. This technique involved comparing dominance in terms of abundance and biomass. It has been successfully applied to marine benthic communities in various parts of the world and has yielded the expected response to disturbance (Warwick *et al*., 1987; Agard *et al*., 1993; Kaiser, 2000; Schejter *et al*., 2008). Recently, ABC curves have been applied in assessing demersal fish communities (Bianchi *et al*., 2001; Blanchard *et al*., 2004; Jouffre and Inejih, 2005; Labropoulou and Papaconstantinou, 2005; Yemane *et al.*, 2005). A study by Bianchi and others (2001) on the dynamics of demersal fish off Namibia found differences between continental shelf and slope assemblages, but without a clear temporal trend for the shelf. The most evident changes were found in the slope community, although Bianchi *et al*. (2001) did not use the *W-statistic*. Theoretically, ABC curves follow the evolutionary theory of *r*- and *k*- selection (Pianka, 1970). The hypothesis is that undisturbed states have a community dominated by *k*-

selected species characterized by slow growth, large body size and late maturity. In this state the biomass curve lies on top of the abundance curve (Clarke and Warwick, 1994, Clarke and Gorley, 2006).

In contrast, increased disturbance leads to a community dominated by the *r-* selected species, which grow fast, are small in size and opportunistic, and in this state the biomass curve lies below the abundance curve (Clarke and Warwick, 1994, Clarke and Gorley, 2006). The ABC method has the advantage that an appropriate data set for any area or time should allow the status of the community to be evaluated without a need for a spatial or temporal control against which to compare the index obtained, since the abundance is compared to the biomass at the same time and place (Clarke and Warwick, 1994, Clarke and Gorley, 2006).

This study assesses the effects of bottom-trawling on the Namibian demersal fish community from 1990 to 2006. Not only has the analytical methodology improved (Clarke and Gorley, 2006; Anderson *et al*., 2008) since the Bianchi *et al*. (2001) study, but the time series data used in this study now spans 17 years of data compared to 10 years of available data at the time of the Bianchi *et al*. (2001) study, which could also potentially yield better results. The primary aim of this study was to assess aspects of community structure of demersal fish assemblages off Namibia that are most likely to reveal evidence of bottom-trawling effects.

5.2 Materials and Methods

The survey data were collected during the annual hake biomass surveys off Namibia from 1990 – 2006. All the details pertaining to the surveys, sampling methods and procedures are fully explained in Chapter 3 of this thesis.

5.2.1 Multivariate Analyses

Fish species abundance and biomass were calculated for each trawl after standardization of the data to an hour per tow for the period of 17 years. The data were fourth root transformed prior to the cluster analysis to avoid over-emphasis of the most abundant species (Field *et al*., 1982, Clarke and Warwick, 1994, 2001). A cluster analysis (group average) was performed on a resemblance matrix employing the Bray-Curtis similarity index for (dis)similarity (Field *et al*., 1982), using standardized biomass values of species using the multivariate techniques in PRIMER *v6* (Clarke and Warwick, 1994). Subsequently, the non-metric multi-dimensional scaling (MDS) ordination analysis was performed on the same similarity matrices as the cluster analysis. A one-way analysis of similarity (ANOSIM) among the groups was performed to test whether the groups were significantly different from each other (Clarke and Warwick, 1994). A similarity percentage (SIMPER) analysis (Clarke, 1993) was conducted to assess which species contributed most to the (dis)similarity of groups (Clarke and Gorley, 2006).

K-dominance curves (Clarke and Gorley, 2006) were constructed, based on averaged species abundance and biomass data for the whole coast pooled together by years and for the groups identified by the cluster analysis and MDS ordination. The abundance biomass comparison (ABC) curves were constructed for the continental shelf and slope for the following regions: northern shelf and slope, central shelf and slope, southern shelf and slope and the whole coast (pooled data by year).

Species abundance and biomass data for all trawls (Table 1) were averaged across the two separate depth ranges (100 – 300 m, 301 – 600 m) before they were used to construct the abundance-biomass-comparison (ABC) curves using the PRIMER v6 software (Warwick and Clarke, 1994; Clarke and Warwick, 2001, Clarke and Gorley, 2006). The same data were pooled together and weighted by the area of the stratum, in order to construct ABC curves for the whole coast. The difference between the two curves is given by the *W– statistic*, which represents the area between the biomass and abundance curve. A *W– statistic* (*W* < 0) indicates that the biomass curve lies below the abundance curve and suggests a disturbed community; *W* ~ 0 indicates that the abundance and biomass curves are close to each other and suggests a moderately disturbed community; if *W* > 0 the biomass curve lies above the abundance curve, which suggests an undisturbed community (Fig. 5.1) (Clarke and Warwick, 1994; Clarke and Gorley, 2006). The following formula was used for calculation of the *W– statistic* (Warwick and Clarke, 1994, Maguran, 2004):

$$W = \sum_{i=1}^{S} (B_i - A_i) \Big/ \left[50 * (S - 1) \right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5.1)$$

where S = total number of species

B_i = percentage in biomass of species rank i

A_i = percentage in abundance of species rank i

B_i and A_i do not necessarily refer to the same species, as dominance in biomass and abundance may not be occupied by the same species in the community. The number 50 in the formula acts as restriction for the value of *W* to fall between -1 and 1, in accordance with the explanation of the *W-statistic* value (Warwick and Clarke, 1994; Maguran, 2004). In theory, the *W* values lie between +1 (when biomass is dominated by a single species and abundance is evenly distributed among species in the community), and -1 (when abundance is dominated by a single species and biomass is evenly distributed among species in the community) (Clarke and Warwick, 2001). The *W-statistic* graphs were constructed for the regions and by depth stratum (shelf and slope). The LOESS smoothers (Cleveland, 1979; Cleveland and Devlin, 1988) were fitted to the time-series *W- statistic* data, in order to determine their overall spatial and temporal trends over the 17 year study period. A generalised additive model (GAM) (Hastie and Tibshirani, 1990) was fitted to the *W– statistic* data for each of the regions, sub-regions, and the whole coast to check whether a non-linear regression would improve the fit.

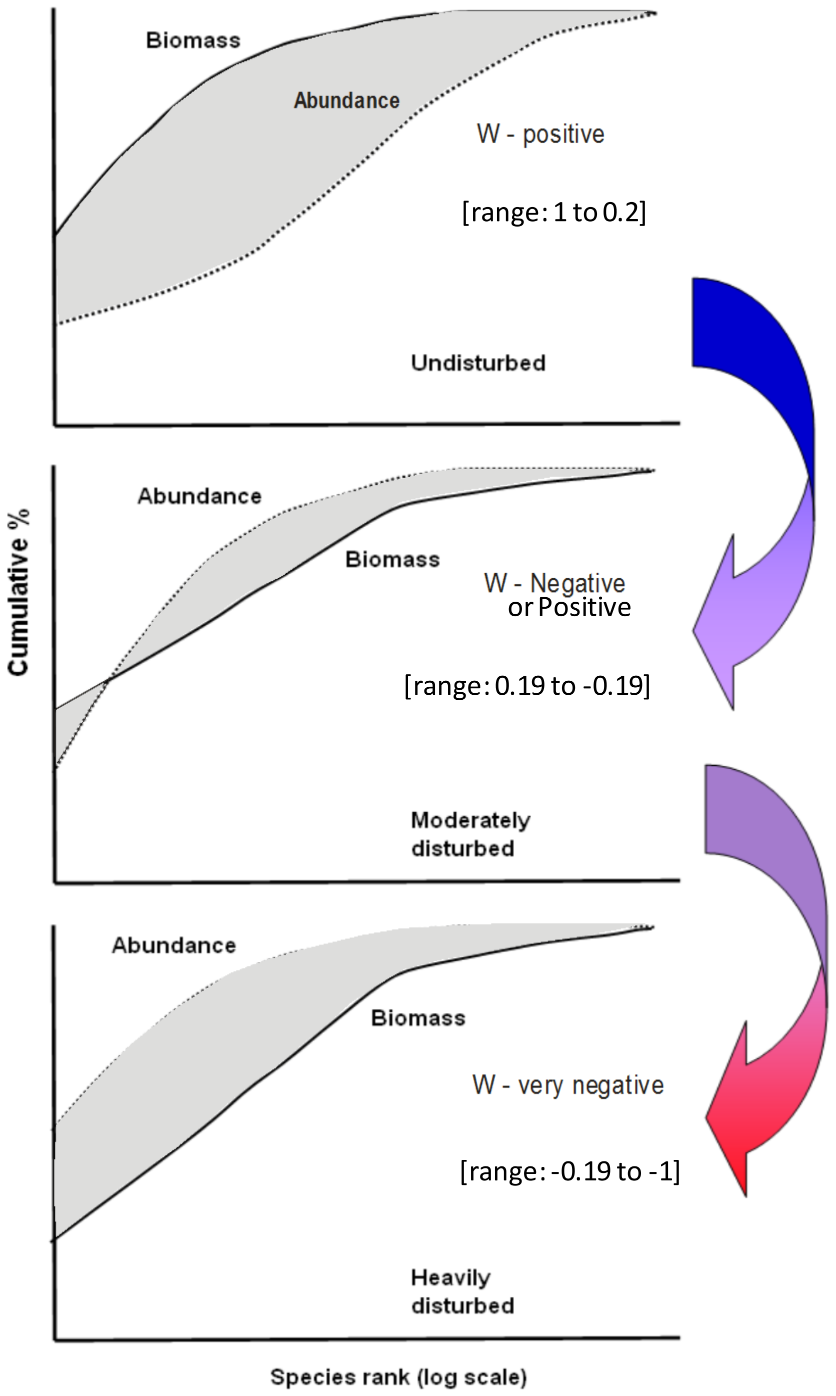


Figure 5.1 Modified theoretical ABC curves showing different patterns of assemblages which are undisturbed (very/large positive), moderately disturbed (positive and negative small values close to zero), and heavily disturbed (very/large negative) (modified from Yemane *et al.*, 2005 and originally from Clarke and Warwick, 1994).

The ABC technique was originally only applied to soft-sediment benthic fauna to indicate the level of disturbance within benthic communities (Warwick and Clarke, 1994; Clarke and Gorley, 2001). Therefore, for the purpose of this study, the above theory is modified in order have a *W– statistic* range which is more meaningful within the current distribution range of the *W– statistic*. Thus, the *W– statistic* ranges are: 1 to 0.2 is undisturbed; 0.19 to -0.19 is moderately disturbed; and -0.19 to -1 indicates a very disturbed demersal fish assemblage (Fig. 5.1). These ranges are arbitrary but still within the limits of the original theory by Clarke and Warwick (1994).

Permutational multi-variate analysis of variance (PERMANOVA) (Anderson *et al.*, 2008) was performed on the dermersal fish species biomass data (1990 – 2006) in order to test for a significant difference in assemblage structure between years and in relation to physical factors such as depth (shelf and slope), region (north, central, and south); and environmental variables (bottom dissolved oxygen). PERMANOVA tests the dissimilarity values generated by the resemblance matrix on which permutations are based, and the output is the test statistic value of the pseudo-F, and alternatively a pseudo-*t* in case of a pair-wise test (Anderson *et al.*, 2008). The data were 4th root transformed to reduce the weighting of more abundant species effectively and a Bray-Curtis similarity measure was used, as it was regarded appropriate since the similarity coefficient is not affected by scale differences (Field *et al.*, 1982). Partial sums of squares of type III error, fixed term effect sum to zero for mixed term, and permutation of residuals were run under a reduced model, with number of permutations equal to 9999 (Anserson *et al*., 2008).

The routine was run separately for physical variables (without and with pooling of terms, due to negative estimate of variance in some cases). Due to gaps in the time series for environmental data, the PERMANOVA was run with and without environmental variables. Only bottom temperature could be used in this exercise, as other environmental variables such as dissolved oxygen and salinity were spatially and temporally incompatible with biological data. Dissolved oxygen and salinity data were not collected in some years and in years when they were collected only a few or none were calibrated. PERMANOVA model designs were adopted for both two-way and three-way designs as follows:

1) Three-way fixed effects without environmental variables and

(a) physical variables (year, depth, and region) as fixed factors;

(b) physical variables (depth, region, and vessel) excluding year since it was highly correlated to vessel;

2) Two-way design with environmental variable (bottom temperature as a co-variate)

(a) physical variables [depth (fixed), year (random)];

(b) region (fixed) and year (random). The interaction effects between and within all the physical variables were summarized using MDS plots (Clarke and Warwick, 1994).

Furthermore, a distance-based linear model (DISTLM) in PRIMER-E v6 and its add-on package PERMANOVA+ (Clarke and Warwick, 1994, 2001; Clarke and Gorley, 2006; Anderson *et al*., 2008) were used to determine the relationship between biological data distribution patterns among each region, depth category and environmental variable (bottom temperature). The influence of physical factors and environmental variables on distribution of the biological data was simultaneously assessed. The partitioning of variation in data distribution by DISTLM is based on multiple regression models (based on predictor variables) where the user has choices to make (e.g. best fit, forward, and step-wise etc.) (Anderson *et al*., 2008). Due to the limited number of environmental variables, the default settings for DISTLM were used, including the AIC (Akaike's Information Criterion) option (Anderson *et al*., 2008). The principal coordinate ordination (PCO) was used to summarise the interaction effects of bottom temperature and depth over the years under review.

5.2.2 Univariate analyses

5.2.2.1 Diversity Indices

Ecological parameters such as species diversity were examined as species richness (*S* = number of species) and composite diversity, which integrates both richness and evenness (Shannon-Wiener *H'*) and Pielou's evenness index *J'* (Pielou, 1966). They were calculated using species abundance data using the following formulae:

Shannon-Wiener Index *H'* = $-\sum P_i * \log_e(P_i)$ ....(5.2)

Pielou's evenness index *J'* = $\frac{H'}{log_e(s)}$ ....(5.3)

where *S* is total number of species

P_i is proportion of species *i* in a sample

H' Shannon-Wiener index

All these ecological parameters were calculated using the DIVERSE function in Primer v6. Thus, species diversity was examined for each station group and for each year as defined by the cluster analysis (Warwick and Clarke, 1994). Physical variables such as depth, longitude, year and log (N) were incorporated in the analysis using Generalized Additive Models (GAMs) (Hastie and Tibshirani, 1990) (all analysis done in *R (mgcv package)* (R Development Core Team, 2004; Wood, 200*6, 2009*), to assess their effects on demersal fish species diversity. GAM was used to examine the relationship among environmental variables (oxygen and temperature); physical parameters and relative species diversity (*S, J'* and *H'*); and analyze the spatial distribution of demersal fish species. A detailed description of GAM is provided in Chapter 2 of this thesis.

The observed response is assumed to obey some underlying statistical distribution from the exponential family (e.g. Gaussian, Poisson, Binomial or Gamma distributions) with the specified mean μ, (Hastie and Tibshirani, 1990). The Poisson distribution was used for the species richness because it is based on frequencies, while the Gaussian distribution was used for the evenness and Shannon-Wiener index, since there was no violation of its assumptions (Zar, 1999). The correlation between depth and longitude was tested using the correlation matrices in Statistica v10 (www.statsoft.com) to establish whether they are correlated before been added to the GAM model.

Table 5.1 Overview of hake biomass surveys used in the analysis for this study along the coast of Namibia, (data supplied by NatMIRC, MFMR).

Year	Date (DD:MM)	Station number	Number of Stations
1990	26/01 - 18/03	2 - 242	241
1991	27/01 - 27/02	501 - 696	196
1992	24/04 - 19/05	1061 - 1225	165
1993	21/01 - 23/02	1566 - 1759	194
1994	21/01 - 21/02	1 - 152	152
1995	22/04 - 26/05	920 - 1104	185
1996	10/01 - 17/02	1185 - 1427	243
1997	12/01 - 19/02	1857 - 2124	267
1998	13/01 - 18/02	2229 - 2442	214
1999	13/01 - 18/02	2600 - 2814	215
2000	17/01 - 22/02	2815 - 3037	223
2001	19/01 - 24/02	3038 - 3241	204
2002	18/01 - 24/02	3242 - 3453	212
2003	17/01 - 20/02	3454 - 3649	196
2004	14/01 - 20/02	3650 - 3861	212
2005	13/01 - 16/02	3862 - 4074	213
2006	12/01 - 18/02	4075 - 4277	203

5.3 Ancillary information

5.3.1 Environmental Data

Environmental variables such temperature, salinity, and dissolved oxygen were collected during some, but not all, surveys , using the CTD. The data are not station specific, and do not match biological data. The CTD data stations are sparsely distributed along the

Namibian coast, thus making it difficult to resolve the envrionmentally-induced effects on the demersal fish assemblages. In the absence of station specific environmental data, some published (Barthalomae and van der Plas, 2007) and unpublished figures on the state of the environment over the study period were used qualitatively to address the effects of environmental variability. Some extra data on winds, upwelling, SST and the position of the Angola-Benguela-Front (ABF) were supplied by NatMIRC, MFMR in Swakopmund. The data were collected daily, monthly, and yearly via land-based stations, *in situ* measurements, and by satellite. This information was collated to assist in explaining and discussing the observed patterns in the community structure.

5.4 Results

5.4.1 Multivariate Analyses:

5.4.1.1 Cluster analysis and MDS

From the 17 hake biomass surveys (Table 5.1), 3535 bottom trawls were conducted off the coast of Namibia. The cluster and the MDS indicated that there were three major groupings in terms of relative species biomass according to the survey years (Fig. 5.1a and b). The first four years (Group A) surveys from 1990–1993 differ significantly (Global R = 0.76, ANOSIM) (see appendix 5.1) from the rest of the years from 1994 onward. However, two more groups were found for the years from 1994 to 2000, (Group B) and 2001 to 2006 (Group C), which were not as distinct from one another as they were from Group A (Fig. 5.1a and b). However, there was a big change in community from 1990 to 1991 in Group A, and another big change in community structure occurred between 1993 and 1994, and then smaller changes thereafter (Fig. 5.1b). SIMPER results showed that *M. capensis* and *Sufflogobius bibarbatus* contributed most to the similarity of Group A and B in order of contribution; while the reverse was true of Group C (Table 5.2). Considering the dissimilarity between Group A and B, *Lampanyctodes hectaris* (group A) and *M. capensis* (group B), and between Group A and C, *Lampanyctodes hectaris* (group A) and *S. bibarbatus* (group C) contributed the most in discriminating the groups, while Group B and C dissimilarities were caused by *S. bibarbatus* (group B) and *M. capensis* (group C) (Table 5.3).

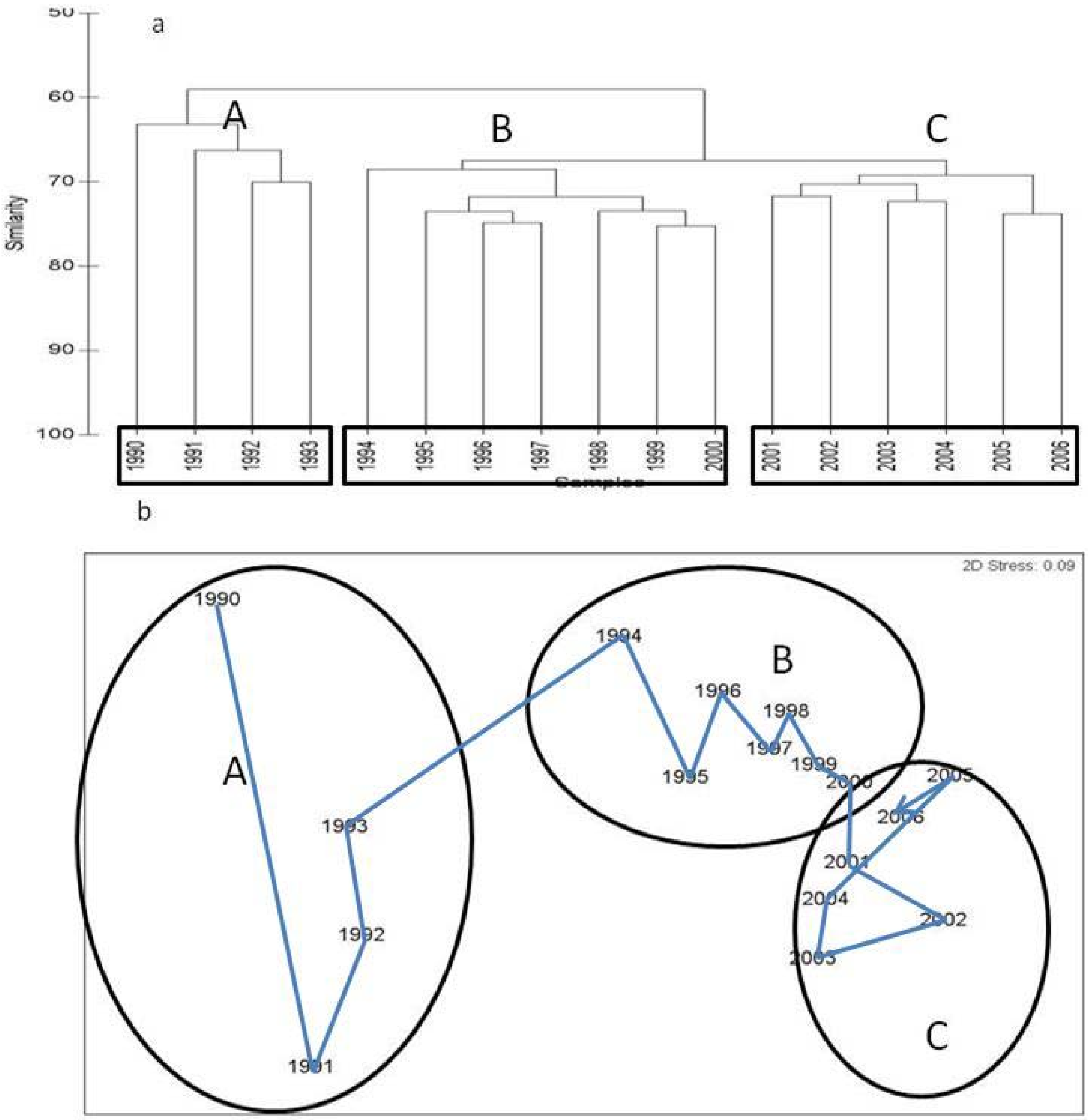


Figure 5.2 Dendrogram (a) and the multi dimensional scaling (MDS) (b) based on 4th root transformed biomass data for demersal fish species off Namibia, from 100 to 600 m. A cluster analysis and the MDS (group average) ordination were performed on a resemblance matrix employing the Bray-Curtis similarity index. Trajectories overlay runs from 1990 – 2006. Data were pooled from the annual hake biomass surveys from 1990 – 2006.

Table 5.2 SIMPER results for the cluster and MDS identified groups: A (1990 – 1993), B (1994 – 2000), and C (2001 – 2006). SIMPER analysis examines the contribution of each variable to average resemblances between sample groups. For Bray-Curtis similarities, it determines the contributions to the average Bray-Curtis dissimilarity between pairs of groups of samples. It also determines the contributions to the average similarity within a group. Individual species contribution to the Bray – Curtis similarity percentage of the identified groups: Av.Abund is average abundance of a particular species, Av.Sim is average similarity within a group, Sim/SD is similarity standard deviation, Contrib% is contribution percentage to the similarity, and Cum% is cumulative percentage to the similarity. The numbers in bold indicate species which contribute the most in terms of abundance.

Group A
Average similarity: 37.36

Species	Av.Abund	Av.Sim	Sim/SD	Contrib%	Cum.%
Merluccius capensis	**1642.29**	20.22	1.37	54.13	54.13
Sufflogobius bibarbatus	1435.74	9.74	1.37	26.08	80.21
Helicolenus dactylopterus	176.56	1.8	1.08	4.82	85.03
Merluccius paradoxus	105.39	0.9	0.67	2.41	87.43
Chlorophthalmus punctatus	102.67	0.85	0.78	2.27	89.71
Dentex macrophthalmus	100.68	0.78	1.46	2.09	91.8

Group B
Average similarity: 53.07

Species	Av.Abund	Av.Sim	Sim/SD	Contrib%	Cum.%
Merluccius capensis	**2370.81**	14.41	2.42	27.16	27.16
Sufflogobius bibarbatus	1988.25	13.86	1.65	26.13	53.29
Merluccius paradoxus	280.41	2.81	3.82	5.29	58.58
Helicolenus dactylopterus	266.66	2.62	2.79	4.93	63.51
Myctophidea	370.62	2.51	0.81	4.72	68.24
Synagrops microlepis	827.28	2.3	1.68	4.34	72.58
Dentex macrophthalmus	336.83	2.29	1.61	4.32	76.9
Chlorophthalmus punctatus	222.69	1.94	1.21	3.65	80.55
Hoplostethus cadenati	183.23	1.63	2.43	3.08	83.63
Caelorinchus simorhynchus	163.87	1.54	7.55	2.91	86.53
Sepia australis	144.41	1.13	1.49	2.12	88.65
Nezumia micronychodon	148.63	1.07	2.05	2.01	90.66

Group C
Average similarity: 70.71

Species	Av.Abund	Av.Sim	Sim/SD	Contrib%	Cum.%
Sufflogobius bibarbatus	**3205.07**	32.85	4.3	46.45	46.45
Merluccius capensis	1631.41	16.82	2.07	23.79	70.24
Helicolenus dactylopterus	336.48	3.83	4.4	5.42	75.66
Merluccius paradoxus	259.98	3.06	4.97	4.33	79.98
Chlorophthalmus punctatus	201.67	2.22	6.19	3.14	83.12
Nezumia micronychodon	217.88	1.82	2.82	2.57	85.7
Hoplostethus cadenati	130.98	1.48	3.25	2.09	87.79
Sepia austrlis	176.96	1.36	2.07	1.93	89.72
Pterothrissus belloci	86.96	1	5.1	1.42	91.14

Table 5.3 SIMPER results for species contributions to the average Bray – Curtis dissimilarity among identified groups A (1990 – 1993), B (1994 – 2000), and C (2001 – 2006). SIMPER analysis examines the contribution of each variable to average resemblances between sample groups. For Bray-Curtis similarities, it determines the contributions to the average Bray-Curtis dissimilarity between pairs of groups of samples. It also determines the contributions to the average similarity within a group. Individual species contribution to the Bray – Curtis dissimilarity percentage of the identified groups: Av.Abund is average abundance of a particular species, Av.Diss is average dissimilarity within a group, Diss/SD is dissimilarity standard deviation, Contrib% is contribution percentage to the dissimilarity, and Cum% is cumulative percentage to the dissimilarity. The numbers in bold indicate species which are more abundant in that group.

Groups A & B
Average dissimilarity = 59.78

Species	Group A Av.Abund	Group B Av.Abund	Av.Diss	Diss/SD	Contrib%	Cum.%
Lampanyctodes hectoris	**8542.34**	564.56	20.44	0.68	34.2	34.2
Sufflogobius bibarbatus	1435.74	1988.25	8.97	1.1	15	49.19
Merluccius capensis	1642.29	**2370.81**	8.03	1	13.43	62.62
Synagrops microlepis	27.01	827.28	4.41	0.62	7.37	69.99
Myctophidea	366.56	370.62	2.63	1.02	4.4	74.4
Dentex macrophthalmus	100.68	336.83	1.73	0.89	2.9	77.3
Chlorophthalmus atlanticus	12.36	222.69	1.48	1.24	2.48	79.78
Merluccius paradoxus	105.39	280.41	1.09	1.19	1.82	81.59
Maurolicus muelleri	0.25	195.68	1.04	0.67	1.74	83.33
Caelorinchus simorhynchus	27.03	163.87	0.86	2.17	1.45	84.78
Sepia australis	21.33	144.41	0.86	1.09	1.43	86.21
Nezumia sp.	23.07	148.63	0.83	1.24	1.4	87.61
Hoplostethus cadenati	48.39	183.23	0.81	1.31	1.35	88.96
Pterothrissus belloci	31.08	155.24	0.77	0.75	1.29	90.25

Groups A & C
Average dissimilarity = 53.85

Species	Group A Av.Abund	Group C Av.Abund	Av.Diss	Diss/SD	Contrib%	Cum.%
Lampanyctodes hectoris	**8542.34**	34.65	18.59	0.58	34.53	34.53
Sufflogobius bibarbatus	1435.74	**3205.07**	14.52	1.38	26.97	61.5
Merluccius capensis	1642.29	1631.41	4.3	1.31	7.98	69.48
Nezumia micronychodon	0.13	217.88	1.51	1.22	2.81	72.29
Chlorophthalmus atlanticus	12.36	201.67	1.31	1.72	2.43	74.72
Synagrops microlepis	27.01	217.35	1.3	0.61	2.42	77.14
Helicolenus dactylopterus	176.56	336.48	1.1	1.21	2.05	79.19
Sepia australis	21.33	176.96	1.1	1.08	2.04	81.23
Myctophidea	366.56	64.39	1.05	1.08	1.95	83.19
Merluccius paradoxus	105.39	259.98	1.02	1.22	1.9	85.09
Caelorinchus simorhynchus	27.03	123.26	0.76	0.78	1.42	86.51
Chlorophthalmus punctatus	102.67	2.96	0.74	1.22	1.37	87.88
Hoplostethus cadenati	48.39	130.98	0.52	1.41	0.97	88.85
Epigonus denticulatus	53.57	12.25	0.48	0.64	0.89	89.74
Trachyrincus scabrus	9.55	69.36	0.45	1.32	0.84	90.58

Groups B & C
Average dissimilarity = 42.44

Species	Group B Av.Abund	Group C Av.Abund	Av.Diss	Diss/SD	Contrib%	Cum.%
Sufflogobius bibarbatus	1988.25	**3205.07**	10.44	1.16	24.6	24.6
Merluccius capensis	**2370.81**	1631.41	8.26	1.13	19.47	44.07
Synagrops microlepis	827.28	217.35	4.28	0.68	10.09	54.16
Lampanyctodes hectoris	564.56	34.65	3.15	0.64	7.42	61.58
Myctophidea	370.62	64.39	2.25	1.06	5.29	66.87
Dentex macrophthalmus	336.83	79.11	1.74	1.15	4.1	70.97
Nezumia micronychodon	45.79	217.88	1.19	1.22	2.8	73.77
Maurolicus muelleri	195.68	6.41	1.04	0.75	2.45	76.22
Nezumia sp.	148.63	5.03	0.87	1.71	2.06	78.27
Caelorinchus simorhynchus	163.87	123.26	0.8	2.19	1.89	80.16
Sepia australis	144.41	176.96	0.72	1.21	1.69	81.86
Chlorophthalmus atlanticus	222.69	201.67	0.71	1.52	1.66	83.52
Helicolenus dactylopterus	266.66	336.48	0.65	1.42	1.53	85.05
Symbolophorus boops	86.48	49.88	0.63	0.77	1.48	86.53
Pterothrissus belloci	155.24	86.96	0.51	0.59	1.2	87.73
Hoplostethus cadenati	183.23	130.98	0.47	1.26	1.1	88.82
Merluccius paradoxus	280.41	259.98	0.43	1.36	1.02	89.85
Trachyrincus scabrus	91.63	69.36	0.33	1.24	0.78	90.63

5.4.1.2 *Abundance Biomass Comparison (ABC) curves*

The cluster and ordination techniques have identified three sub-periods within the study period under review. These assemblages were found to be significantly different from each other (Global R = 0.76, ANOSIM). Figure 5.2 shows the ABC curves for those three sub-periods. In the first period (Group A), the abundance curve lies above the biomass curve (see Fig. 5.1 for explanation), with a negative *W– statistic*, which suggests the demersal fish assemblage was moderately disturbed. The period was also strongly dominated by a single or few species (see SIMPER results in Table 5.2 above). In Group B, although there is a negative *W– statistic*, and moderate disturbance, the biomass curve lies above the abundance curve at low species rank, but crosses it mid-way, a sign that there was a mixture of large-bodied species and small-bodied individuals. In the last period (Group C), the abundance and biomass curves are close to each other and again the abundance curve lies above the biomass curve, suggesting that small individuals that were numerically abundant dominated the demersal fish community. The overall status of the three sub-periods is that the demersal fish assemblages under these regimes were moderately disturbed, according to Clarke and Warwick (1994).

The ABC curves for the continental shelf (100 – 300 m depth range) are shown in Figure 5.3a and b. The biomass curves lie below the abundance curves for the whole study period except 1991, 1993, 1995 and 1998 where the opposite occurred (Fig. 5.3a and b). Initially, the *W– statistic* alternated between negative and positive from 1990 to 1996, and then remained below zero (Fig. 5.3a and b).

Figure 5.4a and b show the ABC curves for the slope (300 – 600 m depth range) for the period 1990 — 2006. In the first two years (1990 and 1991) the abundance curves were above the biomass curves, but in 1992 and 1993 the situation was reversed. Then, in 1994 the biomass and abundance curves crossed at mid-length of the curves. From 1995 to 2004, the biomass curves were above the abundance curves, (suggesting a less disturbed state, according to the theory of *r*- and *k*- selection, Warwick and Clarke, 1994).

ABC curves for the whole coast (100 – 600 m depth range) of Namibia are shown in Figure 5.5a and b. Overall the abundance curves lie above the biomass curves for the entire study period, except for 1993, 1995 and 1998. This suggests a fairly disturbed state for the coast as a whole (Warwick and Clarke, 1994). Regionally, on the northern shelf, the abundance and biomass curves cross each other indicating the existence of a combination of large and small species each with a different rank in terms of abundance and biomass. On the northern and southern slopes and central shelf and slope, the biomass curves lie above the abundance curves, suggesting an undisturbed community, but the reverse occurred on the southern shelf (Fig. 5.6).

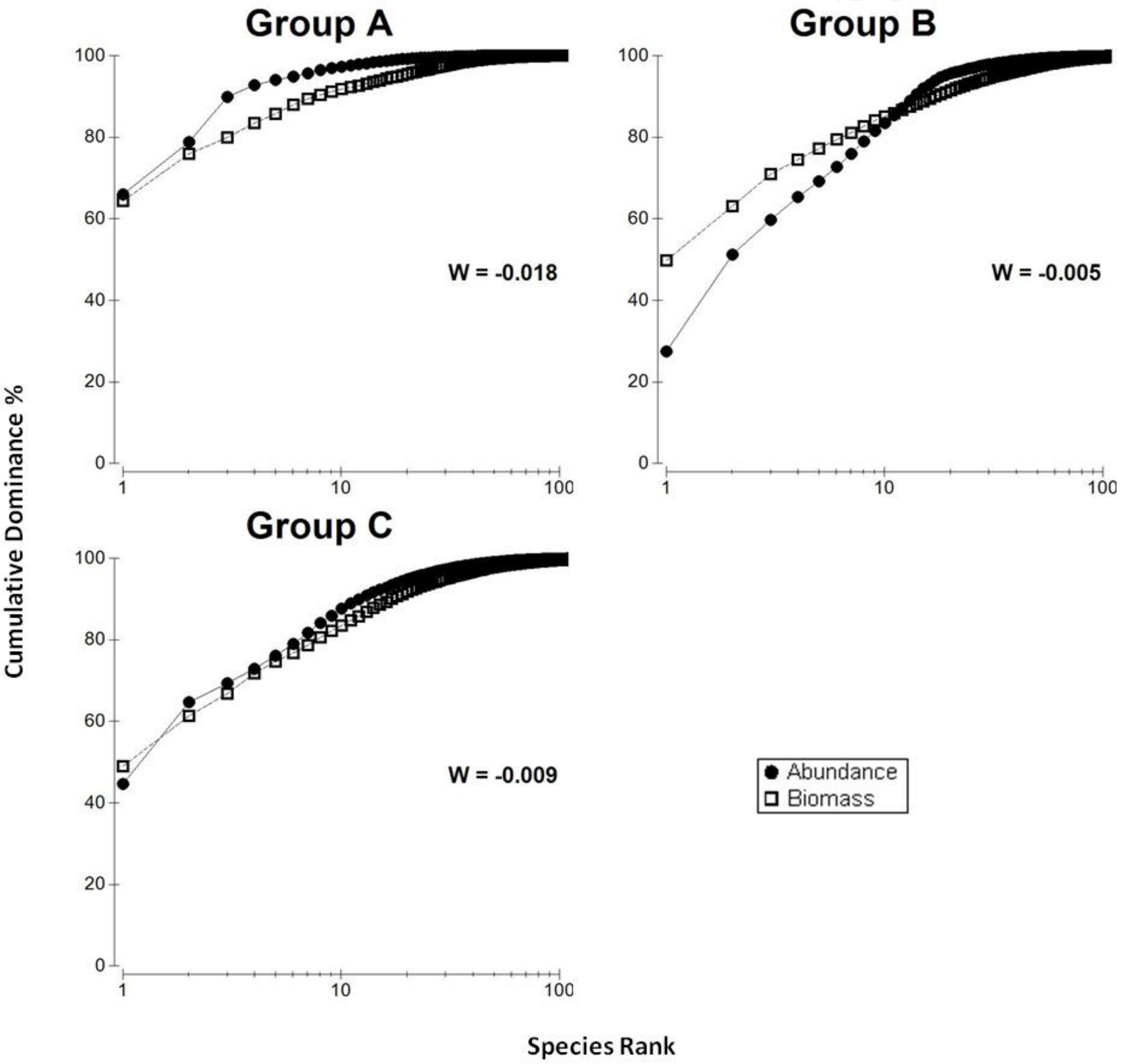


Figure 5.2 ABC curves for three groups identified by the cluster and ordination, Group A (1990–1993), Group B (1994–2000) and Group C (2001–2006).

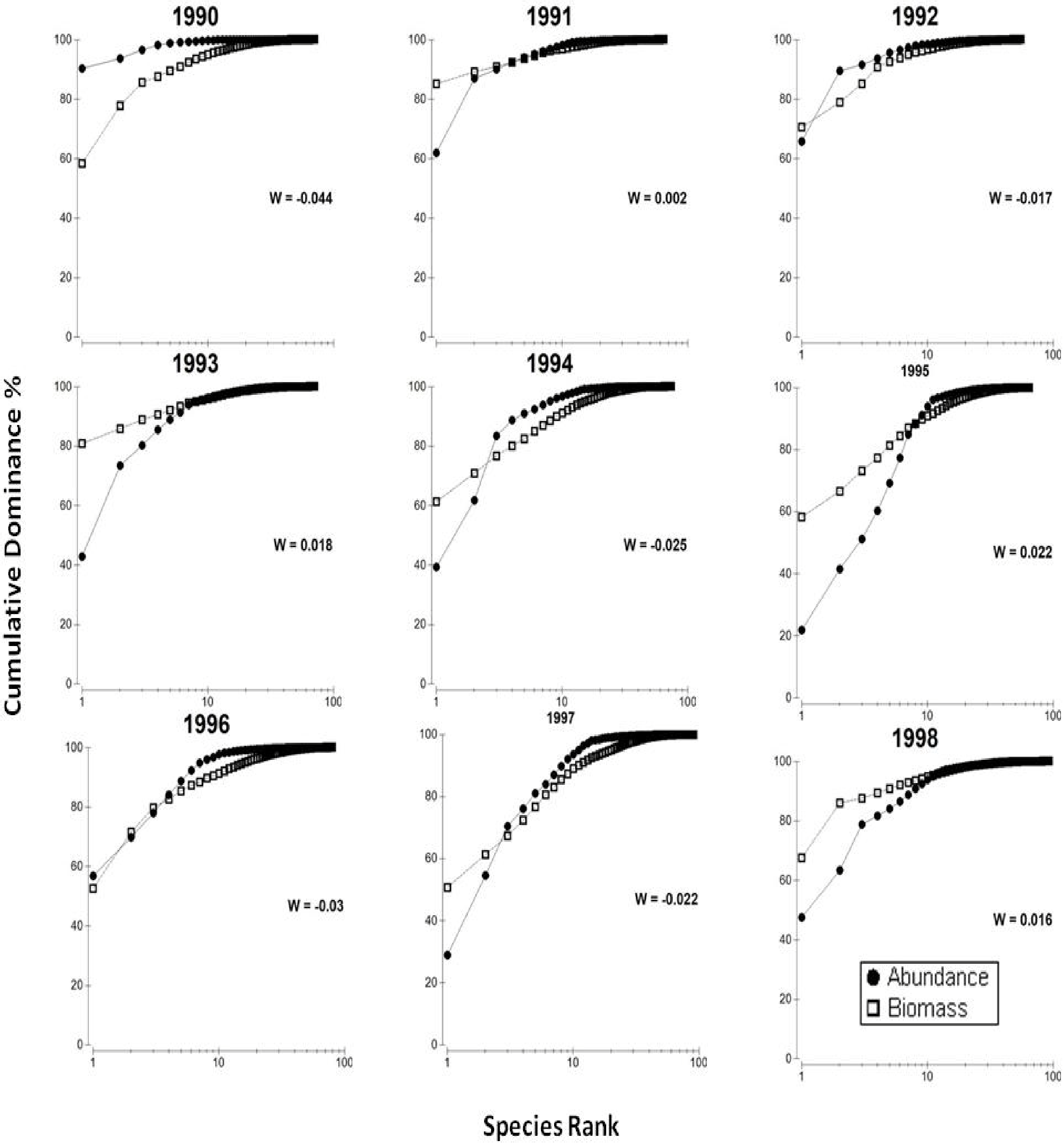


Figure 5.3a 1990 – 1998: ABC curves for the shelf (100 – 300 m depth range) for the demersal fish community off the Namibian coast. Data from the annual hake biomass surveys. Note that the ABC curves were plotted for each year and not according to the groupings of the cluster analysis and MDS mentioned above.

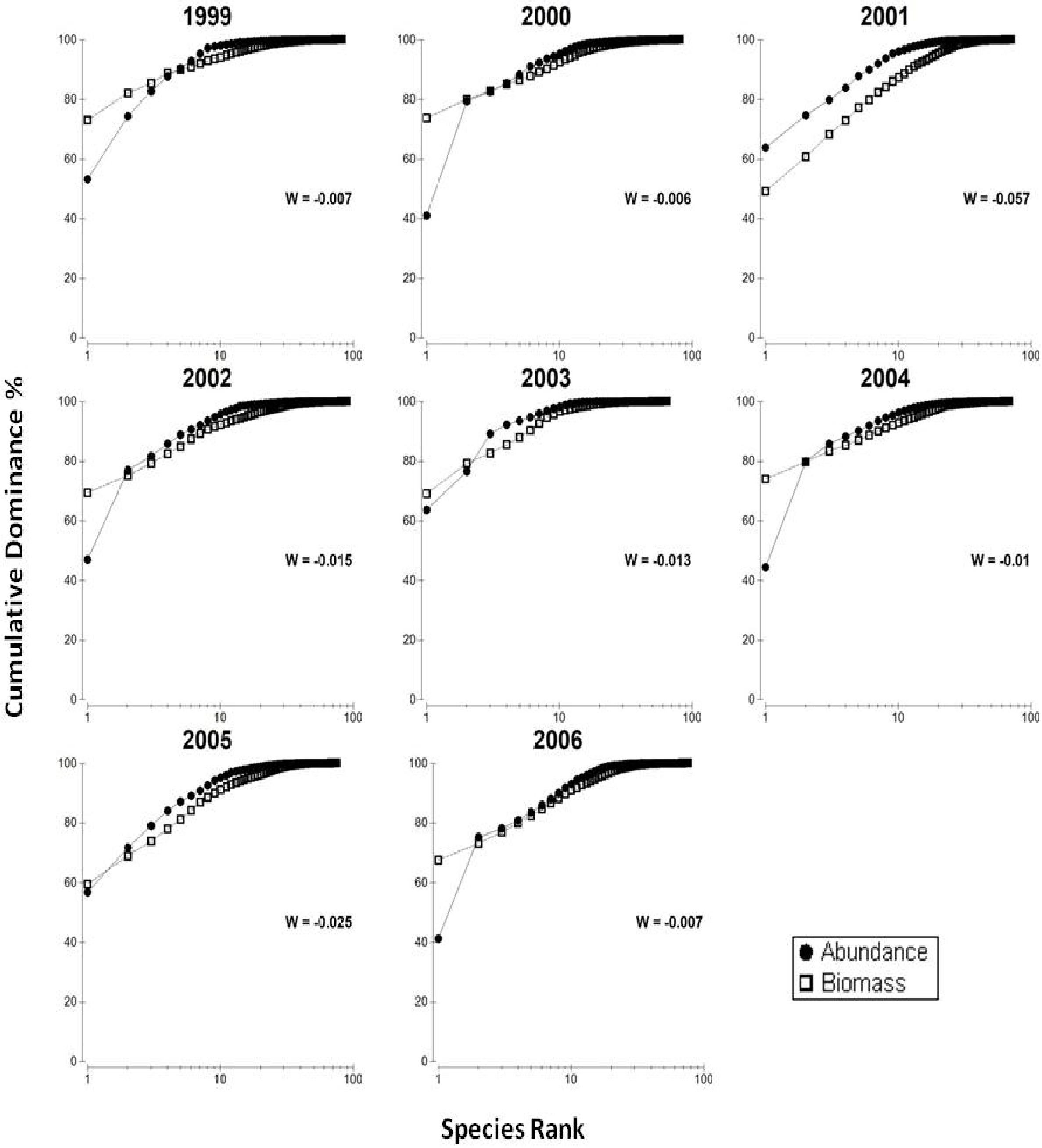


Figure 5.3b 1999 – 2006: ABC curves for the shelf (100 – 300 m depth range) for the demersal fish community off the Namibian coast. Data from the annual hake biomass surveys. Note that the ABC curves were plotted for each year and not according to the groupings of the cluster analysis and MDS mentioned above.

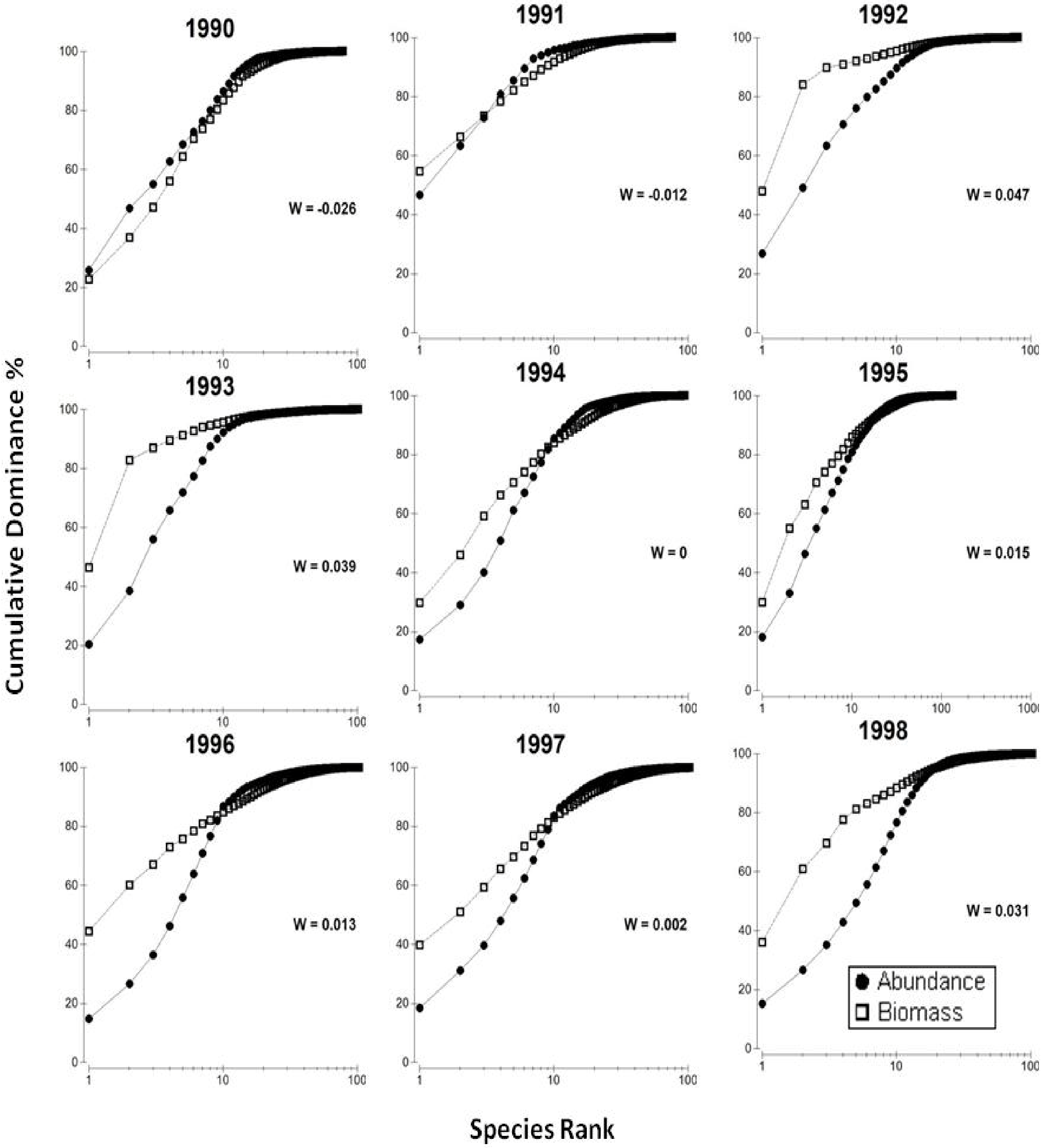


Figure 5.4a 1990 – 1998: ABC curves for the continental slope (300 – 600 m depth range) for the demersal fish community off the Namibian coast. Data from the annual hake biomass surveys. Note that the ABC curves were plotted for each year and not according to the groupings of the cluster analysis and MDS mentioned above.

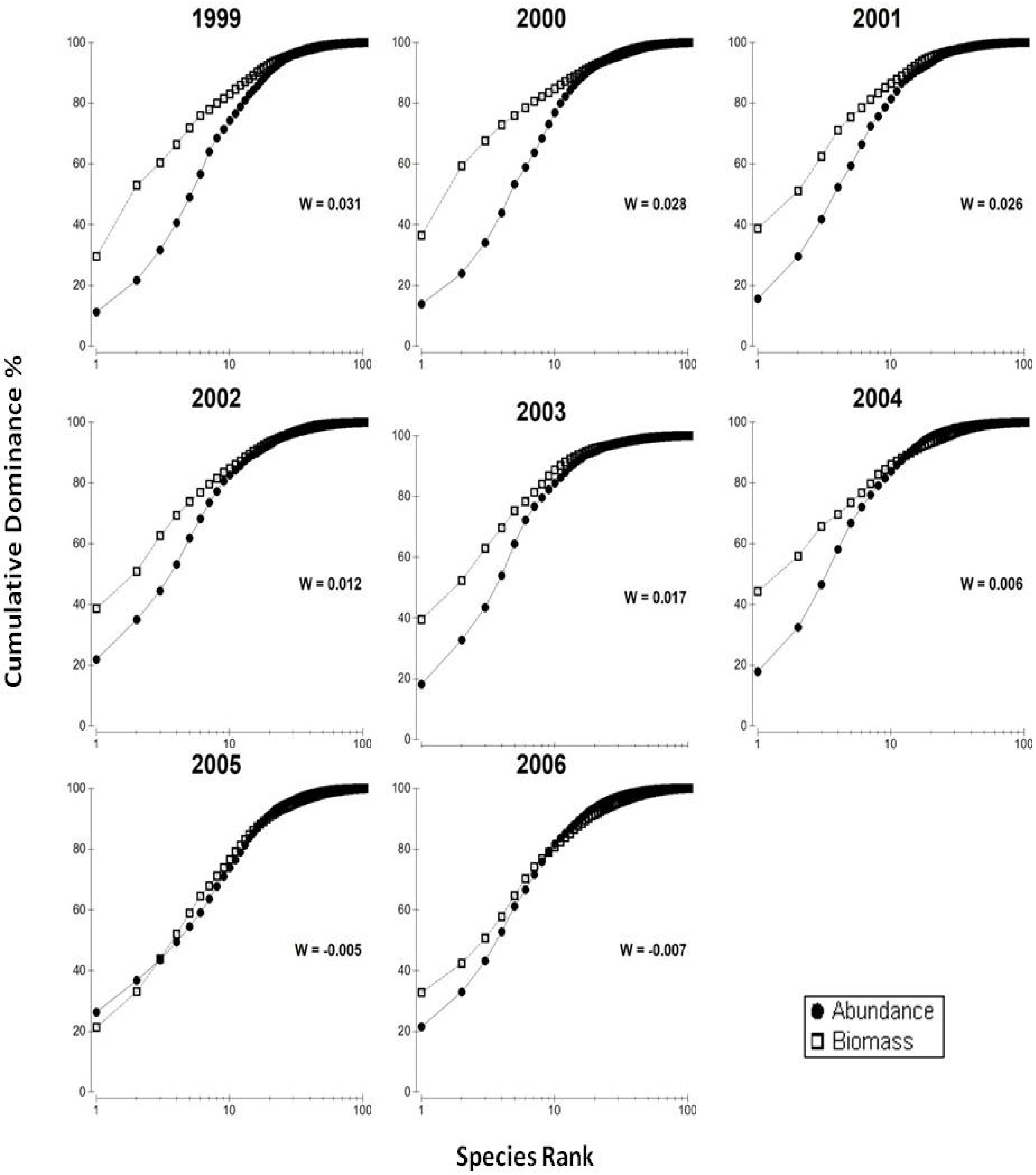


Figure 5.4b 1999 – 2006: ABC curves for the continental slope (300 – 600 m depth range) for the demersal fish community off the Namibian coast. Data from the annual hake biomass surveys. Note that the ABC curves were plotted for each year and not according to the groupings of the cluster analysis and MDS mentioned above.

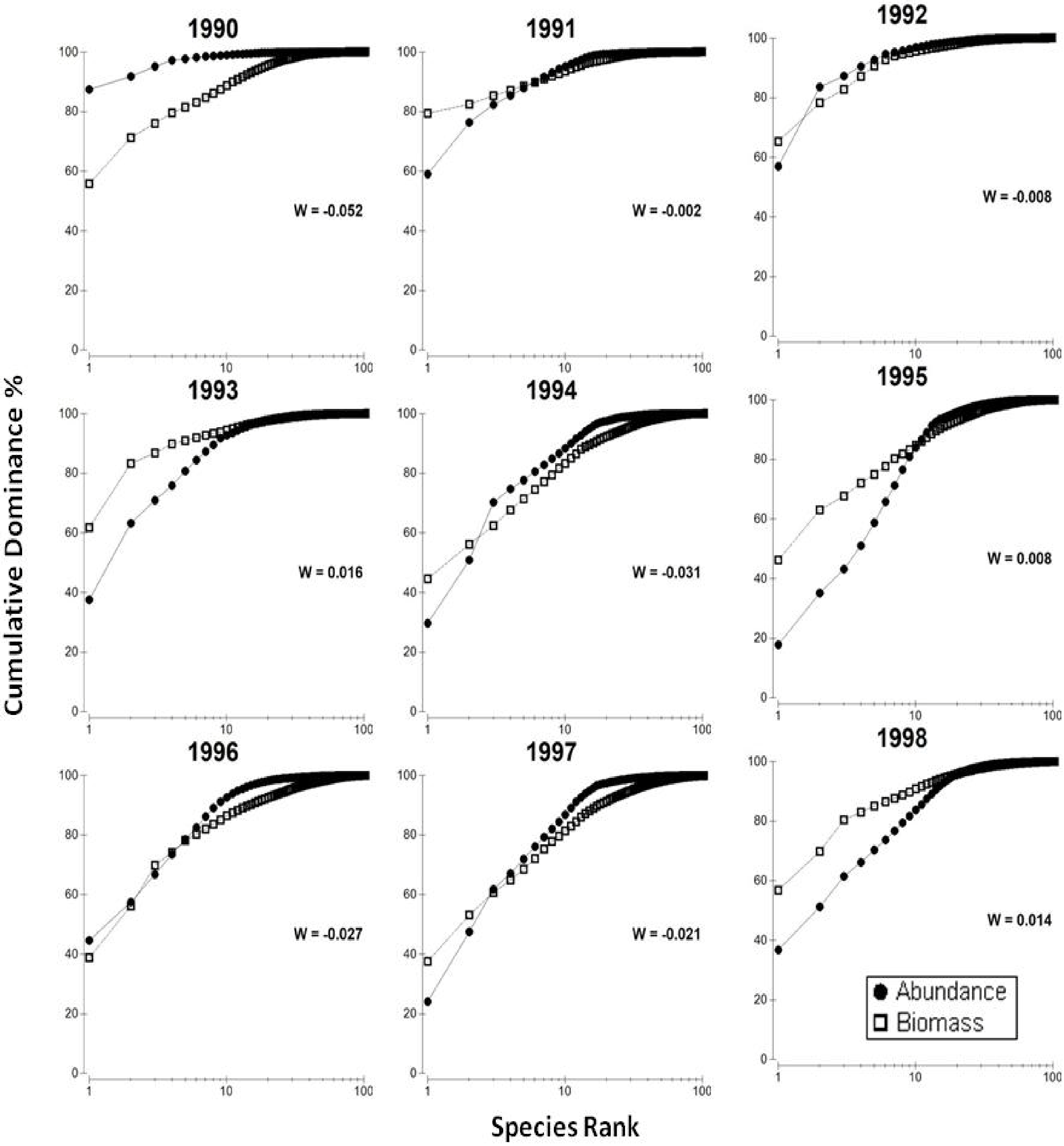


Figure 5.5a 1990 – 1998 Whole coast: ABC curves for the pooled depth (100 – 600 m depth range) for the demersal fish community off the Namibian coast. Data from the annual hake biomass surveys. Note that the ABC curves were plotted for each year and not according to the groupings of the cluster analysis and MDS mentioned above.

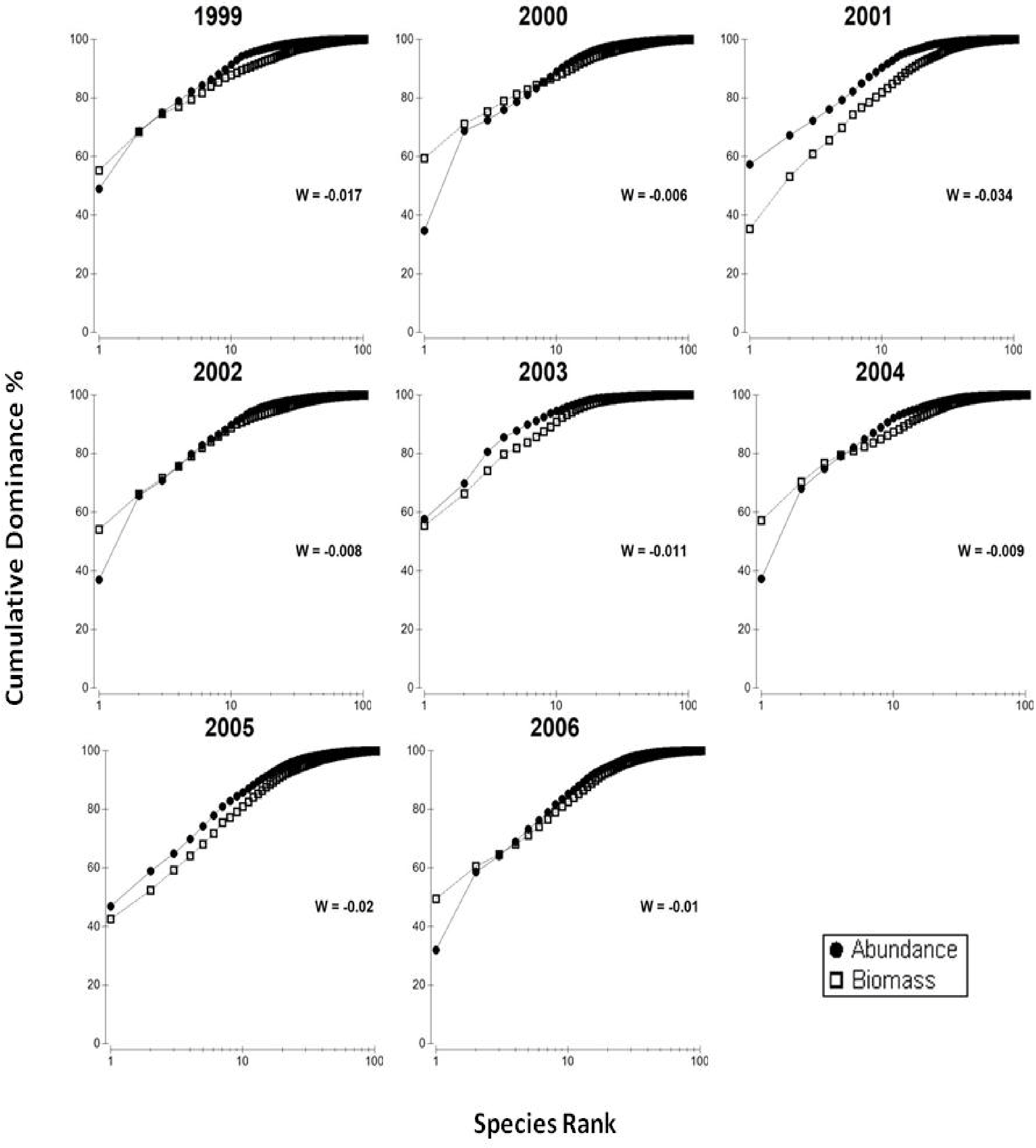


Figure 5.5b 1999 – 2006 Whole coast: ABC curves for the pooled depth (100 – 600 m depth range) for the demersal fish community off the Namibian coast. Data from the annual hake biomass surveys. Note that the ABC curves were plotted for each year and not according to the groupings of the cluster analysis and MDS mentioned above.

