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**ASSESSMENT OF AND MANAGEMENT  
PROCEDURES FOR THE HAKE STOCKS  
OFF SOUTHERN AFRICA**

by

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## Abstract

The hake fishery off southern Africa is a highly valuable and important fishery in terms of both revenue and local employment. This thesis considers the current assessment and management of the Cape hake stocks. It commences with a brief review of the biology of the Cape hakes and the history of the fishery and the management of the resource.

The data available for the assessments are described, giving some details as to how they are collected and analysed. Three models commonly used for fish stock assessment purposes (Biomass Dynamic Models, Virtual Population Analysis and Age-Structured Production Models) are briefly reviewed. An age-structure production model (ASPM), fitted on a maximum likelihood basis, is used to provide an assessment of the southern African hake resource, with reasons for using this model in preference to others being given.

Currently, the management framework separates the resource into three areas: Namibia and South African west and south coasts. Although the resource comprises two species, *Merluccius capensis*, the shallow-water Cape hake, and *M. paradoxus*, the deep-water Cape hake, the Namibian and South African west coast stocks are still modelled as a single species. On the South African south coast however, due to the development of a longlining fishery, which targets principally *M. capensis*, the two species are distinguished in the assessments. It is believed that *M. paradoxus* off the west and south coasts of South Africa form a single stock and this resource is therefore assessed as such.

The Namibian hake stock is estimated to be at about 40% (CV=0.39) in 2001 of its pre-exploitation level in terms of the spawning biomass. Although the best estimate for the 2001 spawning biomass is slightly above that of the early 1990's, the possibility that there has been a net decline in the resource over the last decade cannot be excluded. This resource is estimated to be able to yield a maximum of 300 thousand tons (CV=0.25) per annum, at a spawning biomass level of 46% (CV=0.04) of the pre-exploitation level.

After the heavy exploitation of the 1960's and 1970's, there has been a steady though slow recovery in the South African west coast hake resource. The 2001 spawning biomass is estimated to be at 22% (CV=0.18) of its pre-exploitation level. This is still below the level producing the estimated MSY of 129 thousand tons (CV=0.03). The current status of the resource and MSY values are estimated much more precisely than in the case of the Namibian stock, as a steady increase over the past two decades means that this is not the 'one-way trip scenario' (Hilborn, 1979) reflected by the Namibian case.

The South African south coast *M. capensis* component of the resource is estimated to be currently well above its MSY level. Since the mid-1980's, the stock has remained fairly stable, at around 50% of its pre-exploitation biomass. MSY is estimated to be about 33 thousand tons (CV=0.10).

The South African *M. paradoxus* resource (south and west coasts combined) shows a very similar pattern to that of the west coast hake resource as a whole, with a slow recovery since the mid 1970's. The recovery is estimated to be greater when the fishing selectivity (for both the commercial sector and the research surveys) is assumed to be flat for older ages. However, a decrease in selectivity (selectivity slope of  $0.2 \text{ yr}^{-1}$ ) at older ages provides the best fit of the model to the data in terms of the likelihood. In this case, the spawning biomass in 1999 is estimated to be at 17% (CV=0.15), which is below the estimated MSYL of 26% (CV=0.02), of its pre-exploitation level.

The question of how successfully sustainable utilisation and resource recovery has been achieved since management restrictions were first imposed in the mid-1970's is addressed. Although there has indeed been some recovery – to a greater extent for the stocks off South Africa – the historical record indicates over-optimistic appraisals of likely recovery rates and sustainable yield levels over this period, and some of the reasons for this are discussed. Certain key assessment questions remain: why is recruitment variability estimated to be so low, natural mortality so high, and why do estimates of stock-recruitment steepness, survey selectivity-at-age and bias in swept-area survey estimates differ so greatly between the stocks?

An overview of the Operational Management Procedure (OMP) approach to fisheries management is given. Since 1997, the Namibian hake stock has been managed using a simple OMP. This OMP did not have a specific longer-term target (such as getting the resource to MSYL) and was tested over a limited range of operating model of the possible underlying resource dynamics. A revised OMP for this resource is developed. The anticipated performance, in terms of catch and risk of resource depletion, of a number of candidate OMPs is evaluated. The OMPs are based on generalisations of a constant proportion harvesting strategy coupled to an ASPM of the same form as the operating model used to describe the underlying resource dynamics. Candidate procedures are then tested for robustness on a set of alternative operating models. The baseline procedure appears reasonably robust over the fairly wide range of robustness test scenarios considered, except that unnecessary catch reductions can take place if carrying capacity has decreased, and a possible decrease in biomass can occur when the selectivity is forced to decrease for older ages in the operating model. Of a number of variants of this baseline procedure considered, notable differences in anticipated performance are evident only for a parameter  $\beta$  of the catch control law which controls the rate of increase of TAC with abundance: higher  $\beta$  leads to more substantial resource growth, but also to lesser catches and greater interannual variability in catches. From discussions with NatMIRC scientists

and representatives of the Namibian hake industry a new OMP was recommended from the candidates evaluated and subsequently used to recommend the hake TAC for 2002.

The current OMP used for the management of the west coast hake resource (species combined) has been in place since 1998. It is based on an  $f_{0.075}$  harvesting strategy coupled to a Fox production model (Geromont and Glazer, 1998). On the south coast, an OMP for the *M. capensis* component of the resource has been used for TAC recommendations since 2000. It is of the same form as the one used for the west coast, based on a Fox-form age-aggregated production model, but incorporating a  $f_{0.3}$  harvesting strategy (Geromont and Glazer, 2000). These OMPs are described and the calculations for the 2003 TAC recommendations in terms of these procedures are reported.

An OMP for *M. paradoxus* on the south coast was not developed at the same time as that for the south coast *M. capensis* stock because a separate assessment for this component of the resource did not yield sensible results, given that this stock is likely a component of the west coast *M. paradoxus* stock (Geromont and Butterworth, 1999a). Based on the assessments summarised above, it is suggested that the longer-term replacement yield values estimated from the *M. paradoxus* assessment (between 20 and 28 thousand tons) be used to provide guidance on the extent that the west coast OMP output for the TAC be increased to take account of *M. paradoxus* on the south coast as an interim measure until separate OMPs for the two hake species have been implemented.

Planned future initiatives towards refining the assessment and management of the Cape hakes are summarised. These include moving towards species and possibly sex disaggregated assessments and management of *M. capensis* and *M. paradoxus*, fitting population models to length, rather than age distribution data, using Bayesian approach to estimate assessment precision and allowing for interchange between stocks. Future assessments need to allow for time-series modelling of selectivity-at-age, incorporate temporal changes in somatic growth and possibly include additional CPUE information (such as catch rates from the inshore trawl fishery on the South African south coast). Multi-species models also need to be developed, in particular to include the effects of cannibalism and inter-species predation. Furthermore, future research needs to resolve the issue of why the estimated survey multiplicative bias coefficients are so different on the west and south coasts. Consideration needs to be given to the possible incorporation of socio-economic factors and age data in the development of future management procedures, as well as giving recent data a greater weight in deriving management recommendations.

## Overview of thesis

This thesis is comprised of two sections, preceded by a summary of the biology of the Cape hakes and the history of the hake fishery in southern Africa (Chapter 1). Section I deals with the stock assessments of the Cape hakes, while Section II describes the management of this resource. The thesis ends with Chapter 13, which describes the future work that needs to be carried out in the next 3 to 5 years.

### Section I: Stock assessment

Chapter 2 describes the data available to assess the hake stocks off southern Africa in broad terms, giving some details as to how they are collected and analysed.

Chapter 3 considers three models commonly used for fish stock assessment purposes (Biomass Dynamic Models, Virtual Population Analysis and Age-Structured Production Models) and explains why an Age-Structured Production model was chosen to describe the dynamics of the hake stocks. The details of this model are then given in Chapter 4.

Chapters 5 to 8 report on the assessments of the Cape hakes. Three stocks (each comprising of two hake species) have historically been distinguished: off Namibia and off South Africa's south and west coasts. In this thesis (for historical reasons which are detailed in Chapter 1), four components of the southern African hake resource are assessed: Namibian hake (species combined) in Chapter 5, South African west coast hake (species combined) in Chapter 6, South African south coast shallow-water Cape hake (in Chapter 7) and South African deep-water Cape hake (west and south coasts combined) (in Chapter 8). Each of these Chapters describes in detail the data used, the assumptions made for the Reference Case assessment and the results.

Chapter 9 provides a more general discussion on the results from the stock assessments of the previous Chapters. In the cases of the Namibian and South African west coast, the extent of resource recoveries from the heavy exploitation of the 1960's and early 1970's is discussed and compared to previous assessments. Estimated values for some of the model parameters seem unrealistic, and raise some questions about the assessments.

### Section II: Management

Chapter 10 provides some background information on the 'Operational Management Procedure' or 'OMP' approach which is used to manage the hake stocks off southern Africa. A new

OMP is developed and tested for the Namibian hake stock in Chapter 11. Chapter 12 describes the current procedures used to manage the South African hake stocks. The calculations for the 2003 TAC recommendations for the South African stocks in terms of these procedures are reported.

University of Cape Town



# 1 Biological and historical background

## 1.1 Review of the biology of hake

### 1.1.1 Species and stock structure

Three species of hake inhabit the waters off southern Africa: the shallow-water Cape hake (*Merluccius capensis*), the deep-water Cape hake (*Merluccius paradoxus*) and the Benguela hake (*Merluccius polli*). The last species is mainly caught off Angola with negligible catches off northern Namibia and will therefore not be considered further in this thesis, which focuses on the Namibian and South African hake fisheries. The shallow-water Cape hake and the deep-water Cape hake are known collectively as the Cape hakes. *M. paradoxus* was originally regarded as a sub-species of *M. capensis*, but the two are now recognised as full species (Franca, 1962). Aspects of the general taxonomy, anatomy, biology and distribution of adult Cape hakes have been reviewed in detail by Botha (1980), Payne and Punt (1995) and Gordoa *et al.* (1995).

Maps of the distribution and density of the three species of southern African hake are given in Fig. 1.1. *M. capensis* is distributed between about 16°S lat. on the west coast of Africa to about 31°E long. on the south coast (Payne, 1989). It is widespread over the entire continental shelf and is the dominant of the two hake species off Namibia. This species also dominates the catches of hake made on the Agulhas Bank, to as much as 70% (Payne, 1986). *M. paradoxus* has a more restricted geographic distribution than *M. capensis*, between 17°S lat. on the west coast to about 27°E long. on the south coast (Payne, 1989). The deep-water Cape hake is dominant off the west coast of South Africa, contributing as much as 90% by number to past commercial landings of hake in this region (Botha, 1985). Payne (1989) suggests that the differing abundances of the two species of hake off different parts of southern Africa may be related to the width of the continental shelf and the relative steepness of the adjacent continental slope. Possibly the temperature at the depths preferred by each species is also a factor contributing to the differing abundance.

Fig. 1.1 also shows the management Divisions adopted by the International Commission for South-East Atlantic Fisheries (ICSEAF). During the period of involvement of ICSEAF in the management of the hake fisheries (1975 to 1990), the Cape hake resource was divided into four separate stocks, viz. Divisions 1.3 + 1.4, 1.5, 1.6 and 2.1 + 2.2. In recent years the stocks have been

redefined as three, namely the Namibian stock (similar to the old 1.3, 1.4 and 1.5 Divisions), the South African west coast stock (previously Division 1.6) and the South African south coast stock (previously Divisions 2.1 + 2.2). Rather than using the 30°S line (the actual boundary between ICSEAF Divisions 1.5 and 1.6), the division between the Namibian and the South African west coast stock is now taken as the political boundary between the two countries (i.e., perpendicular to the coastline at the boundary; line (a) in Fig. 1.1), since catches are declared by country. The boundary between the west and south coasts has subsequently also been changed to one parallel to that more northern political boundary; it is shown as line (b) in Fig. 1.1. Catches continue to be declared by ICSEAF Divisions, but the diagonal lines (a) and (b) instead of the conventional ICSEAF boundaries are used to define the Division from which catches are taken.

The shallow-water Cape hake is usually found in depths of less than 400 m, with the largest biomass in the 100-200 m depth range. The depth distribution of the deep-water Cape hake ranges mainly from 150 to 500 m (Badenhorst and Smale, 1991), although this species has been found down to 1000 m water depth (Mas-Riera, 1991). The two species co-exist between 150 and 400 m in ratios that change with depth (Botha, 1985). Because there is a size gradation by depth for both species, with larger fish generally found deeper than smaller ones, medium to large *M. capensis* co-habit with, and feed extensively on small *M. paradoxus* (Botha, 1980; Inada, 1981). Co-habitation among the adults (approximately age 4 and above) of the two species is uncommon (Badenhorst and Smale, 1991), but may occur where the continental shelf is narrow.

Earlier workers were convinced that there was some form of geographical annual migration of the Cape hakes, but such conclusions were based on the erroneous premise that only one species existed. There is a tendency for hake to move offshore into deeper water as they grow older and there appears to be some seasonal movement of adults inshore and offshore (Payne *et al.*, 1989); but although many species of hake show seasonal longshore migrations driven by annual cycles of cooling and warming (Inada, 1981), there is no indication of seasonal longshore movement in concentrations of South African hake. There appears to be, however, at least some seasonal longshore movement of hake stocks in the Namibian region. This movement corresponds with seasonal movement of the boundary between the warm Southern Equatorial current and the cold upwelled Benguela current which is linked to upwelling (Inada, 1981).

Although seasonal migrations may well not occur off South Africa, Le Clus (MCM, pers. commn) suggests that *M. capensis* might be moving to the south as they grow older. Maps of the distribution of *M. capensis*, by size-classes, off South Africa (obtained from research surveys) show that while juveniles and small *M. capensis* are concentrated on the west coast, the bulk of the medium to large shallow-water Cape hake is found on the southern west coast and on the western Agulhas Bank off the south coast. This could be explained by a differential mortality on the west compared to

the south coast, but more likely, medium-sized (>35 cm, corresponding to ages 3 and 4) *M. capensis* move not only offshore, but also south onto the Agulhas Bank. The reason for this movement might be because an important component of their food source (anchovy (*Engraulis capensis*), pilchard (*Sardinops sagax*), round herring (*Etrémus whiteheadi*) and horse mackerel (*Trachurus trachurus capensis*)) also move onto the Agulhas Bank to mature and spawn (Hutchings *et al.*, 2002). Another possibility is that the medium size hakes (which are mostly mature fish) migrate to the south for spawning purposes. Indeed, the strong jet currents on the west coast induce shallow-water Cape hake to migrate southwards as they mature to spawn on the Agulhas Bank, thereby ensuring that the juveniles enter the west coast nursery grounds downstream (Hutchings *et al.*, 2002). A migration of this sort (between what are currently modelled as distinct stocks) could have important implications for the management of the hake resource.

