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**ASSESSMENT OF PATTERNS IN THE NAMIBIAN
HAKE FISHERY BASED ON COMMERCIAL FISHERIES
DATA, IN RELATION TO ENVIRONMENTAL FACTORS**

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This thesis is presented for the degree of

Doctor of Philosophy (PhD)

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Supervisors:

Prof JG Field and Dr A Gordo

The Ocean
by Jamie Vickers

The sounds of the oceans are like friends to me,
They make life easier and help me to see.
That life can be peaceful and yet full of strife,
The waves can be soft or cut like a knife.

You need friends to help you swim,
To struggle alone or rely on them.
Family also can help you move through the sea,
And you can't help but be.
Grateful to all who love you for you,
They are always there to see you through.

God rules the ocean and all the sounds,
So in Him we must be found.
Trusting in Him to carry us through,
The waves of the ocean and all that is blue.

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DECLARATION

I hereby declare that the contents of this dissertation represents the result of research carried out by myself under the supervision of Prof. John Field of the Marine Biology Research Institute of the University of Cape Town and Dr. Ana Gordoá at the Centro de Estudios Avanzados de Blanes in Spain.

I had the assistance of various persons in conducting the research in this thesis in the following specific fields:

Liza Burmeister:

- Preparing the density estimates from Namibian survey data and make it available for me in the correct format for use in Chapter 4.

Ana Gordoá:

- Supplying a macro to change the format of the NOAA climate data downloads from the internet to a more user-friendly format for use in Chapter 5.
- Develop the model in which CPUE is modulated by the environmental cycle used in Chapter 5.
- Recalculating recruitment indices from the Spanish surveys and make them available for me for use in Chapter 6.

Chris Bartholomae:

- Preparing the environmental indices used in Chapter 6.

No portion of this thesis has been previously submitted in support of an application for any other degree or qualification at this or any other university.

.....
Elizabeth Voges

.....
Date

ABSTRACT

This thesis explores the relationships between commercial data and those obtained from research surveys in an attempt to broaden the database available for management, and to cover seasonal and inter-annual changes in density estimates of Cape hake (*Merluccius capensis*). It also attempts to explain hake variability in terms of environmental indices based on satellite remote sensing, carefully chosen to reflect underlying oceanographic processes.

The influence of various factors on catch rates (CPUE) is investigated using a general linear model. Results indicate that the full stepwise regression model is highly significant and accounts for about 51% of variation in CPUE, with vessel size, year and area contributing 27%, 9.5% and 6.9%, respectively.

The spatial distribution of effort of part of the Namibian hake fleet is investigated by looking at: competitive abilities among vessels, spatial allocation of effort, competition among vessels and equalization of CPUE based on the Ideal Free Distribution (IFD). Results show that interference competition does not occur among vessels. Catch rates are equalized among areas. Since there is no interference competition among vessels, the catchability coefficient (q) is not affected by this factor.

Density estimates are compared from research surveys (which do not cover all seasons) and from commercial data with temporal and spatial overlap. Results of the stepwise linear fit to the data indicate that season and year are significant to the model fit. Density estimates from the whole year reveal the least inter-annual variability and those from the first quarter, the greatest. Thus commercial data do augment research data, indicating the extent of inter- and intra-annual variability in hake availability; they could be used for tuning models and identifying the risk and uncertainty in the production models used for management.

The extent of the differences in hake density is related to the strength of the seasonality of the ecosystem through the temporal patterns in sea surface temperature (SST). The findings show that the maximum inter-annual variability in SST takes place during summer. The catchability of Namibian hake shows a strongly seasonal pattern correlated with seasonality in SST and its anomalies.

Multinomial logistic regression analysis is used to calculate the probability of strong, average or weak recruitment of two-year old hake. The model includes environmental indices describing the extent of warm water intrusion from Angola during January to March in the year of spawning, as well as the upwelling intensity from 17°S to 29°S during May to September in the year of spawning and the following year. The model accounts for 79% of the variance in hake recruitment and correctly predicts the category of hake recruitment in 4 years out of 5.

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CHAPTER ONE

INTRODUCTION

1.1. Fish population dynamics

Commercial fisheries are part of complex marine ecosystems involving ocean climate, hydrograph, biological oceanography, and fish ecology, and also the human system including the behaviour and knowledge of fishers, the requirements of the processing industry and markets for fish products, government policy, regulations and political issues (McGlade and Allen 1985). The interface of industry and fishers with fisheries resources is multifaceted, and usually predicated by knowledge of the resource distribution, demand, and availability (Kirby 1982; Pearse 1982). To intervene in or monitor successfully such a complex system, and to formulate appropriate management schemes, it is important to identify the processes and dualities which serve to inter-relate fish and their abundance, fishers, fishery scientists, and managers, all of whom play an important role in the final yield of fish for human consumption (Allen and McGlade 1986).

Fish stocks are known to fluctuate extensively over large spatial and temporal scales (Cushing 1982; Laevastu 1993). Several biotic processes may induce such fluctuations. At the beginning of the previous century, Hjort (1914) suggested that year-class strength depends upon the food availability for larvae and post-larvae. This hypothesis has been further developed into the match-mismatch concept, which has been the subject of several investigations to explain mortality of young stages and resultant stock variations in space and time (May 1974; Cushing 1982; Brander 1994). Other biological factors, such as predation, competition and cannibalism, may however also influence the early survival of marine fish (Bailey and Houde 1989; Myers and Cadigan 1993; Fortier and Villeneuve 1996).

Variation in fish abundance is further more linked to abiotic environmental influences, such as changes in temperature, salinity, wind field and currents

(Cushing and Dickson 1976; Southward *et al.* 1988; Cury and Roy 1989; Ellersten *et al.* 1989; Dickson and Brander 1993; Conover *et al.* 1995; Ottersen and Sundby 1995).

Human exploitation is another process that strongly affects fish dynamics and has been identified as the main cause of the collapse of several regional fish stocks (Garrod and Shumacher 1994; Hutchings 1996; Myers *et al.* 1996; Cooke *et al.* 1997). Thus the causes of fish stock fluctuations are complex and depend upon a variety of direct and indirect effects of biological, environmental and anthropogenic origin. This complexity is likely to be at the core of the difficulty in understanding the mechanisms underlying spatio-temporal patterns of fish abundance (Wooster and Bailey 1989; Brander 1994). The study of these patterns is further complicated by the fact that analyses are commonly based on fishery landings, for which data on the youngest stages are generally unavailable (Fromentin *et al.* 1997).

1.2. Use of fisheries data in stock assessment

Historically, fishery catch and effort data have been collected principally to obtain abundance indices for stock assessment. Although fishing is undeniably a rich source of information about a fish population, both experience and theoretical models have demonstrated that simple abundance indices derived from fishery catch and effort data (e.g. catch per unit effort, CPUE) are not reliable indicators of population trends (Walters and Maguire 1996; Peterman and Steer 1981; Bannerot and Austin 1983). Fisheries biology has often focussed on the biological processes of work within exploited fish stocks. This narrow focus has led to management strategies that ignore the dynamic response of fishers to developments in the stock and to management regulation itself (Hilborn and Walters 1992).

The relationship between indices of fishing effort, catch rate, and fish abundance is of critical importance to the effective management of commercial fisheries, particularly with the increasing use of catch quotas as a

means of optimising yield. Such quotas place heavy demands on the timeliness and accuracy of scientific advice, which in return requires detail and precision in the assessments of stock status and the impact of fishing on the resource. A perusal of the scientific reports of such fisheries commissions as the Northeast Atlantic Fisheries Organisation (NAFO) and the International Council for the Exploration of the Seas (ICES) indicates a continued heavy dependence of stock assessments on commercial catch and effort data, mainly as a source of calibration of sequential population models (Winters and Wheeler 1985). Extensive literature is available (e.g. Paloheimo and Dickie 1964; MacCall 1976; Clark and Mangel 1979; Pope 1980; Ulltang 1976) on the failure of the underlying assumption of a constant catchability coefficient (q) (Beverton and Holt 1957), which underpins the classic catch equation of Baranov (1918). Garrod (1964) and Gulland (1964) have pointed out that variations in q may result from any number of factors including changes in fishing power, vulnerability to the gear, seasonal and spatial patterns of distribution, and changes in stock abundance. Some of these factors can be readily measured and taken into account to provide standardized catch-rates such as those derived by the multiplicative model of Gavaris (1980). However, other factors such as fishing behaviour are more difficult to assess.

1.3. Fleet dynamics

According to Hilborn (1985), a major element of fisheries science should be the study of fishers and fleet dynamics. In Figure 1.1 the four major elements in a fishery can be seen, namely: population dynamics, fleet dynamics, the processing sector and marketing. Many of the important questions occur at the interface between fleet dynamics and population dynamics. The relationships between catch per unit effort (CPUE) and fish abundance require looking at both the fish (population dynamics) and the fishers (fleet dynamics).

Rather than to ignore fishing experience entirely, research into fishing behaviour can provide a better understanding of the appropriate use of catch and effort data in stock assessment and may also result in new approaches to monitor population trends (Hilborn 1985). Research into fishing behaviour is also important to improve communication between fishery scientists and the fishing industry. If management agencies do not acknowledge the validity of

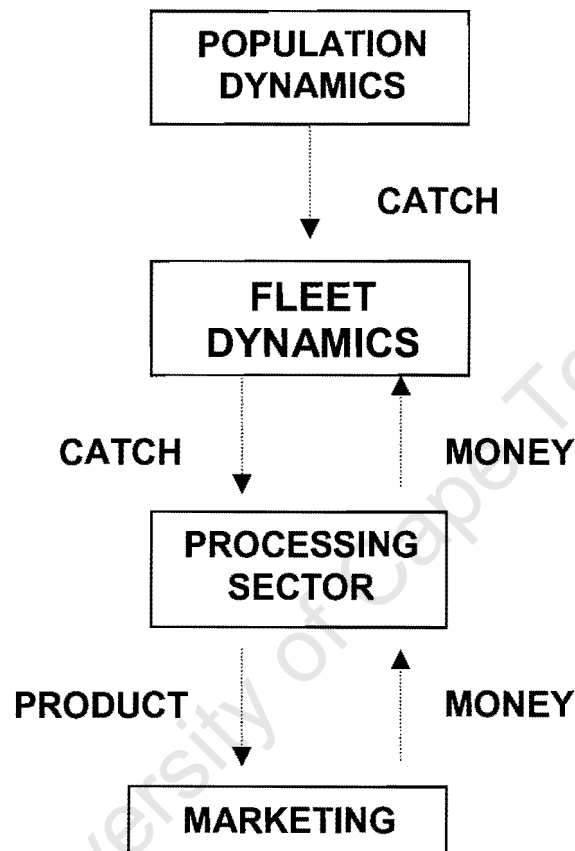


Figure 1.1. Interaction among the four major elements in a fishery (Hilborn 1985).

the fishing experience, they risk alienating the fishing industry, whose participation is essential to the fisheries management process (Doorn 2001). Fishers make decisions, which affect the success of their foraging operations and, like natural predators; they react with varying effectiveness to the conditions of the prey populations. The dynamics, which govern fishers' behaviour, are probably as complex and interesting as those of the fish populations, and yet fisheries science seems to be concerned almost

exclusively with the dynamics of the exploited stocks of fish. Understanding fishers' behaviour is of equal importance for the successful stewardship of a fishery; managers need to anticipate how fishers will react to changes in fish abundance and to fishery regulations.

One of the objectives of this thesis is to contribute to the knowledge of fleet dynamics specifically on the part of effort allocation. The focus will be on the differences in competitive ability among different sizes of vessels, the movement of vessels, the allocation of fishing effort in space, competitive interactions between fishing vessels and equalization of CPUE. Effort allocation will be studied within the theoretical framework of the ideal free distribution (IFD).

1.4. Biological response to oceanographic changes

Biological responses in most studies refer to biological productivity, which is generally measured through the analysis of recruitment success. A detailed description of the recruitment success theories, including physical forcing factors, was precisely summarized by Cole and McGlade (1998), and the link between recruitment and ocean processes has been highlighted by Bakun (1996). Shannon *et al.* (1988) studied the responses of fish population in the Benguela ecosystem to environmental changes. Moreover the control of population biology, oceanographic traits and variability may also alter the distribution of fish stocks. Most of the observed changes in fish distribution reported in the literature refer to horizontal changes in location (latitude and longitude). There are many examples of geographical shifts in pelagic fish stocks triggered by oceanographic processes (e.g. Boyd 1979; Gordo *et al.* 2000a; Waluda *et al.* 2001). Conversely, there is limited information relating the effects of environmental changes to local fish aggregation or aggregative structure through the water column (Smith and Page 1996; Perry and Smith 1994; Perry *et al.* 2000).

Vertical shifts or vertical dispersion in demersal fishes of commercial interest have direct consequences for bottom trawl catch rates through their effects on fishing efficiency. In those cases in which fluctuations in catch rates are not caused by changes in actual abundance, the fluctuations can be attributed to changes in catchability, in other words, to changes in the interaction between the resource and the fishing effort (Arreguin-Sánchez 1996). Catchability (q) may vary with changes in the spatial distribution of the population, with changes in location and changes in aggregation, and also with the degree of matching between fleet and resource (Swain and Sinclair 1994). In short, then, catchability generally is regulated by density-dependent processes (e.g. Hutchings and Myers 1994) and governed by physical or biological factors.

Many fisheries exhibit daily changes in catchability (Beamish 1966; Gordo and Macpherson 1991), in most cases due to a biological factor such as vertical dispersal for feeding at night (Bowman and Bowman 1966). Smith and Page (1996) showed that physical factors played a role in changing the vertical distribution of cod, where environmental variables change its catchability in such a way that some of the annual variations estimated by bottom-trawl surveys might be attributed to changes in catchability and not to annual changes in abundance.

Similarly, the pronounced environmental seasonality in the northern Benguela system seems to be the factor responsible for the strong seasonality observed in hake catchability on research cruises (Macpherson *et al.* 1991) as well as in fleet data.

1.5. Oceanography of the Benguela up welling system

The Benguela up welling system is inherently highly variable, being pulsed on time-scales from hours to months. Superimposed on this is pronounced variability at the system boundaries on inter- and intra-annual time scales. The Benguela is unique among up welling systems in that it is bounded on

both equator ward and pole ward sides by warm-water regimes, the Angola Current and Agulhas Current systems respectively (Shannon *et al.* 1992.)

The Namibian waters known as northern Benguela are characterised by permanent up welling with strong seasonal and interannual fluctuations, with the major interannual anomalies being referred to as “Benguela Niños” (Shannon *et al.* 1986). During Benguela Niños the seasonal warming of central and northern Namibia reaches maximum values due to an extreme intrusion of warm, salty water of equatorial origin. In this region, large-scale fluctuations in fisheries have also been described with signs of being related to environmental fluctuations (Shannon *et al.* 1988; Gordo and Hightower 1991).

The marked environmental variability that characterises up welling regions makes them perfect scenarios for analysing the existence of biological response to oceanographic changes. The time frame of the variability in the physical process linked to the coastal up welling dynamics is a key factor in understanding the potential time scales involved that are liable to affect biological factors and populations. The major environmental fluctuations in the Benguela system are annual and seasonal but the system may fluctuate over short periods as well, since long shore wind varies over periods of typically 2-5 days in the world’s eastern boundary current systems (Nelson 1992). In the Benguela region the environmental fluctuation of shortest period has been reported with a period of 3-6 days and caused by the passage of easterly moving cyclones across the south of the African continent (Nelson and Hutchings 1983).

1.6. Review of the Namibian hake fishery

Hake form the major component of the Southern African bottom-trawl fishery. There are three species of hake (Fig.1.2). Benguela hake, *Merluccius polli*, overlap the northernmost distribution of the Cape hake, *Merluccius capensis*, whose range extends into the waters of southern Angola. Off Namibia,

shallow-water Cape hake is the most common of the three species. The farther south on the West Coast one trawls, the more abundant deep-water Cape hake, *Merluccius paradoxus*, becomes. Just north of the boundary between Namibia and South Africa, the two species are almost equally abundant with a considerable overlap in the distribution between 150 and 350 m (Burmeister 2001). Benguela hake is of little commercial value to the hake fishery in Namibia.

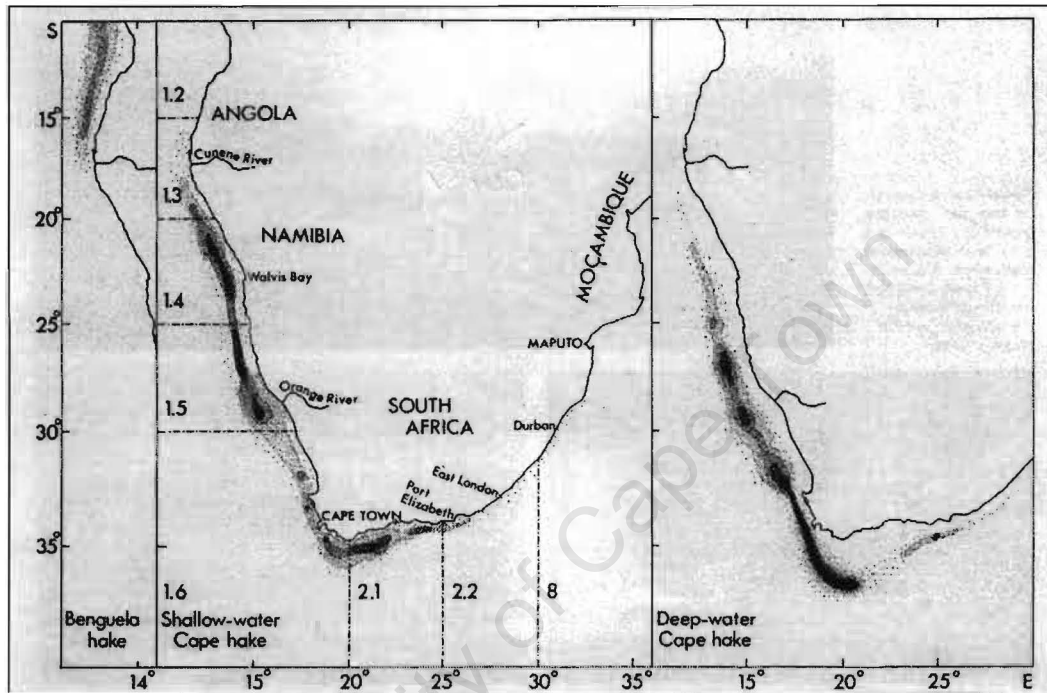


Figure 1.2. Distribution by density of Benguela hake (left), shallow-water Cape hake (centre) and deep-water Cape hake (right) and the ICSEAF statistical areas (Taken from Payne 1989).

The history of hake catches off the Namibian coast spans slightly more than forty years. The offshore trawl fishery for hake started late in the 1950's and had by 1965 already developed into a multinational deep-sea fishery with the introduction of long-distance trawlers (Gordoa *et al.* 1995). The widespread introduction of 200 nautical mile exclusive economic zones (EEZ) off coastal states in the mid 1970's necessitated the search for new fishing areas elsewhere. Thus more and more deep-sea stern trawlers equipped with freezer holds arrived in Namibian water by the late 1960's. In 1969, the International Commission for Southeast Atlantic Fisheries (ICSEAF) was

established in Rome and held its first working group meeting in 1972. In 1975 it implemented the first management measures in the international hake fisheries off South Africa and Namibia. By 1981, many countries were actively involved in hake trawling. They were Spain, the USSR, South Africa, Portugal, Poland, Italy, Cuba, Israel, Germany and Japan. The main functions of ICSEAF were to regulate, manage and control the hake resources.

ICSEAF implemented the use of minimum stretched mesh size of 110 mm from July 1975. That declaration alone afforded some measures of protection to juvenile hake, and to enforce it, ICSEAF also brought in a system of international inspection and later, allocated quotas to each member country (Payne 1989, van der Westhuizen 2001). These regulations did not have the necessary effect of stabilising the hake resources, since foreign trawler man could never have the same interest in preserving a resource as a local fisherman would. Fishing effort continued to remain high towards the end of 1970's, which was accompanied by further declines in catches and catch rates.

Because of the international character of the fishery and the large number of vessels involved, no clear descriptions concerning the size and nature of the fishing fleet exist (Newman *et al.* 1976). The heterogeneity of the fleet was caused not only by differences in vessel tonnage, the countries concerned and the different gear employed, but also by the different fishing strategies used by individual countries. Gordo and Sanchez (1988) presented a standardization approach for this complex fleet.

Hake stocks were exploited to a low level before Namibia's independence in 1990. After independence, the government's priority was therefore to rebuild the depleted fishery stocks to their full potential through the program of catch restrictions and other regulations over an expected period of five to ten years. Some of the measures that were imposed to ensure sustainability were: severe reduction in total allowable catch (TAC), effort restrictions, protection of juvenile hake, declaration of the Exclusive Economic Zone (EEZ), proper control of catches and discards and intensive research on hake stocks. The

government is encouraging shore based processing through various measures because it provides more employment than processing on-board.

The Sea Fisheries Act (Act 29 of 1992) of Namibia provides for the granting of rights of exploitation for commercial fishing (MFMR 1992). Fishing rights are seen as a medium term instrument giving investors the security that there will be a limited number of participants in the distribution of TAC's as quotas. At independence, almost all rights in place were granted from 1987 for a period of seven years and expired on December 31, 1993. There were 17 holders of rights for demersal fishing in 1990. These applications were open to all: foreign, national or joint ventures. Following consideration of the applications, 38 ventures have been granted rights for demersal fishing for hake to date. The pattern of rights granted, represents a major restructuring of hake fishing rights towards Namibian ownership and participation by groups in the Namibian population previously excluded from the industry.

Demersal hake trawl quotas are allocated on a per vessel basis. The principal instrument of by-catch management is the charging of by-catch fees. The minimum mesh size for bottom trawls is 110 mm. No bottom trawling is allowed inside coordinates generally following the 200-meter depth contour, for the protection of juvenile hake, which generally occur in shallower water than adults (Payne *et al.* 1987; Burmeister 2001). All commercial vessels are required to report daily catch and effort. All vessels large enough to take observers, which include all demersal fishery vessels, are required to carry observers. Land-based inspectors monitor all commercial landings. The number of demersal trawlers fishing on hake in Namibia increased from 44 in 1991 to 80 in 1993 (Van der Westhuizen 2001). The number was reduced to 66 in 1994 when the vessel quota system was introduced and it has remained more or less constant at 62 boats in 1999.

1.7. Management of the Namibian hake fishery

Since 1990 the Namibian government has managed the hake stock by setting a total allowable catch (TAC) for each fishing year. From 1990 to 1997 scientific recommendations for the TAC were based on some 20% of the exploitable biomass (fish larger than 35cm) estimated from swept area biomass surveys. In 1998 an interim management procedure (IMP) was adopted in which both survey estimates and catch per unit of effort (CPUE) data from the commercial fleet are used to adjust the TAC from the previous season (Butterworth and Geromont 2001). In 2002 this procedure was adjusted and the operating model currently used is an Age-Structured Production model that is fitted to commercial CPUE data, survey abundance estimates and catch-at-age data. It treats *Merluccius capensis* and *M. paradoxus* as one stock and includes stock-recruitment fluctuations (Rademeyer and Butterworth 2002). The Nansen survey estimates are used as relative indices of abundance.

CPUE are often used to obtain an index of relative abundance of a stock, although it is well known that factors outside of changes in population abundance can influence CPUE (Cooke 1985; Sampson 1991). These factors may reflect changes in the distribution of the stock as well as the behaviour of the fleet (Quinn 1985). In some cases when stock size has been measured independently, CPUE has turned out not to be an index of abundance but of availability, and in some cases to be dangerously misleading (Peterman and Steer 1981; Shardlow 1993, Gordo and Hightower 1991). In this study a multiplicative model will be designed to calculate a standardized CPUE index from commercial data in order to compensate for some of the factors influencing the relationship of CPUE and abundance. This standardized index of abundance can then be used in stock assessment models.

This study will also focus on contributing to the knowledge of fleet dynamics specifically on the part of effort allocation. See study area in Figure 1.3. Effort allocation will be investigated, within the theoretical framework of the

ideal free distribution (IFD). CPUE in particular is examined to determine if the behaviour of the fleet through timing and location of fishing and vessel size influences annual variations in those statistics. Under an Independent Vessel Quota (IVQ) system, one might expect a shift in effort to areas with higher CPUE in an attempt to maximize catch per effort. However, conflicting objectives, such as fishing closer to homeport or marketing factors, may influence this behaviour. The question arises: How do changes in fleet behaviour and corresponding changes in fish distribution (independent or not of the IVQ program) affect the interpretation of CPUE, and how does one account for them? If the fleet size changes in future, the effect on competition among vessels should be monitored and the possible influence on q and the resulting breakdown of the relationship between CPUE and abundance should be kept in mind. Both fish abundance and behaviour of fishers and their interaction will influence CPUE.

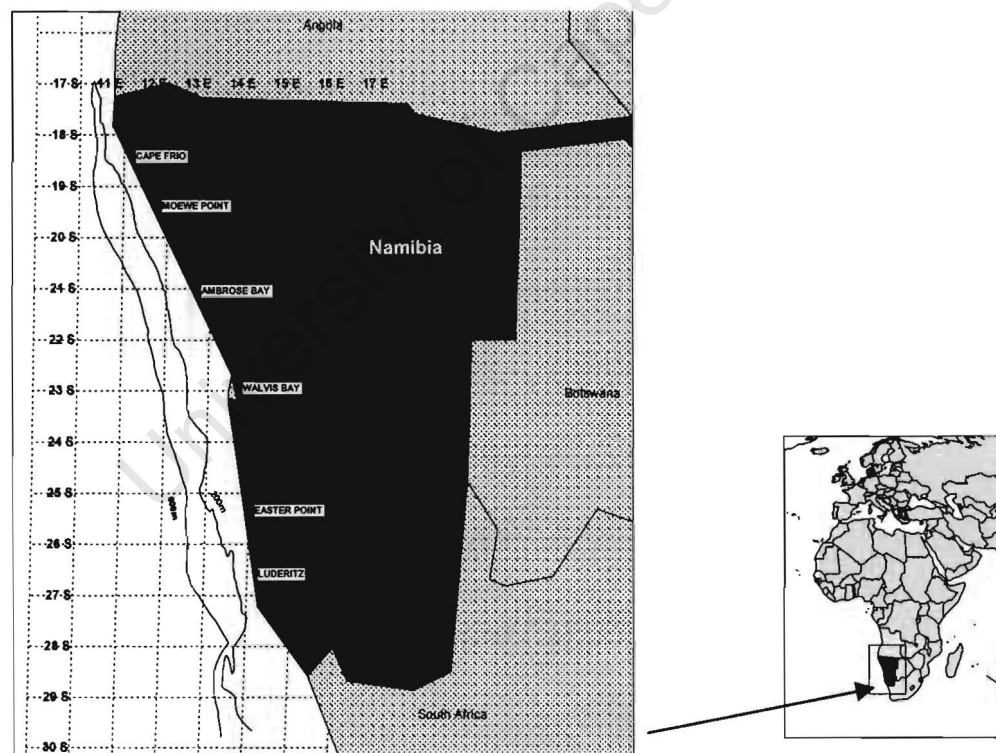


Figure 1.3. Study area off Namibia

Currently hake abundance estimate surveys are conducted during the period from January to February each year. Macpherson *et al.* (1991) detected intra-annual variability in hake densities: the biomass estimated by swept area research surveys during warm summers was anomalously higher than the preceding winter. According to Oelofsen (1999), a better understanding of the fluctuations in the system as well as reliable medium-term predictive capability is invaluable to the management of the Namibian hake resource. These differences cannot be attributed to differences in population biomass, because of their short time period, but to differences in catchability. By the time of this study, no attention was given to the effect of the seasonal changes in the availability of hake to bottom trawls on annual indices of abundance derived from either commercial CPUE or density estimates from research surveys. Density estimates from commercial vessels obtained throughout the year will be used to investigate the intra- and inter-annual variability in q . Recommendations on which time of the year is least variable and thus most suitable for conducting annual biomass estimating surveys can then be made based on the outcome of the analysis. Probably density estimates from the commercial fleet can also be used to tune abundance indices from research surveys or to estimate the confidence limits of the survey estimates.

Roel and Bailey (1987) described relationships between hake catches and bottom oxygen as well as sea surface temperature from two surveys in South African waters. Although the first sign of possible seasonal variability in Namibian hake catchability was described by Macpherson *et al.* (1991), the study was limited by its temporal resolution (two surveys per year). Since 1994 a spatially and temporally highly resolved CPUE database has been maintained, allowing a more fine-scaled temporal analysis. Thus, with the premise that the strongest physical variability of this system occurs on a seasonal scale I will examine the temporal variability of the catchability of Namibian hake in conjunction with the temporal variability of the SST as an indicator of environmental variability on a monthly basis. The new availability of satellite sea surface temperature (SST) data on a regular and reliable basis (since the 1980's) make the study of the linkages between fish availability and recruitment and environmental anomalies, possible. Prior to this study, no

account was taken of the variability in the Benguela system in managing the hake. In the Namibian hake fishery, the discrepancies between survey estimates and those from surplus production models based on CPUE from commercial data have recently been pointed out (Pennington and Strømme 1998). By examining short-term fluctuations in catchability it may be possible to detect changes in fish distribution, independently of fish abundance, affected by other factors such as fish behaviour (spawning or feeding migrations) or environmental factors.