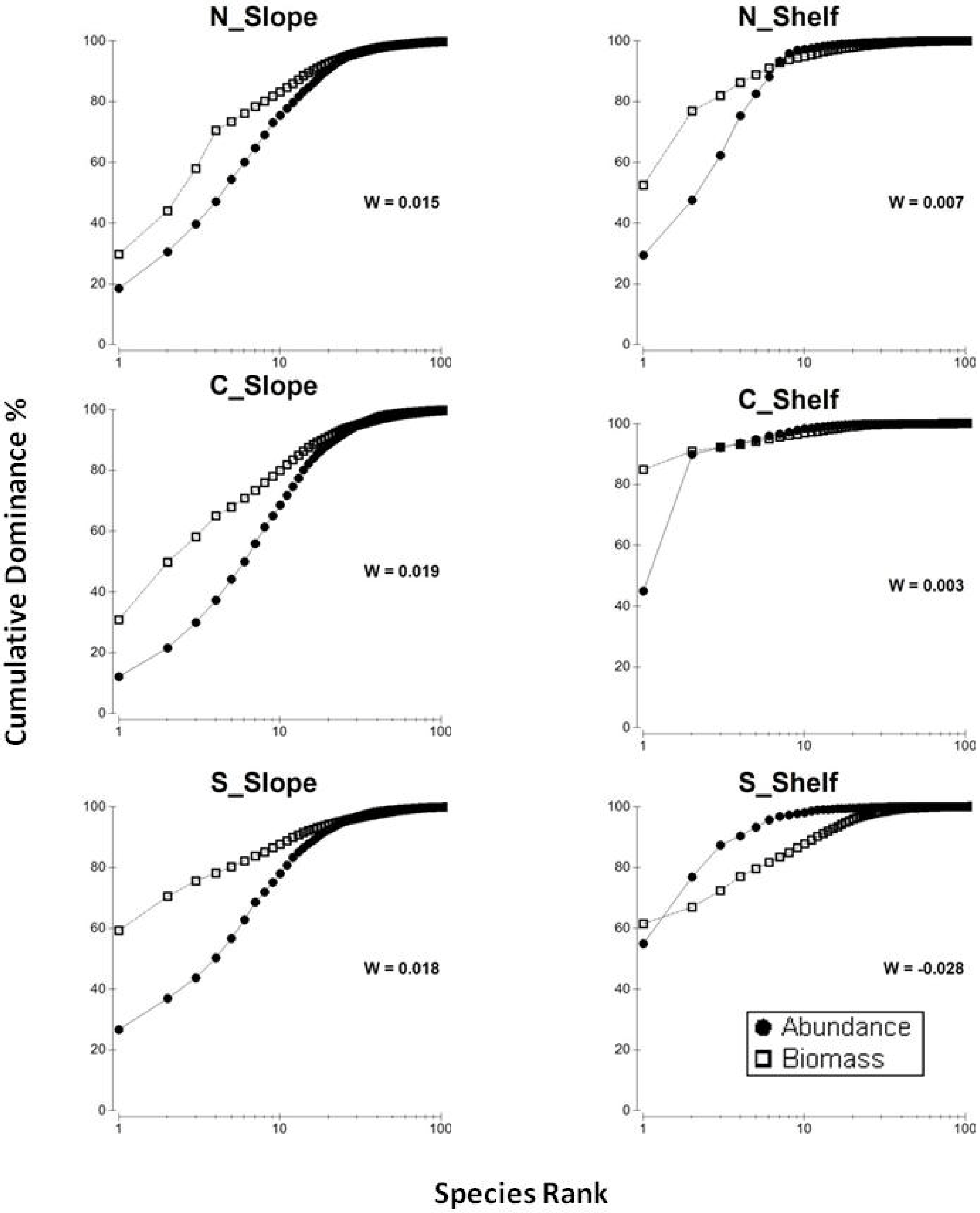


Figure 5.6 ABC curves for the sub-regions: northern, central and southern, divided into continental shelf (100 – 300 m) and slope (300 – 600 m depth range) for the demersal fish community off the Namibian coast. Data from the annual hake biomass survey 1990 to 1998; this is an average of all years. Note that the ABC curves were plotted for each year and not according to the groupings of the cluster analysis and MDS mentioned above. Thus the groups of different ABC curves appear in one Figure per page for comparability.

5.4.1.3 Spatio-temporal trends in the W- statistic

The temporal trends in the *W– statistic* over the 17 year period are shown in Figure 5.7. The linear regression of *W- statistic* versus time fitted to the data (not shown) showed that the continental shelf (100 – 300 m depth range) had no significant trend. The data fluctuated widely around a mean slightly below zero. Non-linear regression was also fitted to the data (not shown) using GAM and was not significant. The Loess smoother was below zero during the entire period, but the interannual variability in the data made it difficult to identify a convincing trend with this method (Fig. 5.7).

For the continental slope (300 – 600 m depth range) the temporal trend in the *W– statistic* depicted no relationship through the linear regression analysis (not shown), and yielded no significant results. Non-linear regression (not shown) was also fitted to the data using R software, but was not significant. However, the Loess smoother showed an upward trend from 1990, which peaked around 1999, then started to decline until the end of the study period (Fig. 5.7).

The *W– statistic* by sub-region showed spatio-temporal trends (Figure 5.8). The southern continental shelf showed a declining trend in *W- statistic* through both the non-linear regression and Loess smoother, while the southern continental slope depicted a positive upward trend through the non-linear regression (not shown) and variable ups and downs through the Loess smoother, but the trends were not significant. However, the *W– statistic* was positive in most years for both the southern continental shelf and slope. Both northern continental shelf and slope showed a steady decline in the *W–statistic* over the study period. The central continental shelf and slope and northern continental shelf and slope, all showed a significant year term, when the *W- statistic* data were fitted using GAM (with the *W- statistic* for each year as dependent variable, and the years 1990 – 2006 as independent variables), suggesting that the temporal trend was important (see Appendix 5.1). They also had positive *W– statistics* for most of the years, suggesting a community deteriorating with increasing disturbance (Warwick and Clarke, 1994).

The linear regression (not shown) for central continental shelf showed a relatively slight decline in the *W– statistic,* and the Loess smoother depicted a variable trend (Fig. 5.8). The *W– statistic* was negative most of the time, suggesting a fairly disturbed central shelf. The central continental slope had a negative slope over the study period as depicted by the Loess smoother. Despite these declining trends, the *W– statistic* remained positive most of the time, suggesting a fairly undisturbed state for the central continental slope. Overall, the temporal trend in the mean *W– statistic* for the whole coast shows an upward trend (suggesting a slight improvement in community state) as depicted by the linear regression (Fig. 5.9). The Loess smoother shows an initial upward trend in the early 1990s, then a declining trend in the mid-1990s; thereafter, it remained more or less stable to the end of the study period. However, the wide interannual fluctuations in the data make it difficult to interpret this trend as convincing (Fig. 5.9).

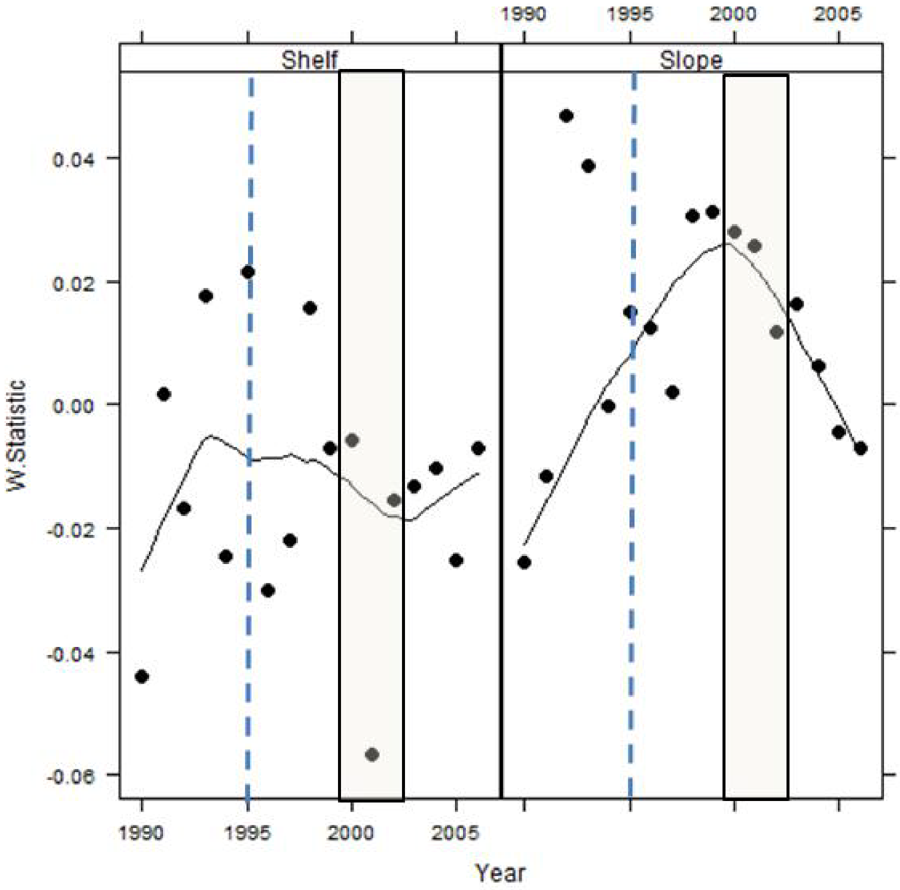


Figure 5.7 Temporal trends in the *W– statistic* for the continental shelf (100 – 300 m) and slope (300 – 600 m depth range) off the coast of Namibia from 1990 to 2006. Solid lines are the Loess smoothers (loess, span = 0.5). The blue vertical dashed lines represent the Benguela Niño year, and vertical rectangles represent the occurrence of the LOW in those years.

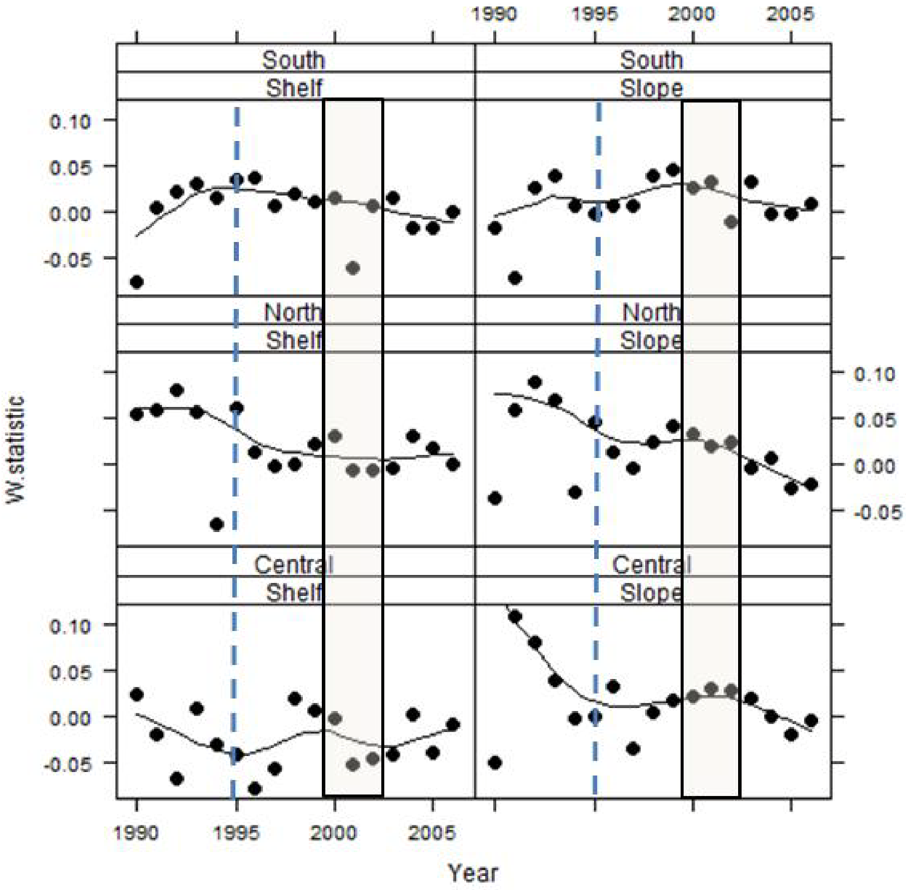


Figure 5.8 Spatio-temporal trends in the *W– statistic* of demersal fish communities in sub-regions off Namibia from 1990 — 2006. Solid lines represent the Loess smoother (Loess, span = 0.5). The blue vertical dashed lines represent the Benguela Niño year, and vertical rectangles represent the occurrence of the LOW in those years.

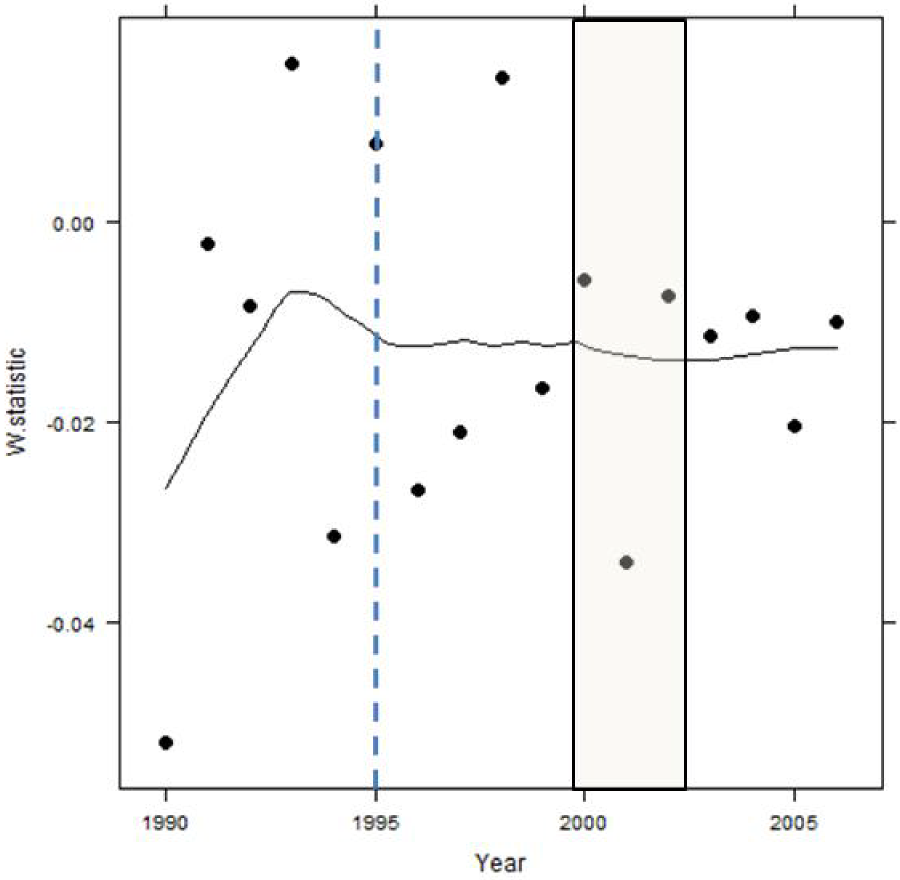


Figure 5.9 Temporal trends in the *W- statistic* for the whole-coast (pooled depth, 100 – 600 m depth range) off Namibia. Solid lines are the Loess smoothers (Loess, span = 0.5). The blue vertical dashed lines represent the Benguela Niño year, and vertical rectangles represent the occurrence of the LOW in those years.

5.4.1.4 *PERMANOVA analysis*

The PERMANOVA test results are shown in Table 5.4 a - c (without environmental variables). The first results (Table 5.4a) are for the test for fixed term effects and the interest here lies in the effects of those levels (in this case levels = df + 1, see Table 5.4) that were included in the analysis. Results show that there were changes in the demersal fish assemblages over the years, and these changes were significantly (all factors $p < 0.001$) attributed to the differences in depth (shelf and slope) along the coast of Namibia, and to the regions (north, central, and south) where different fish species were caught.

All the factors in the model had significant ($p < 0.001$) interactions with each other (Table 5.4a), with greater interaction between depth and region, then year and depth, and the least effects between year and region. The test statistic in the table header labelled “Pseudo-F” helps us to determine which factors are more important than others and which are the least important (Table 5.4a). In Table 5.4a, depth (shelf and slope) is the most important factor in the observed changes in the assemblage, followed by region (north, central, and south), and then year effects (Table 5.4a). Furthermore, the estimate of components variance (Table 5.4b) also revealed a similar trend in order of importance (as in Table 5.4a).

When the analysis included vessel effect, without the year, since year and vessel were correlated, it follows that depth still accounts for most of the effect on the change in assemblage structure, then region, and lastly vessel effects (Table 5.4c). All factors had significant ($p < 0.001$) effects on the distribution pattern of the biomass data (Table 5.4c). The interaction effects between depth and region are greater than those of depth and vessel, with the lowest interaction effects experienced between depth and region (Table 5.4c). The estimated components variance (Table 5.4d) also showed a similar trend in order of importance of the terms and their additional interaction effects.

Table 5.4 PERMANOVA test results (a and c) and the estimate for components variation (b and d). Abbreviations Ye is Year, De is Depth, Re is Region, Res is Residuals, df is degrees of freedom, SS is sum of squares, MS is mean squares, P(perm) permutational p-value, Unique perms is unique permutations, Ve is vessel, .

a) Fixed effects three-way design without vessel effect.

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms
Ye	15	42291	2819.4	6.1122	0.0001	9805
De	1	51409	51409	111.45	0.0001	9942
Re	2	33163	16581	35.947	0.0001	9937
YexDe	15	14979	998.62	2.1649	0.0001	9732
YexRe	29	23318	804.08	1.7432	0.0001	9620
DexRe	2	7859.3	3929.6	8.5191	0.0001	9917
Res	29	13377	461.28			
Total	93	187350				

b) Estimate of components variation in (a) above, ‘S(*)’ is sum of squares fixed effects divided by appropriate degrees of freedom, and ‘V(*)’ is for random term, which is a true measure of variability or variance components.

Source	Estimate	Sq.root
S(Ye)	401.96	20.049
S(De)	1096.8	33.118
S(Re)	520.01	22.804
S(YexDe)	183.19	13.535
S(YexRe)	171.4	13.092
S(DexRe)	223.77	14.959
V(Res)	461.28	21.477

Table 5.4 continues c) PERMANOVA test results for the fixed effects design without year and inclusive of vessel effects. The year was highly correlated with vessel, and therefore removed. Residuals and (RexDexVe) were pooled together.

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms
Re	2	28018	14009	16.739	0.0001	9879
De	1	41096	41096	49.104	0.0001	9903
Ve	2	16339	8169.4	9.7614	0.0001	9886
RexDe	2	7745.8	3872.9	4.6276	0.0001	9850
RexVe	4	5704.7	1426.2	1.7041	0.0002	9771
DexVe	2	4923.1	2461.6	2.9413	0.0001	9842
Pooled	80	66953	836.91			
Total	93	187350				

d) Estimate for components variation in (c) above, 'S(*)' is sum of squares fixed effects divided by appropriate degrees of freedom, and 'V(*)' is for random term, which is a true measure of variability or variance components.

Source	Estimate	Sq.root
S(Re)	493.65	22.218
S(De)	1003.9	31.685
S(Ve)	255.23	15.976
S(RexDe)	194.08	13.931
S(RexVe)	61.434	7.838
S(DexVe)	112.76	10.619
V(Res)	836.91	28.929

The PERMANOVA test results for the analysis which included environmental variable are shown in Table 5.5 (a – d). All factors and their interaction effects were significant ($p < 0.01$) (Table 5.5a). In this case bottom temperature emerges as a more important predictor for the observed changes in assemblage structure, followed by region (Table 5.5a). However, the estimate of components variation (Table 5.5b) points to region as having high variation, and then bottom temperature. Variance is greatest for interaction between bottom temperature and region and lowest for bottom temperature and year (Table 5.5b).

Table 5.5 a – d PERMANOVA test results (with environmental variable) for the two-way design with bottom temperature as a co-variate. Abbreviations as follows: Bt is bottom temperature, Ye is Year, De is Depth, Re is Region, Res is Residuals, df is degrees of freedom, SS is sum of squares, MS is mean squares, P(perm) permutational p-value, Unique perms is unique permutations.

a) Two-way design (Region is fixed and Year is random) and bottom temperature (co-variate). Re+BtxRexYe were pooled to avoid a negative variance estimate.

Source	**df**	**SS**	**MS**	**Pseudo-F**	**P(perm)**	**Unique perms**
Bt	1	41177	41177	58.585	0.001	998
Re	2	28772	14386	14.036	0.001	998
Ye	12	38684	3223.6	5.1938	0.001	996
BtxRe	2	8687.3	4343.6	6.7423	0.001	999
BtxYe	12	17813	1484.4	2.3916	0.001	998
RexYe	24	21583	899.28	1.4489	0.001	999
Pooled	21	13034	620.66			
Total	74	169750				

b) Estimate for components variation in (a) above, ‘S(*)’ is sum of squares fixed effects divided by appropriate degrees of freedom, and ‘V(*)’ is for random term, which is a true measure of variability or variance components.

Source	**Estimate**	**Sq.root**
S(Bt)	539.65	23.23
S(Re)	592.7	24.346
V(Ye)	453.53	21.296
S(BtxRe)	196.24	14.009
V(BtxYe)	157.95	12.568
V(RexYe)	170.66	13.064
V(Res)	620.66	24.913

The same analysis as above, but this time including depth and excluding year, and the PERMANOVA test results are shown in Table 5.5c – d. Looking at the pseudo-F statistic, bottom temperature has the highest and year the lowest, though the factors and their respective interactions exert significant ($p < 0.001$) effects on the assemblage structure

(Table 5.5c). In the estimate of components variation, depth still accounts for much of the variance, followed by bottom temperature (Table 5.5d).

Table 5.5 continues c) PERMANOVA test results for the two-way design (Depth is fixed and Year is random) with bottom temperature as a co-variate. Re+BtxDexYe were pooled to avoid a negative variance estimate.

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms
Bt	1	41177	41177	43.71	0.001	999
De	1	20091	20091	9.7564	0.001	999
Ye	12	40604	3383.6	3.9237	0.001	998
BtxDe	1	3941.6	3941.6	3.3178	0.002	998
BtxYe	12	18928	1577.3	1.8291	0.001	996
DexYe	12	14826	1235.5	1.4327	0.003	998
Pooled	35	30183	862.36			
Total	74	169750				

d) Estimate for components variation in (c) above, 'S(*)' is sum of squares fixed effects divided by appropriate degrees of freedom, and 'V(*)' is for random term, which is a true measure of variability or variance components.

Source	Estimate	Sq.root
S(Bt)	536.46	23.162
S(De)	1735.3	41.657
V(Ye)	439.67	20.968
S(BtxDe)	383.51	19.583
V(BtxYe)	130.97	11.444
V(DexYe)	523.22	22.874
V(Res)	862.36	29.366

The distance-based linear model results are shown in Table 5.6: a) the marginal test results and b) the sequential test results. The relationship between bottom temperature and the change in assemblage structure is significant ($p < 0.001$), and it accounts for 24% of the variance (in both the marginal and the sequential test) (Table 5.6a and b). The PCO shows the strong relationship (note the straight line that is longer and closer to the circumference of the circle) between bottom temperature among years and the within-depth categories (Fig. 5.10). There is a very clear separation of the continental shelf and slope. Their (depth and year) effect on the distribution pattern of the biomass data are different and highly related to bottom temperature.

Table 5.6 DISTLM results for the relationship between biological data and bottom temperature a) marginal test, and b) sequential test. Abbreviations SS is sum of squares, P is p-value, Prop is proportion, AIC is Akaike’s Information Criterion, Cumul is cumulative, res.df is residual degrees of freedom, and Btemp is bottom temperatue,

a)

Variable	SS(trace)	Pseudo-F	P	Prop.
Btemp	41177	23.379	0.001	0.24257

b)

Variable	**AIC**	**SS(trace)**	**Pseudo-F**	**P**	**Prop.**	**Cumul.**	**res.df**
Btemp	562.51	41177	23.379	0.001	0.24257	0.24257	73

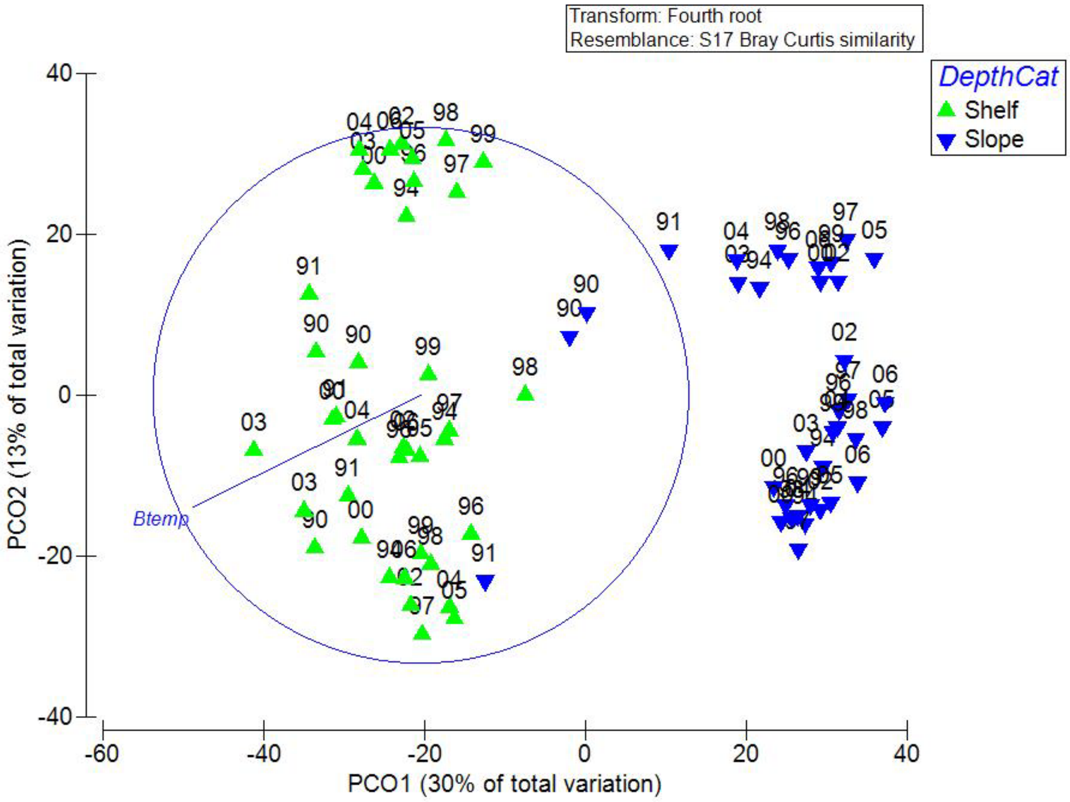


Figure 5.10 Principal Coordinate Ordination (PCO) with vector overlays scaled to represent the relationship between averaged biomass data distribution pattern and each of the significant physical (depth and year) and environmental (bottom temperature) variables.

5.4.2 Univariate approach

5.4.2.1 Diversity indices using Generalized Additive Models (GAM)

The model diagnostics for the biomass survey data used in the GAM are shown in Figure 5.11 and indicate that the assumptions of the Poisson and Gaussian distributions were not violated. The correlation between depth and longitude was 0.04, indicating a weak correlation, thus all of them were eligible for inclusion in the model. The diversity indices as an output from the GAM are shown in Figures 5.12 - 5.14, showing that diversity increases with increasing depth. What is also evident from the model is that the observed increase in diversity was driven more by species richness than by evenness (Fig. 5.12 and 5.13). Spatial coordinates or geographical location such as longitude and latitude also appeared to be important predictors of species richness, which increased with decreasing longitude (increasing depth from the continental shelf to the slope), and also increased with increasing latitude (from northern Namibia to the south) (Fig. 5.12). The effect of year on species richness was negligible, while that of abundance showed an increase in species richness with increasing numbers at low abundances, but decreased again at high abundances (Fig. 5.12).

Regarding evenness, the effect of depth was negligible and the effect of longitude showed that it was not the same for the continental shelf and slope. There was high evenness on the continental slope (300 – 600 m depth) and low evenness on the continental shelf (200 – 300 m depth) off the coast of Namibia (Fig. 5.13). Evenness increased from north to south (with increasing latitude) off Namibia. There was no temporal trend in evenness, thus year had no effect. The logarithm of abundance (N) was found to be a strong predictor for evenness, with low species abundance having high evenness and high species abundance having low evenness. Species richness increased with an increase in abundance then declined at higher abundance (Fig. 5.13).

The Shannon-Wiener Index *H′* (Figure 5.14) shows a combination of the patterns observed for both species richness and evenness, whereas the diversity increases from the continental shelf (100 – 300m) to the continental slope (300 – 600 m depth range). The Shannon-Wiener Index *H′*, being an integrator of species richness and evenness, underlined the pronounced effects of both longitude and latitude on species richness and evenness. High species richness and evenness are experienced offshore (lower longitude) and low species richness and evenness occurred inshore (higher longitude). Species richness and evenness increased with increasing latitude (from north to south) (Fig. 5.14). This suggested that the continental slope off Namibia was more diverse compared to the continental shelf and that this diversity was more pronounced in southern Namibia than in the north.

Table 5.4 shows the proportions (%) of variance as explained by the whole model (GAM) and each of the terms for the three diversity indices (*S, J′* and *H′*). The whole model can explain

66.9% of the species richness and 57% of the species richness and evenness (Table 5.4 and appendix 5.3).

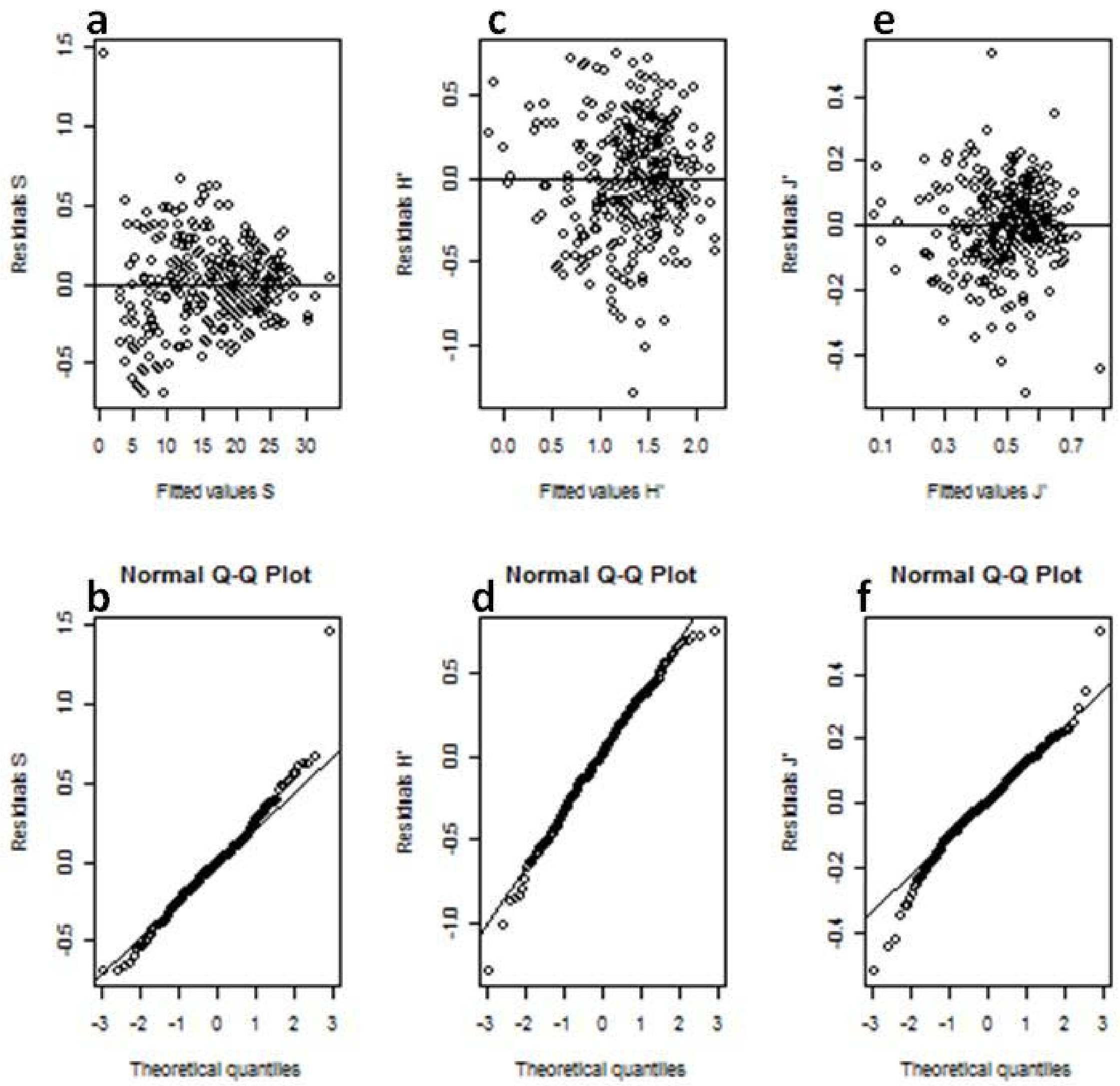


Figure 5.11 Showing the model diagnostics for (a – b) species richness (*S*), (c – d) Pielou's evenness (*J'*), and (e –f) Shannon-Wiener index (H'). Residuals vs fitted values and cumulative probablility curves.

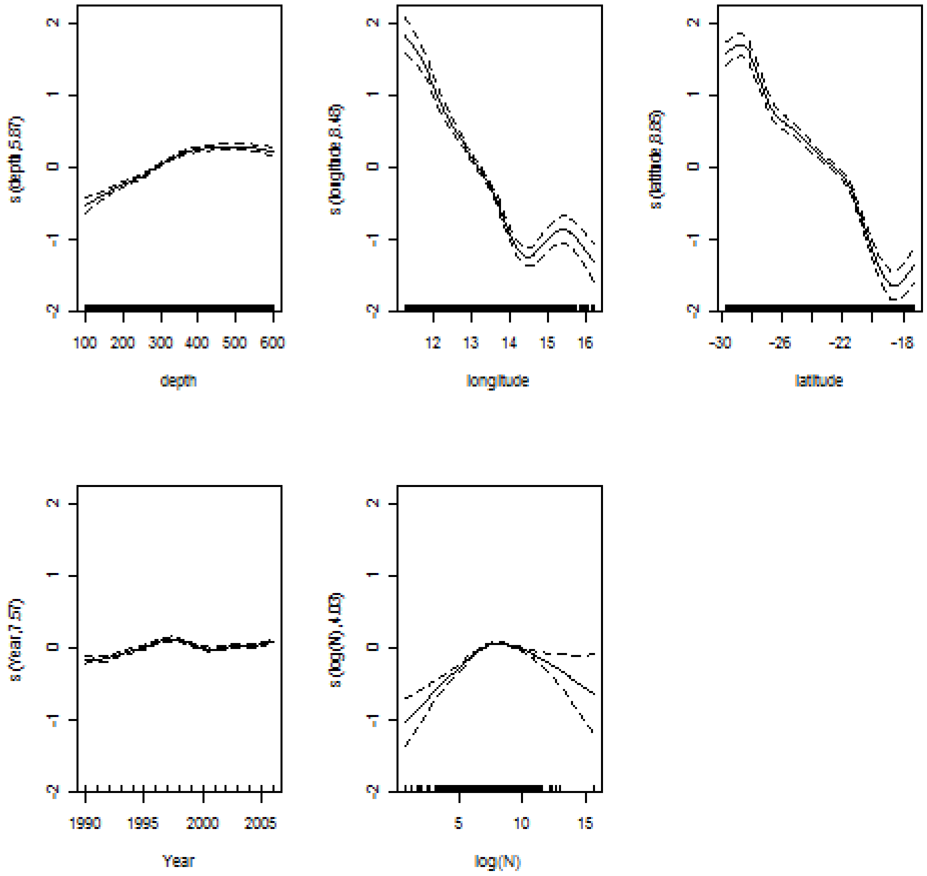


Figure 5.12 Species richness (*S*): Effects of depth (m), longitude, latitude, year, and abundance on the diversity indices for the demersal fish community off Namibia. Output from GAM using the hake biomass survey data (1990 – 2006). Dashed lines indicate 95% confidence limits and the y-axis shows the standardized value of the response.

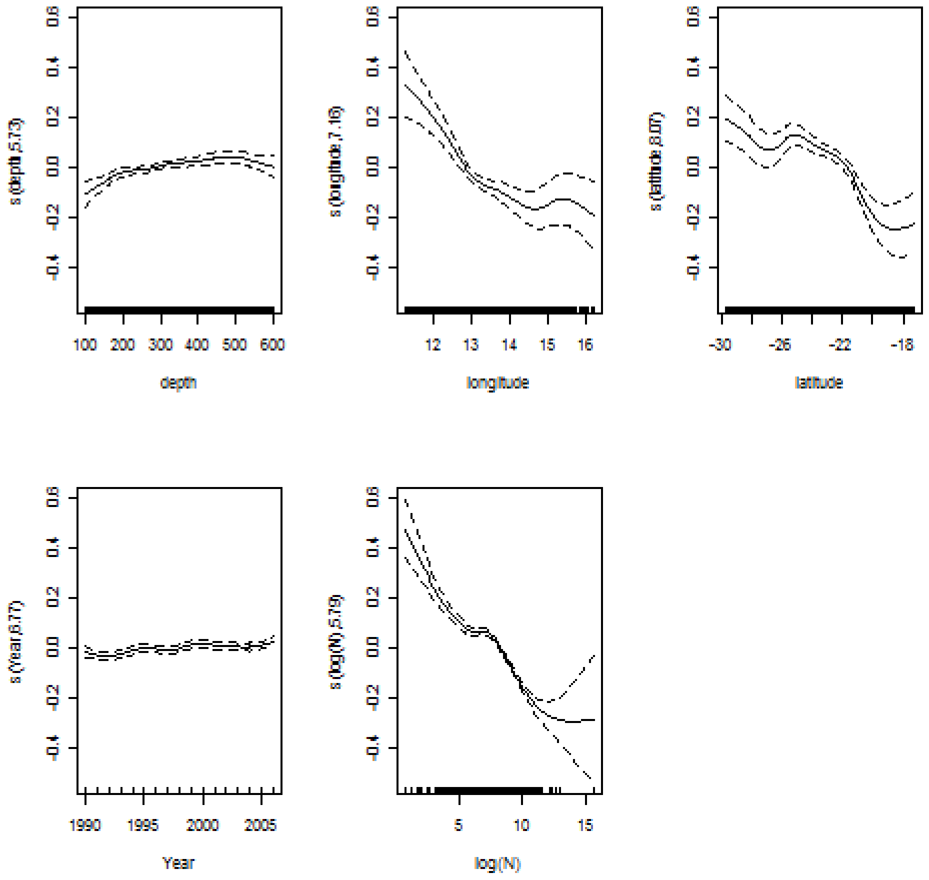


Figure 5.13 Pielou's evenness (*J'*): Effects of depth (m), longitude, latitude, year, and abundance on the diversity indices for the demersal fish community off Namibia. Output from GAM using the hake biomass survey data (1990 – 2006). Dashed lines indicate 95% confidence limits and the y-axis shows the standardized value of the response.

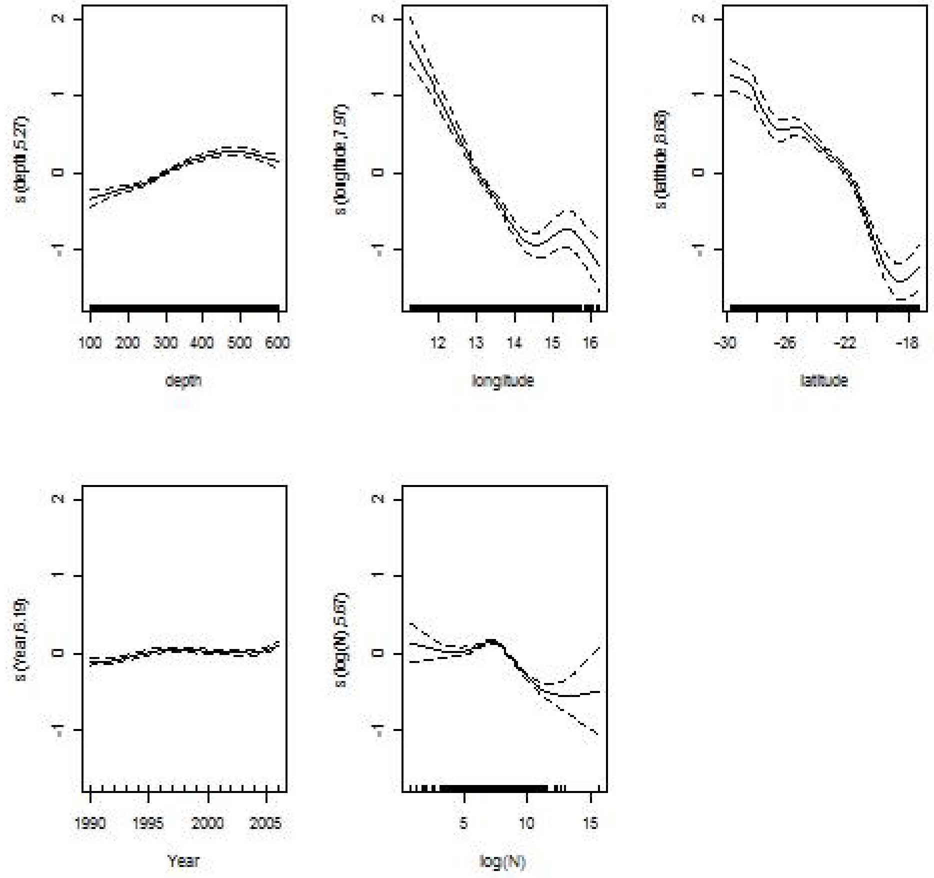


Figure 5.14 Shannon-Wiener Index (*H'*): Effects of depth (m), longitude, latitude, year, and abundance on the diversity indices for the demersal fish community off Namibia. Output from GAM using the hake biomass survey data (1990 – 2006). Dashed lines indicate 95% confidence limits and the y-axis shows the standardized value of the response.

Table 5.4 Proportions (%) of variance explained by the whole model (GAM) and each term of the three diversity indices (species richness *S*; Pielou's evenness *J'*; and Shannon-Wiener Index *H'*).

Terms	***S***	***J'***	**H'**
Whole model	66.90	27.80	57.00
depth	8.70	1.01	4.65
longitude	21.02	2.04	9.69
latitude	18.85	3.06	11.45
Year	5.18	0.84	1.91
ln(Abundance (N))	4.87	13.98	10.35

The relationships between bottom oxygen and diversity indices and between temperature and diversity indices are shown in (Fig. 5.15a - c). Species richness was generally high in cooler water below 6 ^{o}C, and dropped almost linearly between 8 – 12 ^{o}C, then started to increase slightly until 16 ^{o}C (Fig. 5.15a). Low oxygen waters (< 1 ml/l) had low species richness compared to waters with more oxygen (> 1 ml/l), which had higher species richness though with slight variability (Fig. 5.15a). Pielou's evenness index J' had a similar relationship with bottom temperature to that of species richness, with an exception in warmer waters around 12 ^{o}C where evenness has a declining trend (Fig. 5.15b). Evenness with bottom oxygen had no clear trend, with variability very close to zero, (Fig. 5.15b). Shannon-Wiener index H' was high at low temperature, but declined between 3 - 9^{o}C, then a slight increase, but then dropped almost linearly between 9 – 12^{o}C, followed by another slight increase between 12 – 14^{o}C, then declined thereafter (Fig. 5.15c). Low oxygen water was low in diversity. Water with oxygen levels ranging from 1 to 3 ml/l had the highest diversity, and it declined therafter (Fig. 5.15c).

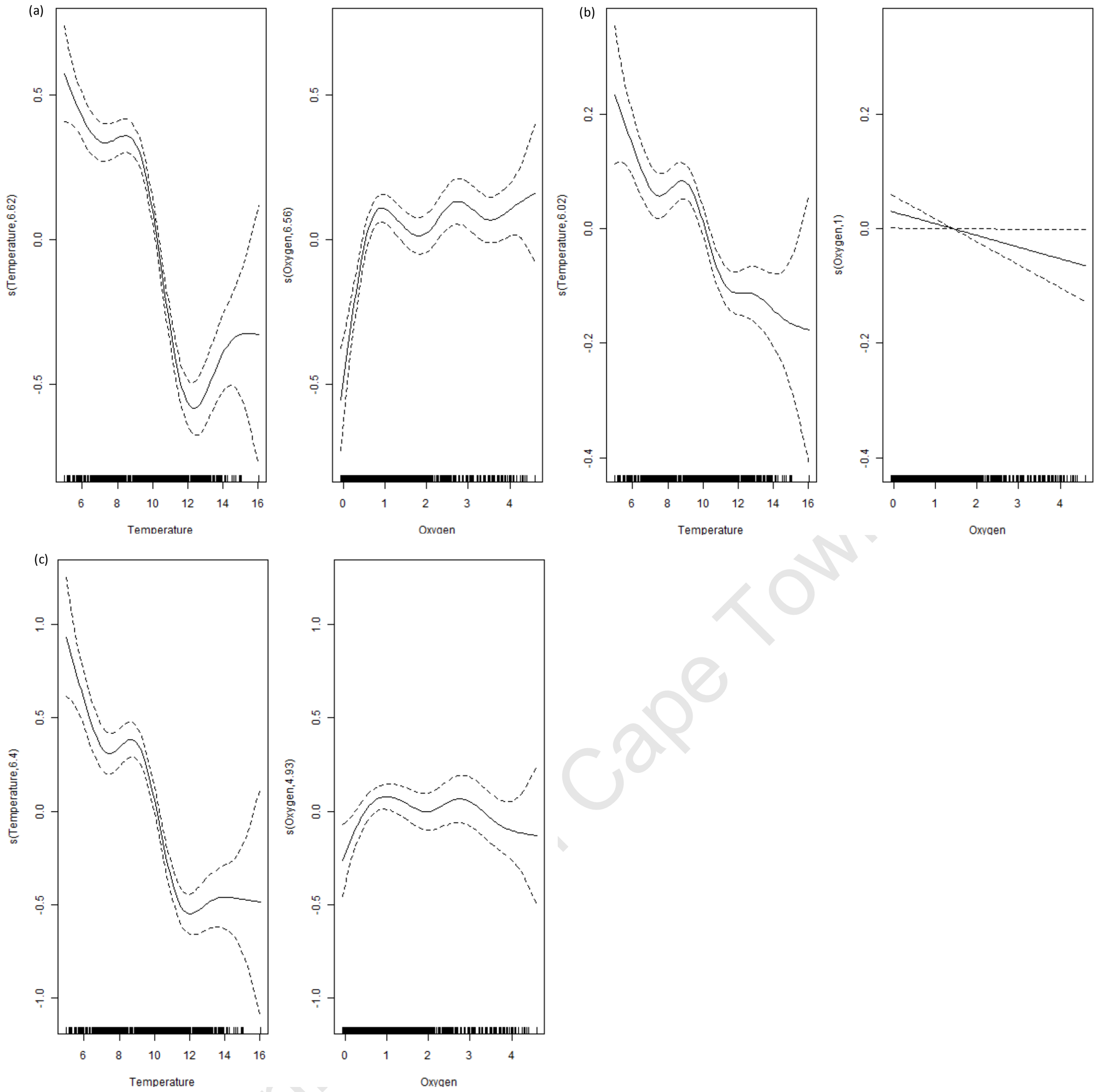


Figure 5.15 Diversity indices a) species richness *S*, b) Pielou's evennes index *J'*, c) Shannon-Wiener index *H'* in relation to bottom temperature and oxygen. Dashed lines indicate 95% confidence limits and the y-axis shows the standardized value of the response.

5.5 Ancillary information

5.5.1 Environmental variability off Namibia

The sea surface temperature (SST) anomalies off Namibia and southern Angola in Fig. 5.16 depict the variability in SST anomalies from 1982 to 2007. These show the intrusion of warm water from the warm Angolan current along the coast of Namibia, causing decadal episodes of Benguela Niños (see black rectangles in Figure 5.16). These are evident in the annual plots (Fig. 5.16); Benguela Niños occurred in 1984 and 1995. However, there was another warm water event in 2001, although it was not reported as a Benguela Niño, but bears similar characteristics, perhaps of low magnitude (see oval overlay in Fig. 5.16). These wam water events were coupled with low oxygen water (LOW) on the continental shelf and the upper slope off Namibia, especially in the north and central region (Fig. 5.17). Figure 5.17 shows the variability in dissolved oxygen at 20 and 70 nm stations at 23^{o}S off Walvis Bay. There was a persistant occurrence of low oxygen water on the continental shelf in waters shallower than 150 m (at 20 nm); and relatively oxygenated waters in deeper waters at (70 nm offshore) over the years (Fig. 5.17). The belt of LOW extended much deeper (over 300 m) further offshore during the 1995 and 2001 warm events, and this also corresponds to the position of the ABF south of 17^{o}S latitude (shown in Chapter 4). Figure 5.18 shows some evidence of progressive warming of sea surface water for the past three decades.

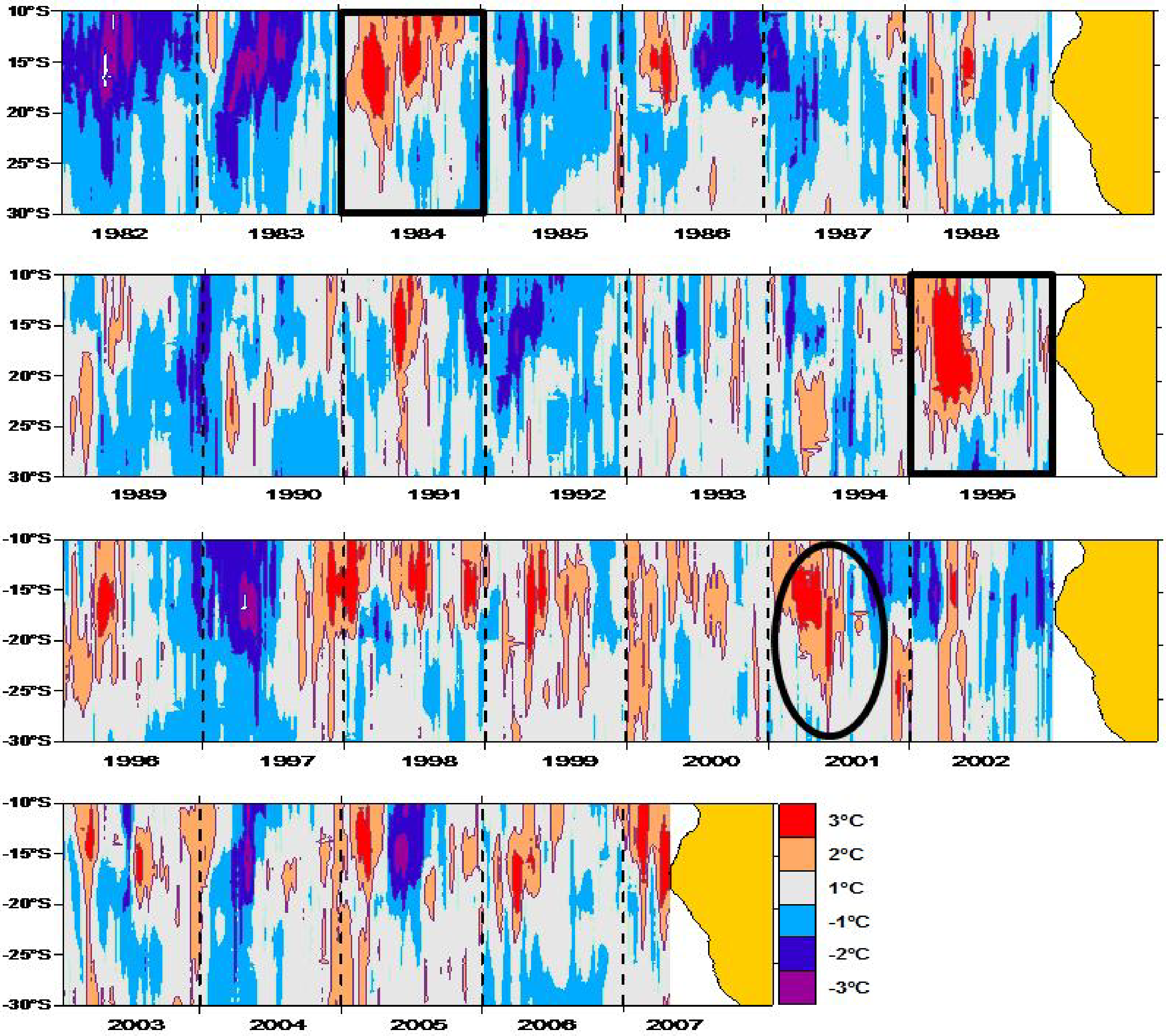


Figure 5.16 Satellite derived sea surface temperature (SST) anomalies off southern Angola and Namibia from 1982 to 2007, depicted using Hofmuller plots of latitude versus time. Rectangle overlay represent years of Benguela Niños and the oval overlay represent a strong signal of warm water intrusion onto the Namibian coast. Source: *A. van der Plas, NatMIRC, Swakopmund: Environmental monitoring in the Benguela current region. BENEFIT/BCLME project, reported in Swakopmund, Namibia, 19-22 Nov 2007.*

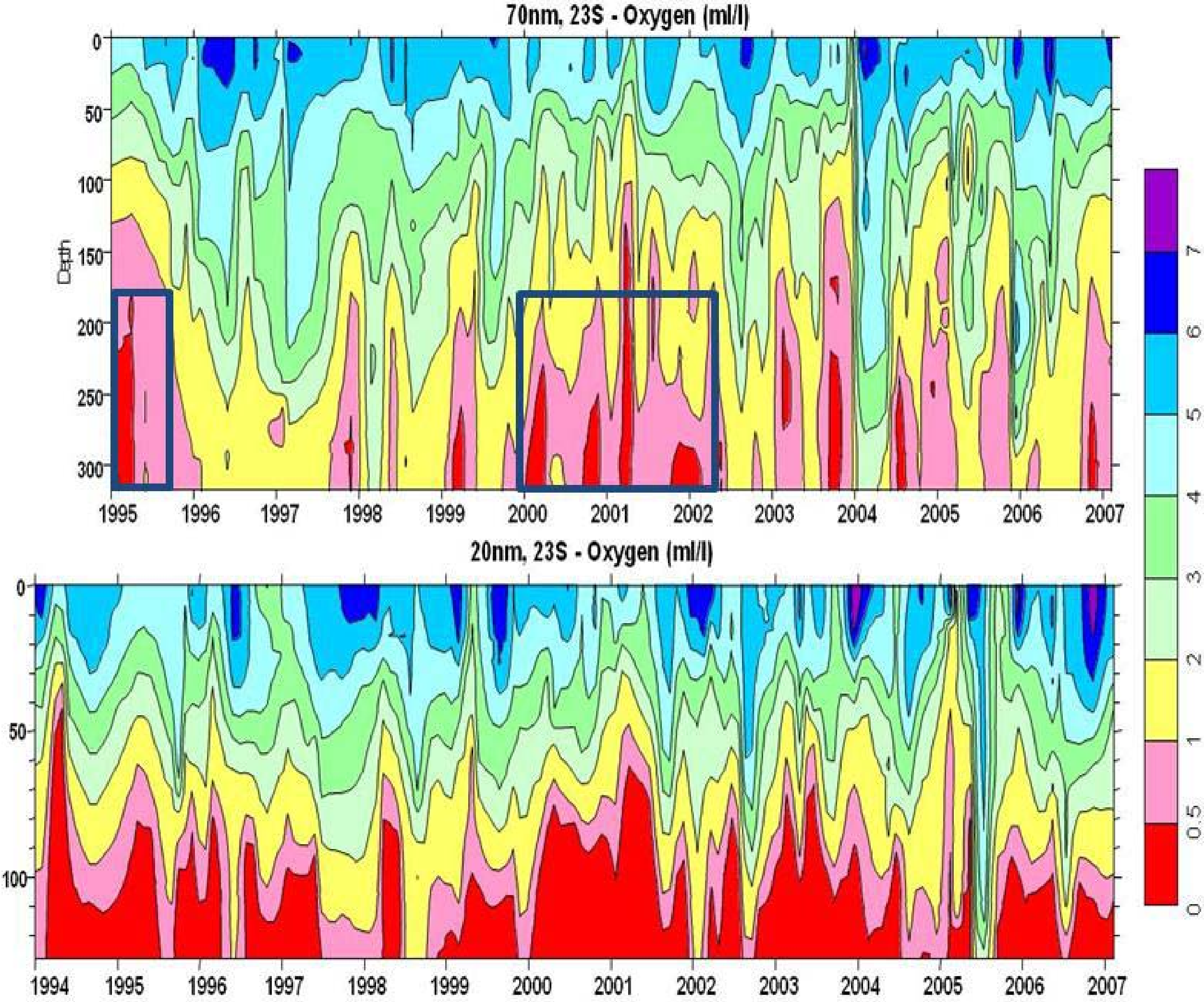


Figure 5.17 Dissolved oxygen (ml/l) at two stations (20 nm and 70 nm) on line 23^{o}S off Walvis Bay, monitored monthly from 1994 to 2007. The y-axis is the water depth (m) and x-axis the years. Dark blue rectangles represent years with low oxygen water (LOW) penetrating deeper than 300 m. Source: *A. van der Plas, NatMIRC, Swakopmund, pers. comm.: Presentation at the BCLME Workshop on "THE CHANGING STATE OF THE BENGUELA CURRENT LARGE MARINE ECOSYSTEM: EXPERT WORKSHOP ON CLIMATE CHANGE AND VARIABILITY AND IMPACTS THEREOF IN THE BCLME REGION", Kirstenbosch Research Centre, Cape Town, 15-16 May 2007.*

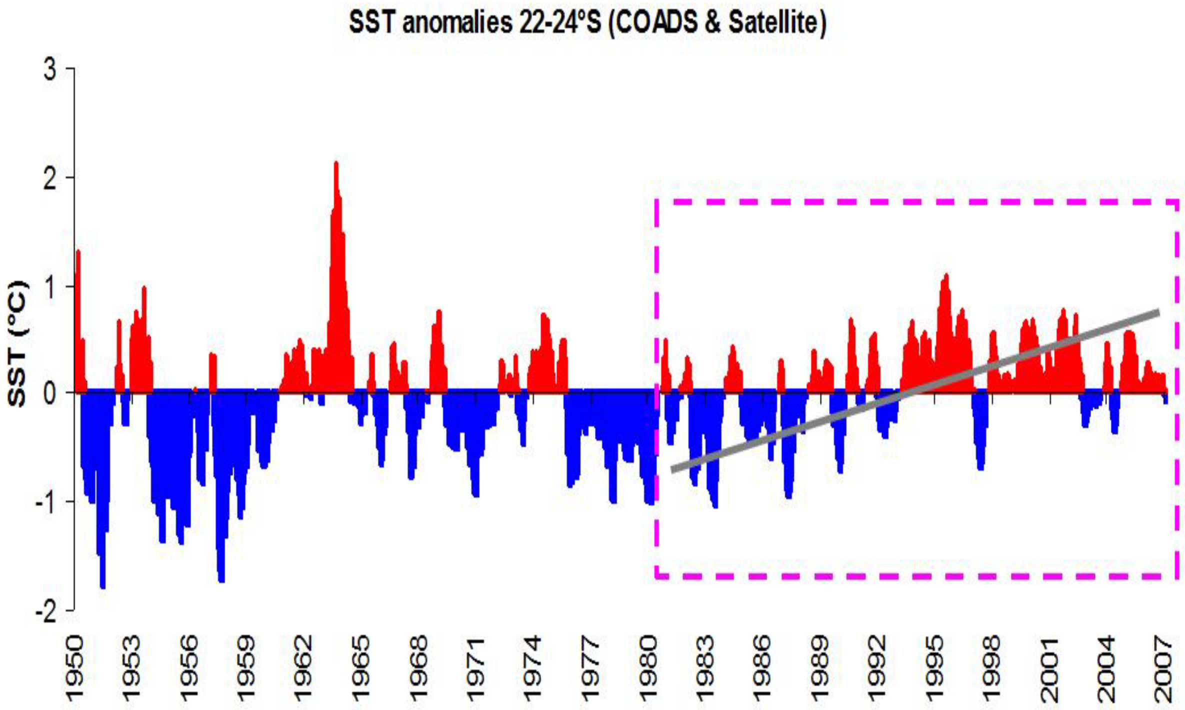


Figure 5.18 Long-term SST anomalies for central Namibia (22 – 24^{o}S) from Comprehensive Ocean-Atmosphere Data Set (COADS) and Satellite (NOAA) from 1950 to 2007. The pink dashed rectangle represents the most recent 27 years, and the grey line shows the upward trend in SST anomalies in recent years (source: Hutchings *et al.*, 2007, Environmental Monitoring in the Benguela Current Region presentation in Swakopmund, 19 – 22 November 2007, BENEFIT/BCLME State of the Environment project; and see also Hutchings *et al.*, 2009).

5.6 Discussion

5.6.1 Cluster and MDS

Both cluster analysis and MDS of the large-scale temporal distribution of biomass of the demersal fish assemblages off Namibia indicated three significantly different demersal fish assemblages. These observed major groupings may be linked to changing environmental conditions periodically occurring within the system. During the study period there was only one major environmental event which took place, namely a warm water event called Benguela Niño in 1995 (Shannon, 1985; Woodhead *et al*., 1997; Gommelsrød *et al*., 1998). Prior to this event there was some cooling in the system in 1993 and 1994 (Gammelsrød *et al*., 1998). This corresponds with the group A cluster (1990 – 1993) (Fig. 5.2), separated from the group B cluster (1994 – 1999) by a break in the community structure (Fig. 5.2), and marked by the occurrence of the Benguela Niño in 1995. Lastly, the group C cluster (2000 – 2006) was also marked by a warm water event in 2001, which may have contributed to the observed patterns.

Low oxygen on the northern and central continental shelf caused major mortalities of juvenile hake (Woodhead *et al*., 1997; Hamukuaya *et al*., 1998). The warm water events are known to bring poorly oxygenated waters on the northern and central shelf, and may even penetrate much deeper to the upper slope (Monteiro *et al.*, 2006). This could affect the distribution of demersal fish species over the continental shelf and slope, since effects of these events could be lagged, only affecting the demersal fish species at a later stage either directly, indirectly or both (Voges *et al*., 2002).

5.6.2 PERMANOVA and DISTLM

Both PERMANOVA and DISTLM test results showed how bottom temperature affected the demersal fish assemblages over years, and revealed that bottom temperature affected assemblages differently on the continental shelf and slope. It matters at which depth the data were collected, and it is a well-known fact that depth plays a significant role in dissolved oxygen distribution along the Namibian coast, with the shelf region being more prone to low oxygen waters than the slope. For the three physical factors that were tested using PERMANOVA with different model designs (Table 5.4), depth (shelf and slope) explained much of the variance in the biological data, indicating that different demersal fish assemblages exist - one on the shelf and the other on the slope (Appendix 5.2). However, these assemblages were further divided by region (north, central, and south), which is the second important factor in the observed changes in assemblage structure (Fig. 5.4 and Appendix 5.2). The vessel effect, though significant, was the least important contributor to the observed patterns in the biotic data.

Anthropogenic influences in this case cannot be ruled out; the breaks in the community structure coincide with changes in fishing vessels that were used for the hake biomass surveys since 1990. There was a change of vessels from the old *R/V Dr Fridtjof Nansen* to the new *R/V Dr Fridtjof Nansen* in 1994, and there was another change from the new *R/V Dr Fridtjof Nansen* to a commercial vessel *Blue Sea 1* in 1999, which may have affected the data collection (T. Strømme and A. B. Erik, *pers. comm.*, *Nansen* program). It might be assumed that this was unlikely given the fact that proper procedures were followed by inter-calibration, use of the same gear and same sampling strategy before the vessels were used for scientific surveys for hake off Namibia. However, the results based on PERMANOVA (Table 5.5) in this study have revealed a significant vessel effect on the distribution pattern of biotic data, meaning different vessels used in different surveys over years affected data collection. Therefore, it is likely that these changes in vessels have contributed to the observed changes in structure of the demersal fish assemblages, although overall depth and region effects were more important (Table 5.4 and 5.5).