Although morphologically the two species of Cape hakes are superficially very similar, they can be identified by differences in the gill structure (Van Eck, 1969), the shape of the otoliths, the length of the pectoral fins (Inada, 1981) and the number of vertebrae (Franca, 1962). Other differences which permit an experienced worker to separate the two species at a glance are the relative eye size, the colour of the anal fin and the general body shape. *M. paradoxus* tends to be a longer, thinner fish with proportionately larger eyes than *M. capensis*. Furthermore, there are small regional genetic and morphologic differences within each species. Grant *et al.* (1987) found some genetic subdivision between the Namibian and South African populations of *M. capensis* although no differences were detected for *M. paradoxus* (though all except one of the thirteen locations sampled were on the west coast of southern Africa). Also, north of the Orange River, the anal fin of *M. capensis* is entirely white and that of *M. paradoxus* is black in colour. However, at the Orange River and to the south, both species tend to have grey anal fins with black edges (Leslie, MCM, pers. comm).

The question of stock definition is of key importance in stock assessment, as trends in one area could, for example, be misinterpreted if they do not actually reflect the trend in a particular stock. The morphological differences described above may reflect real genetic differences between distinct stocks but may also simply be reflecting environmental influences. For example, it has been suggested that the Cape hakes, as many other fish species, have the ability to change colour to fit in with their background environment, although the advantage of such a change is not clear (Leslie, MCM, pers. comm). Grant *et al.* (1987) suggest that movement of adults between Namibian and South African waters is restricted, but that there may be passive northward movement of eggs and larvae by the Benguela current. Burmeister (2000a) furthermore suggests that there is only one stock of *M. paradoxus* off the west coast of South Africa and Namibia, and that interchange between the two populations should be taken into consideration in the management of the Cape hakes. Her conclusion is based on the fact that no genetic differences have been found between the population off Namibia

and South Africa (Grant *et al.*, 1987; 1988) and that spawning has not been recorded off Namibia (Gordoa *et al.*, 1995).

### 1.1.2 Spawning and maturity

Osborne *et al.* (1999) found oocytes present in different maturity stages in the ovaries of the Cape hakes and they concluded that both *M. capensis* and *M. paradoxus* are serial spawners. Although the two species can and do spawn throughout the year in many areas of their distribution, their main spawning season falls in the period August to March. Furthermore, there seems to be a peak in spawning for both species in November/December, followed by a secondary one of reduced intensity in February/March, sustained largely by the deep-water Cape hake (Botha, 1986).

There are several centres of spawning for each species, with nursery areas downstream of the spawning areas (Payne, 1989). However, no spawning grounds for *M. paradoxus* have been located off Namibia, which could suggest that the Namibian and South African populations of deep-water Cape hake in fact form a single stock in the Benguela region. Although some co-existence of adults of the two species is possible owing to the narrowness of the continental shelf in some regions, genetic analyses (Grant *et al.*, 1988; Becker *et al.*, 1988) show that the two species of hake are distinct and that the possibility of hybridisation is remote. Different centres and times of spawning probably help to preserve species integrity. It has been suggested that adult Cape hakes migrate into shallower waters to spawn. This movement to midwater may explain why few fish with very ripe gonads are found in bottom trawls (Botha, 1973).

Length and age at different levels of sexual maturity have been estimated by Punt and Leslie (1991) for both species off the South African west coast. There do not appear to be substantial differences between the lengths-at-sexual-maturity for *M. capensis* and *M. paradoxus* nor between lengths-at-age. Female *M. capensis* and *M. paradoxus* achieve 50% maturity at a length of 47 cm (CV=1.2%) and 49 cm (CV=1.5%) respectively, both corresponding to the approximate age of 4. Females reach a level of 50% sexual maturity more than one year later than their male counterparts and at a greater length. Male *M. capensis* achieve 50% maturity at 30 cm (CV=2.2%) at an age of 2, while males *M. paradoxus* achieve the same level of maturity at 33 cm (CV=2.0%) and at the age of 2.5. Punt and Leslie (1991) pointed out that as the estimates of age and size at maturity for males and females are so different, there is no clear justification for pooling the data by sex for assessment purposes, except that commercial catch information is not available in a disaggregated form (either by species or sex). On the other hand, in terms of age and size at maturity, pooling by species seems appropriate.

The south coast gives a slightly different picture. *M. capensis* reach 50% maturity at a greater length than on the west coast (42 cm for males and 64 cm for females, corresponding to ages 3 and 5 respectively), while *M. paradoxus* seem to achieve 50% maturity at a smaller length than on the west coast (25 cm for males and 41 cm for females) (Payne, 1986). The differences observed between the south and west coast stocks of *M. capensis* could suggest differential exploitation levels on the two coasts. Payne (1989) suggests that hake could have responded to the heavy exploitation of the early 1970's by lowering their sizes and ages at maturity, via density-dependent responses.

Punt and Leslie (1991), however, found that they could not draw any conclusions on whether or not the values of these parameters have responded to changes in abundance because of differences in the estimation procedures used by different authors and the lack of estimates of the precision of historical estimates. Indeed, Payne (1986) collected gonads in a period including anomalous years (1976 and 1977) when possibly fewer fish were spawning. Furthermore, his analysis was macroscopic only and he could therefore not distinguish between resting and immature gonads. Consequently, some mature females with ovaries in the resting stage could have been recorded as immature, thereby inflating the estimated age at 50% maturity. Leslie (MCM, pers. commn) furthermore indicates that gonads of *M. capensis* infested with a common protozoan gill parasite do not develop (these fish being effectively sterile). As this condition seems to be more common on the south coast, it could also have biased the estimates of age at 50% maturity on the south coast. Thus these differences in estimates of lengths at maturity for *M. capensis* on the west and south coasts are not sufficiently conclusive to negate the hypothesis by Le Clus described earlier that the south coast fish have migrated from the west coast as they aged.

### 1.1.3 Growth

The Cape hakes may grow to more than 1 m in length and may live to more than 12 years of age (Botha, 1971). However, depending on the species and on local conditions, growth rates do vary. Furthermore, the growth rate of each sex of the two species differs, females generally growing faster than males. It has been suggested that the male growth rate is slower because more energy is used for spawning, males maturing at an earlier age than females and possibly spawning more frequently (Payne, 1989). Life expectancy is also longer for females and very few males above an age of 8 years (*M. capensis*) and 6 years (*M. paradoxus*) are found in the commercial catches (Payne and Punt, 1995). The reason for the females dominating the sex ratio in the adult size classes caught is not clear, as the slower growth rate after maturity cannot alone explain the absence of large males from the catches (Payne, 1989).

Growth parameters for the Cape hakes, derived from the von Bertalanffy equation, have been published by different authors (e.g., Punt and Leslie, 1991, for the west coast; Payne, 1986, for the south coast). The von Bertalanffy equation is written as:

$$L_t = L_\infty(1 - e^{-\kappa(t-t_0)}) \quad 1.1$$

where  $L_t$  is the mean total length of a fish aged  $t$  years,  $L_\infty$  is the asymptotic or maximum body length,  $\kappa$ , called the Brody growth coefficient, is a growth rate parameter and  $t_0$  is the (theoretical) age at which length would be zero.

Mass-at-length can be provided by the power model:

$$w_t = \alpha(L_t)^\beta \quad 1.2$$

where  $w_t$  is the mean mass at age  $t$  years and  $L_t$  is the length at age  $t$ .

Estimates of the length-at-age and mass-at-age parameters are listed in Table 1.1 for Namibian hake (Anon., 1997) and in Table 1.2 for the west coast (Punt and Leslie, 1991), while the growth curves related to these estimates are shown in Fig. 1.2. For the hake stocks off the west coast of South Africa, the estimates are available for species and sex separately. No recent estimates of growth rates are available for the south coast, and Leslie (1998b) suggests using the west coast estimates of Punt and Leslie (1991).

### 1.1.4 Feeding

The feeding of the Cape hakes off South Africa and Namibia has been studied extensively. Examples of such studies include the works of Botha (1980), Payne *et al.* (1987) and Pillar and Barange (1993) for the South African west coast, those of Payne (1986) and Pillar and Wilkinson (1995) for the South African south coast and those of Andronov (1987), Roel and Macpherson (1988) and Huse *et al.* (1998) for waters off Namibia. Insights gained from all but the most recent of these studies have been reviewed by Payne and Punt (1995) and Gordoia *et al.* (1995) for South African and Namibian waters respectively.

Cape hakes are generally described in the literature as being opportunistic predators, with seasonal and regional differences in their diet reflecting local variations in food availability rather than prey selection (Payne *et al.*, 1987; Roel and Macpherson, 1988; Punt *et al.*, 1992; Pillar and Barange, 1993). The diet of the two species is similar, but the proportion of different groups in the diet can differ, particularly as predator length increases (Roel and Macpherson, 1988; Payne and Punt, 1995). Studies have shown that juvenile Cape hakes typically prefer crustaceans (mainly euphausiids and

amphipods) when young, but that large hake of both species prey preferentially on fish, a large portion of which is hake itself (Payne *et al.*, 1987; Roel and Macpherson, 1988). *M. capensis* however tend to switch to a fish diet at a smaller size than *M. paradoxus*. Because of the reduced availability of zooplankton of suitable size on the south coast (euphausiids for example are nearly an order of magnitude more abundant on the west than on the south coast – Pillar *et al.*, 1992), Cape hakes in this region tend to be more piscivorous than on the west coast. On the south coast, hakes of small and medium size feed primarily on anchovy (*Engraulis capensis*) and round herring (*Etrumeus whiteheadi*) (Pillar and Wilkinson, 1995). Consequently, hake on the south coast operate at a higher trophic level than in the Benguela system (Pillar and Wilkinson, 1995).

The Cape hakes, in common with other *Merluccius* species, undertake nocturnal vertical migrations off the bottom, with small fish migrating into midwater more extensively than larger fish (Punt *et al.*, 1992). This behaviour is believed to be, at least in part, in response to similar migration of their food (Huse *et al.*, 1998). However, a complete explanation for this diel vertical migration has yet to be achieved. Payne *et al.* (1987) found stomachs with fresh prey in samples taken at all times of day, which suggests that Cape hakes may feed at any time of day and that the nocturnal migration (Botha, 1980) should not be considered as entirely a feeding migration.

Cape hakes are preyed upon by other fish (e.g., snoek *Thyrsites atun*, Cape gurnard *Chelidonichthys capensis*, jacobever *Helicolenus dactylopterus*), cephalopods (mainly chokka squid *Loligo vulgaris reynaudii*) and marine mammals such as the Cape fur seal *Arctocephalus pusillus pusillus* and several species of dolphins (e.g., common dolphin *Delphinus delphis*, dusky dolphin *Lagenorhynchus obscurus*) (Pillar and Wilkinson, 1995). However, predation on the Cape hakes by other predators is considerably less than that attributable to cannibalism and interspecific (hake-on-hake) predation (Payne *et al.*, 1987). Indeed, small hakes form by far the most common item (by mass) in the diet of large (>50cm) hake (Punt *et al.*, 1992). This is not all true cannibalism (when only one species is involved) however; indeed, the ratio of *M. paradoxus* to *M. capensis* in the diet is close to 100:0 for *M. capensis* and approximately 75:25 for *M. paradoxus* (Pillar and Wilkinson, 1995). This is due to the different depth distributions of the two species, which results in large shallow-water Cape hake being found in the vicinity of juvenile deep-water Cape hake. Furthermore, true cannibalism in *M. paradoxus* is less common than in *M. capensis* because small deep-water hakes are not available in the vicinity of adults of that species, as size segregation by depth is more pronounced than in *M. capensis* (Gordoa and Duarte, 1991). Cannibalism (including interspecific – hake-on-hake – predation) is considered to be an important factor in regulating hake abundance off Namibia and South Africa, especially on the west coast where the deep-water species is more abundant than elsewhere (Leonart *et al.*, 1985; Payne and Punt, 1995). Cannibalism may affect the structure of the population as well as the natural mortality rate, which may have an important implications for the management of hake.

## 1.2 History of the hake fishery

### 1.2.1 Development of the fishery

The demersal trawl fishery off southern Africa developed before the turn of the 19<sup>th</sup> century. This fishery originally targeted mainly Agulhas sole (*Austroglossus pectoralis*), with hake landed essentially as an incidental catch. At that time, the fishery confined its activities to fishing grounds relatively close inshore, around Cape Town and to a lesser extent off the south coast of South Africa (Botha, 1985). The bulk of the hake catch must have therefore been shallow-water rather than deep-water Cape hake (Jones, 1974). Trawlers started making larger annual catches of hake of about one thousand tons only after the First World War. Thereafter, catches increased steadily, reaching 100 thousand tons in 1954 (Fig. 1.3) (Chalmers, 1976). Before the 1960's, almost all the hake exploited was caught by South African vessels, but after 1962 the Cape hakes also became a target sought by foreign fleets (Payne, 1989). Exploratory fishing by Spain and Japan showed that catch rates were higher off Namibia than off South Africa and this resulted in the fishing grounds expanding from the Cape Peninsula and Agulhas Bank area to cover virtually the entire continental shelf off the coast of southern Africa. Over this period, the hake fishery experienced unprecedented growth. Catches were virtually uncontrolled and escalated rapidly, peaking at just over one million tons in the year 1972 (see Fig. 1.3). This increasing fishing effort made a substantial impact on the stock of Cape hakes, which resulted in an substantial drop in catch rate over this period (Fig. 1.4), threatening the economic viability of the local industry (Payne and Punt, 1995).

In 1972, the International Commission for the Southeast Atlantic Fisheries (ICSEAF) was established to manage the fish resources in the south-east Atlantic, following concern over the combination of increasing catches and decreasing catch rates in the hake fishery. Before this, despite certain checks and restrictions, the industry operated largely as an open access fishery. In an initial attempt to decrease fishing effort, the Commission declared a minimum mesh size for the hake fishery of 110 mm in 1975; it also brought in a system of international inspection and quota allocations to each member country participating in the hake fishery (Payne and Punt, 1995). However, these measures were not sufficient to stabilise or to allow some recovery of the hake stocks. In November 1977, South Africa declared its 200 nm Exclusive Economic Zone (EEZ) and the South African hake fishery finally reverted to an almost exclusively local one as it had been before 1962. However, an appreciable reduction in TAC was still required to allow the hake population to recover. In 1979, the South African Government in association with the industry decided on a rebuilding strategy and introduced individual quotas, based on recommendations made by ICSEAF. Since then, catches of



hake in South African waters have been relatively constant, with a slightly increasing trend, averaging 120 thousand tons per annum (Fig. 1.3). Total catches of Cape hakes in the southeast Atlantic, however, were not reduced in the same proportion because much of the foreign effort was diverted to Namibian waters where the 200 nm EEZ had not yet been enforced (Gordoa *et al.*, 1995). Though catch limits for these waters were set by ICSEAF over this period, there have been reports that they were not respected by all countries participating in that fishery (Anon., 1997). In 1991, after Namibia's independence and the declaration of its 200 nm EEZ, TACs off Namibia were cut dramatically to less than 60 thousand tons. Since then, TACs for this country have increased steadily and reached 200 thousand tons in 2001.