In Namibia, the inter-annual physical variability may result in a strong biological response. Therefore, the strong signals in recruitment variability of Cape hake render this species an ideal candidate to study its response to inter-annual variations in ocean conditions off the coast of Namibia. The study will attempt to identify environmental conditions that may be related to relative recruitment success or failure of Cape hake to explain some of the annual variability in the recruitment strength and possibly provide a system, which will enable the prediction of recruitment strength.

1.8. Objectives and hypotheses

The objectives of this study are to investigate and get a better understanding of the mechanisms underlying spatio-temporal patterns of hake abundance. This includes the biotic process of recruitment, abiotic environmental influences, and the effect of effort allocation by the fishers. The understanding of the processes that cause changes in the catchability of hake will then be used to guide managers (senior personnel in the Ministry of Fisheries and Marine Resources) on how to treat CPUE data from the fishery when used in stock assessment models as well as on how regulations on the fishing fleet might influence the CPUE. A better understanding of the influence of changes in the environment on the spatio-temporal patterns of hake as well as the prediction of recruitment strength based on environmental indices will help the managers in understanding the population dynamics of hake better and equip them to make better management decisions.

The following hypotheses will be tested in this study:

- 1) Several factors other than changes in population abundance have a significant influence on commercial CPUE. In order to use CPUE as an index of abundance, these factors need to be identified and accounted for.
- 2) The movement dynamics of the fishing fleet have a significant influence on the relationship between catch rates and fish abundance. The movement dynamics of the fleet are tested against Ideal Free Distribution theory in order to evaluate the significance of CPUE as an index of abundance.
- 3) Density estimates from commercial fishery data can be used to estimate the variability in availability throughout the year. This can be used to complement or adjust density estimates obtained from research surveys, by identifying seasons with large variability in hake availability.
- 4) The monthly variability in density of Namibian hake is modulated by the seasonal environmental cycle of the system. This can be used to explain the variability in hake availability from season to season, which may influence the density estimates obtained from research surveys.
- 5) Several environmental processes influence the strength of recruitment into the hake fishery. This can be used to explain variability of incoming year-classes, which in turn affects the size of the hake resource.

Thus the overall goal of this dissertation is to analyse:

- 1) the dynamics of the fishing fleet and fish populations, and
- 2) their relationships with one another and the physical environment, so that recruitment success may be forecast from environmental indices.

CHAPTER TWO

INVESTIGATION OF CATCH STATISTICS USING A MULTIPLICATIVE MODEL

2.1. Introduction

Catch per unit effort (CPUE) is used in the stock assessment of Namibian hake as a measure of relative abundance in the Interim Management Procedure that is currently used for the calculations of annual TAC recommendations and so plays a critical role in current levels of exploitation. (Rademeyer and Butterworth 2002).

Standardized CPUE analyses (Gavaris 1980) using multiplicative models have become widely used in assessing fish stocks. They are often used to obtain an index of relative abundance of a stock, although they may actually reflect changes in stock distribution rather than abundance (Quinn 1985).

This study addresses the problem of interpreting hake catch statistics in the light of changes occurring under the Namibian individual vessel quota (IVQ) program. CPUE in particular is examined to determine if the behaviour of the fleet through timing and location of fishing and vessel size influences annual variations in those statistics. Under an IVQ system, one might expect a shift in effort to areas with higher CPUE in an attempt to maximize catch per effort. However, conflicting objectives, such as fishing closer to a homeport or marketing factors, may influence this behaviour. The question arises: How do changes in fleet behaviour and corresponding changes in fish distribution (independent or not of the IVQ program) affect the interpretation of CPUE, and how does one account for them?

The major interest is in the season-area effects, although one wishes to account for vessel effects as well if they are found to be important. According to Sullivan and Rebert (1998) the following scenarios should be considered:

- (i) both the fishers and the fish distribute themselves consistently by season and area across years;
- (ii) the fishers change their distribution, but the fish do not;
- (iii) the fish change their distribution, but the fishers do not; or
- (iv) both the fishers and the fish change their distributions.

If the first scenario, holds then a conventional estimator (e.g., simple mean log CPUE or effort-weighted mean CPUE) should be adequate as an index of abundance. If the second scenario holds, as it might under a change in fishery management, then accounting for changes in the fishery (e.g. season fished, area fished, etc.) and weighting the influence of each factor proportionally and independently of the distribution of effort, should result in an appropriate indicator of abundance. If the third or fourth scenario holds, and fish also change their distribution from one year to the next, then in addition to the main effects, one should expect to see significant interactions between year and the remaining factors, and one would need to make some additional assumptions for the estimators to be representative of annual changes in abundance.

In this study, the influence of various factors on CPUE will be investigated by the use of generalized linear modelling that incorporates the factors of interest. Results from the analysis will indicate which factors play a major role in interpreting this statistic, and a graphical analysis of the distribution of fleet effort will indicate how severe these influences are likely to be. The significant factors and interactions will be employed to highlight fleet behaviour and fish distribution patterns that are likely to affect the conventional CPUE indices of abundance.

2.2. Material and methods

2.2.1. Data

All available trawl data from daily logsheets for trawls targeting hake off Namibia were analysed from 1992 to 1999. For each fishing day, for each

vessel, data as described in Table 2.1 was available. Vessels fall into 17 Gross Registered Tonnage (GRT) classes based on 100 GRT increments. CPUE for each daily record was calculated as $(\sum \text{Catch} / \sum \text{Hours trawled})$. No zero values occurred. Natural log transformation of CPUE was performed in order to meet the Normal distribution assumption. In Figures 2.1 (a) and (b) the frequency distributions of CPUE can be seen before and after transformation. The CPUE distribution is not normally distributed but after the transformation has a normal distribution.

Table 2.1. Summary of variables.

Variable	Type^a	Description
Year	Categorical (8)	Year that tow occurred in
Month	Categorical (12)	Month that tow occurred in
Type	Categorical (2)	Type of vessel – freezer or wet
Area	Categorical (13)	Each latitude degree from 17°S to 29°S for the first trawl of each day
Depth	Continuous	Depth in meters of sea bottom at beginning of first tow of the day
Vessel	Text	The name (license number) of each vessel
GRT	Categorical (17)	Gross tonnage of the vessel

a Type of variable with the number of categories given in parentheses.

Table 2.1 also indicates how each variable was modelled, either as a continuous variable or a categorical variable with a given number of categories in parenthesis. Individual vessel effects were not examined because of the large number (120) of vessels involved in the fishery over the eight-year period. Depth was modelled assuming a quadratic relationship with $\ln \text{CPUE}$.

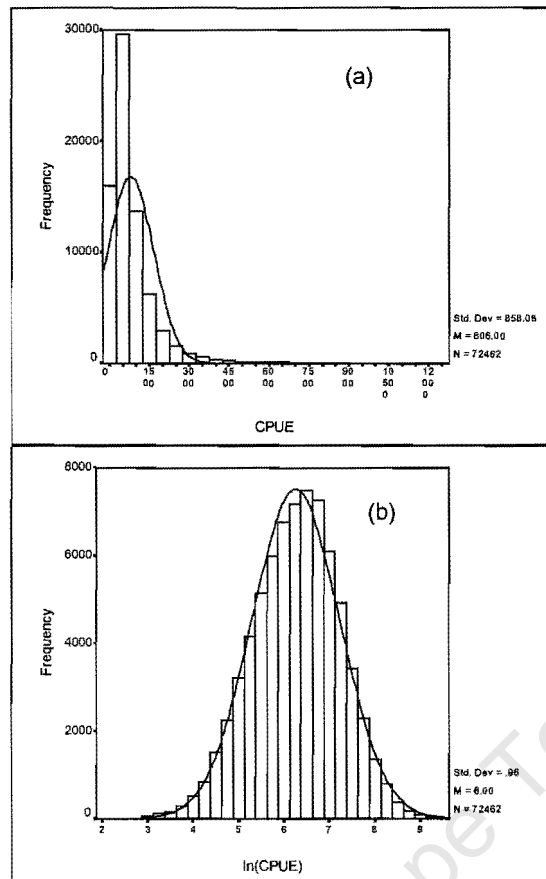


Figure 2.1. Frequency distribution of CPUE (a) and $\ln(\text{CPUE})$ (b) from the Namibian hake CPUE database containing data from 1992 to 1999. The fitted Normal distribution curve is shown on the graphs.

2.2.2 Statistical Methods

All modelling and analysis was done using the statistical package: "SPSS[®] Base 9.0" (SPSS Inc. 1999). To build a generalized linear model of CPUE that explained as much as possible of the variation in CPUE, a simple forward stepwise approach was taken. $\ln(\text{CPUE})$ was regressed against each of a set of variables in turn. The univariate general linear modelling option in SPSS[®] was used for this analysis. The variable that explained the most of the variability in CPUE was included in the model. The CPUE was regressed against it and each of the other predictor variables, to find the next most explanatory variable. Main effects are examined first, followed by interactions. The eta-squared coefficient (partial R^2) is used to indicate the proportion of the variability of the dependent variable that is explained by knowing the

values of the independent variable (SPSS Inc. 1999). This stepwise regression procedure continued until no substantial improvement came from adding an extra variable to the model (R^2 improved by less than 0.5%). With more than 72000 data points, an F-test to determine the significance of variables was found to be inappropriate; all variables appeared to be significant, even when the effect of the variable was negligible. Therefore, the stronger requirement of a useful improvement in R^2 was used.

The factors for GRT and year as well as the interaction between the two variables from the model was used to standardize the effort for each GRT-class and year to be used in the analysis of distribution of fleet effort.

$$\text{The vessel factor (V)} = \exp(\omega_{\text{year} \times \text{GRT}} + \alpha_{\text{GRT}} + \beta_{\text{year}}) \dots \dots \dots (2.1)$$

$$\text{The effort was standardized by: (hours trawled} \times \text{V)} \dots \dots \dots (2.2)$$

2.3. Results

2.3.1. Regression analysis

Results of the stepwise linear fit to the data indicate that GRT-class, year, area and month are significant to the model fit (at the 0.05 level) with GRT-class being the most informative (Table 2.2). Type, vessel and depth were not added, since no substantial improvement came from adding these variables to the model (R^2 improves by less than 0.5%).

In Figure 2.2 the individual effects of GRT-classes, year, area and month on $\ln\text{CPUE}$ can be seen. Month and GRT were found to have statistically significant interactions in combination with the year effect. Statistically significant but lower level interactions appeared between area-year and area-month.

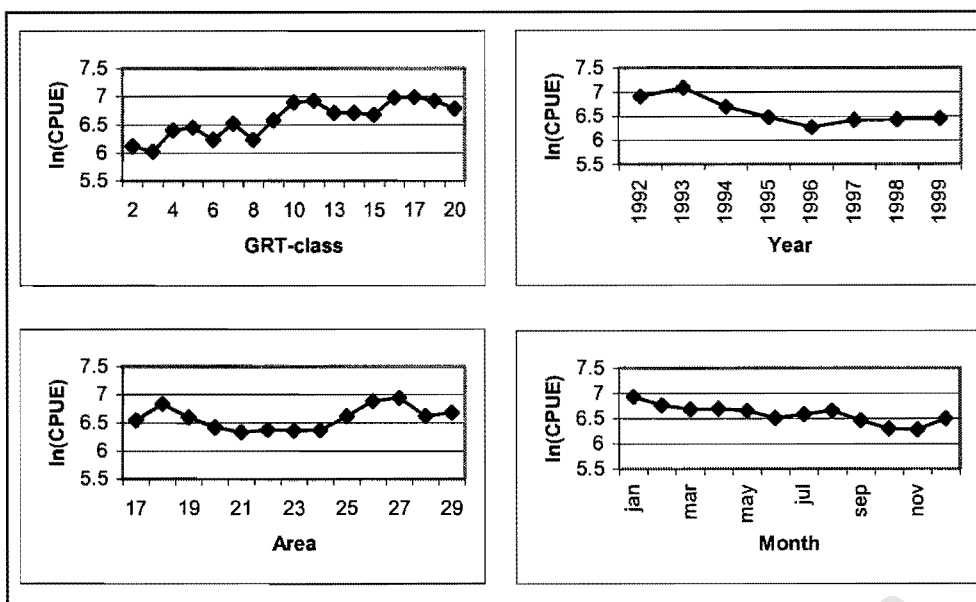


Figure 2.2. Mean ln(CPUE) for each GRT-class;Year; Area and Month under the full model.

ln(CPUE) increases with an increase in the GRT-class. A difference in ln(CPUE) from year to year can also be observed in Figure 2.2. ln(CPUE) is in general higher in the South of Namibia. The monthly changes in ln(CPUE) are also noticeable with highest values in January and the lowest in October. The inter- and intra-annual variability in CPUE will be investigated in relation to the variability in sea surface temperature in Chapter 5.

The final model can be summarized as follows:

$$\ln(\text{CPUE}) = \mu + \alpha \text{ GRT} + \beta \text{ year} + \varepsilon \text{ area} + \gamma \text{ month} + \eta \text{ year*month} + \omega \text{ year*GRT} + \lambda_{\text{area*month}} + \tau \text{ year*area} \dots \dots \dots (2.3)$$

where: μ is the intercept

The eta-squared statistics (Table 2.2) allow comparisons of the relative contribution of each factor or interaction in the full model at each step in the regression process. From this it is clear that GRT contributes the most (27.2%) to the interpretation of CPUE with year and area contributing 9.5%

and 6.9%, respectively. The interactions of area with month and year explain the least about CPUE of all the factors included in the model. With four direct effect variables in the model the multiple R^2 is 50.9%. Thus the full model explains about 51% of the variability in CPUE.

In comparison to studies done by: Large (1992) for sole in the western English Channel ($R^2 = 44.1\%$), Vignaux (1996) for the New Zealand hoki fishery ($R^2 = 23\%$), Megrey (1986) for Alaskan Pollack ($R^2 = 58\%$), Anon. (1981) for Faeroese cod ($R^2 = 35\%$) and Baino (1983) for Irish Sea plaice ($R^2 = 68\%$), this result is encouraging. Unpublished regression studies on the Namibian orange roughy fishery revealed a R^2 value of 35% (Brandão 1999).

Observed $\ln(\text{CPUE})$ was compared with predicted $\ln(\text{CPUE})$ under the full model (Figure 2.3). Half of the 72462 observations occurred between 5.6 and 6.9 $\ln(\text{CPUE})$ (i.e., between 270 and 992 kg/h) with somewhat greater variance observed for lower values. From this it is evident that the distribution is skewed to some extent. Although this non-normality precludes accurate statements about confidence intervals for the resultant estimates, the main objective of this work was to minimize possible bias in the trend of the estimates of standardized CPUE over time. Glazer and Butterworth (2002) encountered the same problem when applying generalized linear modelling to the west coast hake off South Africa to standardize the CPUE series.

2.3.2 Month and area effects

2.3.2.1. Month-year interaction

Interaction between the effects of year and month implies that the monthly pattern of hake density was not constant throughout the period 1992-1999. Results from the full model (Table 2.2) indicate that the year-month interaction is the interaction that explains most of the variability in CPUE with an eta-squared value of 0.077, explaining some 8% of the variation in CPUE.

Table 2.2. Results of the stepwise regression.

Factor	SS	Regression df	MS	F	P	Eta-squared
Intercept		1			<0.000	0.741
GRT	18206.044	16	1147.878	1694	<0.000	0.272
Year	4608.945	7	658.421	1083	<0.000	0.095
Area	3040.930	12	253.411	447	<0.000	0.069
Month	1687.816	11	153.438	282	<0.000	0.041
Year * Month	3013.954	77	39.142	78	<0.000	0.077
Year * GRT	2200.369	98	22.453	47	<0.000	0.061
Area * Month	802.657	130	6.174	13	<0.000	0.024
Year * Area	472.236	83	5.690	12	<0.000	0.014

Note: The partial F-test statistics and associated P values for the proposed factors relative to the prior model fit are given along with the eta-squared statistics to allow comparisons of the relative contribution of each factor or interaction in the full model at each step in the process.

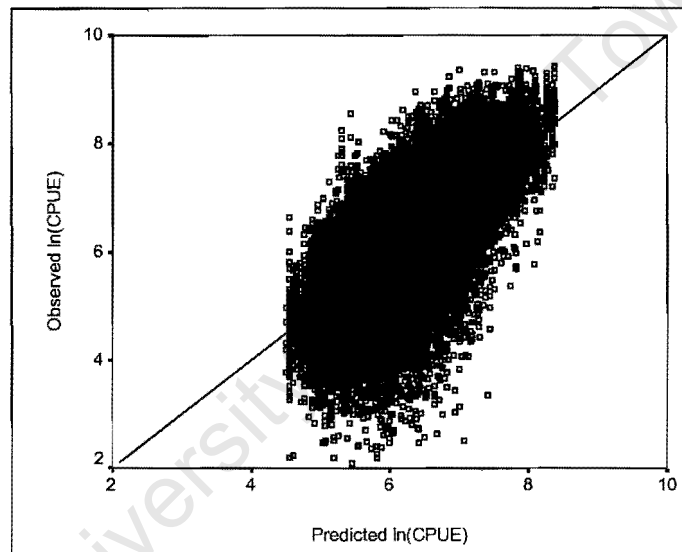


Figure 2.3. Observed $\ln(\text{CPUE})$ versus predicted $\ln(\text{CPUE})$ under the full model. The diagonal line gives the 1:1 ratio.

During 1994, 1995, 1996 and 1999 the seasonal effect was more pronounced than during the other years (Figure 2.5). This, in part, reflects a monthly pattern in stock density possibly caused by changes in the environment and will be investigated in more detail in Chapter 4. The difference between the full model and the reduced model indicates to what extent the month-year

interaction has an influence on CPUE. From Figure 2.5 it can be seen that the difference between the full and reduced model is more profound during the years with larger differences in monthly CPUE (seasonality) (like 1994, 1995 and 1996) than during the years with less variance in monthly CPUE (1992, 1993 and 1999).

Commercial catch statistics on percent-standardized effort expended by year and month indicate a shift in monthly effort (Figure 2.4). Effort occurred primarily during the second half of the year during the period from 1992 to 1996 with 50% of the total effort expended during the last five months of the year. During 1997, 1998 and 1999 the picture is inverted with 50% of the total effort expended during the first five months of the year.

Fishing during periods of high catch rates does not seem to be the overriding objective of the fleet, especially during 1994, 1995 and 1996 when the catch rates were considerably higher during the first part of the year. In fact it seems to be the opposite with greater effort during months with reduced CPUE and lower effort during months with high CPUE. This is most likely because of limited catching capacity of the fleet or/and cautious measures in order not to fill the quota too early in the year. The fleet was reduced from 80 to 66 vessels at the beginning of 1994. The fleet could only handle a limited catch with the reduced number of vessels and could therefore not expend more effort during the periods of high catch rates. During the later part of these years, when the catch rates dropped, more effort was expended in order to fill the quotas. The effort during the last three months of these three years, contributed 30% of the total effort for each year. During the period from 1997 to 1999 the catch rates were more consistent during the year and the quotas were almost filled by the end of November. Very little effort was spent during the month of December. During 1992 and 1993 the number of vessels was not a limiting factor and the effort was expended when most factors were favourable, like catch rates, available markets, weather conditions etc.

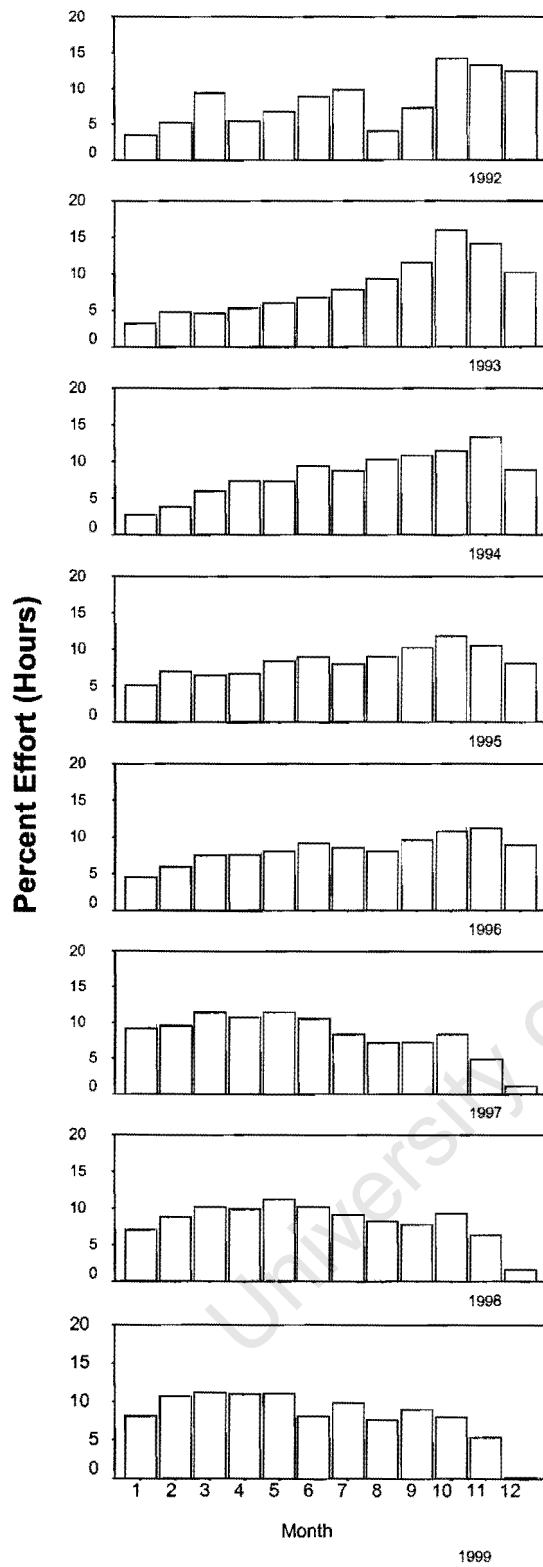


Figure 2.4. Namibian hake commercial effort in percent by month by year.

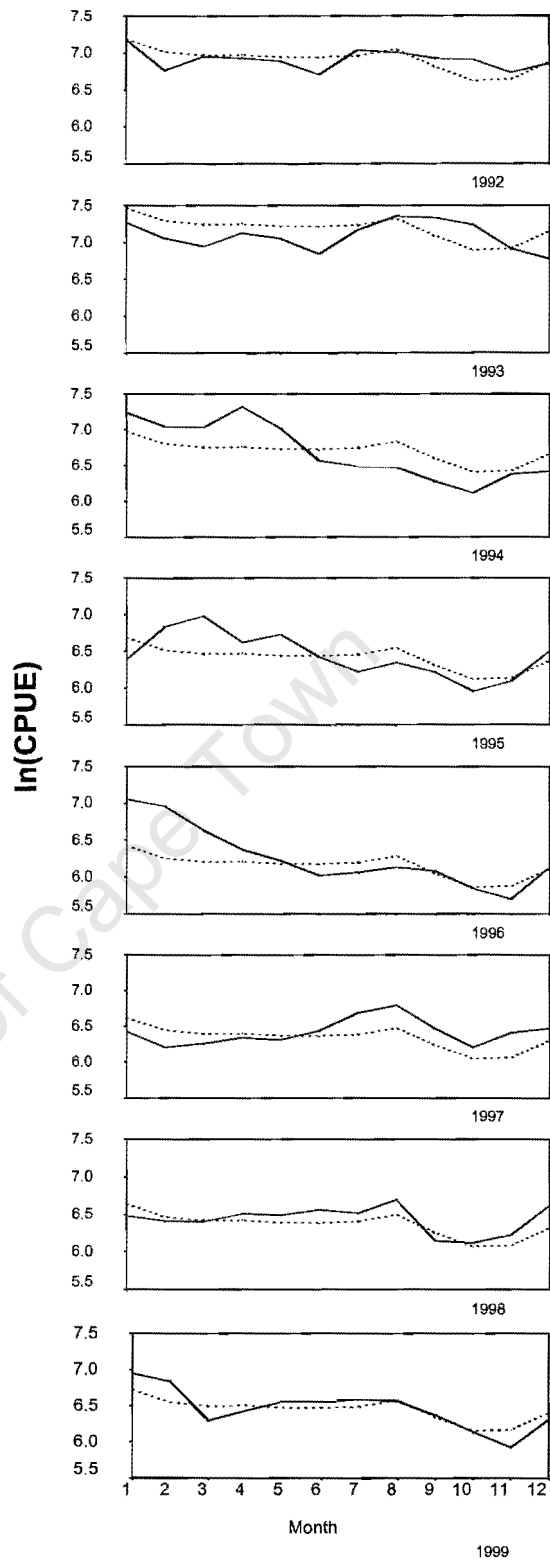


Figure 2.5. Mean $\ln(\text{CPUE})$ by year for the different months under the full model (solid lines) with a reduced model in which the month*year interaction term is left out (broken-line).

2.3.2.2. Area-year interaction

Interaction between the effects of year and area implies that the spatial distribution of hake density or catchability is not constant from year to year. Results from the full model (Table 2.2) show that the year-area interaction is significant but explains very little (1.4%) of the variability in CPUE, thus the spatial distribution of hake density does not have as large an influence on the CPUE as the monthly density (temporal) distribution. Area and year as main effects explain 6.9% and 9.5% respectively of the variability in CPUE. Since not all of the variability due to the year effect can be explained by the interactions of year with month, area and GRT, this can be interpreted as a change in hake abundance or availability from year to year.

In general catch rates are high in the South (Latitudes 26°S and 27°S) (Figure 2.7). A peak is also seen in the north (Latitudes 17°S to 19°S) but very little effort is expended in that area due to the distance from port and the poorer quality of the fish because of warmer water (Hake Association of Namibia, personal communication). The catch rate pattern for the different areas stayed very much the same from year to year. The commercial effort distribution is mainly between 22°S and 27°S. This corresponds to the only two ports in Namibia, Walvis Bay (23°S) and Lüderitz (26°30'S). One would expect more effort to be expended in the area around 26°S where higher catch rates occur. Due to the limitation of the distance from port (because of melting ice to keep the fish cold) for "wet" vessels, which land about 60% of the quota on ice, the vessels landing in Walvis Bay need to fish closer to that area although the catch rates are lower than in the far south.

2.3.2.3. Month-area interaction

Examination of the month-area effect fills out the picture on hake distribution patterns (Figure 2.9). According to the results from the full model (Table 2.2) this interaction is significant but explains very little about the variability in CPUE (2.4%), although more than the year-area interaction of 1.4%.

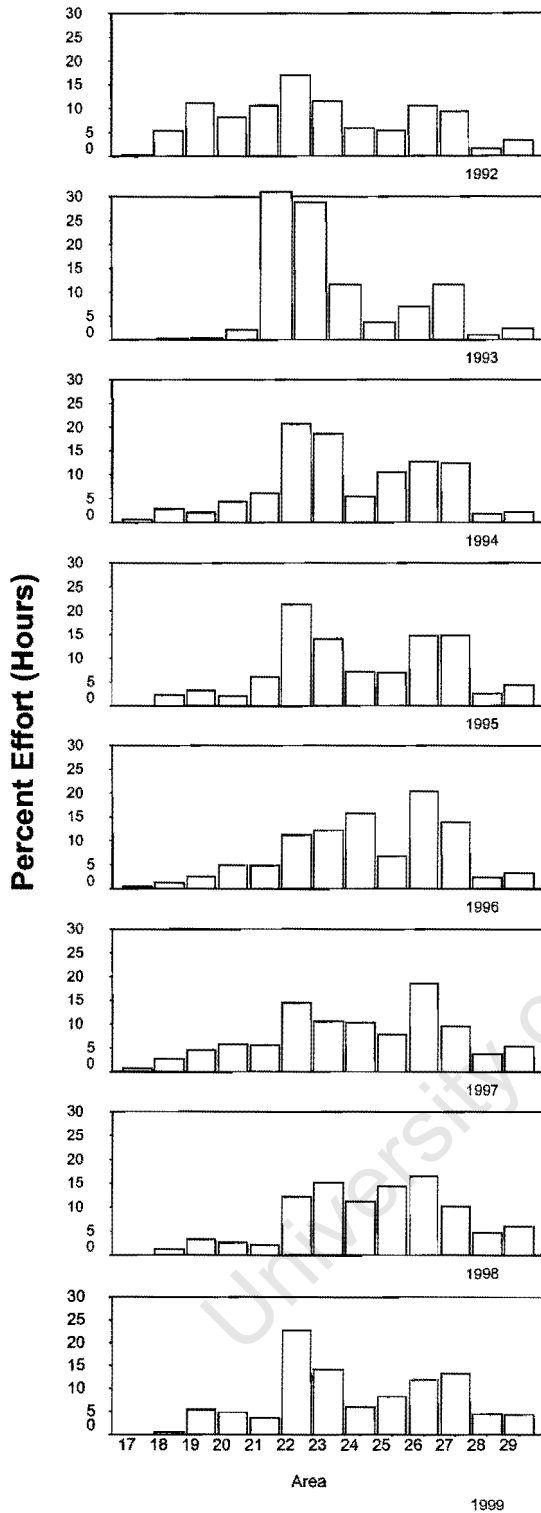


Figure 2.6. Namibian hake commercial effort in percent by area (deg. Latitude) by year.