5.6.3 Abundance Biomass Comparison (ABC) curves and W- statistic

Fishing pressure in the early 1990s was reduced by the MFMR by maintaining a low TAC for *M. capensis* and *M. paradoxus* and other commercial species (MFMR, 2008). However, the fish stocks then were over-exploited and were under remedial fishing controls (Heymans *et al*., 2004; Watermeyer *et al*., 2009). Though the precautionary exploitation was in place, the *W– statistic* of the first four years after Independence in 1990 suggested that the demersal fish assemblages were disturbed (Warwick and Clarke, 1994; Clarke and Warwick, 2001, Clarke and Gorley, 2006). Likewise, during the other two periods, the demersal fish assemblages were also experiencing moderate disturbance from the combined effects of heavy exploitation during the four decades before 1990 and the changing environmental conditions, e.g. Benguela Niños and low oxygen events, Figs. 5.16 – 5.18 (Shannon, 1986; Boyd *et al*., 1987; Gammelsrod *et al*., 1998; Hamukuaya *et al*., 1998; Woodhead *et al*., 1998).

Notably, the effect of recruitment of shallow water hake can be associated with the temporal trends in the *W – statistic* for the continental shelf (Fig. 5.19), whereby the 1995 Benguela Niño affected recruitment negatively thus there were relatively more large fish in the system and few juveniles and the *W– statistic* became more positive (Fig. 5.19). The effects of the warm water event in 1995 (e.g. hypoxia and anoxia) caused mass mortalities of juvenile hake (Woodhead *et al*, 1996, 1997a, b; Hamukuaya *et al*., 1998) and resulted in *M.capensis* recruitment failures. A year after the 1995 event, the recruitment index (see also Chapter 4, Fig. 4.16) was good for *M. capensis*, thus there was a large influx of juveniles into the system, which out-numbered the large fish, thereby making the *W– statistic* negative (Fig. 5.7).

The low recruitment index was further recorded in 2001 and the *W– statistic* was negative, possibly indicating the presence of more juvenile fish than big fish, leading to the default inference that the demersal fish assemblage was moderately disturbed (Warwick and Clarke, 1994). This could suggest a large influx of juveniles or small-sized fish for demersal fish species other than *M. capensis* alone. The poor recruitment index coincided with poor environmental conditions as seen in Figs. 5.11, and 5.12. One should note that a moderate warm water event and moderate upwelling could support good spawning and eventually recruitment (especially for *M. capensis*) (see Voges *et al*., 2002). Stressful conditions in demersal fish assemblages were further exacerbated by an increase in exploitation over the years, as was shown in Chapter 2; fishing effort was increasing with the increases in TAC over the years under review. The LOW and positive SST anomalies (Figs. 5.16 and 5.17) and the low upwelling index (see Chapter 4) for 2001 have affected the community structure with evidence of more small fish than large ones.

Reduced upwelling in combination with other environmental conditions was shown to support spawning and recruitment for *M. capensis* (Voges *et al*., 2002). If warm water is widespread during the spawning period September to March, and upwelling during the following May to September is reduced, the eggs spawned will be retained in favourable nursery areas, which may result in potentially strong recruitment (Voges *et al*., 2002). On the continental slope, the trend (Loess smoothed) depicted an inverted bell-shape (Fig. 5.7), which coincided with the change in the upwelling-favourable wind anomalies over the years (see Chapter 4, Figure 4.17), without any signs of sychrony with the *M. capensis* recruitment index. The latter can be expected due to the limitation of the recruitment index to *M. capensis*, while we are dealing with many more species (for which recruitment information is lacking) in the assemblages. However, a downward trend from 2000 ─ 2003 was noticeable and this reflected the effect of persistent LOW from 2000 ─ 2002 (Fig. 5.17), as well the high positive SST anomaly in 2001 (Fig. 5.16).

The linear regressions that were fitted to the *W– statistic* data for each of the regions, sub-regions, and the whole-coast were all non significant (not shown). However, what is important here is the direction of change in the community in space and time, due to limited application of the ABC method to fisheries. This makes inferences based on the direction of change more reliable than the actual *W– statistic* value, which cannot be associated with a limit reference point of the fish community in question (Yemane *et al*., 2005). Such limits or reference points do not exist yet and need to be developed with increasing application of the method to build consistent reference limits for fisheries. This is one of the directions where fisheries management should focus effort - seeking to establish these limits or reference points. Thus, it makes it easier from the fisheries management perspective to discuss the observed trends in the *W– statistic* of the demersal fish community off Namibia based on the direction of change.

The results of the ABC curves and their corresponding *W- statistics* for both the shelf (100 – 300 m) and slope (300 – 600 m depth range) suggest that the demersal fish assemblages for both the continental shelf and slope were moderately disturbed, according to the classification of the ABC plots by Warwick (1986). Surprisingly, this does not correspond with the variable bottom-trawl levels in Chapter 2, which suggests that some areas are more heavily trawled than others. This study indicates that there was a modest recovery from pre-independence fishing pressures for the slope community, from a very disturbed demersal fish community in the early 1990s to one that is moderately disturbed. Following declines in the early 2000s, which coincided with the warm water event in 2001 as shown from the SST (Fig. 5.17), the fish community subsequently became disturbed again in 2005 and 2006. This may be a result of the lag effect of the environmental variability in the system, combined with effects of bottom-trawling. This change of status was more evident on the southern continental slope, while the central and northern continental slope experienced a downward trend in their *W- statistic*. This inference should, however, should be treated with caution as the *W- statistic* value alone may be less sensitive for capturing the effects of fishing on demersal fish assemblages. Thus it is the direction of change which becomes more important for fisheries management decisions on the status of the fish community.

In the continental shelf regions, the southern shelf was moderately disturbed, while the northern shelf depicted a disturbed community, which became only moderately disturbed with time. The demersal fish community in the central shelf region was disturbed (Fig. 5.7), which corresponds with the occurrence of the heavily trawled areas on the central shelf (Chapter 2). The observed differences in demersal fish assemblages of the continental shelf and slope, and their sub-regions suggest some differences in community structure, and that the demersal fish assemblages in these depth strata and regions could have been subjected to different fishing regimes, as was shown in Chapter 2 - i.e. that fishing intensity varies in time and space. This simply has to do with the time-based advancement of fishing technology and gear to access deeper waters, and the capacity of vessels to stay at sea for longer. The continental shelf area could have been more heavily trawled than the continental slope.

Overall, the analyses of the whole coast (100 – 600 m depth range) suggest the demersal fish community off Namibia has been stressed, with the *W-statistic* below zero for most of the time over the study period (Fig. 5.9). Noticeable are the effects of the 1995 Benguela

Niño and relatively high positive SST anomalies, and also the LOW and high SST anomalies in 2001 on the *W- statistic* for the whole coast. The effects of the Benguela Niño in 1995 on demersal fish assemblages also coincided with fish mortalities for sardine and horse mackerel (*Trachurus trachurus capensis*), among other species, which were reported off northern Namibia and southern Angola at the peak of the Benguela Niño in March 1995 (Gammelsrød *et al*., 1998). A southward movement of the sardine shoals due to warm water intrusion, which made sardine more accessible to fishing fleets, was also documented (Gammelsrød *et al*., 1998; Boyer and Hampton, 2001).

A subtle recovery occurred from the early 1990s onwards, after years of heavy fishing, coupled with reduced fishing effort by reduction of the TAC of hake at Independence in 1990. Most likely, the reduction in fishing effort and the immediate enforcement of fishing regulations at Independence would have contributed to the improvement in the status of the demersal fish community off Namibia, although recovery of the fish stocks could take longer than 17 years. We may perhaps be dealing with a stock which had not yet recovered from the heavy exploitation of the previous four decades. However, the results at this broader scale (whole-coast) should be treated with caution since they tend to overshadow the localized effects of fishing.

The observed changes could also be related to the finding of Chapter 4 that the effects of bottom-trawling on the size structure are not noticeable at the large spatial scale (whole-coast). At a small spatial scale (region or sub-region) a better picture started to emerge on the changes that have occurred over the 17 -year period (Chapter 4).

At a whole coast level, it clear that the demersal fish assemblages were under stress, which is to be expected given the history (Chapter 1) of the hake fishery in Namibia. In South Africa, a study by Yemane *et al*. (2005) carried out on the demersal fish community of South Africa’s south coast over the period 1986 to 2003 found temporal patterns in ABC curves and *W-statistics* for two depth groups (0 – 100 m and 101 – 200 m). For the whole area combined, the authors showed a gradient of change in the *W- statistics* of demersal assemblages from neutral ($W \geq 0$) to negative ($W < 0$), suggesting a disturbed or stressed condition (Yemane *et al*., 2005). The hake fishery in both Namibia and South Africa has targeted the same species of hake. Although studies were conducted in different oceanographic areas and under different oceanographic conditions, they share similar results with the findings of other studies (as in Blanchard *et al*., 2004; Labropoulou and Papaconstantinou, 2005; and Yemane *et al*., 2005).

ABC analyses are sensitive to any large flux of recruits of dominant species, which can bias analyses by reducing the value of the *W- statistic* (Warwick and Clarke, 1994; Yemane *et al*., 2005). However, this was not the case in this study since the observed trend was checked against the available recruitment index (Chapter 4) for *M. capensis,* which is one of the dominant species, and noted that the years when the recruitment index was high and low do not correspond to the pattern of the *W- statistic* for those years (Figures 5.7, 5.8, 5.9), thus no obvious relationship could be established (Fig. 5.19).

5.6.4 Diversity measures, physical factors and environmental variables

The shallow coastal shelves are mostly accessible to a variety of fisheries, which could exert heavy fishing pressure and might contribute to a declining trend in diversity. However, bottom-trawling off Namibia is only permitted in waters deeper than 200 m and so may not be a contributor to this declining trend. This study indicates a diversity pattern where diversity increases with increasing depth off Namibia and that southern Namibia is more diverse than the northern part. The observed pattern in diversity distribution could be attributed mainly to the dissolved oxygen distribution on the continental shelf (Fig. 5.16) and slope. Depth and longitude were both included in the GAM because they were not correlated, and this could be attributed to the shape of the Namibian coastline and the bathymetry, which is straight from north to south. The continental shelf is wider around the Orange River in southern Namibia, and it narrows around the Lüderitz area, widens around Walvis Bay area, and narrows again towards the Kunene River in northern Namibia (see Fig. 2.1, Chapter 2). Thus, different positions would have different depths depending on latitude (north or south) off Namibia. The northern and central shelves are known to harbour low oxygen waters and events of hypoxia leading to anoxia at times (Monteiro and van der Plas, 2006; Bartholomae and van der Plas, 2007). Other studies (Sakko, 1998; Bianchi *et al*., 2001; Bianchi *et al*., undated) though using fewer years' data than this study, also documented similar diversity patterns off Namibia.

Global patterns of species richness indicate that there is evidence of latitudinal gradient, with highest diversity recorded in equatorial regions and lowest diversity towards the poles (Clarke, 1992; Angel, 1993; Lewis and Beardmore, 1995). However, the demersal fish species off Namibia show an opposite gradient to this, since species richness in general is substantially lower in the northern regions than in the southern regions (Chapter 7). This could be due to the distribution of low dissolved oxygen water, which is mostly on the continental shelf close to the seabed (Woodhead *et al*., 1998; Masriera *et al*., 1990), thus making the continental slope more habitable by many different species of fish than the continental shelf. These major low oxygen water events on northern and central shelf took place between 1993 – 1994; and 2000 – 2002 (Fig. 5.16), and LOW was shown to be the main cause of the juvenile hake mortalities off Namibia in 1994 (Woodhead *et al*., 1997; Hamukuaya *et al*., 1998).

These changes could be associated with characteristic features of the Benguela system (e.g. dynamic and unpredictable environment, high productivity), which could be more important than latitudinal gradient when predicting species diversity off Namibia. Yet another important factor in influencing the diversity distribution is bottom temperature, since there are cooler waters on the continental slope and relatively warmer waters on the continental shelf. Northern Namibia is the entry point for warm water intrusion onto the shelf, which then flows down to central Nambia, where cases of hypoxia and anoxia have been reported (Woodhead *et al*., 1996, 1997a, b, 1998; Hamukuaya *et al*., 1998; Monteiro *et al*., 2006; Bartholomae and van der Plas, 2008). Other studies (e.g Masriera *et al*., 1990; Woodhead *et al*., 1998) have documented LOW to have affected hake distribution on the central shelf of Namibia. Despite the high fishing intensity in southern Namibia (Chapter 2), it is unlikely that bottom-trawling affected demersal fish diversity, since continuous fishing leads to decreased diversity. Alternatively, this was formerly a diverse demersal community after 60 years of trawling (Chapter 1 and references therein) which, after 17 years of less intense trawling following Independence, may not have made a sufficiently rapid recovery.

A study by Labropoulou and Papaconstantinou (2005) in the N.E. Mediterranean (Thracian Sea and Thermaikos Gulf, Greece) found that species diversity, richness and evenness decreased with water depth and dominance increased with depth. However, although these are different systems with different hydrographic and biological communities compared to the Benguela Upwelling system, they provide some insights as to how diversity patterns change in space and time. This is somewhat different from what was observed off the coast of Namibia where diversity indices (species richness *S*, Pielou's evenness *J'* and the Shannon-Wiener Index *H'*) have been shown to increase with depth and dominance to decrease with depth (continental shelf and slope). Bottom temperature and oxygen plays an important role in the distribution pattern of diversity indices (Fig. 5.15).

These results on diversity are consistent with the finding of the study by Bianchi *et al* (2001) which looked at trends in community diversity and abundance biomass comparison curves a decade after Independence of Namibia in 1990. The contradictory trends in the Namibian and Mediterranean systems are likely to be a result of different hydrographic and bio-region characteristics of the two systems.

The changes in diversity of the demersal fish community for the whole coast (100 – 600 m) of Namibia were driven more strongly by species richness than by evenness. Species richness increased with depth and abundance, but declined at highest abundances. The shelf (100 – 300 m) was dominated by one or few species (low evenness), which coincides with the results of the *W-statistic* that the continental shelf assemblage off Namibia was relatively disturbed (this study). On the continental slope (300 – 600 m), there was high evenness and a moderately disturbed demersal fish assemblage, according to the classification by Warwick and Clarke (1994), and the results in Chapter 4 revealed a significant decline in mean length of fish surveyed and abundance of various size classes.

However, this is consistent with the ecological theory, suggesting that in less disturbed systems the abundance curve lies below the biomass curve (Warwick and Clarke, 1994). This is also in agreement with the finding of Bianchi and others (2001). Depth, longitude and latitude, and abundance are good predictors of the observed distribution patterns for diversity along the Namibian coast. Establishing thresholds for the *W- statistic* would be an advantage in further applications of the ABC method to demersal fisheries, making the method more meaningful to fisheries management. When more studies have been undertaken, the *W- statistic* values could be adjusted for the demersal fisheries based on comparable and consistent values of the *W- statistic*. With all these developments, the method may in the near future provide a guiding tool for use in an Ecosystem Approach to Fisheries (EAF). As new threshold or reference points are developed, they may provide a safe guiding tool on which to base decisions for fisheries management in the Benguela System.

5.6.5 Summary

The primary aim of this Chapter was to assess the effects of bottom-trawling on demersal fish assemblages off Namibia using both multivariate and univariate analyses. The multivariate approach using cluster analysis and MDS has revealed three significantly different temporal groupings, group A (1990 – 1993), group B (1994 – 2000) and group C (2001 – 2006). Different fishing pressures and to some extent adverse environmental conditions (e.g. Benguela Niño) during the study period corresponded with the three major groupings identified by ordination techniques. The *W– statistics* from the ABC curves showed that the three time periods all experienced moderate disturbance in different ways.

In the first period (Group A), the demersal assemblage was more stressed and dominated by a few species *(e.g. M. capensis; S. bibartus, H. dactylopterus)* mostly of small-bodied individuals that were numerically abundant. In the second period (Goup B), the demersal assemblage, though also under stress was not strongly dominated, and had a mixture of species (evenly distributed) with both small and large bodied individuals. This could be explained by improvements in environmental conditions after the 1995 Benguela Niňo, but more fishing pressure is believed to have been exerted due to an increase in the number of bottom-trawlers in the hake fishery, as the TAC was steadily increased (see Chapter 2 for details). The warm-water events coicided with poor recruitment for *M. capensis*, and the occurrence of LOW on the northern and central shelf of Namibia especially in 1995 and 2001.

Results for the last period (Group C) also showed the fish community to be under stress, but the abundance and biomass curves were close to each other, yielding a *W– statistic* close to zero. This together with the results of heights and slopes of the size spectra in Chapter 4, suggests a demersal fish community under transition from a very disturbed state (before 1990) to a moderately disturbed state (after 1990). Physical variables such as depth and region were significant contributors to the observed changes in the assemblage structure of demersal fish species. Moreover, bottom temperature explained 24% of the changes in assemblage structure. Vessel effect was also important in changing the community structure of demersal fish off Namibia.

The study also brought to light that diversity of demersal fish assemblages off Namibia has a latitudinal (north – south) gradient, as well as a depth (shelf and slope) gradient. The northern part of Namibia was found to be less diverse than the southern part. Diversity increased from the continental shelf to the continental slope. In both cases of diversity changes, it is unlikely that bottom-trawling has contributed significantly to these observed patterns.

Geographical location (latitude and longitude) and abundance appeared to be strong predictors of diversity off Namibia as was reflected in GAMs. Dissolved oxygen and bottom temperature appeared to have contributed to the diversity distribution patterns. At least in part, the intense and perennial upwelling off the coast of Namibia, the irregular temperature anomalies, and variation in dissolved oxygen concentration, resulted in unstable and unpredictable environmental conditions, which contributed to the structuring of the Namibian demersal fish assemblages. For the management of the fishery, research should aim to identify the effects of bottom-trawling at small (sub-regions) and larger (shelf and slope; and wholecoast) spatial scales using long-term data.

Though there were some indirect effects of fishing on the abundance and biomass of demersal fish, due to the continuous removal of large fish leading to negative *W– statistics* over the years, it was difficult to separate the effects of bottom-trawling from those of physical and environmental variability. Physical variables such as depth, region and year have also played a role in changing the assemblage structure. Environmental variables (e.g. bottom temperature) affected the assemblage structure in different regions, depth category and year. More experimental bottom-trawl studies should be conducted in areas that are heavily and lightly trawled, so that proper indices of trawling levels can be developed for specific trawling areas. This could help management to establish fishing (bottom-trawling) zones where effort can be closely monitored, controlled and measured, thus providing a scientific basis for quick decisions pertaining to the sustainability of the hake fishery.

In conclusion, changes in the demersal fish community structure have occurred over the 17-year period under review. These observed changes are attibuted to interrelated factors such as depth (continental shelf and slope), regions (north, central, south), vessel changes (old and new *R/V Dr Fridtjof Nansen*, commercial vessels), and bottom temperatures and oxygen concentrations, but fishing remains the main driver of change in these demersal fish assemblages. Changes in diversity measures are due to changes in dissolved oxygen concentrations and bottom temperatures and their distribution from northern to southern Namibia varies with latitude and depth.

Exploring the effects of bottom trawling in the Benguela Current system: an experimental approach

6.1 Introduction

Bottom trawling is a key source of physical disturbance in shallow shelf seas, and it is known to affect diversity, community structure, size composition and production of the fish and benthic invertebrate communities (Dayton *et al*., 1995; Jennings and Kaiser, 1998; Hall, 1999; Kaiser and de Groot, 2000). It has been documented that a single pass of a beam trawl over a pristine area, the heaviest gear routinely used in shelf sea fisheries, can kill 5–65% of the resident fauna and mix the top few centimetres of sediment (Duplisea *et al*., 2001). However, the most common bottom-trawl gear used in the Benguela ecosystem off the coast of Namibia (Paul Kainge, NatMIRC, MFMR, *pers. comm*.) and South Africa is the otter trawl, which is not as destructive as the beam trawls used in the North Sea for flatfish and shellfish (Kaiser and de Groot, 2000). It is well established that fishing has various effects on the ecosystem, and such effects need to be understood in order to implement an ecosystem approach to fisheries management (EAF). Some of these effects include: changes in predator-prey relationships leading to shifts in food-web structure that are not necessarily reversed by a reduction in fishing pressure; effects on abundance and body size distribution that can result in a fauna dominated by small-bodied organisms; genetic selection for different physical characteristics and reproductive traits (e.g. earlier age-at-maturity); effects on populations of non-target species as a result of bycatch; reduction of habitat complexity and re-suspension of surface sediments (Kaiser *et al*., 2002).

Univariate diversity indices, such as species richness and evenness index, are expected to be different for the fish community from a heavily trawled area compared to one from lightly trawled areas at the two sites. While lightly fished areas are expected to have high species richness and low evenness, the opposite is true for the heavily fished areas. This is due to the continued removal of selected species from heavily fished areas, thus leaving only a few dominant species in the system. This is in contrast to the lightly trawled areas where there is a balance in terms of species numbers and their distribution (Jennings *et al*., 1999; Griffiths, 2000; Fromentin and Fonteneau, 2001). Thus, the main objective is to identify different attributes of community structure that are likely to provide evidence of fishing disturbance (due to bottom-trawling), using multivariate (with PERMANOVA) and univariate analyses. However, studies of this nature are always confounded by natural variability, the history of the fishery and small-scale patchiness (Dayton *et al*., 1995; Jennings and Kaiser, 1998; Auster and Langton, 1999; Gordon *et al*., 2005). The resulting interactions between natural variability and bottom trawling activities are illustrated in Atkinson *et al*., (2011b). Lack of pristine areas in the Benguela, where the before and after experiments could be conducted presents a big problem. Issues of unreplicated and pseudo-replication always occur (Hurlbert, 1984). A similar study in the Benguela by Atkinson *et al*., (2011b) was confronted by issues of pseudo-replication, which becomes a problem in terms of the confidence of the results of the experiment. However, Hurlbert (1984) suggested that caution should be observed when drawing conclusions from unreplicated treatment and should not be applied to a broader perspective.

The main aim of this chapter is to investigate the immediate effects of bottom trawling by comparing the fish catches, abundance, biomass and diversity indices for all the demersal fish caught in trawls from heavily and lightly trawled areas in both Namibia (Sam’s Bank) and South Africa (Child’s Bank), by applying both multivariate and univariate techniques (Clarke and Warwick, 2001). This study hypothesizes that communities of heavily and lightly fished areas at both Sam’s Bank (SB) and Child’s Bank (ChB) will be structurally different. The expected response to exposure to varying degrees of fishing (heavy and light) in terms of mean fish weight is that, since fishing is a selective process which targets larger bodied individuals thus removing them from the community and leaving small bodied individuals, the mean fish weight at SB and ChB is expected to be higher in lightly trawled than in heavily trawled areas. The same applies to total community biomass. In lightly trawled areas at both SB and ChB, fish communities are expected to be dominated by k–selected species (Pianka, 1970) that are large-bodied, grow slowly and mature late (Clarke and Warwick, 2001; Labropoulou and Papaconstantinou, 2005, Yemane *et al*., 2005). With increased bottom-trawl disturbance at heavily trawled sites both at SB and ChB, the k–selected species are not favoured, and so the system tends to become dominated by r–selected species (Pianka, 1970), which grow faster and are small and opportunistic (Clarke and Warwick, 2001; Labropoulou and Papaconstantinou, 2005, Yemane *et al*., 2005). This study is the first of its kind in the Benguela system.

6.2 Materials and methods

The study was conducted onboard the *R/V Dr Fridtjof Nansen* from 1–5 April 2007, off Namibia and South Africa's west coast (Fig. 6.1). The sampling was done at SB and ChB, in heavily and lightly trawled areas. These areas were selected using the commercial trawling data from the hake-directed bottom-trawl fishery for both Namibia and South Africa. The trawl intensity map (Fig. 6.2) was produced using ArcGIS v9.3 (www.esri.com) by plotting the commercial bottom-trawl data, which indicated the relative trawl intensity, expressed as number of hours spent on actual bottom-trawling and number of trawls per 1' x 1' grid square, averaged over the seven year period 2000 – 2006 (see Chapter 5). The two visible black crosses on the map (Fig. 6.2) are the two sites at SB in a lightly trawled and heavily trawled area, where the bottom-trawl experiment was conducted. The trawl intensity at ChB was determined in a relatively similar way by enumerating all the bottom-trawl tracks from the hake fishery in a 20' x 20' grid (Atkinson *et al*., 2011b). The sediment texture and depth were also used to guide the selection of these sites by making sure that they were similar (Table 6.1). Surface sediments were collected at each site and kept frozen for later analysis in the laboratory using the grading system by Folk (1954) (see appendix 6.1 for details). The sand, mud and gravel were weighed and their mass converted to percentages. The gravel-sand-mud texture categories were determined using Folk's sediment classification triangle (see appendix 6.1) (Folk, 1954). Sediment processing and classification were conducted by the Department of Geological Sciences, University of Cape Town under the supervision of Prof. John Rogers.

Three replicate trawls were conducted at the two sampling sites (SB and ChB), each with two sampling stations, heavily and lightly trawled, and each tow had a duration of 30 minutes at 3 knots. The details of the sampling procedures and gear can be found in Chapter 3 of this thesis, and they followed standard sampling procedures by Strømme (1992).

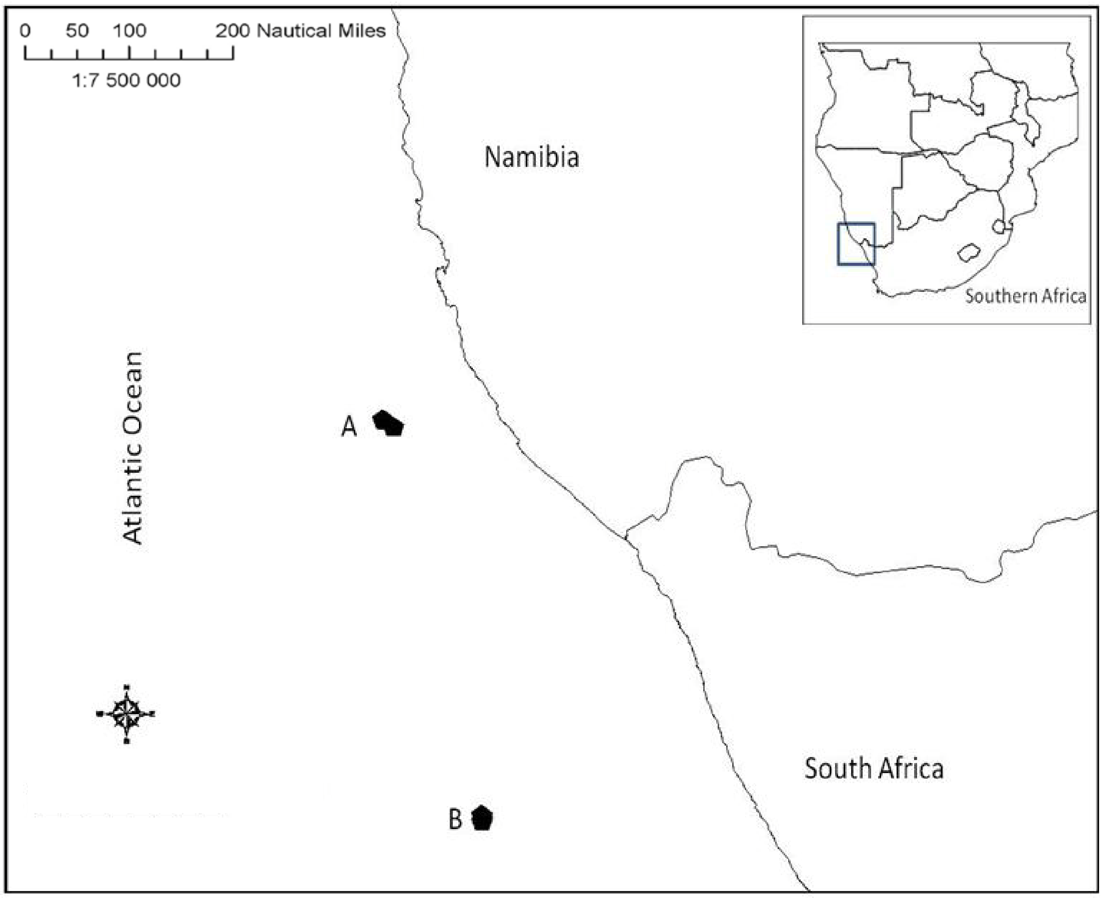


Figure 6.1 Map showing the study sites, (A) Sam's Bank (SB) and (B) Child's Bank (ChB) in Namibian and South African waters respectively. Each site has both a heavily and lightly trawled station.

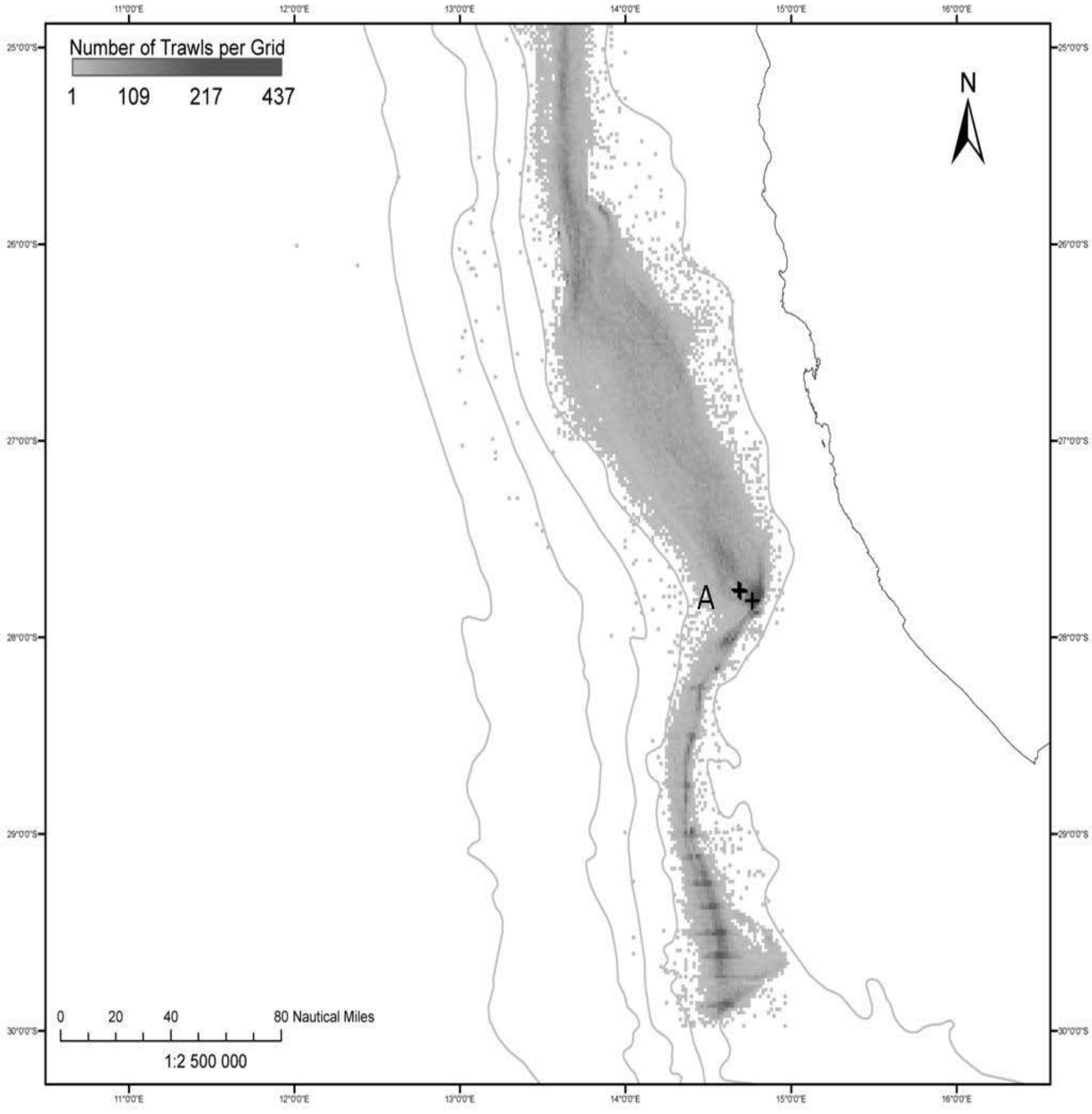


Figure 6.2 A sample map, used as a guide for sampling sites during the bottom-trawl experiment, showing the trawl intensity (measured as number of trawls per 1’ x 1’ grid) off Southern Namibia with special interest at Sam’s Bank (A), where the bottom trawl experiment took place. Two black crosses indicate the location of the lightly and heavily trawled stations.

6.2.1 Multivariate Analyses

Fish species abundance and biomass were calculated for each trawl after standardization of the data to a 30-minute tow. A cluster analysis (group average) employing the Bray-Curtis similarity index (Field *et al*., 1982) was performed to the standardized biomass values of species using the multivariate techniques in PRIMER *v6*: Multi-Dimensional Scaling (MDS), and Cluster analysis (Clarke and Warwick, 1994). The data were transformed by applying a fourth root transformation prior to the cluster analysis to avoid overemphasis of abundant species (Field *et al*., 1982, Clarke and Warwick, 1994, 2001). MDS ordination analysis was performed on the same data as the cluster analysis. The k-dominance curves were constructed from the species abundance and biomass data for each trawl site. Species cumulative frequency distributions (k-dominance curves) were used to show variations in species relative abundance and biomass (Clarke and Warwick, 2001). For the purpose of these calculations, replicates for each treatment site were pooled. The dominance plot was calculated by choosing the single worksheet option and cumulative as the plot type (Clarke and Warwick, 2001).

The abundance biomass comparison (ABC) curves were constructed from the pooled abundance and biomass data averaged for sites and trawl levels. The difference between the two curves is given by the *W–statistic*, which represents the area between the biomass and abundance curves. The *W-statistic* (Clarke and Warwick, 2001) was calculated for each of the treatment sites. A *W-statistic* with negative sign ($W < 0$) indicates that the biomass curve lies below the abundance curve and suggests a disturbed community; $W \sim 0$ indicates that the abundance and biomass curves are close to each other and suggests a moderately disturbed community, and if $W > 0$ (positive sign), the biomass curve lies on top of the abundance curve, which suggests an undisturbed community (Warwick and Clarke, 1994). This method has been applied to fisheries and proved to be a useful tool in detecting changes in community structure (Lambshead *et al*., 1983;; Yemane *et al*., 2005; Labropoulou and Papaconstantinou, 2005; Jouffre and Inejih, 2005; Clarke and Gorley, 2006). This same theory has been modified a bit in Chapter 5, and we use here the same classification of disturbance.

The Similarity Percentage (SIMPER) procedure (Clarke and Warwick, 2001; Clarke and Gorley, 2006) was applied to the species biomass data in order to typify and discriminate species of each group of sites and trawl levels. This procedure indicates the average contribution of each species to the similarity (typifying species) and dissimilarity (discriminating species) between groups of samples (Clarke and Warwick, 2001; Clarke and Gorley, 2006; Labropoulou and Papaconstanou, 2005). For the SIMPER analysis, the biomass data was fourth root transformed. The site factor (SB or ChB) was chosen as factor A and the treatment (L = lightly and H = heavily trawled) was chosen as factor B. A Bray-Curtis similarity was chosen with a 75% cut off for low contributions. This gave the average similarity between sites and treatments. The analysis also gave the dissimilarities between the sites (SB and ChB) and the treatments (L and H). From these the similarity between sites (SB and ChB) and treatments (H and L) were calculated using the following formula:

$$\text{Similarity} = 1 - \text{Dissimilarity}$$

The Permutational Multivariate Analysis of Variance (PERMANOVA) (Anderson, 2005, Anderson *et al*., 2008) was used to test for interaction effects between treatments (region and trawl level), and the effects of depths were taken into consideration as a co-variate. It gives two p-values, the Permanova p-value and the Monte-Carlo (MC) p-value. In this case, the latter was used (Anderson, 2005). This analysis tool was used due to its robustness, as it can handle small sample sizes compared to ANOSIM (Clarke and Gorley, 2006), and can take up to 10 co-variates. Co-variates are the confounding factors, which influence the results, due to the complexity of the natural environment.

6.2.2 Univariate Analyses

Analysis of variance (ANOVA) (Zar, 1999), was applied to the abundance and biomass data. First, the total catch (sum of the catch weight of all species caught in a particular replicate) was log transformed so that assumptions of normality and homogeneity of variance could be met. The two-way ANOVA design was applied to the data for the comparison of biomass across regions and trawl levels. Secondly, the mean fish weight of each species was calculated, and the mean fish weight for each replicate was calculated as a weighted mean (i.e. mean weight of individual species weighted by their corresponding catch weight). The resulting mean fish weight was compared across the region and trawl level using the two-way ANOVA crossed design (Zar, 1999). Least Square Means (LSM) versus arithmetic mean of ln-transformed data; when there are no missing cells in ANOVA designs with categorical predictor variables, the subpopulation (or marginal) means are least square means, which are the best linear-unbiased estimates of the marginal means for the design (see, Milliken and Johnson, 1986). Tests of differences in least square means have the important property that they are invariant to the choice of the coding of effects for categorical predictor variables (e.g., the use of the sigma-restricted or the over-parameterized model) and to the choice of the particular generalized inverse of the design matrix used to solve the normal equations. Thus, tests of linear combinations of least square means in general are said to not depend on the parameterization of the design, while the arithmetic mean is probably the most often used descriptive statistics. The mean is a particularly informative measure of the "central tendency" of the variable if it is reported along with its confidence intervals. Usually we are interested in statistics (such as the mean) from our sample only to the extent to which they can infer information about the population. The confidence intervals for the mean give us a range of values around the mean where we expect the "true" (population) mean is located (with a given level of certainty.

6.2.2.1 Diversity measures

Ecological parameters were calculated: composite diversity, which integrates both richness and evenness (Shannon-Wiener), Pielou’s evenness index *J’* (Pielou, 1966), and species richness (*S* = number of species) for further details see Chapter 5. All these were calculated in PRIMER-E v6 (Warwick and Clarke, 1994) using the diverse function. Species diversity was examined for each of the station groups defined by the cluster analysis (Warwick and Clarke, 1994).

6.3 Results

6.3.1 Environmental Parameters

SB and ChB sites had an overall sediment texture of mud-sand, which was dominated by fine sand (on the Wentworth scale). The bottom dissolved oxygen concentration (DO) was fairly low at SB compared to double the amount at ChB (Table 6.1). A similar pattern was observed for bottom temperature, which was 8°C at SB, but had been 10°C at ChB (Table 6.1). The two sites had a depth range between 346 and 444 m. Both SB and ChB had similar bottom salinity (Table 6.1).

Table 6.1 Trawl site characteristics for the two study sites. (The L at the end of the site name denotes lightly trawled and H denotes heavily trawled).

Site	**Overall Texture** (G-S-M)	**Overall Wentworth Scale**	**DO** mg/L	**Bottom Temp.** deg.Cels.	**Depth** (m)	**Sal** o%
Sam-L	mud Sand	fine Sand	2	8	444	34.7
Sam-H	mud Sand	very fine Sand	2	8	407	34.7
Child-L	(gravel) mud Sand	fine Sand	4	10	346	34.8
Child-H	mud Sand	fine Sand	4	10	398	34.8

6.3.2 Multivariate analyses

A total of 65 species were collected from 12 bottom trawl samples, six samples at each of the sites (Fig. 6.1). Classification and ordination of the 12 trawls in terms of biomass, identified four distinct groupings, with greater differences between regions than between trawl levels, and the effects of trawling in Namibia were found to be more significant than in South Africa (Fig. 6.3a and b). The dendrogram in Fig. 6.3a clearly showed the separation of the 12 bottom trawls into their respective trawl effects (light and heavy) and site. The MDS with the stress level of 0.05 also depicted the same kind of groupings in terms of trawl level and site. The k- dominance curves showed that the heavily trawled sites at SB and ChB (Fig. 6.4) had the highest curves for both abundance and biomass, while the two lower curves were those of the lightly trawled sites. Comparatively, SB had the steepest and more elevated curves on the dominance plots compared to ChB, and it was shown to have the highest curves on the dominance plots (Fig. 6.4), meaning it was more dominated by a single or few species.

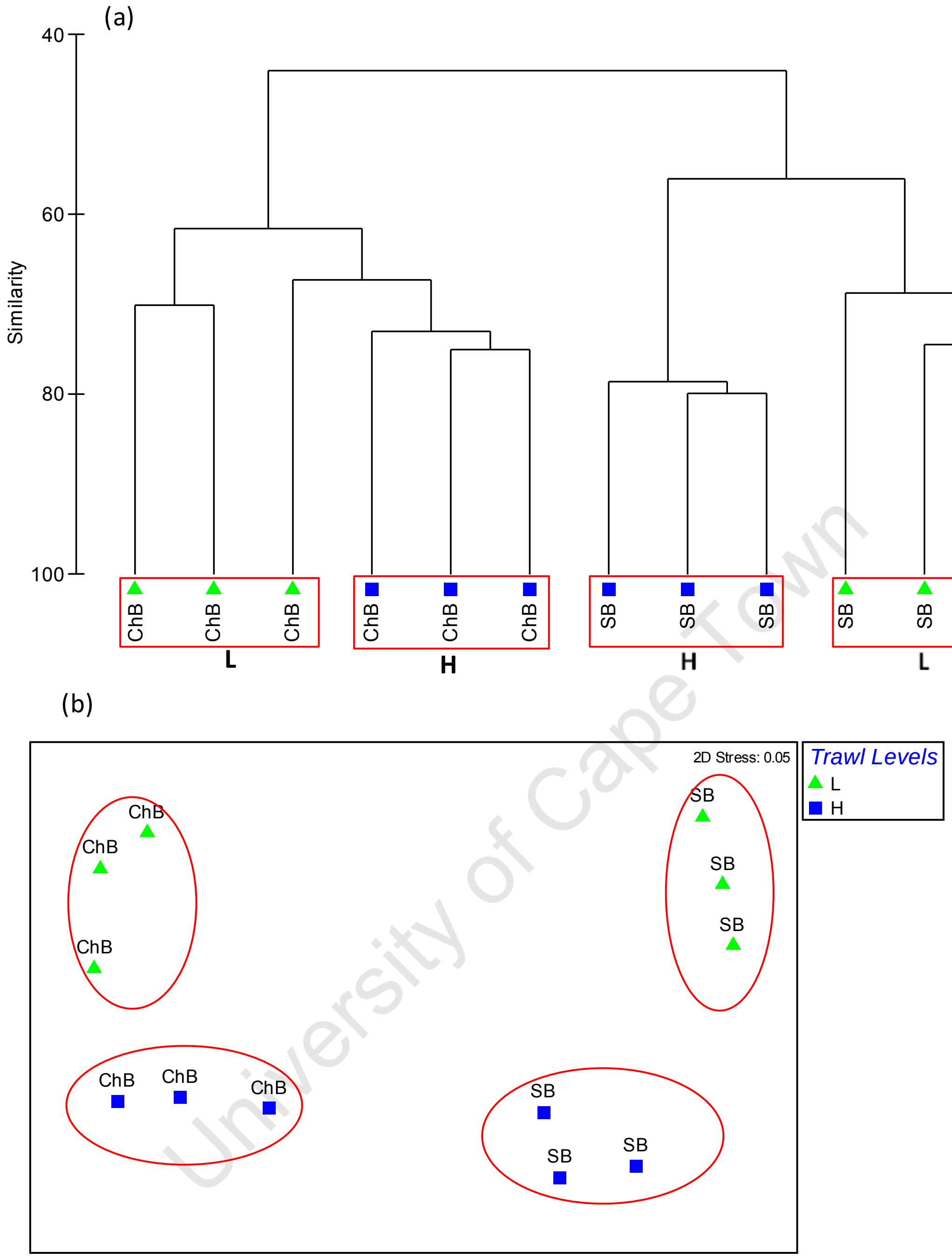


Figure 6.3 Classification (a) and ordination (b) of the sampling stations based on species biomass after 4th – root transformation, based on Bray-Curtis similarity matrix, from both Sam’s Bank (SB) in Namibia and Child’s Bank (ChB) in South Africa. L is lightly trawled and H is heavily trawled.

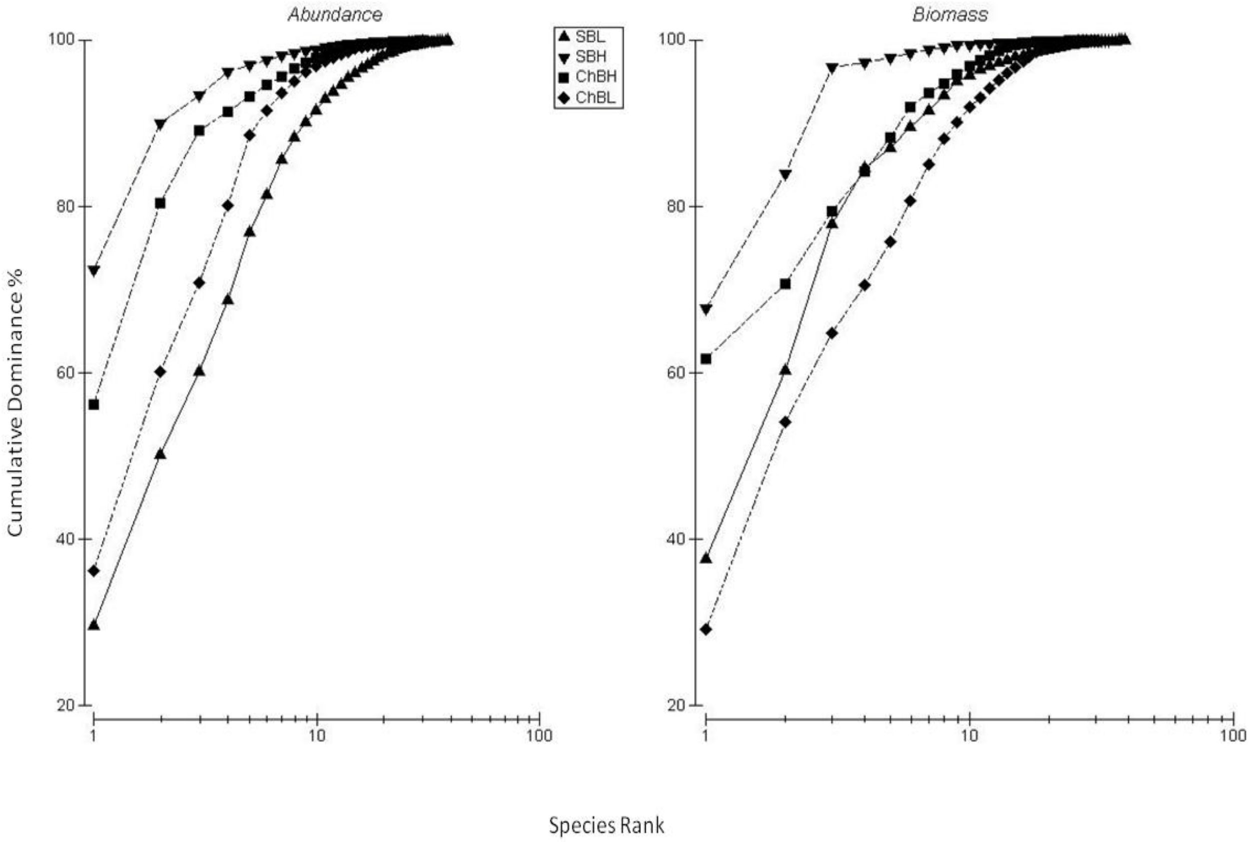


Figure 6.4 K-dominance curves for both Sam’s Bank in Namibia and Child’s Bank in South Africa based on abundance and biomass, upper and bottom curve respectively. SBL: Sam’s Bank Lightly; SBH: Sam’s Bank Heavily; ChBL: Child’s Bank Lightly; ChBH: Child’s Bank Heavily.

The ABC curves are shown in Figure 6.5, which indicate the level of disturbance within the fish community. The figure shows that at a lightly trawled site at SB the biomass curve was above the abundance curve and had a *W-statistic* > 0, which suggests that the site was undisturbed by bottom-trawling. At the heavily trawled site at SB the biomass curve crossed the abundance curve midway, with a *W-statistic* equal to zero, which suggests a moderately disturbed community. Surprisingly, at ChB, for both the lightly and heavily trawled sites, the abundance curves were well above the biomass curves, with the *W-statistics* less than zero, suggesting two disturbed communities.

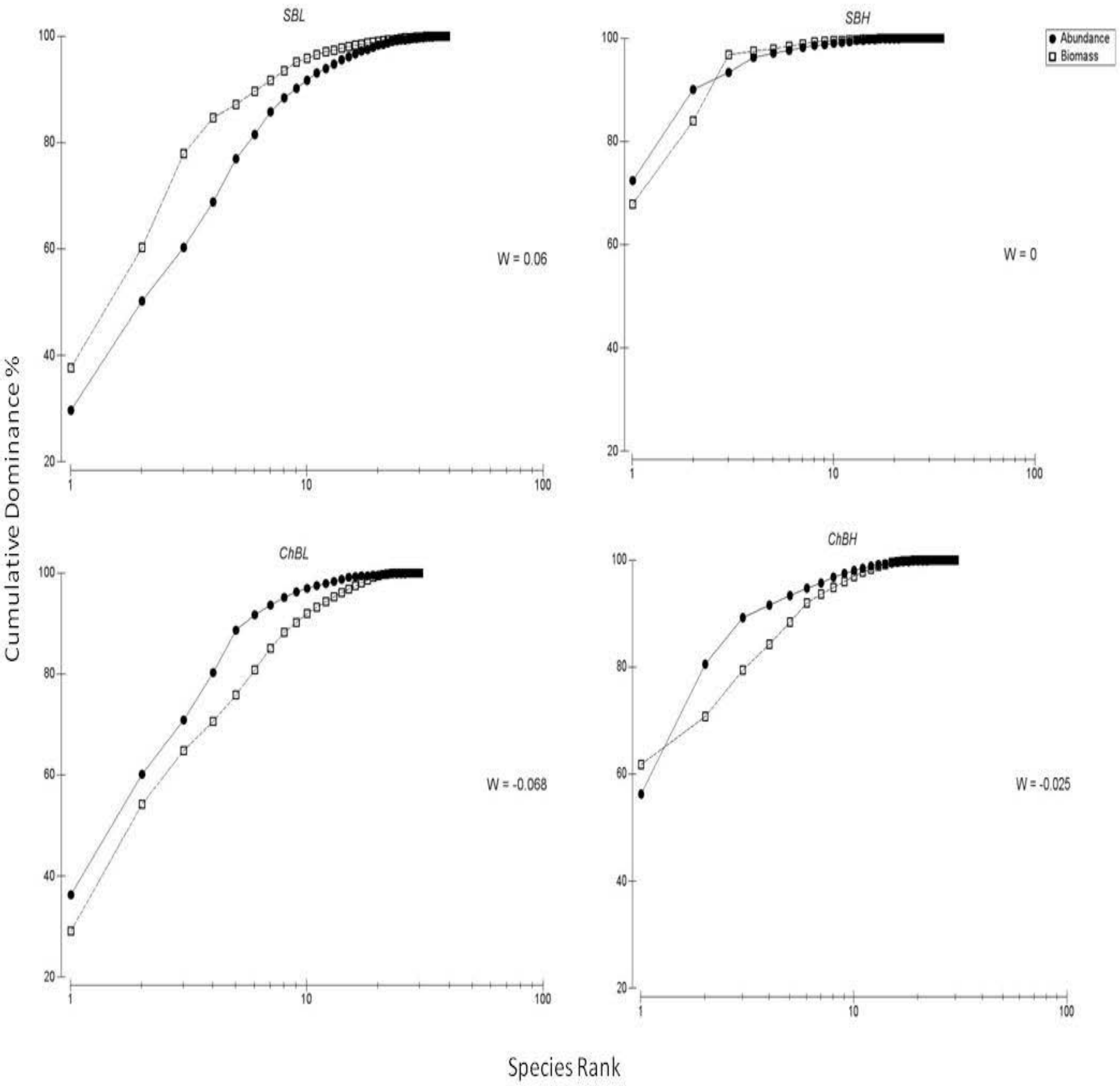


Figure 6.5 Abundance-Biomass-Comparison (ABC) curves for Sam's Bank (lightly and heavily trawled) upper curves, and Child's Bank (lightly and heavily trawled) lower curve.

Table 6.2 Dominant fish species (75 % cut off) on both Sam's Bank (SB) (Namibia) and Child's Bank (ChB) (South Africa), based on rank of each station group identified by the cluster analysis. The top part of the table examines trawl level groups across all region groups, and the lower part examines region groups across all trawl level groups. Contrib % is average contribution to the similarity in each group, Sim/SD is similarity/standard deviation; Cum% is cumulative percentage; and C indicates the commercially exploited species.

Group L (Lightly Trawled)					**Group H (Heavily Trawled)**				
Average similarity: 69.08					**Average similarity: 74.53**				
Species	**Sim/SD**	**Contrib%**	**Cum.%**		**Species**	**Sim/SD**	**Contrib%**	**Cum.%**	
Caelorinchus simorhynchus	3.82	12.24	12.24		*Caelorinchus simorhynchus*	6.51	14.70	14.70	
Merluccius paradoxus	3.51	11.49	23.72	C	*Merluccius paradoxus*	17.02	14.14	28.84	C
Paracallionymus costatus	1.58	6.83	30.56		*Paracallionymus costatus*	2.40	7.93	36.77	
Helicolenus dactylopterus	1.04	5.94	36.49		*Lucigadus sp.*	3.36	6.55	43.31	
Genypterus capensis	8.53	4.43	40.92	C	*Genypterus capensis*	18.32	6.08	49.40	
Notacanthus sexpinis	0.90	4.15	45.07		*Physiculus capensis*	5.06	5.25	54.65	
Lophius vomerinus	1.13	3.99	49.06	C	*Helicolenus dactylopterus*	7.70	5.22	59.87	
Nezumia sp.	0.91	3.60	52.66		*Holohalaelurus regani*	16.66	4.01	63.88	
Hoplostethus cadenati	0.91	3.55	56.22		*Malacocephalus laevis*	1.19	3.74	67.61	
Malacocephalus laevis	1.19	3.41	59.63		*Epigonus sp.*	0.91	3.42	71.04	
Epigonus sp.	0.63	2.92	62.54		*Lepidopus caudatus*	0.89	3.42	74.45	
Physiculus capensis	1.26	2.91	65.45		*Lampanyctodes hectoris*	0.91	3.26	77.71	
Lepidopus caudatus	0.89	2.76	68.21						
Symbolophorus boops	0.91	2.59	70.80						
Gymnoscopelus sp.	0.90	2.36	73.16						
Zeidae	0.90	2.20	75.35						

Group SB					**Group ChB**				
Average similarity: 72.69					**Average similarity: 70.92**				
Species	**Sim/SD**	**Contrib%**	**Cum.%**		**Species**	**Sim/SD**	**Contrib%**	**Cum.%**	
Caelorinchus simorhynchus	2.92	12.87	12.87		*Merluccius paradoxus*	15.73	14.63	14.63	C
Merluccius paradoxus	3.30	11.14	24.01	C	*Caelorinchus simorhynchus*	10.46	14.18	28.81	
Genypterus capensis	4.09	5.29	29.30	C	*Paracallionymus costatus*	10.78	10.94	39.75	
Gymnoscopelus sp.	6.30	5.10	34.40		*Helicolenus dactylopterus*	3.27	8.43	48.18	
Physiculus capensis	3.70	5.08	39.48		*Lepidopus caudatus*	4.10	6.28	54.46	
Lucigadus sp.	1.17	4.93	44.41		*Malacocephalus laevis*	7.00	6.13	60.59	
Photichtys argenteus	5.26	4.89	49.30		*Genypterus capensis*	4.80	5.28	65.87	C
Epigonus sp.	1.29	4.67	53.97		*Lophius vomerinus*	1.28	4.44	70.31	C
Symbolophorus boops	6.13	4.37	58.34		*Lampanyctodes hectoris*	1.24	4.15	74.46	
Paracallionumus costatus	2.96	3.95	62.29		*Merluccius capensis*	22.11	3.95	78.41	C
Notacanthus sexspinis	0.90	3.94	66.23						
Nezumia sp.	1.16	3.93	70.15						
Tripterophycis gilchristi	5.61	3.65	73.81						
Hoplostethus cadenati	0.91	3.38	77.18						

The SIMPER results show that the non-commercial species, Banded-whiptail (*Caelorinchus simorhyncus*) contributed the highest to the average similarity for all the lightly and heavily trawled sites; and at Sam's Bank, this species is only known to occur in the Southeast Atlantic, off Angola to Agulhas Bank (Iwamoto and Anderson, 1994), and second highest conributer to the similarity was the commercial deep-water hake (*M. paradoxus*) (see Chapter 1), except at Child's Bank where *M. paradoxus* contributed the most, followed by *C. simorhyncus* (Table 6.2). The third by % contribution to the similarity was the Cape dragonet (*Paracallionymus costatus*), which occurs from Luderitz Bay, Namibia to Inhaca, Mozambique (Fricke, 1986), at all levels of trawl, mostly at ChB, while the third place was occupied by kingklip (*Genypterus capensis*) at SB (Table 6.2), which is commercially exploited. The distribution of kingklip ranges from Walvis Bay, Namibia to Algoa Bay, South Africa (Nielsen *et al*., 1999). They feed on dragonets, mantis shrimps, hake, squid, and various fish (Nielsen *et al*., 1999) .The Cape dragonet (*P. Costatus*) are not commercially exploited in Namibia, but they are preyed upon by kingklip and other commercial species and by fur seals (Fricke, 1986).

The PERMANOVA results (Table 6.3) showed that there was a significant effect of region (p= 0.001, *df* = 1) and trawl level (p = 0.002, *df* = 1) on the community structure of the demersal fish assemblages. However, there were no significant interaction effects (p = 0.151, *df* =1) between region and trawl level, indicating that trawling has similar effects in both regions.

Table 6.3 Permutational Multivariate Analysis of Variance (PERMANOVA) results. (Data were transformed to square root, no standardisation, analysis based on Bray-Curtis dissimilarities, permutation of residuals under the full model, integer used as seed = 6, number of permutations used = 999). Note: covariables were tested using permutation of raw data, ignoring other terms in the analysis. Re denotes Region and Tr for Trawl levels. P (Perm) = PERMANOVA p-value, P(MC) = Monte-Carlo p-value.

Source	***Df***	**SS**	***MS***	***F***	***P(perm)***	***P(MC)***
Covariables	1	3849.89	3849.89	10.64	0.001	
Re	1	2257.05	2257.05	6.24	0.001	0.001
Tr	1	3744.60	3744.60	10.35	0.001	0.002
Re x Tr	1	595.41	595.41	1.65	0.136	0.151
Residual	7	2533.59	361.94			
Total	11	12980.53				

6.2.3 Univariate Analyses:

6.2.3.1 Mean Catch

The ANOVA results for comparison of the mean catch across region and trawl levels showed that region (SB and ChB) had no significant effect (ANOVA, $F_{1,8}$ = 0.54, *df* = 1, p = 0.483), whereas trawl levels showed significant (ANOVA, $F_{1,8}$ = 35.88, *df* = 1, p = 0.000) effect on the mean catch of demersal fish (Zar, 1999). However, the effect of trawl level does not change with the region (no interaction effects between region and trawl levels) (i.e. trawl level affects both regions in the same way) (ANOVA, $F_{1,8}$ = 2.09, df = 1, p = 0.187). The total fish catch in heavily trawled areas was higher than lightly trawled areas (Fig. 6.6a). If the total catch of the two regions are separated, the same results are obtained (Fig. 6.6b).

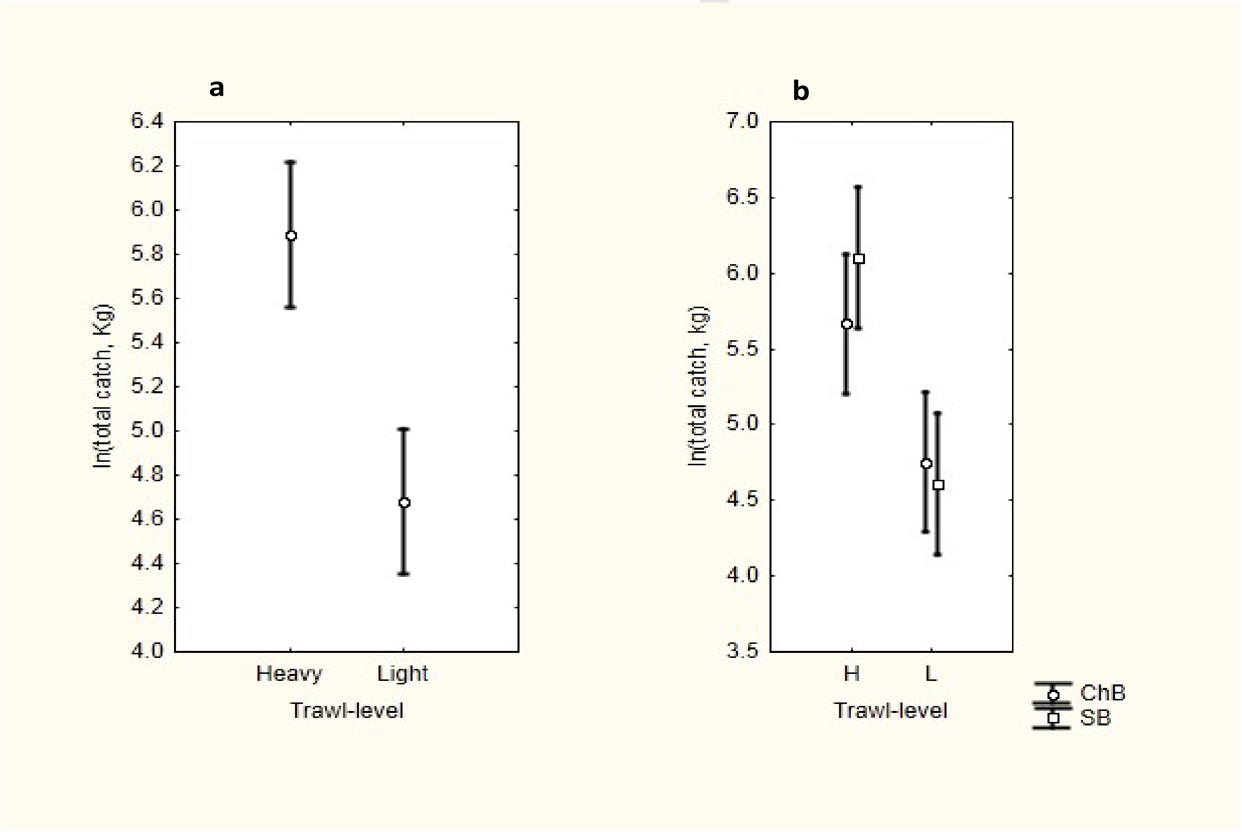


Figure 6.6 a)Least square means (LSM) of demersal fish catch (kg) in the heavily and lightly trawled areas (pooled data for both ChB and SB), b) least square means (LSM) of demersal fish catch (kg) in the heavily (H) and lightly (L) trawled areas, in the two regions (SB: Sam's Bank, squares and ChB: Child's Bank, South Africa, circles). Error bars (+/- 95 confidence intervals).