## 1.2.2 The current fishery

The fishery for Cape hakes in the southeast Atlantic is one of the largest in the world for hake. The current hake fishery is the most important fishing industry in South Africa and Namibia, in terms of both revenue and of local employment. In South Africa, it accounts for approximately 50% of the wealth generated from marine living resources, with the 2001 TAC of 166 thousand tons representing annual sales in the region of R1.5 billion (ESS, 2000). Similarly, the fishery for Cape hakes in Namibia (TAC for 2001 of 200 thousand tons) is one of the largest single contributors (over 10%) to the country's GDP (MFMR, 1999).

Annual catches are still controlled by TACs, which are set annually, and the fishing effort is furthermore controlled by limiting the number of vessels operating in the fishery. On the South African west coast, a minimum mesh size of 110 mm is still enforced. On the South African south coast, the minimum mesh sizes allowed are 110 mm for hake targeted fishing, 85 mm for horse-mackerel targeted fishing and 75 mm for sole targeted fishing. Until recently, a loophole in the law made it impossible to enforce the 110 mm mesh regulation and as a result many operators targeting hake have been using 75 mm mesh on the south coast. This loophole has been closed with the issue of medium term rights in 2002 (Leslie, MCM, pers. commn). Fishing is prohibited within 5 miles of the coast on the west coast.

The demersal hake fishery off southern Africa is split into four sub-sectors according to factors such as species, geographical area, method, gear and vessel size. These four sectors are deep-sea trawl, inshore trawl and more recently, hake-directed longline and hake-directed handline. The deep-sea trawling is concentrated in the Western Cape and operates mainly out of Cape Town and Saldanha Bay (see Fig. 1.1), targeting primarily on Cape hakes, both *M. capensis* and *M. paradoxus*. On the south coast, this offshore fishery is restricted to depths greater than 110 m or, since 2002, to 20 nautical miles from the coast, whichever is the greatest distance offshore. There are no such

restrictions on the west coast, in practice however offshore vessels do not operate in waters shallower than about 180 m (Leslie, MCM, pers. commn). Being capital intensive, deep-sea trawling has traditionally been the domain of a few large fishing companies operating their own trawlers (freezers and wet fish, i.e., delivering frozen and fresh fish). However, with the introduction of a policy to broaden access in the mid-1980's, the number of participants in the deep-sea sector increased from 7 in 1986 to about 60 currently (ESS, 2000). In recent times deep-sea trawler operators have become more quality conscious and often operate below their maximum catch rate in terms of tons per day (ESS, 2000). For the inshore sector, the composition of the catch varies between companies. To a great extent this reflects the amount of hake allocated to each company: the greater the hake allocation, the lower the percent "bycatch" (some of which is clearly targeted rather than incidental) of species other than hake. Large quota holders typically manifest a percent bycatch of less than 10%, while for some others it is as high as 86% (ESS, 2000).

The inshore trawl fishery operates mainly from Mossel Bay and Port Elizabeth (see Fig. 1.1), exploiting fish on the Agulhas Bank, and tends to operate inside the 110 m isobath. It is a mixed species fishery, principally targeting shallow-water Cape hake and Agulhas sole (Booth and Hecht, 1998). Due to the restricted depth range, very few deep-water Cape hake are caught by this sector. Only 20% of the inshore grounds are considered 'safe' for bottom-trawling gear, the rest being hard and rocky. Furthermore, the bay areas on the south coast (representing approximately 20% of the trawlable grounds) are closed to inshore trawling (Japp *et al.*, 1994). The inshore trawling fleet is characterised by relatively small vessels, less than 30 m long and less than 750 hp; currently, there are about 30 such trawlers operating in the industry (Booth and Hecht, 1998).

The longline fishery operates around the coast although most longline vessels operate from Cape Town. Longlining started only in 1983, targeting principally kingklip (*Genypterus capensis*) and Cape hakes (Japp, 1988). At that stage kingklip catches were not restricted, while the hake catches were offset against the quotas of the rights holders. For this reason and because of the high value of kingklip, fishing effort increased considerably on the kingklip stock (catches peaked at more than 10 thousand tons in 1986), which declined sharply from 1984 to 1989 (Punt and Japp, 1994). Kingklip catches fell dramatically and although a longline kingklip TAC was introduced for two years over 1988 and 1989, this fishery was stopped altogether by the end of 1990 (Punt and Japp, 1994). It was only in 1994 that hake-directed longlining was allowed again on an experimental basis, although some 'illegal' longlining continued on the south coast after 1990 (ESS, 2000). Longlining is seen by some as a less capital-intensive method of catching hake than trawling, and as a means by which access to the hake resource can be obtained. Initially, 4000 tons were allocated to this experimental fishery and currently about 10 thousand tons of Cape hakes are caught annually off South Africa using this method. Many of these current longline operators did not have previous quota allocations. On the west

coast, longlining is likely to target the deep-water Cape hake, but on the south coast the bulk of the longline catch is *M. capensis* (Badenhorst, 1988). Initially, longliners targeted large fish on hard or rocky grounds that are largely inaccessible to the bottom trawl fleet (Badenhorst, 1988). However, due to decreasing catch rates and the increasing longline allocations over recent years, longline operators are moving off the rocky grounds onto the trawl grounds. Partly as a result of this increasing proportion of longline catch taken on trawl grounds, the mean size of longline-caught hake has declined dramatically (by about 20 cm over the past three years – Japp, Observer Program, pers. comm).

A commercial handline hake fishery started in the late 1980's with the development of a viable market for fresh whole hake, predominantly in Spain (ESS, 2000). The handline fishery operates up to about 100 m depth, mainly from Plettenberg Bay and, more recently, Knysna (see Fig. 1.1.), where hake is found relatively close to the coast. Conservative estimates put the 1998 handline catch at 2500 – 3000 tons per annum. However, the sector has continued to grow without control and verifiable annual landings now approximate 4 500 tons, with unreported catch probably exceeding 1 500 tons (Sims, MCM, pers. comm). The handline catch consists almost entirely of shallow-water Cape hake of premium quality. Generally the sizes of fresh fish sold by the handliners are smaller than those caught by bottom trawl and longline.

## 1.3 History of assessment and management

### 1.3.1 South Africa

From its inception at the turn of the 19<sup>th</sup> century to 1977, despite certain checks and restrictions, the hake industry operated largely as an open access fishery. After the resulting heavy exploitation of the late 1960's and 1970's, a conservative stock rebuilding strategy was adopted and individual quotas were introduced. The hake resources on the west and south coasts are assessed separately, but a global TAC is set. It has been asserted that the South African hake fishery is one of the best-managed fisheries in the world (ESS, 2000).

Catch and effort statistics collected from the fishery are not species-disaggregated and as a result the assessment methods applied in the past have treated the two hake species, *M. capensis* and *M. paradoxus*, as one. Punt (1993) argues (based upon his management simulation studies) that combining the two hake species in assessments is safe for management purposes, provided that the selectivity pattern of the fishery as a whole (in terms of species and age) remains unchanged. This

assumption has however been violated with the rising catch made by longliners, on the south coast principally, which mainly target older *M. capensis*.

After South Africa declared a 200 nm EEZ in 1977, hake TACs for the west and south coasts have been set by the South African authorities, taking account of recommendations made by ICSEAF. From 1977 to 1983 the recommended TACs were based on the use of steady-state surplus production models: a combination of Fox's (1970) formulation of the surplus production function and Gulland's (1961) effort-averaging procedure (Butterworth and Andrew, 1984). Concerns about the effects of cannibalism on the reliability of Virtual Population Analysis (VPA) approaches were reasons for the use of surplus production approaches (Payne and Punt, 1995). In accordance with the accepted stock rebuilding strategy, a policy aimed at maintaining catches below annual sustainable yields was applied, in general by use of a  $f_{0.1}$ -type strategy (Andrew, 1986). Fig. 1.5 gives a graphical explanation of a  $f_{0.n}$  harvesting strategy, which is a constant fishing effort strategy. This approach means that when the resource size increases (or decreases), the TAC is moved up (or down) in proportion, with the aim that (fluctuations in catchability aside) the same number of vessel-fishing-hours as for the previous year will be required to take the catch.

Due partly to the unsatisfactory fits of the Fox-Gulland models to the CPUE data, it was argued (ICSEAF, 1983) that allowance should be made for dynamic effects in the estimation of TACs. Consequently, the results of the Butterworth-Andrew dynamic (i.e., non-equilibrium) surplus production model were used to recommend TACs. Again, South Africa generally kept to a  $f_{0.1}$ -type policy (Butterworth and Andrew, 1984).

Since 1990, the South African hake fishery has been managed in terms of an Operational Management Procedure (OMP - see Chapter 10). The OMP from 1990 to 1995 was based on a dynamic production model linked to a  $f_{0.2}$  harvesting strategy. A production model, the Butterworth-Andrew observation error estimator (the Schaefer form with the biomass at the start of exploitation set equal to the estimate of the average pristine level), was used to estimate the model parameters from input comprising time series of catches and CPUE and survey abundance estimates (Butterworth and Andrew, 1984; Punt and Butterworth, 1991). More details of the robustness testing and performance criteria used in choosing this OMP are given in Punt (1992, 1993).

Partly because the observed CPUE on the west coast had not increased as much as predicted earlier and given that there was some evidence of model mis-specification, the OMP had to be revised, (Geromont and Butterworth, 1997). The need to take a change in the fishing selectivity (probably a result of phasing out the illegal practice of using small-mesh net-liners) into account was also brought to light (Geromont and Butterworth, 1998a). Furthermore, the CPUE time series for the commercial fleet used in the OMP had been standardised by applying fairly crude power factors instead of using more modern general linear modelling (GLM) techniques. While a revised OMP was being developed

– 1996 and 1997 – the TAC was held fixed. The new OMP adopted in 1998 for the west coast hake resource is still in use at present and is based on a  $f_{0.075}$  harvesting strategy coupled to a dynamic production model with a Fox form of the surplus production function (Geromont and Glazer, 1998).

The revised OMP for the south coast, adopted in 2000, is of the same form as the one used for the west coast, but based on a  $f_{0.3}$  harvesting strategy (Geromont and Glazer, 2000). This OMP is for the *M. capensis* component of the resource only. Indeed, because of changes in fishing selectivity caused by the development of the longline fishery, the assumptions of Punt (1992) (that the selectivity pattern of the fishery stays constant over time) have been invalidated and it is no longer justified to combine the two hake species when assessing the resource. Because commercial catches are not distinguished at the species level, an average proportion of the species composition by depth, obtained from research surveys, is applied to the depth information recorded for commercial trawls to give an approximate split of annual catches into *M. capensis* and *M. paradoxus* (Geromont *et al.*, 1995b). Unlike the situation for *M. capensis* however, an attempted separate assessment for *M. paradoxus* on the South African south coast did not yield sensible results (Geromont and Butterworth, 1999a). The south coast *M. paradoxus* component is therefore for the moment computed as an *ad hoc* proportional addition to the west coast OMP output. This proportion was initially based upon the average ratio of the catches from these two components of the overall resource for the preceding five years, but this adjustment has recently been revised (MCM, 2002). Chapter 12 gives more details on this and the current South African OMPs.

### 1.3.2 Namibia

From 1974 to 1990, when it was dissolved following the independence of Namibia, ICSEAF produced (usually annually) updated assessments of the Namibian component of the hake resource, which were used to recommend annual TACs. Both surplus production models and VPA have been applied to assess the Namibian hake stock. From 1984, management recommendations for the Namibian fishery were based on the results of three dynamic (i.e., non-equilibrium) surplus production models (Butterworth and Andrew, 1984; Babayan *et al.*, 1985, 1986, 1987; Leonart *et al.*, 1985; Leonart and Salat, 1989). The annual TACs were based on a  $f_{0.1}$  harvesting strategy.

After Namibia's independence and up to 1997, TACs were set at 20% of the combined hydro-acoustic/swept-area estimates of fishable biomass (the biomass of fish greater than 35 cm) obtained from surveys carried out by a Norwegian research ship (the *RV Dr Fridtjof Nansen*). These survey estimates were treated as absolute indices of abundance. In 1997 however, after three years during which both the survey and commercial CPUE had shown a decline of some 50%, it was clear that the assessment of the status of the Namibian hake resource was heavily dependent on the interpretation of

the *Nansen* survey data within the assessment (Geromont *et al.*, 1999). The resource was estimated to be severely depleted if the estimates of abundance from the research surveys were taken to provide an absolute index of abundance. The Namibian Ministry's scientists believed this was the case and argued for the TAC to be halved. On the other hand, if the *Nansen* survey data were treated as a relative index of abundance, the resource was estimated to be in a relatively healthy state, above its MSY level (Geromont *et al.*, 1999), and the industry argued that the TAC should be increased.

In response to this debate, an Interim Management Procedure (IMP) was developed by Butterworth and Geromont (2001). Its aim was to provide TAC recommendations that would perform well (in terms of catch and risk of resource depletion) across the wide range of levels argued for the status of the resource. The formulae to provide the TAC recommendations (in thousand tons) were as follow:

$$TAC_{1998} = 150 \left[ 1 + 3 \left( s_{1998}^{CPUE} + s_{1998}^{survey} \right) / 2 \right]$$

$$TAC_y = TAC_{y-1} \left[ 1 + 3 \left( s_y^{CPUE} + s_y^{survey} \right) / 2 \right] \quad 1.3$$

where  $s_y^i$  was a measure of the trend (relative change per annum) in the abundance index  $i$  at the start of year  $y$  over the previous five years. In that way, if the more pessimistic appraisals of the resource were correct, the trend in the surveys and CPUE indices would be negative and the TAC would be reduced. However, if the resource was in fact in a relatively healthy state, the trend in indices would increase over time, which would be reflected by an increase in the TAC.

The control parameters of equations 1.3 (150 and 3) and the number of years over which the trends were calculated (5) were chosen on the basis of the results of simulation testing. The chosen values had to achieve an appropriate trade-off between sufficiently rapid reductions and reasonable increases in the TAC, depending upon whether future data indicated that the more pessimistic or more optimistic appraisals of the resource were correct.

The IMP was adopted in 1998 and was used to provide TAC recommendations until 2000. It led to increases in the TAC, from 120 thousand tons in 1997 to 194 thousand tons in 2000, and it is now accepted that the *Nansen* survey data provide indices of abundance in relative rather than absolute terms. The IMP was, however, designed only as a short-term measure and a revised procedure needed to be developed. Pending species-split data becoming available and an OMP based on a species-disaggregated model being constructed, a revised species-aggregated OMP has been adopted and was used to recommend a TAC in 2002. This revised OMP is detailed in Chapter 11.

**Table 1.1:** Estimates of the parameter values of the von Bertalanffy growth-equation and mass-at-length equation for the Namibian Cape hakes (year-invariant, derived from ICSEAF data for Divisions 1.3 + 1.4; Anon., 1997).

	All data
$\alpha$ (gm/cm <sup><math>\beta</math></sup> )	0.0055
$\beta$	3.100
$L_{\infty}$ (cm)	120.0
$\kappa$ (yr <sup>-1</sup> )	0.089
$t_0$ (yr)	-0.318

**Table 1.2:** Estimates of the parameter values of the von Bertalanffy growth-equation and mass-at-length equation for the west coast Cape hakes (from Punt and Leslie, 1991).