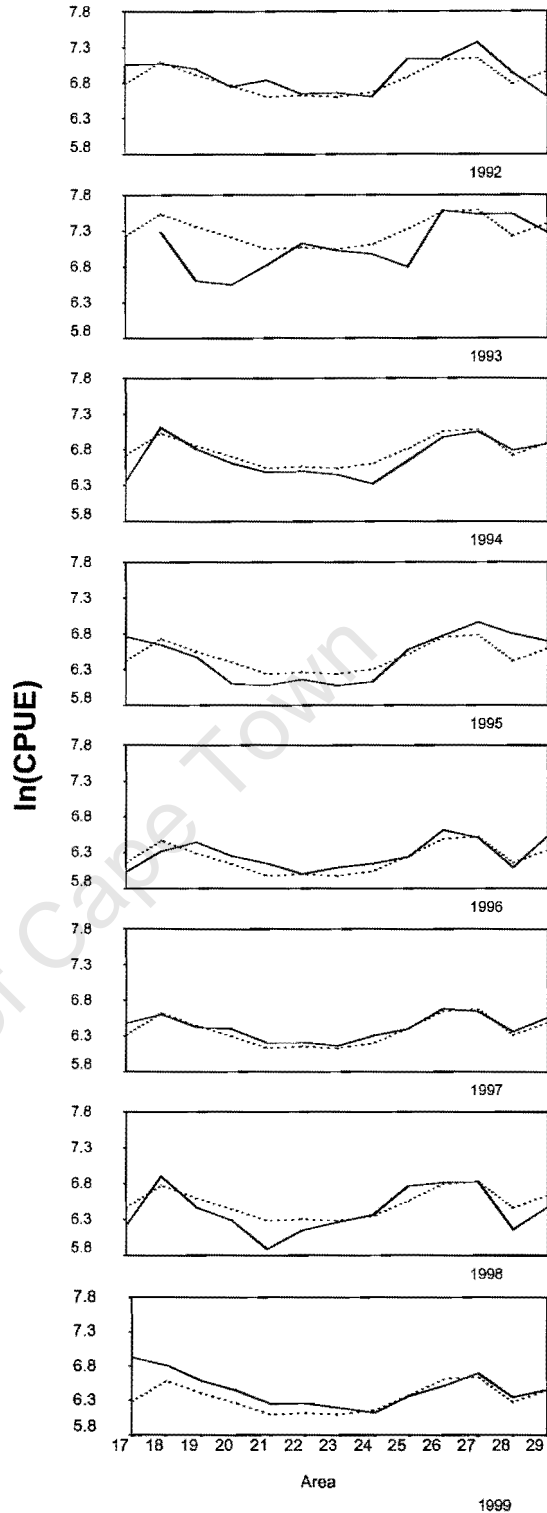
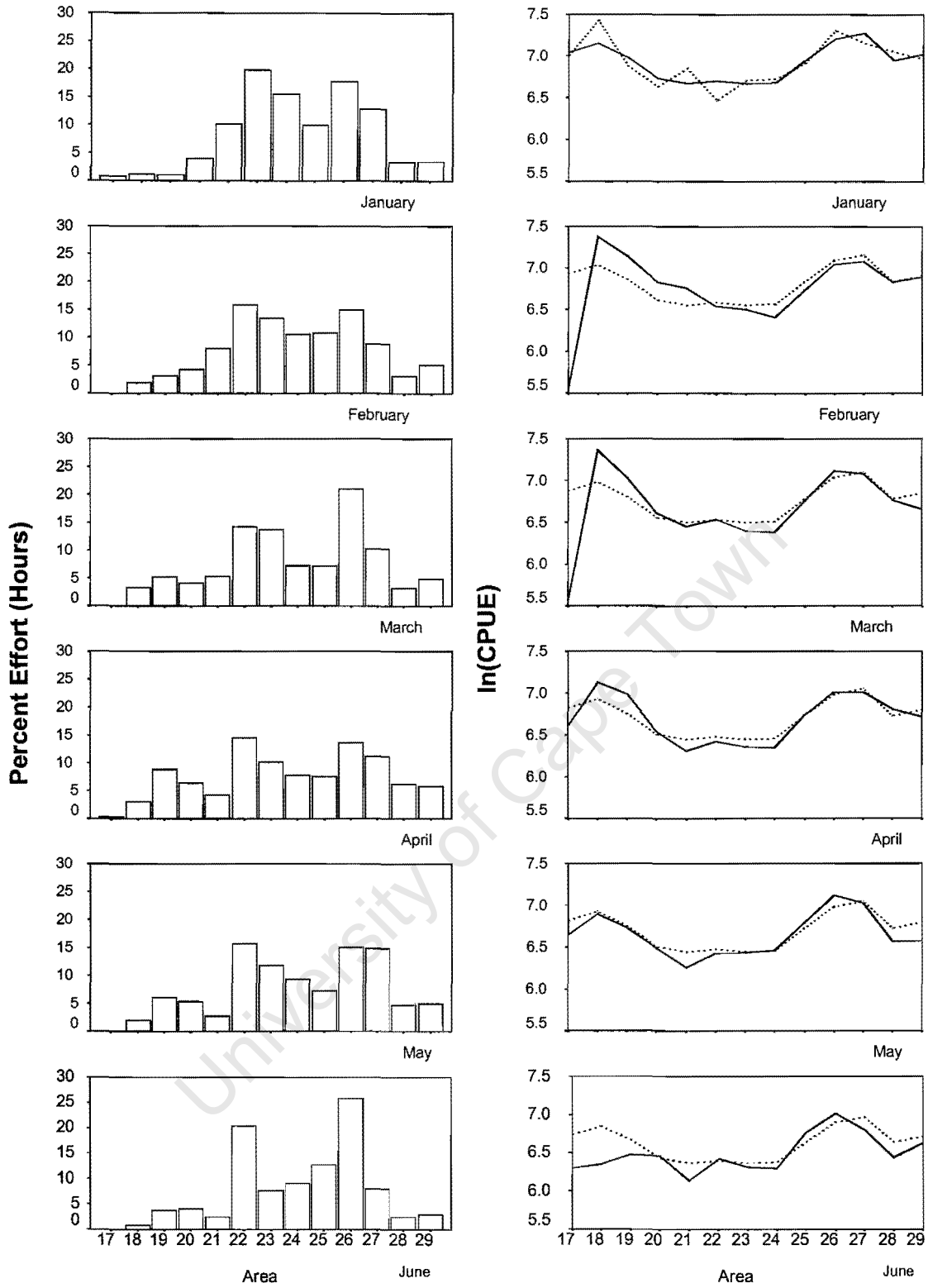


Figure 2.7. Mean ln(CPUE) by year for the different area (deg. Latitude) under the full model (solid line) contrasted with a reduced model in which the area*year interaction term is left out (broken line).



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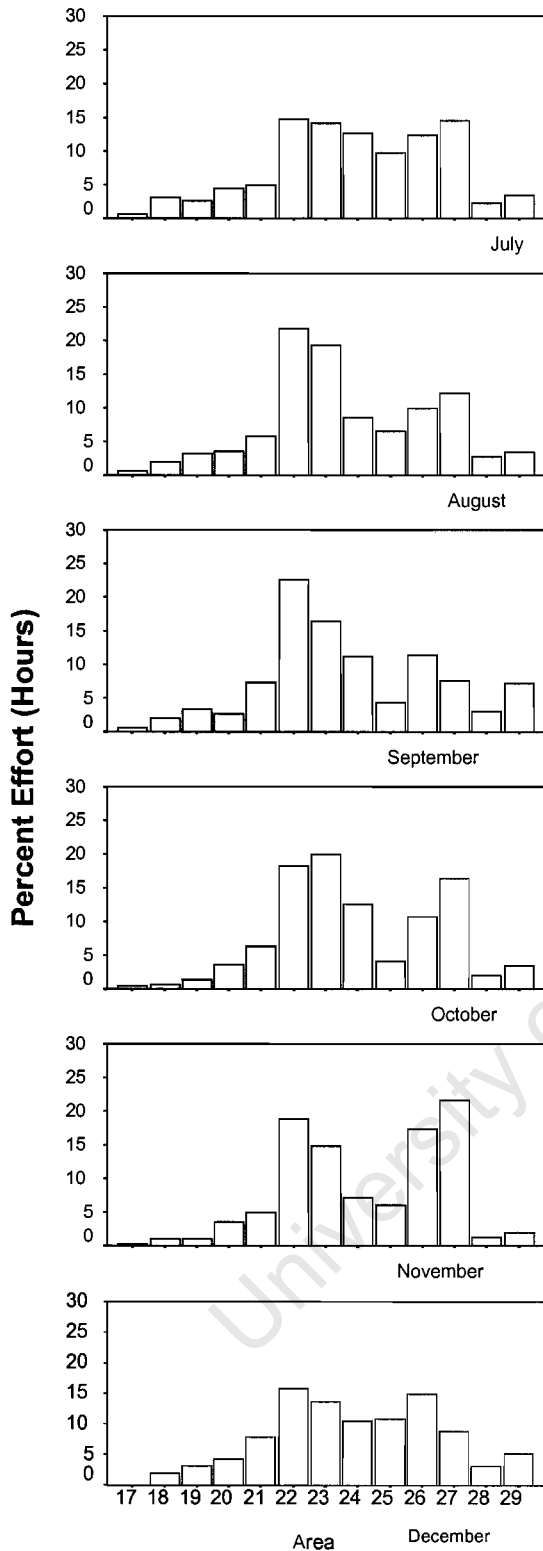


Figure 2.8. Namibian hake commercial effort in percent by area (deg. Latitude) by month.

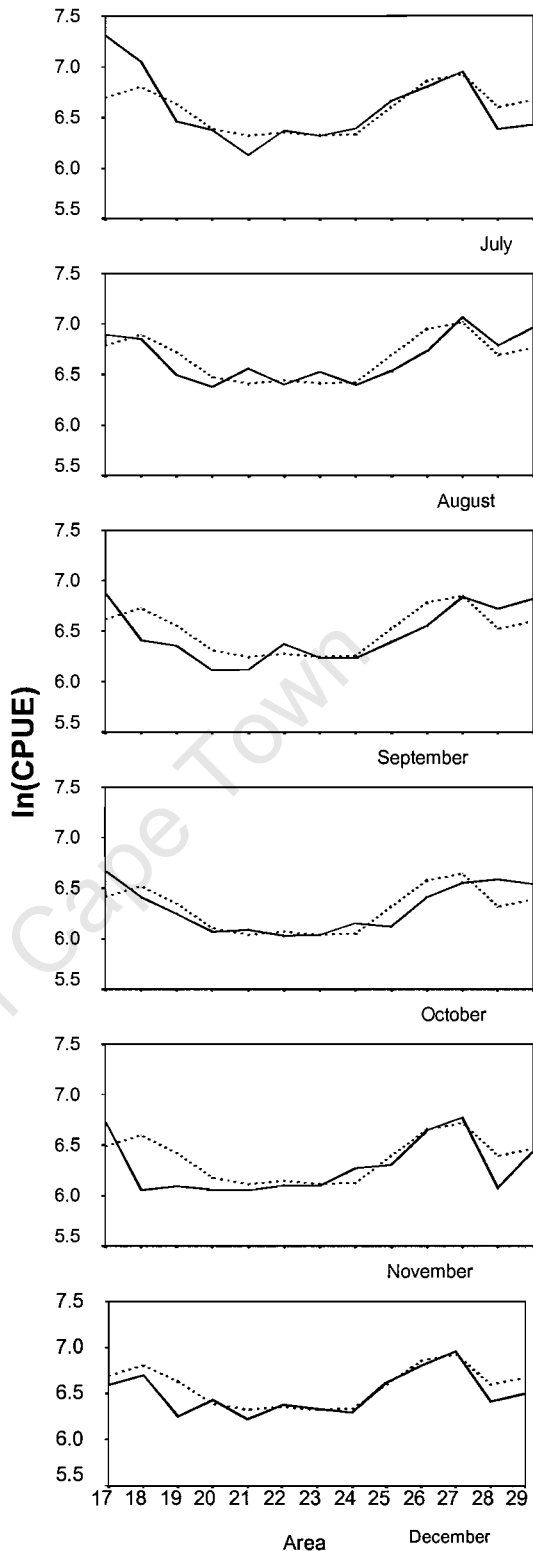


Figure 2.9. Mean ln(CPUE) by month for the different areas (deg. Latitude) under the full model (solid line) contrasted with a reduced model in which the area*month interaction term is left out (broken line).

The general CPUE pattern stays more or less constant for each month for the different areas (Figure 2.9). The overall level of CPUE is the highest in January, decreasing slowly over all areas for the following months until it reaches a low in October and then starts to pick up in November and December. During June the CPUE in the north (17-19°S) has a steeper decline than in the other areas. The huge difference between the full and the reduced model in area 17 during February and March is due to a very small sample size. In general one can conclude that the CPUE levels decrease and increase to the same extent in all areas over all months, except during June. The commercial effort is concentrated in the areas from 22 to 27°S and does not change much from month to month (Figure 2.8).

2.3.3. GRT-year interaction

According to the results of the full model in Table 2.2, the year-GRT interaction is significant and is the second most important interaction (explaining 6.1% of variability). Interactions between the effects of year and GRT imply that CPUE distribution among the vessel fishing power groups has changed over the period 1992-1999.

Changes in the composition of the fleet during 1993 (increased wet fish landings) and 1994 (increased wet fish landings and overall reduction of fleet) are reflected in the effort distribution (Figure 2.10). During 1992 vessels with GRT smaller than 500 GRT (GRT-classes 26) accounted for about 10% of the effort. After the increase of wet fish landings by regulation in 1993, a large increase in effort was expended by boats of GRT 101 to 200 GRT (GRT-class 2). From 1994 onwards most of the effort (about 70-80%) was expended by vessels of GRT smaller than 700 GRT (classes 2-7).

The CPUE from the smaller vessels is lower than that from the bigger vessels (Figure 2.11). Up to GRT class 9 there is not much difference between the full and the reduced models. During 1995, 1996 and 1997 the mean CPUE from the full model, for the vessels with GRT bigger than class 9, were higher than the mean CPUE from the reduced model. This effect is strongly

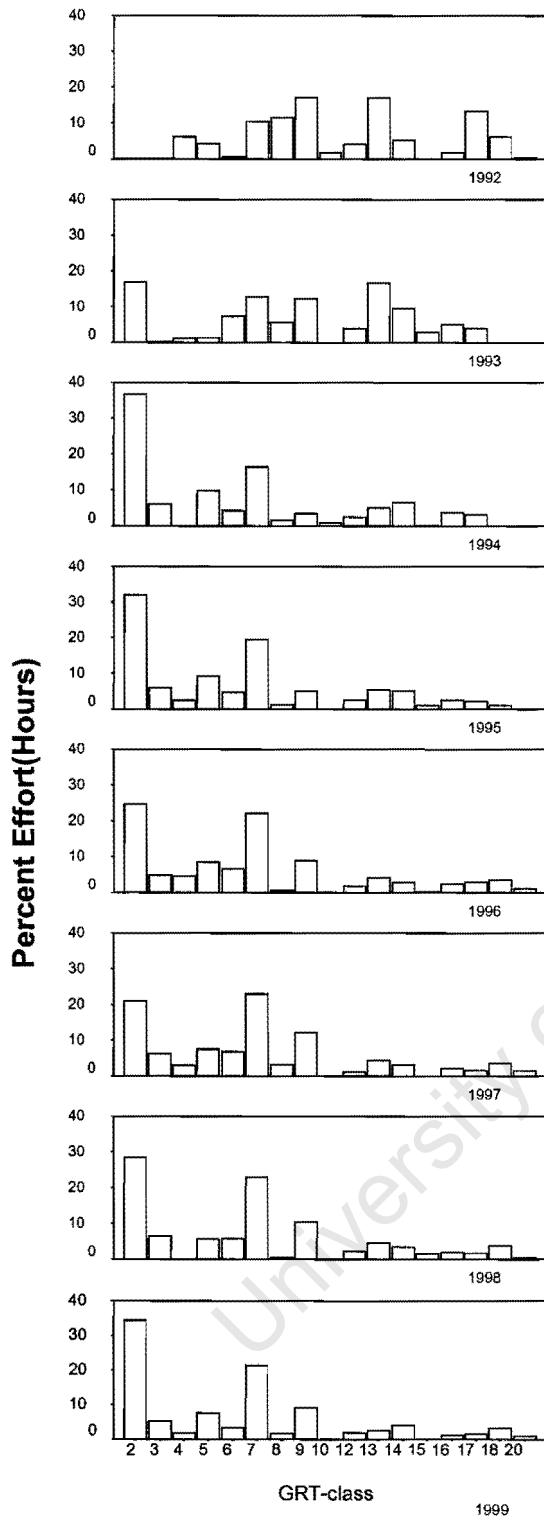


Figure 2.10. Namibian hake commercial effort in percent by GRT by year.

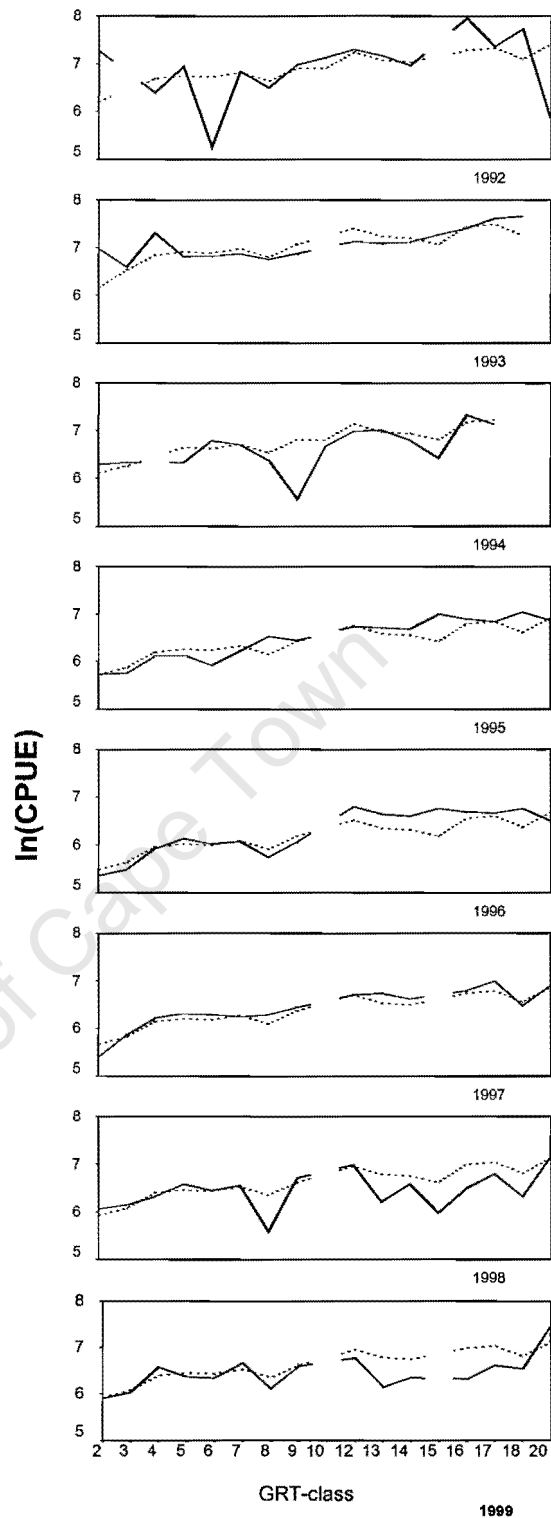


Figure 2.11. Mean ln(CPUE) by year for the different months under the full model (solid line) contrasted with a reduced model in which the year*grt interaction term (broken line) is left out.

reversed during 1998 and 1999 reflecting a reduction in the fishing power of the bigger vessels during 1998 and 1999.

Figures 2.12 and 2.13 contain the data plotted in Figure 2.11.

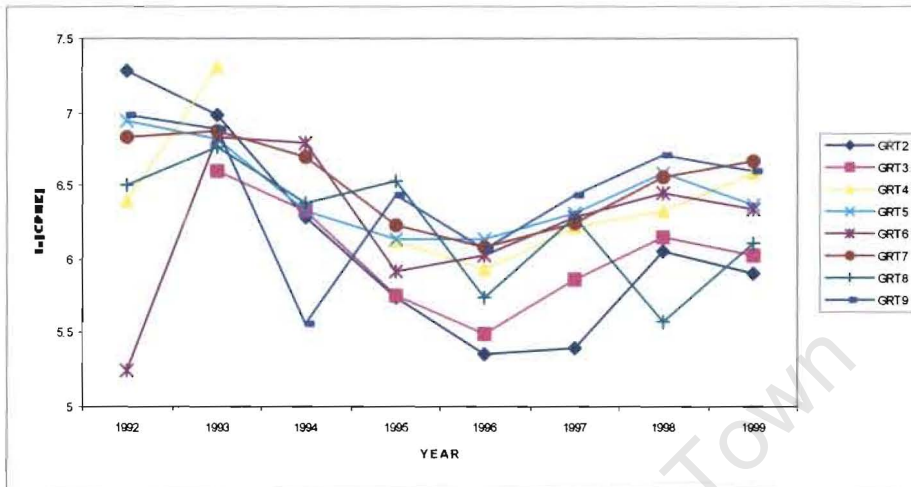


Figure 2.12. lnCPUE for GRT-classes 2 tot 9 from the full model.

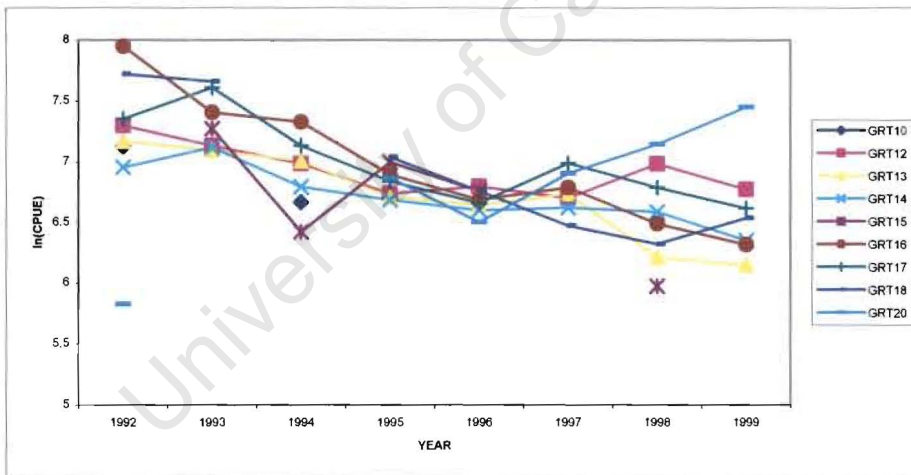


Figure 2.13. lnCPUE for GRT-classes 10 tot 18 from the full model.

The declining trend in ln(CPUE) is bigger from GRT-class 13 and higher (except for GRT-class 20) as seen from linear regression analysis to determine the slope of ln(CPUE) for each of the GRT-classes (Figure 2.14). This means that the bigger vessels have become less efficient in catching hake since the beginning of the series. They have lost more “efficiency” than the smaller vessels.

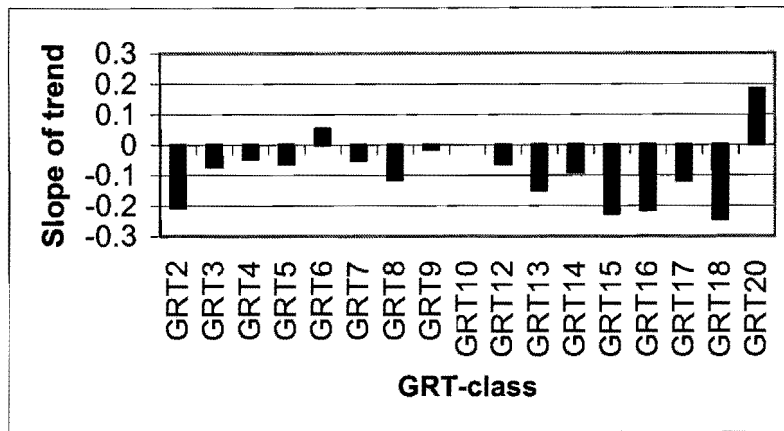


Figure 2.14. Slope of the ln(CPUE) series for each GRT-class

2.3.4. Abundance indices

Estimates of annual CPUE were calculated using:

$$CPUE = \exp(\mu + \alpha_{GRT} + \beta_{year} + \varepsilon_{area} + \gamma_{month} + \eta_{year*month} + \omega_{year*GRT} + \lambda_{area*month} + \tau_{year*area}) \dots \dots \dots (2.4)$$

In Figure 2.15 the CPUE calculated from the regression analysis is compared with mean CPUE. The mean CPUE is calculated by: $\sum Catch / \sum Effort$ for each year. The difference in the two time series is more during 1992, 1993 and 1998.

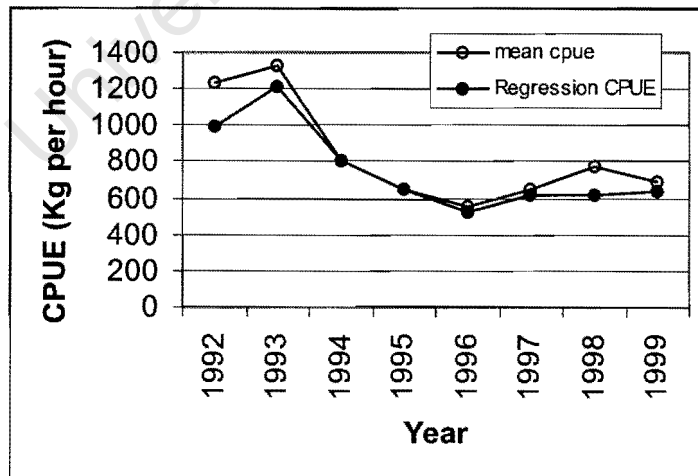


Figure 2.15. Mean CPUE and regression calculated CPUE per year.

2.4. Conclusion

The observed shift in effort by month coupled with the significance of month area and GRT as factors in the regression analysis indicates that changes in fleet distribution will probably influence conventional CPUE estimates. The significance of the year-month, year-area, month-area and year-GRT interaction terms indicates that the nature of these effects must be addressed if the CPUE is to be used as an index of abundance. The regression analysis indicates that month and GRT show the greatest degree of interaction with year. Therefore it is likely that changes in fish distribution patterns have occurred (i.e., fish density changing between months and across years) as well as changes in the fishing power of the fleet. Month and GRT probably alter abundance indices in ways that are different from how indices would change if they were a function of year alone (regional abundance) and independent of the remaining factors. Scenario 4, that both the fish and the fishers changed in distribution over time, seems likely to have occurred. Both the fish and fishers redistributed over month and area and in addition to that, the fishing power of the vessels changed over the years. The bigger vessels show a more declining slope in CPUE than the smaller vessels. This could be due to decreasing quotas for the big freezer fleet as part of the government's strategy to promote processing of fish on land in order to create more jobs. Changes in market demands can also play a role in the fleet behaviour, such as preference for value-added products. This probably results in a search for bigger fish with the consequence of lower catch rates.

Factors critical to the interpretation of Namibian hake catch statistics include year, month, GRT and area. It is often assumed that, all other factors being equal, annual changes in CPUE should reflect year-to-year changes in abundance. However, standard measures of CPUE (e.g. simple averages) can be affected by changes in fleet behaviour, which interact with factors related to abundance. Further complications arise in the use of these standard measures when the factors interact among themselves and in particular when there is an interaction with year.

In the Namibian commercial hake fishery there are factors other than overall abundance that affect CPUE and interactions exist among these factors. The changes in the fleet composition by regulations, the change in fishing power of vessels and the monthly changes of hake availability by year seem to be the major factors influencing the annual CPUE.

To address these dynamic changes and their influence on CPUE as an index of abundance, regression analysis should be used to estimate annual stock trends in order to take account for all the factors that have an influence on CPUE.

In the following chapter, Chapter 3, the relationships between catch and fishing effort will be investigated more closely. Both fish abundance and behaviour of fishers and their interaction will influence CPUE. In spite of the wide use of CPUE, until recently, little work has been directed towards understanding how the movement dynamics of fishing fleets affects fisheries statistics.

CHAPTER THREE

THE MOVEMENT DYNAMICS OF THE NAMIBIAN HAKE FLEET AND THE IMPLICATIONS FOR MANAGEMENT: APPLICATION OF THE IDEAL FREE DISTRIBUTION TO SPATIAL ALLOCATION OF EFFORT

3.1. Introduction

The relationships between catch and fishing effort are known to be complex and not simply governed by fish abundance (Rothschild 1977; Clark and Mangel 1979). Yet for lack of better information, catch-per-unit-effort (CPUE) remains a common index of abundance in many fisheries. It is used either as a direct indicator of abundance (Cooke 1985) or as a means of fine-tuning other stock assessment techniques (Deriso *et al.* 1985). Both fish abundance and behaviour of fishers and their interaction will influence CPUE. In spite of the wide use of CPUE, until recently, little work has been directed towards understanding how the movement dynamics of fishing fleets affects fisheries statistics.