6.2.3.2 Mean Fish Weight

There was no significant difference in the mean fish weights across regions (ANOVA, $F_{1,8}$ = 0.001, *df* = 1, p = 0.98) and between trawl levels (ANOVA, $F_{1,8}$ = 0.001, *df* = 1, p = 0.97), and correspondingly there was no significant interaction effect between region and trawl levels (ANOVA, $F_{1,8}$ = 1.73, *df* = 1, p = 0.23) (Zar, 1999).

6.2.3.3 Diversity Indices

Species richness (S) (number of species) was fairly high at the lightly trawled site at SB and low at the heavily trawled area (Fig. 6.8). The opposite trend was observed at ChB, where species richness was fairly high at the heavily trawled site, and lower in the lightly trawled site (Fig. 6.7). The differences in species richness between trawl levels are more pronounced at SB than ChB. Overall, SB had more number of species recorded than ChB (Fig. 6.7). The effect of trawl levels (light and heavy trawling) on the species richness was not significant (2-way ANOVA, $F_{1,8}$ = 3.959, *df* = 1, p = 0.08). The 2-way ANOVA results showed that region (SB and ChB) had a significant effect ($F_{1,8}$ = 14.918, *df* = 1, p = 0.005) on the species richness S, and there was also a significant interaction effect between trawl level and region ($F_{1,8}$ = 6.041, *df* =1, p = 0.039) on the species richness, indicating that each region was affected differently by trawl levels, thus affecting species richness at these regions (Fig 6.7).

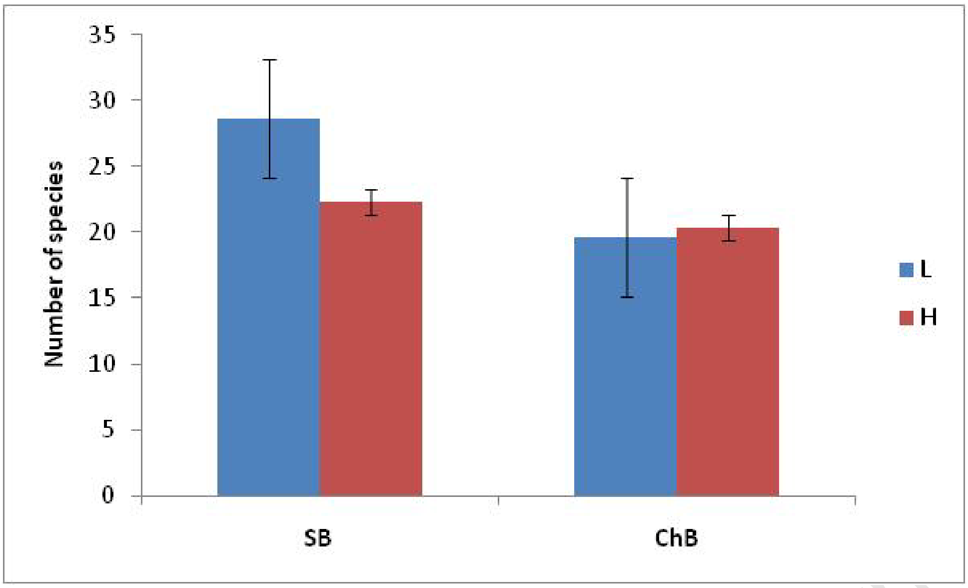


Figure 6.7 Species richness S, (number of species) as recorded at lightly and heavily trawled sites. Data based on demersal fish abundance (SB = Sam's Bank, and ChB = Child's Bank). The L and H denote lightly and heavily trawled sites respectively. Error bars denote standard errors.

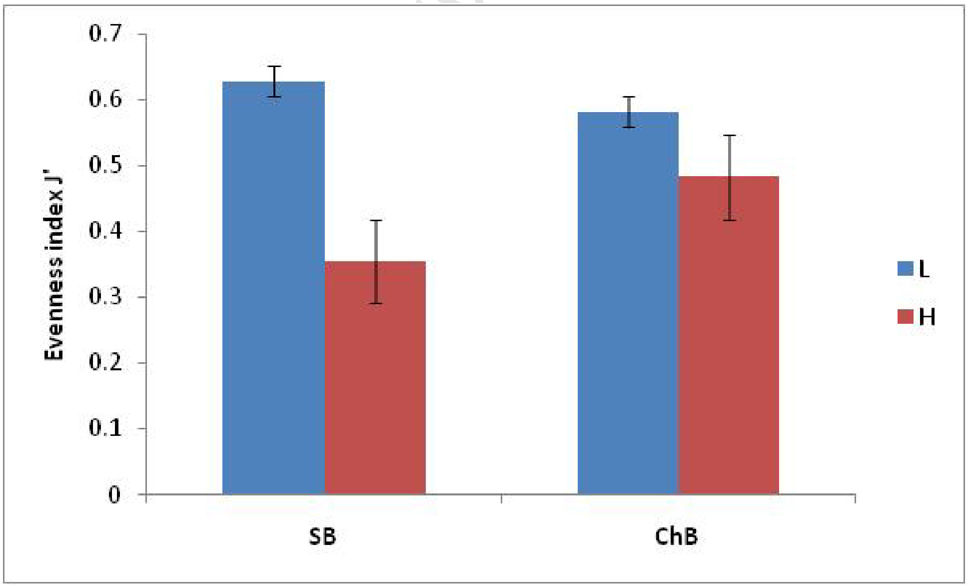


Figure 6.8 Pielou's evenness index J' for the fish assemblages at Sam's Bank (SB) and Child's Bank (ChB). Data based on fish abundance. The L and H denote lightly and heavily trawled sites respectively. Error bars denote standard errors.

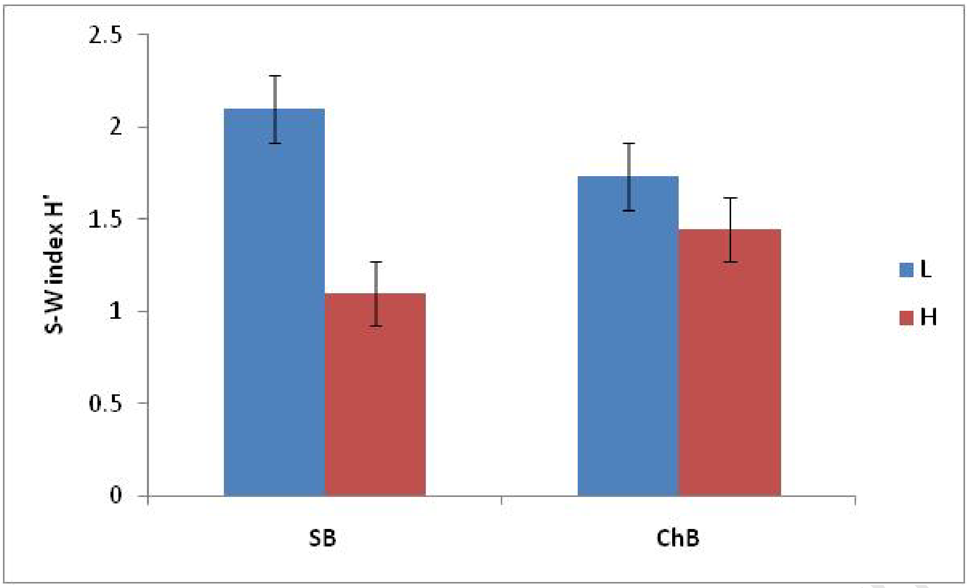


Figure 6.9 Shannon-Wiener Index H’ for the fish assemblages at Sam’s Bank (SB) and Child’s Bank (ChB). Data based on fish abundance. The L and H denote lightly and heavily trawled sites respectively. Error bars denote standard errors.

The distribution of species among regions with different trawl levels also showed marked differences, with high evenness at lightly trawled sites and low evenness in the heavily trawled areas (Fig. 6.8). The trawl level had significant (2-way ANOVA, $F_{1,8} = 12.465$, $df = 1$, $p = 0.01$) effects on the species evenness, while the region had no significant (2-way ANOVA, $F_{1,8} = 0.001$, $df = 1$, $p = 0.98$) effect on the distribution of species. The ANOVA also showed that there was no significant ($F_{1,8} = 3.856$, $df = 1$, $p = 0.09$) interaction effect between trawl levels and regions. Thus the effects of trawl levels on the species evenness are independent of those of regions.

6.3 Discussion

Lack of representative areas which are pristine in the Benguela system, presented the biggest challenge in conducting bottom trawl experiments such as this. The environmental parameters recorded during this study were similar, with minor variations in depth and bottom dissolved oxygen from site to site (Table 6.2).

Although this bottom-trawling experiment was conducted in a natural environment, and fluctuations in environmental conditions could not be controlled, this has not hampered the efforts to conduct this experiment for the first time in the Benguela system.

6.3.1 Cluster and MDS

Both the classification by dendrogram (Fig. 6.3a) and the MDS plot (Fig. 6.3b) clearly indicated the separation of four distinct fish assemblages, with bigger differences between regions (SB and ChB) (Fig. 6.1), and a much bigger difference in trawl levels (lightly and heavily trawled) at the Namibian sites than in South Africa. This could be attributed to the fact that commercial trawling on the Namibian side still reaches as far as the South African border, at a more or less similar fishing effort (Fig. 6.2), while the fewer South African trawlers reach ChB. This may be due to fact that it is not profitable to steam so far due to fuel costs and the declining catches due to the southward shift of hake on South Africa's west coast (Marek Lipinski, MCM, *pers. comm*.). The MDS had a two dimensional stress for the biomass (Fig. 6.3b), which was less than 0.1, and it corresponds to a good ordination, which is unlikely to yield a misleading interpretation (Clarke and Warwick, 2001), however it should be noted that there were fewer data points in the ordination, as this may lead to lower stress level.

6.3.2 Dominance structure

The k– dominance curves for abundance and biomass showed that the two heavily trawled sites at SB and ChB had the highest dominance and lowest diversity (Clarke and Warwick, 2001), due to the fact that they had elevated curves (Fig. 6.4), showing some increased dominance by one or few species. The lightly trawled areas at SB and ChB had relatively low dominance compared to the heavily trawled areas (Fig. 6.4). This suggests that lightly trawled areas had a greater variety of species caught in the trawls. The former and latter statements are strongly supported by the diversity indices such as the species richness *S* (though opposite for the two regions) and Shannon-Wiener *H'* (Figs. 6.7 and 6.8) (Clarke and Warwick, 2001). Due to the reduced dominance at the lightly trawled sites, the likely response for the relatively high species evenness was also observed. Surprisingly, there was a reversal between SBL and ChBL in terms of dominance based on abundance and biomass (Fig. 6.4). This kind of reversal could not be explained, since there were no data entry errors but could possibly be due to lack of sampling effort and pseudoreplication as explained earlier in this chapter. However, what is important is the elevation of the different curves and their interpretation, which contributed towards the purpose of this study.

6.3.3 Assemblage structure (ABC curves)

Another useful technique is the ABC method (Clarke and Warwick, 2001), which has been applied to assess changes in structure of demersal fisheries and results from this technique can assist in our understanding of the demersal fish communities and the move towards an ecosystem approach to fisheries (Bianchi *et al*., 2001, Yemane *et al*., 2005; Jouffre and Inejih, 2005; Labropoulou and Papaconstantinou, 2005; Chapter 5). The lightly trawled site at SB had the expected response, which suggested that the site experienced low disturbance from bottom-trawling, while the heavily trawled site suggested a moderately disturbed site (Fig. 6.5). At ChB, the expected response for the heavily trawled site matched the observed response, whereby the site had high numbers of individuals with relatively low biomass, suggesting a moderately disturbed demersal fish assemblage. The opposite response was expected at the lightly trawled site, but it was the same as the heavily trawled site (Fig. 6.5), which raises questions of site status in terms of bottom-trawl levels in the area. The ABC analysis further illustrated that SB was less disturbed than ChB by virtue of their respective *W-statistics* pooled together (Fig. 6.5). The bottom trawling activities at ChB has recently been reduced (Marek Lipinski *pers. comm.*), the effects after the periods of extended heavy trawling would most likely stay for long.

6.3.4 Similarity percentage for trawl level and regions

The banded whiptail *C. simorhynchus* seems resilient to the bottom-trawl disturbance, as it appears to dominate both the lightly and heavily trawled sites contributing immensely to the average similarity for trawl levels and regions. The shallow water hake *M. capensis ,* which is one of the main species targeted by the hake bottom-trawlers, was common at all trawl levels and region (except for ChB, with *M. paradoxus* was a second important contributor to the similarity). On one hand, this may explain why fishermen repeatedly catch Cape hakes in the same areas they trawled before, and target fish are expected to occur in low densities due to heavy trawling. On the other hand, there are good reasons why fishermen do not trawl more frequently in lightly trawled areas, due to the presence of rough ground and obstacles, which may damage their nets or low catch rates. In principle, one would expect to catch more fish in less disturbed environments than in heavily disturbed ones. However, this does not seem to be the case here, as fish are more on the heavily trawled sites.

In an experiment like this, it may not be easy to identify the cause of a disturbance, as some research suggests there may be other factors which could contribute to the disturbance apart from fishing, and these may range from natural perturbations, geochemical processes, etc. (Dayton *et al.*, 1995; Duplisea *et al.*, 2001; Hall, 1999; Jennings and Kaiser, 1998; Kaiser and De Groot, 2000). In most cases experiments conducted in the natural environment are difficult to control, and one needs to be aware of physical variables such depth, bottom dissolved oxygen, salinity and temperature. Pseudoreplication as defined by Hurlbert (1984) creates some uncertainty in terms of accepting the results at a certain confidence level, as the results might be confounded by factors other than those was measured. Thus, interpretation of the results may be difficult due to pseudpreplication in experimental field work. The PERMANOVA analysis showed that the differences in demersal fish assemblages are attributed to the differences in regions and trawl intensity levels. Nonetheless, bottom trawling affected both SB and ChB in a similar way.

Due to some increased fishing disturbance at all the heavily trawled sites, lower mean fish catches were expected compared to all the lightly trawled sites, where bottom-trawling is minimal. However, this was not the case, since the heavily trawled sites had higher mean fish catches than the lightly trawled sites. These observed differences in the mean fish catches may not necessarily be as a result of different levels of bottom trawling but other factors. However, the mean fish weight in the assemblages was not significantly different across regions and trawl levels. This suggests that the heavily and lightly trawled sites had the same proportions of small and large fish. A similar study at Coquille Bank, Oregon, observed that there were 23% more fish over untrawled compared to trawled seafloors, and recorded 27 fish species on untrawled bottoms, but only 19 species on trawled seafloor (Hixon and Tissot, 2007). This kind of scenario was what was observed at SB, only in terms of number of species, but the opposite was found at ChB. Could this explain the reasons why fishermen continue to fish at same spots, due to higher catches, though experiencing a decrease in size of fish over time? If fishermen are interested in target species (*M. capensis* and *M. paradoxus*), then this suggests that the Cape hakes frequent heavily trawled areas, on assumption that there are no trawl barriers in lightly trawled areas. This coincides with the occurrence of high concentration of bottom-trawlers in heavily trawled areas (Chapter 2). It seems reasonable, to think that fish go where there is other fish and more food. The lightly trawled sites had lower mean fish catches, low abundance but relatively high biomass, which means larger bodied individuals present. This similar pattern was also shown by the ABC curves, at SB (lightly and heavily trawled sites) and ChB (heavily trawled site only).

6.3.5 Bottom trawling and diversity

Ecologically, species diversity can be a good indicator for disturbance studies, with areas with high disturbance accounting for very low species richness and low species evenness, the opposite is true at areas which are in an intermediate disturbance state, and the areas with too little disturbance, and competitive superiors drive the pioneer species to extinction (Dial and Roughgarden, 1998; Murawski, 2000; Shea *et al.*, 2004; Labropoulou and Papaconstantinou, 2005). The lightly trawled site at SB had higher species richness, evenness and diversity than the heavily trawled site, while the opposite was true for species richness, except for evenness and diversity at

ChB (Figs. 6.7 and 6.8). This suggests that the lightly trawled sites have a relatively low dominance (Fig. 6.3), and that they are not dominated by a few species. The differences in number of species for the two regions were most likely due to the difference in regions (SB and ChB), which are spatially distant from each other on latitude gradient. The differences in species evenness were influenced by the trawl levels (light and heavy). This again supports the fact that any form of fishing is selective and takes out bigger species (those that can be retained by a 20 mm mesh codend). A natural replacement takes place with smaller individuals, which are opportunistic especially in areas where disturbance is high (Jennings *et al*., 1998, 1999; Kaiser and De Groot, 2000). The community remained dominated by one or two species at more disturbed sites (Jennings *et al*., 1999; Kaiser *et al*., 2002), which was also found in the current study.

The results of the PERMANOVA analysis suggested that the differences in species richness was due to different geographic locations by region (SB and ChB), this effect was also dependent on trawl levels. Trawling was shown to have a significant effect on the species evenness (distribution of the species among different levels of trawling), and it was dependent on region. Species evenness at the lightly trawled sites was relatively high, due to the low level of disturbance at these sites, while the heavily trawled sites displayed relatively low species evenness due to high disturbance. In a similar study, epifaunal assemblages showed greater differences at heavily trawled sites with significantly low species diversity, average number of species and individuals (Atkinson *et al*, 2011 *in press*). This is in agreement with the demersal fish assemblages, which showed similar differences, with an exception of species richness at ChB. High levels of disturbance have generally been considered to decrease diversity, species richness and evenness, which is evident in this study. However, some studies have shown that intermediate levels of disturbance or stress can influence the diversity in such way that diversity could be highest at intermediate levels of disturbance (Murawski, 2000; Labropoulou and Papaconstantinou, 2005).

Experimental bottom trawling at a small spatial scale can provide evidence of the immediate impacts by comparing fished and unfished in single habitat type (McConnaughey *et al*., 2000; Gordon *et al*., 2005). Although these kinds of experiments can provide a more structured study approach in most cases, they do not accurately represent the effort and spatial scale for commercial fishery. Therefore, it is recommended that more experimental bottom trawl studies should be conducted in the Benguela system at greater spatial scale, so that vital information on the effect of bottom-trawling can be teased apart from effects of natural variability.

6.3.6 Conclusion

This study marks the first of its kind in the Benguela region, and has shown, despite the absence of pristine untrawled areas in the Benguela system, that this type of comparative work can be conducted effectively in lightly and heavily trawled areas. Direct effects of bottom-trawling on demersal fish assemblages were found. However, other factors such as spatial differences and depth, have been shown to play a role in the observed changes in fish assemblages. ABC curves were close to each other with the *W – statistic* close to zero for both heavy and light trawl levels, suggesting all the demersal fish assemblages at these sites were moderately disturbed. Mean catch of fish was high at the heavily trawled sites compared to the lightly trawled sites, presumably reflecting the fishery operating at sites more densely populated by fish. As expected, both species evenness and diversity were high at lightly trawled sites and low at heavily trawled sites at SB and ChB. Both multivariate and univariate analyses showed significant differences in the demersal fish assemblages among the sites and between the trawl treatments.

The community structure, diversity indices, spatial and density distribution of demersal fish species from bottom-trawls off Namibia and the west coast of South Africa during the 2007 hake biomass surveys

7.1 Introduction

The hake-directed bottom-trawl fishery in both Namibia and South Africa targets the shallow water Cape hake *Merluccius capensis* and the deep-water hake *M. paradoxus*. A summary account of the Namibian hake fishery can be found in Chapter 1. The South African hake fishery commenced in the early 1900s, after successful research catches attracted the first commercial trawler to the Cape in 1899, pioneering the South African fishing industry (Lees, 1969). The demersal fishery targeted Agulhas sole *Austroglossus pectoralis* and west coast sole *A. microlepis* (Payne and Badenhorst, 1989). However, this situation changed with the discovery of the hake resource off the west coast, which then became the targeted catch for the demersal trawl fishery (Payne and Punt, 1995), which became the most important fishery in the region. Commercially important bycatch in the bottom-trawl hake fisheries in both the Namibian and South African fisheries includes angelfish *Brama brama*, Cape dory *Zeus capensis*, gurnards *Chelidonichtys capensis* and *C. quekettr*, horse mackerel *Trachurus capensis*, jacopever *Helicolenus dactylopterus*, kingklip *Genypterus capensis* and monkfish *Lophius vomerinus* (MFMR, 2006; Walmsley *et al*., 2007).

The two species overlap in their distribution, with *M. capensis* occurring mainly on the shelf to approximately 400 m. This species is more abundant off the coast of Namibia and the south coast of South Africa. *M. paradoxus* overlaps with *M. capensis* between 150 and 400 m (Botha, 1980, 1985; Payne, 1996; Boyer and Hampton, 2001) although its range extends to 900 m (Payne and Punt, 1995). *M. paradoxus* occurs mainly south of 22^{o}S making it more abundant along the west coast of South Africa than further north (Payne andand Punt, 1995). The hake trawl fishery is the most economically valuable fishery in both Namibia and South Africa, and is managed separately in the two countries. However, Burmeister (2005) concludes that *M. paradoxus* in Namibian and South African waters is probably a single stock shared between two countries. Both fisheries in Namibia and South Africa were subjected to heavy exploitation in the mid- 1970s (Payne and Punt, 1995). Following restructuring of demersal fisheries after independence inNamibia (1990) and democracy in South Africa (1994), both fisheries are managed independently by means of TACs.

The declaration of the Exclusive Economic Zone (EEZ) in 1978 and exclusion of foreign distant fleets enabled South Africa to regain control of its resources and start to rebuild the stock (Enviro-Fish Africa, 2006). Before then, the fishery was largely unregulated and participants were not limited (Enviro-Fish Africa, 2006). The annual TAC was only introduced in South Africa in 1978 and a year later the quota allocation for participants in the fishery (Enviro-Fish Africa, 2006). This has contributed to the low effort, and eventually to reducing the fishing intensity off South Africa.

The development of the hake-directed fishery in Namibia was described in detail in Chapter 1. Studies off Namibia and South Africa's west coast have separated the two data sets according to the borders of the countries, due to different sampling methods and gear types. This is the first study which uses the pooled data for both Namibia and South Africa. The data were collected using the same gear and following the same sampling procedures.

The aims of this chapter were (a) to investigate whether there are any structural changes in demersal fish assemblages by way of latitudinal variation in the diversity and density distribution of demersal fish species from the Kunene River (Namibia) to Agulhas Bank (South Africa) during the 2007 demersal surveys, and (b) to relate the observed patterns of diversity to factors such as depth, abundance, latitude, longitude, and environmental variables.

7.2 Materials and Methods

The study was conducted in the Benguela Ecosystem from the Namibian northern border at the Kunene River to the Agulhas Bank covering the west coast of South Africa (Fig. 7.1). The survey was conducted in Namibia by the MFMR scientists onboard a commercial vessel (*Blue Sea 1*), which was calibrated with the *R/V Dr Fridtjof Nansen* and on the South African side the *R/V Dr Fridtjof Nansen* was used. These surveys were conducted during January and early February by *Blue Sea 1*, and early April by *R/V Dr Fridtjof Nansen* in 2007; and followed a systematic transect design in both countries, (for full details of the sampling procedures and gears see Chapter 3 and Strømme (1999). A total of 289 tows were completed during the two surveys (Fig. 7.1).

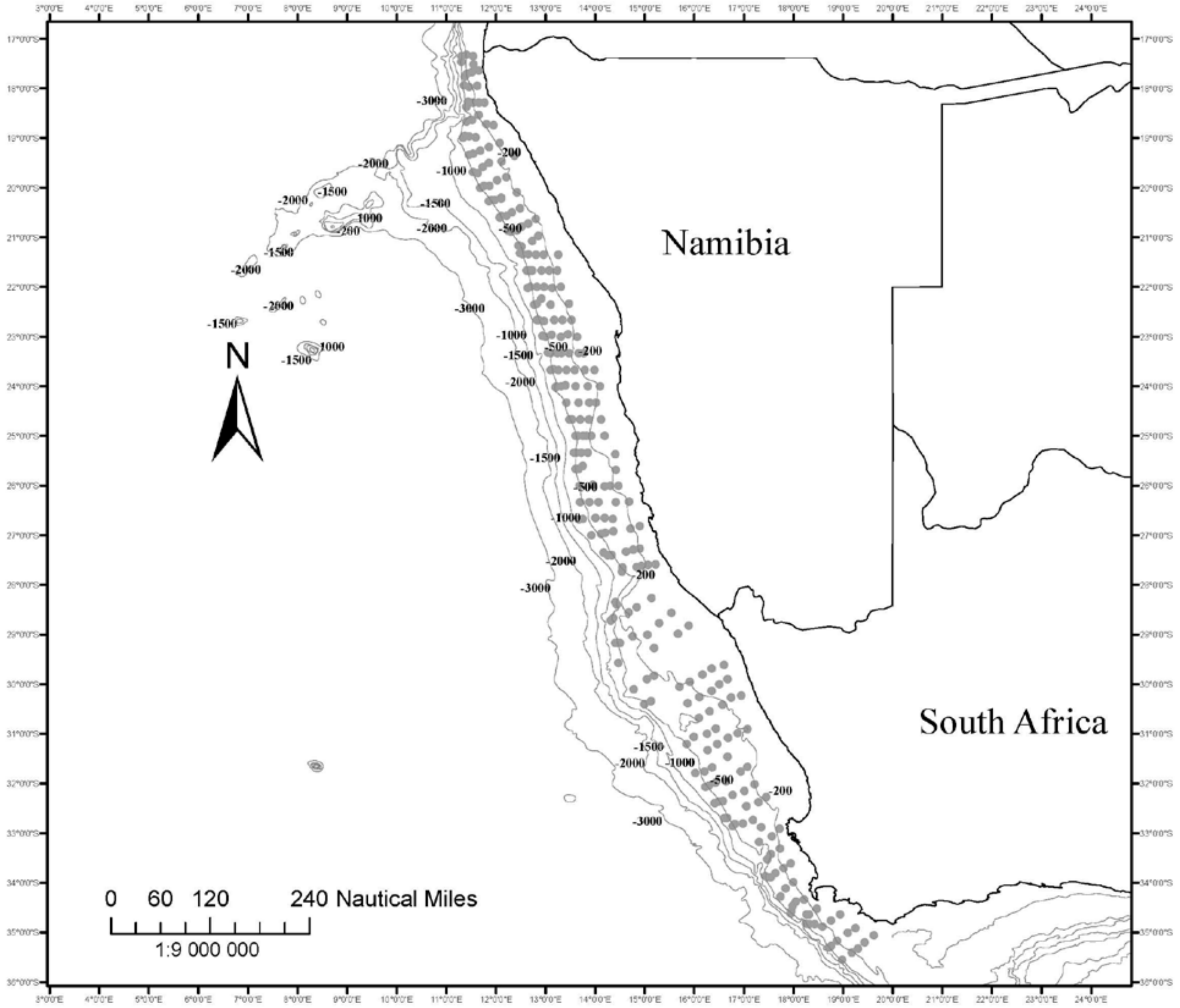


Figure 7.1 Sampling stations covered during the hake biomass surveys in January/February 2007 off Namibia and early April 2007 along the west coast of South Africa.

The fish density distribution map was developed using the *ArcGIS v9.2* (GIS software, www.esri.com). The abundance and biomass data from all the stations were first normalised by dividing them by the number of stations covered in each survey. All fish species caught in the trawls were included in the analysis, although the emphasis is on demersal fish species.

7.2.1 Multivariate analysis

A cluster analysis (group average) employing the Bray-Curtis similarity index (Field *et al*., 1982) was performed on the standardised abundance values of species using the multivariate techniques in PRIMER *v6*: MDS and cluster analysis (Clarke and Warwick, 1994). The data were transformed by applying a fourth-root transformation prior to the cluster analysis to avoid overemphasis of the most abundant species (Field *et al*., 1982, Clarke and Warwick, 1994, 2001). MDS ordination analysis was performed on the same data as the cluster analysis. For details on the cluster analysis and MDS see Chapter 5, the difference is only the data set.

The ABC curves were constructed from the pooled abundance and biomass data averaged for both the shelf and slope. The *W- statistic* (Clarke and Warwick, 2001) was calculated for each of the treatment sites (shelf and slope) (more details in Chapter 5). Species abundance and biomass data for all trawls (Fig. 7.1) were transformed by the fourth root, and then averaged across the two separate depth ranges: shelf (100 – 300 m) and slope (301 – 600 m), before being used to construct ABC curves using the PRIMER v6 software (Warwick and Clarke, 1994; Clarke and Warwick, 2001, Clarke and Gorley, 2006). The same data were pooled and weighted by the number of stations (in northern and southern Benguela separately, then combined), in order to construct ABC curves for the Benguela region.

Similarity percentage (SIMPER) was used to indicate the average contribution of each species density to the similarity (typifying species) and dissimilarity (discriminating species) between groups of samples (Clarke and Warwick, 1994, 2001). The SIMPER analysis was done on abundance data after a fourth-root transformation. The cluster group factors were chosen as A for the Namibian continental shelf, B for the Namibian continental slope, and C for South Africa (both continental slope and shelf), as these groupings were identified by the cluster analysis and MDS. A Bray-Curtis similarity was chosen with a 90% cut for low contribution, to avoid some insignicant contributions. However, only the top ten species contributing most to the similarity and dissimilarity are shown in this study.

7.2.2 Univariate analysis

7.2.2.1 Diversity Indices

Ecological parameters such as species diversity were examined as species richness (*S* = number of species) and composite diversity, which integrates both richness and evenness (Shannon-Wiener *H’*) and Pielou’s evenness index *J’* (Pielou, 1966). They were calculated using species abundance data using equations 5.2 and 5.3 in Chapter 5.

All these ecological parameters were calculated using the DIVERSE function in Primer v6. Thus, species diversity was examined for each station group as defined by the cluster analysis (Warwick and Clarke, 1994). Physical variables such as depth, longitude, latitude, and abundance (log N) were analysed using Generalised Additive Models (GAM), (Hastie and Tibshirani, 1990). All analyses were done in *R,* using *mgcb package* (R Core Development Team, 2010) to examine their effects on demersal fish species diversity. GAMs were used to examine the relationship between measures of species diversity (*S, J’* and *H’*) and physical variables. The spatial distribution of demersal fish species was also examined. For more description on GAM see Chapter 2 methods section and the following sources (Hastie and Tibshirani, 1990, Swartzman *et al*., 1992; Maravelias and Reid, 1997).

The Poisson distribution was used for the species richness because the data are counts, while the Gaussian distribution was used for the evenness and Shannon-Wiener index, since there was no violation of its assumptions (Zar, 1999). An additional measure of model fit was based on a pseudo-coefficient of determination (R^2), which was the fraction of the total variation accounted for by the model (see Equation 2.6 in Chapter 2), where a similar calculation was performed earlier. All the factors were tested for correlation, using the correlation matrices as in Chapter 2 and 5. If two factors were highly correlated then one of the dependent factors was removed from the model.

7.3 Ancillary information

Environmental variables during the survey

Since two vessels were used for the survey off Namibia and the west coast of South Africa, the sampling details are separated by vessel.

The *F/V Blue Sea 1* was used to conduct the hake biomass survey in 2007 off Namibia, and the *Seabird SBE19Plus* CTD instrument and the battery operated *Hydro-bios Slimline rosette* were used to measure hydrographic information such as dissolved oxygen and to collect four water samples for calibration purposes, salinity and temperature. Predetermined water depths were used to collect water samples as follows: near surface, two intermediate depths, and at the bottom, in order to calibrate dissolved oxygen using the Winkler titration with the aid of the *Metrohm Dorsimat* instrument aboard the vessel. Bottom salinities were used as provided by Kainge *et al*. (2007a). The CTD was not available for the first leg of the survey, which covered from the Orange River to Walvis Bay, thus only 57 stations were covered and limited to dissolved oxygen only. The second leg from Walvis Bay to Kunene River had a total of 42 oceanographic stations, and during this leg the CTD was functional (Kainge *et al*., 2007). Horizontal and vertical profiles of temperature, salinity, and dissolved oxygen were drawn using *Surfer 8* software. Weekly averaged wind conditions (speed and direction) were obtained from *QuickScat* Scatterometer estimates. The Marine Remote Sensing Unit (MRSU), Oceanography department at the University of Cape Town (Mathieu Rouault, pers. comm.), supplied weekly averaged SST satellite images. Furthermore, CTD and dissolved oxygen profile and distribution of the two species of Cape hakes were mapped using *Surfer 8* software (www.goldensoftware.com).

Onboard *R/V Dr Fridtjof Nansen*, the underway weather data were logged with the Aanderaa Weather Station unit fitted with sensors to measure air temperature (^{o}C), wind speed (m/s), solar radiation (W/m^{2}), wind direction (degrees with real Magnetic N. Pole), and Sea Surface

Temperature (°C). The mast of the ship hosts the sensors at about 20 m above sea-level, except for the SST sensor which is located at the intake of seawater for cooling the ship's engine, and its readings are representative of a water layer about 5 meters below the sea-level. The weather station data were logged continuously throughout the survey, and the data presented here as standard outputs from the logging system comprising one nautical mile averages along the ship's track.

Hydrographical information such as dissolved oxygen, salinity, and temperature was collected on each trawl station using the CTD *Seabird19Plus* probe between the surface and 10 meters off the bottom. Additionally, water bottle samples were collected at each sampling station for oxygen and salinity calibrations. The standard Winkler method was used to titrate for dissolved oxygen within 12 hours after taking the water samples, while the salinity samples were analysed using the Guildline Portasal salinometer unit.

7.4 Results

7.4.1 Multivariate analysis:

7.4.1.1 Cluster and MDS

The group average dendrogram and MDS plots for the demersal fish assemblages of the Benguela System (off Namibia and the west coast of South Africa) are shown in Figs. 7.2 and 7.3. At about 19% of similarity, the dendogram shows three main groups, two in northern Benguela (separated into shelf and slope assemblages) and one in the southern Benguela (Fig. 7.2). These identified cluster groups (assemblages) are also shown on the map and they are spatially distinct (Fig. 7.4). However, there is an overlap in assemblages whereby the southern Benguela assemblage extends slightly into Namibian waters. In northern Benguela, the southern Namibian shelf assemblage is different from the rest of Namibia, but similar to the South African demersal fish assemblage in southern Benguela (Figs. 7.3 and 7.4). Further cluster analysis of group C at 25% similarity separates the group into shelf and slope, thus making the demersal fish assemblages of southern Benguela different. Finally, ordination techniques on pre-selected groups by depth (shelf and slope) showed that the demersal fish assemblages of the continental shelf and slope in northern and southern Benguela are different from each other (Fig. 7.2). At 25% similarity the northern Benguela continental shelf separates into northern and southern shelf.

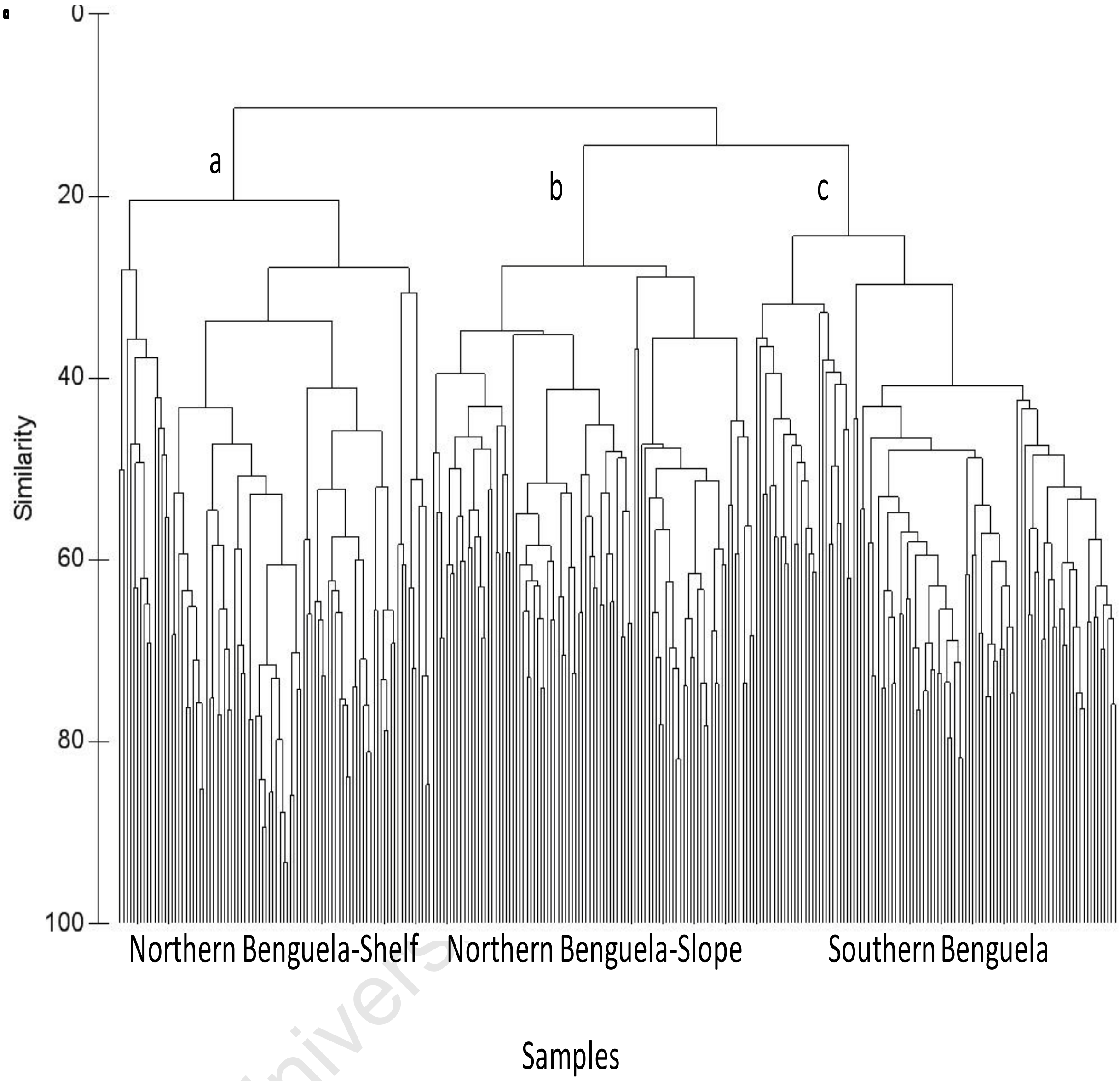


Figure 7.2 Cluster dendrogram of demersal fish species per station, based on Bray-Curtis resemblance (at 19% similarity), after fourth root transformation and group-average sorting, in the Benguela System (off Namibia and the west coast of South Africa) in 2007. Station groupings are shown as a, b, and c, corresponding approximately to northern Benguela continental shelf and slope, and southern Benguela (pooled depth) respectively.

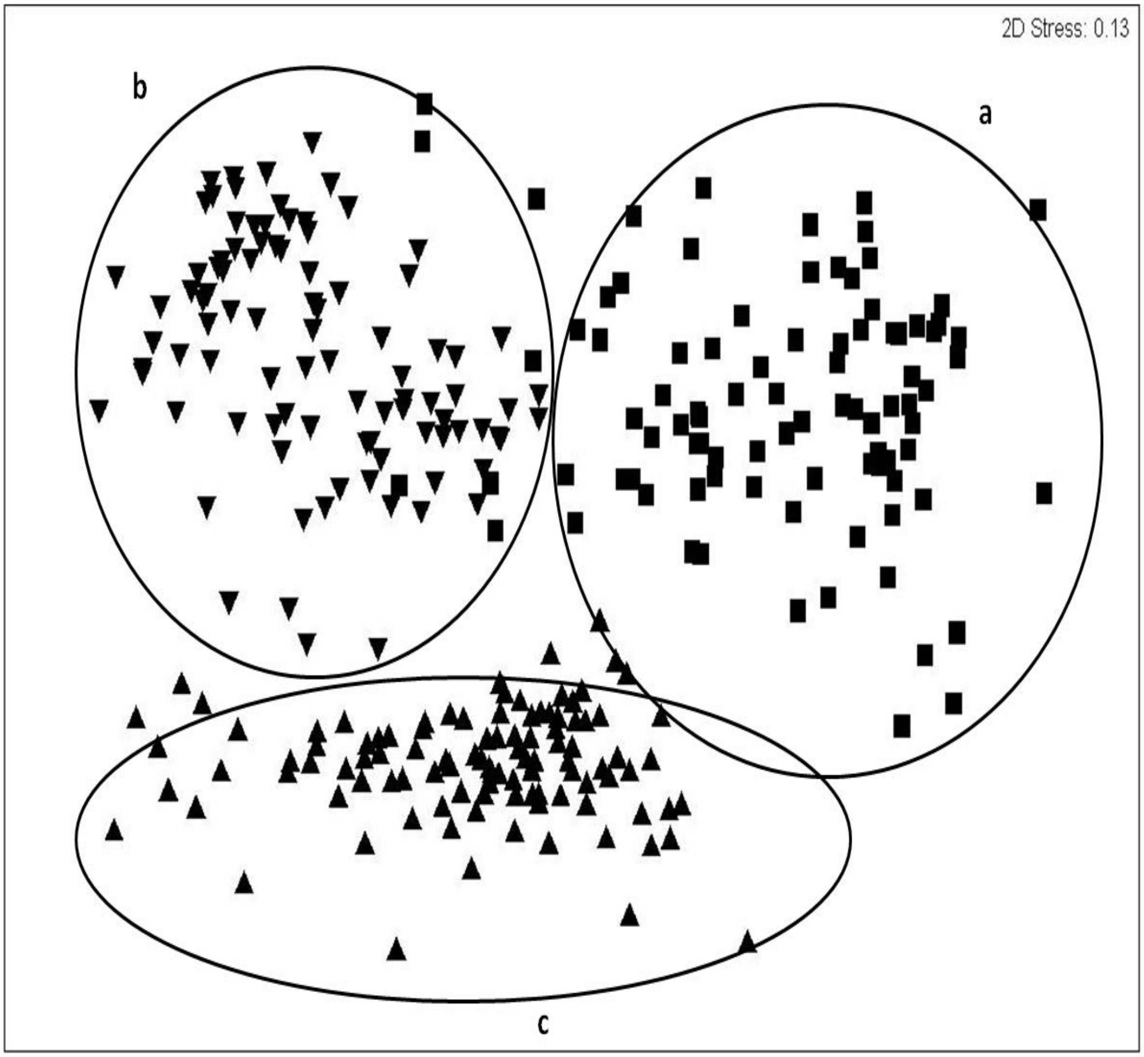


Figure 7.3 The MDS plot of group averages for the demersal fish communities per station, based on Bray-Curtis resemblance after fourth root transformation, off Namibia and the west coast of South Africa, as identified by the cluster analysis. Groups are indicated at 19% similarity, shown here as (a) squares for northern Benguela slope, (b) inverted triangles for northern Benguela shelf and (c) triangles for southern Benguela.

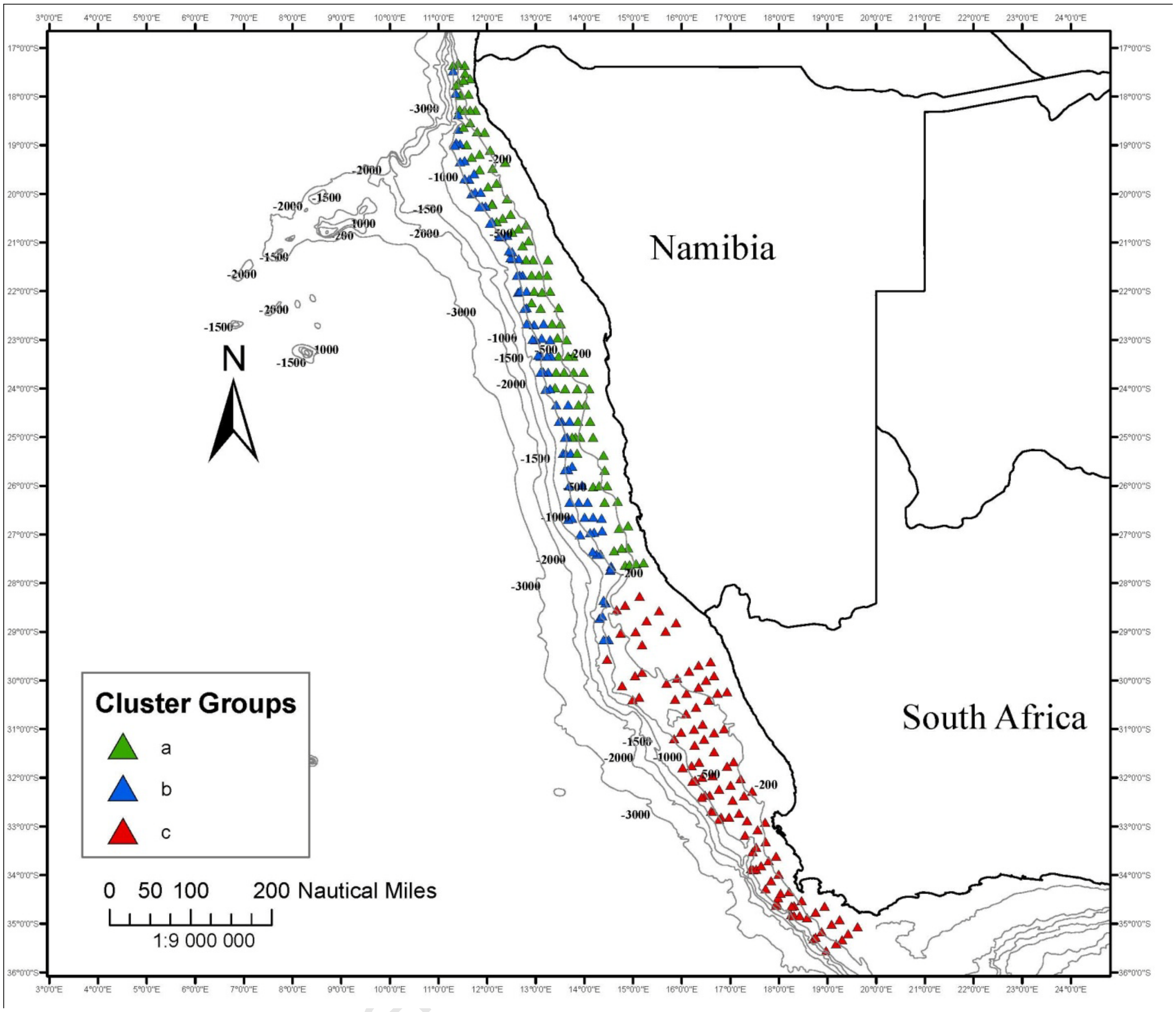


Figure 7.4 Cluster groups for the demersal fish communities of the Benguela System (off Namibia and west coast of South Africa), as identified by the cluster analysis at 19% similarity, (a) northern Benguela shelf; (b) northern Benguela slope; (c) southern Benguela, based on 2007 hake biomass surveys.

7.4.1.2 SIMPER Analysis

The SIMPER analysis results are shown in Tables 7.1 and 7.2. The average density similarities on the continental shelf in northern Benguela (group a) were driven by the following top three species: shallow water hake *M. capensis,* pelagic goby *Sufflogobius bibarbatus* and horse mackerel *Trachurus trachurus capensis*; on the continental slope (group b) they were driven by deep water hake *M. paradoxus,* smalltooth grenadier *Nezumia micronychodon* and blackbelly rosefish (Jacopever) *Helicolenus dactylopterus*; while the similarities in southern Benguela assemblages (group c) were driven by *M. paradoxus, Helicolenus dactylopterus* and monk fish *Lophius vomerinus,* in order of % contribution (Table 7.1). The top three species distinguishing the cluster groups on the continental shelf and slope in northern Benguela were *M. paradoxus, M. capensis*, and *N. micronychodon*; the northern Benguela shelf and southern Benguela assemblages were distinguished by *M. paradoxus, M. capensis*, and *H. dactylopterus*; and the northern Benguela continental slope and southern Benguela assemblages by *N. micronychodon, M. paradoxus*, and *M. capensis* (Table 7.2).

Table 7.1 Average similarity within the cluster groups, (a) Namibian continental shelf assemblage, (b) Namibian continental slope assemblage, and (c) South African assemblage, broken into species contributions to the average Bray-Curtis similarity after 4th root transformation of abundance data. The similarity: standard deviation ratio, % contribution of each species to the group similarity, and cumulative % contribution are given. The abbreviations in the table are: Sim/SD = similarity/standard deviation; Contrib% = contribution percentage, and Cum.% = cumulative percentage. This table shows the species that hold each cluster together listed in order of their contributions to the similarity index.

Group a Average similarity: 33.74				Group b Average similarity: 37.72			
Species	Sim/SD	Contrib%	Cum.%	Species	Sim/SD	Contrib%	Cum.%
Merluccius capensis	1.63	45.38	45.38	*Merluccius paradoxus*	3.08	22.45	22.45
Sufflogobius bibarbatus	0.8	23.02	68.41	*Nezumia micronychodon*	2.3	16.47	38.92
Trachurus capensis	0.29	4.43	72.83	*Helicolenus dactylopterus*	0.94	7.91	46.83
Astroglossus microlepis	0.44	3.03	83.77	*Hoplostethus cadenati*	0.85	6.44	53.27
Pterothrissus belloci	0.3	2.99	86.76	*Selachophidium guentheri*	0.83	5.5	58.77
Lophius vomerinus	0.34	2.18	88.95	*Todarodes sagittatus*	0.72	5.19	63.96
Caelorinchus simorhynchus	0.32	2.01	90.96	*Lophius vomerinus*	0.64	4.57	68.53
				Caelorinchus simorhynchus	0.52	4.5	73.03
				Trachyrincus scabrus	0.4	3.08	76.11
				Galeus polli	0.51	2.35	78.46

Group c Average similarity: 37.76			
Species	Sim/SD	Contrib%	Cum.%
Merluccius paradoxus	1.54	20.55	20.55
Helicolenus dactylopterus	2.15	11.68	32.23
Lophius vomerinus	1.24	7.89	40.12
Merluccius capensis	0.83	7.67	47.79
Caelorinchus simorhynchus	0.86	6.4	54.19
Paracallionymus costatus	1.52	5.82	60.01
Todarapsis eblanae	1.02	4.82	64.84
Genypterus capensis	0.84	3.89	68.73
Centroscymnus crepidater	0.71	3.01	71.74
Zeus capensis	0.58	2.77	74.51

Table 7.2 Table showing the species that best separate two clusters in order of their contribution. Average dissimilarity between cluster groups, (a) Namibian continental shelf assemblage, (b) Namibian continental slope assemblage, and (c) South African assemblage, divided into species contributions to the average dissimilarity between pairs of groups. Abbreviations: Av.Abund. = average abundance, Av.Diss. = average dissimilarity, Diss/SD = dissimilarity/standard deviation, Contrib% = contribution percentage, and Cum% = cumulative percentage. Bold numbers in the table indicate the cluster with the greater abundance of each species.

Groups a & b
Average dissimilarity = 89.47

Species	Group a Av.Abund	Group b Av.Abund	Av.Diss	Diss/SD	Contrib%	Cum.%
Merluccius paradoxus	0.21	**1.99**	6.43	2.29	7.18	7.18
Merluccius capensis	**2.22**	0.35	6.41	1.68	7.17	14.35
Nezumia micronychodon	0.09	1.56	4.99	2.19	5.58	19.93
Sufflogobius bibarbatus	1.1	0	3.87	1.19	4.33	24.26
Helicolenus dactylopterus	0.37	1	3.4	1.23	3.8	28.06
Hoplostethus cadenati	0.06	0.95	3.04	1.17	3.4	31.46
Caelorinchus simorhynchus	0.43	0.82	2.98	0.94	3.33	34.79
Selachophidium guentheri	0	0.87	2.72	1.17	3.04	37.83
Lophius vomerinus	0.43	0.75	2.55	1.09	2.85	40.68
Todarodes sagittatus	0.33	0.79	2.48	1.12	2.77	43.45

Groups a & c
Average dissimilarity = 86.42

Species	Group a Av.Abund	Group c Av.Abund	Av.Diss	Diss/SD	Contrib%	Cum.%
Merluccius paradoxus	0.21	**2.79**	7.72	1.63	8.93	8.93
Merluccius capensis	**2.22**	1.43	4.22	1.26	4.88	13.81
Helicolenus dactylopterus	0.37	1.52	3.87	1.74	4.48	18.29
Sufflogobius bibarbatus	1.1	0	3.29	1.18	3.81	22.1
Caelorinchus simorhynchus	0.43	1.14	2.98	1.18	3.44	25.54
Lophius vomerinus	0.43	1.17	2.83	1.4	3.28	28.82
Trachurus capensis	0.75	0.54	2.73	0.77	3.16	31.98
Paracallionymus costatus	0	0.87	2.39	1.65	2.76	34.75
Todarapsis eblanae	0.13	0.77	2.04	1.29	2.36	37.11
Genypterus capensis	0.17	0.73	2.02	1.13	2.34	39.45

Groups b & c
Average dissimilarity = 81.13

Species	Group b Av.Abund	Group c Av.Abund	Av.Diss	Diss/SD	Contrib%	Cum.%
Nezumia micronychodon	**1.56**	0	3.45	2.61	4.26	4.26
Merluccius paradoxus	1.99	**2.79**	3.19	1.35	3.93	8.18
Merluccius capensis	0.35	1.43	2.92	1.24	3.6	11.79
Caelorinchus simorhynchus	0.82	1.14	2.32	1.26	2.86	14.65
Hoplostethus cadenati	0.95	0	2.07	1.2	2.55	17.19
Helicolenus dactylopterus	1	1.52	1.96	1.36	2.42	19.61
Lophius vomerinus	0.75	1.17	1.91	1.33	2.35	21.96
Paracallionymus costatus	0.01	0.87	1.86	1.69	2.29	24.25
Selachophidium guentheri	0.87	0.07	1.81	1.18	2.23	26.49
Todarodes sagittatus	0.79	0.03	1.71	1.13	2.11	28.6

7.4.2 Univariate analysis

7.4.2.1 ABC curves and W- statistic

The ABC curves for the three demersal fish assemblages of the Benguela System, identified by the cluster analysis at 19% similarity are shown in Figure 7.5. The demersal fish assemblage on the continental shelf (a) in northern Benguela was moderately disturbed, while both the continental slope assemblages (b) in the northern and southern Benguela (c) were lightly to moderately disturbed, deduced from the fact that the abundance and biomass curves are close to each other with positive *W– statistic* value close to zero (Fig. 7.5) (see Chapter 5, Figure 5.1; Warwick and Clarke, 1994). The pooled abundance and biomass data for both north and southern Benguela were used to construct ABC curves by depth stratum, for both the continental shelf (100 – 300 m depth) and slope (300 – 600 m depth) (Figure 7.6). These depth strata are consistent with an ecotone (Hamukuaya *et al*., 2001) off Namibia and are used here for comparisons. The ABC curves for the continental shelf (Fig. 7.6) showed that initially the biomass curve lies above the abundance curve and crosses mid-way and has a positive *W– statistic*. In the ABC curves for the continental slope (Fig. 7.6), the biomass curve lies above the abundance curve, with a slightly positive *W– statistic* suggesting a lightly or moderately disturbed state (see Figure 5.1, Chapter 5).

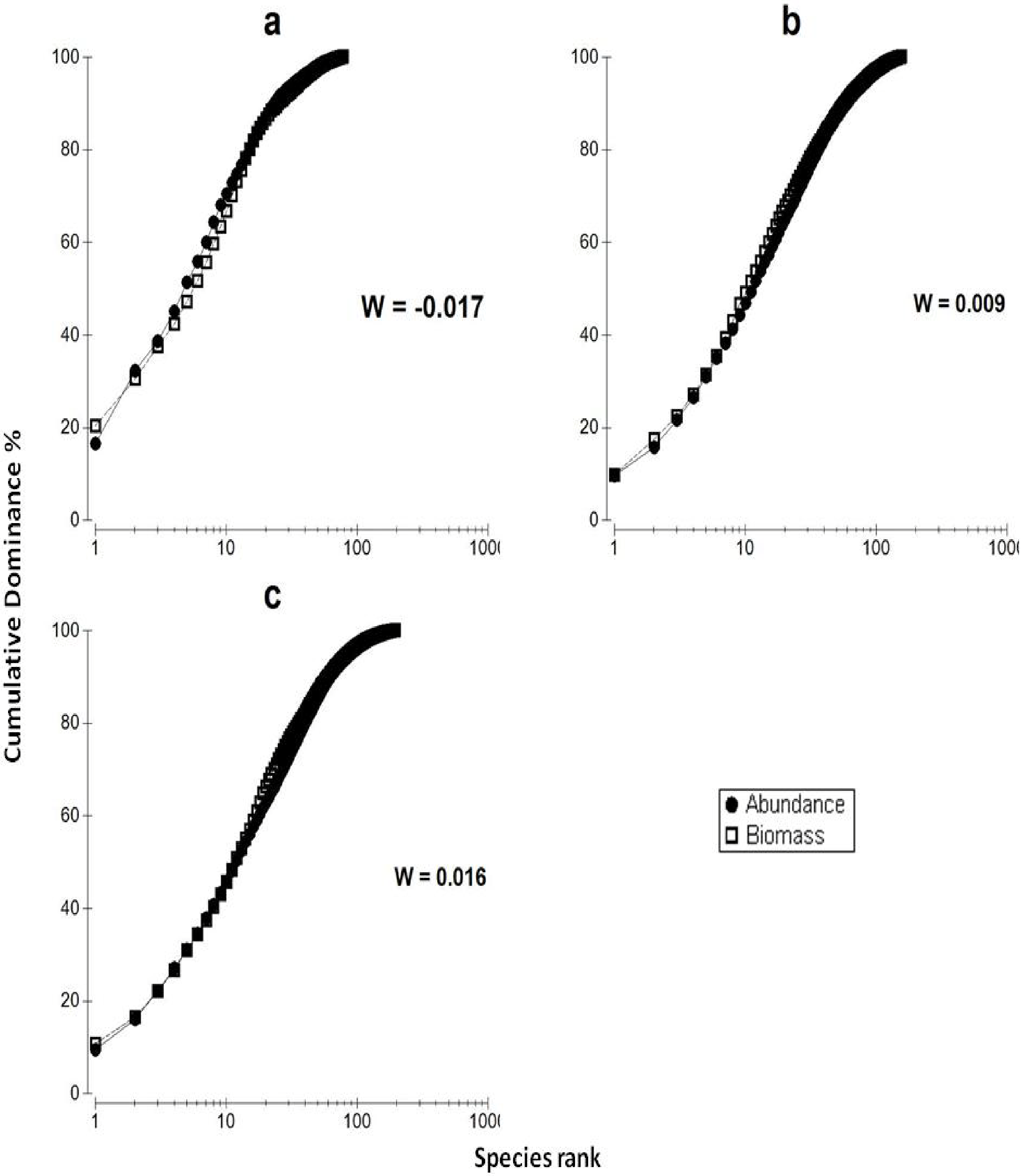


Figure 7.5 ABC curves for demersal fish assemblages of northern Benguela (a) continental shelf, (b) continental slope, and (c) southern Benguela (pooled depth) based on the hake biomass survey 2007.

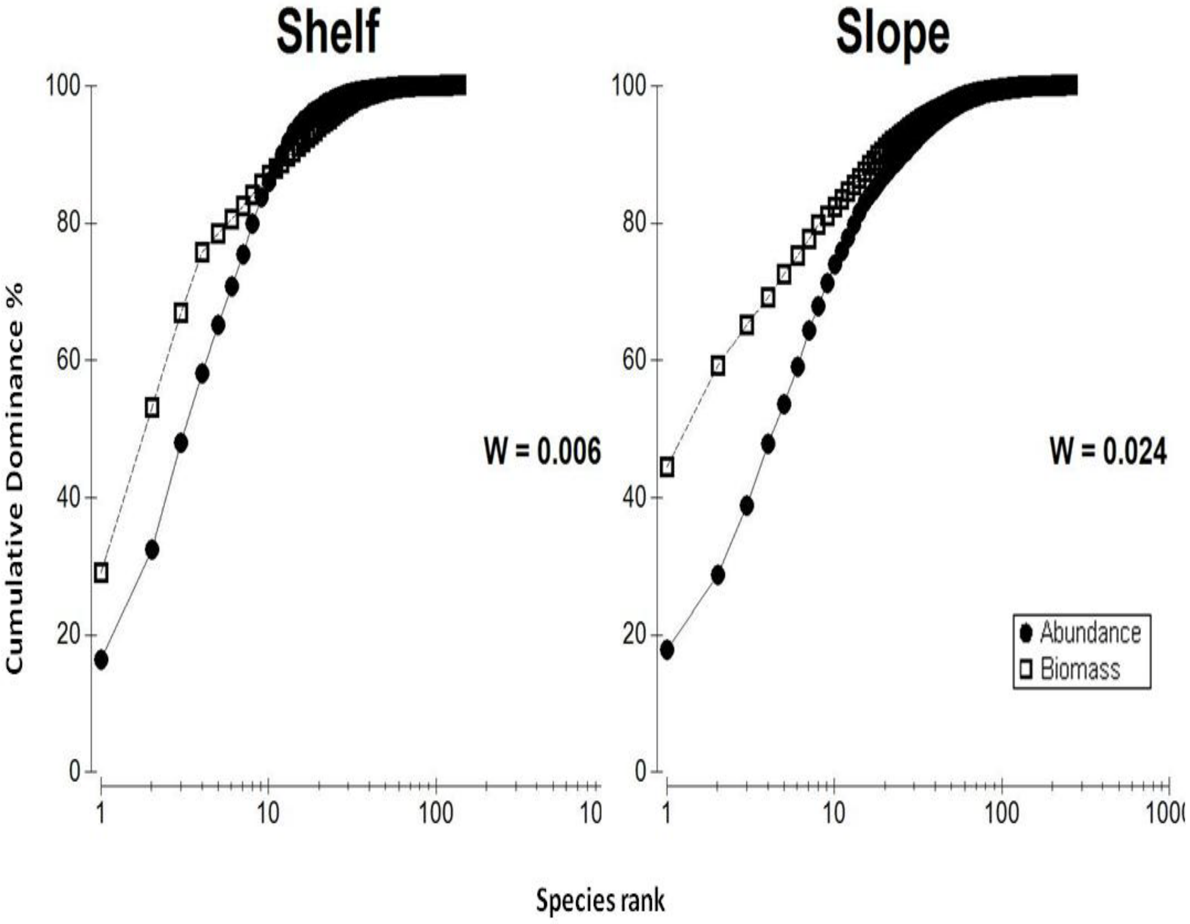


Figure 7.6 Large spatial scale: ABC curves for the Benguela System (off Namibia and South Africa) using pooled data for the continental shelf (100 – 300 m deep) and continental slope (300 – 600 m deep) based on species abundance and biomass data from the 2007 hake biomass surveys.