	All data	<i>M. capensis</i>			<i>M. paradoxus</i>		
		Males	Females	Both sexes	Males	Females	Both sexes
$\alpha$ (gm/cm <sup><math>\beta</math></sup> )	0.0055	0.0052	0.0050	0.0050	0.0067	0.0061	0.0062
$\beta$	3.084	3.105	3.116	3.113	3.022	3.048	3.046
$L_{\infty}$ (cm)	230.3	144.6	260.9	270.6	126.6	207.9	219.4
$\kappa$ (yr <sup>-1</sup> )	0.046	0.086	0.041	0.039	0.093	0.051	0.049
$t_0$ (yr)	-0.825	-0.449	-0.707	-0.730	-0.755	-0.912	-0.914

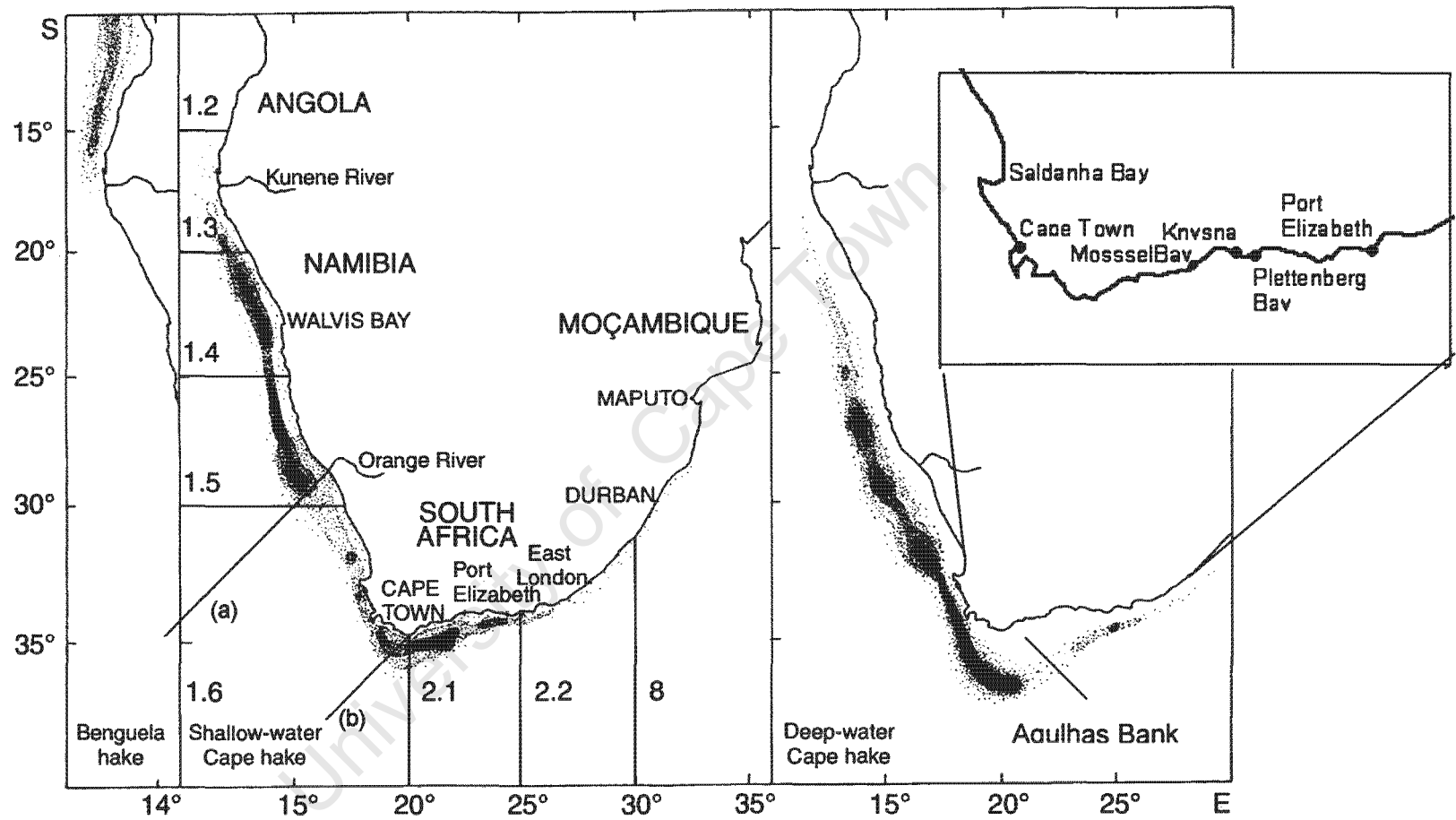


Fig. 1.1: Management units and species distribution for southern African hake (from Payne, 1989, with permission)



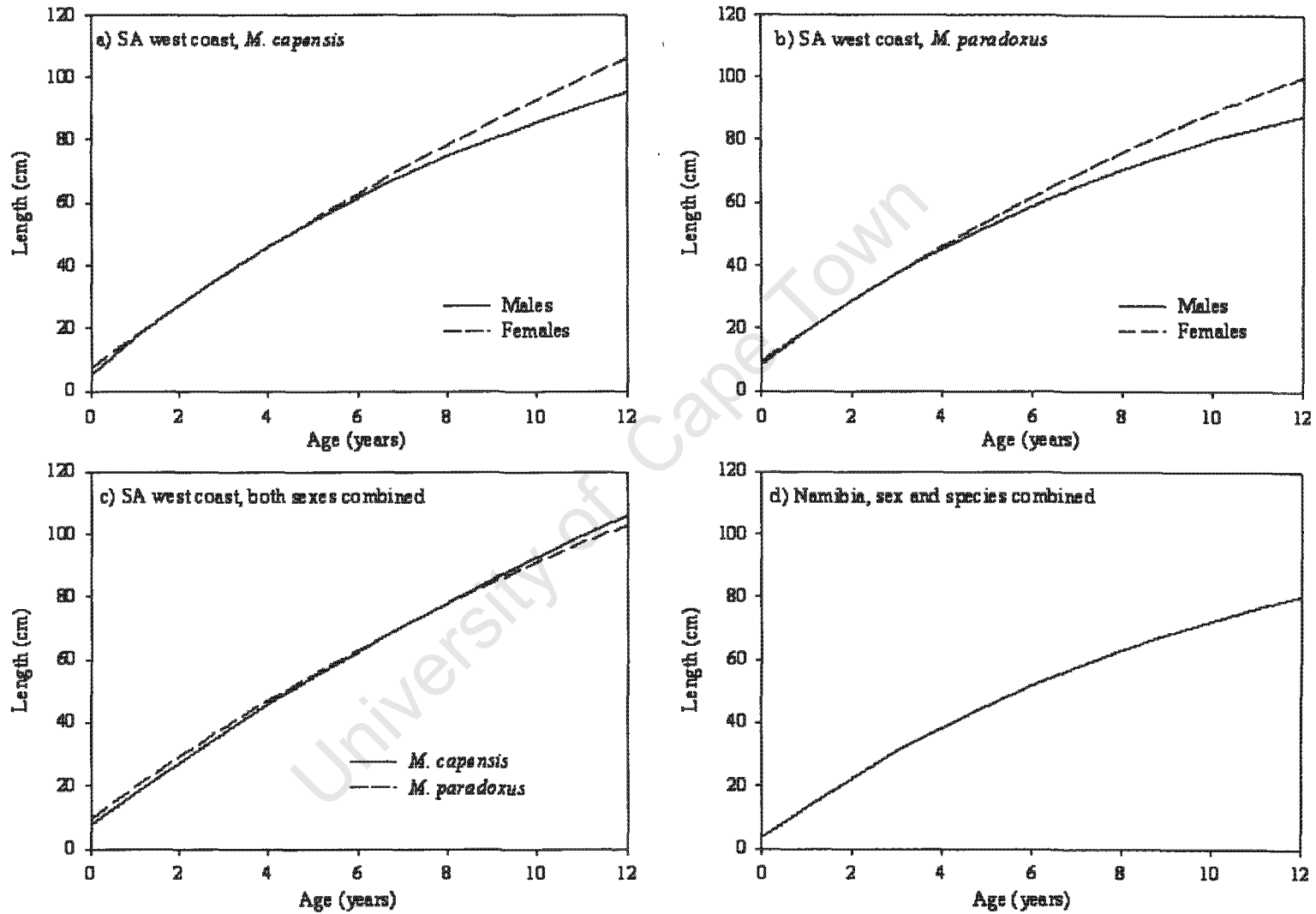


Fig. 1.2: Estimated mean length-at-age from the Von Bertalanffy growth equation for males and females for a) *M. capensis*, b) *M. paradoxus* and c) for both sexes combined off the west coast of South Africa, and d) for sex and species combined of Namibia.

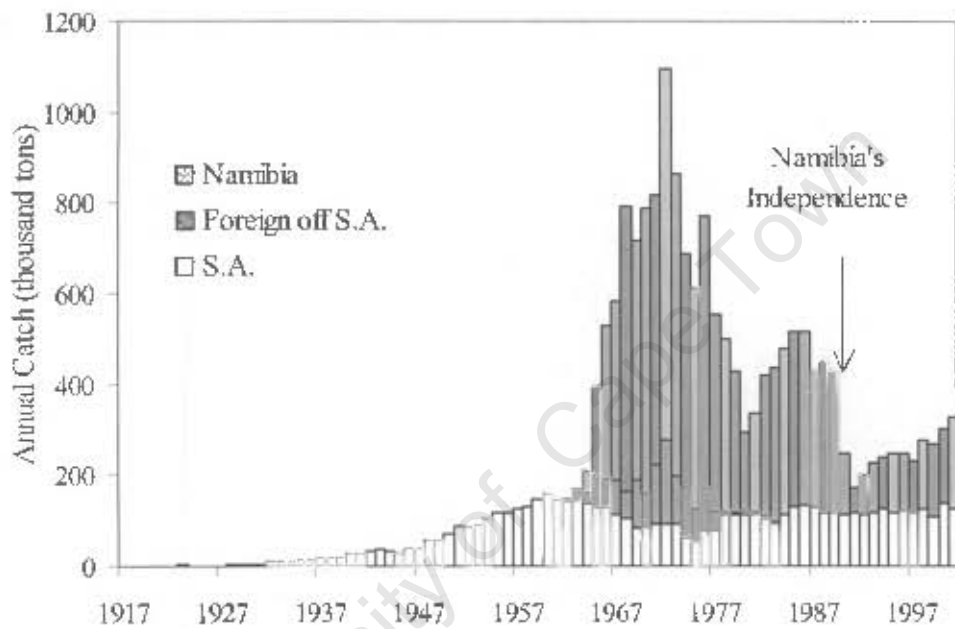


Fig. 1.3: Catch time series for Namibian and South African (west and south coasts combined) hake (See main text for data sources). The catches off South Africa that are shown distinguish between domestic and foreign operators. Namibian catches refer to catches landed in Namibia by Namibian and foreign operators.

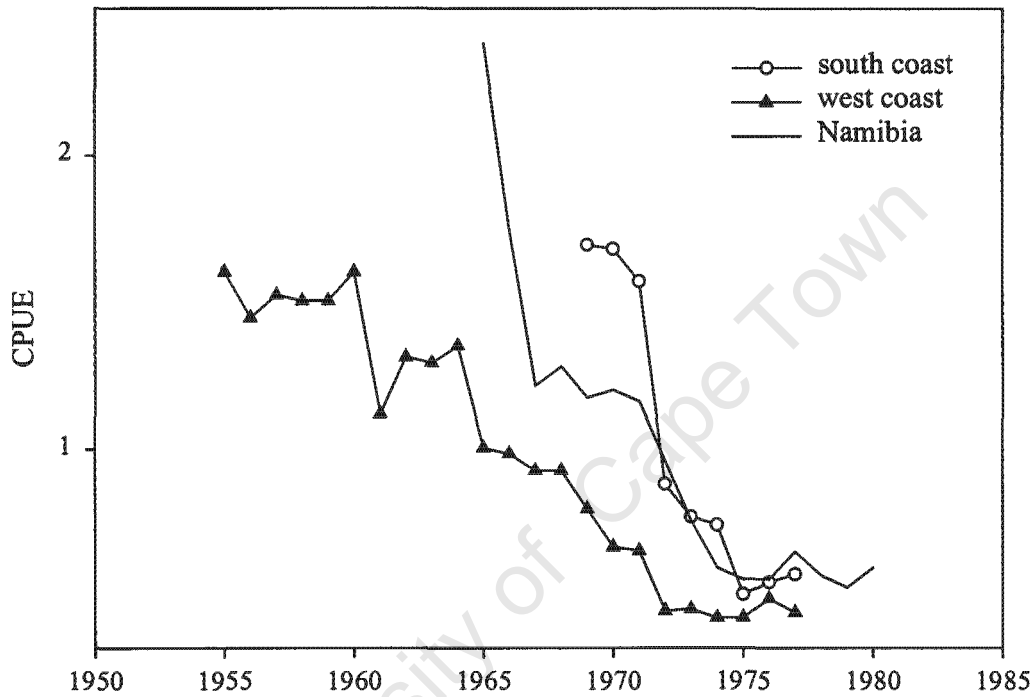
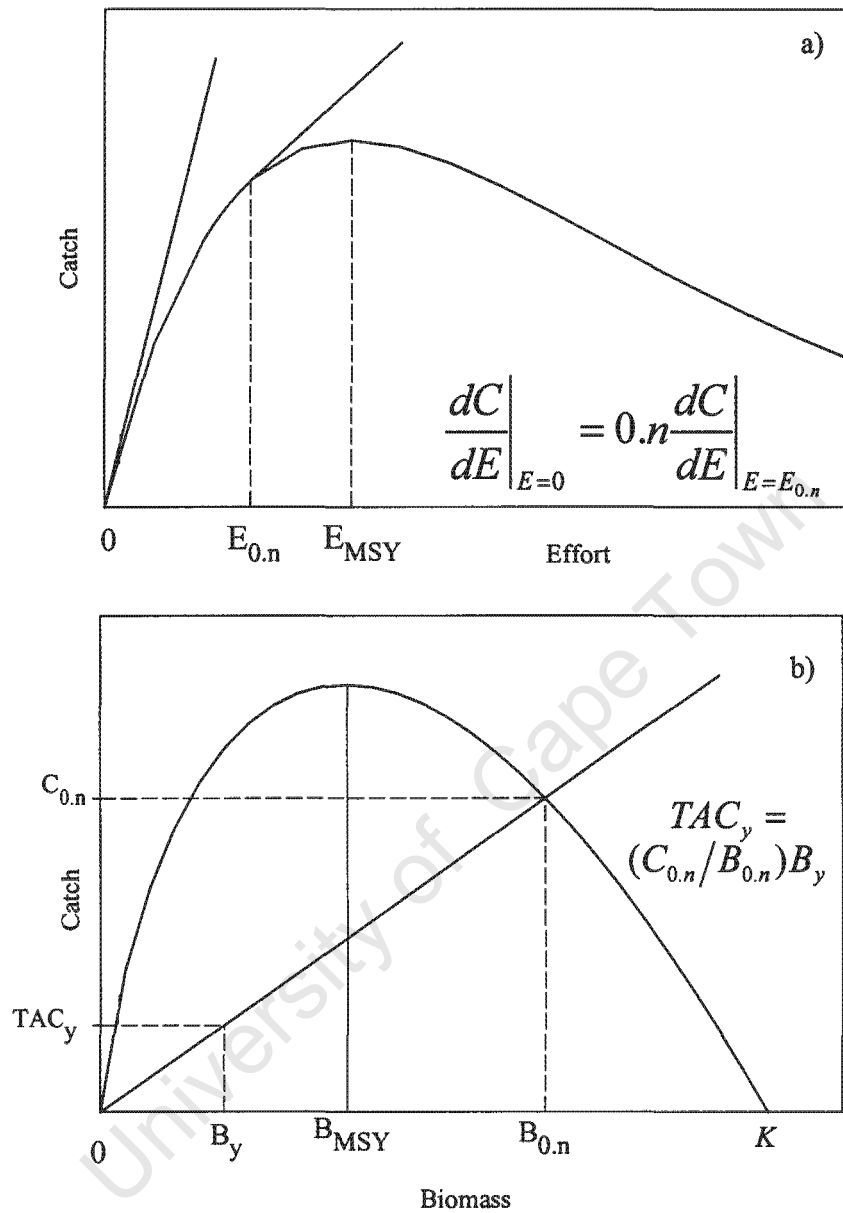


Fig. 1.4: Historic catch rate data (each series is normalised to its mean) for the hake resources off Namibia and the South African west and south coasts (ICSEAF, 1989).