The objective of this chapter is to contribute to the knowledge of fleet dynamics specifically on the part of effort allocation. Effort allocation will be investigated, within the theoretical framework of the ideal free distribution (IFD). This theory explains the distribution of foraging animals in relation to the distribution of their resources (Fretwell and Lucas 1970; Sutherland 1983). The assumptions of the IFD are that: (i) vessels have equal fishing power; (ii) skippers have perfect knowledge about the distribution of their target species; (iii) travel cost between fishing grounds is negligible; (iv) skippers select fishing grounds on the basis of maximizing fishing efficiency. Although the assumptions will certainly be violated in the real world, Milinski and Parker (1991) showed that the IFD presented a reasonably robust starting point for such analyses.

The IFD has been applied successfully to a wide variety of biological systems as well as to the problem of effort allocation within fishing fleets (Abrahams

and Healey 1990, 1993; Healey and Morris 1992; Gillis *et al.* 1993; Gillis and Peterman 1998). Most models assume that some inverse relationship must exist between catch rate and vessel density. Abrahams and Healey (1990) suggested that the spatial distribution of the British Columbia salmon troll fleet could be described through a modified form of the ideal free distribution.

Although competitive interactions may be inferred from the distribution of fishing vessels (Hilborn and Ledbetter 1979; Healey and Morris 1992; Gillis *et al.* 1993), direct evidence is scarce. Some work tends to model fishing effort in an aggregate manner from the effort or the space perspective (Mangel and Clark 1983; Mangel and Beder 1985; Allen and McGlade 1986; Mangel and Clark 1986; Hilborn and Walters 1987; Anganuzzi 1996). However, analysis on a fine scale of searching effort by individual vessels has seldom been done (Polacheck 1988). In an experimental study, Abrahams and Healy (1993) manipulated vessel density of salmon trawlers and found that catch rates in the low-density area were higher for Chinook salmon and spiny dogfish, supporting the operation of competitive interactions. However, no such effect was observed for Coho salmon. Competitive interactions among beam trawlers in the southern North Sea are likely since beam trawlers exhibit a patchy distribution with more than 70% of effort concentrated in only 20% of the fished area (Rijnsdorp *et al.* 1998). Strong support for interference interactions comes from a study of the Dutch beam trawl fleet that showed that individual catch rates of beam trawlers increased by 10% when vessel density was reduced to about 25% of the initial density (Rijnsdorp *et al.* 2000). It was also demonstrated that catch rate was positively related to engine power while the increase in catch rate could only be partly explained by the larger area swept per unit of time by the more powerful vessels, suggesting that the competitive ability increased with engine power.

Applied to fisheries, IFD theory predicts that vessels will distribute themselves over their resources such that the density of vessels will be proportional to resource abundance and that vessels will have equal catch rates, irrespective of the vessel density. If vessels differ in competitive ability, better competitors will generally be over-represented in the better patches while poorer

competitors will be over-represented in the poorer patches (Sutherland and Parker 1985).

The most relevant assumptions of the IFD for our study are that: (i) vessels have equal competitive abilities; (ii) vessels can change areas without restrictions or travel costs; (iii) competition among foragers occurs in proportion to their local density. However, violations of these assumptions also generate typical spatial distributions (Fretwell, 1972; Abrahams, 1986; Houston and McNamara, 1988) that may be used to diagnose which assumptions have been violated.

Under these circumstances, the IFD predicts that the profit rate or catch rate for an individual in an area will be proportional to the availability of resources divided by the number of individuals foraging there. When each forager is free to move so as to maximize its own profitability the result is an equilibrium distribution where foragers in different spatial areas have the same catch rate, which is called equalization of catch rate (Hilborn and Ledbetter 1979). This theory thus predicts that the number of foragers in each area will reflect the abundance of resources better than catch rate.

3.2. Materials and methods

3.2.1. Data

Catch and effort data from the bottom trawl fleet, targeting on both *Merluccius capensis* and *Merluccius paradoxus* off Namibia, were used in the analysis for the period from 1994 to 1999. All vessels included were active in the hake fisheries for three years or longer. The basic data have a spatial resolution of grids (20 x 20 nautical miles) and a temporal resolution of one day. The data originated from the logbooks completed for each fishing vessel and handed to the authorities at the end of each fishing trip. The daily data comprise: Vessel code; engine power; gross registered tonnage; date; hours trawled; number of trawls; water depth; landings; target species and grid number.

3.2.2. GLM correction of effort

From the generalized linear modelling (GLM) analysis in Chapter 2 it is shown that Gross registered tonnage (GRT) of the vessels explains most of the variability in CPUE. Since the GLM analysis also showed that GRT-year interactions have a significant influence on the CPUE, these effects need to be taken into account in this study of the movement and behaviour of the fleet.

In this analysis of fleet dynamics, the effect of the different GRT-classes on CPUE can be removed to a certain extent by applying the correction calculated by the GLM. From the GLM analysis, the factors for GRT and year, as well as the interaction between the two variables from the model were used to standardize the effort for each GRT-class and year to be used in the analysis in this chapter (Figure 3.1).

$$\text{The vessel factor (V)} = \exp(\omega_{\text{year} \times \text{GRT}} + \alpha_{\text{GRT}} + \beta_{\text{year}}) \dots \dots \dots (3.1)$$

$$\text{The effort was standardized by: (hours trawled} \times \text{V)} \dots \dots \dots (3.2)$$

3.2.3. Spatial dynamics of effort

In order to judge whether the movement assumption of the IFD that vessels can change areas without restrictions, fits in this fishery, the distribution of effort over the fishing grounds was investigated. The number of trawling days was used as a measure of effort. To investigate to what extent the vessels move freely over the whole area, the number of trawling days for each latitude degree for vessels landing at the two ports, Walvis Bay and Lüderitz, was plotted separately for the period from 1994 to 1999. The total number of statistical grid squares in the fishing area (between 200 and 1000 m of depth) is 121 grid squares. The total number of grid squares covered during each fishing year is expressed as a percentage of the total fishing area.

To assess whether the spatial fishing strategies of different vessels were a major determinant of fishing success, the spatial diversity of each vessel for each year was described by the Shannon-Wiener diversity index (Abrahams and Healey 1990). The Shannon-Wiener diversity index (H') is calculated as:

$$H' = - \sum_{i=1}^k p_i \log p_i \dots\dots\dots(3.3)$$

where: p_i is the proportion of time spent fishing in grid square i , and k is the number of grids squares trawled (Zar 1999).

The minimum value occurs if a vessel fishes only in one area. The index increases as vessels distribute their time equally among a large number of grid squares. The diversity index was calculated for each vessel for each year. The evenness index (E) (Pielou 1966) was calculated from the diversity index:

$$E = H' / \ln(S) \dots\dots\dots(3.4)$$

where: S is the total number of grid squares covered by each vessel.

Evenness is a measurement of how well dispersed the distribution of effort is. When effort is spread evenly over the whole area covered, evenness is one, but when the effort distribution is concentrated in certain areas the value decreases. A plot of E versus the CPUE of all vessels for the period from 1994 to 1999 year was made to investigate if there is any relationship between the evenness index and the relative catch rates of individual vessels, using a curve estimations method from the statistical package: "SPSS® Base 9.0" (SPSS Inc. 1999).

3.2.4. Competition among vessels

Competition is defined as an interaction among vessels that results in a decrease in CPUE associated with an increase in number of vessels and is a

necessary condition for the operation of an IFD (Gillis *et al.* 1993). Indirect evidence for competition has been obtained in several studies analysing commercial logbook data. In these studies it was found that catch rates were generally equalized among fishing grounds, as predicted by the IFD (Hilborn and Ledbetter 1979; Healey and Morris 1992; Gillis *et al.* 1993). Gillis *et al.* (1993) inferred the existence of competitive interactions from changes in catch rate following a change in vessel density. However, direct evidence for competition among vessels is scarce.

Competition can be either interference competition or exploitative competition or a combination of the two. Interference competition usually results in a reversible reduction in CPUE due to interactions among foragers or between forager activities and prey behaviour. Exploitative competition is not reversible and occurs when limited resources are taken by other foragers (Gillis and Peterman 1998). In this study the short-term effect of vessel activity on catch rates in a specific area is tested and thus interference competition is investigated.

The change in effort was compared between weeks for an area (statistical grid) with the corresponding changes in CPUE in the same area to test for competition, as done by Gillis *et al.* (1993). Interference competition would be indicated if CPUE tended to decrease more during weeks when effort increased than during weeks when effort decreased. Competition would also be evident if the number of declining cases of CPUE was more than the number of increasing cases during the periods of increasing effort from one week to the next.

For this analysis, data from the whole fleet was grouped into grids squares and weeks. Seven day standard weeks were used, beginning on January 1, 1994. The unit of effort used was hours trawled (corrected using the GLM results from Chapter 2). The comparison between the changes in CPUE values between weeks of increasing and decreasing effort was made using two different procedures, namely the Mann-Whitney U test, as applied by Gillis *et al.* (1993) as well as a 2 X 2 contingency table (Zar 1999). The Mann-

Whitney U test takes into account the magnitude of the changes in CPUE for increasing and decreasing effort. The second procedure was built up with the purpose of considering only the sign of the changes regardless of their magnitude. The numbers of increasing and decreasing events in CPUE were counted when effort decreased and increased for every year and for the whole study period. The null hypothesis was that frequencies of changes in CPUE are independent of the frequencies of changes in effort.

3.2.5. Equalization of CPUE

Previous authors (e.g. Hilborn and Ledbetter 1979) focused their studies on the ratio of CPUE within an area to the average CPUE among all areas. They hypothesized that this ratio would remain constant through time and would reflect the relative costs of fishing in each area. Also, if CPUE and costs were equal in all areas, then this ratio would be one. Regressing the arcsine-transformed proportions of total catch and total effort in each grid for each week in each year tested the equality of CPUE among areas. According to Gillis *et al.* (1993): if effort is allocated among areas so that CPUE is equalized among areas, then, when C_i and f_i are the catch and effort in area i for a particular week:

$$C_i / f_i = \sum C_i / \sum f_i = R \dots\dots\dots(3.5)$$

Where R is the ratio, or CPUE value, that is equalized among all areas in the week being considered. By rearrangement, then:

$$C_i / \sum C_i = f_i / \sum f_i \dots\dots\dots(3.6)$$

This is the general form of a linear regression $Y = aX + b$ where $a = 1$ and $b = 0$.

Thus, if the IFD applies, the regression of the proportion of catch in area i on the proportion of effort in area i will be a line with an intercept of 0 and a slope of 1. If the IFD holds, all points will fall on this line, regardless of the weekly values of R .

3.3. Results

3.3.1. GLM correction of effort

In Figure 3.1 the mean GLM adjusted and unadjusted CPUE per grid for each year for the period from 1994 to 1999, are shown.

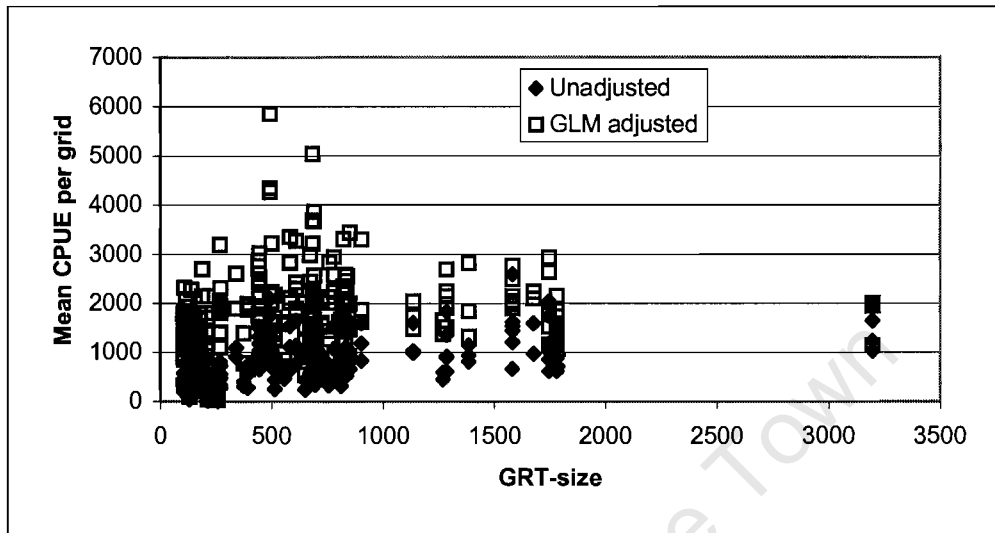


Figure 3.1. Mean CPUE per grid and per year for the unadjusted data and the GLM-adjusted for GRT and year effects for the period from 1994 to 1999.

3.3.2. Spatial dynamics of effort

The distribution of effort by latitude of the hake fleet, landing at the two different ports, is shown in Figure 3.2. It is clear from this that vessels from both ports cover the entire area, but that most effort is concentrated closer to the homeports. The percentage of the total area (as number of grids) covered during each fishing year is shown in Figure 3.3. It varies from 68% to 88% from 1994 to 1999.

There is no significant relationship between the evenness index for each vessel for each year and the CPUE as determined by curve estimation statistics (Table 3.1).

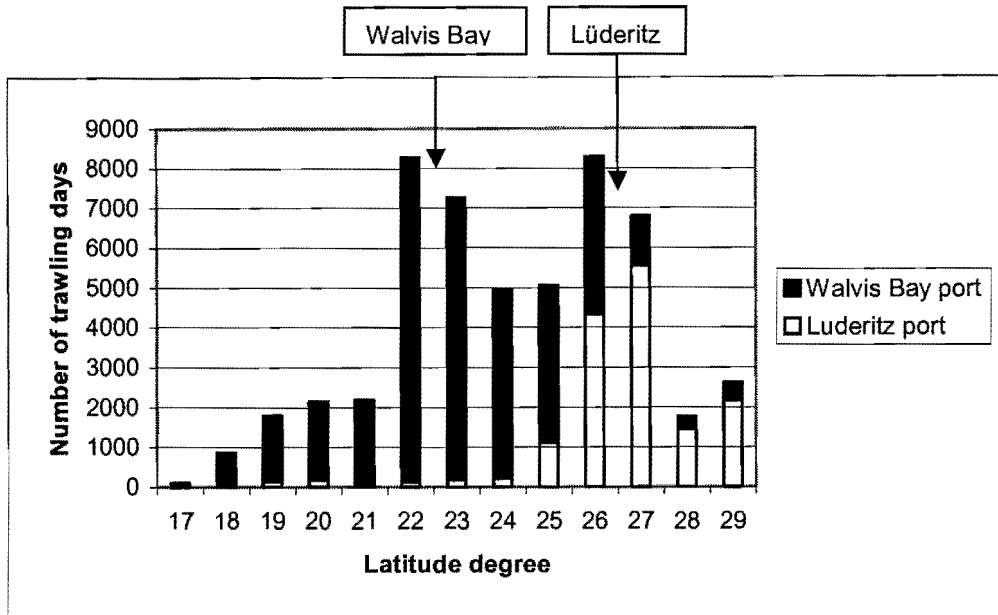


Figure 3.2. Number of trawling days spend by the hake fleet in each latitude area during 1994-1999 for the vessels landing in the ports of Walvis Bay and Lüderitz. The Latitudinal positions of the two harbours are indicated on the chart.

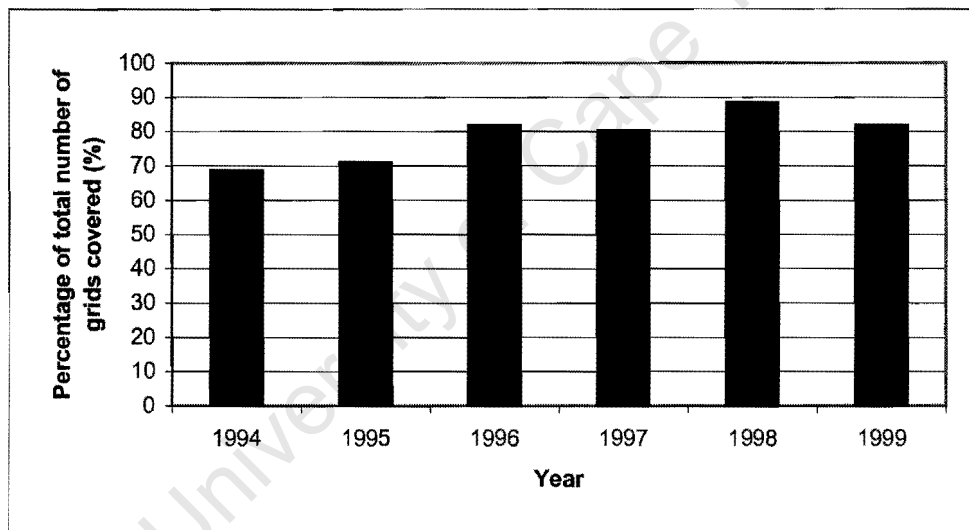


Figure 3.3. Percentage of the total number of grid squares covered by the hake fleet during each fishing year.

This indicates that the strategy of effort distribution does not have an effect on catch rates. The evenness index for all boats is below 0.5 (Figure 3.4), indicating that effort is not evenly distributed over the whole area in which case the evenness index would have been close to 1. Therefore the effort distribution can be considered as concentrating in certain areas to a certain extent.

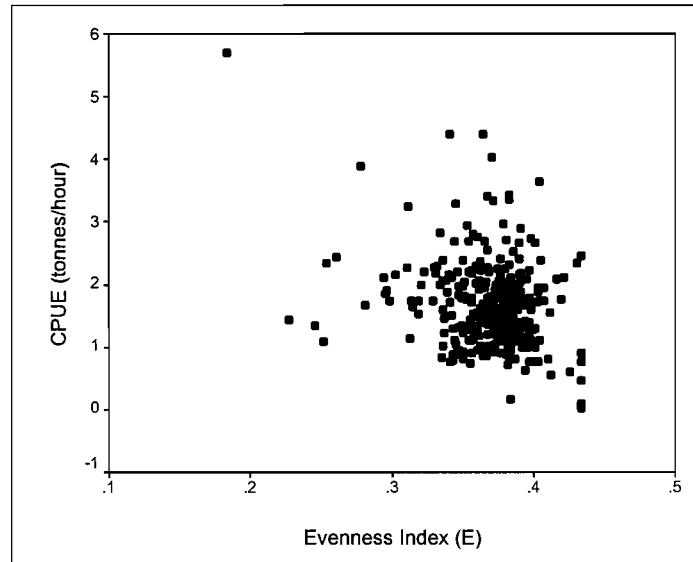


Figure 3.4. CPUE (tonnes/hour) as a function of the evenness index for each vessel for each year.

Table 3.1. Curve estimation results of the relationship of the independent evenness index and CPUE. $P < 0.05$.

* Significant difference from curve estimate.

Curve	Rsq	d.f.	F	P
LIN	0.088	329	31.67	* 0.000
LOG	0.094	329	34.18	* 0.000
INV	0.101	329	36.99	* 0.000
QUA	0.093	328	16.76	* 0.000

3.3.3. Competition among vessels

No significant inverse relationship was detected between changes in effort and the corresponding changes in CPUE within an area when looking at the mean change in CPUE values (Table 3.2), suggesting that there has been no interference competition among vessels. During 1994 and 1995 the distributions of changes in CPUE were not significantly different under the presence of increasing or decreasing effort. There was however a significant positive relationship from 1996 to 1999 (Figure 3.5) with increasing CPUE when effort increases.

When looking at the count of decreasing and increasing CPUE events with the increase in effort as shown in the 2 x 2 tables (Table 3.3), basically the same results were obtained as when using the two-tailed Mann-Whitney U test. For 1994 increasing or decreasing effort caused no significant change in CPUE. Thus there was a significant difference between the change in CPUE during increasing and decreasing effort for all years except for 1994 using both tests. This was, however positive relationships, since overall CPUE decreased when effort decreased and increased when effort increased. Therefore it can be concluded that there is little or no evidence of competition among vessels, whether it is exploitation or interference competition.

Table 3.2. Tests for competitive effects in catch-effort data. The two-tailed Mann-Whitney U test ($P < 0.05$) was used to compare changes in CPUE associated with increases or decreases in effort for an area. The test results are given as well as the mean change in CPUE. The values in parentheses are the number of cases in the category. U = Mann-Whitney U statistic, N = total sample size, and P-level = probability of the null hypothesis of no association between changes in effort and changes in CPUE being true.

* Significant difference between CPUE changes with decreasing and increasing effort.

Year	Mean change in CPUE		U	N	P-level	
	Decreased effort	Increased effort				
1994	13.31 (456)	-151.42 (437)	98270	893	0.723	
1995	69.57 (594)	*86.47 (563)	163595	1157	0.524	
1996	-119.59 (702)	-54.70 (713)	218632	1415	<0.000	*
1997	-136.39 (814)	32.13 (775)	263542	1589	<0.000	*
1998	-56.68 (723)	-9.87 (677)	220.726	1400	0.001	*
1999	-117.6 (830)	-35.53 (866)	323152	1696	<0.000	*

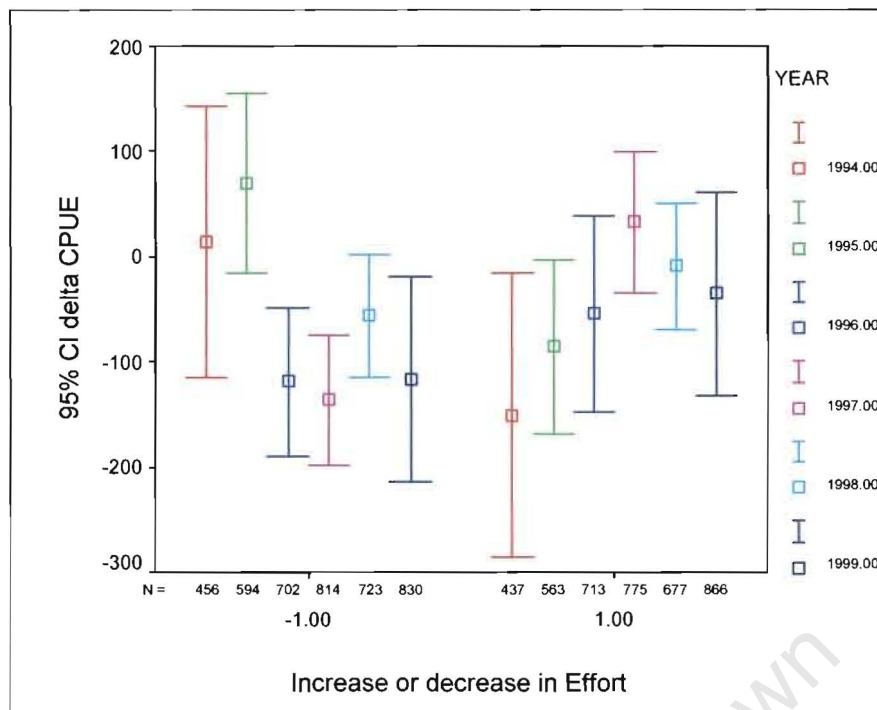


Figure 3.5. Mean and 95% CI of delta CPUE with increasing (1.00) and decreasing (-1.00) of Effort for each year from 1994 to 1999.

Table 3.3. Results of the Chi-square analysis ($P < 0.05$) of the contingency table to test for competition between all vessels for each year and the whole study period combined. The counts of increases and decreases in CPUE in the event of increases and decreases in effort are shown in the 2 x 2 tables. The Chi-square value and the P-level are reported.

* Significant difference between CPUE changes with decreasing and increasing effort.

Year	2X2 Table		Chi-square	P-level	
	Effort decrease	Effort increase			
1994-1999	CPUE decrease	2436	1984	8284.32 Df = 4	0.000*
	CPUE increase	1683	2047		
1994	CPUE decrease	253	233	0.42 Df = 1	0.516
	CPUE increase	203	204		
1995	CPUE decrease	343	287	1177.40 Df = 4	0.000*
	CPUE increase	251	276		
1996	CPUE decrease	421	345	1472.63 Df = 4	0.000*
	CPUE increase	281	368		
1997	CPUE decrease	495	367	28.96 Df = 1	0.000*
	CPUE increase	319	408		
1998	CPUE decrease	424	325	15.91 Df = 1	0.000*
	CPUE increase	299	352		
1999	CPUE decrease	500	427	20.44 Df = 1	0.000*
	CPUE increase	330	439		

3.3.4. Equalization of CPUE

The linear regression of the proportion of the weekly catch in an area on the proportion of weekly effort in that area do provide a significant fit to the predicted data (Figure 3.6). An examination of the transformed proportional effort values revealed a nearly bell-shaped distribution. Therefore, linear regression was used as the statistical model for the hypothesis tests about the equalization of CPUE among areas. For each of the years and the years combined, there was a significant difference between the observed slope and the slope of 0 that was predicted by the IFD (Table 3.4). This suggests that CPUE was equalized among areas fished as predicted by the IFD.

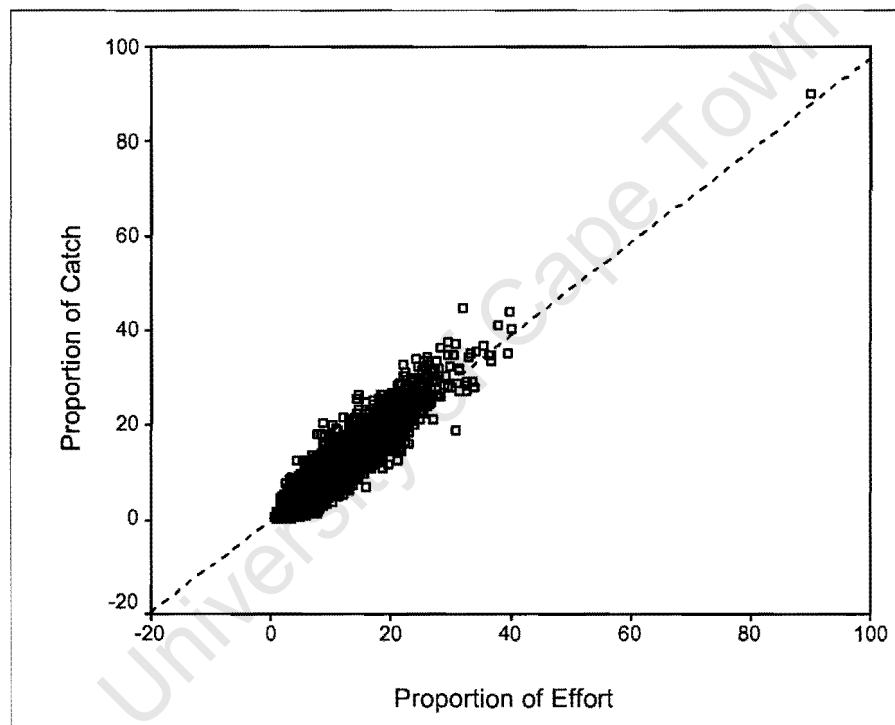


Figure 3.6. Test for equality of CPUE using proportional effort and proportional catch. The proportions are calculated among the areas fished for each week and all proportions are arcsine transformed. The broken line is the least squares regression line for the data from 1994 to 1999 (r -squared = 0.955, slope = 0.975).

Table 3.4. Test for the equality of CPUE among areas by proportional regression analysis. Equalized CPUE is indicated by a slope (b) of 1 in the regression of proportional catch on proportional effort. The estimated slopes were compared to 1.0 using a two-tailed t-test ($P < 0.05$). R-squared is the coefficient of determination and N is the sample size.

* Significant different from $b = 0$.

	R-squared	b (SE)	N	P
All data	0.955	0.975 (0.002)	11183	<0.001 *
1994	0.957	0.963 (0.005)	1301	<0.001 *
1995	0.972	0.966 (0.005)	1577	<0.001 *
1996	0.960	0.980 (0.005)	1927	<0.001 *
1997	0.979	0.983 (0.004)	2149	<0.001 *
1998	0.975	0.978 (0.005)	1949	<0.001 *
1999	0.978	0.980 (0.004)	2280	<0.001 *

3.4. Discussion

The theory of IFD has proven to be a useful way to understand distribution of fishing effort and to predict the possible effect of that on CPUE as an index of abundance. In this analysis it was assumed that vessels have the same competitive abilities after the effort was adjusted using the results of the GLM analysis. Although the fleet does not distribute its effort evenly over the whole area, it does cover a considerable part of the total fishing area. It can be concluded that the fleet is generally able to move freely between fishing grounds.

3.4.1. Differences in competitive ability

The GLM analysis in Chapter 2 has shown that the different GRT-classes of the vessels, together with the year effect, play the most important role in influencing the CPUE. This effect did change over the years with a resulting loss in “fishing power” of the bigger vessels.

The difference in catch rates between the small and big vessels can mainly be ascribed to differences in the fishing power of the vessels while the decrease in efficiency of the big vessels over time can be ascribed to a change in fishing strategy. It is known, from the industry, that this loss in fishing power does not indicate changes in hake abundance but a change in the strategy of the big vessels. Quotas for the big freezer boats have been decreasing gradually since 1994 when an onshore processing policy was introduced in order to create more employment for Namibians. The result of that, as well as market preferences, forced owners of large vessels to increasingly produce value-added products. Therefore smaller quantities of hake are caught in order to optimise the value of the catch. The search for bigger fish results in reduced catch rates.

The GLM analysis indicated that the big vessels have lost competitiveness or fishing power compared to the beginning of the series. It is therefore very important to adjust the CPUE figures from year to year using the GLM calculated GRT-class and year effects. This will take care of both differences in catchability between different GRT-classes and changes in fishing strategies from year to year.