7.4.2.2 *Diversity indices*

The effects of depth and geographical position (latitude, longitude) on species richness (*S*) are shown in Fig. 7.7. The model (Appendix 7.1) explained about 78.4% of the deviance. The correlation between depth and longitude is -0.147, which is a weak negative correlation, thus both depth and longitude were included in the model. Species richness increased slightly with depth, and spatially there was a stronger increase in species richness with depth in northern Benguela and a weaker increase in southern Benguela, suggesting a decreasing pattern in species richness with increasing depth further south of the Orange River (Fig.7.7a). Demersal fish species richness decreased between 11^{o}E and 14^{o}E and then steadily increased from 14^{o}E to 19^{o}E (Fig.7.7b). There was a slight increase in species richness between 30^{o}S and 34^{o}S, and thereafter a decline in species richness (Fig.7.7c). The species richness also increased with species abundance at low abundances, stabilised at medium abundance and increased slightly at the highest abundance (Fig. 7.7d).

Pielou's evenness index (*J'*) initially increased with depth between 100 and 200 m depth then stabilised between 200 and 500 m depth, and decreased in waters deeper than 500 m (Fig. 7.8a). Spatially, the evenness index (*J'*) increased from the continental shelf to the slope in northern Benguela, and the opposite pattern was observed further south in southern Benguela (Fig. 7.8b). There was an increasing trend in the evenness between 35^{o}S and 31^{o}S, a declining trend between 32^{o}S and 20^{o}S, and a slight increase from 20^{o}S to 17^{o}S (Fig.7.8c). However, it decreased with an increase in species abundance (Fig. 7.8d). The model could only explain 47.5% of deviance (Appendix 7.1).

The Shannon-Wiener index (*H'*) was slightly affected by depth with a slight increase in deeper waters. However, strong spatial patterns were observed, suggesting that there was an increase in diversity with decreasing longitude (from the continental shelf to the slope) (Fig. 7.9). Effects were more pronounced in northern Benguela than the southern Benguela. There was an increase in species diversity at low species abundances, but diversity declined at high species abundances (Fig. 7.9). The whole model explained 62.1% of the deviance (Appendix 7.1). The plot in Figure 7.10 shows GAM diversity diagnostics for the species richness (*S*), Pielou's evenness index (*J′*) and Shannon-Wiener index (*H′*). The model was a good fit to the data (for more results on GAM see Appendix 7.1).

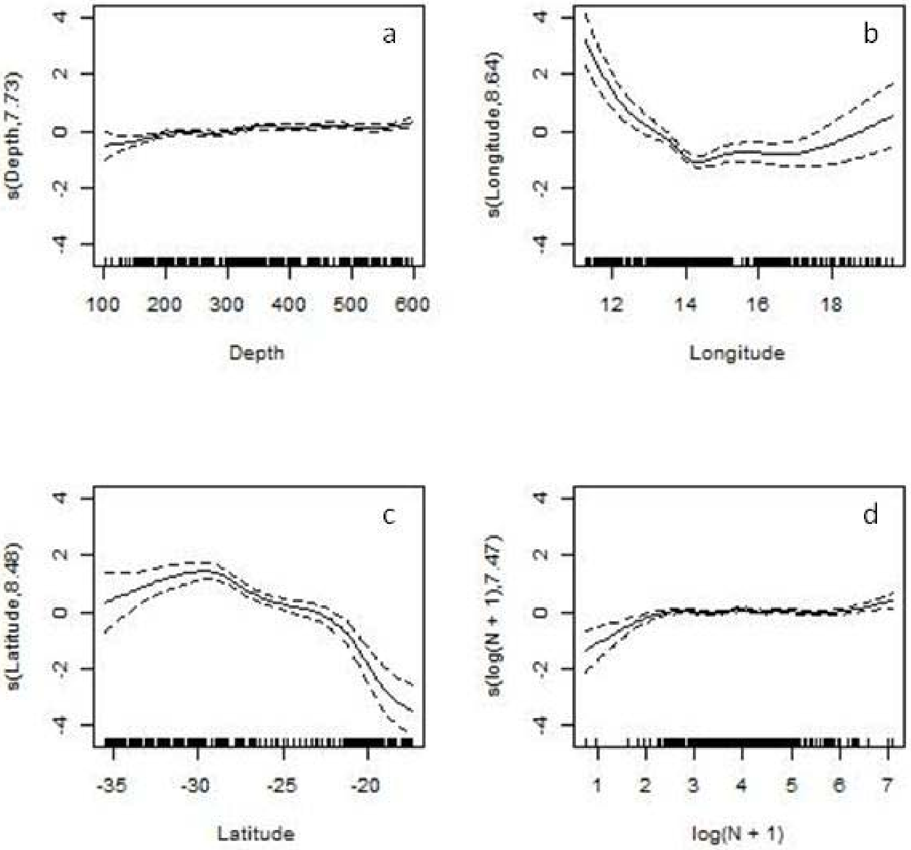


Figure 7.7 Species richness *S*: Generalized Additive Model (GAM) smooths of the partial effect of (a) bottom depth, (b) longitude, (c) latitude, and (d) logarithm of abundance (N) on the diversity of demersal fish assemblages of the Benguela System, off Namibia and the west coast of South Africa in 2007.

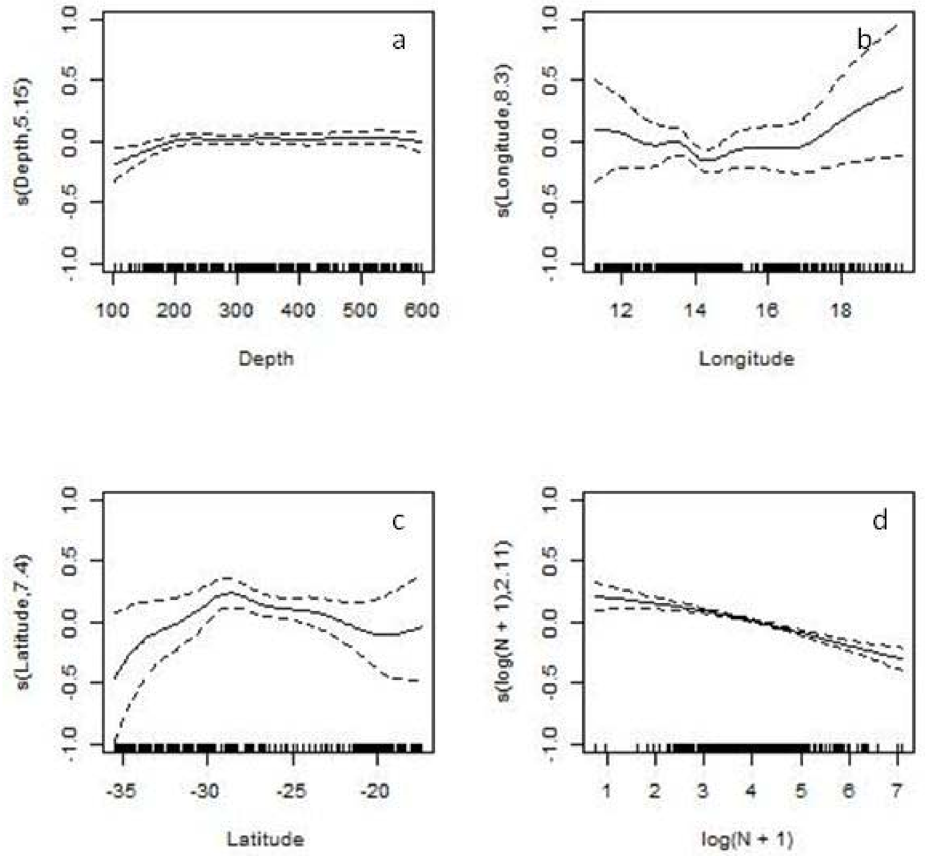


Figure 7.8 Pielou's evenness index *J'*: Generalized Additive Model (GAM) smooths of the partial effect of (a) bottom depth, (b) longitude (c) latitude, and (d) logarithm of abundance (N) on the diversity of demersal fish assemblages of the Benguela System, off Namibia and the west coast of South Africa in 2007.

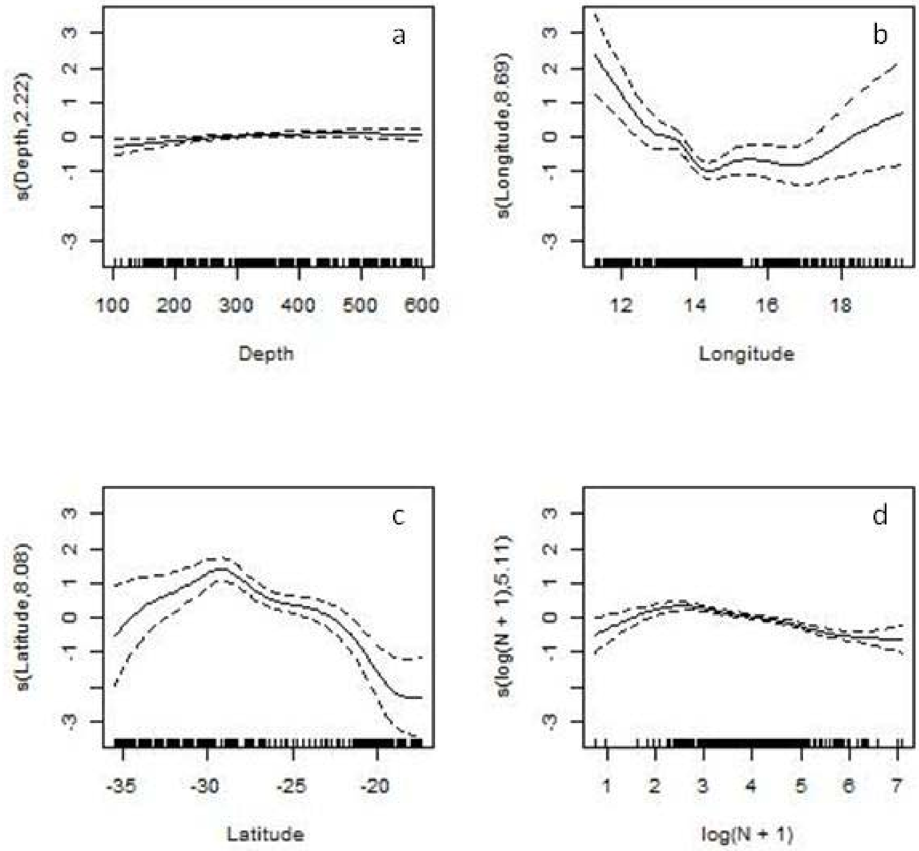


Figure 7.9 Shannon-Wiener index *H'*: Generalized Additive Model (GAM) smooths of the partial effect of (a) bottom depth (m), (b) longitude, (c) latitude, and (d) logarithm of abundance (N) on the diversity of demersal fish assemblages of the Benguela System, off Namibia and the west coast of South Africa in 2007.

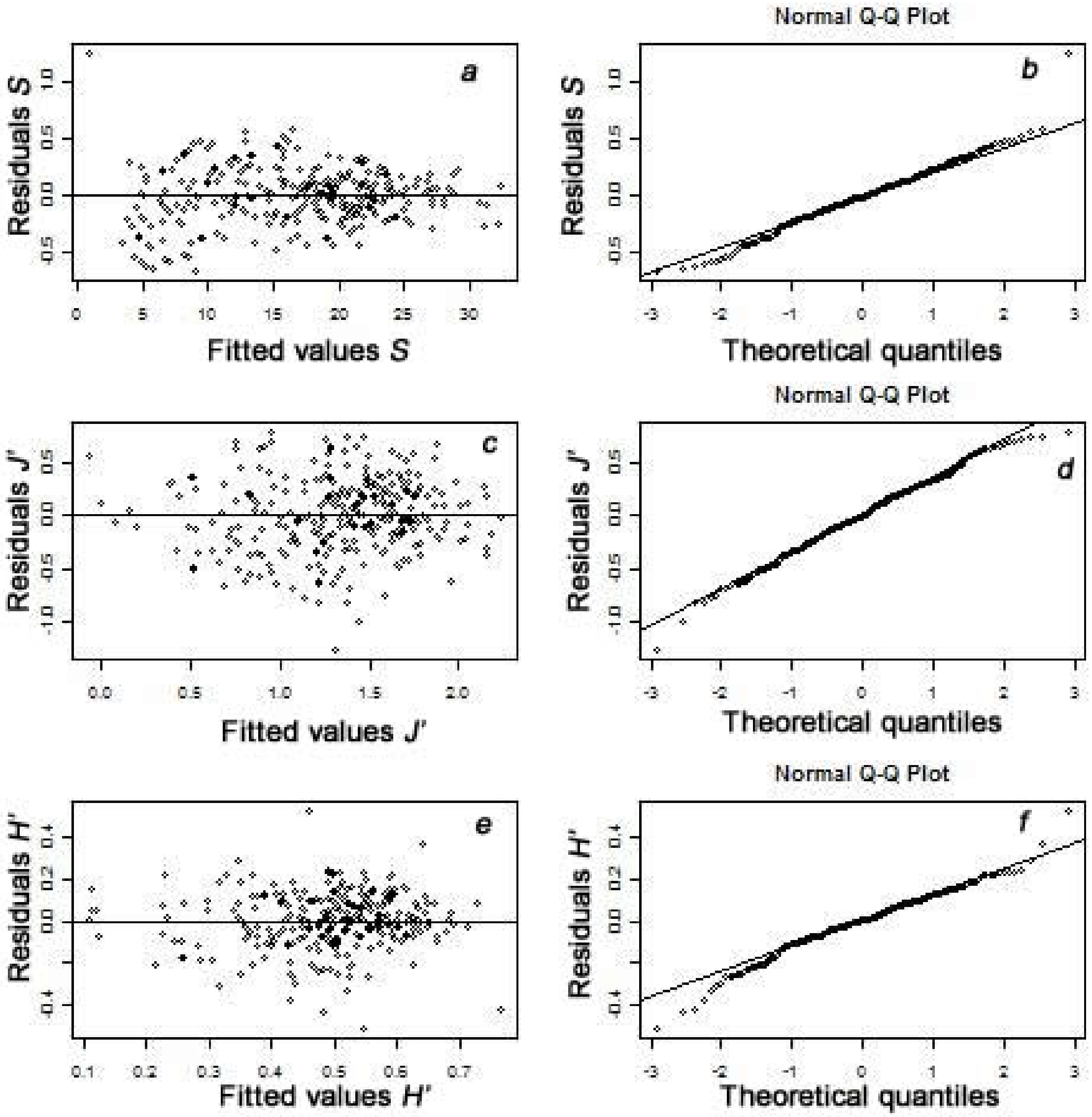


Figure 7.10 Plots of the deviance residuals against predicted values and Quantile-Quantile plots from GAMs diagnostics for (a – b) species richness (*S*), (c – d) Pielou's evenness index (J'), and (e – f) Shannon-Wiener index (*H'*).

7.4.3 Spatial distribution patterns

7.4.3.1 Diversity distribution

The species richness of the demersal fish assemblages was greater on the continental slope than on the shelf and on a north-south gradient, there were more species recorded in southern Benguela than in the north (Fig. 7.11). Most of the sampling stations on the continental shelf in northern Benguela were occupied by few species (less than five), while in southern Benguela, most sampling stations had 15 - 36 species (Fig.7.11). Evenness tends to be higher on the continental slope and lower on the shelf; the evenness also changes from low at low latitudes (in northern Benguela) to high further south (in southern Benguela) (Fig. 7.12). The spatial distribution of the Shannon-Wiener index (*H'*) showed a difference between continental shelf and slope in northern Benguela, with diversity increasing from continental shelf to the slope; however, a different pattern was observed in southern Benguela where the diversity was the same for both the continental shelf and slope (Fig. 7.13). On a north-south gradient, diversity increased from northern Namibia to southern Namibia in northern Benguela, with the highest diversity index at the Orange River area (Fig. 7.9 and 7.13). South of the Orange River diversity was low and it increased further south (in southern Benguela) (Fig. 7.13).

7.4.3.2 Fish density distribution

The fish density (kg/nm^2) from the scientific bottom-trawl data showed that there was a gradient in fish density from north to south (Fig. 7.14). In northern Benguela, the fish densities were high on the continental shelf compared to the slope, while in southern Benguela they were similar on both the shelf and slope (Fig. 7.14). Notably high fish densities were observed west of Cape Columbine in southern Benguela between latitude 31^{o}S and 33^{o}S, and between 34^{o}S and 35^{o}S off Cape Point (Fig. 7.14), suggesting that very good catches could be associated with these fish densities as they coincided with high effort distributions (Chapter 2; Atkinson *et al.*, 2011b).

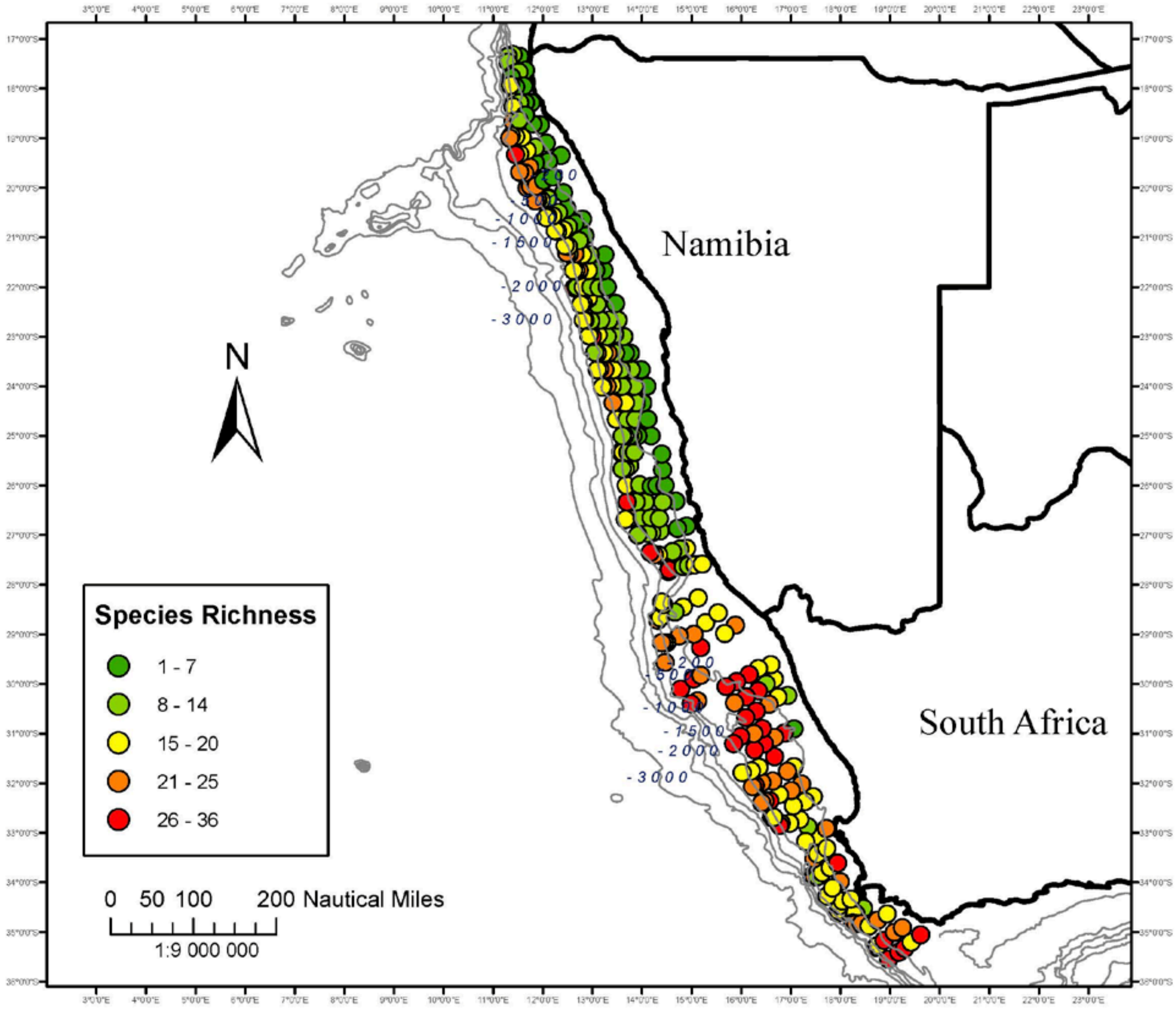


Figure 7.11 Species richness (*S*) spatial distribution for demersal fish of the Benguela System, off Namibia and along the west coast of South Africa for both the continental shelf (100 – 300 m) and continental slope (301 – 600 m). The coloured circles are sampling station positions. The colour represents the total number of species as guided by the colour legend.

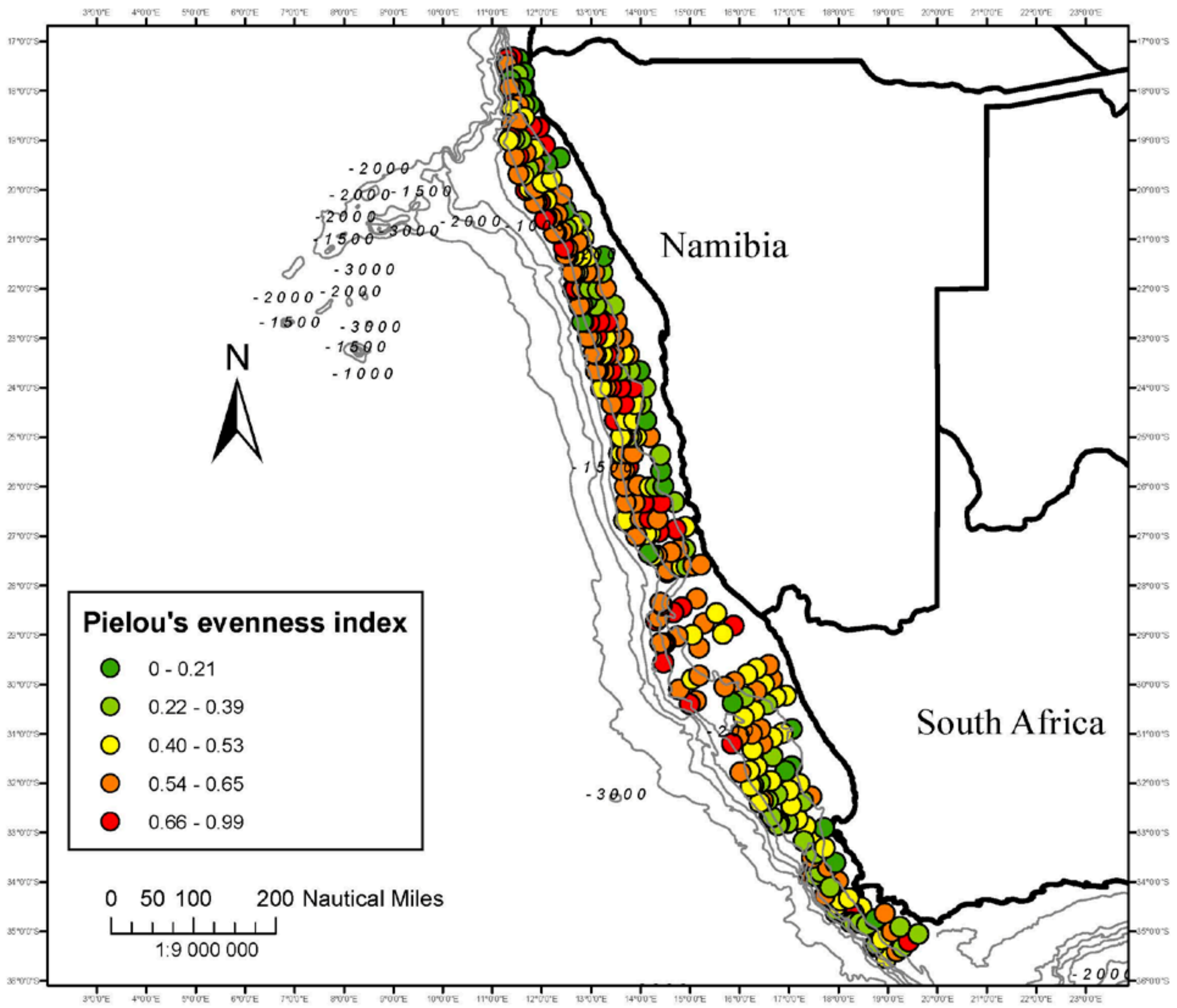


Figure 7.12 Pielou’s evenness index (*J’*) spatial distribution for demersal fish of the Benguela System, off Namibia and along the west coast of South Africa, for both the continental shelf (100 – 300 m) and continental slope (301 – 600 m). The coloured circles are survey sampling station positions. The colour represents the Pielou’s evenness index (*J’*) of species as guided by the colour legend.

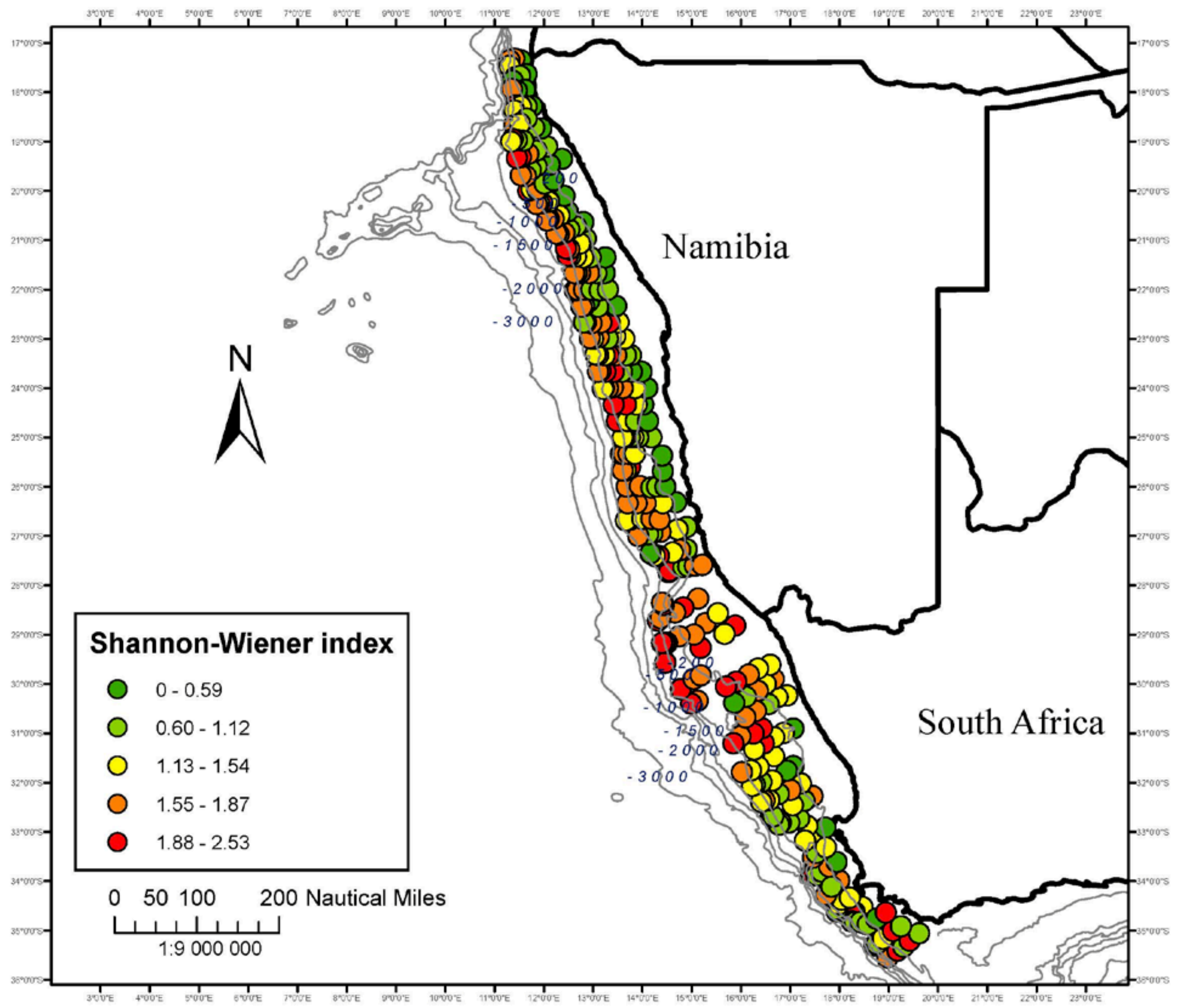


Figure 7.13 Shannon-Wiener index (*H'*) spatial distribution for demersal fish of the Benguela System, off Namibia and along the west coast of South Africa, for both the continental shelf (100 – 300 m) and the continental slope (300 – 600 m). The coloured circles are sampling station positions. The colour represents the Shannon-Weiner index (*H'*) of species as guided by the colour legend.

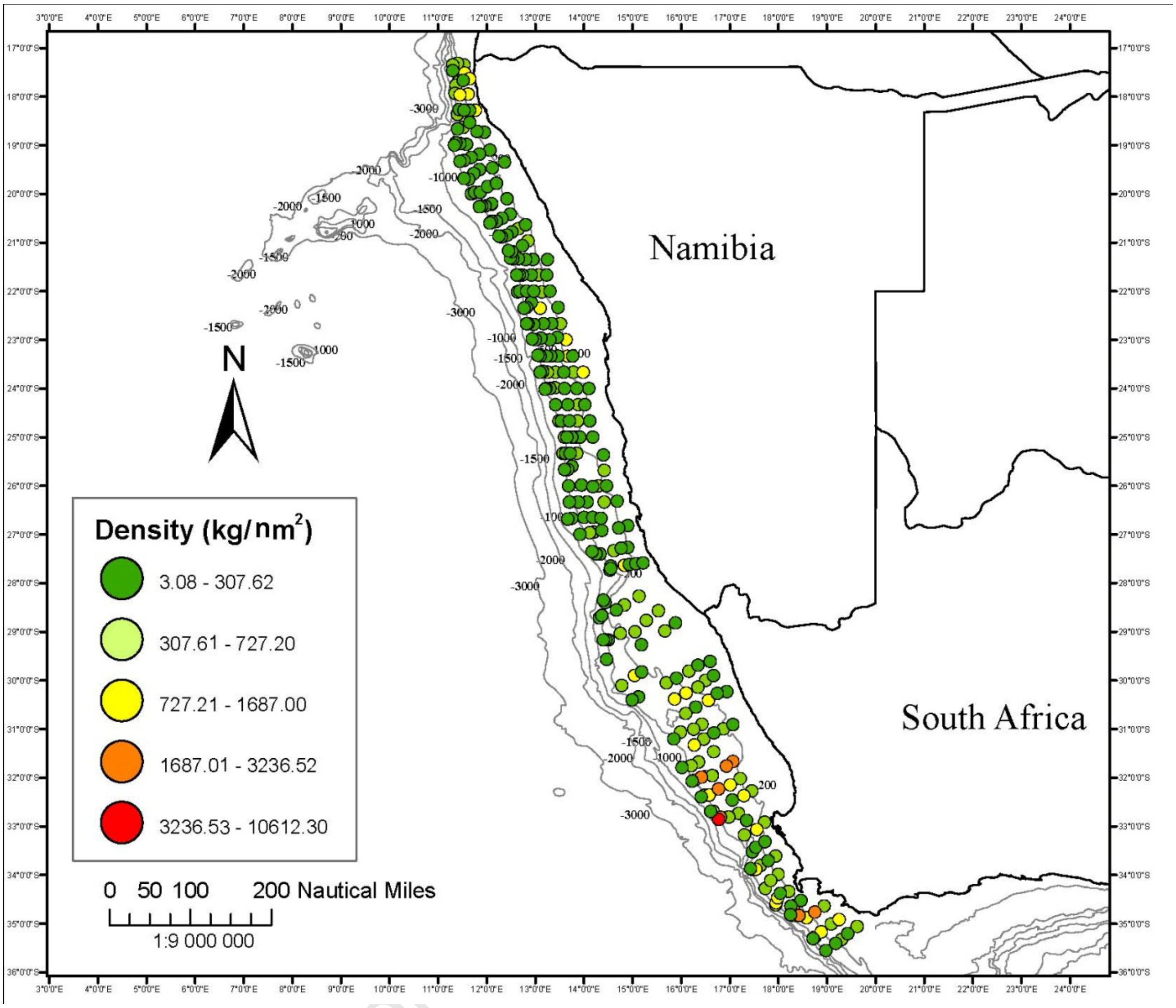


Figure 7.14 Density (kg/nm^2) for the demersal fish species of the Benguela System, off Namibia and along the west coast of South Africa during the 2007 hake biomass surveys.

7.5 *Environmental Variables*

7.5.1 Northern Benguela: Namibia

Taking a closer look at the *QuickScat* scatterometer estimates of wind direction and speed off Namibia (Fig. 7.15), the prevailing conditions were calm during the survey, with moderate southerly and southeasterly wind patterns with wind speeds ranging from 3 to 10 m/s. However, the last week of the survey the wind speed peaked in excess of 10 m/s especially in the southern part of Namibia. The sea surface temperature maps (Fig. 7.16) showed that there was some upwelling activity taking place, characterized by cooler subsurface waters with temperature of 10 ^{o}C and lower upwelled around the Lüderitz area, with varying intensity in response to the wind patterns.

Figure 7.17 shows the vertical sections for two bottom zones (80 – 365 m, and 366 – 600 m) of temperature, salinity, and dissolved oxygen for northern Namibia (22 – 17 ^{o}S), since there was no CTD while sampling the southern part. The summer conditions are reflected in the water temperature profiles, with the thermocline becoming more pronounced farther offshore. The surface waters measured up to 21 ^{o}C with salinity measuring 35.5 psu. The dissolved oxygen profiles depicted values over 5 ml/l on the surface, and oxygen-poor waters (< 0.5 ml/l) persisted in a meandering pattern between 150 m and the bottom in depth zone 80 ─ 365 m. Oxygen-poor waters were measured in mid-waters between 200 and 400 m in depth zone 366 – 600 m north of the 20 ^{o}S latitude. Figure 7.20 shows the distribution of the two species of hake in relation to the dissolved oxygen distribution both on the continental shelf and on the slope.

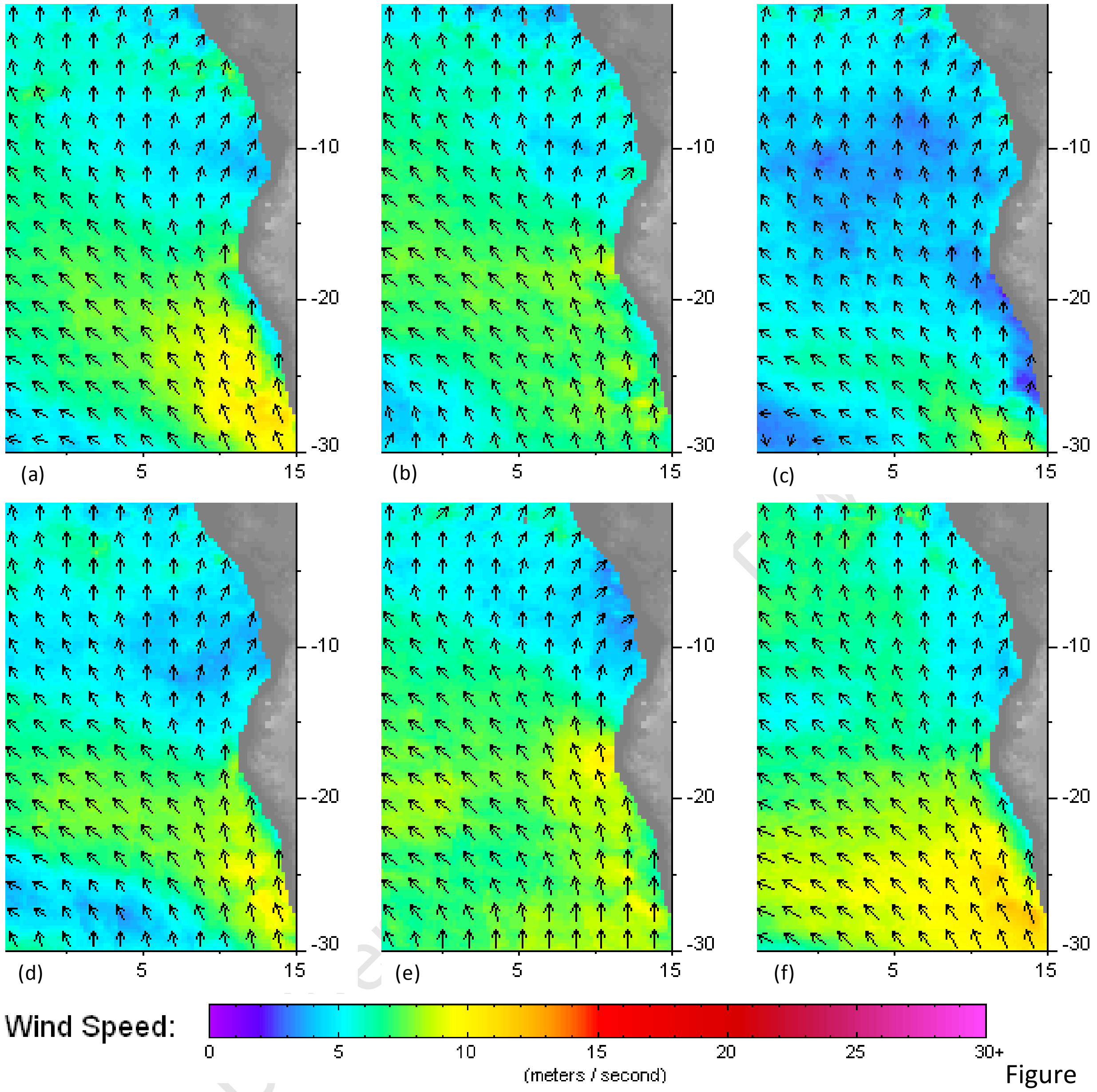
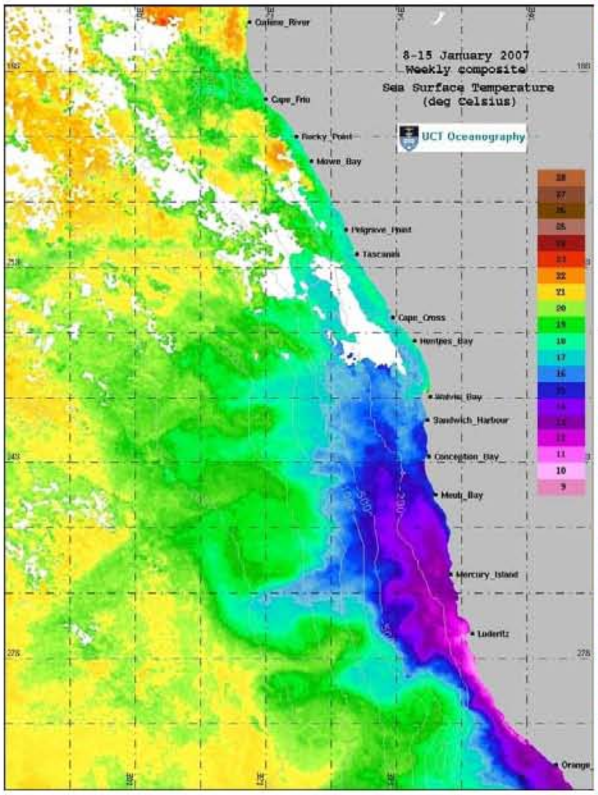
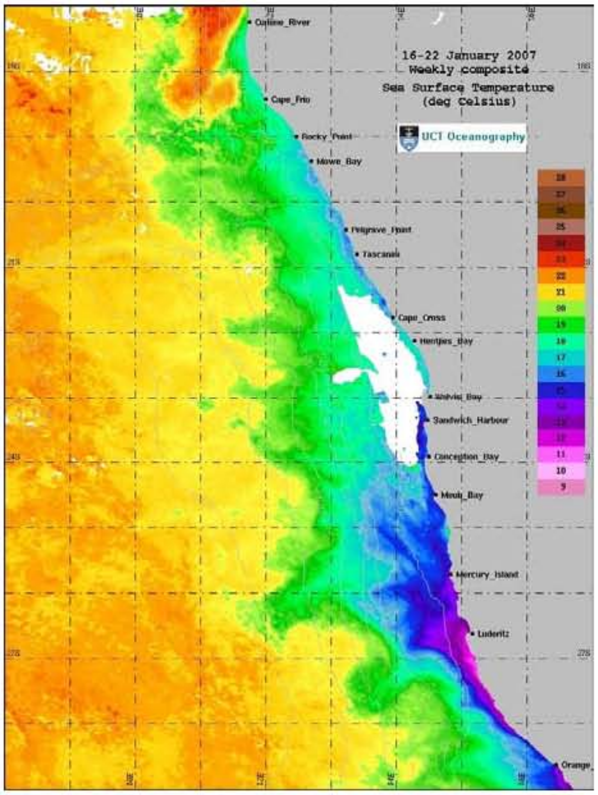
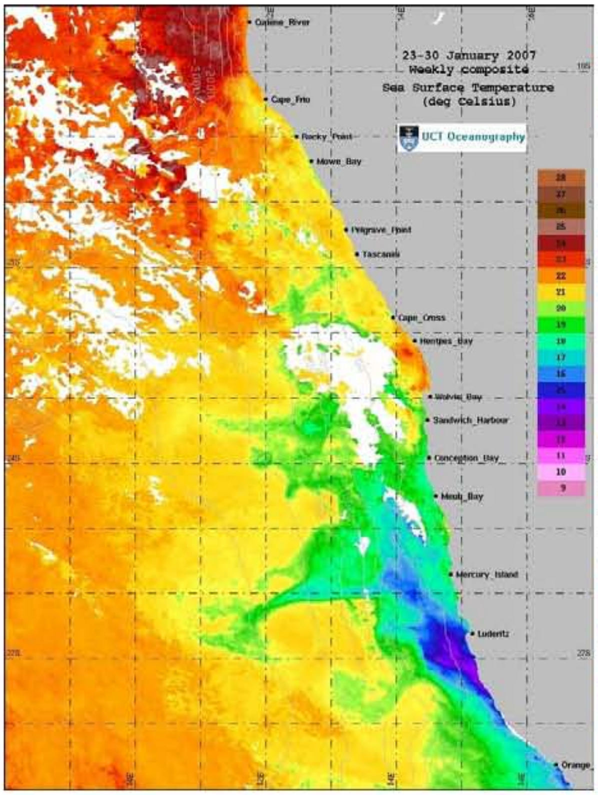
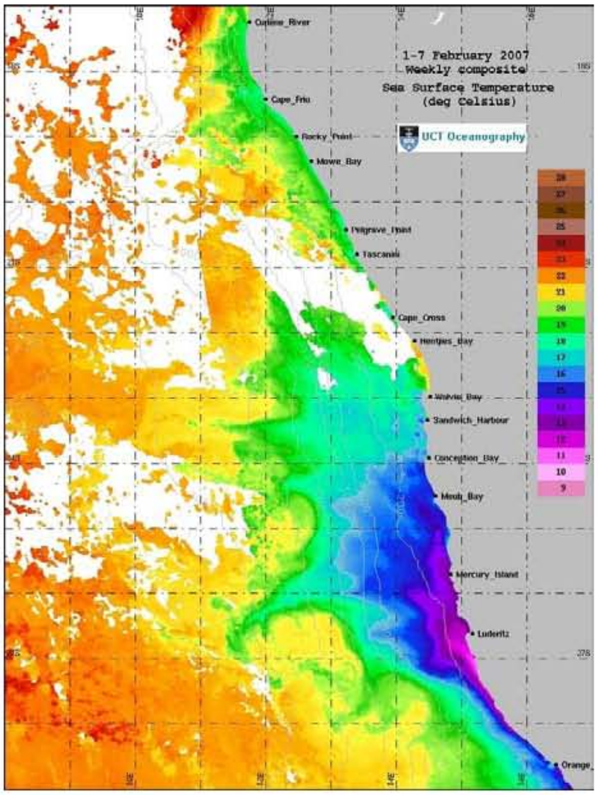


Figure 7.15 Weekly composite of *QuikScat scatterometer* estimate of wind speed and direction along the coast in northern Benguela for (a) 7-13 Jan, (b) 14-20 Jan, (c) 21-27 Jan, (d) 28 Jan-3 Feb, (e) 4-10 Feb and (f) 11-17 Feb for 2007 (*Courtesy: Remote Sensing Systems,* from Kainge *et al.*, 2007a).


8-15 January 2007
Weekly composite
Sea Surface Temperature
(deg Celsius)
UCT Oceanography
Cunene_River
Cape_Frio
Rocky_Point
Mowe_Bay
Pelgrave_Point
Toscanini
Cape_Cross
Henties_Bay
Walvis_Bay
Sandwich_Harbour
Conception_Bay
Meob_Bay
Mercury_Island
Luderitz
Orange
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9


16-22 January 2007
Weekly composite
Sea Surface Temperature
(deg Celsius)
UCT Oceanography
Cunene_River
Cape_Frio
Rocky_Point
Mowe_Bay
Pelgrave_Point
Toscanini
Cape_Cross
Henties_Bay
Walvis_Bay
Sandwich_Harbour
Conception_Bay
Meob_Bay
Mercury_Island
Luderitz
Orange


23-30 January 2007
Weekly composite
Sea Surface Temperature
(deg Celsius)
UCT Oceanography
Cunene_River
Cape_Frio
Rocky_Point
Mowe_Bay
Pelgrave_Point
Toscanini
Cape_Cross
Henties_Bay
Walvis_Bay
Sandwich_Harbour
Conception_Bay
Meob_Bay
Mercury_Island
Luderitz
Orange


1-7 February 2007
Weekly composite
Sea Surface Temperature
(deg Celsius)
UCT Oceanography
Cunene_River
Cape_Frio
Rocky_Point
Mowe_Bay
Pelgrave_Point
Toscanini
Cape_Cross
Henties_Bay
Walvis_Bay
Sandwich_Harbour
Conception_Bay
Meob_Bay
Mercury_Island
Luderitz
Orange

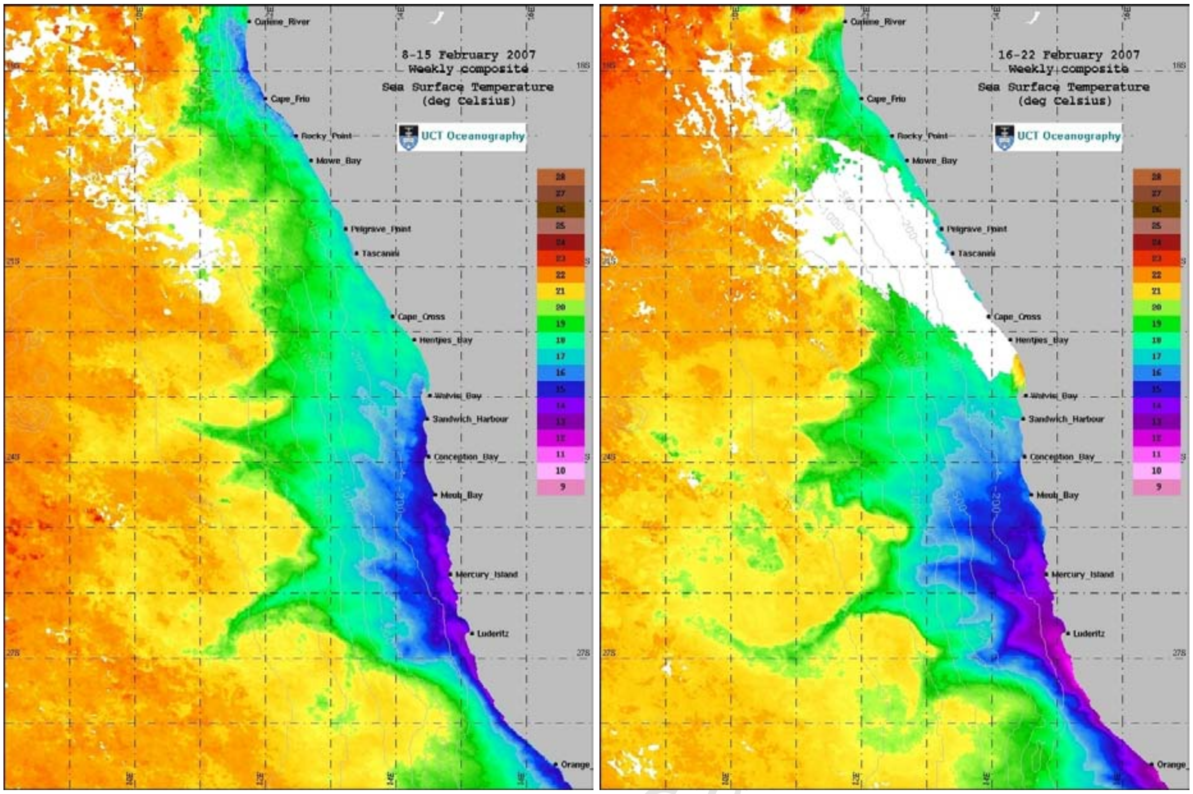


Figure 7.16 Mean SST composites of northern Benguela for the weeks 8-15 January, 16-22 January, 23-30 January, 1-7 February, 8–15 February and 16–22 February 2007 [Courtesy of the Marine Remote Sensing Unit (MRSU), Oceanography department, UCT, (Mathieu Rouault *pers. comm.*)].

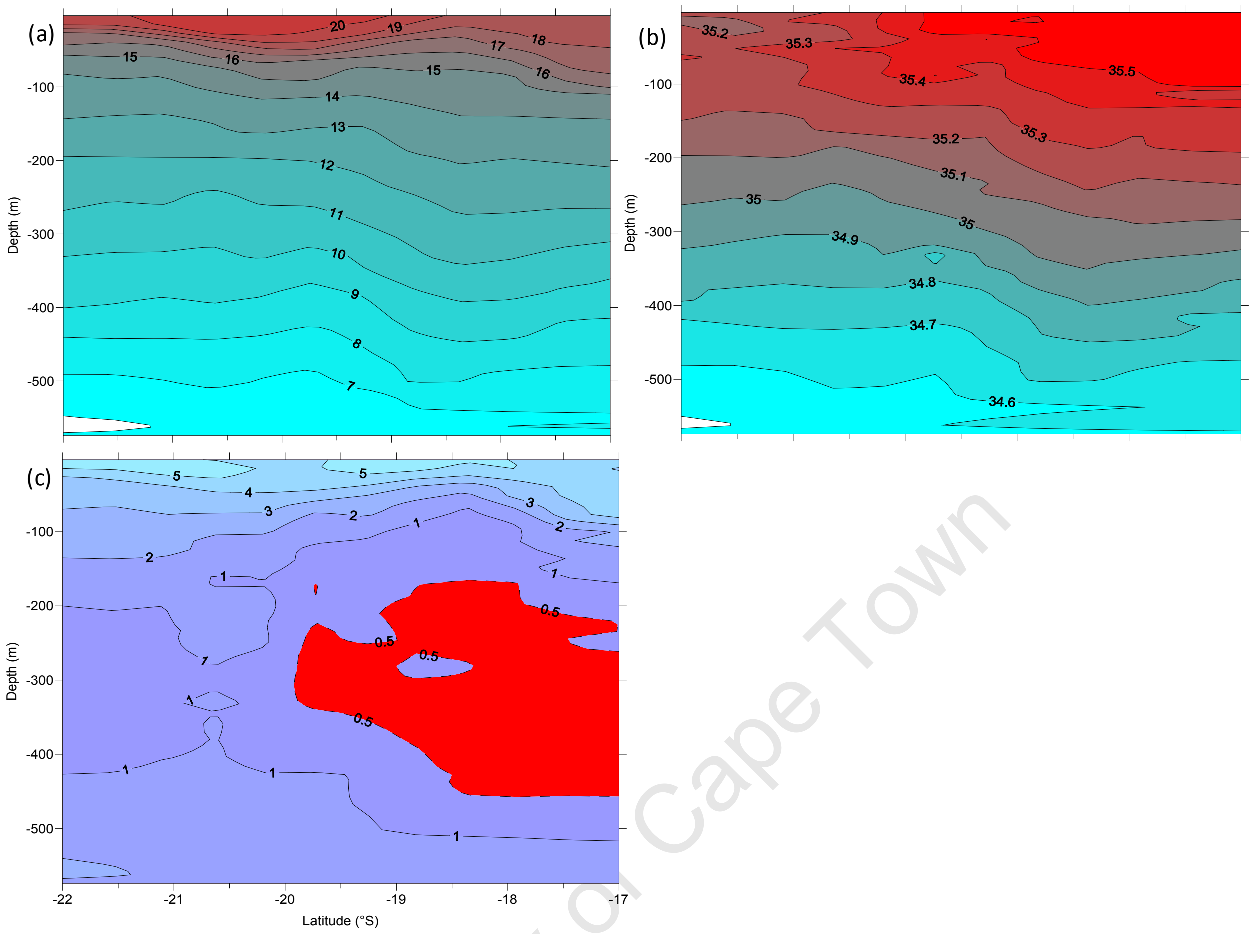


Figure 7.17 Latitudinal sections of (a) temperature, (b) salinity and (c) dissolved oxygen during the January/February 2007 hake biomass survey (Anja van der Plas and Chris Bartholomae, NatMIRC, MFMR, *pers. comm.*).

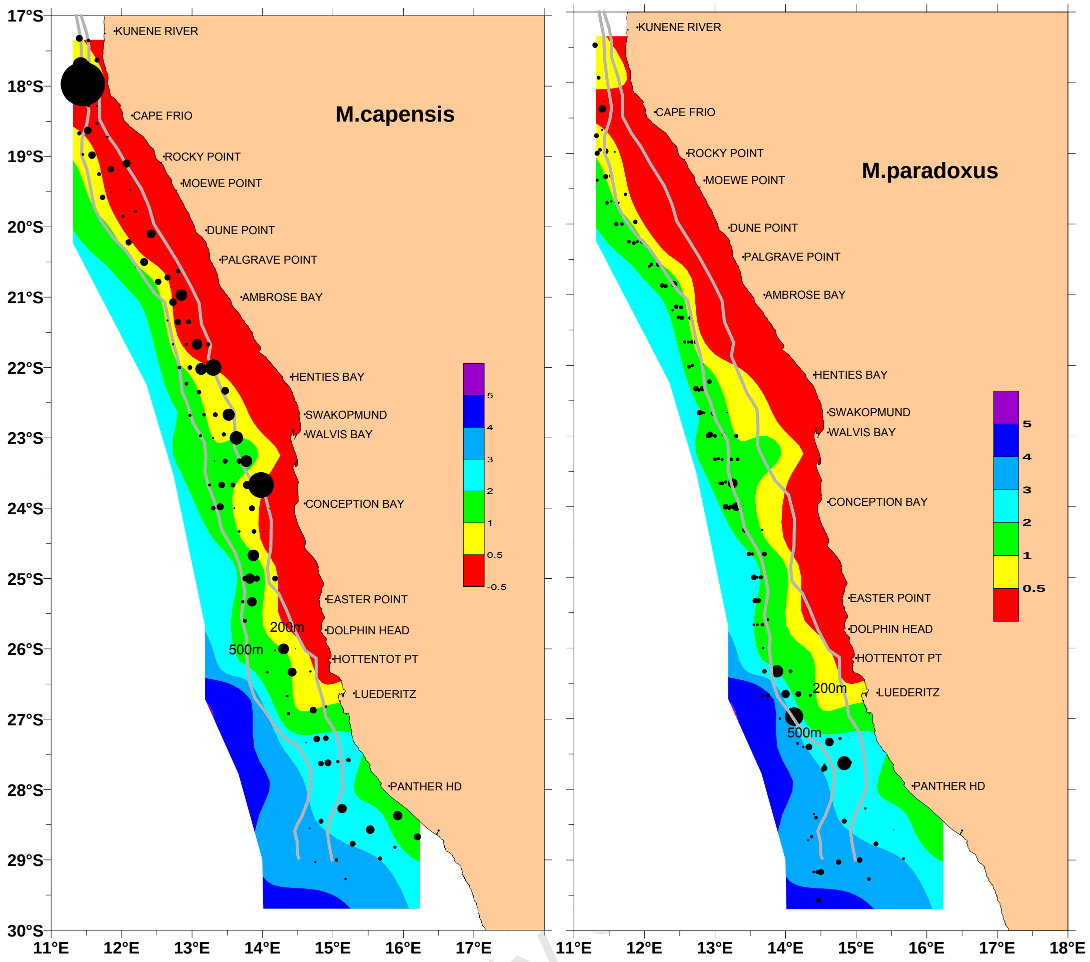


Figure 7.18 Distribution patterns of *M. capensis* and *M. paradoxus* in relation to bottom dissolved oxygen (ml/l) during the 2007 hake biomass survey in northern Benguela. The black dots represent the hake densities. Dashed grey lines represent the 200 m and 500 m depth contours (Source: Kainge *et al*., 2007a).

7.5.1.2 Southern Benguela: west coast of South Africa

The west coast of South Africa experienced calm, windless conditions, which prevailed for the first part of the cruise. Moderate southerly wind was experienced only for one day, followed by calm conditions, and then gentle northwesterly and westerly winds prevailed for the remainder of the cruise (Fig. 7.19). These were normal conditions for the end of the summer upwelling season. Satellite imagery (Fig. 7.20) showed some active upwelling (cool water trapped closer inshore), with relatively warmer water over most of the shelf, which was typical for the autumn months of April – June. A conjugated front with weak gradients occurred offhsore at 1000 m isobath, with a moderate mesoscale eddy at 31^o S.

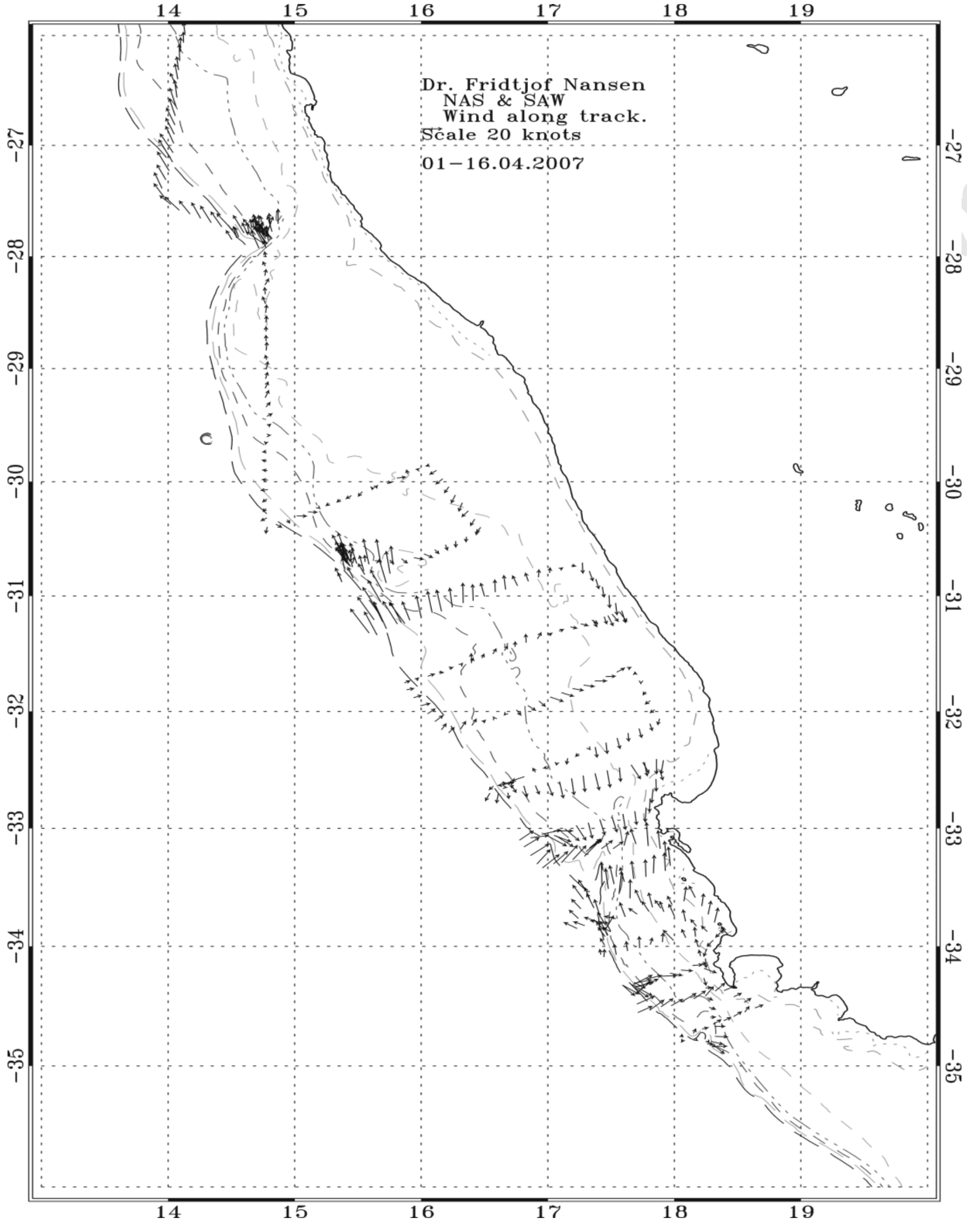


Figure 7.19 Wind along the track during the survey off the west coast of South Africa (Source: *R/V Dr Fridtjof Nansen* survey 2007).