**Fig. 1.5:** A graphical explanation of the  $f_{0,n}$  harvesting strategy: a) shows how the effort level  $E_{0,n}$  is obtained from a sustainable catch vs. fishing effort curve; this effort level corresponds to an equilibrium biomass  $B_{0,n}$  and yield  $C_{0,n}$ ; b) shows how the sustainable catch vs. biomass plot is used to convert this information into a TAC recommendation ( $TAC_y$ ) for year  $y$ . The following relationships hold for the Fox surplus production model:

$f_{0,n}$	$E_{0,n}/E_{MSY}$	$B_{0,n}/K$
$f_{MSY}$	1	0.37
$f_{0.1}$	0.78	0.46
$f_{0.2}$	0.63	0.54
$f_{0.3}$	0.50	0.60

## **SECTION I: STOCK ASSESSMENT**

University of Cape Town

## 2 Available data for stock assessment

The data which are available to assess the hake resources off southern Africa can be divided into four main types. These are the annual catches (by mass), commercial catch rates, survey biomass estimates and age-structure information. Biological data such as mass and length-at-age (see Chapter 1, section 1.1.3) are also used to model the resource. The general types of data utilized in the assessments are discussed below, while the specific data and assumptions used in the assessment of a particular stock are given in the relevant Chapters.

In the assessments of the southern African hake resource, the hake population in each region (Namibia and South Africa's west and south coasts) is analysed as a separate closed unit stock. Although some immigration and emigration must take place between the stocks, these effects are currently assumed to be small enough to be ignored. The data described below are available for each of these three stocks separately.

### 2.1 Catches

Throughout this thesis, if not indicated otherwise, the term "catch" refers to the part of the catch that is retained and brought ashore, i.e., the landing, which does not include discards.

Commercial catches (by mass) for hake are available from the beginning of the fishery in each region (Namibia and South African west and south coasts), and are, where possible, disaggregated by fleet. Prior to 1954, annual catches were estimated from data reported in logbooks (skippers' estimates), in contrast to catches estimated after this period which are based on the actual measured mass of fish landed. The catch estimates prior to 1954 are therefore less precise than the more recent estimates.

The estimates of annual catch based on landed values are not the actual catches made, because they ignore the practice of discarding small fish and as a consequence total removals are underestimated, particularly for the younger age classes. To take this bias into account catches prior to 1972 were increased by 39% (ICSEAF, 1978). It is not clear how this figure of 39% was chosen and, if this increase is applied to compensate for all discarding, why no correction is applied post-1972. Discarding practices have undoubtedly changed over time and it has been suggested that, because of a lesser demand for fish and a greater availability of large fish, the minimum size of fish retained prior to 1972 was somewhat larger than post-1972.

Even taking discard levels into consideration, the reported catch is still an underestimate of the total fishing mortality as it ignores the effect of fishing on the individual fish not actually caught (e.g., death to some fish as a result of passing through the net meshes).

Catch statistics are reported as the nominal (or live) mass rather than the actual landed mass of cleaned, processed hake. The nominal mass is calculated from the landed mass by applying raising factors: 1.16 for head-on gutted hake, 1.46 for headed and gutted hake, 1.94 for skin-on fillets and 2.25 for skinless fillets (Leslie, 1998a). A general conversion factor of 1.46 (Chalmers, 1976) was applied when the breakdown of the landed catch was not known, which could also lead to some imprecision in the total catch estimates.

The combined effect, in terms of precision and accuracy of the catch estimates, of the biases described above is assumed to be sufficiently small to be ignored in the assessments of the hake resource off southern Africa. Sensitivity of these assessments and the related management procedures to such errors in the data can nevertheless be tested by simulation.

Due to the very similar morphologies of the two species of Cape hakes, the catches are reported as one group. In Namibian waters however, for the past four years, on-board observer schemes have allowed catch statistics to be split by species and these data will be available for future assessments. In South Africa, where it has become necessary to assess the two hake species separately because of the growing importance of longlining (and consequently differing fishing effort and selectivities on the two species), the proportions of *M. capensis* and *M. paradoxus* in the commercial catches have been estimated using species-by-depth information obtained from research surveys (Geromont *et al.*, 1995b). These analyses assume a depth range (different for the west and south coasts) above which only *M. capensis* is present and below which only *M. paradoxus* is present. Within this depth range, the two species are assumed to mix in a proportion which changes linearly with depth. Because the depth of each trawl is recorded, the proportion of the two species can be estimated and attributed to the catch made during a particular trawl.

## 2.2 Catch rates

Commercial catch rates, or catch-per-unit-effort (CPUE) series, are key to stock assessment analyses as these time-series are conventionally assumed to be proportional to abundance. They are calculated from the total hake directed landings and hake directed trawl effort. To take into account some of the factors which could bias the estimation of effort (and therefore catch rate), such as changes in technology, vessel power, fishing patterns or extent of targeting, recent effort data have been standardised using General Linear Modelling (GLM). Factors generally included in the GLM

model are 'year', 'month', 'latitude', 'depth' and 'GRT' (the gross tonnage of the vessel) (Glazer, 1999; Brandão and Butterworth, 2001). The GLM-standardised CPUE time-series are updated annually.

Data on which such standardisation is based are however available only from 1978 for South Africa and from 1992 for Namibia. Prior to those years, the CPUE time series used have been standardised only by applying crude vessel power factors calculated in the early 1970's, which fail to account for technological improvements and shifts in fishing patterns. The information on CPUE over this period is however essential for the assessment of the hake resources off southern Africa as it includes the period of heavy exploitation in the 1960's and 1970's and the resulting substantial decrease in catch rates. These historic CPUE time-series are therefore still used in the assessments. It is possible to test the sensitivity/robustness of the assessment and the management procedures to possible biases in these data.

## 2.3 Survey biomass

Research surveys have been conducted in more recent years to provide indices of biomass which are independent of the commercial operations. They are particularly useful because the vessel characteristics are constant over time, and the region and time of the surveys can be controlled. Abundance indices from research surveys are therefore less likely to be biased than indices obtained from the commercial fishery. However research surveys typically take place only once or twice a year, while commercial CPUE series are obtained from data averaged over a whole year. Consequently, survey biomass estimates might be expected to show more variability than CPUE indices.

Research surveys have been conducted in summer and winter off Namibia and off South Africa's west coast (although in more recent years only in summer) and in spring and autumn off South Africa's south coast. Off South Africa, the stations are selected using a pseudo-random stratified sampling design, within the 500 m depth contour (Leslie, 1998a). Off Namibia, the stations are selected using a systematic transect design, with a semi-random distribution of stations along each transect. At least one trawl per 100 m depth range is obtained (Burmeister, 2001). Different types of data are collected during these cruises; they include catch per tow-time data to provide estimates of abundance, length frequency data to provide estimates of numbers-at-age and biological information. The survey biomass (abundance) indices are calculated by the swept-area method and are assumed to reflect the true abundance of the fish in relative terms only (Leslie, 1998a, Butterworth and Rademeyer, in press). This is because of possible herding effects, the possibility of avoidance of the net by the fish and the fact that the water column above the net is not sampled. These effects are,



however, assumed to be more or less constant over the years so that the assumption of proportionality to abundance remains appropriate. The sampling standard errors associated with the survey abundance indices are also available.

## 2.4 Age-structure

Commercial catch-at-age data are obtained from length frequency data (catch-at-length) in conjunction with annual age-length keys (Leslie, 1998a). The age-length keys are based on the count of annual growth rings in otoliths collected during both commercial and research sampling. Individual fish are selected for ageing using a random stratified sampling design, while trying to ensure at least six hakes of each species per 1 cm length class. Age-length keys are available disaggregated by species and sex.

However, length frequency information from the commercial catch is not available by species or sex, the reason being that it is often based on cleaned (headed and gutted) fish, which cannot be sexed or easily identified by species (Leslie, 1998a) (the length of headed fish is estimated by measuring the cloaca-to-tail length and transforming it to total length). As result it is not possible to disaggregate the commercial catches-at-age by species or sex. A species-aggregated age-length key is developed and applied to the length distribution data for the two species combined to obtain the species-aggregated catches-at-age. In Namibia however, observers on-board commercial vessels have been collecting hake data since 1997. On-board, the fish are still identifiable to species and hake length frequency information off Namibia is therefore available by species for recent years.

Length information collected by land-based sampling does not reflect the lengths of discarded hake (mainly small fish). In addition to providing sex and species disaggregated catch-at-length data, sea-based sampling would have the further advantage of analysing actual catches rather than landings (i.e., no problem of ignoring the discard of fish); however, this method of sampling requires many more samplers than land-based sampling to obtain the same coverage of the total catch. Indeed, a sea-based sampler is restricted to a particular vessel and area for a relatively long period of time (the length of fishing trip, typically 1-2 weeks for an offshore trawler), while a land-based sampler can analyse catches from several vessels and areas in the same amount of time.

The age-structure of catches made by research vessels is calculated in the same manner as for commercial catch-at-age data. The sampling is sea-based and a large proportion (often 100%) of the catch is measured. Length frequency information is furthermore available for each sex and species so that survey catches-at-age are available by species.

For commercial data particularly, but also for survey data, because of a combination of gear selectivity (e.g., mesh size) and mortality (natural and fishing), a relatively small number of fish in the youngest and oldest age classes are caught. In consequence, there can be relatively larger errors (in terms of variance) associated with these data. To reduce this effect, the assessments are conducted with 'minus-' and 'plus-groups' obtained by summing the data over the ages below and above  $a_{minus}$  and  $a_{plus}$  respectively. Combining certain age-classes in this way also helps reduce the effect of ageing error, which occurs for older ages particularly.

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## 3 The choice of model

The choice of which mathematical model to use in assessing fish stocks depends primarily on the quality and quantity of data available and on the actual dynamics of the population under study. Models which are commonly used in fishery stock assessments include biomass dynamic models, Virtual Population Analysis (VPA) and Age-Structured Production Models (ASPM). These models are discussed briefly below, together with the motivation for using an ASPM for assessing the hake stocks in this thesis.

### 3.1 Biomass Dynamic Models

One of the key difference between biomass dynamic models and the other two types of stock assessment analysis described in this Chapter is the level at which they model the fish abundance, *viz.* whether the abundance is modelled as comprising of one or several components. Biomass dynamic models are so called because they deal only with the total biomass of the fish stock, while VPAs and ASPMs keep a separate account of the number of individuals in several age groups. Biomass dynamic models, also referred to as simple production models, therefore assume that the natural growth in stock size is independent of the age composition of the population. Despite their relative simplicity, biomass dynamic models are frequently used in fisheries, particularly in cases where catch-at-age data are difficult to obtain.

The change in population biomass from one year to the next is simply written as:

$$\left( \begin{array}{c} \text{Biomass} \\ \text{this year} \end{array} \right) = \left( \begin{array}{c} \text{Biomass} \\ \text{last year} \end{array} \right) + (\text{Recruitment}) + (\text{Somatic Growth}) - (\text{Natural Mortality}) - \left( \begin{array}{c} \text{Catch} \\ \text{last year} \end{array} \right)$$

which states that, ignoring immigration and emigration, the population increases through the recruitment of new individuals (births) and the growth in weight of the individuals already present in the population. Natural and fishing mortality are the two sources of loss.

Biomass dynamic models do not explicitly consider growth, recruitment or differential vulnerability to fishing gear. The “net growth rate” function combines recruitment, growth and natural mortality. It can take on different forms; a more general form is that of the Pella-Tomlinson model (1969), which is written as:

$$\frac{dB}{dt} = rB \left[ 1 - (B/K)^P \right] \quad 3.1$$

where  $dB/dt$  is the rate of change of population biomass,  $r$  is the intrinsic growth rate,  $K$  is the carrying capacity, a parameter which corresponds to the unfished equilibrium stock size, and  $P$  is the degree of compensation parameter.

Two special cases of the Pella-Tomlinson model are the Schaefer (1954) and Fox (1970) models, which are both commonly used in fisheries:

$$\text{Schaefer: } \frac{dB}{dt} = rB(1 - B/K) \quad (P = 1) \quad 3.2$$

$$\text{Fox: } \frac{dB}{dt} = rB[1 - \ln(B)/\ln(K)] \quad (P \rightarrow 0) \quad 3.3$$

These functions all assume that the rate of increase in abundance depends only on the existing stock size. The basic features of these net growth rate functions ( $f(B)$ ) is that the growth rate is small at low stock sizes; it increases with stock level until it reaches a maximum and then begins to decrease again until it becomes zero because of some combination of slower somatic growth, higher mortality rates and limitations on recruitment (density dependent responses). In the case of the Schaefer model, the surplus production curve ( $f(B)$ ) is perfectly symmetric in relation to stock size, while the production relationship for the Fox model shows a peak skewed to the left. Similarly, the parameter  $P$ , in the Pella-Tomlinson model allows the production curve to show a maximum skewed to the left ( $P < 1$ ), or the right ( $P > 1$ ). This has important implications for what constitutes biological overexploitation, because a stock is defined to be biologically overexploited when its biomass falls below that corresponding to the maximum for such models.

In the discrete form, a general form of the biomass dynamic model can then be written as:

$$B_{y+1} = B_y + f(B_y) - C_y \quad 3.4$$

where  $B_y$  is the biomass at the start of year  $y$ ,  $f(B_y)$  is the net growth rate in year  $y$  (a function of the population size) and  $C_y$  is the catch in year  $y$ .

To estimate the parameters of the biomass dynamic models when only an index of abundance, such as catch rate, is available, it is assumed that the catch rate (catch per unit effort or CPUE) is proportional to the stock abundance, i.e.:

$$C_y/E_y = qB_y \quad 3.5$$

where  $E_y$  is the fishing effort in year  $y$  and  $q$  is the catchability coefficient, a parameter that describes the effectiveness of each unit of fishing effort.