3.4.2. Movement of vessels among areas

The fishing pattern of individual vessels (according to the evenness index) does not have a significant relationship with the catch rates of the vessel. Thus whether a vessel distributes most of its effort only in a small area, or whether it covers a bigger area, has no significant influence on the catch rates of the vessel. The range of the evenness index is between 0.45 and 0.2. When effort is spread evenly over the whole area covered, evenness is one, but when the effort distribution is concentrated in certain areas the value decreases. Therefore it can be concluded that the spatial distribution of effort is not even but about 60% patchy.

Coverage of the total fishing area is good in all years with an average of about 80% of the number of grid squares covered. Although more effort is

expanded in the area between 22°S and 28°S, it can be assumed that the vessels are relatively free to move between areas, if needed. This is one of the assumptions of the IFD.

3.4.3. Competition among vessels and equalization of CPUE

One of the assumptions of IFD is that competition among foragers occurs in proportion to their local density. In this study no evidence of interference competition could be detected among vessels. Although this is surprising, it may be a positive sign for the Namibian hake fishery. This observation may indicate that the current level of exploitation of the resource is at a favourable level for both the fishers and the hake stock. Increases in effort from one week to another in a specific grid square do not have a negative influence on CPUE and that may be because the effort is not enough to have an interference effect or to disrupt the fish.

Hilborn (1985) emphasized that the best starting point for the investigation of effort allocation is to assume the vessels will move to equalize CPUE. In this study it was seen that this does indeed happen. If interference competition occurs among vessels, the slope would tend to be less than 1. Since CPUE is equalized over the whole area, the number of vessels in a specific area should be a better indication of stock abundance than the CPUE.

3.4.4. Implications for Stock assessment and Management

The importance of this work for the management of the hake stock is as follows:

In order to use CPUE as an index of abundance in any stock assessment model or in any other way, the difference in competitive ability of the different GRT-class of vessels should be addressed. The recommendation of this study is to adjust for GRT-class and year effects by using the result from the GLM analysis.

The main implication of the results from the proportional regression analysis is that the changes in CPUE values will reflect trends in abundance within the

stocks. In the case where equalization of CPUE occurs, a local decline in abundance in the stock would be tracked by changes in the proportion of fleet effort expended on that stock rather than the CPUE value (Gillis *et al.* 1993). CPUE for different areas may be pooled when used as an index of abundance.

Interference competition among vessels will contribute to variability in the catchability coefficient (q), which is usually considered to remain constant in traditional stock assessment methods. In this study it has been shown that there is no evidence of interference competition among vessels and thus q is not influenced. The size of the Namibian hake fleet was reduced in 1994 and the effort expended by the fleet seems to be at a favourable level so that there is very little to no interference competition among the vessels. If the fleet size changes in future, the effect on competition among vessels should be monitored and the possible influence on q and the resulting breakdown of the relationship between CPUE and abundance should be kept in mind.

The CPUE data from the fishing fleet comprises an enormous amount of information that is collected on a daily basis. In the next chapter, density estimates of the hake stock are calculated using the catch rates from the hake fishery as well as from the hake surveys. The estimates are then compared in order to determine to what extent the density estimates from the commercial fishery can be used to correct the survey estimates before being applied as an annual index of abundance in the assessment model.

CHAPTER FOUR

COMPARISON OF DENSITY ESTIMATES OF THE NAMIBIAN HAKE STOCKS FROM COMMERCIAL FISHERY AND RESEARCH CATCH DATA

4.1. Introduction

Since 1990 the Namibian government has managed the hake stock by setting a total allowable catch (TAC) for each fishing year. From 1990 to 1997 scientific recommendations for the TAC were based on some 20% of the exploitable biomass (fish larger than 35cm) estimated from swept area biomass surveys. In 1998 an interim management procedure (IMP) was adopted in which both survey estimates and catch per unit of effort (CPUE) data from the commercial fleet are used to adjust the TAC from the previous season (Butterworth and Geremont 2001, Rademeyer and Butterworth 2002). Both survey estimates of abundance and commercial catch data play an important role in the management of the Namibian hake.

The marine environment off Namibia is under the influence of the Benguela current, which is an eastern boundary current of the South Atlantic. It is a cold-water system bounded by two warm-water regimes, making it unique amongst coastal upwelling systems (Shannon 1985). The area influenced by upwelled water has considerable seasonal variability, and during summer and autumn this area contracts (Boyd and Agenbag 1985). Gordo *et al.* (2000b) indicated that inter-annual variability of either the system or catchability is much larger during the summer than the winter, which has direct implications for resource monitoring and management. Iilende *et al.* (1991) recorded intra-annual variability in the pelagic component of Namibian hake during survey periods and Huse *et al.* (1991) and Gordo and Macpherson (1991) reported on diurnal variability in the pelagic component of the Namibian hake.

The purpose of this analysis is to compare logbook data from the Namibian commercial trawl fishery with data from research cruises conducted at the

same time in the same area (Figure 4.1). The overlap area between the survey and commercial data is mainly between 200 and 600 m depth. The objective is to investigate inter- and intra-annual variability in density estimates. This variability will indicate the usefulness of a once a year survey estimate of hake abundance for use as an index of abundance.

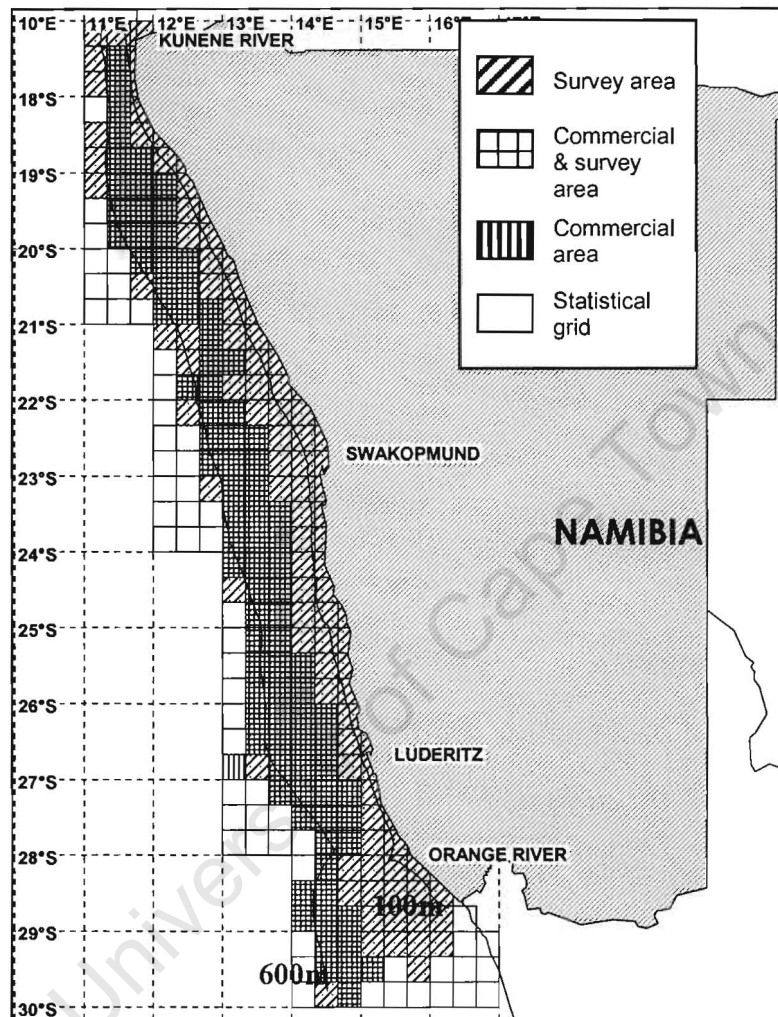


Figure 4.1. Commercial fishing and survey areas along the Namibian coast by statistical grid (20 by 20 minutes) for the period from 1992 to 1999. Depth contours (100 and 600m).

4.2. Material

Commercial fishing data used in these analyses were compiled from demersal bottom trawl fishery logbooks collected by the Ministry of Fisheries and Marine

Resources of Namibia (MFMR) from 1992 to 1999. The trawlers are restricted by law to fish deeper than 200m-bottom depth. This 8-year logbook database contains over 67 000 individual records, each representing a single day of fishing targeting on hake. Information for each record includes vessel license number, date, grid square number (20 X 20 minutes statistical squares – Figure 4.1), latitude and longitude position (since 1997), footrope length, hours of trawling, number of trawls and catches in kilograms. Most of the time bottom trawls were used, with semi-pelagic nets only when hake lifted off the bottom. The analysis includes only the bottom trawls. The mesh size used was between 110 and 140 mm.

The procedures used for collecting and processing logbook data included catch recording by fishers, logbook collection by inspectors, logbook screening, computer data entry and error checking. The numerous fishing vessels and trips provided a large quantity of data, so I was selective of information included in the analyses. Only those logbooks that were complete and legible and had location information for each day were analysed. Computer error checking procedures included automated and manual review checks to detect tows that had unreasonable locations, effort, and catches in relation to depth and previous and succeeding tows.

The scientific fishery data used in this study originated from a series of Namibian bottom trawl surveys of hake resources conducted from once to three times per year from 1992 to 1999. The surveys were conducted by MFMR on board of the R.V. Dr. Fridtjof Nansen (which was supplied by the Norwegian agency for Foreign Aid Development (NORAD)) with assistance from the Institute of Marine Research – Norway (IMR). The respective periods during which the surveys were conducted can be seen in Table 4.1.

The surveys have excellent spatial overlap with the commercial fishery data set (Figure 4.1). The surveys were conducted for a period of 6 weeks; a total of 13 surveys were conducted during the study period. A total of 2838 tows were completed during the 13 surveys. The commercial logbook data set contained 18726 days of towing and the survey data set 624 tows for the

quarters and geographical areas that overlapped between the surveys and commercial fishery.

Table 4.1. Periods during which the thirteen different bottom trawl research surveys were conducted off Namibia from 1992 to 1999.

Survey nr	Year	Quarter	Months
1	1992	2 nd	Apr-May
2	1992	4 th	Oct-Nov
3	1993	1 st	Jan-Feb
4	1993	2 nd	Apr-May
5	1994	1 st	Jan-Feb
6	1994	2 nd	Apr-May
7	1994	4 th	Oct-Nov
8	1995	2 nd	Apr-May
9	1996	1 st	Jan-Feb
10	1996	4 th	Sep-Oct
11	1997	1 st	Jan-Feb
12	1998	1 st	Jan-Feb
13	1999	1 st	Jan-Feb

Trawl survey methods are described by Strømme *et al.* (1999). The R.V. Dr. Fridtjof Nansen used a Gisund Super two-panel bottom trawl with head rope length of 31m, footrope 47 m and the vertical net opening 4.5 m (Huse *et al.* 1997). The mesh size of the front panels and wings ranged between 22 and 40 mm and the mesh size of the cod end was 22 mm. SCANMAR sensors were used to monitor the spread and opening of the trawl. The trawling speed was between 3 and 4 knots, which is similar to that of the commercial bottom trawlers. The research tows were about 0.5 h long, whereas commercial bottom tows averaged 3.9 h.

Commercial boats with Gross Registered Tonnage (GRT) larger than 600 GRT were selected. In chapter 2 it was found that the relative catch rate of commercial vessels did not differ much for GRT larger than 600 GRT while relative catch rates for vessels with GRT smaller than 600 GRT has a linear relationship with GRT.

4.3. Methods

Density estimates from the logbook data were obtained using a swept area methodology similar to that employed in the survey estimates (Strømme *et al.* 1999). Footrope specifications and estimates of net opening width for several vessels were obtained from the bottom trawl fleet. On the basis of this information and a similar study by Fox and Starr (1996), a net opening of 41% of the footrope length was used. The commercial database contained the footrope length for each vessel since 1997. The assumption was made that the same gear was used before 1997. The width of the net opening of the RV Dr. Fridtjof Nansen (18 – 21 m) is also 41% of the footrope length (47 m) on average. Applying the average ratio of net opening width to footrope length, a net opening width was estimated for each of the vessels in the trawl fleet. Commercial vessel trawling speed averaged 3.5 knots. The area swept was calculated as follows:

$$\text{Area swept} = (t \times 3.5 \text{ knots}) * w \dots \dots \dots (4.1)$$

where, t is the duration of trawling in hours and w is width of net opening in nautical miles.

The density for both commercial and survey tows are then calculated as:

$$\text{Density} = \text{Catch (tonnes)} / \text{Area swept} \dots \dots \dots (4.2)$$

Density estimates were calculated from fishery logbooks for each quarter of each year for four different areas. The areas were defined as North (17°S – 20°59'59"S), Central (21°S – 24°59'59"S), South (25°S – 29°59'59"S), according to the areas used during research surveys and all the areas combined (17°S – 29°59'59"S). Mean densities were calculated from survey and logbook data for the quarters corresponding to the respective survey periods (Table 4.1) for each of the four areas. The 95% confidence intervals (CI) for each estimate were calculated using methods described in Cochran

(1977). For comparison of density, tows from logbooks and surveys were used for the same statistical grids only.

Univariate generalized linear modelling analysis was used to investigate the effect of different seasons (quarters and years) on density estimates from the commercial fleet. All modelling and analysis was done using the statistical package: "SPSS® Base 9.0" (SPSS Inc. 1999). To build a model that explained as much as possible of the seasonal variation in density a simple forward stepwise approach was taken. These estimates allowed me to explore the effects of sampling during one season relative to year-round sampling.

4.4. Results

Logbook density estimates were similar in magnitude to those derived from research data for the four different areas (Figure 4.2). The 95% confidence intervals for densities from the commercial fleet are narrower than those for the research cruises for all the areas, because of the larger number of commercial observations. The confidence limits for the commercial density estimates in the northern region are wider than in the other regions due to the limited sample size in that area. The variability in density in the south is higher than in the central area especially for the survey estimates.

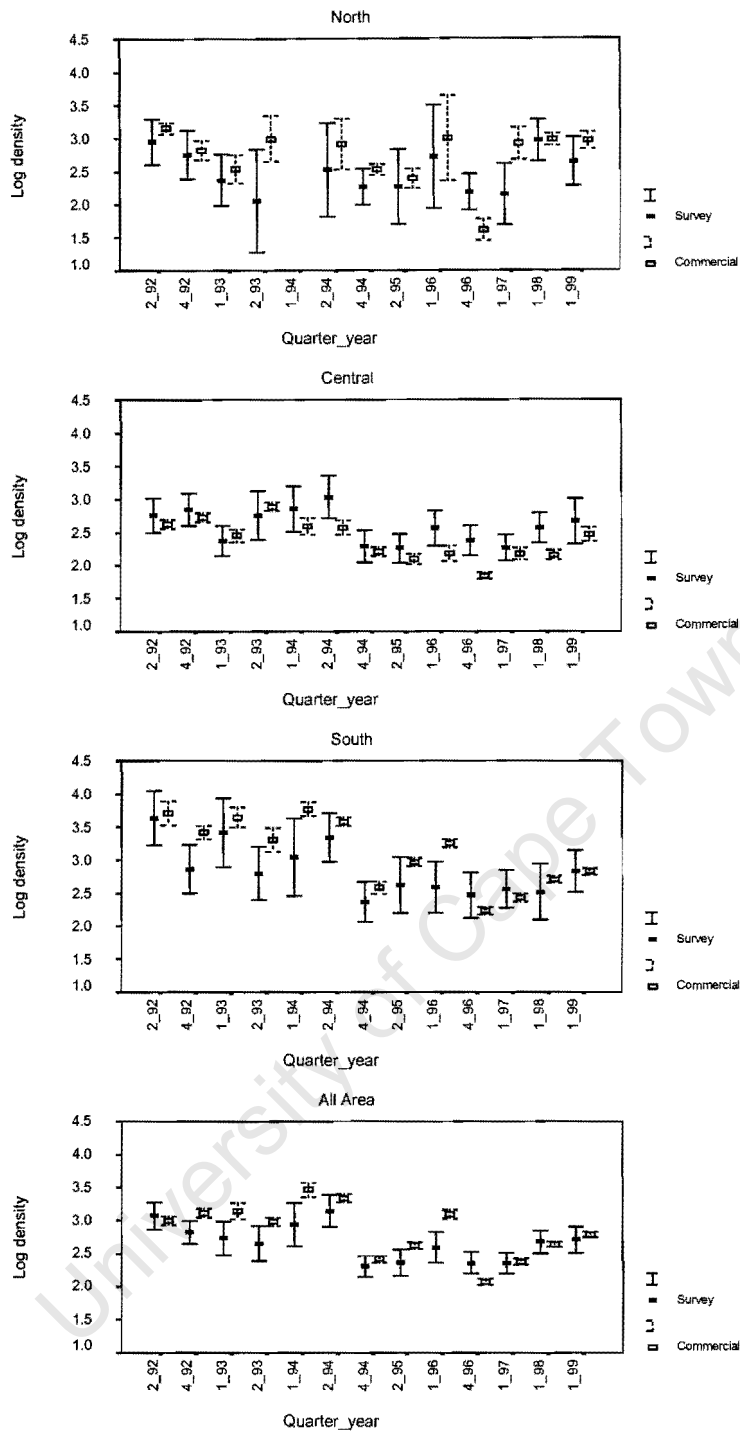


Figure 4.2. Mean density estimates and 95% CI derived from trawls conducted during different quarters and years in the commercial fishery and the research trawl cruises for hake.

Comparisons of the mean densities using t-tests for independent samples showed no significant difference ($P > 0.0760$ in all cases) between the commercial densities and the survey densities for the strata tested (Table 4.2).

Table 4.2. Results of independent samples t-tests comparing the means of $\log(x+1)$ transformed densities (tonnes/nm²) in different areas from commercial and research catches in the same statistical grid squares. Equal variances were assumed.

Area	df	t	Sig (2-tailed)
North	22	-1.617	0.120
Central	24	1.856	0.076
South	24	-1.424	0.167
All areas	24	-1.298	0.206

A linear regression of log-transformed density estimates fitted to all survey periods yielded lines with significant negative slopes, which are also significantly different from a slope of 0 for the commercial data in the Central, South and all areas as well as for the surveys in the South (Table 4.3).

Table 4.3. Trend in densities derived from linear regression analysis applied to density estimates for each survey period from logbook and research catch data. *, $P < 0.05$; **, $P < 0.01$. Where $Y = a + bX$ with Y the log transformed densities and X the different survey periods in quarters and only the grids covered by both survey and commercial data. Data from Figure 4.2.

Area		Slope	Intercept	R-squared	P	CI for slope		
						Lower 95	Upper 95%	
North	Survey	-0.006	2.530	0.006	0.808	-0.061	0.049	
	Commercial	-0.017	2.850	0.026	0.620	-0.089	0.056	
Central	Survey	-0.027	2.776	0.167	0.165	-0.067	0.013	
	Commercial	-0.051	2.742	0.446	0.013	*	-0.089	-0.013
South	Survey	-0.070	3.337	0.458	0.011	*	-0.12	-0.019
	Commercial	-0.102	3.823	0.586	0.002	**	-0.159	-0.045
All Area	Survey	-0.037	2.934	0.274	0.067		-0.077	0.003
	Commercial	-0.060	3.268	0.325	0.042	*	-0.117	-0.003

Results of the stepwise linear fit to the data indicate that quarter and year are significant to the model fit (at the 0.05 level) for the whole area combined (Table 4.4). Similar results were obtained for the north, central and southern areas (Appendix 4.1). The final model can be summarized as follows:

$$\ln(\text{density}) = \mu + \alpha_{\text{quarter}} + \beta_{\text{year}} + \omega_{\text{year*quarter}} \dots\dots\dots(4.3)$$

where μ is the intercept

Table 4.4. Results of the stepwise general linear regression for each quarter and for the whole year for the whole area. R-squared = 0.172

Factor	SS	df	Mean Square	F	P
Intercept	22915.48	1	22915.47	79408.6	<0.000
Year	218.98	7	31.28	108.4	<0.000
Quarter	33.15	4	8.28	28.7	<0.000
Year * Quarter	187.93	28	6.71	23.2	<0.000

Mean density estimates are shown in Figure 4.2 together with 95% confidence intervals for each season calculated from the model. It can be seen from these results that for each area the differences between density estimates for each period are more profound in 1994 and 1995 corresponding to increased seasonality in the system (Gordoa *et al.* 2000b).

Bonferroni multiple comparisons (Zar 1999) revealed that the significant effect of different quarters on density estimates is caused by differences between the first and the second half of the year (Table 4.5). Density estimates from sampling throughout the whole year differed significantly from densities for each of the quarters. Figure 4.3 shows the mean densities and 95% confidence intervals for each quarter and the whole year. Density estimates

from the whole year reveal the least inter-annual variability while the variability is greatest during the first quarter.

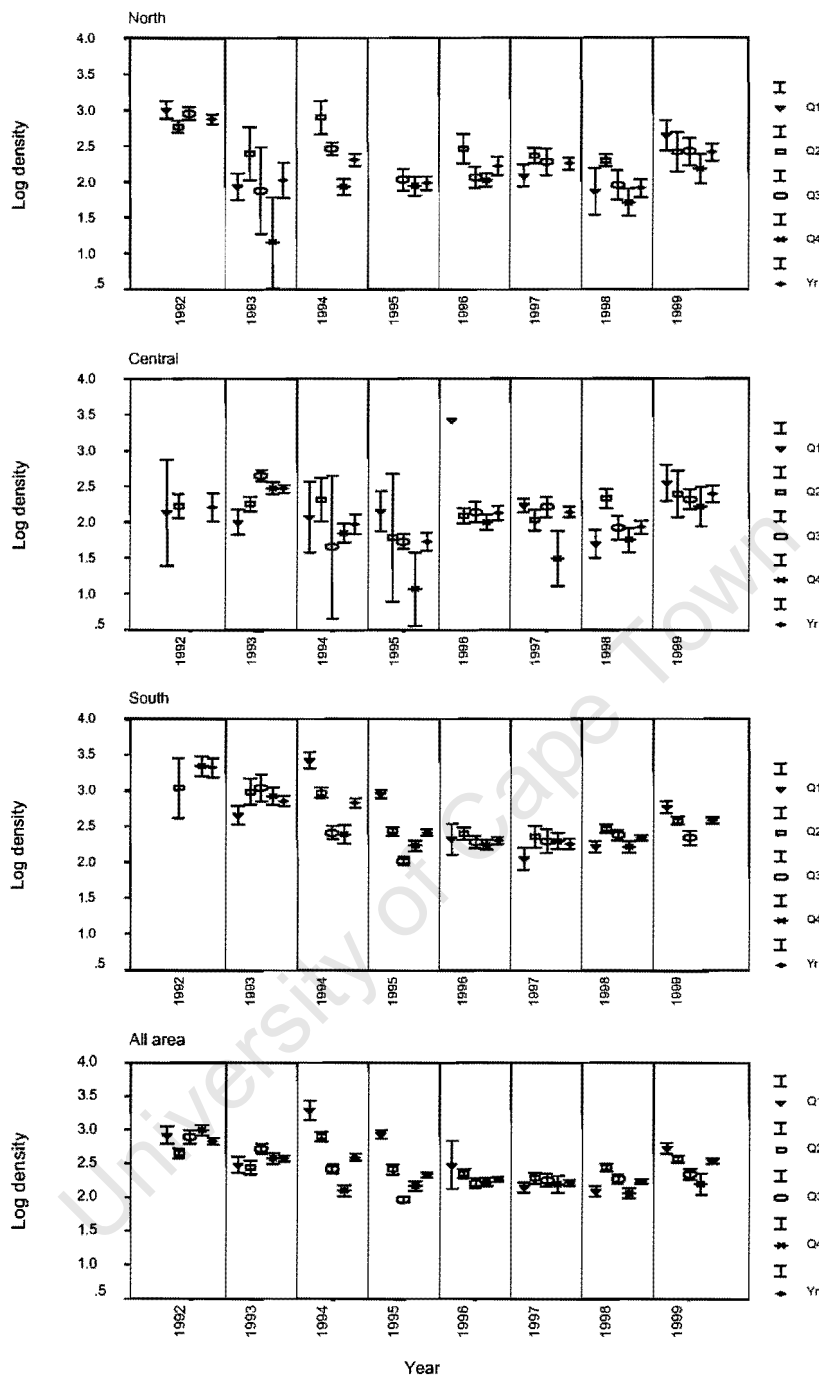


Figure 4.3. Commercial data: Mean density estimates and 95% CI derived from trawls conducted in all four quarters of the year and for the whole year in the commercial fishery as calculated by general linear regression analysis.

Table 4.5. Multiple comparison tests (Bonferroni) to measure the difference in densities between the four quarters and the whole year for the whole area. *, $P < 0.05$; **, $P < 0.01$.

(I) Period	(J) Period	Mean Difference (I-J)	Std. Error	P	95% Confidence Interval		
					Lower Bound	Upper Bound	
Quarter 1	Quarter 2	0.0491	0.0218	0.2444	-0.01	0.11	
	Quarter 3	0.2509	0.0222	0.0000	**	0.19	0.31
	Quarter 4	0.2903	0.0232	0.0000	**	0.23	0.36
	Whole year	0.1481	0.0184	0.0000	**	0.10	0.20
Quarter 2	Quarter 3	0.2018	0.0203	0.0000	**	0.14	0.26
	Quarter 4	0.2411	0.0213	0.0000	**	0.18	0.30
	Whole year	0.0990	0.0160	0.0000	**	0.05	0.14
Quarter 3	Quarter 4	0.0393	0.0217	0.7026		-0.02	0.10
	Whole year	-0.1028	0.0165	0.0000	**	-0.15	-0.06
Quarter 4	Whole year	-0.1421	0.0178	0.0000	**	-0.19	-0.09

4.5. Discussion

4.5.1. Comparison of logbook and research catch data

In general logbook data receive only limited use in stock assessments because scientists and managers have assumed that logbook CPUE data do not provide an accurate index of fish abundance (Clark and Mangel 1979; Cooke 1985; Mangel and Beder 1985). This assumption is based on the concept that research catches are better able to reflect actual fish distribution and abundance, whereas commercial fishing patterns and catches are more greatly influenced by market conditions, regulations, weather, proximity to port and possible misreporting. Comparisons of trawl, submersible and remotely operated vehicle surveys suggest that trawl sampling may not accurately reflect the distribution and abundance of many species (Kulbicki and Wantiez 1990; Krieger 1993; Adams *et al.* 1995) either. In spite of that I chose to use the research trawl surveys as the best available reference with which to compare commercial catches.

The relationship between research and logbook densities in the same statistical grids squares is significant. My results indicate that data collected from research cruises and the commercial fishery are similar, especially in the

south. It follows then, that commercial fishery logbook data may be used to evaluate or augment research survey data. Since the commercial fishery samples every month of every year and at many thousand sites, logbook data may provide information to help identify sampling error, increase sample size or fill spatial and temporal gaps in research data and narrow confidence limits. The additional information provided by logbooks should be useful in tuning population models and helping managers to identify the degree of risk and uncertainty in stock assessments, thus aiding in the development of risk-based fishery models, such as proposed by Hilborn *et al.* (1993).

Since 1997 MFMR trawl surveys have been performed only in the first quarter of the year and the plan is to continue this in the future, whereas the commercial fishery occurs throughout the entire year. The logbook data were analysed by quarter to assess whether a seasonal estimate of density provides a different picture of density trends relative to sampling conducted throughout the year. Significant differences between the density estimates in the different quarters and the whole year period imply that the time of sampling does have a significant influence on density estimates. This is mainly due to changes in availability of hake as a result of seasonality in the ecosystem, which varies from year to year. Density estimates from the second quarter of the year have the least inter-annual variability. Density estimates during the first quarter may create high inter-annual variability especially in years with large seasonal environmental signals (see chapter 5). Sampling from the commercial fleet throughout the year can be used to adjust/calibrate the survey estimates in some way in such anomalous years.

4.5.2. Factors affecting the use of commercial fishery data

The co-operation of a large number of commercial fishers is obviously critical for logbooks to be useful. Proper collection, preparation, and analysis of logbook data are also essential to maximise the usefulness of the information. Logbook data need to be thoroughly error-checked with verification of depth and location information. Catches from the logbooks need to match the reported landings or be close enough to enable correction and adjustment.

A critical assumption in the use of any trawl surveys is the fishing efficiency of the gear and resulting catchability of fish. For estimating biomass, MFMR assume a catchability of 1.0 for their surveys, indicating that all fish in the path of a trawl would be caught and there is no herding effect. Here the same assumption is made for commercial trawls. For short periods, constant catchability may be a valid assumption. Over longer periods, such as a decade or more, the assumption of constant catchability is invalid. Kimura (1981), for example, reported that improved echo sounders and improved roller gear doubled the estimated efficiency of commercial vessels. Catchability should be studied periodically to ensure that CPUE estimates are comparable from decade to decade (Fox and Starr 1996). A multiplicative model, such as the ones used by Gavaris (1980), Kimura (1981) or Large (1992) may then be needed to account for variability associated with differences in gear. In this study it is also proved that catchability of hake in a system with high seasonable variability, has high inter- and intra-annual variability.