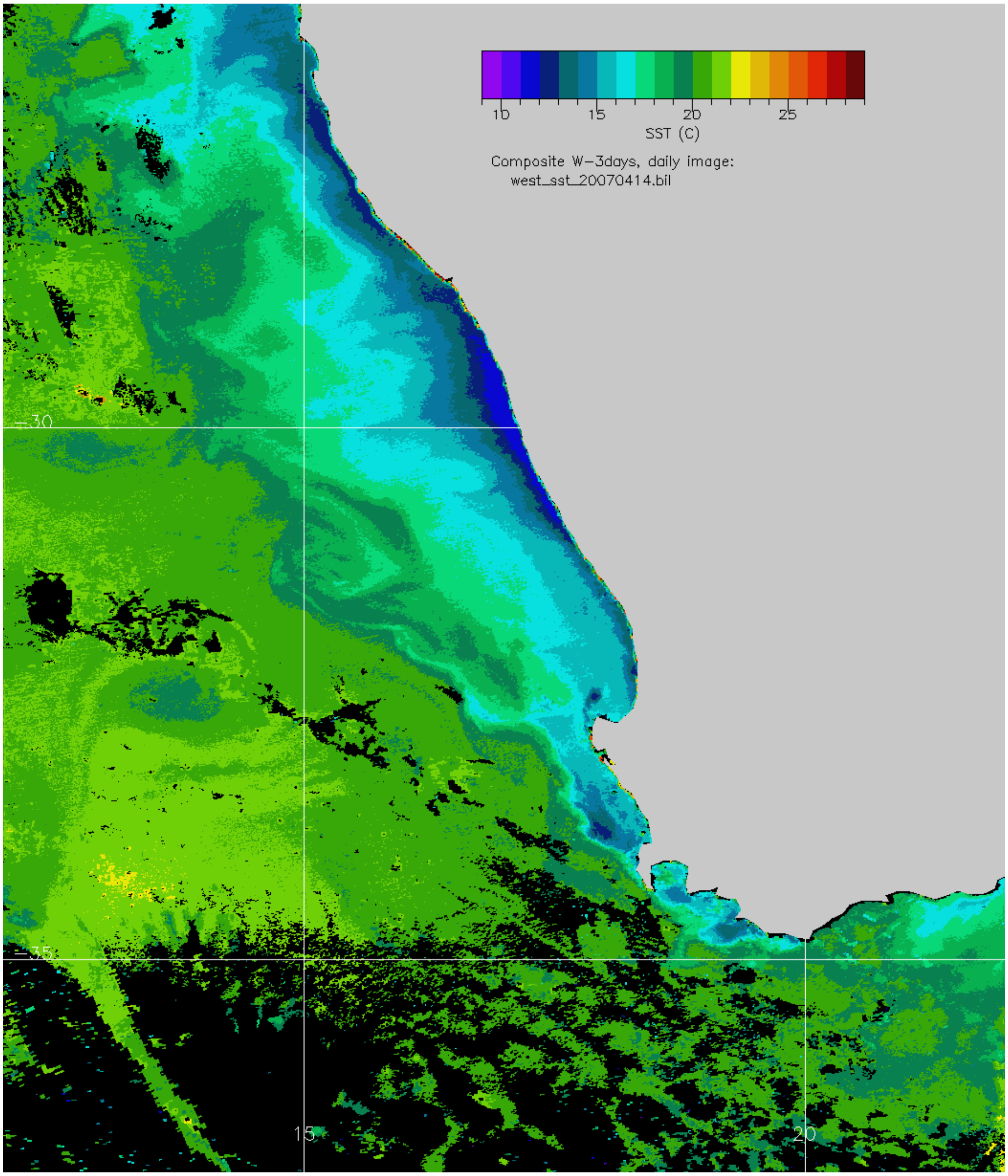


Figure 7.20 Sea surface temperature (SST) from satellite for 14-04-2007 in southern Benguela (Source: *R/V Dr Fridtjof Nansen* survey 2007).

Most of the inshore-offshore sections on the west coast, north of 32 °S, showed a stable surface layer with marked, shallow thermoclines (see Appendix 7.2a S. of Lüderitz and Lines 1-7 RSA). A subsurface shallow salinity maximum indicated some upwelling prior to the survey, followed by sun warming of the upper mixed layer. Dissolved oxygen values were less than 2 ml/l inshore, but less than 1 ml/l in St Helena Bay (transect 7). Offshore, dissolved oxygen levels were high from surface to bottom and no potential barrier to survival of organisms.

South of Cape Columbine (33 °S) to Cape Point (34 °S), vertically orientated isohalines and steeply sloping isotherms indicated recent upwelling, with the southernmost transects showing relaxation of the upwelling again in the upper layers, following westerly winds and shoreward movement of the warm surface layers (see Appendix 7.2a, lines 8-11).

Some evidence of an upwelling front and the associated northward-flowing jet current could be seen from lines 6 (33 °S) to line14 (35 °S), lying over the 200 - 300 m isobath in the south and over the 300 - 400 m isobath further north (Appendix 7.2a).

A longshore section of the temperature, salinity and oxygen over the 300 - 400 m isobaths (Appendix 7.23) indicated no marked alongshore gradients in water masses close to the bottom, from Lüderitz to Cape Point. Bottom temperatures at 300 - 400 m ranged from 6-8 °C, bottom salinities from 34.6 - 34.8 PSU and 3.5 - 4.0 ml/l dissolved oxygen.

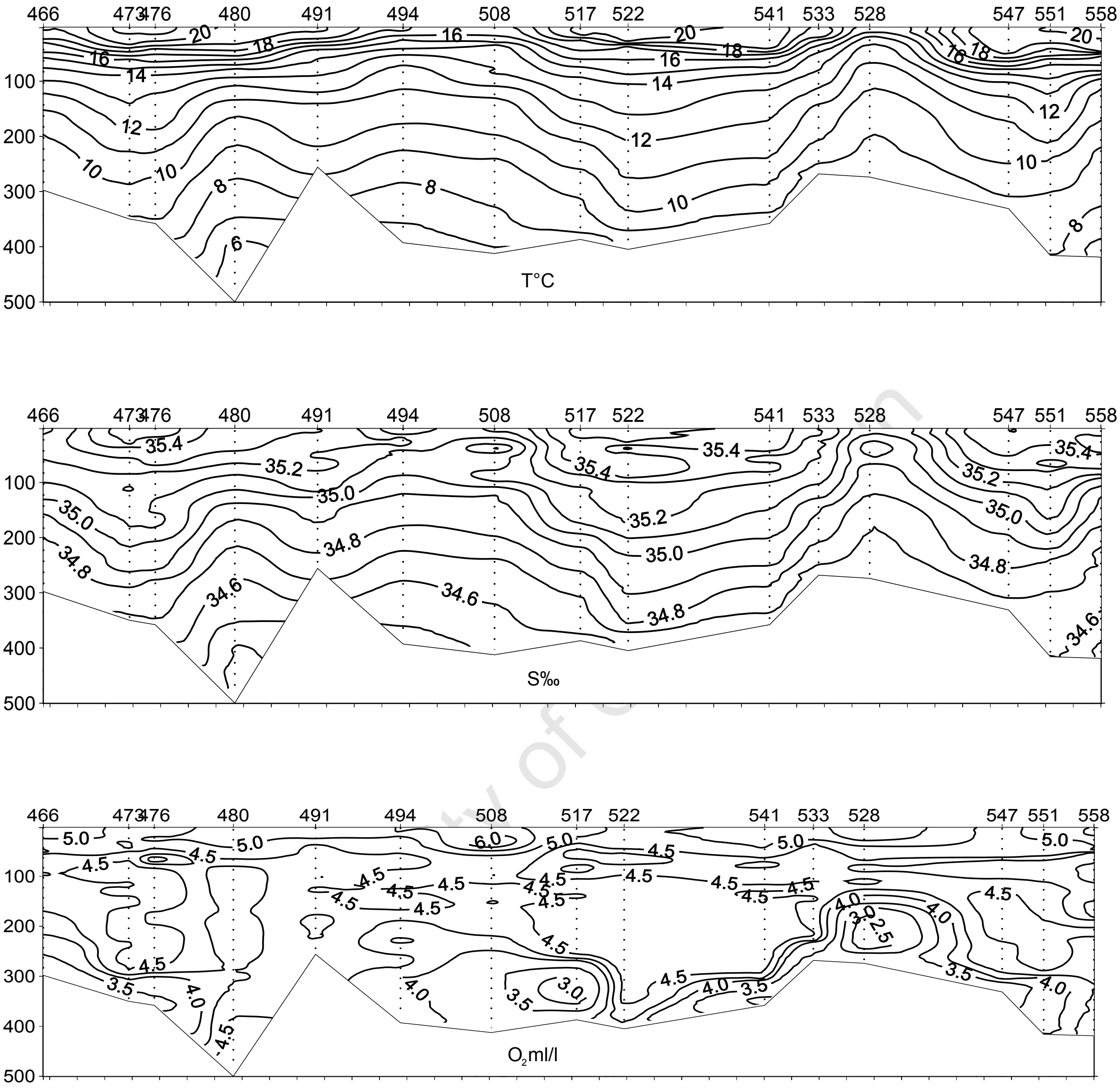


Figure 7.21 Longshore N-S sections at 300 – 400 m for temperature, salinity and oxygen in southern Benguela during the 2007 hake biomass survey conducted by the *R/V Dr Fridtjof Nansen*.

7.6 Discussion

This is the first time that the demersal fish assemblages of the Benguela System and its sub-systems, northern and southern Benguela have been studied together. Cluster and MDS analyses on demersal fish abundance data suggest that there are three major demersal fish assemblages, indicating that the southern Benguela (off the west coast of South Africa) assemblage was different from those of northern Benguela (off Namibia), where two separate assemblages emerged for the continental shelf (100 – 300 m) and slope (300 – 600 m) (Figs. 7.2 and 7.3). Thus, the demersal fish assemblages of the two sub-systems appear to differ. Clearly, the separation of the continental shelf and slope assemblages in the northern Benguela corresponds well to the distributional range of the two species of Cape hake. There was no separation between demersal fish species of the continental slope and shelf in southern Benguela, which therefore emerged as one assemblage in the cluster analysis and the MDS at 19% similarity (Fig. 7.4). The former coincides with the findings in Chapter 4, where the continental shelf and slope assemblages of the northern Benguela were clearly shown to be different. Bianchi *et al*. (2002) writing on the dynamics of the demersal fish assemblages off Namibia found a similar pattern.

The demersal fish assemblage of the continental shelf in northern Benguela showed some signs of moderate disturbance (Fig. 7.5), which could be attributed to fishing (Chapter 2), and low dissolved oxygen distribution especially in the northern and central shelf (Fig.7.17 and 7.19). The oxygen-poor waters may have affected the distribution of other demersal fish based on their tolerance levels to low dissolved oxygen, as shown for *M. paradoxus* and *M. capensis* (Fig. 7.19). Should this be the case for all other fish species in northern Benguela, then dissolved oxygen concentration plays a vital role apart from other environmental variables in determining the distribution of demersal fish assemblages leading to these observed patterns. Nonetheless, there was no major adverse environmental variability (e.g. Benguela Niño) reported during 2006 or early 2007, which could have influenced the actual distributions (see Chapter 5).

However, there was moderate disturbance reflected by the fish assemblages of the continental slope off Namibia and South Africa. Most of the commercial trawling (Chapter 2) was concentrated in the depth range 200 – 399 m, which could skew the effort distribution. This similar pattern of disturbance was found when considering 17 years of hake biomass survey data using the ABC method to detect change in the community structure of the demersal fish assemblages off Namibia (Chapter 5). The results of the ABC method and the corresponding *W-statistic* should be carefully interpreted, since the method has only recently been applied to fisheries. Therefore, it may be tempting to over-interpret results. The upper continental slope is mostly trawled by commercial trawlers for hake, thus it was expected to reflect heavy disturbance, as shown in the bottom-trawl intensity in Chapter 2. Temperature (6 – 8 ^{o}C), salinity (34.6 – 34.8 psu), and bottom oxygen (3.5 – 4 ml/l) from Lüderitz to Cape Point from 300 to 400 m were all favourable enough to support the presence of Cape hakes during the 2007 southern summer survey period. This suggests that no low oxygen, high salinity central water, derived from the western south Atlantic via the Angolan Basin, was present along the shelf, but well ventilated South Atlantic “eastern” Central water from the Cape Basin was present along the shelf at depths favoured by hakes, during the survey period.

The cluster analysis has shown three main groups, and within each group ABC analyses have suggested moderate disturbance (*W* > 0 but close to zero, see Figure 5.1, Chapter 5), according to the classification by Warwick and Clarke (1994). However, this is a broad scale assessment, and localised effects of fishing could be concealed at this large scale. Long term spatial and temporal observations of the *W- statistic* off the coast of Namibia have shown that within sub-regions in some years there are detectable signs of disturbance by fishing and other factors (e.g. environmental) (Chapter 4). Classical changes in the size spectra from those of the same sub-regions in some years also revealed changing assemblage size structure over the years (Chapter 4). Therefore, the observed patterns in the ABC curves reported in this chapter should be treated with caution, since they are based on only one survey. The possibility for time series data should also be taken into account when defining indicator thresholds for the *W – statistic*.

Interestingly, the cluster and MDS separation between the demersal fish assemblages in southern Benguela and those of northern Benguela extends slightly into southern Namibia (Fig. 7.4). This is thought unlikely to be an artefact of vessel effect. This could be due to the difference in hydrographic conditions leading to the separation between northern and southern Benguela. South of Lüderitz, a change in upwelling source water to a less saline and more oxygenated source from the Cape basin has been reported, though the major barrier layer is the surface on the narrow continental shelf region (Lett *et al*., 2007). This supports the widely accepted idea that the Benguela system off Namibia and South Africa can be subdivided into the northern Benguela and southern Benguela (Shannon, 1985; Shannon and Field, 1985; and re-emphasised in Hutchings *et al*., 2010 and the references therein), with the boundary near Lüderitz in Namibia.

Another feature of this area is the Orange River cone; the continental shelf in this area extends offshore then it narrows on both the northern and southern parts. These two zones are distinct from one another due to differences in oceanographic conditions marking the pelagic boundary, especially for small pelagic fish such as anchovy and sardine (Andrews and Hutchings, 1980; Nelson and Hutchings, 1983; Shannon, 1985; Chapman and Shannon, 1985; Shannon and Pillar, 1986; Crawford *et al*., 1987; Shannon and Nelson, 1996; Hill *et al*., 1998; Field and Shillington, 2004; Mackas *et al*., 2006; Shannon *et al*., 2006; Shillington *et al*., 2006; and van der Lingen *et al*., 2006). However, this is unlikely to apply to demersal fish that are found much deeper than the marine pelagic boundary, which only affects the epipelagic zones (Hutchings, 2009). Nevertheless, findings of this study point to the fact there are signs of latitudinal differences in terms of the demersal fish community structure along the coast of Namibia and the west coast of South Africa, which cannot be linked to the different types of vessels used. However, there was some overlap between the demersal fish assemblages in northern and southern Benguela as identified by the cluster analysis and MDS. This shows that despite the data being collected by different vessels, they were comparable, and further carefully co-ordinated and intercalibrated surveys would be helpful in terms of management of the hake fisheries of the Benguela System. Often ecosystem conservation and management starts and stops at an international border, which does not always correlate with ecosystem boundaries (Richelefs, 1987, Graham *et al*., 1991).

Due to the configuration of the coastline and bathymetry from the Kunene River to the Agulhas Bank, depth and longitude had a weak negative correlation. It is surprising though to note that the effect of depth was less pronounced than that of longitude in all the diversity indices. Likewise, the spatial distribution of diversity for demersal fish species in the northern and southern Benguela also supports the hypothesis that different demersal fish assemblages exist. The changes in diversity from north to south could be attributed to distribution of dissolved oxygen on the continental shelf and slope, and its variability from north to south (Monteiro and van der Plas, 2006; Bartholomae and van der Plas, 2007), as supported by this study. There are areas in northern and southern Benguela that could possibly be biodiversity hotspots. These potential hotspot areas are around 20 ^{o}S off Cape Frio, and another one around 30 ^{o}S off the Orange River, and moving further south around 32 ^{o}S off Port Nolloth in southern Benguela (Figs. 7.11 – 7.12). Careful consideration of protected areas could be beneficial to the surrounding fishing areas through potential spillover effects of fish from Marine Protected Areas (MPAs) (Harmelin-Vivien *et al*., 2008). Possibly other potential biodiversity hotspots could be identified by using long-term data from both demersal and pelagic surveys, thereby providing a wider perspective of the new conservation frontier that may need protection from fishing in the future.

The demersal fish densities in the northern Benguela are lower than those in the southern Benguela, which may suggest the effect of the periodic occurrence of low oxygen water on the shelf in the northern Benguela compared to the southern Benguela, which does not have such incursions. It may also be a reflection of different demersal fish assemblages in the two Benguela sub-systems as shown earlier by the cluster analysis and MDS. However, there has been a notable shift in terms of effort in southern Benguela, where trawlers have moved further south in pursuit of better catches of hake and proximity to ports, which in turn cuts the fuel costs (Marek Lipinski, MCM (now DAFF), 2007, *pers. comm.*).

Using information from SA bottom trawl surveys off the west coast, Atkinson *et al*. (2011a) have indicated that several demersal fish species have undergone population shifts between 1986 and 2009. Long-term shifts were detected in 27% of demersal species and these occurred in the early 1990s or in the past decade (2000 – 2010). Sequential T-test Algorithms for detecting Regime Shifts (STARS) analyses, as well as MDS scaling indicated temporal differences in demersal fish assemblages from the northern to southern regions of the west coast of South Africa (Atkinson *et al*., 2011a).

The two target species of the hake bottom fishery were found to dominate in terms of average density in their respective depth ranges (shallow and deeper water). There was a general increase in demersal fish densities with increasing latitude, although there are similar bottom-trawl intensities in northern (Chapture 2) and southern Benguela (Atkinson *et al*., 2011 in press; Wilkinson and Japp, 2005), suggesting this is due to environment variability of the two sub-systems. Changes in fish communities with increasing depth are well documented in the Benguela region (Roel, 1987; Smale *et al*., 1993; MacPherson and Gordoa, 1992; Bianchi *et al*., 2001) and the results of this study are consistent with these previous studies. Generally, the southern Benguela was found to be more diverse than the northern Benguela. The increase in diversity with increasing depth was noticeable in northern Benguela. In contrast, a study by Yemane *et al*. (2009) showed that demersal fish species diversity decreased with increasing depth on the south coast of South Africa — a region with different topography and oceanography.

Therefore, the observed pattern in the distribution of diversity with depth in these studies has revealed a contrast in diversity patterns, with diversity increasing with depth at low latitude in northern Benguela and decreasing with depth at higher latitude in southern Benguela and on the south coast of South Africa. This is the opposite of the generally expected diversity patterns which increase from the poles toward the equator.

Demersal fish densities increased from north to south. The northern and southern Benguela are two major ecosystems with varying upwelling intensities, which is an important factor contributing to the observed pattern of demersal fish densities. The influence of geographical features such as the Agulhas Bank shelf ecosystem on the South African south coast should not be ignored. The Agulhas Bank is characterized by different oceanographic conditions compared to the west coast of South Africa, which is dominated by the Benguela current.

The Southern Benguela supports high species diversity. Some of these species, among them demersal species, may find their way to the west coast of South Africa. Univariate analyses indicated that the diversity of demersal fish communities increased with increasing latitude. The southern Benguela is more diverse than northern Benguela in terms of demersal fish species. Diversity also increased with increasing depth, and this pattern was stronger in the northern than in southern Benguela. Fish densities were higher in the southern than the northern Benguela, and increased with increasing latitude. Water temperature, and dissolved oxygen appear to have an influence on the distributions of the major demersal species. Demersal fish species assembled outside low oxygen waters, suggesting an avoidance strategy. The highest Cape hake densities occurred outside and at the edge of the severely hypoxic (<0.5 ml/l) bottom waters as was shown off Walvis Bay and off Cape Frio (Fig. 7.18). Nevertheless, this species tends to move more inshore (inside the 200 m isobath) south of Lüderitz where bottom waters are generally oxygenated, further highlighting the role of hypoxic bottom waters in the distribution of Cape hakes on the shelf (Kainge *et al*., 2007). The deeper distribution of *M. paradoxus* provides the species an opportunity to avoid exposure to low oxygen bottom waters.

Although, this study was based on only one year of survey data, (2007), it sheds some light in terms of the community structure and diversity patterns of demersal fish assemblages of the Benguela System with its sub-systems, northern and southern Benguela (off Namibia and South Africa respectively), as no such combined studies had been conducted in the past. Therefore, more reliable, consistent and comparable data are needed to further understand the linkages between the two sub-systems' demersal fisheries. This is also a contribution in terms of management of these trans-boundary resources, and, through the focus on communities rather than target and bycatch species, a step towards the realization of an ecosystem approach to fisheries.

Synthesis and Conclusions

8.1 Introduction

The ecosystem approach to fisheries (EAF) is a relatively new concept in the management of fisheries. Its ecological research basis requires the consistent study and monitoring of the effects of the fisheries on marine habitats, benthic assemblages and fish communities (FAO, 2003). This thesis contributes to the EAF in Namibia through quantifying the trawl intensity and fishing effort of the Namibian hake-directed bottom-trawl fishery, investigating the effects of bottom-trawling on the size structure (e.g. mean catch, mean length, size spectrum), community structure (by way of cluster analysis and MDS, abundance biomass comparison curves) and diversity of demersal fish assemblages off Namibia. Analysis is also undertaken of biodiversity patterns in the northern and southern Benguela upwelling ecosystems, combined for the first time, in line with the regional approach supported through the Benguela Current Commission.

8.2 Data considerations and limitations of the study

Though not new to studies of this nature, there are relevant data issues that need to be kept in mind. These include the use of survey data for studying changes in fish communities and diversity, the use of commercial catch data and the use of reference indicator directions of changes for management.

Firstly, the hake biomass surveys off Namibia were conducted bi-annually from 1990 until 1995 and thereafter annually. Thus, no seasonality effects could be deduced from these data. Despite inter-calibration amongst hired commercial vessels and the *R/V Dr Fridtjof Nansen*, there are still some artefacts in the data collected as a result of change of gear, personnel, and some differences in the accuracy of species identifications, etc. Further, the sampling procedures on deck may have created biases, especially as sub-sampling could lead to rare species being missed. The observed changes in community structure could also be influenced by the variability in the catchability of species resulting from differences in species demography, e.g. spatial distribution and length composition, as well as differences in vessel type and sampling gear. Despite these issues, and although Namibian hake biomass data were collected by different vessels and there were some gear changes, the data are comparable and the best available. No consistent data were collected on environmental variables such as dissolved oxygen, salinity and temperature at each sampling station. It was thus difficult to distinguish effects of fishing from those of the environment.

Commercial catch data (Chapter 2) are often biased when assessed over a long period of time due to changes in discards and market-oriented forces influencing what part of the catch is landed. Therefore, marked changes in fish assemblages may not be reflected in the landings. The Ministry of Fisheries and Marine Resources (MFMR) employs fisheries observers onboard all commercial fishing vessels, thus their logbooks and those of the captains are reconcilable, improving the reliability of catches recorded in the Ministry's database. All data were checked and verified before use in this study.

The *in situ* bottom-trawl experiments (Chapter 6) suffered from a lack of representative untrawled areas of comparable habitat in the Benguela System. Thus, the experiment was conducted in comparable habitats where bottom-trawl intensity was characterized as heavy and light (Chapter 2) as opposed to pristine or untrawled. Vessel time is very expensive, and hence this experiment was done only once, covering only two sites (Sam's Bank and Child's Bank).

It is difficult for the trawl gear to sample the three dimensional environment. Most trawl gears are designed to sample a small portion of the column at a time; and they are both species and size selective, thus making it difficult to evaluate how this may affect the diversity measures. However, it should be understood that we are only dealing with the demersal environment and assemblages, but varying species behaviour and swimming speeds do make selection and size a problem. Therefore, this study excluded all the pelagic fish from the analysis, although many of the demersal fish species perform diel vertical migration, thus making fish behaviour an important aspect when dealing with the diversity measures.

Finally, the issue of using indicators in community studies has been referred to in this thesis. Indicators often pose technical implications for management under the old paradigm of hard predictability (Degnbol and Jarre, 2004), due to their complexity and the uncertainty in measuring their attributes. Ecosystems and their properties respond differently and nonlinearly, and over different time periods. However, size-based indicators (heights and slopes of the size spectra, mean length) (Chapter 4) can be used in the medium term, though these size-based indicators, as derived from survey data, lack the power to detect trends at shorter time scales (Jennings and Dulvy, 2005). Thus, a precautionary approach should be adopted when considering reference directions in size-based indicators for the purposes of management. Particular cut-off points based on indicator values are difficult to justify, as they are not absolute or based on theory. Hence the need to use indicator directions to indicate whether the ecosystems or communities are getting better or worse in terms of disturbance (Shin and Shannon, 2010).

8.3 Key Questions and Findings

Key Question 1: a) *Is there any spatial variability in bottom-trawl intensity off the coast of Namibia? b) How does fishing effort vary geographically and bathymetrically?*

These were the key questions examined in Chapter 2. The commercial hake bottom-trawl intensity off Namibia was shown to be patchy when trawl intensity was estimated as an annual mean of the number of trawls; and increasingly uniform in space and time when trawl intensity was estimated as an annual mean of trawl duration. However, southern Namibia was the most frequently trawled compared to central and northern Namibia. Observations from this study and others (Magnússon and Magnússon, 1995; Ragnarsson and Steingrímsson, 2003; Rijnsdorp *et al*. 1998) show that patchiness in bottom-trawls is not an unusual finding, since fishermen tend to trawl in areas with historically high catches (e.g. for Namibia with average landing > 500 000 tons in the 1970s, and > 300 000 tons in the 1980s) (ICSEAF, undated). Another factor at play includes the distance from fishing grounds to landing ports; Namibia has only two ports (Walvis Bay in central Namibia and Lüderitz in southern Namibia). More than half the total effort (both trawl duration and number of trawls) was generally concentrated in waters in the depth range 200 – 399 m, and most of this effort was directed towards the southern part of Namibia. The pattern emphasises the difficulty in trawling in deeper waters in view of the time and fuel expenses. Most of the bottom-trawling took place on sand-mud and sand-gravel sediment textures, and implications of this need to be thoroughly investigated off Namibia, as these different bottom-types have different sensitivity to bottom-trawl disturbance (Gislason, 1994; Hall, 1998, Collie *et al*., 2000).

Areas with high mean catch rates were observed to coincide with areas with high fishing effort concentration, which translates into heavy bottom-trawling intensity (number of trawls ranging between 217 and 437 trawls/grid). Bottom-trawling as tow frequency per 1'x 1' grid square off Namibia was found to be patchy, but it was more uniform when measured as number of hours trawled per grid square. Contrary to the diversity pattern, southern Namibia was most frequently trawled, followed by northern Namibia and last central Namibia. The patchy distribution of bottom-trawls points to areas with high, medium and low concentrations of demersal fish, which was reflected in the demersal fish densities, which increased with increasing latitude (towards the south). Effort, expressed as the number of boats participating in the fishery, increased from 88 vessels (in 2000) to a maximum of 129 (in 2003), and then declined steadily to 99 vessels in 2006. The increase in number of vessels coincided with the fluctuations in the TAC. Effort as duration of trawling (h) varied from year to year, with highest effort in 2003.

On a seasonal basis, effort was highest in autumn, followed by winter, and spring and least in summer. Low effort in spring could be attributed to the low catchability of the main target species by the fishery, due to migration of these species to spawning grounds, as demonstrated by *M. capensis*, which spawns in Namibian waters and *M. paradoxus* which spawns on the west coast of South Africa (Kainge *et al*., 2007b). Thus, it is reasonable to think that skippers strive to increase or maintain their usual catch levels, when weather permits (Barbara Patersen, *pers. comm*.). Another reason which could influence high effort, is the management measure introduced in Namibia for a closed season in the month of October to allow hake to spawn (MFMR, 2007). In summer the effort is low due to the fact that most fishing companies have exhausted their quotas, and are waiting for the new TAC announcement. It is also break time for Christmas and New Year holidays.

Freezer vessels expend more effort per hour trawled and number of trawls per year than wetfish vessels; this is attributed to their capacity to stay at sea longer than wetfish vessels which spend only a few days (maximum of 5 days per trip) fishing before returning to port to land their iced catch. Catch per unit effort (CPUE) varied from year to year, being seasonally higher in summer and lowest in spring. Freezer vessels had higher CPUE than wetfish vessels. The CPUE was the same for central and northern regions but lowest in the south. It should be noted that high-resolution data on spatial and temporal distribution of trawling effort are needed to support assessments of the impacts of trawling on species, habitat, and ecosystems. The modelling of the data with GAM was unsuccessful due to data limitations, as information on other factors (e.g. actual horse-power used while trawling, distance to port, fuel consumption of vessels, and fish value etc.), which played a role in the dynamics of the hake bottom-trawl fishery, was not available. I would recommend that these factors and others not mentioned here, should be included in the commercial database in order to remedy this situation in the future.

Thus, this study has established, for the first time, the trawl intensity and fishing effort and their distribution with latitude and depth in Namibian waters. There are areas that are heavily and lightly fished along the Namibian coast, with most trawling by both freezer and wetfish vessels taking place in sand-mud and sand-gravelly sea bottoms in waters within the depth range 200 – 399 m. The lack of detailed data precluded further analysis of temporal and spatial trends in effort of the fleet segments.

Key Question 2: ***Are there any spatio-temporal changes in size structure, species composition and community structure of the demersal fish assemblages off Namibia that can be attributed to fishing?***

This key question was addressed in Chapters 4 and 5. Studies on demersal fish assemblages in the Benguela Ecosystem are limited to those of various authors (Lleonart and Roel, 1984; Macpherson and Roel, 1987; Mas-Riera *et al*., 1990; Bianchi *et al*., 2001) who have evaluated the structure of fish communities in the northern Benguela system. Bianchi *et al*. (2001) analysed changes (data from 1990 to 2000) in the size spectrum, diversity, species composition and trends in abundance of the dominating species, and found that the most evident changes were those related to overall abundance and diversity of the slope assemblage. This thesis analysed the same data as in Bianchi *et al*. (2001), but extended the analysis with six additional years of data and used additional techniques and analysis tools

(Chapter 3). The effects of bottom-trawling tend to be localised and thus were hidden at a large spatial scale (whole coast, shelf and slope), but were more pronounced at a small spatial scale (sub-regions).

Long-term spatio-temporal changes in the size structure of demersal fish assemblages were detected in all four sub-regions of Namibia. Changes were observed in the form of a reduction in mean catch rates of larger fish and increases in mean catch rates for smaller fish for the whole coast. However, the linear regression analysis of the mean catch rates, considered at a long term temporal and large spatial scale, was not significant for the coast of Namibia as a whole. This could be a result of broad scale analysis overshadowing localized effects of bottom-trawling. Thus, when the coast of Namibia is divided into continental shelf and slope, temporal patterns were observed in mean catch rates for both shelf and slope. The most notable, ecologically consistent pattern was the overall decline in the mean catch rate with an increase in fish size on both the continental shelf and slope. Also notable was the significant decline in the mean catch rate over the continental shelf for the size class (41 – 60 cm) over the study period, where 40 cm marks the legal lower size limit for the main target species of hake in Namibia. On the continental slope, the mean catch rates were significantly higher for the smallest size classes < 20 cm and 21 – 40 cm, in line with fish distribution. Significant declines were found in the mean catch rate of demersal fish species in size class 41 – 60 cm on the northern continental shelf and slope. Notable significant increases in mean catch rate, and marked high abundances of small fish < 40 cm were observed on the central continental shelf and slope, and northern slope.

The mean catch lengths of demersal fish surveyed off Namibia are also testimony, to some extent, to the variability in the size of fish sampled. Although there was no clear pattern for the slope, the shelf showed evidence of a declining trend in mean catch length, with steeper slopes of the size spectra indicating larger proportions of smaller fish, over the study period (1990 – 2006) (Chapter 4).

The size spectra of the demersal fish community for the whole coast also showed an overall downward trend, with respect to both steeper slope and reduced height. The size spectra for the continental shelf and slope depicted a typical size spectrum of an exploited fish assemblage, i.e. large abundances of small fish with relatively few large fish. The slopes and heights of the size spectra for both the continental shelf and slope depicted some changes. Consistent declines were found in the heights of the size spectra, suggesting a decline in the overall abundance of demersal fish on the continental shelf. By comparison, the heights of the size spectra on the continental slope showed an increasing trend from 1990 to 1999, and 2003 to 2006 (Chapter 4, Figure 4.10), which suggests an increase in overall abundance over the 17-year study period. Changes were found in the size spectra, whereby there was an increase in overall abundance of small fish, and a decline in large fish at a small spatial scale, which is an effect of fishing.

Characteristics of the size spectra may vary in different ecosystems, as fishing affects them differently (Pope and Knights, 1982; Murawski and Iodine, 1992). The Namibian sub-regions (northern slope and shelf; central slope and shelf; and southern slope and shelf) are serving as different macro-habitats within larger ecosystems. They have different characteristics ranging from wind stress and upwelling intensity, to bottom dissolved oxygen and are subjected to different fishing intensities (Chapter 5). The size spectral dynamics of the demersal fish species off Namibia were to some extent influenced by environmental variation in dissolved oxygen and temperature. It was further demonstrated by the PERMANOVA and DISTLM analyses that factors such as depth, region, year, and vessels had significantly contributed to the observed changes in the community structure of demersal fish species off Namibia. The mean catch length was significantly lower on the continental shelf than over the slope. The continental slope was marked by a significant increase in mean catch length over time. These changes in the mean length of demersal fish are directly attributable to the effects of fishing. The slopes of the size spectra for the Namibian continental shelf were quite variable with no clear pattern, whereas the continental slope (with its sub-regions) showed a declining trend (steeper, more negative slope) over time, suggesting a long-term shift in size composition of the demersal fish assemblage towards smaller fish (Chapter 4).

Changes in community structure were found using multivariate techniques: multidimensional scaling (MDS) and dendrograms showed three major distinct temporal groupings of demersal fish assemblages over the study period (Chapter 5). The groups (assemblages) consisted of the following year groups: 1990 – 1993, 1994 – 1999, and 2000 – 2006, respectively. Univariate techniques and generalized additive models (GAM) were also applied to establish the effects of physical factors on changes in diversity indices. The changes in diversity of demersal fish off Namibia are driven by species richness rather than evenness, according to the GAM results. The southern region was more diverse than the northern region, and this difference in diversity is attributed to the periodic occurrence of low oxygen and warm water events in the northern and central regions. These conditions have contributed to the observed distribution diversity patterns. Species richness increased with increasing depth and abundance, and peaked at mid-overall abundance, but declined at the highest abundance. The demersal fish assemblage on the continental shelf tended to be dominated by a few species (had low evenness); thus it is considered to be comparatively fairly disturbed (negative *W – statistic* with a large absolute value), while the slope assemblage had higher evenness, suggesting a moderately disturbed (negative *W– statistic* but close to zero) assemblage (Chapter 5), according to the classification of Warwick and Clarke (1994).

Spatially, the diversity of demersal fish species increased with increasing latitude, and increased with increasing depth. This was contrary to the effort distribution, which was higher in southern Namibia compared to central and northern Namibia, thus making the effects of bottom-trawling on species diversity difficult to distinguish in this case. However, there is a possibility that fishing may be partly responsible for the increase in diversity of demersal fish from the shelf to the slope, since ABC results (Chapter 5) suggested that the shelf assemblage was more disturbed than the slope assemblage.

Temporally, the species richness increased significantly with survey year. GAMs revealed that the strongest predictors of diversity were location (latitude, longitude) and abundance. Other environmental variables such as bottom dissolved oxygen cannot be ruled out in influencing diversity as was indicated by the DISTLM analyses. A previous study by Mas-Riera (1990) showed that fish diversity decreased in areas with low oxygen. MacPherson and Roel (1987) reported low diversity at depths below 200 m off northern Namibia between 19 ^{o}S and 23 ^{o}S, and this area has been reported to have frequent anoxic conditions (Chapman and Shannon, 1985). PERMANOVA results have shown the importance of vessel (old and new *R/V Dr Fridtjof Nansen*; and commercial vessels), depth, and bottom temperature as factors playing a role in influencing changes in demersal community structure, using species-based indicators (Chapter 5). GAM analysis suggests that among the factors used in the model, latitude and oxygen distribution had strong effects on the diversity of demersal fish species. Further analysis using DISTLM suggests bottom temperature variability also played a role in the observed changes in the community structure. More detailed sampling of the environmental variables at every station during future hake biomass surveys would be of great assistance in improving our understanding of demersal community diversity.

In summary, this study found that the observed changes in community structure are likely to have been caused mostly by bottom-trawling, and partly by the physical and environmental variability.

Key Question 3: ***How does bottom-trawling affect the fish communities in areas that are heavily and lightly trawled in the Benguela system?***

Most of the trawl impact studies around the world have been conducted on sandy seafloors and concentrated on invertebrates, e.g. Gulf of Alaska (Freese *et al*., 1999; Stone *et al*., 2005); eastern Bering Sea (McConnaughy *et al*., 2000, 2005); southeastern Bering Sea (Brown *et al*., 2005); Monterey Bay (Engel and Kvitek, 1998). At Coquille Bank, Oregon, Hixon and Tissot (2007) compared trawled versus untrawled mud seafloor assemblages of fishes and macroinvertebrates. Until this study, there was no empirical study of this nature in the Benguela System. However, lack of untrawled grounds of comparable habitats off Namibia makes it difficult to undertake comparative studies on the impacts of bottom-trawling in areas that are heavily trawled compared to lightly or untrawled areas. This experimental study was conducted in the Benguela ecosystem off southern Namibia and the north west coast of South Africa, in areas which were heavily and lightly trawled, but had similar physical variables such as depth, sediment type, temperature and dissolved oxygen.

The study involved replicate bottom-trawls as far as possible along the same tracks. This study compared fish assemblages found in both heavily and lightly trawled areas using multivariate analyses (cluster-analysis, MDS, k-dominance curves, ABC curves, Similarity Percentage (SIMPER); and Permutational Analysis of Variance (PERMANOVA). Heavily trawled areas had lower evenness than lightly trawled areas, and were dominated by a few species. The mean fish abundance (number per standardised catch) found during the experiment were higher at heavily trawled than at lightly trawled sites. However, the mean fish weight was not different for the two areas sampled. This suggests that heavily trawled areas have more small-bodied individuals than lightly trawled sites, which is a sign of disturbance mainly due to fishing. The diversity of demersal fish was higher at lightly trawled and lower at heavily trawled sites. The main target species *M. capensis and M. paradoxus,* as well as some other demersal fish species, are highly migratory species, which can move and replenish favourable habitats. A recent study in the same areas has shown that epifauna were more susceptible than infauna to bottom-trawling (Atkinson *et al*., 2011 in press). More empirical studies of this nature are needed to identify both the direct and indirect effects of bottom-trawling in the Benguela ecosystem.

The spatial pattern in the ABC curves and their corresponding *W– statistics* showed that Sam's Bank in Namibia was only lightly or moderately disturbed with respect to the demersal fish assemblages ($W \geq 0$), while Child's Bank in South Africa was more disturbed ($W < 0$) than Sam's Bank. The following species formed the common element of most assemblages (highest similarity percentages): rattails *Caelorinchus simorhynchus,* deep-water hake *M. paradoxus,* and small dragonet *Paracallionymus costatus,* in that order of dominance (Chapter 6).

Diversity differences between heavily and lightly trawled areas are due to different levels of bottom-trawling. Thus these results suggest that either bottom-trawling tends to increase dominance of a few species, or trawling grounds have less diverse communities than less-trawled areas. The higher overall catch in heavily trawled areas is the probable reason that they are targeted.

Key Question 4: a) ***Is there any latitudinal variation in the distribution and diversity of demersal fish assemblages from the Kunene River to the Agulhas Bank?***

b) How do the observed distribution and diversity patterns relate to factors such depth, abundance, latitude, longitude, year, and environmental variables?

Chapter 7 used a combination of both multivariate and univariate techniques to address these questions.The cluster analysis and MDS have shown that three main demersal fish assemblages can be distinguished, two in the northern Benguela (off Namibia) on the continental shelf and slope, and one in the southern Benguela (west coast of South Africa). The demersal fish assemblage in the southern Benguela as identified by cluster and MDS extends slightly beyond the border into the northern Benguela. This supports the idea that the Benguela System off Namibia and South Africa can be subdivided into the northern Benguela and southern Benguela systems, with the boundary south of Lüderitz in Namibia (Shannon, 1985; Shannon and Field, 1985; and re-emphasised in Hutchings *et al*., 2009 and the references therein). These two sub-systems are treated as being different due to their differences in oceanographic conditions as was established in various studies of the system (Andrews and Hutchings, 1980; Nelson and Hutchings, 1983; Shannon, 1985; Chapman and Shannon, 1985; Shannon and Pillar, 1986; Crawford *et al*., 1987; Shannon and Nelson, 1996; Hill *et al*., 1998; Field and Shillington, 2004; Mackas *et al*., 2006; Shannon *et al*., 2006; Shillington *et al*., 2006; van der Lingen *et al*., 2006). The Lüderitz upwelling cell provides a boundary especially for small pelagic fish (e.g. sardine and anchovy). Transboundary studies on the spawning of hake have been published, e.g. Kainge *et al.* (2008). Nevertheless, none of these studies looked at the latitudinal variation of assemblages of demersal fish species for the whole Benguela region from the Kunene River to Cape Agulhas.

Despite the occurrence of three demersal fish assemblages (two in northern Benguela and one in southern Benguela), which were identified by cluster analysis and ordination at 19% similarity, the southern Benguela assemblage split at 19% similarity, but it is split into shelf and slope at about 25% similarity. Two demersal fish assemblages (on the continental slope off northern and southern Benguela) were found to be moderately disturbed (W > 0 but close to zero), whereas the continental shelf assemblage in northern Benguela was found to be more disturbed (W < 0). Both diversity and density increased with increasing latitude. They were found to be relatively low in the northern Benguela and high in the southern Benguela, which could be attributed to different levels of bottom-oxygen and to some extent to different oceanographic conditions. The northern Benguela is known to have periodic intrusions of warm water from the equator and episodic hypoxic conditions (Monteiro and van der Plas, 2006; Monteiro *et al*., 2004; Bailey, 1991; Chapman and Shannon, 1985).

Univariate analyses indicated that diversity of demersal fish assemblages increased (*H'* values from 0.1 to 2.59) with increasing latitude (Chapter 7, Fig. 7.9 and 7.13). Diversity also increased with increasing depth, and this pattern was stronger off Namibia than in South Africa, with possible biodiversity hotspots off Cape Frio and off the Orange River (Chapter 7, Fig. 7.11 - 7.13). Fish densities were higher (mean: 11.7 kg/nm^2, ranging from 3 to 10612 kg/nm^2) off South Africa than off Namibia (mean: 3.6 kg/nm^2 ranging from 3 to 1687 kg/nm^2). Therefore, fish densities increased with increasing latitude. However, the bottom trawl intensities are similar in the northern (Chapter 2) and southern Benguela (Atkinson *et al*., 2011a; Wilkinson and Japp, 2005). Thus, the observed density distributions are due to environmental variables.

This study has shown that factors such as latitude and depth play important roles in the community structure, distribution, and density of demersal fish species in the northern and southern Benguela. Moreover, that diversity of demersal fish assemblages was also influenced by dissolved oxygen and depth.

8.4 Implications for fisheries management using an ecosystem approach

This thesis contributes to our understanding of the demersal fishery communities of the northern Benguela and identifies the need to conduct more studies of this nature, to explore other aspects not covered here. A result of problem-driven research of this nature is to guide policy makers on the possible management strategies for demersal fisheries off Namibia. The current study has shown significant changes in demersal fish community structure in space and time. The entire trawling grounds of Namibia are fully exploited by bottom trawlers; however the demersal fish communities in these areas mostly moderately disturbed. Thus, protection measures, such as closed areas, in appropriate ecologically important areas, could be of both ecological and economic benefit to Namibia specifically, but also the entire Benguela region. The ecosystem approach to the demersal fisheries in Namibia seeks a balance between, and integration of, conservation and use of the resources. For instance, the size limits, mesh size restrictions, closed season, trawl ban in waters shallow than 200 m (MFMR, 2006), are all measures that are conservation and resource-use based. Appropriate legislation is in place, but it is the interpretation and implementation of the legislations that may be a challenge.

This study has shown that effects of fishing differ between sub-regions off Namibia. Sub-divisions of the coast of Namibia into six sub-regions (northern shelf and slope; central shelf and slope; and southern shelf and slope) could therefore be beneficial in terms of management, as these could become management blocks for the bottom-trawled areas off Namibia. Increased monitoring and evaluation on a regular basis in one or two of these blocks, in addition to the EEZ-wide annual surveys as conducted currently, could provide high quality data needed to establish relevant indicators and thresholds (habitat status, species- and size-based indicators) for implementation of an EAF (Garcia *et al*., 2003) in Namibia. The concept of ABC curves and their associated *W– statistics,* as examined in Chapter 5, provides a promising first step.

In addition to the development of indicators and thresholds; trawl gear modifications; and improved education for stakeholders are likely to contribute to limiting the effects of fishing on demersal communities in the Benguela. These are outlined in the following sub-sections below:

Fishing gear modification: Although this is beyond the scope of this thesis, ensuring the selectivity of the fishing gear is the main aim of gear modification, such that undersized and non-target fish species can escape from the gear. Survey trawl data showed that both target and non-target species are caught in the trawl nets (Chapter 5). Fish behaviour becomes central to different designs of fishing gear, thus good knowledge of fish behaviour is required for this purpose. In an effort to reduce by-catch, it is generally accepted that the use of net panels of square mesh, which remain open during towing and allow undersized fish to escape, is better than diamond mesh (e.g., van Marlen, 2000). Considerations given to fish behaviour, especially with respect to by-catch, have led to the successful construction of fish exclusion devices, which are widely used in many fisheries and need to be evaluated in the northern Benguela. However, invertebrate by-catches appear unavoidable in bottom-trawls, as there is little to prevent them from been caught. Simple measures such as bobbins and rock hoppers keeping the ground rope from digging into the seafloor have reduced the impact, but trawl gear still damages a great deal of epibenthic fauna (van Marlen, 2000). The benefit of such gear modification should be explored for the Namibian demersal trawl fisheries.

Education: There is a need for awareness campaigns as part of management to inform and educate all stakeholders on issues pertaining to the sustainability of the fishery. A good understanding by all stakeholders of the importance of protecting and conserving marine fisheries resources would be of benefit, as such knowledge can enhance good compliance with the rules and regulations governing the resource use. Increased attention to the human dimension of an EAF would be beneficial as there is a knowledge gap in this area (Shannon, *et al*., 2010). More training workshops for all commercial fisheries in Namibia should be developed to cater for fishers, managers, fisheries observers, and compliance officers. This should be aimed at imparting some more skills and knowledge towards the implementation of the EAF, as was conducted in 2008 in South Africa by WWF Responsible Fisheries programme (Patersen and Petersen, 2010, Shannon *et al*., 2010). Scientific studies conducted in the Benguela System are usually published in international journals and written in a scientific style, which is not of direct benefit to the skippers and other non-academic stakeholders who have no access to such journals. These publications could be used to provide syntheses in local languages by local media. Outreach programmes could serve as a good tool for communication among fisheries managers, fishermen, consumers, communities and interest groups, but require journalists with good scientific understanding.

8.5. Conclusion

This thesis has followed several approaches, which quantified bottom-trawl intensity off Namibia for the first time and confirmed the various responses of demersal fish assemblages to bottom-trawling. The major aim was to assess the ecosystem effects of bottom-trawling in the Benguela Ecosystem, particularly the northern Benguela. Long-term retrospective data analysis, short-term data analysis, and the experimental approach all helped to unravel these effects. The demersal fish community composition and size structure has changed temporally (1990 – 2006), and these changes were more pronounced at a small spatial scale (sub-region level) than at the large spatial scale (over the whole coast), so that the effects of bottom-trawling were spatially localized off Namibia within different sub-regions. The demersal fish assemblage of the continental shelf was dominated by few species and had low evenness, low diversity, and large numbers of small fish. The continental slope assemblage was less dominated, had higher evenness, higher species richness, higher diversity, and more large fish. The *W– statistic* of the continental shelf assemblage was negative suggesting that it was disturbed, while the slope assemblage was moderately disturbed with *W– statistic* close to zero. The diversity of demersal fish increased with increasing latitude and depth, driven more by species richness than by evenness.

The experimental bottom-trawling study revealed that heavily trawled areas were characterized by large abundances of small fish and low diversity, while lightly trawled areas had greater abundances of large fish and higher diversity. Bottom-trawling intensity was patchily distributed off Namibia, with heavy trawling occurring more in southern Namibia than in central and northern Namibia. Three demersal fish assemblages (shelf and slope assemblages off northern Benguela were identified by a cluster analysis and MDS. The diversity and density of fish increased with increasing latitude.

The effects of fishing are evident in this thesis, but fishing alone is unlikely to be accountable for all these observed changes, as factors such as latitude, region, depth, and dissolved oxygen played important roles. More research on bottom-trawling impacts on demersal fish, and benthic invertebrates is needed to confirm the trends found here and to provide a longer time series of data. It is suggested that the hake biomass surveys should incorporate data on physical and chemical variables for each station sampled (e.g. temperature, salinity, O_2 concentration); and that all benthic invertebrates caught in the net are recorded. This holistic approach to sampling would enhance the usefulness of the data for the whole ecosystem and eventually provide a better scientific basis for an ecosystem approach to fisheries management. Overall, this thesis has demonstrated that effects of bottom-trawling on demersal fish communities are evident off Namibia, despite the complicating influence of environmental variability. The next step is research on how to limit and possibly mitigate them by appropriate management and education interventions. More research is encouraged in order to understand some aspects of these effects in future.

REFERENCES

AGARD, J.B.R., GOBIN, J., AND R.M. WARWICK. 1993. Analysis of marine macrobenthic community structure in relation to pollution, natural oil seepage and seasonal disturbance in a tropical environment (Trinidad, West Indies). *Mar. Ecol. Progr. Ser*. **92**: 233 – 243.

ALVERSON, D.L., FREEBERG, M.H., POPE, J.G., AND S.A. MURAWSKI. 1994. A global assessment of bycatch and discards. FAO *Fisheries Technical Paper* **339**, 233pp.

ANDERSON, M.J. 2005. PERMANOVA: a FORTRAN computer program for permutational multivariate analysis of variance. Department of Statistics, University of Auckland, New Zealand.

ANDREWS, W.R.H., AND L. HUTCHINGS. 1980. Upwelling in the southern Benguela Current. *Progr. Ocean.* **9**: 1 – 81.

ANNALA, J.H., SULIVAN, K.J., O'BRIEN, C.J., AND N.W.M. SMITH. 2001. Report from the Fisheries Assessment Plenary: Stock Assessments and Yield estimates. Ministry of Fisheries, 511. Online http://www.fish.govt.nz/sustainability/research/stock/status.htm [date accessed 06/08/2007].

ANON. 2000 – Report of the Benefit Stock Assessment Workshop, University of Cape Town, 20-24 November 2000, pp. 19.

AUSTER, P.J. AND R.W. LANGTON. 1999. The effects of fishing on fish habitat. In *Fish Habitat: Essential Fish Habitat and Rehabilitation*, Benaka, L.(ed.). *American Fisheries Society*, Bethesda, MD.

ATKINSON, L.J., LESLIE, R.W., FIELD, J.G., and A. JARRE. 2011a. Changes in the demersal fish assemblages on the west cost of South Africa, 1986 – 2009. *Afr. J. Mar.Sci*. **33** (1).

ATKINSON, L.J., FIELD, J.G., and L. HUTCHINGS. 2011b. Effects of demersal trawling along the west coast of southern Africa: multivariate analysis of benthic assemblages. *Mar. Ecol. Prog. Ser.* **430**: 241 - 255.

ATKINSON, L.J. 2010. Effects of demersal trawling on marine infaunal, epifaunal and fish assemblages: studies in the Southern Benguela and Oslofjord. *PhD thesis*. University of Cape Town, pp 141.

BABCOCK, R.C., KELLY, S., SHEARS, N.T., WALKER, J.W., and T.J. WILLIS. 1999. Changes in community structure in temperate marine reserves. Mar. Ecol. Prog. Ser. 189: 125 – 134.

BAILEY, G.W. 1991. Organic carbon flux and development of oxygen deficiency in modern Benguela continental shelf south 22oS spatial and temporal variability. In Tyson, R.V., and T.H. Pearson (eds.) *Modern, and Ancient Continental Shelf Anoxia,* 171 183.

BARTHOLOMAE, C., and A.K. VAN DER PLAS. 2007. Towards the development of environmental indices for the Namibian shelf, with particular reference to fisheries management. *Afr. J. Mar. Sci.* **29(1)**: 25 – 35.

BALL, B., MUNDAY, B., and I. TUCK. 2000a. Effects of otter trawling on the benthos and environment in muddy sediments. In: *Effects of fishing on non-target species and habitats: biological conservation and socio-economic issues*. Kaiser, M.J., and S.J. De Groot (Eds), Blackwell Science, Oxford, pp. 69 – 82.

BALL, B.J., FOX, G., and B.W. MUNDAY. 2000b. Long- and short-term consequences of a *Nephrops* trawl fishery on the benthos and environment of the Irish Sea. *ICES J Mar. Sci.* **57**: 1315 – 1320.

BAS, C. 2005. Fishery research: current approaches, tensions and emerging aspects. The future and how to approach it. *Sci. Mar*. **69**(suppl. 1): 139 – 156.

BEGG. G.A., and G. MARTEINSDOTTIR. 2002. Environmental and stock effects on spatial distribution and abundance of mature cod *Gadus morhua*. *Mar. Ecol. Prog. Ser*. **229**: 245 – 262.

BERGMAN, M.J.N, and P.J. MOORE. 2001. Mortality of *Asterias rubens* and *Ophiura ophiura* discarded in the *Nephrops* fishery of the Clyde Sea area, Scotland. *ICES J. Mar. Sci.* **58**: 531 – 542.

BERGMAN, M.J.N., and J.W. VAN SANTBRINK. 2000. Mortality in megafaunal benthic populations caused by trawl fisheries on the Dutch continental shelf in the North Sea in 1994. *ICES J. Mar. Sci*. **57**: 1321 – 1331.

BERGMAN, M.J.N., and M. HUP. 1992. Direct effects of beam trawling on macrofauna in a sandy sediment in the southern North Sea. *ICES J. Mar. Sci*. **49**: 48 – 49.

BIANCHI, G., HAMUKUAYA, H., AND O. ALVHEIM. 2001. On the dynamics of demersal fish assemblages off Namibia in the 1990s. In Payne, A.I.L., Pillar, S.C., and R.J.M. Crawford (Eds). A Decade of Namibian Fisheries Science. *S. Afr. J. mar. Sci*. **23**: 419 – 428.

BIANCHI, G., GILASON, H., GRAHAM, K., HILL, L., JIN, X., KORANTENG, K., MANICKCHAND-HEILMAN, S., PAYA, I., SAINSBURY, K., SANCHEZ, F, AND K, ZWANESBURG. 2000. Impacts of fishing on size composition and diversity of demersal fish communities. *ICES J. Mar. Sci.* **57**:558 -571.

BIANCHI, G., CARPENTER, K.E., ROUX, J – P., MOLLOY, F.J., BOYER, D., AND H.J. BOYER. 1999. Field guide to the living marine resources of Namibia. FAO species identification guide for fisheries purposes. Rome, FAO, 265 pp. 11 colour plates.

BIANCHI, G., K.E. CARPENTER, J.-P. ROUX, F.J. MOLLOY, D. BOYER AND H.J. BOYER. 1999. Field guide to the living marine resources of Namibia. FAO species identification guide for fishery purposes. Rome, FAO. 265 p., 11 colour plates.

BIANCHI, G., CARPENTER, K.E., ROUX, J – P., MOLLOY, F.J., BOYER, D., AND H.J. BOYER. 1993. Field guide to the living marine resources of Namibia. FAO field identification guide for fisheries purposes. Rome, FAO.

BLANCHARD, F., LELOC'H, F., HILY, C., AND J. BOUCHER. 2004. Fishing effects on diversity, size, and community structure of the benthic invertebrate and fish megafauna on the Bay of Biscay coast of France. *Mar. Ecol. Prog. Ser*., **280**: 249 – 260.

BORGMANN. U. 1987. Models on the slope of, and biomass flow up, the biomass size spectrum. *Can. J. Fish. Aquat. Sci*. **44**: 136 – 140.

BOTHA, L. 1980. The biology of Cape hakes *Merluccius capensis* Cast. and *M. paradoxus* Franca in the Cape of Good Hope area. *Ph.D. thesis*, University of Stellenbosch: 182 pp.

BOUDREAU, P.R. and L. E. DICKIE. 1992. Biomass spectra of aquatic ecosystems in relation to fisheries yield. *Can. J. Fish. Aquat. Sci*. **49**: 1528 – 1538.

BOYER, D.C. AND I. HAMPTON. 2001. An overview of the living marine resources of Namibia. In *A decade of Namibian Fisheries Science*. Payne, A.I.L., Pillar, S.C. and R.J.M. Crawford (eds). *S. Afr. J. Mar. Sci.* **23**: 5 – 35.

BOYER, D.C., KIRCHNER, C.H., MACALLISTER, M. K., STABY, A., AND B. I. STAALESEN. 2001. The Orange roughy Fishery of Namibia: Lessons to be learned about managing a developing fishery. In *A decade of Namibian Fisheries Science*. Payne, A.I.L., Pillar, S.C. and R.J.M. Crawford (eds). *S. Afr. J. Mar. Sci.* **23**: 205 – 221.

BRANCH, T.A. 2001. A review of orange roughy *Hoplostethus atlanticus* fisheries, estimation methods, biology and stock structure. In *A decade of Namibian Fisheries Science*. Payne, A.I.L., Pillar, S.C. and R.J.M. Crawford (eds). *S. Afr. J. Mar. Sci.* **23**: 181 – 203.

BROWN, E.J., FINNEY, B., HILLS, S., and M. DOMMISSE. 2005. Effects of commercial otter trawling on benthic communities in the southeastern Bering Sea. *Am. Fish. Soc. Symp*. **41**: 439–460.

BULMAN, C. M., AND J. A. KOSLOW. 1992. Diet and food composition of deep-sea fish, orange roughy *Hoplostethus atlanticus* (Pisces: Trachichthyidae), off southeastern Australia. *Mar. Ecol. Prog. Ser*. **82**: 115 – 129.

BURMEISTER, L. 2000 – Survey based assessment of the stock identity of *Merluccius paradoxus* FRANCA in the Benguela. M.Phil. Thesis, University of Bergen: 93 pp.

BURMEISTER, L. IILENDE, T. and O. ALVHEIM 2001 – Surveys of the hake stocks 16 January – 25 February 2002, Cruise Report No 1/2001, pp 89.

CASTILLO, J., BARBIERI, M.A, and A. GONZALEZ. 1996. Relationship between sea suface temperature, salinity, and pelagic fish distribution off northern Chile. *ICES J. Mar. Sci*. **53**(2): 139 - 146.

CHAPMAN, P., AND L.V. SHANNON. 1985. The Benguela Ecosystem, Part 2. Chemistry and related processes. *Ocean. Mar. Biol*. **23**: 183 – 251.

CLARK, M. R, ANDERSON, O.F., FRANCIS, R.I.C., AND D.M. TRACEY. 2000. The effects of commercial exploitation on orange roughy (*Hoplostethus atlanticus*) from the continental slope of the Chatham Rise, New Zealand, from 1979 to 1997. *Fish. Res.* **45**: 217 – 238.

CLARK, M. R. 1997. Report on deep-water resources of Namibia. The commercial fishery, stock assessment, proposed future research and management. Unpublished report. National Marine Information and Research Centre, Swakopmund, Namibia. WG/01/98/DWFWG/ORH: **11**: 47 pp.

CLARKE, K.R. AND R.N. GORLEY. 2006. *PRIMER v6. User Manual/Tutorials*. Plymouth Marine Laboratory, Plymouth. 190pp.

CLARKE, K.R. AND R.M. WARWICK. 2001. *Change in Marine Communities: an Approach to Statistical Analysis and Interpretation* (Second Edition). Plymouth Marine Laboratory, Plymouth. 144pp.

CLEVELAND, W.S. 1979. Robust locally weighted regression and smoothing scatterplots. *J. Amer. Stat. Assoc*. **74** (368): 829 – 836.

CLEVELAND, W.S., AND S.J. DEVLIN. 1988. Locally weighted regression: an approach to regression analysis by local fitting. *J. Amer. Stat. Assoc*. **83** (403): 596 – 610.

COCHRAN, W.G. 1977. Sampling techniques, 3rd edition. John Wiley & Sons, Chichester, pp. 428.

COHEN, D.M., INADA, T., IWAMOTO, T., AND N. SCIALABBA. 1990. FAO species catalogue, vol. 10. Gadiform fishes of the world (Order Gardiformes). An annotated and illustrated catalogue of cods, hakes, grenadiers, and other gadiform fishes known to date. FAO, Rome.

COLLIE, J. S, HALL. S. J., KAISER. M. J. AND I. R. POINER. 2000. A quantitative analysis of fishing impacts on shelf sea benthos. *J. Anim. Ecol*., **69:** 785–798.

COLLIE, J.S., ESCANERO, G.A., and P.C. VALENTINE. 1997. Effects of bottom fishing on the benthic megafauna of Georges Bank. *Mar. Ecol. Prog. Ser*. **155**: 159 – 172.

CRAWFORD, R.J.M., SHANNON, L.V., AND D.E. POLLOCK. 1987. The Benguela Ecosystem, Part 4. The major fish and invertebrate resources. *Ocean. Mar. Biol*. **25**: 353 – 505.

CURRIE, D.R., and G.D. PARRY. 1996. Effects of scallop dredging on a soft sediment community: a large-scale experimental study. *Mar. Ecol. Prog. Ser.* **134**:131–150.

DAAN, N., GISLASON, H., POPE, J.G., and J.C. RICE. 2005. Changes in the North Sea fish community: evidence of the indirect effects of fishing? ICES J Mar. Sci.62: 177 – 188.

DAYTON. .P. K., THRUSH. S. F., AGARDY. M. T. AND R. J. HOFMAN. 1995. Environmental effects of marine fishing. *Aquat. Conserv*., **5**: 205–232.

DEGNBOL, P., and A. JARRE. 2004. Review of indicators in fisheries management – a development perspective. In Ecosystem approaches to fisheries in the southern Benguela, Shannon, L.V., Cochrane, K.L., and S.C. Pillar (eds). Afr. J. mar. Sci. 26: 303 – 326.

DE SILVA, J., CONDREY, R., and B.THOMPSON. 2001. Profile of shark by-catch in the U.S. Gulf of Mexico Menhaden Fishery. *N. Am. J. Fish. Manage*. **21**: 111–124.

DIAL, R., and J. ROUGHGARDEN. 1998. The theory of marine communities – the intermediate disturbance hypothesis. *Ecol*. **79**: 1412 – 1424.