From an initial estimate of the stock size at the beginning of the data series available and an initial estimate of the intrinsic growth rate  $r$ , the model is then used to predict the whole time-series. The parameter values (e.g.,  $r$ ,  $K$  and  $q$ ) are then adjusted to provide the best fit of the predicted-to-observed time-series of relative abundance or catch data. This best fit of the predicted biomass, given the observed catches, is obtained using non-linear parameter estimation techniques, with the notion of “best” based upon least squares or the maximum likelihood criteria.

Biomass dynamic models can be useful tools in fisheries, particularly when catch-at-age information is not available. However, some of the assumptions underlying these types of models are open to question. For example, they assume that the parameters of the production function remain unchanged over time, which is not always the case. Also, because they model only the total biomass of a population, they do not take into account the consequences of time lags related to the age structure of the population.

### 3.2 Virtual Population Analysis

Virtual Population Analysis (VPA) was first used in fish stock assessment by Gulland (1965). This method, based on the analysis of catch-at-age data, is now widely used in fisheries. Traditional VPA methods are recursive algorithms that calculate stock size based on catches with no underlying statistical assumptions.

The stock is broken down into cohorts, which are groups of fish of the same age (and therefore of more or less the same size, maturing at the same time and often found in the same area) and the model follows each cohort from year to year. A cohort in year  $y$  of age  $a$  is subject to a total mortality ( $Z_{y,a}$ ), which defines the rate of decrease of the cohort size ( $N_{y,a}$ ). Furthermore, the total mortality is composed of the fishing mortality ( $F_{y,a}$ ) and the natural mortality ( $M_a$ ) (all defined as instantaneous rates). Within a time interval where the mortality rates are constant, an exponential decrease in numbers follows, i.e.:

$$Z_{y,a} = F_{y,a} + M_a \quad 3.6$$

$$N_{y+1,a+1} = N_{y,a} e^{-Z_{y,a}} \quad 3.7$$

where  $N_{y,a}$  is the number of fish of age  $a$  at the start of year  $y$ .

It can be shown by integration that the number of fish of age  $a$  removed from a cohort by fishing during year  $y$  is governed by the ‘Baranov catch equation’ (Baranov, 1918), i.e.:

$$C_{y,a} = \frac{F_{y,a} N_{y,a}}{F_{y,a} + M_a} (1 - e^{-Z_{y,a}}) \quad 3.8$$

where  $C_{y,a}$  is the number of fish of age  $a$  caught in year  $y$ .

Equation 3.8 cannot be solved for  $N_{y,a}$  or  $F_{y,a}$  directly but must be solved using numerical techniques such as Newton-Raphson iteration. Given values for  $C_{y,a}$ ,  $M_a$  and either the population size  $N_{y,a}$  or the fishing mortality  $F_{y,a}$ , the remaining unknown can be calculated.

By solving a series of equations 3.8, the sequence of  $F$ 's and  $N$ 's for each cohort can be defined. However, to start this process, at least one  $F$  or  $N$  is needed for each cohort. This is usually the terminal  $F$ . In classical VPA, these parameters are pre-defined, but in tuned VPA, they are estimated from other data, such as effort data or survey abundance indices. In the tuned VPA approach, the terminal fishing mortalities are re-estimated iteratively until a solution which is consistent with the additional information is found.

Although the method is valid for all levels of catch data, the estimates of  $F$  provided by VPA will be more precise if a large proportion of the total removals for each cohort are due to fishing. Indeed, the VPA procedure is simply using the summed catches adjusted for losses to the natural mortality as the stock estimate. This suggests that when fishing mortality is high (compared to natural mortality) the recruitment estimate is insensitive to the initial guess on survivors or fishing mortality of the oldest age group, because the remaining fish that are assumed to be still alive will constitute only a small fraction of the total recruitment.

There are three major problems with VPA:

- 1) It requires catch-at-age information for the whole period under assessment, and assumes each information to be completely free of errors.
- 2) It can give unreliable estimates for cohorts that have not completely disappeared from the fishery. This is very problematic because it is the current status of the resource, which relates to exactly those cohorts, which is usually of the greatest importance for management purposes.
- 3) It requires a reliable value for the rate of natural mortality  $M$ . Over or under-estimating  $M$  will have large effect on absolute values such as those for  $F$  and stock size (although less so on relative statistics such as  $\frac{F}{F_{MSY}}$  and  $\frac{B}{B_{MSY}}$ ).

### 3.3 Age-Structured Production Models

An Age-Structured Production Model (ASPM) is based on a fully age-structured population model (e.g., Hilborn, 1990). From an initial estimate of abundance (usually taken to be the unexploited equilibrium biomass or some fraction of this size), annual changes in biomass are calculated by applying standard dynamics equations to each cohort. In a key difference from VPA, annual catches-at-age in these model computations are not taken to be equal to values obtained from length distribution data and age length keys. Instead, some assumptions are made about the pattern of fishing mortality-at-age (selectivity), and this is used to compute predicted catches-at-age which are compared to observations in the model fitting process.

For each year, the recruitment (i.e., the number of 0 year old fish) is calculated using a stock-recruitment relationship (which can be either deterministic, or make some allowance for fluctuations about this relationship). The model is typically then fitted to indices of abundance, such as CPUE or survey abundance estimates, and catch-at-age information by maximising a likelihood function. Parameters typically estimated in this fitting process are the parameters of the stock-recruitment function and fishing selectivity pattern assessment, and sometimes also the natural mortality rate. The model used for the southern African hake stocks is described in detail in the next Chapter.

Given that some catch-at-age data are available for the hake stocks, VPA or ASPM approaches seem preferable to biomass dynamics models so that these data can be taken into account in the assessments. The key reason for favouring ASPM over VPA is that it is more flexible, allowing extension to years for which catch-at-age data are not available. Furthermore, Punt (1994) found that some estimates provided by the VPA method are very sensitive to the value assumed for the natural mortality  $M$ , which is not well known; the ASPM approach, however, given general assumptions about the shape of the selectivity pattern, allows  $M$  to be estimated for a self-consistent assessment. Some problems remain however when using ASPM. For instance, in periods without age-structure data, the model relies heavily on the assumed stock-recruit function. This stock-recruit function usually also has to be assumed to remain unchanged over time, an assumption which is not necessarily realistic. Furthermore, although the ASPM approach makes allowance for errors in the catch-at-age data, rather than having to assume that they are exact as in the VPA approach, to do this it requires the assumption of a constant selectivity function (or one for which the basis for any changes over time is prespecified), particularly to be able to deal with years without catch-at-age information.

## 4 The Age-Structured Production Model

The model used in the revised assessments of the southern African hake stocks developed in this thesis is a fleet-disaggregated Age-Structured Production Model (ASPM) (e.g., Hilborn, 1990). Punt (1994) first applied an ASPM to the west and south coasts stocks of Cape hakes off South Africa. Geromont and Butterworth (1996; 1999; Butterworth and Geromont, 2001) later extended this application in a number of ways. The approach used in an ASPM assessment involves constructing an age-structured model of the population dynamics and fitting the model output to the available abundance indices and catch-at-age information by maximising the likelihood function. The model equations and the general specifications of the model are described below, followed by details of the contributions to the log-likelihood function from the different data considered. Quasi-Newton minimisation is used to minimise the total negative log-likelihood function (implemented using AD Model Builder™, Otter Research, Ltd.).

### 4.1 Population Dynamics

#### 4.1.1 Numbers-at-age

The resource dynamics of the southern African hake stocks are modelled by the following set of population dynamics equations:

$$N_{y+1,0} = R_{y+1} \quad 4.1$$

$$N_{y+1,a+1} = \left( N_{y,a} e^{-M_a/2} - \sum_f C_{y,a}^f \right) e^{-M_a/2} \quad \text{for } 0 \leq a \leq m-2 \quad 4.2$$

$$N_{y+1,m} = \left( N_{y,m-1} e^{-M_{m-1}/2} - \sum_f C_{y,m-1}^f \right) e^{-M_{m-1}/2} + \left( N_{y,m} e^{-M_m/2} - \sum_f C_{y,m}^f \right) e^{-M_m/2} \quad 4.3$$

where

$N_{y,a}$  is the number of fish of age  $a$  at the start of year  $y$ ,

$R_y$  is the recruitment (number of 0-year-old fish) at the start of year  $y$ ,



- $M_a$  denotes the natural mortality rate on fish of age  $a$ ,  
 $C_{y,a}^f$  is the number of hake of age  $a$  caught in year  $y$  by fleet  $f$ , and  
 $m$  is the maximum age considered (taken to be a plus-group).

These equations simply state that for a closed population, i.e., with no immigration and emigration, the only sources of loss are natural mortality (predation, disease, etc.) and fishing mortality (catch). They reflect Pope's approximation (Pope, 1984) (the catches are assumed to be taken as a pulse in the middle of the year) rather than the more customary Baranov catch equations (Baranov, 1918) (catches are incorporated in the form of a continuous fishing mortality). As long as mortality rates are not too high, the differences between the Baranov and Pope formulation will be minimal. Tests showed this approximation to be adequate for the hake stocks (Punt, University of Washington, pers. commn).

### 4.1.2 Recruitment

Next year's recruitment depends upon the reproductive output of this year's fish. The number of recruits (i.e., new zero-year old fish) at the start of year  $y$  is assumed to be related to the spawning stock size (i.e., the biomass of mature fish) by a stock-recruitment relationship. Traditionally, the Beverton-Holt function (Beverton and Holt, 1957) has been used for southern African hake assessments. However, given that cannibalism is common in hake, strong density dependent effects might be expected and future work should investigate the effect of using a Ricker's model of stock and recruitment (Ricker, 1954), which has recruitment per spawner declining linearly with increasing spawning stock.

The Beverton-Holt stock-recruitment relationship, allowing for annual fluctuations, is written as:

$$R_y = \frac{\alpha B_y^{sp}}{\beta + B_y^{sp}} e^{(\zeta_y - \sigma_R^2/2)} \quad 4.4$$

where

- $\alpha$  and  $\beta$  are spawning biomass-recruitment relationship parameters,  $\alpha$  being the maximum number of recruits produced, and  $\beta$  the spawning stock needed to produce a recruitment equal to  $\alpha/2$ , in the deterministic case,  
 $\zeta_y$  reflects fluctuation about the expected recruitment for year  $y$ , which is assumed to be normally distributed with standard deviation  $\sigma_R$  (whose value is input in the applications considered

here); these residuals are treated as estimable parameters in the model fitting process. Estimating the stock-recruitment residuals is made possible by the availability of catch-at-age data, which give some indication of the age-structure of the population. The  $-\sigma_R^2/2$  term is to correct for bias given the skewness of the log-normal distribution; it ensures that, on average, recruitments will be as indicated by the deterministic component of the stock-recruitment relationship;

$B_y^{sp}$  is the spawning biomass at the start of year  $y$ , computed as:

$$B_y^{sp} = \sum_{a=1}^m f_a w_a N_{y,a} \quad 4.5$$

where

$w_a$  is the begin-year mass of fish of age  $a$  and  $f_a$  is the proportion of fish of age  $a$  that are mature.

In order to work with estimable parameters that are more biologically meaningful, the stock-recruitment relationship is re-parameterised in terms of the pre-exploitation equilibrium spawning (“virgin”) biomass,  $K^{sp}$ , and the “steepness”,  $h$ , of the stock-recruitment relationship, which is the proportion of the virgin recruitment ( $R_1$ ) that is realised at a spawning biomass level of 20% of the virgin spawning biomass:

$$\alpha = \frac{4hR_1}{5h-1} \quad 4.6$$

and

$$\beta = \frac{K^{sp}(1-h)}{5h-1} \quad 4.7$$

where

$$R_1 = K^{sp} / \left[ \sum_{a=1}^{m-1} f_a w_a \exp\left(-\sum_{a'=0}^{a-1} M_{a'}\right) + f_m w_m \frac{\exp\left(-\sum_{a'=0}^{m-1} M_{a'}\right)}{1 - \exp(-M_m)} \right] \quad 4.8$$

In the fitting procedure, both  $h$  and  $K^{sp}$  are estimated. The steepness parameter is important, as the overall potential yield of a resource estimated by an ASPM depends primarily on the steepness of the stock-recruitment curve and on the natural mortality rate.

### 4.1.3 Total catch and catches-at-age

The fleet-disaggregated catch by mass in year  $y$  is given by:

$$C_y^f = \sum_{a=0}^m w_{a+1/2} C_{y,a}^f = \sum_{a=0}^m w_{a+1/2} N_{y,a} e^{-M_a/2} S_{y,a}^f F_y^f \quad 4.9$$

where

$w_{a+1/2}$  denotes the mid-year mass of fish of age  $a$ , which is assumed to be the same for each fleet (as there are no data available to discriminate between fleets),

$C_{y,a}^f$  is the catch-at-age, i.e., the number of fish of age  $a$ , caught in year  $y$  by fleet  $f$ ,

$S_{y,a}^f$  is the fleet-disaggregated commercial selectivity (i.e., vulnerability to fishing gear, which may depend not only on the gear itself, but also on distribution patterns of the fish by age compared to the areal distribution of fishing effort) at age  $a$  for year  $y$  and fleet  $f$ ; when  $S_{y,a}^f = 1$ , the age-class  $a$  is said to be fully selected, and

$F_y^f$  is the fished proportion of a fully selected age class, for fleet  $f$ .

The model estimate of the mid-year exploitable (“available”) component of biomass for each fleet is calculated by converting the numbers-at-age into mid-year mass-at-age (using the mid-year individual weights) and applying natural and fishing mortality for half the year:

$$B_y^f = \sum_{a=0}^m w_{a+1/2} S_{y,a}^f N_{y,a} \exp(-M_a/2) (1 - \sum_f S_{y,a}^f F_y^f / 2) \quad 4.10$$

whereas for survey estimates of biomass at the start of the year (summer):

$$B_y^{surv} = \sum_{a=0}^m w_a S_a^{surv} N_{y,a} \quad 4.11$$

and in mid-year (winter):

$$B_y^{surv} = \sum_{a=0}^m w_{a+1/2} S_a^{surv} N_{y,a} \exp(-M_a/2) (1 - \sum_f S_{y,a}^f F_y^f / 2) \quad 4.12$$

where

$S_a^{surv}$  is the survey selectivity, and

$w_{a+1/2}$  is the mid-year weight of fish of age  $a$  at the start of the year.

It is assumed that the resource is at the deterministic equilibrium that corresponds to an absence of harvesting at the start of the initial year considered, i.e.,  $B_{y_0}^{sp} = K^{sp}$ .

## 4.2 The likelihood function

The model is fitted to CPUE and survey abundance indices, commercial and survey catch-at-age data, as well as to the stock-recruitment curve to estimate model parameters. Contributions by each of these to the negative of the log-likelihood ( $-\ell nL$ ) are as follows.