4.6. Conclusion

It is apparent that commercial fishery logbook data provide a comprehensive source of information because of the broad temporal and spatial fishing patterns of the fleet. The commercial data however do not cover the whole distribution area of hake, because of the ban of trawling inside 200m depths. For the period 1992 – 1999, estimates of relative abundance derived from logbook data closely resemble those from MFMR trawl survey data for the overlapping areas between 200 – 600 m contours. Due to inter- and intra-annual variability in catchability of hake the survey estimates is not useful as an annual index of abundance.

These results suggest that information derived from logbooks can augment research data and improve estimates of the relative abundance of hake. The commercial density estimates will especially be of use during years with seasonal temperature anomalies (see chapter 5) when the variability during

the first quarter increases remarkably. The density estimates from commercial data throughout the year can then be used to adjust the survey estimates from the first quarter if necessary. It is important however to correct the commercial catch rates annually by using the GLM analysis in order to make provision for changes in fleet behaviour with resulting changes in efficiency of the different GRT-classes of vessels.

From this study it can be seen that there are definite seasonal changes in catchability of hake, which are not directly the result of changes in fish abundance. To try and understand what causes this variability in catchability, the relationship of the seasonality in the environment to the monthly variability in the catchability of the hake will be investigated in the following chapter.

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CHAPTER FIVE

MONTHLY VARIABILITY IN THE CATCHABILITY OF NAMIBIAN HAKE AND ITS RELATIONSHIP WITH ENVIRONMENTAL SEASONALITY

5.1. Introduction

Off Namibia, upwelling is intense over most of the year but is particularly strong during the winter months, which reinforces the seasonal solar heating effect and causes a very definite SST cycle (Boyd and Agenbag 1985). Advection of warm water masses also plays an important role in the seasonal SST cycle. The area influenced by upwelled water has considerable seasonal variability, and during summer and autumn this area contracts (Boyd and Agenbag 1985). Seasonal warming of central and northern Namibia occurs due to the intrusion of warm and saline water of equatorial origin. The extreme case is named a "Benguela Niño" and occurs at about 10-year intervals (Shannon *et al.* 1986; Boyd *et al.* 1987). Thus, the seasonal SST cycle is enhanced by this warm water intrusion because it occurs during the least active upwelling periods (summer and autumn).

Namibian hake fishing is continuous throughout the year. Bottom trawls are used at depths of 200-600 m. Various aspects of these species have been studied, such as annual changes in catchability (Gordoa and Hightower 1991), schooling behaviour (Gordoa and Duarte 1991), feeding (Roel and Macpherson 1988; Macpherson and Gordoa 1994; Pillar and Wilkinson 1995; Pillar and Barange 1995) and daily distribution (Gordoa and Macpherson 1991; Huse *et al.* 2001). A review of the main aspects of Namibian hake biology and fisheries can be found in Gordoa *et al.* (1995). Long-term changes of hake populations have been analysed by Shannon *et al.* (1988). Macpherson *et al.* (1991) detected intra-annual variability in hake densities: The biomass estimated by swept area research surveys during warm summers was anomalously higher than the preceding winter. These

differences cannot be attributed to differences in population biomass, because of their short time period, but to differences in catchability.

The catchability coefficient (q), the proportion of a population captured per unit of effort, has been analysed in many fisheries. The scientific effort expended on this coefficient is justified because its constancy depends on the general assumption that catch rates are an index of fish abundance. Consequently it can validate or invalidate the use of the catch per unit of effort (CPUE) data in fisheries assessment models. In the Namibian hake fishery, the discrepancies between survey estimates and those from surplus production models based on CPUE from commercial data have recently been pointed out (Pennington and Strømme 1998). Although the analysis of catchability has mainly focused on its annual changes (e.g. Pope and Garrod 1975; Crecco and Overholtz 1990; Fréchet 1990; Gordo and Hightower 1991; Swain *et al.* 1994), little, though increasing attention, has been paid to its variability on shortest time scales (Fréchet 1988; Atran and Loesch 1995). By examining short-term fluctuations in catchability it may be possible to detect changes in fish distribution, independently of fish abundance, affected by other factors such as fish behaviour (spawning or feeding migrations) or environmental factors.

Although the first sign of possible seasonal variability in Namibian hake catchability was described by Macpherson *et al.* (1991), the study was limited by its temporal resolution (two surveys per year). Since 1994 a spatially and temporally highly resolved CPUE (catch per unit of standardized effort) database has been maintained, allowing a more fine-scaled temporal analysis. Thus, with the premise that the strongest physical variability of this system occurs on a seasonal scale, I examine the temporal variability of the catchability of Namibian hake in conjunction with the temporal variability of the SST as an indicator of environmental variability on a monthly basis.

5.2. Material and Methods

I have used commercial fishing data from the bottom trawl fishery logbooks collected by the National Marine Information and Research Centre (NatMIRC) from 1994 to 1997, with the numbers of individual daily records per year being 8000, 10 462, 13 205 and 10 407 respectively. The daily information included in each record was: vessel license, date, latitude, longitude and/or grid square (20 x 20 miles), depth, number of trawls, catch (kg), effort (trawling hr), type of vessel, horsepower and tonnage. Computer errors were reviewed to detect entries of unreasonable catches or locations: Around 90% of the daily data was correctly represented spatially and considered for further analysis. The standardised catch per unit of effort (kilograms of hake per hour) was calculated for each individual record; effort was standardised by the tonnage class of vessels.

To examine whether monthly CPUE patterns were limited to certain regions or resulted from horizontal migrations (north-south and onshore-offshore), the daily CPUE was used to estimate: the mean monthly CPUE, the mean monthly CPUE per 100 m depth (from 200m to 600m isobaths), the mean monthly CPUE per 3 degrees of latitude (from 18°S to 29°S) and the mean monthly CPUE by strata (1 degree of latitude and 50 m depth). To examine the relationship between the temporal pattern of fishing effort and both CPUE and the area fished, the Spearman correlation coefficient was calculated. To analyse whether catch rates are providing information about changes in hake density, or are distorted by the distribution of fishing effort (in relation to the distribution of fish), the correlation coefficient between CPUE and total standardised effort by strata was estimated separately for each month by each year.

The Namibian hake population has been monitored since 1990 by means of bottom trawl surveys by the Institute of Marine Research (IMR, Bergen, Norway) in a co-operative research program with the National Marine Information and Research Centre (NatMIRC, Namibia). The NatMIRC provided the data from the surveys of my study period (1994-1997) to allow, in

this study, the comparison between the commercial and survey data. In 1994 three surveys were performed: January-February, April-May and October-November; in 1995 one: April-June; in 1996 two: January-February and October and one in 1997: January-February. To compare commercial and survey data, the mean CPUE (kilograms per trawling hour) of each survey was estimated from those trawls located within the fishing grounds (200-600 m).

Sea surface temperatures from 18°S to 30°S for each degree square were downloaded from the NOAA CLIMATE DATA server (weekly NCEP Sea Surface analyses). A weekly time period was selected, and every second week of each month was arbitrarily chosen as representative of each month. To examine the SST spatial-temporal variability in the fishing area, limited by 200m-600m isobaths, a square (1 x 1 degree) was selected for each degree of latitude along the coast (Figure 5.1). Mean monthly representative temperatures were calculated, averaging from 18° to 30° S, to be compared with the mean monthly CPUE. To detect monthly anomalies from the temperature cycle that characterised this region, a monthly index of temperature anomaly for each year was estimated as:

$$I_{m y} = T_{m y} - \frac{1}{4} \sum_{y=1}^4 T_{m y} \dots\dots\dots(5.1)$$

Where: I is the index of temperature (monthly anomalies), T is temperature and m and y are the indices of month and year respectively.

Finally, to explain the monthly variability of the catch rates I develop a model in which CPUE is modulated by the environmental cycle and its monthly anomalies. The equation fitted by an iterative process using the Quasi-Newton method (STATSOFT 1996) is:

$$CPUE = a + b \cdot \cos(\lambda \cdot t) + c \cdot \sin((\lambda \cdot t) + d \cdot I_{m y} \dots\dots\dots(5.2)$$

Where: t is the unit of time (1^{st} – 48^{th} month) and $\lambda = 2 * \pi * \nu$, where π is the constant $\pi = 3,1416$ and ν is the frequency (number of cycles per unit time).

Frequency ν (the number of cycles per unit of time) was previously estimated by Fourier analysis (STATSOFT, 1996).

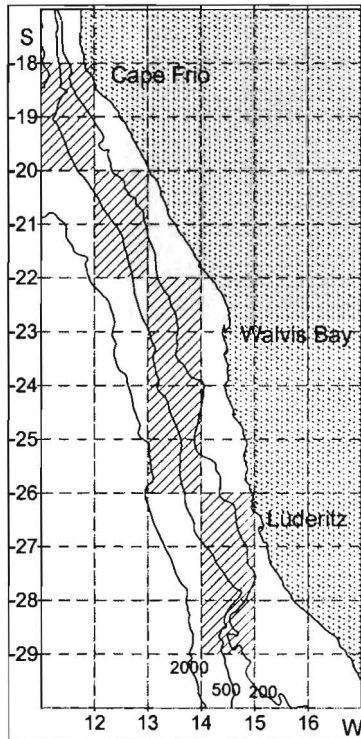


Figure 5.1. Map of Namibian waters. Depth contours (200, 500 and 2000 m). Shaded squares indicate the areas selected to represent SST along the coast and used to estimate mean monthly temperatures.

5.3. Results and Discussion

5.3.1. Relationship between CPUE and Effort

The monthly time series of CPUE and fishing effort from 1994 to 1997 are shown in Figure 5.2. CPUE shows a seasonal cycle during the first three years but this is absent in 1997. Similarly I observe a seasonal cycle in the effort series during the first three years, but opposite to the CPUE one, which also disappeared in 1997. The Spearman correlation coefficient between these time series was significantly negative ($r = -0.72$ $p < 0.001$), which may be interpreted as a strong negative relationship between these two variables. On the monthly scale used in this work, the effect of effort cannot be attributed to periods of stock over-exploitation or under-exploitation. On this time scale, if

the effort affected the CPUE, it could be through a dispersal process; an increase in the number of fishing vessels in a certain area may disperse the bottom distribution of hake, which would recover after a subsequent decrease in the fishing pressure. Similar observations have been reported for the Dutch beam trawl fleet (Rijnsdorp *et al.* 1998 and Rijnsdorp *et al.* 2000). But I observed periods of limited change in effort (circled in Figure 5.2.A) where the CPUE trend, whether positive or negative, did not change. This may indicate that the observed relationship is a coincidence. The same conclusion is suggested by the fact that the local fishing intensity did not increase proportionally to the increase in fishing effort, but rather when fishing effort increased the fishing area increased. This is shown in Figure 5.2.B, where the number of strata covered by the fleet are represented and a high correlation was found between the number of strata and the effort ($r = 0.83$ $p < 0.05$). Moreover, no significant monthly correlation of CPUE and effort by strata was found in the four years analysed (Appendix 5.1), which indicates that the fleet did not track the areas of high CPUE. Thus, I exclude the possibility that CPUE as an index of density is being distorted by monthly fleet distribution in any of the years analysed.

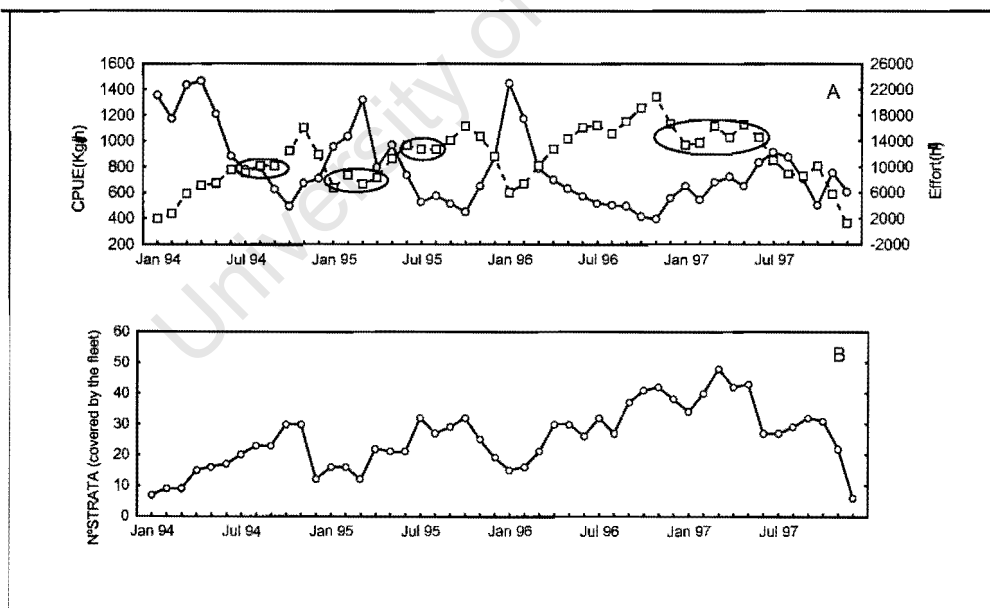


Figure 5.2. Monthly time series (A) standardised CPUE (Kg/hr) \circ and standardised fishing effort (hr) \square ; (B) Number of strata covered by the fleet. Periods of constant effort are encircled.

The seasonal dynamics of the fishing effort, which did not follow the pattern of hake catchability, is apparently incongruous. *A priori*, this behaviour is unexpected and opposite to what is observed in other fisheries like the Lofoten cod fishery (Angelsen and Olsen 1987). The only explanation I can suggest for the low effort invested at high-density periods and the high effort expended at low densities is either the handling capacity of the industry or/and the caution of filling the quota too early in the year. During periods of high CPUE periods (austral summers), the total catch is higher with minimum effort than that achieved at periods of maximum effort; if the fleet invested more effort during the period of high CPUE, such large catches would be unmanageable by the current industry. This corresponds with the results obtained in Chapter 3, which indicated that CPUE is equalised among all areas and that no interference competition exists among vessels.

5.3.2. Spatial-temporal variation of the CPUE.

The monthly CPUE by depth for each year (Appendix 5.2) shows that the seasonal pattern observed in the period 1994-1996 occurred at every depth within the fishing grounds, and for every year the pattern observed in the monthly time series is shown at every depth. Therefore the seasonal changes in hake density are a general feature at any depth in the area. The differences in density between depths decreased as total density decreased and disappeared or even reversed at the periods of minimum CPUE (October) with the exception of 1996, when no differences in density between depth strata were observed at any period. The monthly CPUE by latitude strata (Figure 5.3) presented the same pattern observed by depth, and both showed the same seasonal trend of the total density seen in Figure 5.2.A. Differences between latitudes occurred in 1994 and 1997 but decreased with density and reverted in 1994 during the period of minimum density (August-October).

These results exclude any possible migration, offshore onshore or north south, as the cause of changes in monthly catchability. Similar seasonal changes in hake catchability were described almost four decades ago in the Humboldt upwelling system (Chilean coast) (Brandhorst 1959) and in

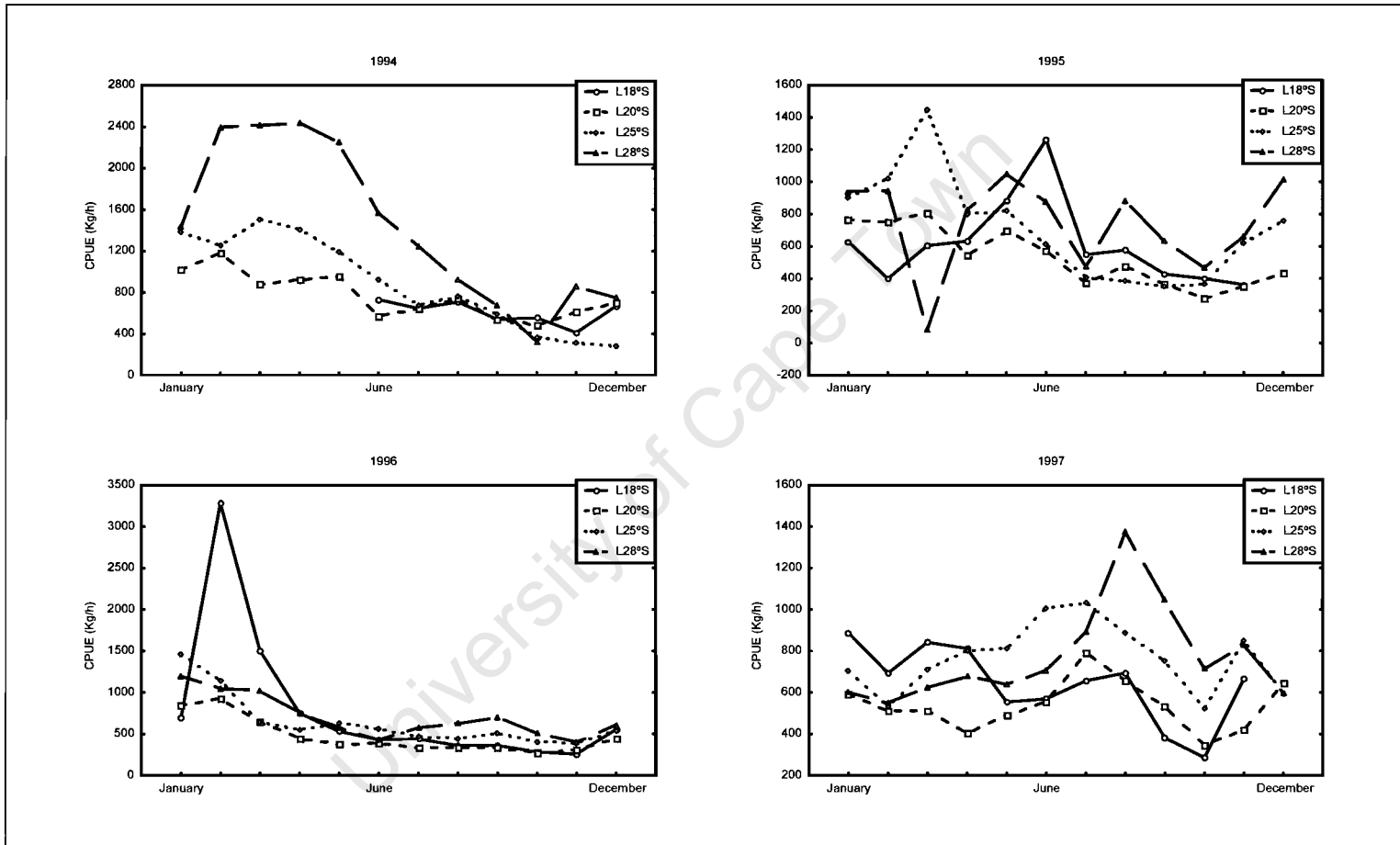


Figure 5.3. Monthly standardized CPUE per three degrees of latitude for each year.

Argentinean hake stocks (Bezzi *et al.* 1995), although in both cases a north-south seasonal migration was described.

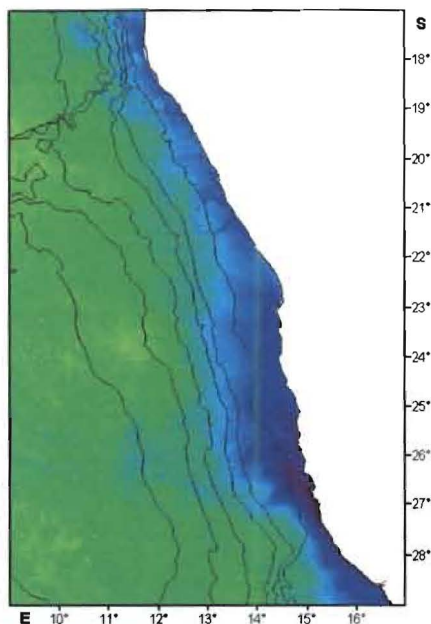


Figure 5.4. Thermal infrared image of the Namibian coast during April 1997 (Gordoa *et al.* 1999).

5.3.3. Seasonal pattern of CPUE and SST cycles

The strong seasonal patterns that characterise this ecosystem are clearly shown through the mean monthly SST (Figure 5.5). Moreover, the seasonal cycle is modulated (increased or diminished) by interannual differences. Of the four years analysed, 1997 presented the weakest seasonal pattern. The summer of 1997 was substantially cooler than previous years. This cool period began in the previous spring (October 1996) and lasted until the beginning of winter 1997. The seasonal SST differences in 1997 are the lowest observed because, while the summer and autumn season were the coolest of the studied period, late winter and spring are the warmest, to the extent that the northern area, in the spring of this year, was warmer than in summer. The same observation of the SST pattern in 1997 was reported by Boyer *et al.* (2001). This breaks the general latitudinal pattern that characterises this region (Boyd and Agenbag, 1985). During the summer-autumn period, upwelling did not diminish as is common for that area and season. At the beginning of April 1997 upwelling was active along the whole coast, even in Central Namibia, and warm equatorial waters were restricted to

the northernmost area (Figure 5.4). Summarising, I conclude that 1997 was an anomalous year.

CPUE shows a clear seasonal pattern during the first three years of this study, changing by up to a factor of three in 6 months, and matches the SST cycle almost perfectly. Furthermore, both variables exhibit their seasonal oscillations with the same relative strength. The cycles differ mostly at their minima: CPUE showed its minimum in October even during the anomalous year 1997, SST on the contrary shows its minimum between July and October, depending on the year, while the maxima of both series coincided almost exactly and correspond to the time of minimum upwelling intensity (Shannon 1985). Because of the coupling, when it occurred, of the CPUE cycle with the SST cycle, I presume that CPUE seasonality is a response to the environmental seasonality, although the coupling of both cycles may be a coincidence and not a true causal effect. The results obtained in 1997 suggest that hake are responding directly or indirectly to the environmental seasonality

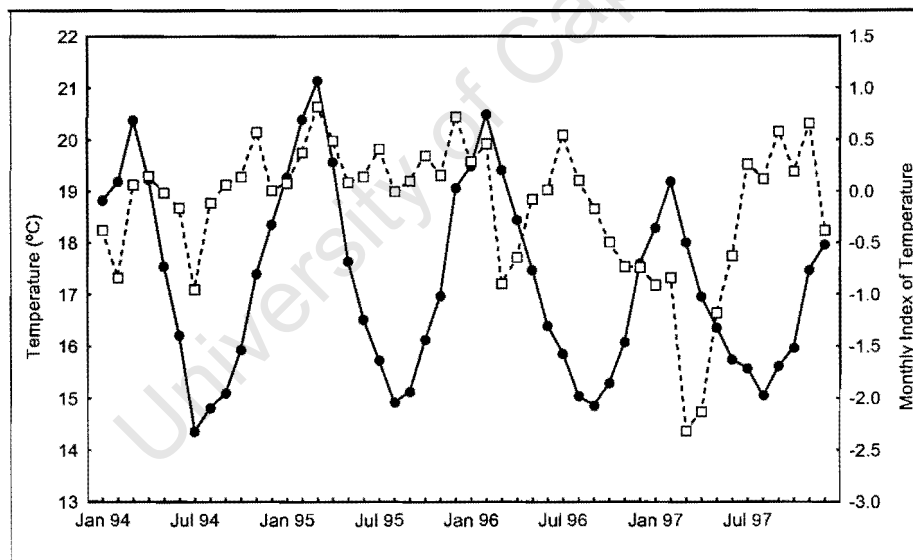


Figure 5.5. Monthly Sea Surface Temperatures (SST, °C) are averaged from 18° to 30° S nearest to the 200 m isobath (●) and monthly index of temperature anomaly (□).

and its anomalies. The coolest summer was in 1997, with temperatures two to three degrees lower than the mean compared to the other years (Figure 5.4) and up to 6 degrees cooler than the hot summer of 1995. The peculiarity in 1997 (Figure 5.6) was that the upwelling did not cease during the summer-autumn period and no intrusion of equatorial water took place. Thus the general seasonality of upwelling was interrupted and it coincided with the broken seasonality in CPUE. This coincidence strengthens the argument that hake behaviour follows an environmental cycle.

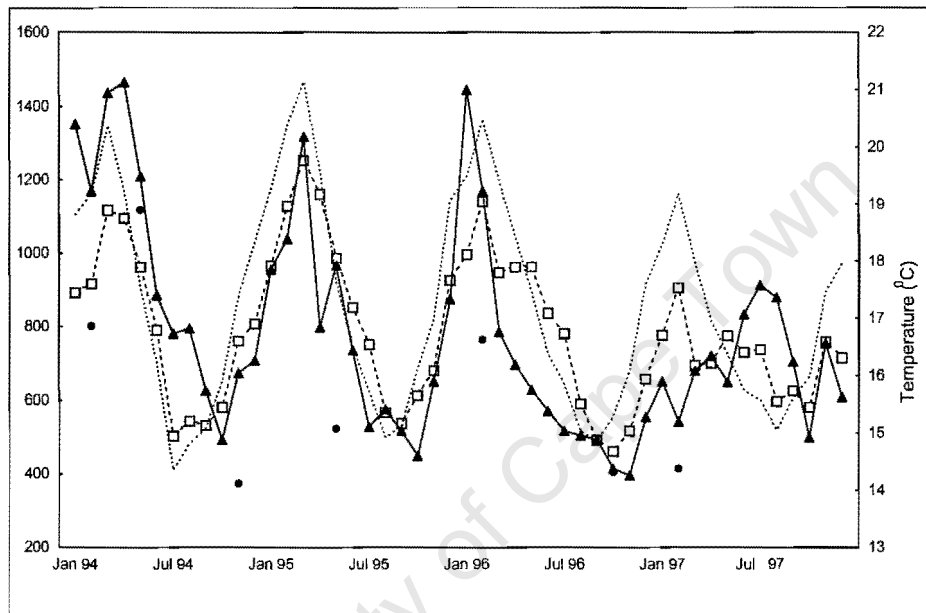


Figure 5.6. Monthly time series of: observed standardised CPUE (□) and predicted CPUE (▲) ($=808+0.694\cos(0.083*\pi*t)+296*\sin(0.083*\pi*t)+182*I$). Mean CPUE estimated from survey data (●). SST has been superimposed (...).

The response of the population may be driven directly or indirectly by environmental cycles. Direct response should be possible, because there are significant changes in the physical structures of the water masses at depths inhabited by hake that are associated with the upwelling cycle. Hake occur mainly at depths between 200 and 600 meters (MacPherson *et al.* 1985; Burmeister 2001). Variability in upwelling intensity modifies the structure of water masses at these depths, changing the origin, location and body of the upwelling waters. In addition a pole-ward compensation flow at 300-400 m appears to be a permanent feature but may show seasonal variability in

intensity and localisation associated with the upwelling cycle (Shannon 1985). Moreover, this undercurrent has been associated (mainly in summer) with advection of hypoxic water (Salat *et al.* 1992). However, the response of hake may be indirect through the seasonal changes of its prey by following either a direct or indirect response to environmental cycles, following a cascade effect through the trophic chain.

Whichever the type (direct or indirect) of hake response to environmental variability, the analysis strongly suggests that bottom density of hake is modulated by it. I present here a model (equation 5.2) of how it may be modulated. This is based on two factors: first the seasonality and second the anomaly of the seasonality. The frequency of the seasonal wave estimated by Fourier analysis was 0.083, which corresponds to a period of 12 observations, thus to an annual cycle. Figure 5.6 also shows the observed CPUE and the CPUE estimated by the model that explains 51% of the variability in CPUE during the study period. The mean CPUE, estimated by research surveys on the fishing grounds (Figure 5.6), also seems to be affected by the same seasonal variability in catchability observed in the commercial CPUE. The findings show that monthly estimates of biomass from CPUE data are distorted by changes in monthly catchability, though annual catchability may remove the seasonal effect. However, it may be sensitive to seasonal anomalies in certain years. Thus, the annual CPUE may be underestimated in years with particularly cool summers (reduced catchability).

This study shows that short-term analysis contributes to an understanding of the dynamics of processes controlling fish behaviour. Moreover, the results show that interannual changes in upwelling intensity (as measured by SST) may produce interannual changes in catchability. In a number of demersal fish stocks it has been observed that the interannual changes in catchability are regulated by density-dependent processes (e.g. Hutchings and Myers 1994; Swain and Sinclair 1994), which induces overestimation of these stock sizes. From the results, I suggest that in the Namibian hake fishery the annual strength of environmental seasonality may be another factor regulating

changes in annual catchability, although a longer time series and independent indices of abundance are required to demonstrate it fully.

5.4. Conclusion

Namibian hake catchability shows a strong seasonal pattern, which correlates with environmental seasonality in SST and its anomalies. Nevertheless, no change in the horizontal spatial distribution (i.e. migration process) that could explain that seasonal cycle has been detected. Neither can it be explained by changes in the spatial fishing behaviour because no spatial correlation between CPUE and fishing effort was found. The findings show that the maximum interannual variability takes place during summer and provide an oceanographic basis for understanding changes in hake distribution, which may be predicted by monitoring a few selected oceanographic parameters as shown here with the SST and its anomalies. Walters and Maguire (1996) advise investment in survey indices of abundance trends needed for a proper stock assessment. They highlight the difficulty of designing these surveys in situations where the spatial distribution of fish is rapidly changing and/or is highly variable from year to year. These results and previous studies (Fox and Starr 1996) highlight the usefulness of information derived from logbooks and I believe that they can be very useful for improving the design of surveys and of great help in fisheries management.

From this study I have established a relationship between the abiotic environmental influences and the spatial and temporal distribution of hake. Other factors, however, that may induce fluctuations in a fish stock are the biotic processes. In the next chapter I will use environmental indices to predict the strength of the two year old hake and thus to predict the strength of recruitment.