DOUBLEDAY, W.G and D. RIVARD (ed.) 1981. Bottom Trawl Surveys. *Can. Spec. Publ. Fish*. *Aquat. Sci.* **8:** 273

DRAPEAU, L., PECQUERIE, L., FREON, P., and L.J. SHANNON. 2004. Quantification and representation of potential spatial interactions in southern Benguela ecosystem. *Afr. J. mar. Sci*. **26**: 141 – 159.

DUBOCOCHKIN, A.S., AND A.N. KATLYAR. 1989. On the feeding of alfoncino (*Beryx splendens*). *J. Ichthyol.*, **29**(5): 1 – 8.

DULVY, N.K., POLNIN, N.V.C., MILL, A.C., and N.A. GRAHAM. 2004. Size structural change in lightly exploited coral reef fish communities: evidence for weak indirect effects. *Can. J. Fish. Aquat. Sci*. **61**: 466 – 475.

DUPLISEA, D.E., JENNINGS, S., and T.A. DINMORE. 2002. A size-based model of the impacts of bottom trawling on benthic community structure. *Can. J. Fish. Aquat. Sci.* **59**: 1785 -1795.

DUPLISEA, D.S, JENNINGS, S, MALCOM, S.J, PARKER, R AND B, SIVYER. 2001. Modelling potential impacts of bottom trawl fisheries on soft-sediment biogeochemistry in the North Sea. *Geochem. Trans*. **14**: 1 – 6.

DUPLISEA, D.E., KERR, S.R., and L.M. DICKIE. 1997. Demersal fish biomass size spectra on Scotian Shelf, Canada: species replacement at the shelfwide scale. *Can. J. Fish. Aquat. Sci.* **54**: 1725 – 1735.

ELLIOT, J.M. 1977. Some methods for the statistical analysis of samples of benthic invertebrates. Freshwater Biological Association Scientific Publication no. 25. 156 pp.

ENGEL, J., and R. KVITEK. 1998. Effects of otter trawling on a benthic community in Monterey Bay National Marine Sanctuary. *Conserv. Biol*. **12**: 1204–1214.

FAO. 2002. Report of the Reykjavik Conference on Responsible Fisheries in the Marine Ecosystem. Reykjavik, Iceland, 1 – 4 October 2001. *FAO Fisheries Report*, No. 658, Rome, 128pp.

FAO. 1995. *Code of Conduct for Responsible Fisheries*. FAO, Rome, 41pp.

FAUTH, J.E., BERNADO, J., CAMARA, M., RESETARITS (Jr), W.J., VAN BUSKIRK, J., AND S.A. MAcCOLLUM. 1996. Simplifying the Jargon of Community Ecology: A conceptual approach. *Amer. Natur*. **147**(2): 282 – 286.

FENTON, G. F., SHORT, S. A., AND D. A. RITZ. 1991. Age determination of orange roughy, *Hoplostethus atlanticus* (Pisces: Trachichthyidae) using ^{210}Pb:^{226}Ra disequilibria. *Mar. Biol*. **109**: 197 – 202.

FIELD, J.G., AND F.A. SHILLINGTON. 2004. Variability of the Benguela Current System. *In* Robinson, A.R., and K.H. Brink (eds.) The Sea, The Global Ocean, Interdisciplinary Regional Studies and Syntheses. Harvard University Press **14**: 833 – 860.

FIELD. J.G., CLARKE. K.R. AND R.M. WARWICK. 1982. A practical strategy for analysis of multispecies distribution patterns. *Mar. Ecol. Prog. Ser.*, **8**: 37 – 52.

FISHING INDUSTRY HANDBOOK. 2006. Fishing Industry Handbook: South Africa, Namibia, and Moçambique. George Warman Publications, 34th Edition.

FOGARTY, M.J., AND S.A. MURAWSKI. 1998. Large scale disturbance and structure of marine systems: fishery impacts on Georges Bank. *Ecol. Appl.* 8: S6 – S22.

FOLK, R.L. 1954. The distinction between grain size and mineral composition in sedimentary rock nomenclature: J. Geol. **62** (4): 344-359.

FRANCA, P. 1960. Nova contribución para o conhocimento do genero *Merluccius* no Atlantico Oriental ao Sud do Equador. *Mem. Jta. Invest. Ultramar Ser*. **2** (18): 57 – 101.

FREESE, L., AUSTER, P.J., HEIFETZ, J., AND B.L. WING. 1999. Effects of trawling on seafloor habitat and associated invertebrate taxa in the Gulf of Alaska. *Mar. Ecol. Prog. Ser*. **182**, 119–126.

FRÉON, P., and O.A. MISUND. 1999. *Dynamics of Pelagic Fish Distribution and Behaviour: Effects on Fisheries and Stock Assessment.* Oxford, Fishing News Books, 348 pp.

FRICKE, R. 1986. Callionymidae. *In* Smith M.M., and P.C. Heemstra (eds.). Smiths' sea fishes. Springer-Verlag, Berlin, p. 770 – 774..

FRID, C.L.J., HARWOOD, K.G., HALL, S.J and J.A. HALL. 2000. Long-term changes in the benthic communities on North Sea fishing grounds. *ICES J. Mar. Sci*. **57**: 1303 – 1309.

FROMENTIN, J-M. and A. FONTENEAU 2001 — Fishing effects and life history traits: a case study comparing tropical versus temperate tunas. *Fish. Res*. **53**: 133–150.

GAMMELSRØD, T., BARTHOLOMAE, C.H., BOYER, D.C., FILLIPE, V.L.L., AND M.J. O'TOOLE. 1998. Intrusion of warm surface water along the Angola-Namibian coast in February-March 1995. The 1995 Benguela Nino. *In* Pillar, S.C., Payne, A.I.L., and F.A. Shillington (eds) *Benguela Dynamics: Impacts of Variability on Shelf-Sea Environments and their Living Resources. S. Afr. J. Mar. Sci*. **19**: 41 – 56.

GARCIA, E.G., RAGNARSSON, S.A., STEINGRÍMSSON, S.A., NÆVESTAD, D., HARALDSSON, H., FOSSÅ, J.H., TENDAL, O.S., AND H. EIRÍKSSON. 2007. Bottom trawling and scallop dredging in the Arctic: Impacts of fishing on non-target species,vulnerable habitats, and cultural heritage. *Nordic Council of Ministers*, Copenhagen, Denmark, 375pp.

GARCIA, S., ZERBI, A., ALIAUME, C., DO CHI, T., and G. LASSERRE. 2003. The Ecosystem Approach to Fisheries. Issues, terminologies, principles, and institutional foundation, implementation and outlook. FAO Technical Paper **443**, 71 pp.

GISLASON, H., and J.C. RICE. 1998. Modelling the response of size and diversity spectra of fish assemblage to changes in exploitation. *ICES J. Mar. Sci*. **55**: 362 – 370.

GISLASON, H., SINCLAIR, M., SAINSBURY, K. and R. O'BOYLE. 2000. Symposium overview: incorporating ecosystem objectives within fisheries management. *ICES J. mar. Sci*. **57**: 468 – 475.

GORDOA, A., MASÓ, M., and L. VOGES. 2000. Monthly variability in the catchability of Namibian hake and its relationship with environmental seasosonality. *Fish. Res*. **48**: 185 – 195.

GORDOA, A., MACPHERSON, E., and M.P. OLIVAR. 1995. Biology and fisheries of Namibian hakes (*M. paradoxus* and *M. capensis*). In: *Hake Fisheries, Ecology and Markets*. Alheit, J., and T.J. Pitcher (eds). Chapman and Hall, London, pp. 49 - 88.

GORDOA, A, and C.M. DUARTE. 1991. Size-dependent spatial distribution of hake (*Merluccius capensis* and *Merluccius paradoxus*) in Namibian waters. *Can. J. Fish. Aquat. Sci*. **48:** 2095 – 2099.

GORDOA, A., and J.E. HIGHTOWER. 1991. Changes in catchability in a bottom-trawl fishery for Cape hake (*Merluccius capensis*). *Can. J. Fish. Aquat. Sci*. **48**: 1887 – 1991.

GORDOA, A., and E. MACPHERSON. 1991. Diurnal variation in the feeding activity and catch rate of cape hake (*Merluccius capensis* and *M. paradoxus). Fish. Res.* **12**: 299 – 305.

GORDON Jr, D.C., GILKINSON, K.D., KENCHINGTON, E.L.R., BOURBOUNNAISE, C., MacISAAC, K.G., McKEOWN, D.L., and W.P. VASS. 2005. Summary of the Grand Banks Otter Trawling Experiment (1993 – 1995): Effects on benthic habitat and macrobenthic communities. *Amer. Fish. Soc. Symp*., **41**: 411 – 424.

GREENSTREET, S.P.R., AND S.J. HALL. 1996. Fishing and the ground-fish assemblage structure in the north-western North Sea: an analysis of long-term and spatial trends. *J. Anim. Ecol*., **65**: 577 – 598.

GRIFFITHS. M.H. 2000. Long-term trends in catch and effort of commercial linefish off South Africa's Cape Province: snap-shots of the 20th Century. *S. Afr. J. mar. Sci*. **22**: 81 – 110.

GULLAND, J. A. and S. GARCIA. 1984. Observed patterns in multi-species fisheries. In *Exploration of Marine Communities.* May, R. M. (Ed). *Verlag – Springer*, Berlin. 155 – 190.

HAEDRICH, R. L. and S. M. BARNES. 1997. Changes over time of the size structure in an exploited shelf fish community. *Fish. Res*. **31**: 229 – 239.

HALL. S. J. 1998. The effects of fishing on marine ecosystems and communities. Blackwell Science, Oxford.

HALL-SPENCER, J., ALLAIN, V., FOSSÅ, J.H. 2002. Trawling damage to Northeast Atlantic ancient coral reefs. *Proc. R. Soc. Lond.* **269**: 507–511.

HALL-SPENCER, J, and P. MOORE. 2000. Scallop dredging has profound, long-term impacts on maerl habitats. *ICES J Mar. Sci* **557**: 1407–1415.

HAMUKUAYA, H., BIANCHI, G., and D. BAIRD. 2001. The structure of demersal assemblages off Namibia in relation to abiotic factors. In *A Decade of Namibian Fisheries Science.* Pyane, A. I. L., Pillar, S.C. and R. J. M. Crawford (eds). *S. Afr. J. mar. Sci.* **23**: 397 – 417.

HASTIE, T.J., and R.J. TIBSHIRANI. 1990. Generalized additive models. Chapman and Hall, London.

HEEMSTRA, P.C. 1986. Oplegnathidae. In: *Smiths's sea fishes*. Smith, M.M., and P.C. Heemstra (eds). Springer-Verlag, Berlin, p 632 – 633.

HERMALIN-VIVIEN, M., LE DIREACH, L., BAYLE-SEMPERE, J., CHARBONNEL, E., GARCIA-CHARTON, J.A., ODY, D., PEREZ-RUZAFA, A., RENONES, O., SANCHEZ-JEREZ, P., and C. VALLE. 2008. Gradients of abundance and biomass reserve boundaries in six Mediterranean marine protected areas: Evidence of fish spillover? *Biol. Conserv*. **141** (7): 1829 – 1839.

HERMSEN, J.M., COLLIE, J.S., and P.C. VALENTINE. 2003. Mobile fishing gear reduces benthic megafaunal production on Georges Bank. *Mar. Ecol. Prog. Ser*. **260**: 97 – 108.

HILL, A.E, VEALE, L., PENNINGTON, S., WHYTE, A., BRAND, A., R. HARTNOLL. 1999. Changes in Irish Sea benthos: possible effects of 40 years of dredging. *Est Coast and Shelf Sci* **48**: 739–750.

HILL, A.E., HICKEY, B.M., SHILLINGTON, F.A., STRUB, P.T., BRINK, K.H., BARTON, E.D., AND A.C. THOMAS. 1998. Eastern ocean boundaries. *In* Robinson, A.R., and K.H. Brink (eds.), The Sea, The Global Ocean, Interdisciplinary Regional Studies and Syntheses. John Wiley and Sons, New York, 11: 29 – 68.

HIXON, M.A., and B.N. TISSOT. 2007. Comparison of trawled vs untrawled assemblages of fishes and macroinvertebrates at Coquille Bank, Oregon. *J. Exp. Mar. Biol. Ecol*. **344**: 23 – 34.

HORN, P.L., TRACEY, D.M., AND M.R. CLARK. 1998. Between-area differences in age and length at first maturity of the Orange roughy *Hoplostethus atlanticus. Mar. Biol.* **132**:187 – 194.

HURLBERT, S.H. 1984. Pseudoreplication and the design of ecological field experiments. *Ecol. Monogr*. **54**: 187 – 211.

HUREAU, J.C., AND N.I. LITVINENKO. 1986. Scorpaenidae In: *Fishes of the North-eastern Atlantic and the Mediterranean*. Whitehead, P.J.P., Bauchot, M.L., Hureau, J.C., Nielsen, J., Tortonese, E. (eds). UNESCO, Paris, **3**: 1211 - 1229.

HUSE, I., HAMUKUAYA, H., BOYER, D.C., MALAN, P.E., AND T. STROMME. 1998. The diurnal vertical dynamics of Cape hake and their potential prey. In *Benguela Dynamics: Impacts of Variability on Shelf-Sea Environments and their Living Resources*. Pillar, S. C., Moloney, C. L., Payne, A. I. L., and F.A. Shillington (Eds). *S. Afr. J. mar. Sci.* **19**: 365 – 376.

HUTCHINGS, L., VAN DER LINGEN, C.D., SHANNON, L.J., CRAWFORD, R.J.M., VERHEYE, H.M.S., BARTHOLOMAE, C.H., VAN DER PLAS, A.K., LOUW, D., KREINER, A., OSTROWSKI, M., FIDEL, Q., BARLOW, R.G., LAMONT, T., COETZEE, J., SHILLINGTON, F., VEITCH, J., CURRIE, J.C., AND P.M.S. MONTEIRO. 2009. The Benguela Current: An ecosystem of four components. *Progr. Ocean*. **83**: 15 – 32.

ICES. 2000. Ecosystem effects of fishing. Proceedings of an ICES/SCOR Symposium held in Montpellier, France, 16 - 19 March 1999. *ICES J. Mar. Sci.* **57**: 465 – 792.

IILENDE T, STRØMME T and E. JOHNSEN 2001 – Dynamics of the pelagic component of Namibian hake stocks. In Payne AIL, Pillar SC, Crawford RJM (eds) *A decade of Namibian Fisheries Science. South African Journal of Marine Science* **23**: 337-346

IILENDE, T. JOHNSEN, E. KAINGE, P. IITA, A. VAN DER PLAS A. and N. LETH 2000 – Surveys of the hake stocks. *Cruise Report No 1/2000*. Ministry of Fisheries and Marine Resources, Swakopmund, Namibia, pp. 40.
INADA, T. 1981. Studies on the Merluciid fishes. *Bull. Far Seas Fish. Res. Lab*. **18**: 1 – 172.

INFOSA, 2010. FISH INFO network Market Report. INFOSA, Windhoek, Namibia.

INGÓLFSSON, Ó. JØRGENSEN, T. KATHENA, J. and P. SCHNEIDER 2005 – Diurnal vertical distribution of deepwater hake. BENEFIT surveys. *Preliminary Cruise report* No 9/2005, Ministry of Fisheries and Marine Resources, Swakopmund, Namibia

IWAMOTO, T, and E. ANDERSON. 1994. Review of the grenadiers (Teleostei: Gadiformes) of southern Africa, with descriptions of four new species. *Ichthyol. Bull.***61**: 1 – 28.

JENKINS, S., BEUKERS-STEWART, B., and A. BRAND. 2001. Impact of scallop dredging on benthic megafauna: A comparison of damage levels in captured and noncaptured organisms. *Mar. Ecol. Prog. Ser.* **215**: 297–301.

JENKINS, S., and A. BRAND. 2001. The effects of dredge capture on the escape response of the great scallop, *Pecten maximus* (L.): implications for the survival of undersized discards. *J. Exp. Mar. Biol. Ecol.* **266**: 33–50.

JENNINGS, S., NICHOLSON, M.D., DINMORE, T.A., and J. LANCASTER. 2002. The effects of chronic trawling disturbance on production of infaunal communities. *Mar. Ecol. Prog. Ser*. **243**: 251 – 260.

JENNINGS, S., DINMORE, T.A., DUPLISEA, D.E., WARR, K.J., and J.E. LANCASTER. 2001. Trawling disturbance can modify benthic production processes. *J. Anim. Ecol*. **70**: 459 - 475.

JENNINGS. S., GREENSTREET. S.P.R., and J.D. REYNOLDS. 1999. Structural changes in an exploited fish community: a consequence of differential fishing effects on species with contrasting life histories. *J. Anim. Ecol*. **68**: 617 – 627.

JENNINGS. S. AND M. J. KAISER. 1998. The effects of fishing on marine ecosystems. *Adv. Mar. Biol*., **34**: 201–352.

JOUFFRE, D., AND C.A. INEJIH. 2005. Assessing the impact of fisheries on demersal fish assemblages of the Mauritanian continental shelf, 1987 – 1999, using dominance curves. *ICES J. Mar. Sci*., **62**: 380 – 383.

KAINGE, P.,KATHENA, J., IITEMBU, J., and A. VAN DER PLAS. 2008. Surveys of hake stocks. *Survey No. 2008501*: 10 January – 15 February. Ministry of Fisheries and Marine Resources, Swakopmund, Namibia., pp 82.

KAINGE, P., KATHENA, J., IITEMBU. J., AND J. WEIDENGE. 2007a. Hake Cruise Report. MFMR, Swakopmund, Namibia. Cruise Report No. 1/2007. 97 pp.

KAINGE, P., KJESBU, O.S., THORSEN, A., AND A.G. SALVANES. 2007b. *Merluccius capensis* spawn in Namibian waters, but do *M. paradoxus*? *Afr. J. mar. Sci.* **29** (3): 379 – 392.

KAINGE, P.,KATHENA, J., IITEMBU, J., and J. WEIDENGE. 2006. Surveys of hake stocks. *Cruise Report No 1/2006***.** Ministry of Fisheries and Marine Resources, Swakopmund, Namibia, pp 75.

KAINGE, P. IILENDE, T. and VAN DER PLAS, A. 2004. Surveys of the hake stocks. *Cruise Report No 1/2004*. Ministry of Fisheries and Marine Resources, Swakopmund, Namibia, pp. 69.

KAINGE, P. IILENDE, T. JOHNSEN, E. and VAN DER PLAS, A. 2003. Surveys of the hake stocks. *Cruise Report No 1/2003*. Ministry of Fisheries and Marine Resources, Swakopmund, Namibia, pp. 63.

KAISER. M.J., COLLIE. J.S., HALL. S.J., JENNINGS. S. AND I.R. POINER. 2002. Modification of marine habitats by trawling activities: prognosis and solutions. *Fish and Fisheries*, **3**: 114 – 136.

KAISER, M.J., AND S.J. DE GROOT. 2000. *Effects of Fishing on Non-Target Species and Habitats. Biological Conservation and Socio-Economic Issues*. London, Blackwell Science: 399 pp.

KAISER, M.J., RAMSAY, K., RICHARSON, C., SPENCE, F., AND A. BRAND. 2000. Chronic fishing disturbance has changed shelf sea benthic community structure. *J. An. Ecol***. 69**: 494–503.

KAISER, M.J., and S.J. DE GROOT (eds). 1999. Effects of Fishing on Non-target Species and Habitats: Biological, Conservation and Socio-economic Issues. Blackwell Science, Oxford (UK).

KAISER, M.J. and B.E.SPENCER. 1996. The effects of beam-trawl disturbance on infaunal communities in different habitats. *J. Anim. Ecol*. **65**: 348 – 358.

KELLEHER, K. 2005. Discards in the world's marine fisheries: an update. *FAO Technical Paper* **470**, Rome, 131 pp.

KRAKSTAD, J. 2001. The Namibian Horse Mackerel stock. http://www.iodeweb1.vliz.be/odin/handle/1834/711. accessed date: 08 June 2007.

KRAMER, D.L., RANGELEY. R.W., and L.J. CHAPMAN. 1997. Habitat selection: patterns of spatial distribution from behavioural decisions. *In* Godin J-G. J. (ed.) *Behavioural Ecology of Teleost Fishes*. Oxford University Press, 37 – 80.

LABROPOULOU, M., AND C. PAPACONSTANTINOU. 2005. Effects of fishing on community structure of demersal fish assemblages. *Belg. J. Zool*., **135**(2): 191 – 197.

LAMBSHEAD, P.J.D., PLATT, H.M., AND K.M. SHAW. 1983. The detection of differences among assemblages of marine benthic species based on an assessment of dominance and diversity. *J. Natur. Hist*., **17**: 859 – 874.

LAURS, R.M., FIELDLER, P.C., and D.R. MONTEGOMERY. 1984. Albacore tuna catches distribution relative to environmental features observed from satellites. *Deep-Sea Res*. **31**: 439 – 453.

LE ROUX, L. 1997. Stock assessment and population dynamics of the deep-sea red crab *Chaceon maritae* (Brachyura, Geryonidae) off the Namibian coast. *M.Sc. thesis*. University of Iceland: 88 pp.

LEES. R. 1969. Fishing for Fortunes. The story of the Fishing Industry in Southern Africa – and the Men who Made It. *Purnell*, Cape Town, pp. 283.

LESCH, H. 1995. Cruise report R.V. Matsuyama Maru. Exploratory fishing of orange roughy, *Hoplostethus atlanticus*, on the southern Namibian shelf: 04/11/95-19/11/95. National Marine Information and Research Centre, Swakopmund, Namibia.

LESLIE, R. W., AND W. S. GRANT. 1990. Lack of congruence between genetic and morphometric stock structure of the southern African anglerfish *Lophius vomerinus*. *S. Afr. J. mar. Sci*. **9**: 379 – 398.

LINDEBOOM. H. J. AND S. J. DE GROOT. (ed.) 1998. The effects of different types of fisheries on the North Sea and Irish Sea benthic invertebrates. Netherlands Institute of Sea Fisheries, Texel.

LLEONART, J., AND B. A. ROEL. 1984. Analisis de las comunidades de peces y crustaceos demersales de la costa de Namibia (Atlantico Sudoriental). *Investigacion pesq*. **48**: 187-206.

MAARTENS, L. AND A.J. BOOTH. 2001. Stock assessment of the Namibian monkfish (*Lophius* species) resource. In *A decade of Namibian Fisheries Science.* Payne, A.I.L., Pillar, S.C. and R.J.M. Crawford (eds). *S.Afr. J. Mar. Sci.* **23**: 275 – 290.

MAARTENS, L. 1999. An assessment of monk fish resource of Namibia. *Ph.D. thesis*, Rhodes University, Grahamstown. 190 pp.

MACKAS, D., STRUB, P.T., THOMAS, A., AND V. MONTEIRO. 2006. Eastern ocean boundaries pan-regional overview. *In* Robinson, A.R., and K.H. Brink (eds.), The Sea, The Global Ocean, Interdisciplinary Regional Studies and Syntheses. Harvard University Press, Chapter **10**: 21 – 59.

MACPHERSON, E. 1985. Daily rations and feeding periodicity of some fishes off the coast of Namibia. *Mar. Ecol. Prog. Ser*. **26**(3): 253 – 260.

MACPHERSON, E. AND A. GORDOA. 1996. Biomass spectra in the benthic fish assemblages in the Benguela System. *Mar. Ecol. Prog. Ser*. **138**: 27 – 32.

MACPHERSON, E., AND A. GORDOA. 1994. Effect of prey densities on cannibalism in Cape hake (*Merluccius capensis*) off Namibia. *Mar. Biol.* **119**(1): 145 – 149.

MACPHERSON, E., AND A. GORDOA. 1992. Trends in the demersal fish community off Namibia from 1983 to 1990. *S. Afr. J. Mar. Sci.* **12**: 635 – 649.

MACPHERSON, E., AND B. A. ROEL. 1987. Trophic relationships in the demersal fish community off Namibia. *In*: Payne, A.I.L., Gulland, J.A., J.H. Brink. (Eds). The Benguela and comparable ecosystems. *S. Afr. J. mar. Sci*. **5**: 585 – 596.

MACPHERSON, E., MASO, M., BARANGE, M., and A. GORDOA. 1991. Relationship between measurements of hake biomass and Sea Surface Temperature off Southern Namibia. *S. Afr. J. Mar. Sci.* **10**: 213 – 217.

MAGNÚSSON, J.V., and J. MAGNÚSSON. 1995. The distribution, relative abundance and biology of the deep-sea fishes of the Icelandic slope and Reykjanes Ridge. *In* Hopper, A.G. (ed.), *Deep-water Fisheries of the North Atlantic Oceanic Slope*, pp 161 – 199. NATO ASI series E: *Applied Sciences*, **296**, 420 pp.

MARAVELIAS, C.D., and D.G. REID. 1997. Identifying the effects of oceanographic features and zooplankton on prespawning herring abundance using generalized additive models. *Mar. Ecol. Prog. Ser*. **147**: 1 – 9.

MAS-RIERA, J., LOMBARTE, A., GORDOA, A., AND E. MACPHERSON. 1990. Influence of Benguela upwelling on the structure of demersal fish populations off Namibia. *Mar. Biol*. **104**: 175 – 182.

MAUL, G.E**.** 1990. Berycidae. p. 626. In J.C. Quero, J.C. Hureau, C. Karrer, A. Post and L. Saldanha (eds.) Check-list of the fishes of the eastern tropical Atlantic (CLOFETA). JNICT, Lisbon; SEI, Paris; and UNESCO, Paris. Vol. 2. www.fishbase.org [Date accessed: 20/07/2011].

MAUL, G.E., 1986. Trachichthyidae. *In*: *Fishes of the north-eastern Atlantic and the Mediterranean*. Whitehead, P.J.P., Bauchot, M.-L., Hureau, J.-C. Nielsen, J. and E. Tortonese (eds.). UNESCO, Paris. 2: 749 - 752. Available Online: www.fishbase.org. [Date Accessed: 27/08/ 2008].

MAY, J.L. AND J.G.H. MAXWELL. 1986: Trawl fish from temperate waters of Australia.

McCONNAUGHEY, R.A., SYRJALA, S.E., and C.B. DEW. 2005. Effects of chronic bottom trawling on size structure of soft-bottom benthic invertebrates. *Am. Fish. Soc. Symp*. **41:** 425–437.

McCONNAUGHEY, R.A., MIER, K., DEW, C.B., 2000. An examination of chronic trawling effects on soft-bottom benthos of the eastern Bering Sea. *ICES. J. Mar. Sci.* **57**: 1377–1388.

McCULLAGH, P., and J.A. NELDER. 1989. Generalized Linear Models, 2nd ed. Chapman and Hall, 225 pp.

MERRET, N.R. AND R.L. HAIDERICH. 1997. Deep-Sea Demersal Fish and Fisheries. London, Chapman and Halls: 282pp.

MFMR. 2007. Report for the Marine Resources Advisory Council. Management recommendations for hake, orange roughy and monkfish. Ministry of Fisheries and Marine Resources, Swakopmund, Namibia, **March 2007**

MFMR. 2005. Report on issues raised by the Hon. Minister during his annual address to the fishing industry on 13th of April 2005. Ministry of Fisheries and Marine Resources, Swakopmund, Namibia, **December 2005**

MFMR. 2001a. Sea Fisheries Advisory Council. State of the environment and recommendations for hake and orange roughy. Ministry of Fisheries and Marine Resources, Swakopmund, Namibia, 1/2001.

MFMR. 2001b. Regulations relating to the exploitation of marine resources. *Government Gazette of the Republic of Namibia*, Windhoek, No. 241, 50 pp.

MFMR. 1991. White paper: Towards Responsible Development a Fishery Sector. Windhoek, Namibia. MFMR.

MILLIKEN, G. A., and D.E. JOHNSON. 1984. Analysis of Messy Data, Volume 1: Designed Experiments. New York: Van Nostrand Reinhold.

MILLS, C. M., TOWNSEND, S. E., JENNINGS, S., EASTWOOD, P. D., and C.A. HOUGHTON. 2007. Estimating high resolution trawl fishing effort from satellite-based vessel monitoring system data. *ICES J. Mar. Sci*. **64**: 248–255.

MILLNER ,R., WHITING, C.,and D. G. HOWLETT .1993. Estimation of discard mortality of plaice from small otter trawlers using tagging and cage survival studies*. ICES CM* 1993/G:24.

MOLONEY, C.L., FIELD, J.G., and M.L. LUCAS. 1991. The size-based dynamics of plankton food webs. II. Simulations of three contrasting southern Benguela food webs. *J. Plankton Res*. **13**: 1039 – 1092.

MONTEIRO, P.M.S., and A. VAN DER PLAS. 2005. Low Oxygen Waters (LOW) variability in the Benguela System: Key processes and forcing scales relevant to forecasting. *In* Shannon, V., Hempel, G., Malanotte-Rizzoli, P., Moloney, C., and J. Woods (eds.), *Large Marine Ecosystems*, **14**: 91 – 106.

MONTEIRO, P.M.S., VAN DER PLAS, A.K., BAILEY, G.W., and Q. FIDEL. 2004. Low Oxygen Variability in the Benguela System: a review and new understanding. *CSIR Report* (*Internally Peer Reviewed*) ENV-S-C-075, 67 pp.

MURAWSKI. S.M. 2000. Definitions of Overfishing from an Ecosystem Perspective. *ICES J. Mar. Sci*. **57**: 649 – 658.

MURAWSKI, S.A., and J.S. IODINE. 1992. Multispecies size composition: a conservative property of exploited fishery systems? *J. Northw. Atl. Fish. Sci.* **14**: 79 – 85.

NATIONAL RESEARCH COUNCIL. 2002. Effects of trawling and dredging on the seafloor habitats. *Natinal Academy Press*, Washington, D.C. 136 pp.

NATIONAL RESEARCH COUNCIL. 1994. *Improving the Management of U.S.Marine Fisheries*. *National Academy Press*, Washington, D.C.

NAKAMURA, I. AND PARIN N.V., 1993 FAO species catalogue. Snake mackerels and cutlassfishes of the world (families Gempylidae and Trichiuridae). An annotated and illustrated catalogue of the snake mackerels, snoeks, escolars, gemfishes, sackfishes, domine, oilfish, cutlassfishes, scabbardfishes, hairtails, and frostfishes known to date. FAO *Fish. Synop*. **125**(15):136.

NELSON, G., AND L. HUTCHINGS. 1983. The Benguela upwelling area. *Progr. Ocean*. **12**: 333 – 356.

NIELSEN, J.G., COHEN, D.M., MARKLE, D.F., and C.R. ROBINS. 1999. Ophidiiform fishes of the world (Order Ophidiiformes). An annotated and illustrated catalogue of pearlfishes, cusk-eels, brotulas and other ophiddiform fishes known to date. FAO Fisheries Synopsis no. 125, Vol. 18. Rome, FAO, 178 p. 136 figs.

OELOFSEN, B., AND A. STABY. 2003. Namibian Orange roughy. In *Deep Sea 2003: Conference on the Governance and Management of Deep-sea Fisheries*. Part 1: Conference Reports, Queenstown, New Zealand, 1 – 5 December 2003. Shotton, R. (ed.). FAO *Fisheries Proceedings* No 3/1. Rome, FAO. 2005. 718 pp.

OLIVAR, M-P, RUBIES, P.AND J. SALAT. 1988. Early life history and spawning of *Merluccius capensis* Castelnau in the Northern Benguela Current. *S. Afr. J.mar. Sci*. **6**: 245 – 254.

PARAMO, J., QUINONES, R.A., RAMIREZ, A., and R.WIFF. 2003. Relationship between small pelagic fishes and environmental factors in Colombian Caribbean Sea: an analysis based on hydroacoustic information. *Aquat. Living. Resour*. **16:** 239 – 245.

PATERSEN, B., and S.L. PETERSEN. 2010. The EAF implementation in South Africa: lessons learnt. *Mar. Polic.* **34**: 276 – 292.

PAULY, D., CHRISTENSEN, V., DALSGAARD, J., FROESE, R., AND F. TORRES. 1998. Fishing down marine food webs. *Sci*. **279**: 860 – 863.

PAULY, D. 1979. Theory and management of tropical multi-species stocks: a review, with emphasis on Southeast Asian demersal fisheries. *ICLARM* Studies and Reviews. International Centre for Living Aquatic Resources Management, Manila. No. 1. 35 pp.

PAXTON, J.R. 1999. *Berycidae*, Alphonsino. In:. FAO Species identification guide for fishery purposes. *The living marine resources of the WCP. Bony Fishes part 2 (Mugilidae to Carangidae)*. Carpenter, K.E., and V.H. Niem (eds). FAO, Rome, p 2218 – 2220.

PAYNE, A.I.L. AND A.E. PUNT. 1995. Biology and fisheries of South African Cape hakes (*M.capensis* and *M. paradoxus*). *In* Hake: Biology, Fisheries and Markets. Alheit. J and T.J. Pitcher (eds.) London: Chapman and Hall, pp. 15 – 47.

PAYNE, A.I.L. AND A. BADENHORST. 1989. Other groundfish resources. *In* Payne, A.I.L and R.J.M. Crawford (eds.) Oceans of Life off southern Africa. Vlaeberg Publishers, Cape Town, South Africa, pp. 380.

PAYNE, A.I.L., ROSE, B., AND R.W. LESLIE. 1987. Feeding of hake and a first attempt at determining their trophic role in South African west coast marine environment. *In* Payne. A.I.L., Gulland, J.A., and K.H. Brink (eds.), The Benguela and Comparable Ecosystems. *S. Afr. J. Mar. Sci*. pp. 471 – 501.

PECQUERIE, L., DRAPEAU, L., FREON, P., COETZEE, J.C, LESLIE, R.W., and M.H. GRIFFITHS. 2004. Distribution patterns of key fish species of the southern Benguela Ecosystem: an approach combining fishery-dependent and fishery-independent data. *Afr. J. Mar. Sci.* **26**: 115 – 139.

PIANKA, E.R. 1970. On r and K selection. *Amer. Natur*. **104**: 592 – 597.

PIELOU, E.C. 1966. Species diversity and pattern diversity in the study of ecological succession. *J. Theor. Biol*. **10**: 370 – 383.

PILLAR, S. C., AND M. BARANGE. 1995. Diel feeding periodicity, daily ration, and vertical migration of juvenile Cape hake off the west coast of South Africa. *J. Fish Biol.* **47**(5): 753 -768.

POPE, J.G., and B.J. KNIGHTS. 1982. Comparison of length distributions of combined catches of all demersal fishes in surveys in the North Sea and Faroe Bank. *In* Mercer, M.C. (ed.). Multispecies approaches to fisheries management advice. *Can. Spec. Publ. Fish. Aquat. Sci*. No. 9.

PRANOVI, F., RAICEVICH, S., FRANCESCHINI, G., TORRICELLI, P., and O. GIOVANARDI. 2001. Discard analysis and damage to nontarget species in the "rapido" trawl fishery. *Mar Biol* **139**: 863–875.

PRENA, J., SCHWINGHAMER, P., ROWELL, T.W., GORDON, J.D.C., GILKINSON, K.D., WASS, W.P., AND D.L. McKEOWN. 1999. Experimental otter trawling on a sandy bottom ecosystem of the Grand Banks of Newfoundland: analysis of trawl bycatch and effects on epifauna. *Mar Ecol Prog Ser* **181**: 107–124.

PUNT, A. E., LESLIE, R. W. AND S.E. DU PLESSIS. 1992. Estimation of annual consumption of food by Cape hake *Merluccius capensis* and *M. paradoxus* of the South African west coast. In *Benguela Trophic Functioning*. Payne, A. I. L., Brink, K. H., Mann, K. H., and R. Hilborn (eds). *S. Afr. J. mar. Sci.* **12**: 611 – 512.

QUEIROS, A.M., HIDDINK, J.G., KAISER, M.J., and H. HINZ. 2006. Effects of chronic bottom trawling disturbance on benthic biomass, production and size spectra in different habitats. *J. Exp. Mar. Biol. Ecol*. **335**: 91 – 103.

QUETGLAS, A., ALEMANY, F., CARBONELL, A., MERELLA, P., and P. SANCHEZ. 1999. Diet of the European flying squid *Todarodes sagittatus* (Cephalopda: Ommastrephidae) in the Balearic Sea (western Mediterranean). *J. Mar. Biol. Ass. UK*. **79**: 479 – 486.

R Development Core Team. 2010. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org.

RAGNARSSON, S. A and S. A. STEINGRÍMSSON. 2003. Spatial distribution of otter trawl effort in Icelandic waters: comparison of measures of effort and implications for benthic community effects of trawling activities. *ICES J. Mar. Sci*. **60**: 1200 – 1215.

RAISZ, E. 1948. *General Cartography*. New York, McGraw-Hill, 54 – 62.

RICE, J., AND M-J. ROCHET. 2005. A framework for selecting a suite of indicators for fisheries management. *ICES J. Mar. Sci*. **62**: 516 – 527.

RICE, J.C. 2003. Environmental health indicators. *Ocean and Coastal Management*. **46**: 235 – 259.

RICE, J.C. 2000. Evaluating fishery impacts using metrics of community structure. *ICES J. Mar. Sci.* **57**: 682 – 688.

RICE, J. C. and H. GISLASON. 1996. Patterns of change in the size spectra of numbers and diversity of the North Sea fish assemblage, as reflected in survey and models. *ICES J. mar. Sci*. **53**: 1214 – 1225.

RIJNSDORP, A.D., BUYS, A.M., STORBECK, F., and E.G. VISSER. 1998. Micro-scale distribution of beam trawl effort in the southern North Sea between 1993 and 1996 in relation to the trawling frequency of the sea bed and the impact on benthic organisms. *ICES J. Mar. Sci*. **55** 403 – 419.

RIJNSDORP, A.D., VAN LEEUWEN, P.I., DAAN, N., AND H.J.L. HEESSEN. 1996. Changes in abundance of the demersal fish species in the North Sea between 1906 – 1909 and 1990 – 1995. *ICES J. mar. Sci.*, 53: 1054 – 1062.

ROCHET, M. J. and V. M. TRENKEL. 2003. Which community indicators can measure the impact of fishing? A review and proposals. *Can. J. Fish. aquat. Sci*. **60**: 86 – 99.

ROEL, B. A. AND E. MACPHEARSON. 1988. Feeding of *Merluccius capensis* and *M. paradoxus* off Namibia. *S. Afr J. mar. Sci.* **6**: 227 – 243.

ROEL, B.A. 1987. Demersal communities off the west coast of South Africa. *In* Payne, A.I.L., Gullard, J.A., and K.H. Brink (eds.), The Benguela and comparable ecosystems. *S. Afr. J. Mar. Sci.*, **5**: 575 – 584.

RUSSELL, S.1993. Shark by-catch in the northern Gulf of Mexico tuna longline fishery, 1988–91m with observations on the nearshore directed shark fishery. *In*: Branstetter S (ed) Conservation biology of Elasmobranchs. NOAA *Technical Report* NMFS, 19–30.

SAETERSDAL, G., BIANCHI, G., STROMME, T., AND S.C. VENEMA. 1999. The *Dr Fridtjof Nansen* Programme 1975 – 1993. Investigation of fishery resources in developing countries: History of the programme and review of results. FAO. *Fish. tech. Pap*. **392**: 434 pp.

SAINSBURY, K. J., CAMPBELL, R. A., LINDHOLM, R., and A. W. WHITELAW. 1997. Experimental management of an Australian multi-species fishery: examining the possibility of trawl-induced habitat modification. In Global Trends: Fisheries Management. Pikitch, E. K., Hupert, D. D. and M. P. Sessenwine (Eds). Bethesda, Maryland, 328 pp. *Amer. Fish. Societ*. 107 – 112.

SANCHEZ, P., SARTOR, P., RECASENS, L., LIGAS, A., MARTIN, J., DE RANIERI, S., and M, DEMESTRE. 2007. Trawl catch composition during different fishing intensity periods in two Mediterranean demersal fishing grounds. *Sci. Mar*. **71** (4): 765 – 773.

SCHEJTER, L., BREMEC, C.S., AND D. HERMANDEZ. 2008. Comparison between disturbed and undisturbed areas of the Patagonian scallop (*Zygochlamys patagonica*) fishing ground “Reclutas” in the Argentine Sea. *J. Sea. Res*. **60**: 193 – 2000.

SHANNON, L.J., JARRE, A.C., and S.L. PETERSEN. 2010. Developing a science base for the ecosystem approach to fisheries in South Africa. *Progr. Ocean*. **87**: 289 – 303.

SHANNON, L.V. 1985. The Benguela Ecosystem, Part 1. Evolution of the Benguela, physical features and processes. *Ocean. Mar. Biol.*, 23: 105 – 182.

SHANNON, L.V., AND G. NELSON. 1996. The Benguela: large scale features, processes and system variability. In Wefer, G., Berger, W.H., Siedler, G., and D.J. Webb (eds.), The South Atlantic: Present and Past Circulation. Springer-Verlag, Berlin, Heidelberg, 163 – 210 pp.

SHANNON, L.V., AND S.C. PILLAR. 1986. The Benguela ecosystem, Part 3. Plankton. *Ocean. Mar. Biol.*, 24: 65 – 170.

SHANNON, L.V., HEMPEL, G., MALANOTTE-RIZZOLI, P., MOLONEY, C.L., AND J. WOODS (Eds.). 2006. Benguela: Predicting a Large Marine Ecosystem. Large Marine Ecosystems 14, Elsevier, Amsterdam, 410 pp.

SHARP, G. and J. CSIRKE. 1984. Proceedings of the Expert Consultation to examine changes in abundance and species composition of the neritic fish resources, (Eds). *FAO Fisheries Report 291*, vol. **2**. 553 pp.

SHEA, K., ROXBURG, S.H., and E.S.J. RAUSCHERT. 2004. Moving from patterns to process: coexistence mechanisms under the intermediate disturbance regimes. *Ecology Letter (Review)*, **7**: 491 – 508.

SHILLINGTON, F.A., REASON, C.J.C., DUNCOMBER-RAE, C.M., FLORENCHIE, P., AND P. PENVEN. 2006. Large scale physical variability of the Benguela Current Large Marine Ecosystem (BCLME). *In* Shannon, L.V., Hempel, G., Malanotte-Rizzoli, P., Moloney, C.L., and J. Woods (Eds.), Benguela: Predicting a Large Marine Ecosystem. Large Marine Ecosystems 14, Elsevier, Amsterdam, 49 – 70 pp.

SHIN, Y-J., ROCHET, M-J., JENNINGS, S., FIELD, J.G., and H. GISLASON. 2005. Using size-based indicators to evaluate the ecosystem effects of fishing. *ICES J. mar. Sci*. **62**: 384 – 396.

SHIN, Y-J., and P. CURRY. 2004. Using an individual based model of fish assemblages to study the response of size spectra to changes in fishing. *Can. Fish. Aquat. Sci*. **61**: 414 – 431.

SMALE, M.J., ROEL, B.A., BADENHORST, A., AND J.G. FIELD. 1993. Analysis of the demersal community of fish and cephalopods on the Agulhas Bank, South Africa. *J. Fish. Biol*. **43**: 169 – 191.

SMITH, D. C., FENTON, G. E., ROBERTSON, S. G., AND S. A. SHORT. 1995. Age determination and growth of orange roughy (*Hoplostethus atlanticus*): A comparison of annulus counts with radiometric ageing. *Can. J. Fish. aquat. Sci.* **52**(2): 391 – 401.

STATSOFT, Inc. 2007. STATISTICA (Data analysis software system), v8. Available on line: www.statsoft.com [accessed date: 2008-11-25].

STONE, R.P., MASUDA, M.M., and P.W. MALECHA. 2005. Effects of bottom trawling on soft-sediment epibenthic communities in the Gulf of Alaska. *Am. Fish. Soc. Symp*. **41**: 461–475.

STRØMME, T., KAINGE, P., LIPINSKI, M., OSTROWSKI, M., STENEVIK, E. K., AND O. ALVHEIM. 2006. A trans-boundary survey between Namibia and South Africa with focus on spawning and early life history of hakes. BCLME Survey No. 3/2005 (Cruise Report No. 10/2005), Ministry of Fisheries and Marine Resources, Swakopmund.

STRØMME, T., LIPINSKI, M., OSTROWSKI, M., AND O. ALVHEIM. 2005. A transboundary survey between Namibia and South Africa with focus on shared stocks of hake. BCLME Survey No. 1/2005 (Cruise Report No. 2/2005), Ministry of Fisheries and Marine Resources, Swakopmund.

STRØMME, T., LIPINSKI, M., OSTROWSKI, M., AND O. ALVHEIM. 2004. A transboundary study with emphasis on deep-water hake in the Lüderitz – Orange River cone area. BCLME Survey No. 3/2004 (Cruise Report No. 10/2004), Ministry of Fisheries and Marine Resources, Swakopmund.

STRØMME, T. 1992. NAN-SIS: Software for fishery survey data logging and analysis. User's manual. FAO Computerised information series (Fisheries), No. 4. Rome, FAO., pp. 103.

SWARTMAN, G., HUANG. C., and S. KALUZNY. 1992. Spatial analysis of Berring Sea groundfish survey data using generalized additive models. *Can. J. Fish. Aquat. Sci.* **49**: 943 – 962.

TAYLOR, J.C., and P. S. RAND. 2003. Spatial overlap and distribution of anchovies (*Anchoa sp*.) and copepods in shallow stratified estuary. *Aquat. Living. Resour*. **16**: 191 - 196.

TRAUT, P. J. 1996. Diet and annual consumption for the Cape hakes on the Namibian shelf, with special reference to cannibalism. *M.Phil*. thesis, University of Bergen: 66pp.

TUCK, I.D,, HALL, S.J., ROBERTSON, M.R., ARMSTRONG, E., and D.J. BASFORD. 1998. Effects of physical trawling disturbance in a previously unfished sheltered Scottish sea Loch. *Mar. Ecol. Prog. Ser.* **162**: 227–242.

United Nations. 2005. Millenium Development Goals. UN, Rome. Available online: http://www.un.org/milleniumgoals/poverty.shtml (Accessed: 04 October 2009).

United Nations. 1992. Report on the UN Conference on Environment and Development. General Assembly, Rio de Janeiro, 3 – 14 June 1992. A/Conf.151/26, vol. I. (http://www.un.org/esa/dsd/agenda21 (Accessed date: 10 April 2010).

VAN DER LINGEN, C.D., SHANNON, L.J., CURY, P., KREINER, A., MOLONEY, C.L., ROUX, J-P., AND F. VAZ-VELHO. 2006. Resource and ecosystem variability, including regime shifts in the Benguela Current System. *In* Shannon, L.V., Hempel, G., Malanotte-Rizzoli, P., Moloney, C.L., and J. Woods (Eds.), Benguela: Predicting a Large Marine Ecosystem. Large Marine Ecosystems 14, Elsevier, Amsterdam, 147 – 185.

VAN DER WESTHUIZEN, A. 2001. A decade of exploitation and management of the Namibian hake stock. In *A decade of Namibian Fisheries Science.* Payne, A.I.L., Pillar, S.C. and R.J.M. Crawford (eds). *S. Afr. J. Mar. Sci.* **23**: 307 – 315.

VAN ECK, T.H. 1969. The South African hake: *Merluccius capensis* or '*Merluccius paradoxus*'? *S.Afr. Shipp News Fish Ind. Rev*. **24**: 95 – 97.

VEALE, L.O., HILL, A.S., HAWKINS. S., and A.R. BRAND. 2000. Effects of long-term physical disturbance by commercial scallop fishing on subtidal epifaunal assemblages and habitats. *Mar. Biol*. **137**: 325–337.

VOGES, E. 2003. Assessment of patterns in the Namibian hake fishery based on commercial fisheries data, in relation to environmental factors. PhD thesis, Zoology Department, University of Cape Town, 122 pp.

VOGES, E. 1999 – Surveys of the Namibian hake stocks. Cruise Report No 1/1999. Ministry of Fisheries and Marine Resources, Swakopmund, pp 34 + 38 pp. of Appendices.

VOGES, E., GORDOA, A., BARTHOLOMAE, C., and J.G. FIELD. 2002. Estimating the probability of different levels of recruitment for Cape hakes off Namibia, using environmental indices. *Fish. Res.* **58**: 333 – 340.

WALMSLEY, S.A., LESLIE, R.W., AND W.H.H. SAUER. 2007. Bycatch and discarding in South African demersal trawl fishery. *Fish. Res*. **86**: 15 – 30.

WARWICK, R.M. 1993. Environmental impact studies on marine communities: pragmatical considerations. *Aust. J. Ecol.* **18**: 63 – 80.

WARWICK, R.M. 1988. Analysis of the community attributes of the macrobenthos of Frierfjord/Langesundfjord at taxonomic levels higher than species. *Mar. Ecol. Progr. Ser*. **46**: 167 – 170.

WARWICK, R.M. 1986. A new method for detecting pollution effects on marine macrobenthic communities. *Mar. Biol.* **92**: 557 – 62.

WARWICK, R.M., and K.R. CLARKE. 1994. Relearning the ABC: taxonomic changes and abundance/biomass relationships in disturbed benthic communities. *Mar. Biol*. **118**: 739 – 744.

WARWICK, R.M., and K.R. CLARKE. 1993. Comparing the severity of disturbance: a meta-analysis of marine macrobenthic community data. *Mar. Ecol. Progr. Ser*. **92**: 221 – 231.

WARWICK, R.M., PEARSON, T.M., AND RUSHWAHYUNI. 1987. Detecting pollution effects on marine macrobenthos: further evaluation of the species abundance/biomass method. *Mar. Biol*. **95**: 193 – 200.

WATERMEYER, K.E., SHANNON, L.J., ROUX, J-P, AND C.L. GRIFFITHS. 2008. Changes in the trophic structure of the northern Benguela before and after the onset of industrial fishing. *Afr. J. Mar. Sci.* **30** (2):

WATLING, L. and E.A. NORSE, 1998. “Disturbance of the Seabed by Mobile Fishing Gear: A Comparison to Forest Clearcutting” *Conserv. Biol.* **12(6):**1180-1197.

WATSON, R., and D. PAULY. 2001. Systematic distortions in world fisheries catch trends. *Nature*. **414**: 534 – 536.

WILKINSON, S., and D. JAPP. 2005. Description and evaluation of the Hake-directed trawling intensity on benthic habitats in South Africa. *Fisheries and Oceanographic Support Services cc*. 69 pp.

WOOD, S.N. 2011. “mgcv: GAMs with GCV/AIC/REML smoothness estimation and GAMs by PQL”. http://cran.r-project.org/web/packages/mgcv/mgcv.pdf [date accessed: 20 May 2011].

WOOD. S.N. 2009. “mgcv: GAMs with GCV/AIC/REML smoothness estimation and GAMs by PQL”. http://cran.r-project.org/src/contrib/PACKAGES.html#mgcv. [date accessed: 10 July 2010].

WOOD, S.N. 2008. Fast stable direct fitting and smoothness selection for generalized additive models. *J. Royal Stat. Soc.* (B) **70**(3):495-518.

WOOD. S.N. 2006. Generalized Additive Models: an introduction with R. Chapman-Hall.

WOOD, S.N. 2004. Stable and efficient multiple smoothing parameter estimation for generalized additive models. *J. Amer. Stat. Assoc*. **99**:673-686.

WOODHEAD, P.M.J., HAMUKUAYA, H. AND M. J. O’TOOLE. 1996. Co-operative studies on the ecology of Cape hake in Namibian waters with particular reference to the effects of low oxygen conditions. In *Proceedings of a Seminar and Workshop, The Benguela Current and Comparable Eastern Boundary Upwelling Systems, Swakopmund, Namibia, May* 1995: 112 – 116.

WOODHEAD, P.M.J., HAMUKUAYA, H., O' TOOLE, M.J., STRØMME, T., and S. KRISTMANNSSON. 1997a. Recruit mortalities in Cape hake, following exclusion from shelf habitat by persistent hypoxia in the Benguela current.In *ICES International Symposium, Recruitment Dynamics of Exploited Marine Populations: Physical-Biological Interactions*, September 22 – 24, Baltimore, Maryland, pp 26 – 27.

WOODHEAD, P.M.J., HAMUKUAYA, H., O' TOOLE, M.J., STRØMME, T., SAETERSDAL. G., and M. REISS. 1997b. Catastrophic loss of two billion Cape hake recruits during wisespread anoxia in the Benguela Current off Namibia. In *ICES International Symposium, Recruitment Dynamics of Exploited Marine Populations: Physical-Biological Interactions*, September 22 – 24, Baltimore, Maryland, pp 105 – 106.

WOODHEAD, P.M.J., HAMUKUAYA, H., O' TOOLE, M.J., and M. McENROE. 1998. Effects of oxygen depletion in shelf waters on hake population off central and northern Namibia. In Shannon, V., and M. O' Toole (eds) *International Symposium, Environmental Variability in the South East Atlantic.* National Marine Information and Research Centre, MFMR, Swakopmund, Namibia.

YEMANE, D., FIELD, J.G., and R.W. LESLIE. 2008. Indicators of change in the size structure of fish communities: A case study from the south coast of South Africa. *Fish. Res*. **93**: 163 – 172.

YEMANE, D., FIELD, J.G., AND R. LESLIE. 2005 a. Exploring the effects of fishing on fish assemblages using Abundance Biomass Comparison (ABC) curves. *ICES J. Mar. Sci*. **62**: 374 – 379.

YEMANE, D., GRIFFITHS, M. H. and J. G. FIELD. 2005 b. Comparison of fish community size spectra based on length frequencies and mean lengths: a note. *Afr. J. mar. Sci*. **27**(1): 337 – 341.

YEMANE, D., FIELD, J. G., and M. GRIFFITHS. 2004. Effects of fishing on the size and dominance structure of the linefish of the Cape region, South Africa. *In* Ecosystem Approaches to Fisheries in the Southern Benguela. Shannon, L. J., Cochrane, K. L. and S.C. Pillar (Eds). *Afr. J. mar. Sci*. **24**: 161 – 177.

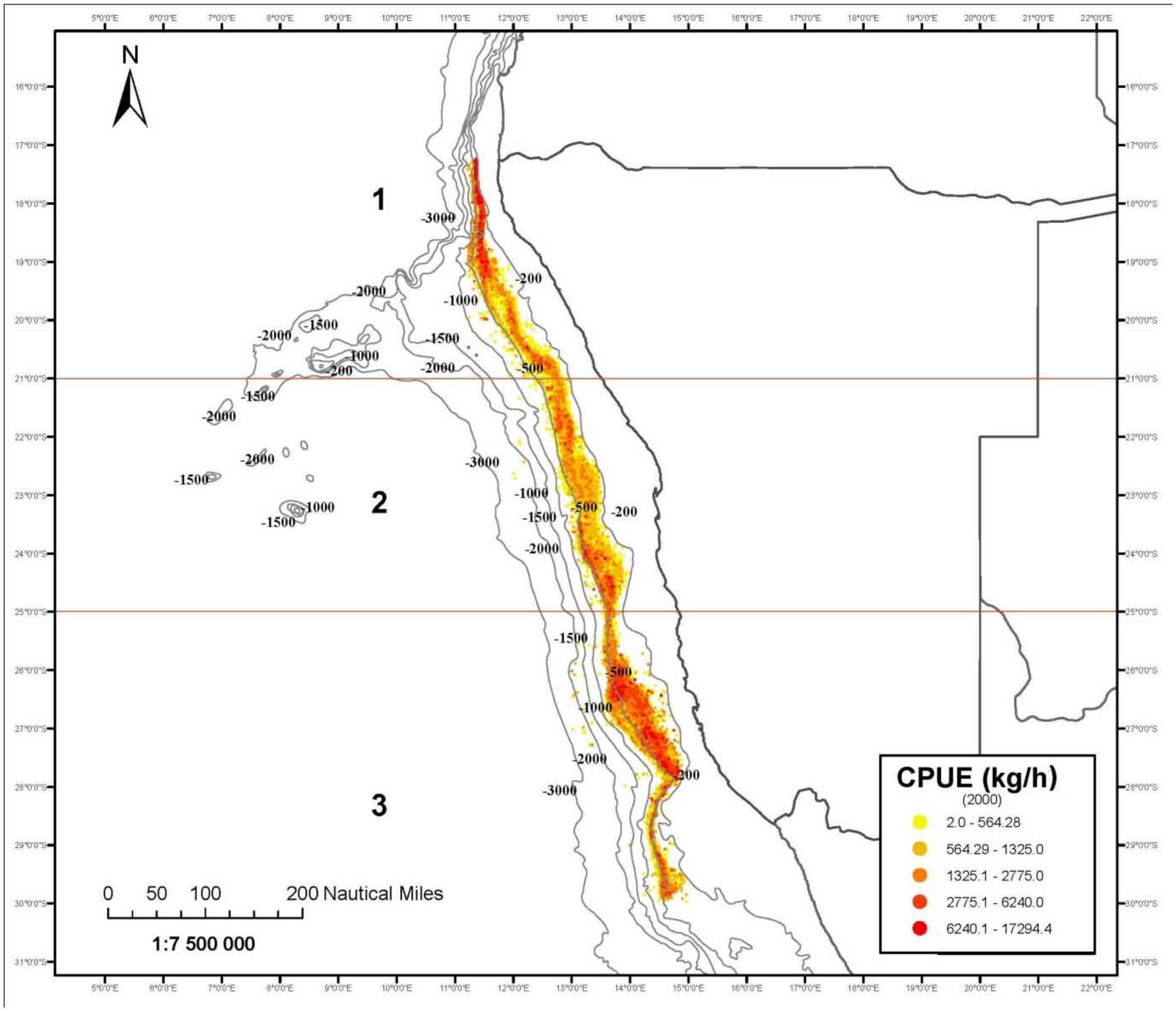
ZAR. G. 1999. *Biostatistical Analysis* (4th ed.) Prentice Hall, New Jersey. 663p.

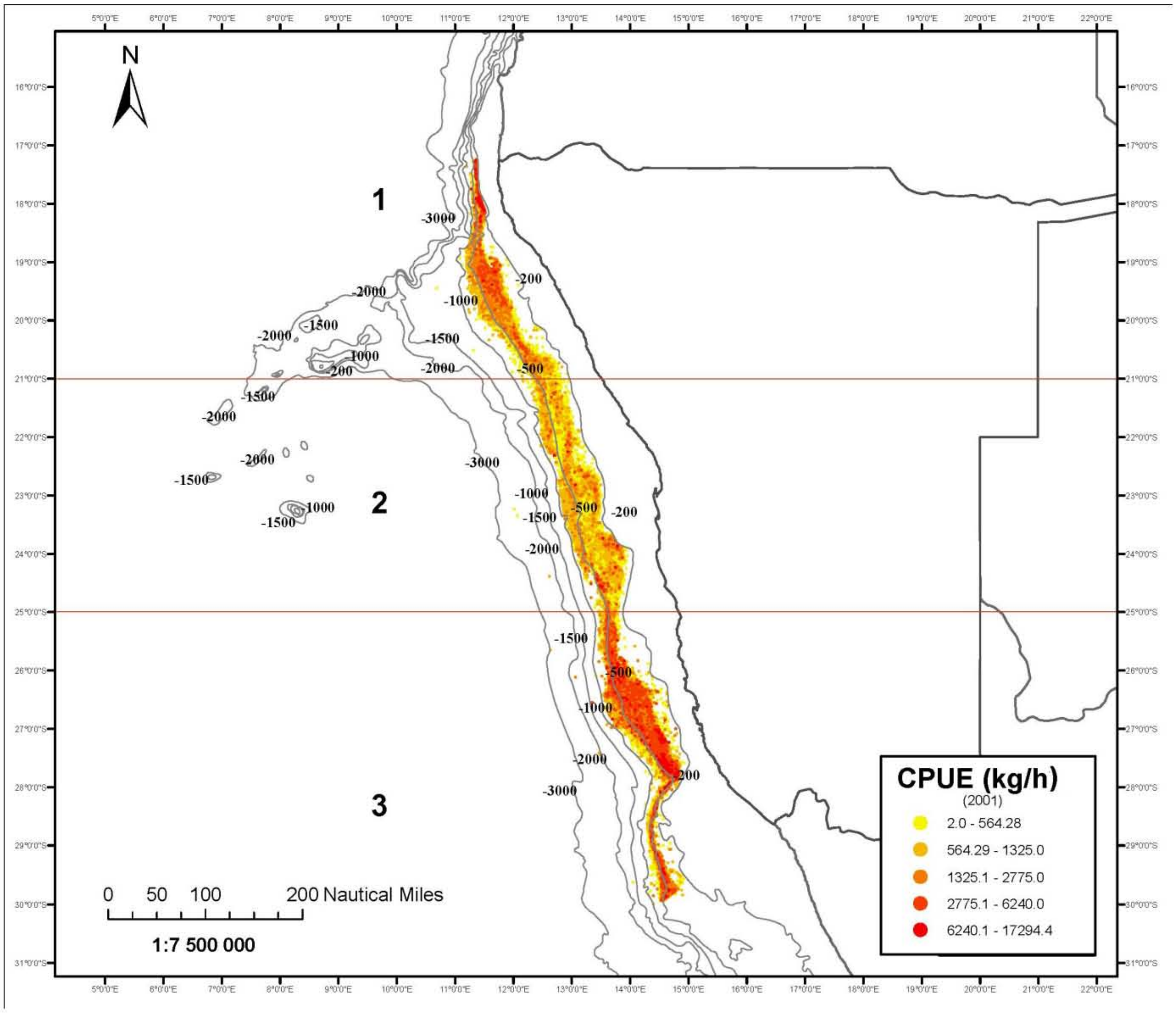
ZWANENBURG, K.C.T. 2000. The effects of fishing on demersal fish communities of the Scotian Shelf. *ICES Journal of Marine Science* **57**: 503–509.