### 4.2.1 CPUE relative abundance data

The likelihood is calculated assuming that the observed abundance index is log-normally distributed about its expected value:

$$I_y^{f,i} = \hat{I}_y^{f,i} \exp(\varepsilon_y^{f,i}) \quad \text{or} \quad \varepsilon_y^{f,i} = \ln(I_y^{f,i}) - \ln(\hat{I}_y^{f,i}) \quad 4.13$$

where

$I_y^{f,i}$  is the abundance index for year  $y$  and series  $i$  corresponding to the  $f$ th fleet,

$\hat{I}_y^{f,i} = \hat{q}^{f,i} \hat{B}_y^f$  is the corresponding model estimate, where  $\hat{B}_y^f$  is the model estimate of exploitable resource biomass corresponding to fleet  $f$ , given by equation 4.10,

$\hat{q}^{f,i}$  is the constant of proportionality for abundance series  $i$ , and

$\varepsilon_y^{f,i}$  from  $N(0, (\sigma_y^{f,i})^2)$ .

To correct for possible negative bias in estimates of variance  $(\sigma_y^{f,i})^2$  and to avoid according unrealistically high precision (and so giving inappropriately high weight) to the CPUE data, a lower bound  $(\sigma_A^{f,i})^2$  on each CPUE series is sometimes input to the assessment model.

The contribution of the CPUE data to the negative of the log-likelihood function (after removal of constants) is then given by:

$$-\ell nL^{CPUE} = \sum_f \sum_i \sum_y \left\{ \ln \sqrt{(\sigma_y^{f,i})^2 + (\sigma_A^{f,i})^2} + (\varepsilon_y^{f,i})^2 / \left[ 2 \left( (\sigma_y^{f,i})^2 + (\sigma_A^{f,i})^2 \right) \right] \right\} \quad 4.14$$

where

$\sigma_y^{f,i}$  is the (minimum, when  $\sigma_A^{f,i} = 0$ ) standard deviation of the residuals for the logarithms of index  $i$  for fleet  $f$  in year  $y$ ,

$\sigma_A^{f,i}$  is the square root of the additional variance for abundance series  $i$ , which is an input value; alternatively, this can be used to as a means of specifying an effective lower bound for  $\sigma_y^{f,i}$ .

Homoscedasticity of residuals is usually assumed, so that  $\sigma_y^{f,i} = \sigma^{f,i}$  is estimated in the fitting procedure by its maximum likelihood value:

$$\hat{\sigma}^{f,i} = \sqrt{1/n_{f,i} \sum_y (\ln(I_y^{f,i}) - \ln(q^{f,i} \hat{B}_y^f))^2 - (\sigma_A^{f,i})^2} \quad 4.15$$

where  $n_{f,i}$  is the number of data points for abundance index  $i$  for fleet  $f$ .

The catchability coefficient  $q^{f,i}$  for abundance index  $i$  for fleet  $f$  is estimated by its maximum likelihood value, which in the more general case of heteroscedastic residuals, is given by:

$$\ln \hat{q}^{f,i} = \frac{\sum_y \left[ 1 / \left\{ (\sigma_y^{f,i})^2 + (\sigma_A^{f,i})^2 \right\} \right] (\ln I_y^{f,i} - \ln \hat{B}_y^f)}{\sum_y \left[ 1 / \left\{ (\sigma_y^{f,i})^2 + (\sigma_A^{f,i})^2 \right\} \right]} \quad 4.16$$

## 4.2.2 Survey abundance data

Data from the research surveys are treated as relative abundance indices in a similar manner to the CPUE series above, with survey selectivity function  $S_a^{surv}$  replacing the commercial selectivity  $S_{y,a}^f$  (see equations 4.11 and 4.12 above). Account is also taken of the begin- or mid-year nature of the survey.

An estimate of sampling variance is available for most surveys and the associated  $\sigma_y^i$  is generally taken to be given by the corresponding survey CV. However, these estimates likely fail to include all sources of variability, and unrealistically high precision (low variance and hence high weight) could hence be accorded to these indices. The contribution of the survey data to the negative log-likelihood is of the same form as that of the CPUE abundance data (see equation 4.14). The procedure adopted takes into account an additional variance in the same manner as for the CPUE abundance indices, but instead of being input, the additional variance  $(\sigma_A)^2$  is treated as another

estimable parameter in the minimisation process. This procedure is carried out enforcing the constraint that  $(\sigma_A)^2 > 0$ , i.e., the overall variance cannot be less than its externally input component.

### 4.2.3 Commercial catches-at-age

The contribution of the catch-at-age data to the negative of the log-likelihood function when assuming an “adjusted” lognormal error distribution is given by:

$$-\ln L^{age} = \sum_f \sum_y \sum_a \left[ \ln \left( \sigma_{com}^f / \sqrt{\hat{p}_{y,a}^f} \right) + \hat{p}_{y,a}^f \left( \ln p_{y,a}^f - \ln \hat{p}_{y,a}^f \right)^2 / 2 \left( \sigma_{com}^f \right)^2 \right] \quad 4.17$$

where

$p_{y,a}^f = C_{y,a}^f / \sum_{a'} C_{y,a'}^f$  is the observed proportion of fish caught by fleet  $f$  in year  $y$  that are of age  $a$ ,  
 $\hat{p}_{y,a}^f = \hat{C}_{y,a}^f / \sum_{a'} \hat{C}_{y,a'}^f$  is the model-predicted proportion of fish caught by fleet  $f$  in year  $y$  that are of age  $a$ , where:

$$\hat{C}_{y,a}^f = N_{y,a} e^{-M_a/2} S_{y,a}^f F_y^f \quad 4.18$$

and

$\sigma_{com}^f$  is the standard deviation associated with the catch-at-age data for fleet  $f$ , which is estimated in the fitting procedure by:

$$\hat{\sigma}_{com}^f = \sqrt{\sum_y \sum_a \hat{p}_{y,a}^f \left( \ln p_{y,a}^f - \ln \hat{p}_{y,a}^f \right)^2 / \sum_y \sum_a 1} \quad 4.19$$

The log-normal error distribution underlying equation 4.17 is chosen on the grounds that (assuming no ageing error) variability is likely dominated by a combination of interannual variation in the distribution of fishing effort, and fluctuations (partly as a consequence of such variations) in selectivity-at-age, which suggests that the assumption of a constant coefficient of variation is appropriate. However, for ages poorly represented in the sample, sampling variability considerations must at some stage start to dominate the variance. To take this into account in a simple manner, motivated by multinomial distribution properties, Punt (pers. commn) advocates weighting by the expected proportions (as in equation 4.17) so that undue importance is not attached to data based upon a few samples only.

Commercial catches-at-age are incorporated in the likelihood function using equation 4.17, for which the summation over age  $a$  is taken from age  $a_{minus}$  (considered as a minus group) to  $a_{plus}$  (a plus

group). The ages for the minus- and plus-groups are chosen so that typically a few percent, but no more, of the fish sampled fall into these two groups.

#### 4.2.4 Survey catches-at-age

The survey catches-at-age are incorporated into the negative of the log-likelihood in an analogous manner to the commercial catches-at-age, assuming an adjusted log-normal error distribution (equation 4.17) with:

$p_{y,a}^{surv} = C_{y,a}^{surv} / \sum_{a'} C_{y,a'}^{surv}$  is the observed proportion of fish of age  $a$  from survey  $surv$  in year  $y$ ,

$\hat{p}_{y,a}^{surv}$  is the expected proportion of fish of age  $a$  in year  $y$  in the survey  $surv$ , given by:

$$\hat{p}_{y,a}^{surv} = \frac{S_a^{surv} N_{y,a}}{\sum_{a'=0}^m S_{a'}^{surv} N_{y,a'}} \quad 4.20$$

for begin-year (summer) surveys, or

$$\hat{p}_{y,a}^{surv} = \frac{S_a^{surv} N_{y,a} \exp(-M_a/2) \left(1 - \sum_f S_{y,a}^f F_y^f / 2\right)}{\sum_{a'=0}^m S_{a'}^{surv} N_{y,a'} \exp(-M_{a'}/2) \left(1 - \sum_f S_{y,a'}^f F_y^f / 2\right)} \quad 4.21$$

for mid-year (winter) surveys.

#### 4.2.5 Stock-recruitment function residuals

The stock-recruitment residuals are assumed to be log-normally distributed and serially correlated. Thus, the contribution of the recruitment residuals to the negative of the log-likelihood function is given by:

$$-\ln L^{SR} = \sum_{y=y1+1}^{y2} \left[ \ln \sigma_R + \left( \frac{\zeta_y - \rho \zeta_{y-1}}{\sqrt{1 - \rho^2}} \right)^2 / 2\sigma_R^2 \right] \quad 4.22$$

where

$\zeta_y = \rho\zeta_{y-1} + \sqrt{1-\rho^2}\varepsilon_y$  is the recruitment residual for year  $y$ , which is estimated for year  $y1$  to  $y2$  (see equation 4.4),

$\varepsilon_y$  from  $N(0, (\sigma_R)^2)$

$\sigma_R$  is the standard deviation of the log-residuals, which is input, and

$\rho$  is the serial correlation coefficient, which is input.

Because of the maximum-likelihood nature of the assessment methodology applied to incorporate recruitment fluctuations, the value of  $\sigma_R$  cannot be estimated from the data but must be independently specified. Indeed, the penalised likelihood formulation used will always yield a maximum for the deterministic limit of  $\sigma_R \rightarrow 0$ . This is problematic particularly in cases where estimates of stock status and productivity are strongly dependent on the value chosen for  $\sigma_R$ . One would need to adopt fully Bayesian methodology, together with a prior for  $\sigma_R$  to deal properly with this difficulty.

In the interest of simplicity, equation 4.22 omits a term in  $\zeta_{y1}$  for the case when serial correlation is assumed ( $\rho \neq 0$ ), which is generally of little quantitative consequence to values estimated (Cryer, 1986).

However, for the applications reported in this thesis for the southern African hake stocks, the stock-recruitment residuals have been assumed not to be serially correlated, i.e.,  $\rho = 0$ .

### 4.3 Estimation of precision

Coefficients of variation (CVs) and probability intervals have been evaluated using the Hessian-based approximation, which involves replacing the log-likelihood surface in the vicinity of its global maximum by a quadratic form (Rice, 1995). The delta method is used by ADMB to compute CVs for quantities that are functions of estimable parameters of the model. This approach does not give exact answers. However, the more accurate likelihood profile calculations are very time consuming, and the Hessian-based results regarding precision were considered adequate for the purposes for which such results were used here.



## 4.4 Model parameters

### 4.4.1 Estimable parameters

In addition to the virgin spawning biomass ( $K^{sp}$ ) and the “steepness” of the stock-recruitment relationship ( $h$ ), the following parameters are also estimated in some of the model fits undertaken.

#### Natural mortality:

Natural mortality ( $M_a$ ) is assumed either to be independent of age or age-specific, and input (fixed) or estimated using the following functional form in the latter case:

$$M_a = \begin{cases} M_2 & \text{for } a \leq 1 \\ \alpha^M + \frac{\beta^M}{a+1} & \text{for } a \geq 2 \end{cases} \quad 4.23$$

$M_0$  and  $M_1$  are set equal to  $M_2$  ( $= \alpha^M + \beta^M / 3$ ) as there are no data (hake of ages younger than 2 are rare) which would allow independent estimation of  $M_0$  and  $M_1$ .

#### Fishing selectivity-at-age:

The fleet-specific fishing selectivity,  $S_a^f$ , is either estimated directly:

$$S_a^f = \begin{cases} \text{estimated separately} & \text{for } a \leq a_{est} \\ = 1 & \text{for } a > a_{est} \end{cases} \quad 4.24$$

or in terms of a logistic curve given by:

$$S_a^f = \begin{cases} 0 & \text{for } a = 0 \\ \left[ 1 + \exp\left(-\frac{(a - a_c^f)}{\delta^f}\right) \right]^{-1} & \text{for } a \geq 1 \end{cases} \quad 4.25$$

where

$a_c^f$  years is the age-at-50% selectivity,

$\delta^f$  year<sup>-1</sup> defines the steepness of the ascending limb of the selectivity curve.

The selectivity is sometimes modified to include a decrease in selectivity at older ages, as follows:

$$S_a^f \rightarrow S_a^f \exp\left(-s^f (a - a_{slope})\right) \quad \text{for } a > a_{slope}, \quad 4.26$$

where

$s^f$  measures the rate of decrease in selectivity with age for fish older than  $a_{slope}$  for the fleet concerned, and is referred to as the “selectivity slope” in this thesis.

## 4.4.2 Input parameters

### Age-at-maturity:

The proportion of fish of age  $a$  that are mature is approximated by

$$f_a = \begin{cases} 0 & \text{for } a < a_{mat} \\ 1 & \text{for } a \geq a_{mat} \end{cases} \quad 4.27$$

where  $a_{mat} = 4$  for the southern African hake stocks (Punt and Leslie, 1991).

### Weight-at-age:

The weight-at-age (begin and mid-year) is calculated from the combination of the von Bertalanffy growth equation and the mass-at-length function (equations 1.1 and 1.2 in Section 1.1.3).

## 5 Assessment of the Namibian hake resource

The assessment described below was originally reported in Rademeyer and Butterworth (2001a).

### 5.1 Data

The data used for the assessment of the Namibian hake stock were obtained from NatMIRC (National Marine Information and Research Centre) of Namibia. For the last four years, on-board observer schemes in Namibia have allowed catch statistics to distinguish between the two hake species. However, these data are not yet available and the following assessment treats the two Cape hake species as one.

#### 5.1.1 Total catch

Information on overall annual catch (by mass), CPUE and survey biomass estimates (with their estimated coefficient of variation) is listed in Table 5.1. Although hake off Namibia are also caught by longlining, the principal fishing method is deep-sea bottom trawling. Because of the relatively small proportion of hake caught by longlining in this region (less than 10%, Illende, NatMIRC, pers. commn), the model assumes a single fleet fishery, with the catches all assumed to come from the offshore fleet. Catches are available from 1964 to 2000 (1964 to 1988, ICSEAF, 1989; 1989 to 1996, Anon., 1997; 1997 to present: Illende, NatMIRC, pers. commn). The catch for 2001 is set to the TAC value for that year, as catch estimates for that year were not available at the time of this analysis.

#### 5.1.2 Abundance indices

Both CPUE indices and survey biomass estimates are treated as relative indices in the Reference Case assessment. Three CPUE time-series are available for assessing the status of the resource:

- ICSEAF CPUE for Divisions 1.3 + 1.4, from 1965 to 1988 (ICSEAF, 1989),
- ICSEAF CPUE for Division 1.5 from 1965 to 1988 (ICSEAF, 1989), and

- GLM standardised CPUE from 1992 to 2000 (Brandão *et al.*, 2001).

The ICSEAF CPUE values for 1981-1988 (in italics in Table 5.1), however, are not used in the Reference Case assessment, as recommended by the 2000 BENEFIT stock assessment workshop (BENEFIT, 2000). Indeed, these data, which show a clear positive trend, are considered unreliable due to the known misreporting of catches over this period (Anon., 1997; see Section 1.2.1) (the sensitivity of the model results to the inclusion of the 1981-1988 ICSEAF CPUE data is shown in Appendix A1, as well as the effect of increasing the 1980-1989 catches by 25%). Furthermore, the two ICSEAF CPUE series are each downweighted by 50% in the likelihood maximisation procedure, as they are treated as equivalent indices of the same quantity. The 1992-2000 GLM standardised CPUE series is as revised by Brandão *et al.* (2001), and takes account the following factors: latitude, year, month, depth and gross tonnage of a vessel.