CHAPTER SIX

ESTIMATING THE PROBABILITY OF DIFFERENT LEVELS OF RECRUITMENT FOR CAPE HAKES *MERLUCCIOUS CAPENSIS* OFF NAMIBIA, USING ENVIRONMENTAL INDICES

6.1. Introduction

In Namibia coastal upwelling occurs mainly between 17-20°S, 22-24°S and 26-28°S (Lutjeharms and Meeuwis 1987), where the coastline runs in a southward direction and prevailing southeasterly winds drive surface water masses away from the coast. The northern extent of the Benguela Current system coincides approximately with the termination of the zone of upwelling-favorable wind stress (Picaut *et al.* 1985) and the confluence with the poleward-flowing Angola Current. According to Shannon and Agenbag (1987), the Angola-Benguela front is a permanent feature of the oceanography of the region. The meridional mid-point of the front (i.e. the zone of maximum horizontal gradient) near the coast varies between about 15 and 17°S, being on average farthest north and south during August and March, respectively (Figure 6.1).

Sea-surface temperature (SST) was used as an index of environmental changes. The SST anomalies in the central to northern part of Namibia do reflect interannual variability in the tropical Atlantic (Taunton-Clark and Shannon, 1988). In particular they highlight Benguela Niños during which occasions the Angola-Benguela front migrates pole wards over several degrees of latitude from its usual location at around 16°S (Shannon *et al.* 1987).

From the information collected from gonadal examination and from egg and larval distribution by Olivar *et al.* (1988), O'Toole (1978), Porebski (1976); Sedletsкая (1988) and Sundby *et al.* (2001), the main spawning period of Cape hake in Namibia could be placed during spring and summer - September to March. Nevertheless, the onset of the spawning season may

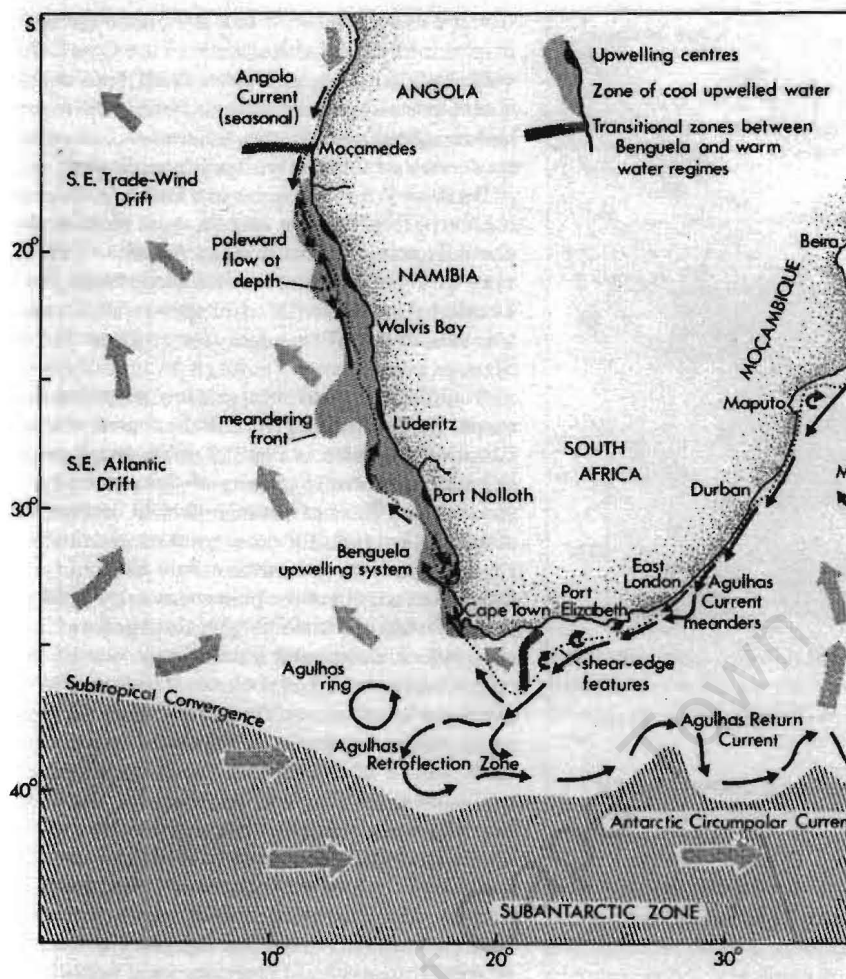


Figure 6.1. A conceptual picture of some aspects of the physical oceanography of the Benguela (Shelton *et al.* 1985).

vary from year to year and in some cases spawning activity has been described to occur during late winter (Assorov and Berenbeim 1983, Jones and Van Eck 1967). According to O'Toole (1978), the months of heaviest spawning generally coincide with the period when the north-flowing Benguela Current weakens and movements of warm offshore water take place towards the south and the coast. The interaction of these two water masses off Walvis Bay appears to contain developing larvae within the main spawning area (23° to $24^{\circ}30'S$) (Figure 6.2) thereby allowing them to remain in the productive coastal environment (O'Toole 1978; Sundby *et al.* 2001).

According to Bakun (1985) recruitment refers to: "the quantity of younger fish

surviving the various egg, larval, juvenile, etc., stages to reach a stage at which they become susceptible to fishing gear and thus begin to be sampled by the fishery." The stock of the Cape hake exhibits large variations in recruitment strength since 1998 (Figure 6.3). During In Namibia, the inter-annual physical variability may result in a strong biological response. Therefore, the strong signals in recruitment variability of Cape hake render this species an ideal candidate to study fish response to inter-annual variations in ocean conditions off the coast of Namibia.

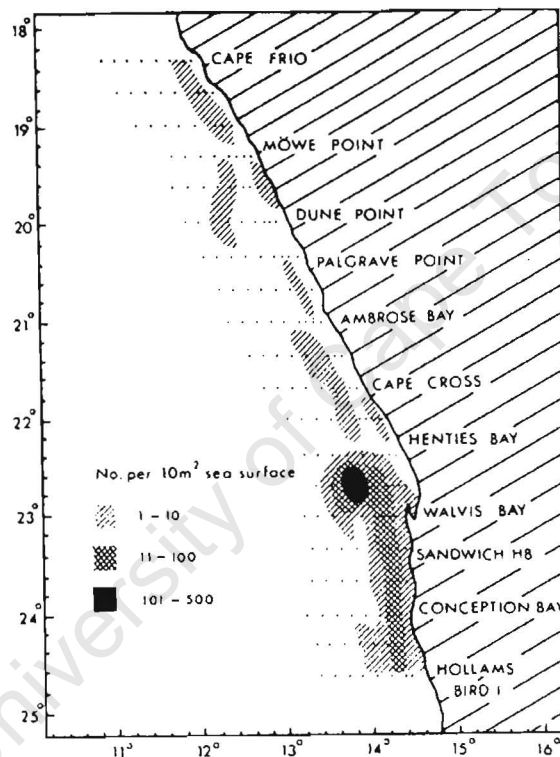


Figure 6.2. Distribution and abundance of hake larvae during August 1972 and March 1973 (values represent cumulative standard hauls totals for all cruises) (O'Toole 1978).

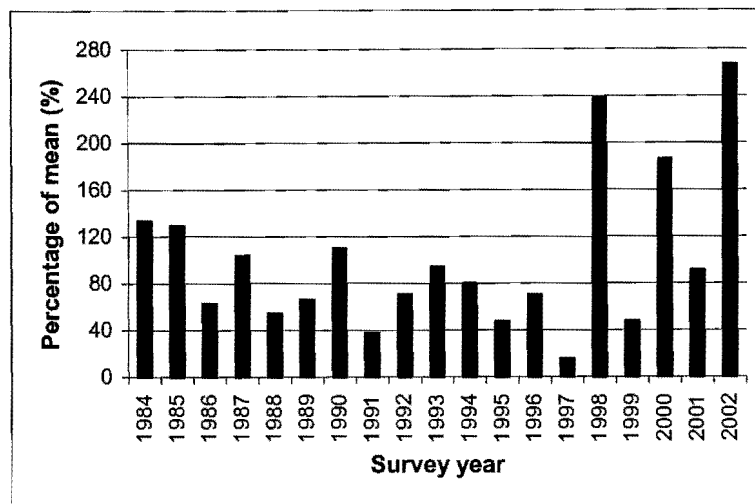


Figure 6.3. Recruitment of 2-year old Cape hake as percentage of the mean estimated during research surveys from 1984 to 2002 (Kainge *et al.* 2003; Gordoa personal communication).

The purpose of this analysis is to identify environmental conditions that may be related to relative recruitment success or failure of Cape hake to explain some of the annual variability in the recruitment strength. Shelton *et al.* (1985) noted that: "Rapid egg development in the warmer water may result in increased early survival, and first-feeding larvae may benefit from food concentrated in strong fronts and thermo-clines set up by the interplay between upwelling, advective processes and solar heating." This hypothesis will be tested in the present chapter.

6.2. Biological Data Sources

The time series of the abundance of two-year-old hake from research surveys were collected from Spanish and Namibian surveys. Eleven Spanish surveys were conducted off the West Coast of Namibia during the period from 1984 to 1990 between 23°S to 30°S (Macpherson *et al.* 1985; Gordoa *et al.* 1995; Macpherson and Gordoa 1996). The nineteen Namibian surveys covered the area between 17°S to 30°S from 1990 to 2002. These surveys were conducted one to three times annually.

Estimates of the numbers of fish recruited to the fishery at age 2 were derived from an age-length key for the Spanish surveys (A. Gordo, pers. Comm.) and by cohort analysis for the Namibian surveys (Kainge *et al.* 2003). Recruitment estimates from surveys conducted in October/November were not included in the analysis, since the recruit strength can be biased due to two different factors: first, due to a new cohort moving in by October, and second due to the strong seasonal signal in the availability of Cape hake (Gordo *et al.* 2000b). Thus, using data from the same season in each year removed the major factor of availability, and choosing summer surveys removed the effect of any new cohort. For each year the average of the different recruitment estimates for that year has been used. For the model construction, recruitment data from 1984 to 1997 were included.

For use in the model, the two data series had to be standardized separately due to the large differences between the two surveys (Macpherson *et al.* 1985; Burmeister 2000) from the type of vessel and area surveyed, to methodology of biomass estimation and sampling design. The standardization recruitment (A_i) for each series was calculated as follows:

$$A_i = \frac{R_i - \bar{R}}{\bar{R}}$$

Where:

R_i is the recruitment for survey i .

\bar{R} is the mean recruitment for all the surveys in each of the series separately.

6.3. Environmental Data Sources

In this analysis, three indices of upwelling intensity and three indices of warm water intrusion were examined. A sea surface temperature (SST) data set, obtained from monthly SST images from the NOAA (AVHRR) satellite from January 1982 to December 1996 at 4.5km resolution, was used to construct

the different indices for the Namibian shelf. Data from 1996 to 2001 were used for predictions. Data were obtained from 17°S to 28°S at 25 pixels per degree latitude, thus 300 pixels in total, extending 427,5km offshore (95 pixels - land excluded from data set).

The SST data array used is: $A(95_c, 300_r, 192_m)$.

Where: m = month; c =column/longitudinal; r = row/latitudinal.

6.3.1. Upwelling indices:

- i. Upwelling index 1 (UW1): The upwelling index between 20°S and 24°S and up to 162km miles offshore during the period May to September was calculated as the anomaly from mean monthly SST per month for each one degree latitude.

$$UW1 = B(12_r, 192_m) - C(12_r, 12_m)$$

$B(12_r, 192_m)$ = SST array calculated from $A(95_c, 300_r, 192_m)$ by averaging all pixels per latitude (25 pixels) up to 162km (36 pixels) offshore.

$C(12_r, 12_m)$ = mean monthly SST calculated from $B(12_r, 192_m)$.

- ii. Upwelling index 2 (UW2): The upwelling index between 17°S and 29°S was constructed by subtracting all SST values for each latitudinal line from the furthestmost offshore value. This resulted in a series of grid squares (4.5km wide) with temperature differences displaying cool upwelling water (usually inshore) as large positive values and ending in zeros offshore. The percentage area with values above 3°C was calculated. The anomaly from this data set for the period May to September was then used as the upwelling index.

$$UW2 = E(16_y, 12_m) - F(1_y, 12_m)$$

$D(95_c, 300_r, 192_m) = A(1_c, 1-300_r, 1-192_m) - A(1-95_c, 1-300_r, 1-192_m)$.

$E(16_y, 12_m) = \% \text{ pixels per month that are } > 3^\circ\text{C}$ (indicating upwelling areas) calculated from $D(95_c, 300_r, 192_m)$.

$F(1_y, 12_m) = \text{mean monthly } \% \text{ pixels } > 3^\circ\text{C}$.

$y = \text{year}$

- iii. Upwelling index 3 (UW3): The upwelling index for the area between 17°S and 21°S was calculated in the same manner as for the area between 17°S and 29°S (UW2) also for May to September.

6.3.2. Indices of the extent of warm water intrusion:

- i. Warm water intrusion index 1 (WI1): Southerly penetration of the Angola Current was measured as the anomaly of the latitudinal position of the 17°C isotherm in the zone up to 72 km from the coastline for January to March as defined by Stogalev (1983).

$$WI1 = H(192_m) - I(12_m)$$

$G(300_r, 192_m) = \text{SST array calculated from } A(95_c, 300_r, 192_m)$ by averaging all pixels per row up to 72km (16 pixels) offshore.

$H(192_m) = \text{latitudinal position of the } 17^\circ\text{C isotherm per month from } G(300_r, 192_m)$.

$I(12_m) = \text{monthly mean latitudinal position of } 17^\circ\text{C isotherm}$.

- ii. Warm water intrusion index 2 (WI2): Lack of upwelling was measured by the anomaly of percentage of blocks from 17 to 21°S with a difference in SST of 3°C or more compared to the offshore value for January to April.

$$WI2 = J(16_y, 12_m) - K(1_y, 12_m)$$

$J(16_y, 12_m) = \% \text{ pixels per month that are } < 3^\circ\text{C}$ (indicating areas of weak or no upwelling) calculated from $D(95_c, 300_r, 192_m)$.

$K(1_y, 12_m) = \text{mean monthly } \% \text{ pixels } < 3^\circ\text{C}$.

- iii. Warm water intrusion index 3 (WI3): Warm intrusion offshore was measured as the anomaly of the distance from the coast (in kilometres) of the 17°C isotherm at 21°S for December to April.

$$WI3 = M(192_m) - N(12_m)$$

$L(95_c, 192_m)$ = SST array calculated from $A(95_c, 300_r, 192_m)$ by averaging all pixels at 21°S (25 pixels).

$M(192_m)$ = offshore position of the 17°C isotherm per month from $L(95_c, 192_m)$.

$N(12_m)$ = monthly mean offshore position of 17°C isotherm.

The indices described above, are applied in this study with one or two year time lags with respect to the time of the recruitment measured. The time lags are indicated by 1 (for a one year time lag) or 2 (for a two year time lag). For example: Warm water intrusion index 1 with a two-year time lag, is written as WI1_2. All the environmental indices were used as input into the model in such a way that the smallest (negative) index values represent the strongest upwelling conditions (cool conditions).

The rationale for using these indices in this specific way is mainly based on findings on year-class strength of Pacific hake that is influenced by variations in physical processes of the California Current system. Bailey and Francis (1985) found that weak upwelling during January and February could be linked to successful year-classes of Pacific hake. They submitted the following possible explanations for the observed relationship between temperature and survival:

1. Since cold temperatures are typically associated with periods of strong upwelling, cold years may be associated with greater advection of eggs and larvae offshore. Survival may be inhibited in the offshore environment due to reduced growth resulting from reduced prey abundance.
2. Since cold temperatures are typically associated with increased southward flow, spawning may occur further south or eggs and larvae

may be advected to the south. These processes may be detrimental to survival of Pacific hake due to reduced zooplankton abundance in the southern nursery areas or reduced juvenile habitat due to the narrowing of the shelf there.

3. Cold temperatures may result in slower growth rates, which may extend the period when larvae are most vulnerable to predation.

Off Namibia, the peak spawning period of Cape hake generally occurs from September to March. If warm water is widespread during the spawning period and the upwelling during the following May to September is reduced, the eggs spawned will be retained in favourable nursery areas and potentially strong recruitment may result. During the following year, intensified upwelling should provide enough food for the juveniles resulting in strong recruitment of the two-year-olds a year later. In Figure 6.4 mean monthly sea surface temperature images of Namibia for 1999 show the upwelling period from May to November with little or no upwelling from December to April (spawning period of hake).

6.4. Methods

For constructing the model, environmental data from 1982 to 1996 were used with hake recruitment data from 1984 to 1997.

The recruitment index as well as all the environmental indices were examined for the goodness-of-fit to the normal distribution by using the Kolmogorov-Smirnov (KS) test as described in Hennemuth *et al.* (1982). This was done since one of the assumptions for the logistic regression model is that the predictors should have normal distributions. Test results indicated that the distribution of the recruitment index as well as all but one (W13_2) of the environmental indices were not significantly different from normal. Log transformation of the data was therefore not necessary.

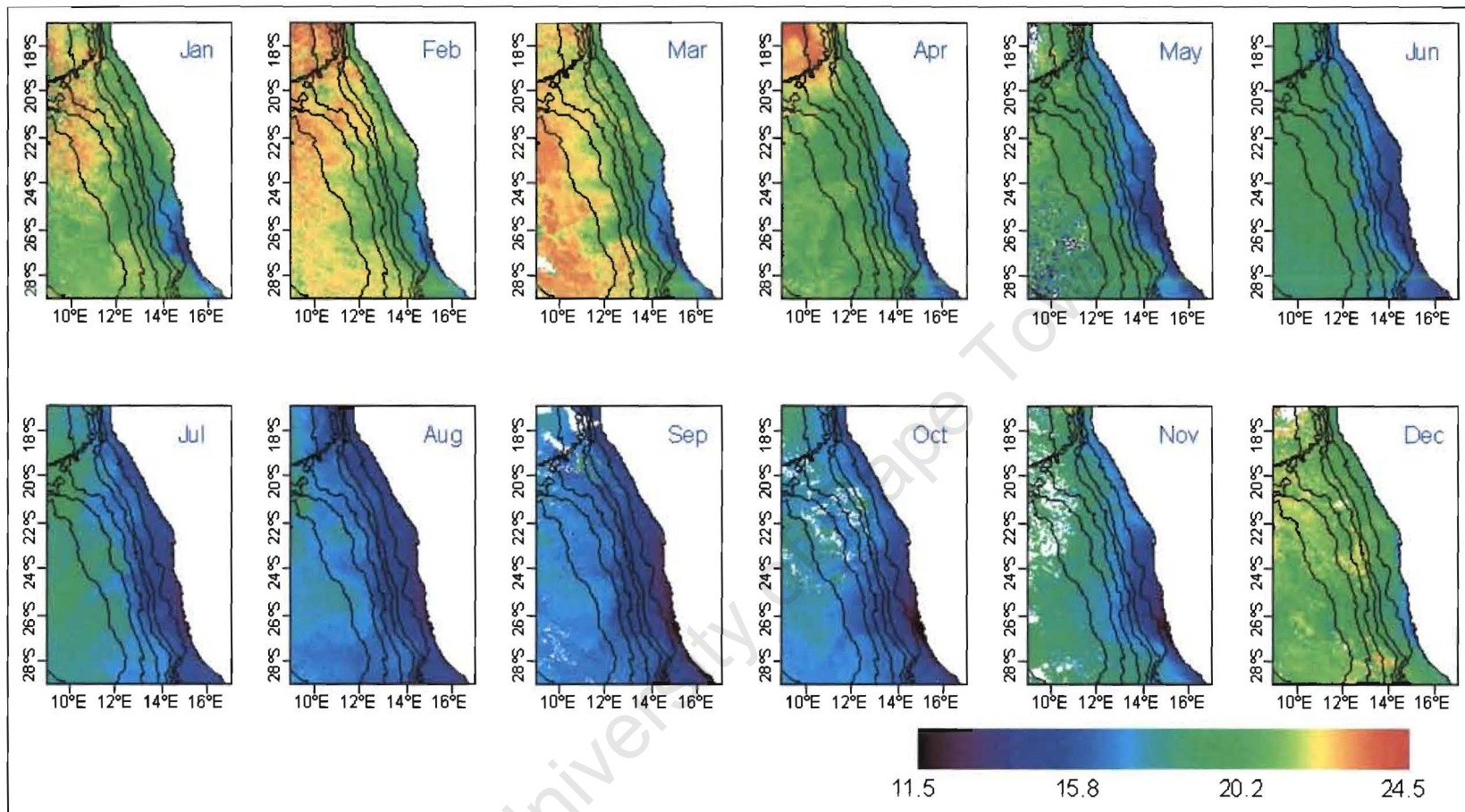


Figure 6.4. Mean monthly Sea Surface Temperature images for 1999 for 17 – 29°S; 8 - 17°E from 1.1 km resolution data. Averages for each month were calculated using 9 images with cloudiness lower than 25% (Gordoa *et al.* 2002).

Relationships were examined between the environmental variables by constructing a matrix of Pearson correlation coefficients (Zar 1999) to identify co linearity among the environmental variables. From scatter plots of recruitment and all the individual environmental variables, tests for possible linear, log linear, inverse, quadratic and cubic relationships were performed using the curve fitting procedure in SPSS.

Multinomial logistic regression (Agresti 1990), using the SPSS regression module, was applied to examine the combinations of environmental variables that most effectively explain the recruitment of Cape hake. The multinomial logistic regression examines the relationship between the categorical dependent variable and a set of predictor variables and calculates the probability of an event occurring. Strong and weak recruitments were defined as those that fell into the upper or lower quartiles respectively, and all others were defined as average. The upper 75% cut-off point was defined as 0.352 and the lower 25% point as -0.344 standardized units of recruitment. The environmental variables were entered into the model as covariates and recruitment was treated as a categorical variable.

If the baseline category is J for the i^{th} category, the model is:

$$g_i = \log \left(\frac{P_{\text{category}_i}}{P_{\text{category}_j}} \right) = B_{i0} + B_{i1}X_1 + B_{i2}X_2 + \dots + B_{ip}X_p \dots \dots \dots (6.1)$$

The probability of the event happening is calculated by:

$$P(\text{group}_i) = \frac{\exp(g_i)}{\sum_{k=1} \exp(g_k)} \dots \dots \dots (6.2)$$

The Nagelkerke pseudo R^2 is calculated as follows (SPSS Inc. 1999):

$$\tilde{R}^2 = \frac{R^2}{R^2_{MAX}}$$

$$\text{where } R^2 = 1 - \left[\frac{L(0)}{L(B)} \right]^{2/N};$$

$$\text{where } R^2_{MAX} = 1 - [L(0)]^{2/N};$$

where $L(0)$ is the likelihood for the model with only a constant;

where $L(B)$ is the likelihood for the model under consideration;

where N is the sample size

Predictions of recruitment strength were done, using the model created in the descriptions above. Environmental anomaly indices from 1996 to 2001 for UW2 and WI2 were replaced into the estimated model equation (6.1) to obtain predicted probabilities of recruitment strength for 1998 to 2002 using the logic equations.

6.5. Results

6.5.1. Exploration of the variables

Correlation analysis of the environmental variables (Table 6.1) revealed significant correlation between the following environmental variables: WI1_2 and UW1_2; UW2_1 and UW3_1; UW2_2 and UW3_2 as well as UW1_1 and UW3_2. WI2_2 and WI3_2 are not correlated with any other environmental variable. WI3_2 is not normally distributed and performed poorly in the model fits. It seems to be a poor index of warm water intrusion and has no relationship with recruitment.

Table 6.1. Comparison of correlations between environmental variables.

		1	2	3	4	5	6	7	8	9
1	WI1_2		0.48	-0.08	0.20	0.26	-0.22	0.72	0.43	0.02
2	WI2_2	ns		0.04	-0.08	0.09	0.03	0.50	0.43	0.07
3	WI3_2	ns	ns		0.11	-0.17	-0.00	0.11	-0.26	-0.07
4	UW1_1	ns	ns	ns		0.24	-0.14	0.07	-0.34	-0.64
5	UW2_1	ns	ns	ns	ns		0.55	0.32	0.21	-0.17
6	UW3_1	ns	ns	ns	ns	*		0.06	-0.11	-0.36
7	UW1_2	**	ns	ns	ns	ns	ns		0.12	-0.18
8	UW2_2	ns	ns	ns	ns	ns	ns	ns		0.63
9	UW3_2	ns	ns	ns	*	ns	ns	ns	*	

^a Not significant

* P < 0.05.

** P < 0.01.

WI2_2, is the only environmental variable showing a significant linear relationship with recruitment ($P = 0.016$; $R^2=0.393$). Scatter plots of the three variables (WI1_2, UW2_2 and UW2_1), significantly influencing recruitment in the model, are depicted in Figures 6.5 (a) – (c). None of these variables has a significant relationship with recruitment on its own, but a cubic relationship result in the highest r-squared values (Figure. 6.5).

6.5.2. Multinomial logistic regression

Three environmental indices were selected for the final model by forward selection using the likelihood-ratio statistic for deleting variables. The variables are: WI1_2, UW2_1, and UW2_2.

The test statistics for the model are as follows:

Nagelkerke R squared = 0.789

Model Chi-square = 16.387, df = 6, P = 0.012

Pearson Chi-square = 10.862, df = 20, P = 0.950

The Nagelkerke R squared value indicates that about 79% of the variation in the recruitment is explained by the regression model. The model chi-square tests the null hypothesis that the coefficients for all of the terms in the model, except the constant, are 0. In this case the null hypothesis is rejected for all the variables ($P < 0.05$). Therefore the final model is significantly better than the intercept model. The Pearson chi-square statistic is used to assess the discrepancy between observed and expected counts in a multidimensional

cross-tabulation (SPSS). Since the probability level is high ($P = 0.95$) the null hypothesis, that the model fits the data well, is accepted.

The logit equations can be written as follows, using fomula (6.1).

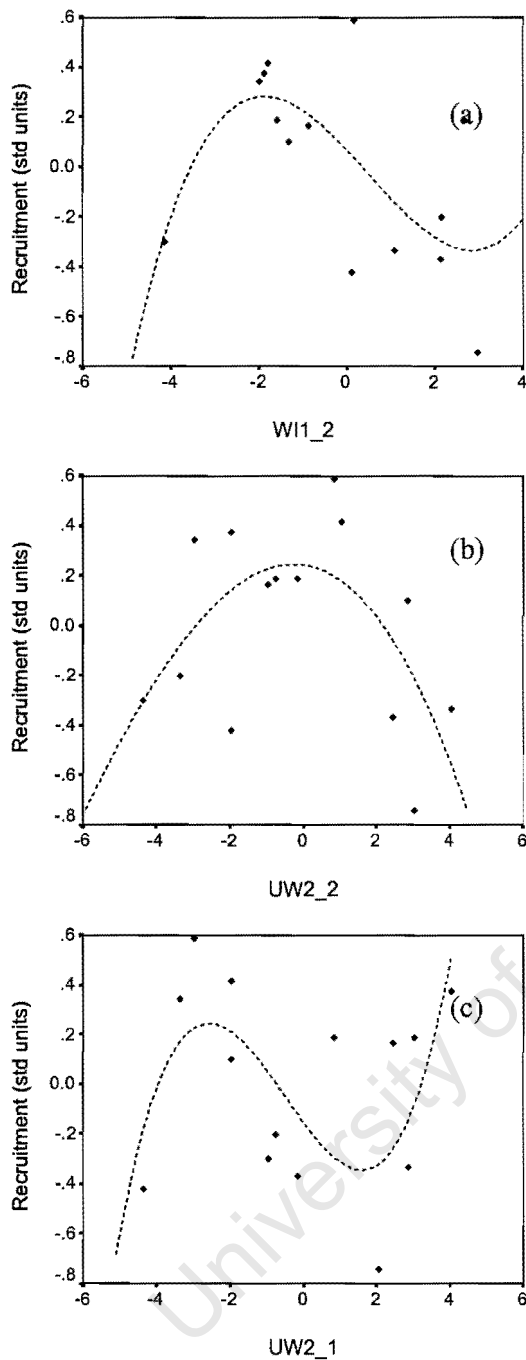
$$g_1 = \log\left(\frac{P(\text{strong})}{P(\text{average})}\right) = -0.815 - 0.241 (W11_2) + 0.005(UW2_2) - 0.278(UW2_1)$$

$$g_2 = \log\left(\frac{P(\text{weak})}{P(\text{average})}\right) = -284.303 + 131.948(W11_2) + 22.940(UW2_2) - 76.604(UW2_1)$$

$$g_3 = 0$$

The probability of the event happening is calculated using formula (6.2). Scatter plots of the calculated probability of recruitment being the same as the observed recruitment (events), as calculated from the model, can be seen in Figure 6.6. If the estimated probability of the event is less than 0.5, the prediction is that the event will not occur. If the probability is greater than 0.5, the prediction is that the event will occur.

The results from the logistic regression analysis indicated that strong and average recruitment can be correctly classified 50% and 71.4% of the time respectively, and weak recruitment 100% of the time. This gives an overall correct classification of recruitment for ten out of the fourteen years of data used in the model (71.4%).