Appendices

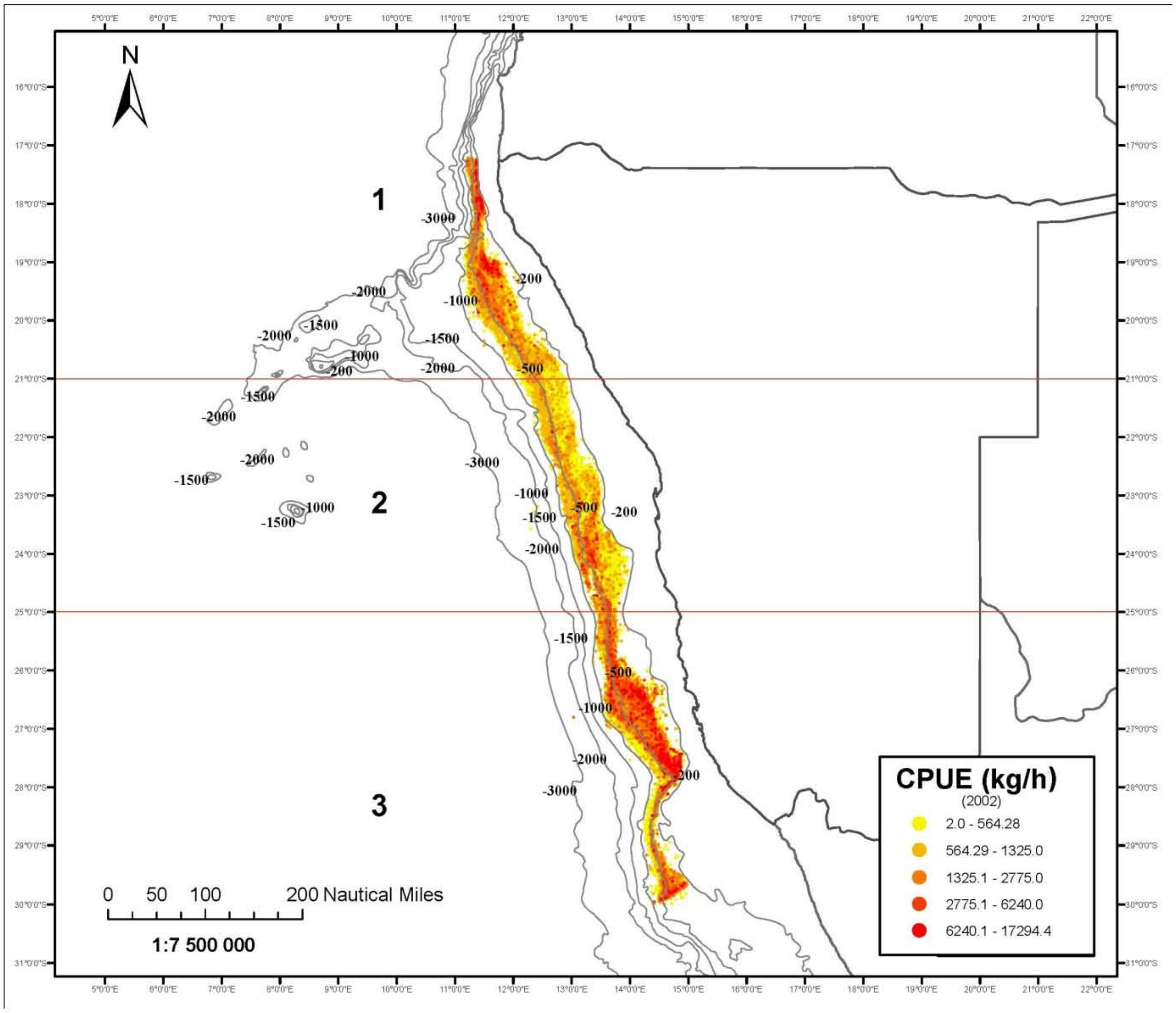
Appendix 2.1 (a – g): CPUE for the commercial hake fishery (bottom-trawl only) from 2000 to 2006).

a)

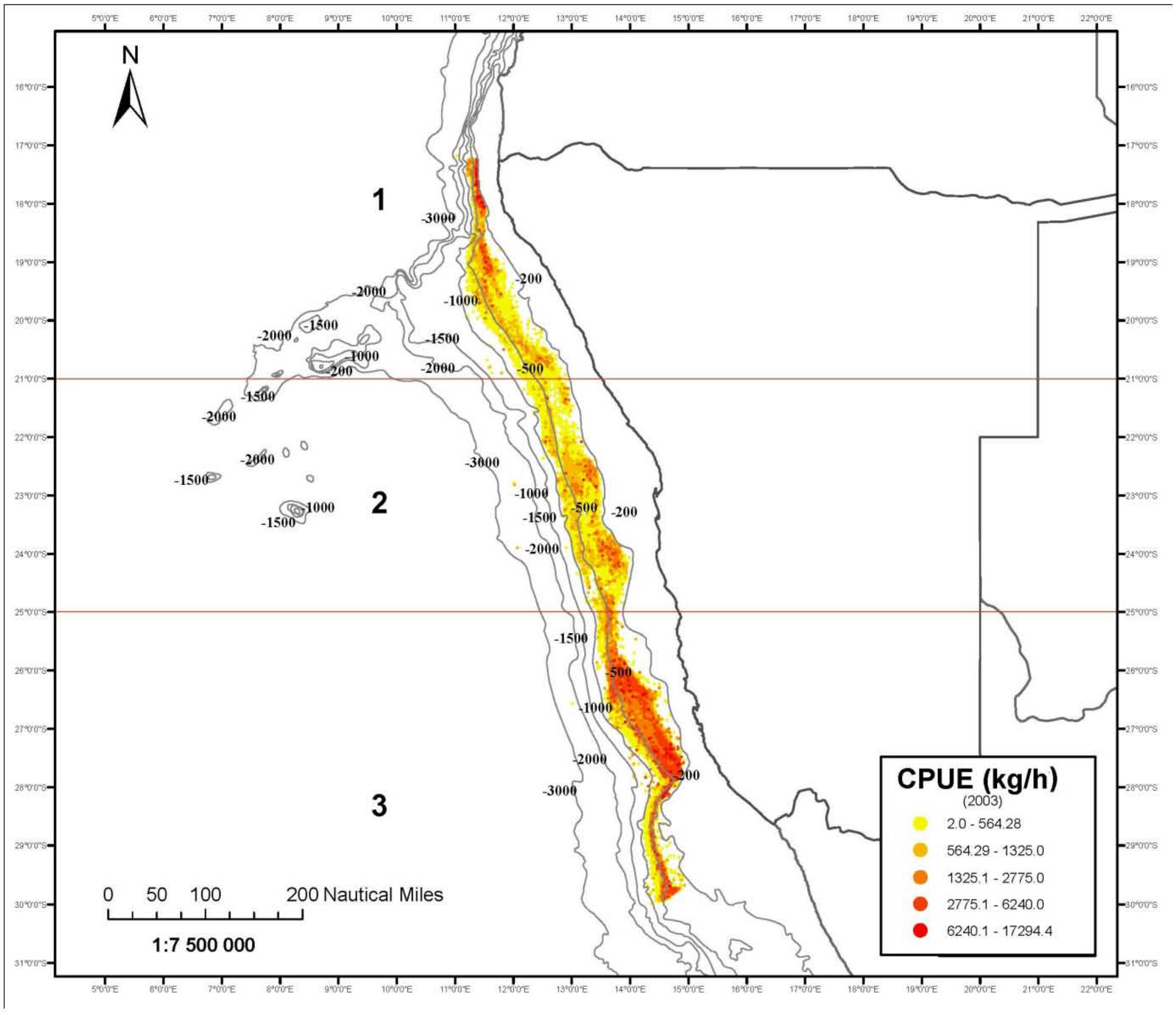



5°0'0"E
6°0'0"E
7°0'0"E
8°0'0"E
9°0'0"E
10°0'0"E
11°0'0"E
12°0'0"E
13°0'0"E
14°0'0"E
15°0'0"E
16°0'0"E
17°0'0"E
18°0'0"E
19°0'0"E
20°0'0"E
21°0'0"E
22°0'0"E
16°0'0"S
17°0'0"S
18°0'0"S
19°0'0"S
20°0'0"S
21°0'0"S
22°0'0"S
23°0'0"S
24°0'0"S
25°0'0"S
26°0'0"S
27°0'0"S
28°0'0"S
29°0'0"S
30°0'0"S
31°0'0"S
N
1
2
3
-3000
-2000
-1500
-1000
-500
-200
0 50 100 200 Nautical Miles
1:7 500 000
CPUE (kg/h)
(2001)
● 2.0 - 564.28
● 564.29 - 1325.0
● 1325.1 - 2775.0
● 2775.1 - 6240.0
● 6240.1 - 17294.4

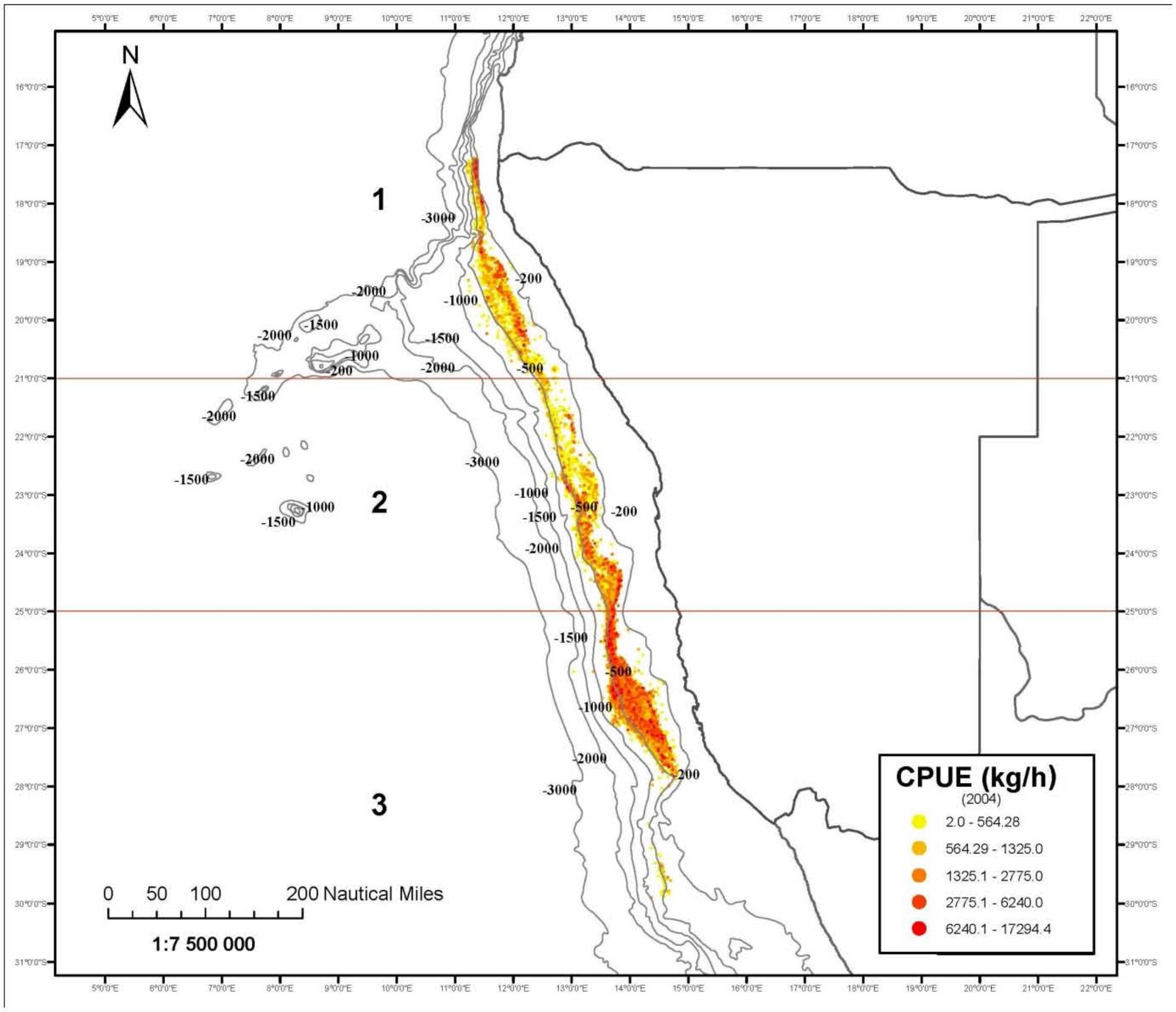
b)


N
1
2
3
-3000
-2000
-1500
-1000
-500
-200
0 50 100 200 Nautical Miles
1:7 500 000
CPUE (kg/h)
(2002)
2.0 - 564.28
564.29 - 1325.0
1325.1 - 2775.0
2775.1 - 6240.0
6240.1 - 17294.4

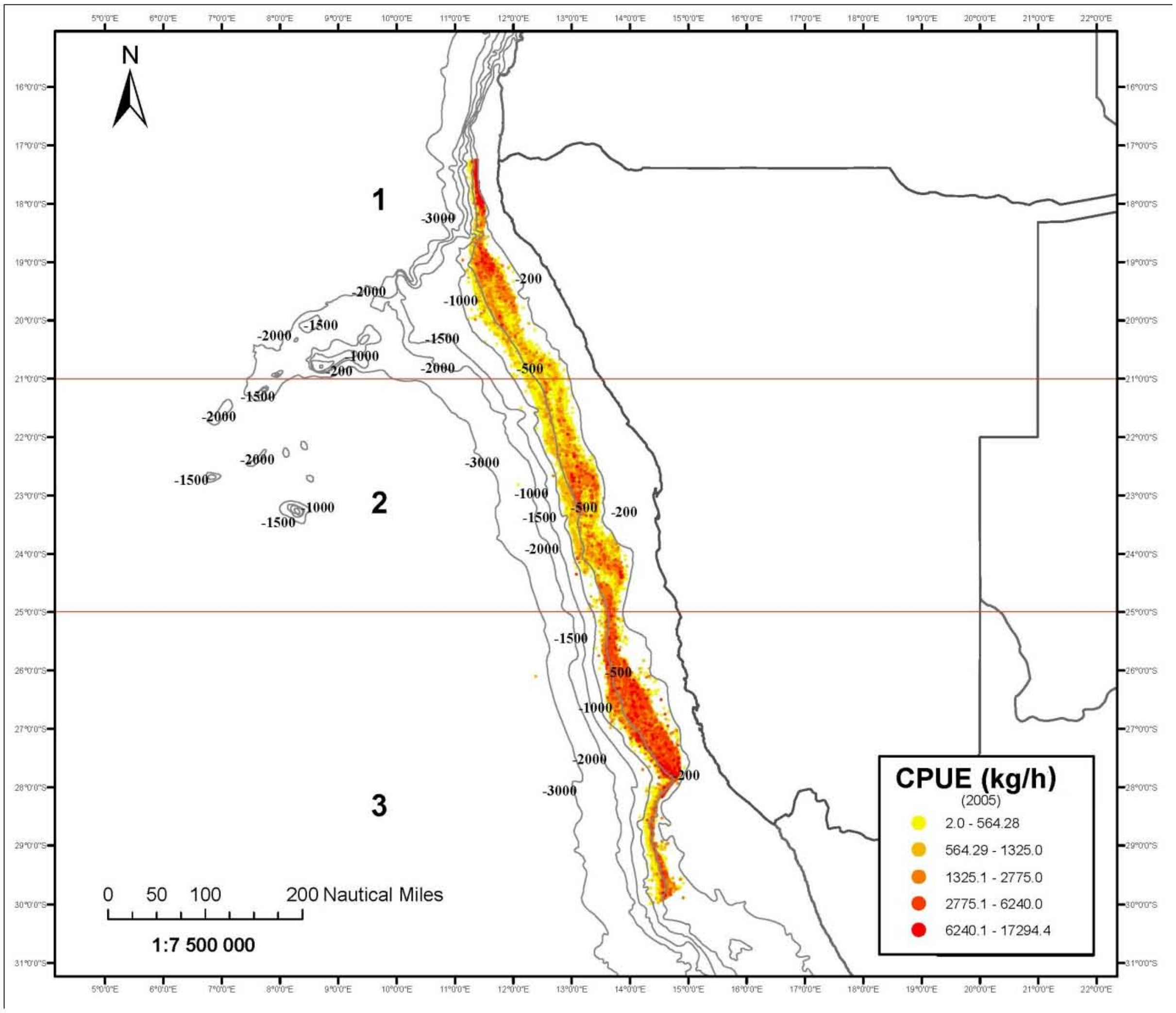
c)


5°0'0"E
6°0'0"E
7°0'0"E
8°0'0"E
9°0'0"E
10°0'0"E
11°0'0"E
12°0'0"E
13°0'0"E
14°0'0"E
15°0'0"E
16°0'0"E
17°0'0"E
18°0'0"E
19°0'0"E
20°0'0"E
21°0'0"E
22°0'0"E
16°0'0"S
17°0'0"S
18°0'0"S
19°0'0"S
20°0'0"S
21°0'0"S
22°0'0"S
23°0'0"S
24°0'0"S
25°0'0"S
26°0'0"S
27°0'0"S
28°0'0"S
29°0'0"S
30°0'0"S
31°0'0"S
N
1
2
3
-3000
-2000
-1500
-1000
-500
-200
CPUE (kg/h)
(2003)
● 2.0 - 564.28
● 564.29 - 1325.0
● 1325.1 - 2775.0
● 2775.1 - 6240.0
● 6240.1 - 17294.4
0 50 100 200 Nautical Miles
1:7 500 000

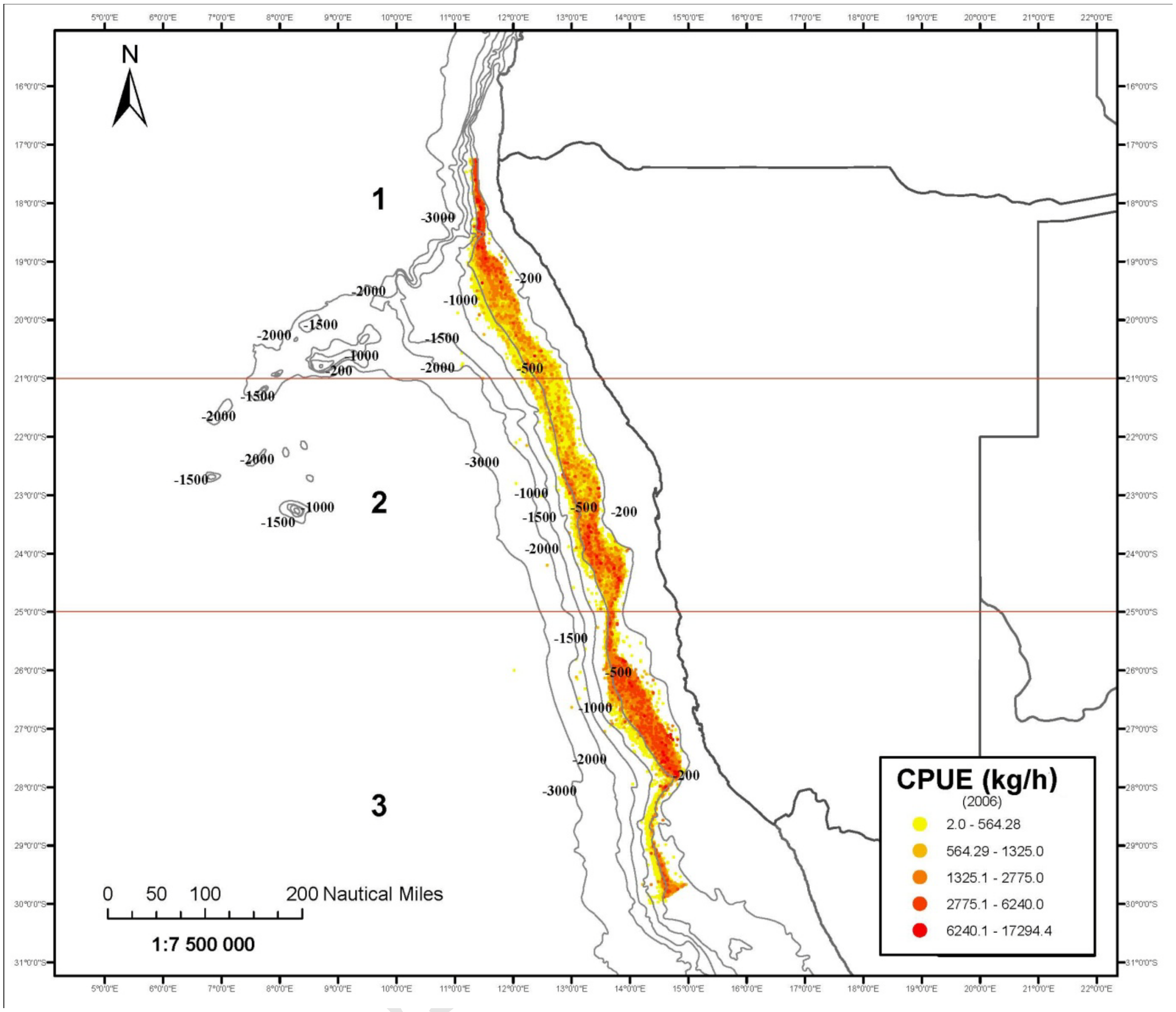
d)


N
1
2
3
-3000
-2000
-1500
-1000
-500
-200
0 50 100 200 Nautical Miles
1:7 500 000
CPUE (kg/h)
(2004)
2.0 - 564.28
564.29 - 1325.0
1325.1 - 2775.0
2775.1 - 6240.0
6240.1 - 17294.4

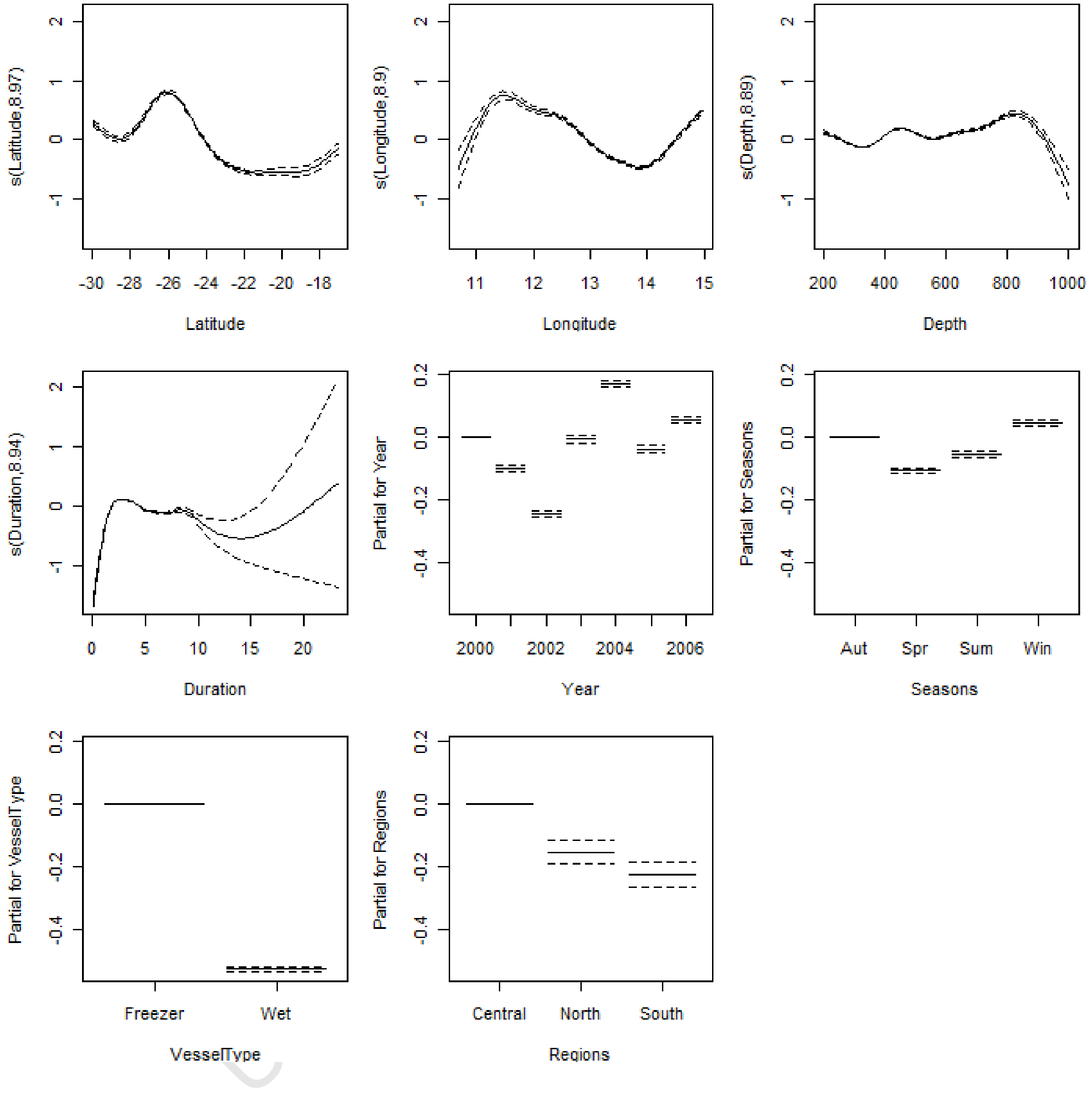
e)


N
1
2
3
-3000
-2000
-1500
-1000
-500
-200
0 50 100 200 Nautical Miles
1:7 500 000
CPUE (kg/h)
(2005)
● 2.0 - 564.28
● 564.29 - 1325.0
● 1325.1 - 2775.0
● 2775.1 - 6240.0
● 6240.1 - 17294.4
5°0'0"E
6°0'0"E
7°0'0"E
8°0'0"E
9°0'0"E
10°0'0"E
11°0'0"E
12°0'0"E
13°0'0"E
14°0'0"E
15°0'0"E
16°0'0"E
17°0'0"E
18°0'0"E
19°0'0"E
20°0'0"E
21°0'0"E
22°0'0"E
16°0'0"S
17°0'0"S
18°0'0"S
19°0'0"S
20°0'0"S
21°0'0"S
22°0'0"S
23°0'0"S
24°0'0"S
25°0'0"S
26°0'0"S
27°0'0"S
28°0'0"S
29°0'0"S
30°0'0"S
31°0'0"S

f)


N
1
2
3
-3000
-2000
-1500
-1000
-500
-200
CPUE (kg/h)
(2006)
2.0 - 564.28
564.29 - 1325.0
1325.1 - 2775.0
2775.1 - 6240.0
6240.1 - 17294.4
0 50 100 200 Nautical Miles
1:7 500 000
5°0'0"E
6°0'0"E
7°0'0"E
8°0'0"E
9°0'0"E
10°0'0"E
11°0'0"E
12°0'0"E
13°0'0"E
14°0'0"E
15°0'0"E
16°0'0"E
17°0'0"E
18°0'0"E
19°0'0"E
20°0'0"E
21°0'0"E
22°0'0"E
16°0'0"S
17°0'0"S
18°0'0"S
19°0'0"S
20°0'0"S
21°0'0"S
22°0'0"S
23°0'0"S
24°0'0"S
25°0'0"S
26°0'0"S
27°0'0"S
28°0'0"S
29°0'0"S
30°0'0"S
31°0'0"S

g)



Appendix 2.2 Catch (kg) variations as a function of latitude, longitude, depth, duration, year, seasons, vessel type, and regions as modelled by the GAM fitted with Loess smoothers.

Appendix 4.1

Areas (in nm) for each of the 100-m depth strata as used in the stratified calculations and weighting of the mean catch rate by area of the shelf (100 – 300 m) and slope (301 – 600 m)..

Depth Zone (m)	Area in nautical miles (nm)
101 - 200	20921
201 - 300	9942
301 - 400	8518
401 - 500	3387
501 - 600	2283

Appendix 5.1

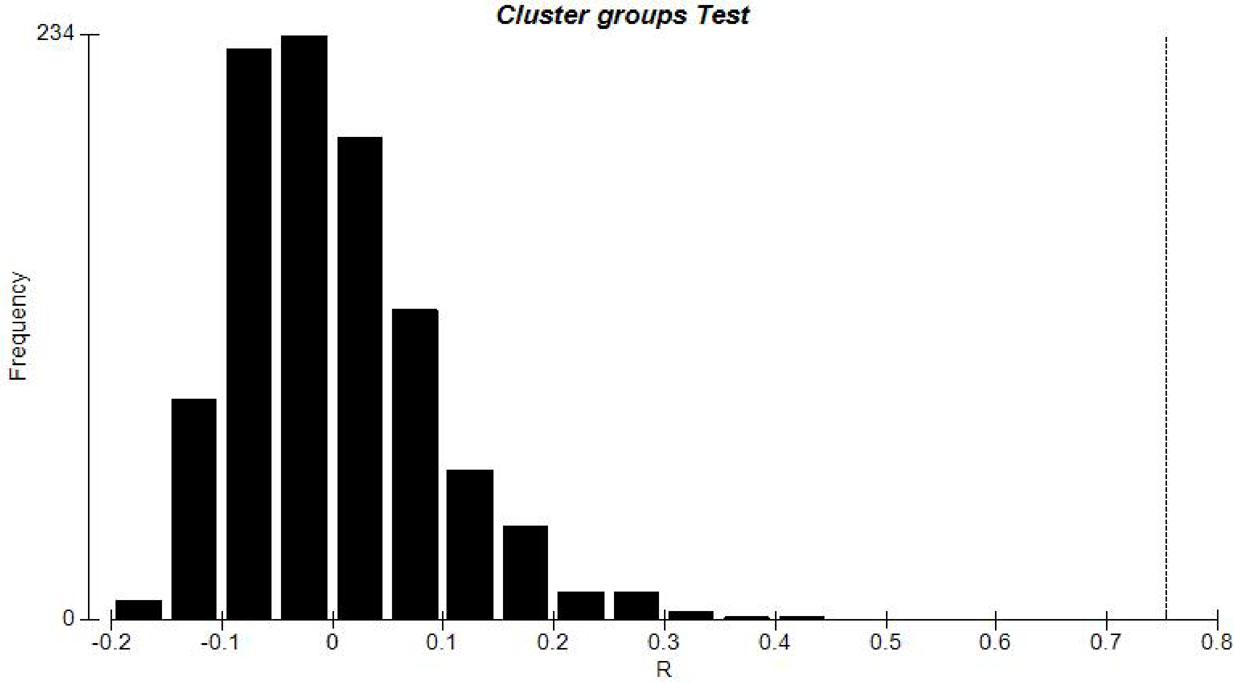
ANOSIM test for significant difference of the Groups

Global Test
Sample statistic (Global R): 0.755
Significance level of sample statistic: 0.1%
Number of permutations: 999 (Random sample from 4084080)
Number of permuted statistics greater than or equal to Global R: 0

Pairwise Tests

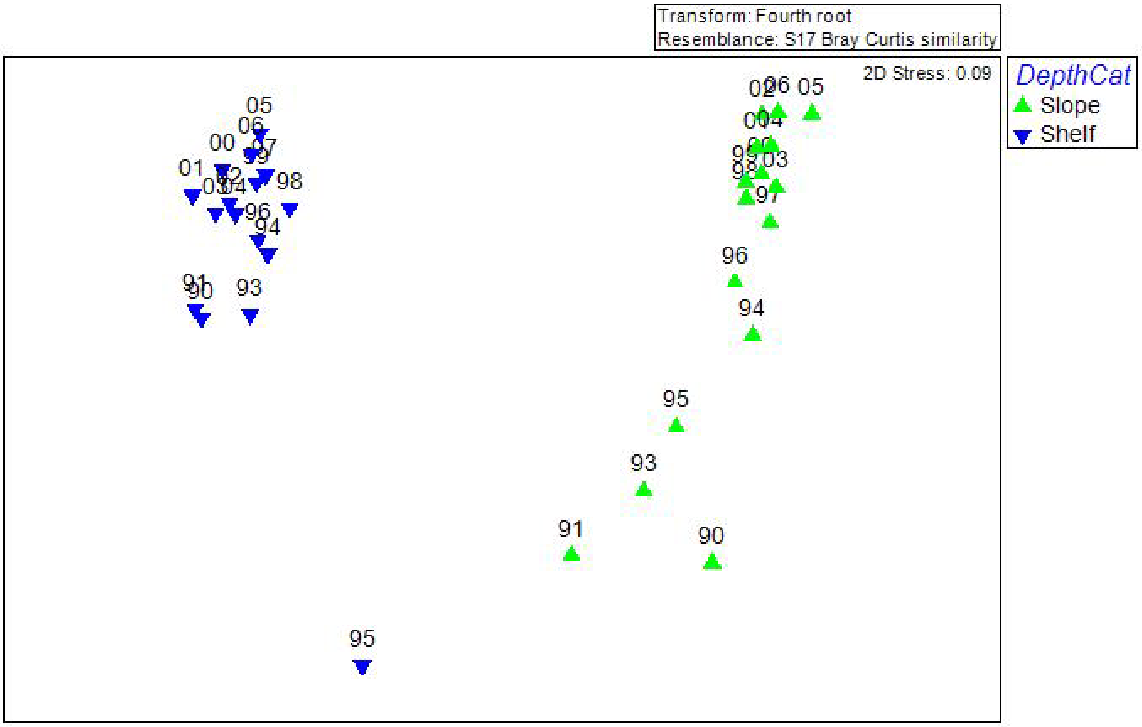
Groups	R Statistic	Significance Level %	Possible Permutations	Actual Permutations	Number >= Observed
A, B	0.942	0.3	330	330	1
A, C	1	0.5	210	210	1
B, C	0.631	0.3	1716	999	2

ANOSIM graph

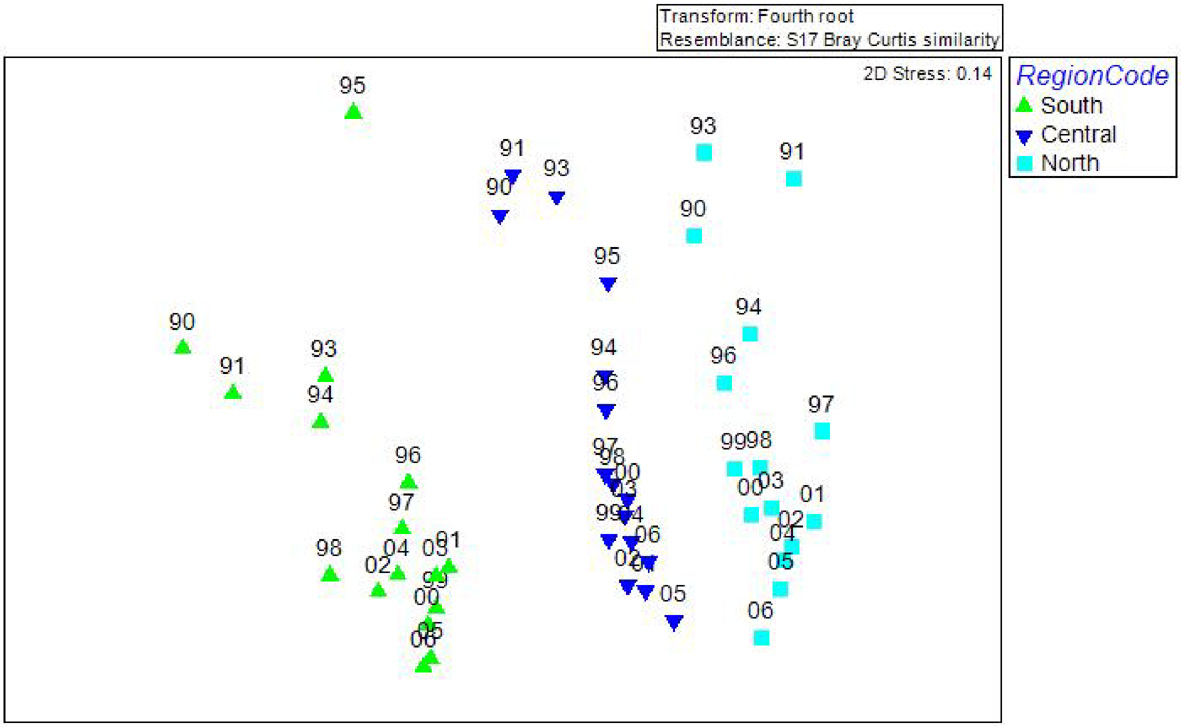


Appendix 5.2

a) MDS for depth categories (shelf and slope) based averaged biomass data for years and depth category.



b) MDS for the regions (north, central, and south) based averaged biomass data for years and region categories.



Appendix 5.3

a) Wholecoast

```
Call:
lm(formula = W.statistic ~ Year, data = wwhole)

Residuals:
      Min       1Q    Median       3Q       Max
-0.037323 -0.008942  0.001321  0.006594  0.029582

Coefficients:
                         Std.
              Estimate   Error       t value     Pr(>|t|)
(Intercept)    -0.4203    1.77488     -0.237       0.816
Year          0.000204   0.000888       0.23       0.822

Residual standard error: 0.01794 on 15 degrees of freedom
Multiple R-squared: 0.0035,     Adjusted R-squared: -0.06293
F-statistic: 0.05269 on 1 and 15 DF,  p-value: 0.8216
```

b) Stratum

```
                                     SHELF
Call:
lm(formula = W.Statistic ~ Year, data = wstrat, subset = Stratum ==
   "Shelf")

Residuals:
      Min       1Q    Median       3Q       Max
-0.042647 -0.009774  0.001655  0.008788  0.033537

Coefficients:
                         Std.
              Estimate   Error       t value     Pr(>|t|)
(Intercept)   0.675181   2.107438       0.32       0.753
Year          -0.00034   0.001055     -0.327       0.749

Residual standard error: 0.02131 on 15 degrees of freedom
```

```
Multiple R-squared: 0.007058,   Adjusted R-squared: -0.05914
F-statistic: 0.1066 on 1 and 15 DF,  p-value: 0.7485
```

SLOPE

```
Call:
lm(formula = W.Statistic ~ Year, data = wstrat, subset = Stratum ==
   "Slope")

Residuals:
      Min        1Q     Median        3Q       Max
-0.0385616 -0.0131864 -0.0002012  0.0154223  0.0338307

Coefficients:
                        Std.
             Estimate   Error       t value    Pr(>|t|)
(Intercept)  0.073508   1.975393     0.037      0.971
Year           -3E-05   0.000989    -0.031      0.976

Residual standard error: 0.01997 on 15 degrees of freedom
Multiple R-squared: 6.304e-05,  Adjusted R-squared: -0.0666
F-statistic: 0.0009456 on 1 and 15 DF,  p-value: 0.9759
```

c) Sub-regions

CENTRAL SHELF

```
Call:
lm(formula = W.statistic ~ Year, data = wregion, subset = Subregion ==
   "C_Shelf")

Residuals:
      Min        1Q    Median        3Q       Max
-0.052712 -0.018497 -0.007689  0.028585  0.045822

Coefficients:
                                                 t
                   Estimate      Std. Error    value     Pr(>|t|)
(Intercept)        0.575566       3.15418      0.182      0.858
Year                -0.0003      0.001579      -0.19      0.851
```

```
Residual standard error: 0.03189 on 15 degrees of freedom
Multiple R-squared: 0.002413,   Adjusted R-squared: -0.06409
F-statistic: 0.03629 on 1 and 15 DF,  p-value: 0.8515
```

CENTRAL SLOPE

```
Call:
lm(formula = W.statistic ~ Year, data = wregion, subset = Subregion ==
   "C_Slope")

Residuals:
     Min       1Q   Median       3Q      Max
-0.081939 -0.020756  0.003707  0.014018  0.077052

Coefficients:
                                                     t
                         Estimate       Std. Error   value     Pr(>|t|)
(Intercept)              4.248417       3.715279     1.143       0.271
Year                     -0.00212       0.001859    -1.139       0.272

Residual standard error: 0.03756 on 15 degrees of freedom
Multiple R-squared: 0.07964,    Adjusted R-squared: 0.01828
F-statistic: 1.298 on 1 and 15 DF,  p-value: 0.2724
```

SOUTH SHELF

```
Call:
lm(formula = W.statistic ~ Year, data = wregion, subset = Subregion ==
   "S_Shelf")

Residuals:
     Min       1Q   Median       3Q      Max
-0.082398 -0.002577  0.008950  0.015074  0.032269

Coefficients:
                      Estimate      Std. Error    t value     Pr(>|t|)
(Intercept)           1.025642      3.112212        0.33        0.746
Year                  -0.00051      0.001558      -0.329        0.747

Residual standard error: 0.03146 on 15 degrees of freedom
Multiple R-squared: 0.007156,   Adjusted R-squared: -0.05903
F-statistic: 0.1081 on 1 and 15 DF,  p-value: 0.7468
```

SOUTH SLOPE

```
Call:
lm(formula = W.statistic ~ Year, data = wregion, subset = Subregion ==
   "S_Slope")

Residuals:
      Min        1Q     Median        3Q       Max
-0.0698025 -0.0152986  0.0002781  0.0192951  0.0362874

Coefficients:
                  Estimate      Std. Error    t value     Pr(>|t|)
(Intercept)        -3.01871     2.769474       -1.09        0.293
Year               0.001516     0.001386       1.093        0.291

Residual standard error: 0.028 on 15 degrees of freedom
Multiple R-squared: 0.07382,    Adjusted R-squared: 0.01207
F-statistic: 1.196 on 1 and 15 DF,  p-value: 0.2915
```

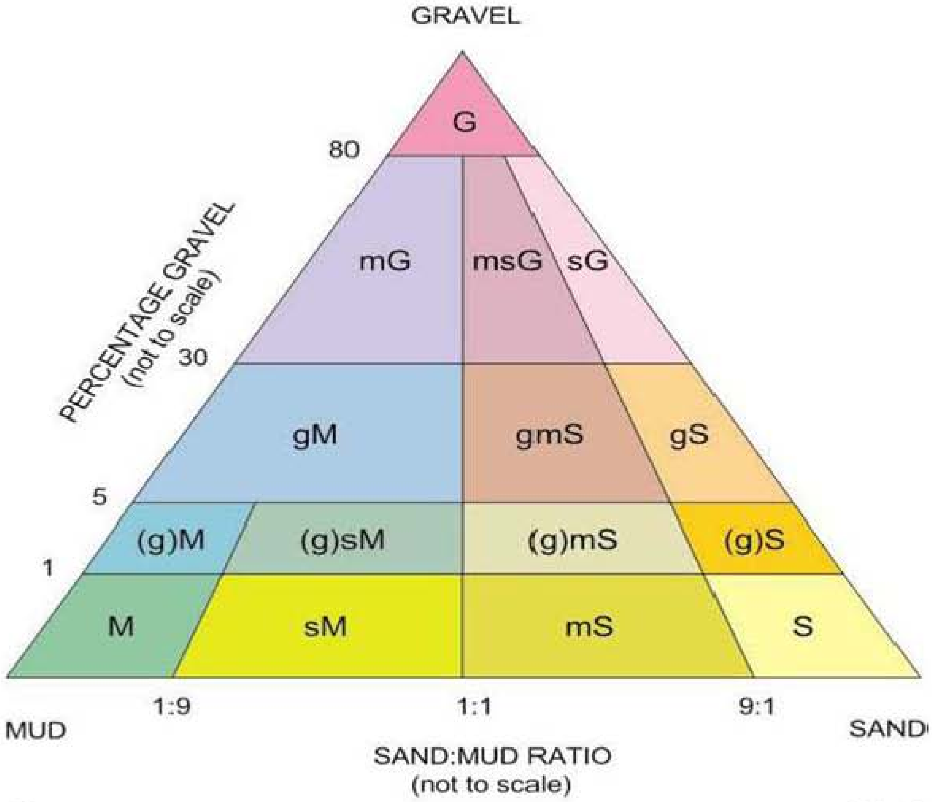
NORTH SHELF

```
Call:
lm(formula = W.statistic ~ Year, data = wregion, subset = Subregion ==
   "N_Shelf")

Residuals:
     Min       1Q    Median      3Q       Max
-0.097013 -0.014675  0.004405  0.018029  0.042247

Coefficients:
                          Std.
               Estimate   Error        t value    Pr(>|t|)
(Intercept)    6.110361   3.249804       1.88       0.0796   .
Year           -0.00305   0.001627     -1.874       0.0805   .
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.03285 on 15 degrees of freedom
Multiple R-squared: 0.1897,     Adjusted R-squared: 0.1357
F-statistic: 3.513 on 1 and 15 DF,  p-value: 0.08051
```

NORTH SLOPE

```
Call:
lm(formula = W.statistic ~ Year, data = wregion, subset = Subregion ==
   "N_Slope")

Residuals:
     Min       1Q    Median       3Q       Max
-0.075772 -0.018164  0.006481  0.019449  0.054407

Coefficients:
                         Std.
              Estimate   Error       t value   Pr(>|t|)
(Intercept)   5.515126   3.408746      1.618       0.127
Year          -0.00275   0.001706     -1.613       0.128

Residual standard error: 0.03446 on 15 degrees of freedom
Multiple R-squared: 0.1478,     Adjusted R-squared: 0.09098
F-statistic: 2.601 on 1 and 15 DF,  p-value: 0.1276
```

Appendix 6.1 Marine Sediment Classifications used in this study (Folk, 1954).



M	Mud
sM	Sandy mud
(g)M	Slightly gravelly mud
(g)sM	Slightly gravelly sandy mud
gM	Gravelly mud
S	Sand
mS	Muddy sand
(g)S	Slightly gravelly sand
(g)mS	Slightly gravelly muddy sand
gmS	Gravelly muddy sand
gS	Gravelly sand
G	Gravel
mG	Muddy gravel
msG	Muddy sandy gravel
sG	Sandy gravel

Appendix 7.1

a) Species Richnness

```
Family: poisson
Link function: log

Formula:
S ~ s(Depth, bs = "cs") + s(Longitude, bs = "cs") + s(Latitude,
    bs = "cs") + s(log(N + 1), bs = "cs")

Parametric coefficients:
            Estimate Std. Error z value Pr(>|z|)
(Intercept)  2.69345    0.01661   162.2   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Approximate significance of smooth terms:
                edf    Ref.df    Chi.sq    p-value
s(Depth)      7.726     8.544     29.97   0.000321   ***
s(Longitude)  8.635     8.957    181.41   < 2e-16    ***
s(Latitude)   8.484     8.922    203.84   < 2e-16    ***
s(log(N + 1)) 7.472     8.259      29.5   0.000314   ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R-sq.(adj) =  0.742   Deviance explained = 78.4%
UBRE score = 0.10066  Scale est. = 1        n = 286
```

b) Evenness Index (J’)

```
Family: gaussian
Link function: identity

Formula:
J ~ s(Depth, bs = "cs") + s(Longitude, bs = "cs") + s(Latitude,
    bs = "cs") + s(log(N + 1), bs = "cs")

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
```

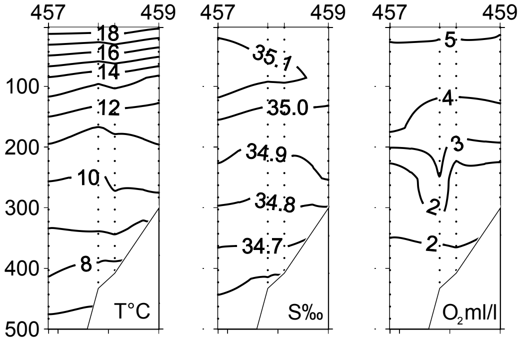
```
(Intercept) 0.494706   0.007965   62.11   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Approximate significance of smooth terms:
                 edf     Ref.df     F          p-value
s(Depth)         5.155    6.249      2.013    0.061433   .
s(Longitude)     8.304    8.848      2.615    0.006911   **
s(Latitude)      7.401    8.362      3.858    0.000202   ***
s(log(N + 1))    2.111    2.705     40.033    < 2e-16    ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R-sq.(adj) =  0.429   Deviance explained = 47.5%
GCV score = 0.019805  Scale est. = 0.018145  n = 286
```

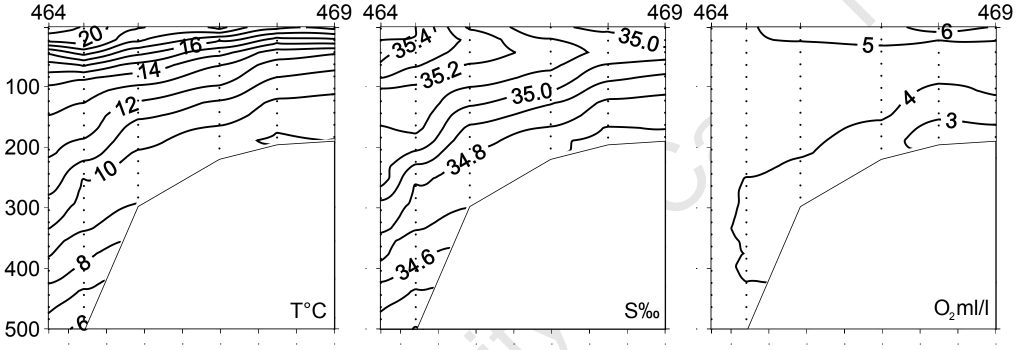
c) Shannon-Wienner index (H’)

```
Family: gaussian
Link function: identity

Formula:
H ~ s(Depth, bs = "cs") + s(Longitude, bs = "cs") + s(Latitude,
   bs = "cs") + s(log(N + 1), bs = "cs")

Parametric coefficients:
           Estimate Std. Error t value Pr(>|t|)
(Intercept)  1.33193   0.02142   62.18   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Approximate significance of smooth terms:
                 edf     Ref.df     F          p-value
s(Depth)         2.218    2.831      2.414      0.0707   .
                                                6.57E-
s(Longitude)     8.692    8.964       9.82          13   ***
                                                4.82E-
s(Latitude)      8.085    8.766       12.4          16   ***
s(log(N + 1))    5.111     6.05     16.729    < 2e-16    ***
---
```

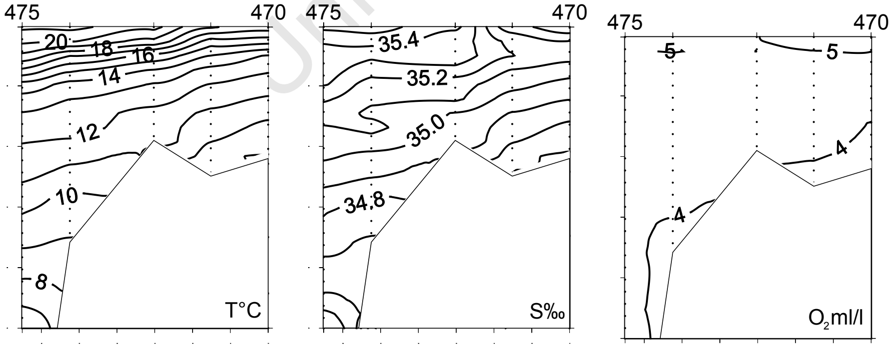
```
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R-sq.(adj) =  0.586   Deviance explained = 62.1%
GCV score = 0.14387  Scale est. = 0.13124   n = 286
```

Appendix 7.2 Temperature, salinity and dissolved oxygen sections for the west coast of South Africa.

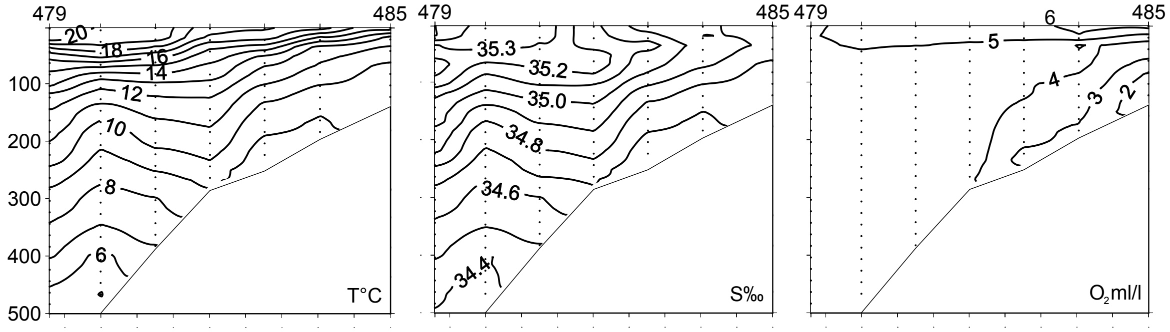




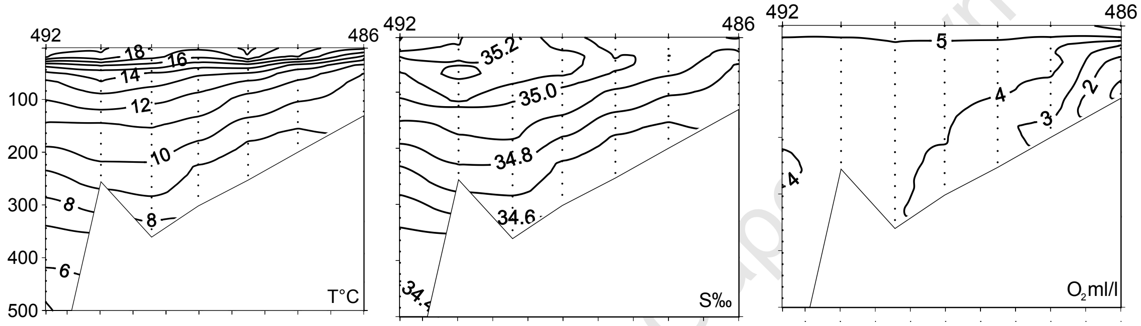
Line 1 RSA – 03-04.04.2007



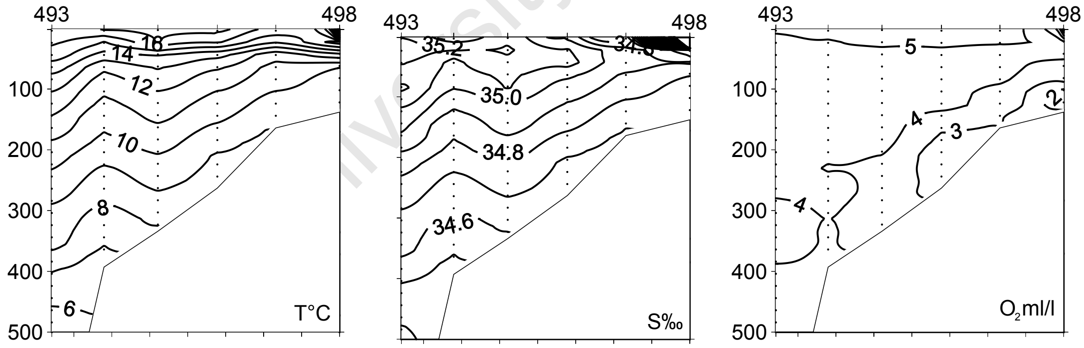
Line 2 RSA – 04.04.2007



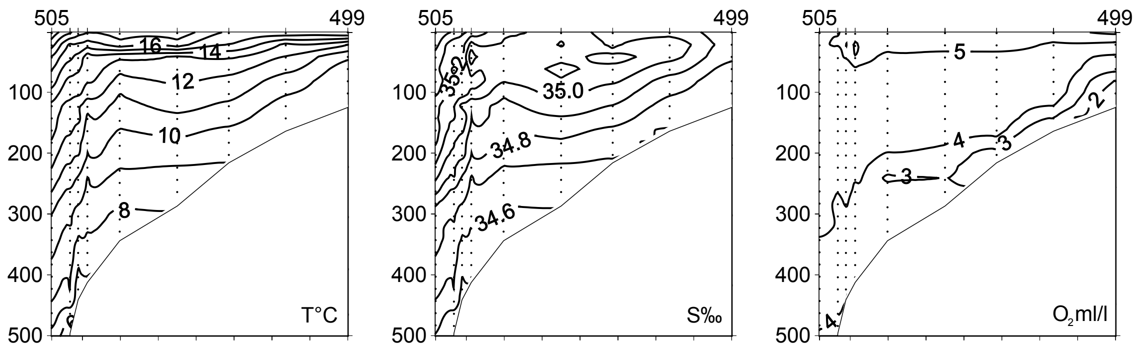
Line 3 RSA – 06-07.04.2007



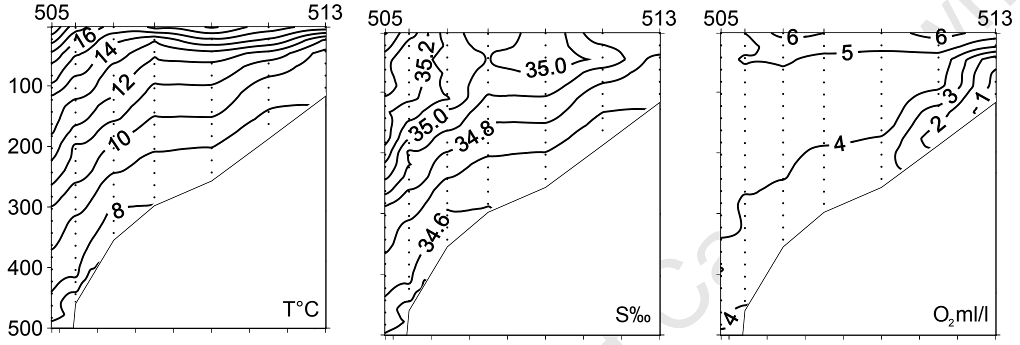
Line 4 RSA – 07.04.2007



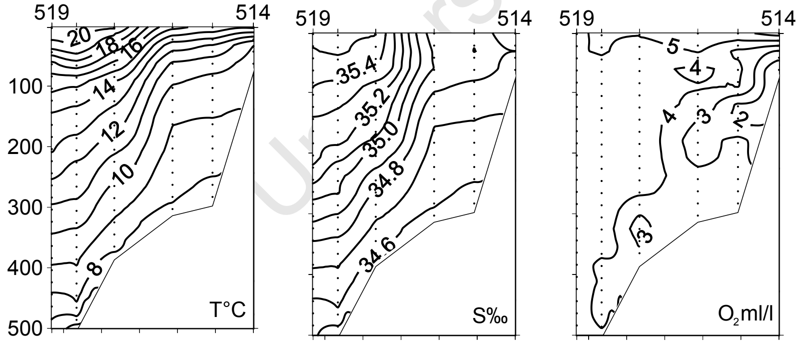
Line 5 RSA – 08.04.2007



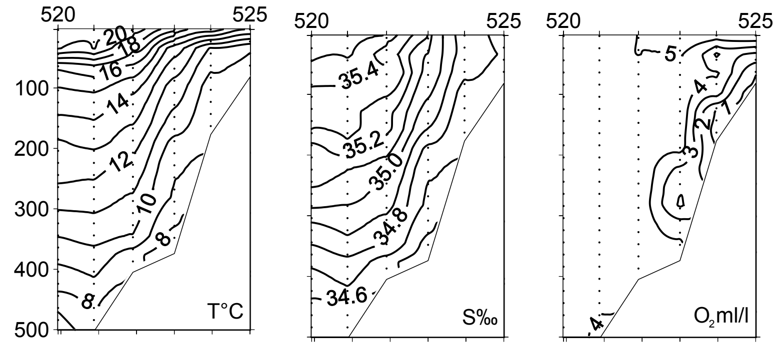
Line 6 RSA – 08-09.04.2007



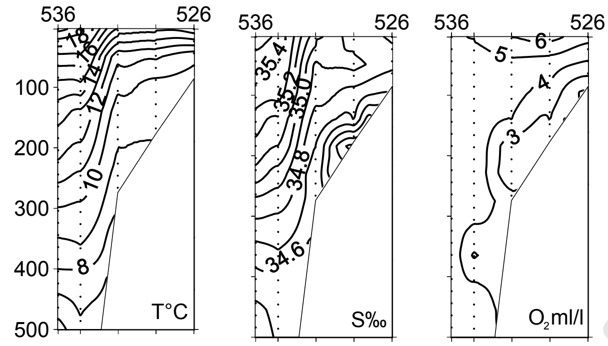
Line 7 RSA – 09-10.04.2007



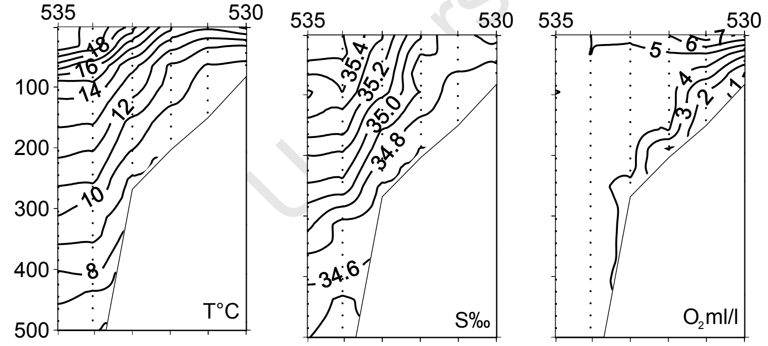
Line 8 RSA – 10.04.2007



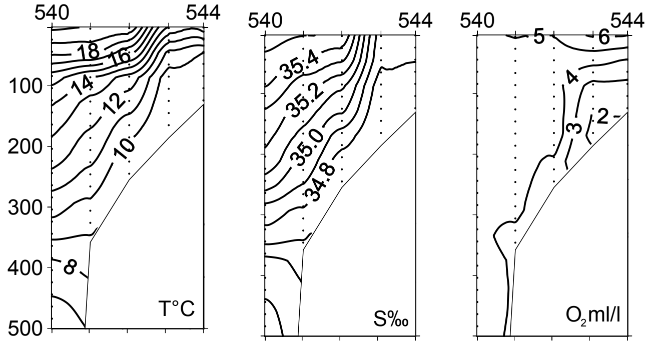
Line 9 RSA – 11.04.2007



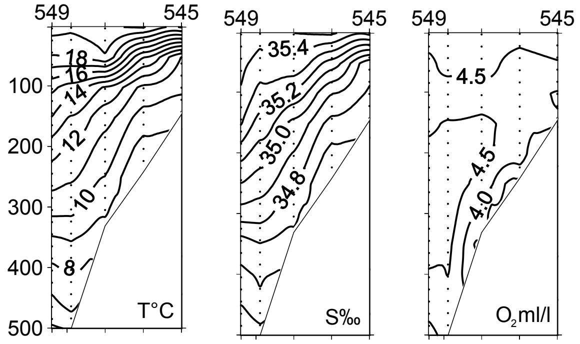
Line 10 RSA – 11-12.04.2007



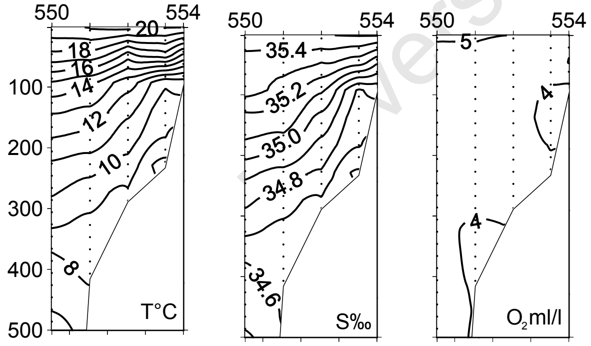
Line 11 RSA – 12-13.04.2007



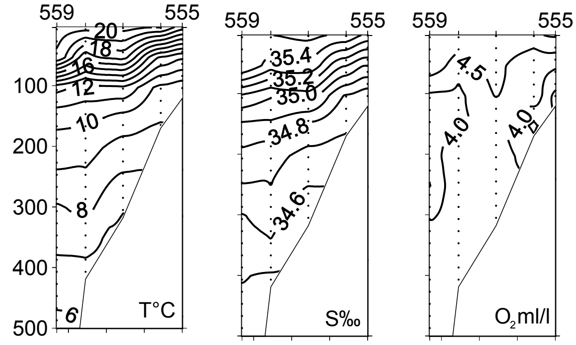
Line 12 RSA – 13-14.04.2007



Line 13 RSA – 14.04.2007



Line 14 RSA – 14.04.2007



Line 15 RSA – 15.04.2007