Figures 6.5 (a), (b) and (c). Scatter plots of recruitment versus warm intrusion index one (W11_2) (a), upwelling intensity index two with a one-year time lag (UW2_1) (b) and with a two-year time lag (UW2_2) (c). The dotted line indicates the most likely (not significant) relationship between the two variables.

Having developed the model using SST data from 1982 to 1996, the same model was rerun using SST data from 1996 to 2001 to forecast recruitment from 1998 to 2002. From the prediction of recruitment strength with five years of data not included in the model, four of the five years were correctly predicted (80% success). From the five years of data available, four years

were classified as strong recruitment and one as average (Figure 6.6). Predicted probabilities of 0.5 and higher are regarded as correctly predicted.

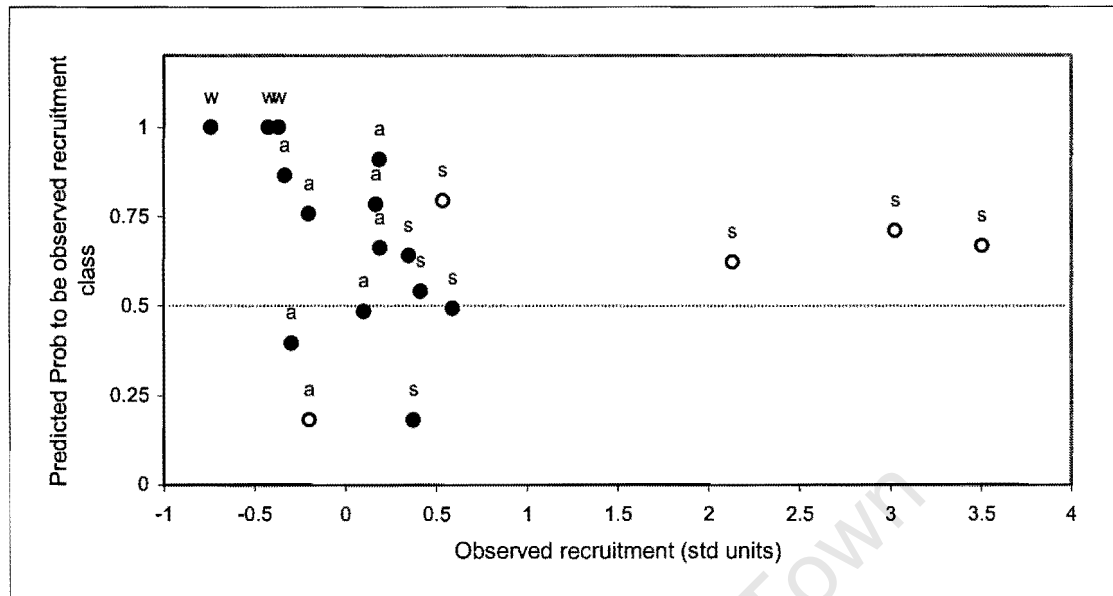


Figure 6.6. Scatter plot of the calculated probability of recruitment being the same as the observed recruitment. The data labels indicate the observed strength of recruitment: s = strong; a = average; w = weak. Data not included in model development: (o).

6.6. Discussion

The environmental indices used in this study were chosen because of their possible influence on the survival of eggs, larvae and young (one-year-old) fish as described in the introduction. From the six environmental anomaly indices that were used, four were left out of the final model by stepwise regression. The two indices that resulted in a model explaining 78,9% of the variability in recruitment of hake, are Upwelling Index 2 (UW2) and Warm Water Intrusion Index 1 (WI1).

All upwelling indices were for the period from May to September. Upwelling index 1 (UW1) was compiled for the area from 20 to 24°S by calculating the anomaly from mean monthly SST per month for each one-degree latitude. Indices UW2 and UW3 were calculated over the areas 17 to 29°S and 17 to 21°S respectively. For both, the anomalies were calculated by using 4.5 km

grid square data. For each latitudinal line, all SST values were subtracted from the furthest offshore value. This technique is used to minimize the effect of solar radiation and other seasonal variability that causes changes in SST that are not related to upwelling. The anomaly of the percentage area with values above 3°C was then calculated. In this study it was arbitrarily decided to use only grid squares with at least 3°C differences as an indication of upwelling.

Indices UW1 and UW3 were left out of the model by stepwise regression. Index UW1 is limited to the area from 20 to 24°S and is a rough indicator of upwelling strength since it is calculated from the mean SST per month for each one-degree latitude. Although the area 20 to 24°S defines the area of main occurrence of hake larvae, it does not appear to adequately measure upwelling activity, which occurs over a much wider area. Index UW3 was also excluded from the final model. Although the method of estimating the upwelling anomaly for indices UW2 and UW3 are the same (using 4.5 km resolution data) the area covered by index UW3 was only between 17 and 21°S. Index UW2 that showed significant relationship with recruitment covered the area from 17 to 29°S. It seems that the upwelling index calculated with fine resolution data and with data from the whole Namibian area has the most significant relationship with hake recruitment.

Three indices of warm water intrusion were also compiled for possible use in the model. Warm water intrusion index 1 (WI1) was calculated as the anomaly of the latitudinal position of the 17°C isotherm close to the shore (up to 72 km offshore) for the period from January to March. This is the main spawning period of hake. The position of the 17°C isotherm was defined by Strogalev (1983) as an indicator of the strength of the warm water intrusion from Angola. Index WI2 was calculated in the same way as upwelling indices UW2 and UW3, only for the period from January to April and from 17 to 21°S in order to measure the "lack of upwelling" and interpret it as warm water intrusion from offshore. Warm water index WI3 was constructed by calculating the anomaly of the distance offshore of the 17°C isotherm at the 21°S latitude for the period December to April.

Index WI1 is the only warm intrusion index that has a significant relationship with recruitment. Index WI2 is probably not a good index of warm water intrusion since it is calculated using the furthest value offshore. The warm intrusion effect is closer to the shore. Index WI3 has also no significant influence on recruitment probably due to the fact that the offshore position of the 17°C isotherm at 21°S is not a good indicator of warm water intrusion from offshore. For this study only index WI1 was used in the final model as the indicator of the warm water intrusion from the north during and shortly after the main spawning season of hake.

The quadratic relationship (not significant) between recruitment and the intensity of warm water intrusion from the north (WI1) suggests that recruitment strength is influenced by an optimum amount of warm water intrusion (Figure 6.5(a)). The strongest recruitment occurs in a narrow window of WI1_2 between index units of -2 and 0, the weakest when the warm intrusion is at its strongest (about 3). The relationship between recruitment strength and the upwelling intensity in May to September (directly after spawning) also has the form of a cubic relationship with an optimum for UW2_2 (between -3 and 1) associated with the highest recruitment (Figure 6.5 (b)). The weakest recruitment occurs at UW2_2 of about +3 (reduced upwelling). The relationship of upwelling intensity during May to September the year after spawning (UW2_1) is not as clearly defined as for the other two indices. However, strongest recruitment usually occurs when the upwelling intensity is high (around -3) and the weakest recruitment occurs when upwelling is reduced (around +2).

From the individual relationships of the three variables (WI1_2, UW2_2, UW2_1) with recruitment strength it is inferred that there is an optimum window for good recruitment when there is warm water intrusion during spawning. If the warm intrusion is too strong or too weak, strong recruitment does not occur. The same applies for the upwelling intensity just after spawning. The optimum window for upwelling is broader than for the warm water intrusion, but if the upwelling is too strong or too weak, strong recruitment does not occur. It is, however, the combined effect of these three

environmental variables that influences recruitment strength to a large extent. The balance between the three environmental indices seems critical since in the 14 years of data used in developing the model, four years of strong recruitment were observed, with only three years of weak recruitment.

The results of this study show that relative recruitment (two-year-olds) strength is related to the intensity of warm water intrusion from the north during and shortly after spawning (January to April) and to the upwelling intensity (May to September) measured from 17 to 29°S for the same year and the following year. This is in agreement with the results from a similar study by Hollowed and Bailey (1989) on Pacific hake, who concluded that relative year-class strength is determined at the larval and early juvenile stages. The main spawning period of Cape hake is adjusted to the seasonal pattern of Namibian upwelling in a way that matches the optimal conditions found for the survival of Pacific hake: periods of weak offshore transport followed by periods of increased upwelling. However, from the results presented here, the year class strength of Cape hake depends on the magnitude of both down- and upwelling events, which varies between years. Years of good recruitment were observed when the down-welling period is moderate to quiescent and it is immediately followed by an upwelling period of normal extent. I can generalize that extreme values during either the down-welling or the upwelling periods operate negatively on the survival of Cape hake larvae.

Figure 6.7 shows the observed recruitment strength each year (standardized for each survey series) and the predicted recruitment category (-1, 0 and +1) for each year. Observed recruitment values that were not used in developing the logistic model (1998-2002) are highlighted. The model is remarkably successful in predicting broad categories of recruitment. The result of greatest importance is the power of the model for predicting the worst years of recruitment ($p=1$) (i.e. 3 ex 3 events over 19 years), which should make it possible to anticipate the most dangerous situations for the hake stock and to adjust management measures accordingly. The predictive power of the

model as tested with five years of data not included in the model shows encouraging results with four out of five of the years correctly predicted.

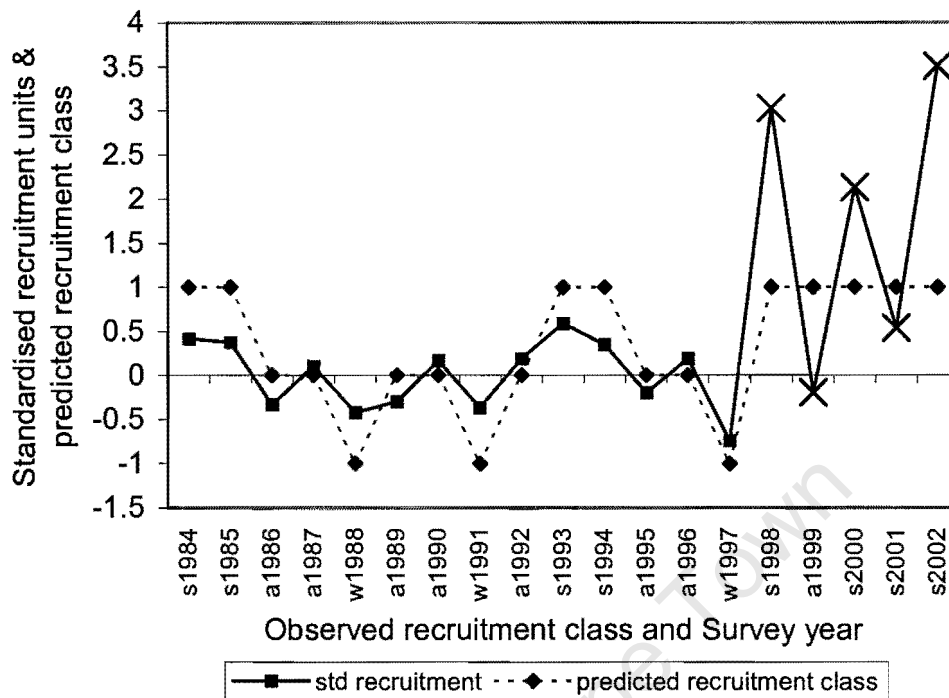


Figure 6.7. Standardized recruitment units and the predicted recruitment class. The data marked X were not included in model development. Predicted recruitment classes are scaled: 1 = strong, 0 = average, -1 = weak (see text for definitions).

6.7. Conclusion

Logistic regression is an excellent tool to use for estimating the probability of categorized recruitment. The availability of good SST data from satellite, make it possible to prepare environmental indices which represent certain oceanic processes that are detrimental to recruitment success of many fish species. By using this model, the probability of the strength of recruitment was correctly predicted ($P > 0.5$) for ten out of fourteen years (71%) for the data included in the model and a further forecast of recruitment was above 0.5 for four of five years (80%) outside the model (Figure 6.6). It should, however, be taken into account that the time series used in this analysis is relatively short. It seems that the predictive power of the model for weak recruitment is

better than for average and strong recruitment since all of the observed weak recruitment events were also correctly predicted ($p = 1$). Furthermore, additional factors affecting strong recruitment may not have been included in the present model. It may be useful to managers to have an indication of a weak recruitment event one year in advance in order to be cautious when TAC's are allocated and to implement special regulations to protect the few recruits in such years.

This study may be further expanded by estimating the proportion of two-year-olds are represented in commercial catches, using the size information from the commercial catches, in cohort analysis. The extent to which commercial data can be used as an index of recruitment could then be assessed. Size frequency data from the commercial fleet have only been available since 1997.

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CHAPTER SEVEN

DISCUSSION AND CONCLUSION

7.1. Discussion

The overall goal of this dissertation is to analyze some of the assumptions used for management of the Namibian fishery for Cape hake (*Merluccius capensis*). In chapter 1, several hypotheses were put forward concerning the dynamics of the fishing fleet, the use of catch-per-unit effort (CPUE) as an index of abundance, the relationship between research survey data and fishing fleet data, and seasonal variability in hake density estimates due to seasonal and inter-annual environmental changes, culminating in how oceanographic processes may influence hake recruitment and be used to forecast recruitment strength. In the following discussion I will summarize how these objectives have been met.

7.1.1. The influence of fleet dynamics on CPUE

Commercial Catch per Unit Effort (CPUE) is used in age-structured production models for assessing the state of the Namibian Cape hake stock for making recommendations on management measures such as the Total Allowable Catch (TAC). Understanding the influence of fleet dynamics on CPUE on an intra- and inter-annual basis is thus very important, since the commercial CPUE is used as an annual index of abundance in the assessment.

The standard measures of CPUE (e.g. simple averages) can be affected by changes in fleet behaviour, which interact with factors related to abundance. Further complications arise in the use of these standard measures when the factors interact among themselves and in particular when there is an interaction with year. Factors critical to the interpretation of Namibian hake catch statistics include year, month, vessel size (GRT), and area. The full stepwise regression model is highly significant and accounts for about 51% of variation in CPUE, with vessel size, year and area contributing 27%, 9.5% and

6.9%, respectively. The interactions of area with month and year explain the least about CPUE of all the factors included in the model.

From the generalized linear modelling analysis in Chapter 2, the observed shift in effort by month, coupled with the significance of month, area and GRT as factors in the regression analysis, indicate that changes in fleet distribution will influence conventional CPUE estimates on a seasonal basis. The significance of the year-month (8% of variability), year-area (1.4% of variability), month-area (2.4% of variability) and year-GRT (6.1% of variability) interaction terms indicates that the nature of these effects must be addressed if the CPUE is to be properly used as an index of annual abundance. The scenario, in which both the fish and the fishers have changed in their distribution over time, seems likely to have occurred. Both the fish and fishers redistributed over month and area and in addition to that, the fishing power of the vessels has changed over the years.

7.1.2 Fleet dynamics and the Ideal Free Distribution

A more thorough investigation of the movement dynamics of the fishing fleet was conducted in order to better understand the dynamics of the interaction between catch and fishing effort. In this analysis the differences in competitive abilities among vessels with different GRT's, were corrected by recalculating the CPUE after applying the year and GRT factors and the interaction of year and GRT, from the GLM analysis, to adjust the effort. No interference competition could be proved among vessels fishing in the same area. Since there is no evidence for interference competition among vessels, the catchability coefficient (q) is unlikely to be influenced. Furthermore catch rates were equalized among areas. This equalization may be a result of the limited carrying capacity of the fleet.

Although it was seen that the effort is not distributed evenly over the whole area, almost 75% of the area is covered each year. Therefore it is assumed that the vessels can move freely between fishing grounds if they want to and thus meet the assumption of the IFD of free movement without restriction.

7.1.3. Comparison of survey and commercial densities

Hake biomass estimates from research surveys are used as another annual index of abundance in age structured production assessment models used to manage the Namibian hake fishery. Density estimates from research surveys and commercial vessels are compared in order to determine to what extent the density estimates from the commercial fishery can be used to augment the survey estimates before being applied as an annual index of abundance in the model.

The results indicate that data collected from research cruises and the commercial fishery are similar, especially in the south. The commercial data, however, do not cover the whole distribution area of hake, because of the ban on trawling inside 200m depths. For the study period, estimates of relative abundance derived from logbook data closely resemble those from MFMR trawl survey data for the overlapping areas between 200 – 600 m contours. It follows then, that commercial fishery logbook data may be used to evaluate and augment research data and narrow the confidence limits of hake abundance estimates.

From this study it can be seen that there are definite seasonal and inter-annual changes in catchability of hake, which are not directly the result of changes in fish abundance. Since horizontal migrations like in the Argentina hake stock could not be detected from the data, the changes in catchability could be due to either vertical movement of hake or dispersion on the bottom. Further studies are needed to understand the reason for the changes in catchability of hake. It is recommended that research surveys should not be conducted in the first quarter when variability is greatest but in the second quarter when it is least. The information about the inter-and intra annual variability in availability of hake can be used in tuning models and to identify the degree of risk and uncertainty in the age-structured production model that is used.

7.1.4. The relationship of hake availability and recruitment to sea surface temperature

To try to understand what causes the variability in catchability mentioned above, I investigated the relationship of the seasonality in Sea Surface Temperature (SST) to the monthly variability in the availability of hake. The catchability of Namibian hake shows a strongly seasonal pattern, which correlates with seasonality in SST and its anomalies. Nevertheless, no change has been detected in the horizontal spatial distribution (i.e. migration process) that could explain the seasonal cycle in hake catchability. Neither can it be explained by changes in the spatial fishing behaviour because no spatial correlation was found between CPUE and fishing effort. The findings show that the maximum inter-annual variability in SST takes place during summer and provides an oceanographic basis for understanding changes in hake distribution, which may be predicted by monitoring a few selected oceanographic parameters as shown in this study with the SST and its spatial and temporal anomalies.

Environmental indices based on satellite-derived SST measurements were used to predict the abundance of two-year-old hake and thus to predict the strength of recruitment. The environmental indices used in this study were chosen because of their possible influences on the survival of eggs, larvae and young (one-year-old) fish, through physical and oceanographic processes.

From the six environmental anomaly indices that were used, four were left out of the final model by stepwise regression. Warm water intrusion index 1 (WI1) is the only warm intrusion index that has a significant relationship with recruitment and measures the strength of warm water intrusion from the north up to 72km offshore from January to March. Warm water intrusion index 2 (WI2) is probably not a good index of warm water intrusion since it is calculated up to the furthest value offshore while the warm intrusion effect is closer to the shore. Warm index 3 (WI3) has also no significant influence on recruitment probably due to the fact that the offshore position of the 17°C isotherm at 21°S is not a good indicator of warm water intrusion from offshore.

For this study only WI1 is used in the final model as the indicator of the warm water intrusion from the north during and shortly after the main spawning season of hake.

Upwelling indices 1 and 3 were left of the model by stepwise regression. Upwelling index one (UW1) is restricted to the area from 20 to 24°S and is a rough indicator of the upwelling strength since it is calculated from the mean SST per month for each one-degree latitude. Although the area 20 to 24°S defines the area of main occurrence of hake larvae, it does not seem to measure the upwelling activity, which occurs over a much wider area. Upwelling index 3 was also excluded from the final model. Although the methods of estimating the upwelling anomaly for upwelling indices 2 and 3 are the same (using 4.5 km resolution data) the area covered by upwelling index 3 is only between 17 and 21°S. Upwelling index 2 that showed significant relationship with recruitment covered the area from 17 to 29°S. It seems that the upwelling index calculated with fine resolution data and with data from the whole Namibian area has the most significant relationship with hake recruitment.

The two indices that resulted in a model explaining 78,9% of the variability in recruitment of hake, are UW2 and WI1. From the individual relationships of the warm water intrusion index with recruitment strength it is inferred that there is an Optimal Environmental Window (OEW) of warm water intrusion during the spawning period for good recruitment. If the warm intrusion is too strong or too weak, strong recruitment does not occur. The same applies for the upwelling intensity just after the main spawning period. The OEW for upwelling intensity is broader than for the warm water intrusion, but if the upwelling is too strong or too weak, strong recruitment does not occur. It is, however, the combined effect of these two environmental variables that to a large extent allows prediction of recruitment strength.

The results of this study show that relative recruitment (two-year-olds) strength is related to the intensity of warm water intrusion from the north during and shortly after spawning (January to April) and to the upwelling

intensity (May to September) measured from 17 to 29°S for the same year and the following year. This is in agreement with the results from a similar study by Hollowed and Bailey (1989) on Pacific hake, who concluded that relative year-class strength is determined at the larval and early juvenile stages. The main spawning period of Cape hake is adjusted to the seasonal pattern of Namibian upwelling in a way that matches the optimal conditions found for the survival of Pacific hake: periods of weak offshore transport followed by periods of increased upwelling. However, from the results presented here, the year class strength of Cape hake depends on the magnitude of both down- and upwelling events, which varies between years. Years of good recruitment were observed when the down welling period is moderate to quiescent and it is immediately followed by an upwelling period of normal extent. I can generalize that extreme values during either the down welling or the upwelling periods operate negatively on the survival of Cape hake larvae.

7.2. Conclusion

In the Namibian commercial hake fishery there are factors other than overall abundance that affect CPUE and interactions exist among these factors. The changes in the fleet composition by regulations, the change in fishing power of vessels and the monthly changes in hake availability from year to year have been shown to be the major factors influencing the annual CPUE estimates.

To address these dynamic changes and their influence on CPUE as an index of abundance, regression analysis should be used to estimate annual stock trends in order to take account of the major factors that have an influence on CPUE. The main implication of the catch rates being equalised among areas is that the changes in CPUE values do not reflect trends in abundance within the stock, but the number of vessels present in an area reflects more the actual abundance.

The size of the Namibian hake fleet was reduced in 1994 and the effort now expended by the fleet seems to be at a favourable level so that there is very little or no interference among the vessels. If the fleet size changes in future, the effect on competition among vessels should be monitored and the possible influence on catchability (q) and the resulting breakdown of the relationship between CPUE and abundance should be kept in mind at the decadal time scale.

From the analysis of hake density estimates from research surveys and commercial data, it is apparent that commercial fishery logbook data provide a comprehensive source of information because of the broad temporal and spatial fishing patterns of the fleet and the large amount of data provided. Due to inter-annual and seasonal variability in catchability of hake, the research survey estimates have been shown to have limitations as an annual index of abundance. The commercial density estimates will be especially useful during years with seasonal temperature anomalies when the hake variability increases remarkably during the first quarter. The density estimates from commercial data throughout the year can then be used to adjust the survey estimates or to identify the degree of risk and uncertainty of the survey results. Since the commercial fishery samples every month of every year and at many thousand sites, logbook data may provide information to help identify sampling error, increase sample size and also fill spatial and temporal gaps in research data. However, proper collection, preparation, and analysis of logbook data are essential to maximize the usefulness of the information. Catchability (q) should be studied periodically to ensure that CPUE estimates are comparable from decade to decade. A multiplicative model, such as the ones used by Gavaris (1980), Kimura (1981) or Large (1992) may then be used to account for variability associated with differences in gear. In this study it is clearly shown that catchability of hake has high seasonal and inter-annual variability in an ecosystem with similarly large seasonal and inter-annual variability as shown in SST images.

Walters and Maguire (1996) advise investment in survey indices of abundance trends needed for proper stock assessment. They highlight the

difficulty of designing these surveys in situations where the spatial distribution of fish changes rapidly and/or is highly variable from year to year. These results highlight the usefulness of information derived from commercial logbooks and specifically the fact that they can be very useful for improving the design of surveys and are of great help in fisheries management.

Furthermore, it has been shown that the year class strength of Cape hake depends on the magnitudes of both down- and upwelling events, which vary between years. Years of good recruitment were observed when the down-welling period is moderate to quiescent and it is immediately followed by an upwelling period of average extent. I can generalize that extreme values either during the down welling or during the upwelling periods operate negatively on the survival of Cape hake larvae. The result of greatest importance is the power of the model for predicting the worst years of recruitment ($p=1$) (i.e. 3 ex 3 events over 14 years), which will make it possible to anticipate the most dangerous situations in the hake stock and to adjust management policy accordingly using satellite-derived indices of upwelling, down-welling and intrusion of the Angola-Benguela front. The predictive power of the model as tested with five years of data not included in the model development shows encouraging results with four out of five of the years predicted correctly.

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APPENDICES

University of Cape Town

Appendix 4.1. Results of the stepwise general linear regression for each quarter and for the whole year for the different areas.

North (R-squared = 0.391)

Factor	SS	df	Mean Square	F	P
Intercept	2161.80	1	2161.80	10584.59	0.000
Year	66.37	7	9.48	46.42	0.000
Quarter	8.31	4	2.07	10.17	<0.000
Year * Quarter	14.81	22	0.67	3.29	<0.000

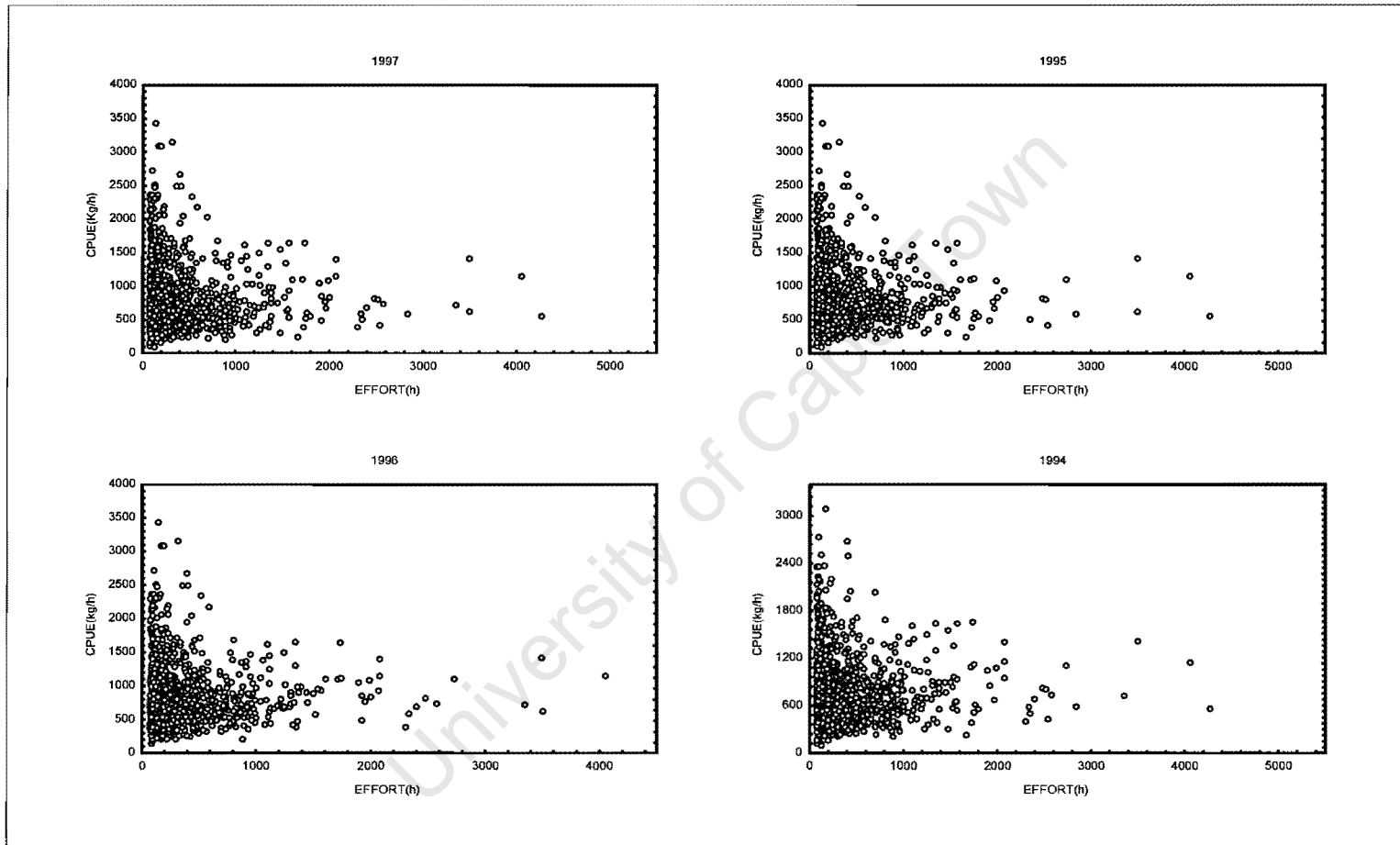
Central (R-squared = 0.204)

Factor	SS	df	Mean Square	F	P
Intercept	1930.68	1	1930.68	6563.00	0.000
Year	46.13	7	6.59	22.40	0.000
Quarter	6.93	4	1.73	5.89	<0.000
Year * Quarter	35.10	26	1.35	4.58	<0.000

South (R-squared = 0.212)

Factor	SS	df	Mean Square	F	P
Intercept	5870.64	1	5870.64	22544.22	0.000
Year	155.74	7	22.24	85.44	0.000
Quarter	13.18	4	3.29	12.65	<0.000
Year * Quarter	105.13	25	4.20	16.14	0.000

Appendix 5.1. Relationship between the standardised CPUE and standardised effort per stratum (1 degree of latitude per 50 m of depth) for each year.



Appendix 5.2. Monthly standardised CPUE per 100 m depth for each year.