Data from Spanish research surveys (summer and winter) are available from 1983 to 1990 (Anon., 1997). More recent research surveys have been conducted bi-annually from 1990 to 1996, and in summer only from 1997 (Johnson, NatMIRC, pers. commn). Until 1999, these surveys were conducted by the Norwegian vessel, *RV Dr Fridtjof Nansen* (referred to as the “*Nansen* surveys” hereafter). However, from 2000 onwards, the surveys have been conducted by commercial trawlers and a different value for the multiplicative bias factor  $q$  (“catchability”) is assumed to apply to the surveys conducted by these trawlers. Calibration experiments have been conducted between the *Nansen* and three of the trawlers used in the research surveys in order to provide a basis to relate the catchability coefficients of the two types of vessel ( $q_{Nansen}$  and  $q_{trawler}$ ) (Butterworth *et al.*, 2001). The log CPUE ratios between the *Nansen* and the trawlers are shown in Table 5.2. Applying inverse variance weighting to these results gives the following estimates:

$$\Delta \ln q = 0.100 \quad \text{with } \sigma_{\Delta \ln q} = 0.032.$$

where

$$\ln q_{trawler} = \ln q_{Nansen} + \Delta \ln q \quad 5.1$$

The following contribution is therefore added to the negative log-likelihood in the assessment:

$$-\ln L^{q-ch} = (\ln q_{trawler} - \ln q_{Nansen} - \Delta \ln q)^2 / 2\sigma_{\Delta \ln q}^2 \quad 5.2$$

Note that  $q_{trawler}$  above refers to the average value for the commercial trawlers, so in order to allow for inter-trawler variability in  $q$ , the sampling CVs from the surveys from 2000 onwards ( $\sigma_y$ ) are increased as shown below to account for the standard deviation of 0.153 of the three means in Table 5.2 about their global weighted mean, i.e.,:

$$\sigma_y^2 \rightarrow \sigma_y^2 + 0.153^2 \quad 5.3$$

Equation 4.16 for the maximum likelihood estimate of  $q$  no longer applies with the addition of the term in equation 5.2 to the log-likelihood, but closed-form solutions are still available for the maximum likelihood estimates of  $q_{Nansen}$  and  $q_{trawler}$  from setting partial derivatives of the total log-likelihood with respect to these two variables equal to zero. For the survey data, the likelihood contributions (and only ones which involve  $q_{Nansen}$  and  $q_{trawler}$ ) are as follows:

$$\begin{aligned} -\ln L^{surv} = & \sum_{y_N} \left[ \ln \sqrt{\sigma_y^2 + \sigma_A^2} + \frac{(\ln I_y^{surv,i} - \ln q_{Nansen} - \ln B_y^{surv})^2}{2(\sigma_y^2 + \sigma_A^2)} \right] \\ & + \sum_{y_T} \left[ \ln \sqrt{\sigma_y^2 + \sigma_A^2} + \frac{(\ln I_y^{surv,i} - \ln q_{trawler} - \ln B_y^{surv})^2}{2(\sigma_y^2 + \sigma_A^2)} \right] \\ & + (\ln q_{trawler} - \ln q_{Nansen} - \Delta \ln q)^2 / 2\sigma_{\Delta \ln q}^2 \end{aligned} \quad 5.4$$

where  $y_N/y_T$  are the years with Nansen/trawler surveys.

A minimum is obtained from setting partial derivatives of the total log-likelihood with respect to these two variables equal to zero, i.e.:

$$\begin{aligned} \sum_{y_N} \left( \frac{(\ln I_y^{surv,i} - \ln q_{Nansen} - \ln B_y^{surv})}{\sigma_y^2 + \sigma_A^2} \right) \left( -\frac{1}{q_{Nansen}} \right) \\ + \frac{(\ln q_{trawler} - \ln q_{Nansen} - \Delta \ln q)}{\sigma_{\Delta \ln q}^2} \left( -\frac{1}{q_{Nansen}} \right) = 0 \end{aligned} \quad 5.5$$

and

$$\begin{aligned} \sum_{y_T} \left( \frac{(\ln I_y^{surv,i} - \ln q_{trawler} - \ln B_y^{surv})}{\sigma_y^2 + \sigma_A^2} \right) \left( -\frac{1}{q_{trawler}} \right) \\ + \frac{(\ln q_{trawler} - \ln q_{Nansen} - \Delta \ln q)}{\sigma_{\Delta \ln q}^2} \left( \frac{1}{q_{trawler}} \right) = 0 \end{aligned} \quad 5.6$$

It follows that:

$$\ln q_{Nansen} \left( \frac{1}{\sum_{y_N} \sigma_y^2 + \sigma_A^2} + \frac{1}{\sigma_{\Delta \ln q}^2} \right) + \ln q_{trawler} \left( -\frac{1}{\sigma_{\Delta \ln q}^2} \right) = \sum_{y_N} \frac{(\ln I_y^{surv,i} - \ln B_y^{surv})}{\sigma_y^2 + \sigma_A^2} - \frac{\Delta \ln q}{\sigma_{\Delta \ln q}^2} \quad 5.7$$

and

$$\ln q_{trawler} \left( \frac{1}{\sum_{y_T} \sigma_y^2 + \sigma_A^2} + \frac{1}{\sigma_{\Delta \ln q}^2} \right) + \ln q_{Nansen} \left( -\frac{1}{\sigma_{\Delta \ln q}^2} \right) = \sum_{y_T} \frac{(\ln I_y^{surv,i} - \ln B_y^{surv})}{\sigma_y^2 + \sigma_A^2} + \frac{\Delta \ln q}{\sigma_{\Delta \ln q}^2} \quad 5.8$$

For given  $\sigma_y$ ,  $\sigma_A$ ,  $I_y^{surv,i}$ ,  $B_y^{surv}$ , these are two simultaneous linear equations which have a closed form solution for  $\ln q_{Nansen}$  and  $\ln q_{trawler}$ .

### 5.1.3 Catches-at-age

Available commercial catch-at-age data are shown in Table 5.3, and those for the *Nansen* surveys in Tables 5.4 and 5.5 for summer and winter surveys respectively. They are given as proportions. Commercial catches-at-age for the period 1968 to 1988 are from the ICSEAF records for Divisions 1.3, 1.4 and 1.5 (obtained from summing the values for ICSEAF Div. 1.3 + 1.4 with the values for ICSEAF Div. 1.5; 1965 to 1987, ICSEAF 1989), whereas those from 1997 to 1999 are from NatMIRC catch-at-length data for the fishery off Namibia, coupled to an age-length key for the 1999 season (Dealie, NatMIRC, pers. comm). The survey catches-at-age are also based upon 1999 age-length keys. A separate age-length key for each species is available and has been applied to get the survey catches-at-age for each species, which were subsequently combined (Dealie, NatMIRC, pers. comm). Commercial catch-at-age data since 1997 were computed in the same way. The use of an age-length key obtained for one year to estimate catches-at-age for other years is undesirable, because even if growth is constant over time (which is not necessarily the case), changing recruitment levels from year to year will result in changes to the age-length key. However, despite the consequent possible bias of the commercial catch-at-age data for 1997 and 1998 and of the survey catch-at-age data, they still provide important information about the structure of the catch, and seem desirably taken into account in an age-structured production model. Future assessments should, however, consider fitting the model to the length-frequency data of the catches rather than the catch-at-age data, to avoid some of these problems.

The minus- and plus-groups chosen for the commercial catches-at-age are ages 2 and 8 respectively, while for the survey these ages have been chosen as 0 and 8.

## 5.2 Reference Case assessment specifications

The following assumptions have been made for the Reference Case assessment of the hake stock off Namibia:

- 1)  $B_{1964}^{sp} = K^{sp}$ : The model assumes that the stock was at its pristine level when the fishery commenced. Although it might be appropriate to relax this assumption, there are no age or size composition data in the early years of the fishery to provide a signal to assess whether or not such an assumption is justified. It is also implicitly assumed that the unexploitation equilibrium level has not changed over the period to which the assessment applies, i.e., no regime shifts have occurred (sensitivity of the model to a regime shift is however investigated in the OMP context, see Chapter 11).
- 2) *Natural mortality*:  $M_a$  is taken to be independent of age ( $M$ ), as there is not enough information in the data to estimate an age-dependent natural mortality.
- 3) *Commercial selectivity-at-age*: The selectivity takes the form of a logistic curve (equation 4.25), with the slope parameter  $s$  of equation 4.26 set at zero. Furthermore, the selectivity is taken to differ pre- and post-independence. The post-independence period was marked by the exclusion of vessels from fishing in waters shallower than 200 m (to avoid juveniles), i.e., it is characterised by a lower selectivity on the younger age classes. The selectivity function is taken to be independent of time during this period (1990 to 2001) and is denoted in Tables by  $S_{post,a}$ . For the pre-independence period, the catch-at-age data indicate a trend over time towards selecting younger fish. Selectivity has therefore been modelled by a form  $S_{pre1,a}$ , which is constant over the 1964 to 1973 period, after which it changes in a linear fashion to reach a form ( $S_{pre2,a}$ ) in 1984, and this remains constant from then until the end of this earlier period in 1989.
- 4) *Survey selectivity-at-age*: The survey selectivity function also takes the form of a logistic curve (equation 4.25), with a slope parameter  $s$  (equation 4.26) of zero. It is kept constant over the whole period of the assessment and is assumed to be the same for all surveys (i.e., Spanish and *Nansen*, whether summer or winter). By setting  $s = 0$  for both the commercial fishery and the surveys, the assumption is being made that older fish are all equally susceptible to fishing – this is discussed further in Chapter 9.
- 5) *Stock-recruitment residuals*:  $\sigma_R$ , which measures the extent of residual variability, is fixed at 0.25 (the reasons for this are discussed later). The residuals are assumed not to be serially correlated, i.e.,  $\rho = 0$ . They are estimated from year 1964 to 1997 which correspond to years  $y_1$  and  $y_2$  in

equation 4.22; reliable estimation for subsequent years is not possible given the limited sampling to date of the cohorts in question.

- 6) *Lower bound on the variance on the CPUE data:* Since maximum likelihood estimates of the standard deviations ( $\sigma^{f,i}$ ) associated with these CPUE series turn out not to be unrealistically small, no minima for these  $\sigma^{f,i}$  estimates have been assumed.
- 7) *Additional variance on surveys:* A common variance is estimated for the Spanish surveys for which no individual estimates are available. For the *Nansen* surveys, for which sampling CVs are available for each survey, an additional variance is estimated.

## 5.3 Results and Discussion

Only results from the Reference Case assessment are provided in this Chapter; however, variants of this assessment which deal with some of the uncertainties about the model-assumptions/structure are described in Appendix A1 and Chapter 11. Management quantity estimates for the Reference Case assessment are given in Table 5.6, while Fig. 5.1 shows the resource abundance time-series estimated. This shows a rapid drop in abundance from the beginning of the fishery to the mid-1980's, as is to be expected from the trend in the ICSEAF CPUE abundance indices.

A strong recruitment was observed in the catches in 1982 and 1983 (1981 and 1982 year classes – Table 5.3) and is clearly reflected in the estimated resource abundance: the spawning biomass (age 4+) shows a substantial increase in 1985. The years 1983 and 1984 were characterised by intense upwelling and strong penetration by the Angola current (Boyd *et al.*, 1985), two oceanographical features which have been associated with larger stock sizes (Strogalev, 1984). These strong cohorts came when the resource was at its lowest (about 25% of pre-exploitation level) and brought the stock close again to its Maximum Sustainable Yield Level. After this substantial increase, the hake resource off Namibia shows a decrease again until the early 1990's.

Since Namibia's declaration of independence in 1990, the large reduction in the TAC at that time has assisted a slight recovery. The best estimate of current status of the Namibian hake stock is that it is relatively healthy, at 40% of its pre-exploitation level in terms of spawning biomass. This resource is estimated to be able to yield a maximum of 300 thousand tons per annum, at a spawning biomass level of 46% of the pre-exploitation level. The statistical precision of these estimates however is relatively low. Fig. 5.1b shows the 90% probability intervals for the spawning biomass estimates (in terms of the pre-exploitation level), as well as for the MSY level. The 90% probability interval is 21 to



66% for  $B_y^{SP} / K^{SP}$  in 2001, and the possibility that there has been some net decline in this resource over the last decade cannot be excluded (see lower probability limit in Fig. 5.1b).

Fig. 5.2 and Fig. 5.3 show the Reference Case model fit to the abundance indices and catch-at-age data respectively, comparing the observed values and the corresponding model predictions. The model shows generally reasonable fits to all the indices. However it does not seem to be able to provide a decrease in the resource abundance in the first two years of the assessment as substantial as the one reflected by the historic CPUE series; but catches in those years were relatively small, so that these anomalies could reflect either or both of higher sampling variability, and the fishery exploiting small dense localised concentrations in its initial stage. Furthermore, the model indicates relatively high levels of residual variance, particularly for more recent years. The additional variance for the *Nansen* surveys is estimated to be  $\sigma_A = 0.225$ , which suggests that there is considerably more variability in these indices than that accounted for by sampling variability alone. Changes in the availability of the fish with environmental conditions are probably an important source of this additional variability.

From Fig. 5.3a and b, it is clear that before independence, when fishing vessels were not excluded from waters shallower than 200 m, the commercial catches consisted mainly of relatively small hake (less than 4 years old). Since independence, the catches have been more widely spread across ages, with a mode at fish of age 5, but also relatively large proportions of 6 and 7-year old fish. Fig. 5.3c and d show the model fit to the *Nansen* survey catches-at-age. Although the selectivity is assumed to be the same for winter and summer, the summer surveys are catching a slightly smaller proportion of small to medium sized fish (3-years and younger) on average. Fig. 5.4 plots the

standardised catch-at-age residuals ( $\varepsilon_{y,a} \rightarrow \frac{(\ln p_{y,a}^i - \ln \hat{p}_{y,a}^i)}{\sigma^i / \sqrt{\hat{p}_{y,a}^i}}$ ) for the commercial and survey data.

This plot allows for the identification of potential yearly patterns in the residuals, which is not possible in Fig. 5.3 where the data are averaged over the years for which data is available. There are some indications of systematic effects in the residuals, which warrant further investigations in terms of the fishing selectivities. In the first few years of the commercial data for example, the model systematically predicts too much catch in the higher age classes (age 6 and above). The year 1983 in the commercial data also looks problematic in terms of the catch-at-age residuals, with predicted values systematically greater than the observed values for ages above 2.

The multiplicative biases  $q$  for the surveys are 0.37 and 0.42 for summer and winter *Nansen* surveys respectively. These biases are slightly higher for the 2000 and 2001 summer surveys (0.40), which were conducted by commercial trawlers (Table 5.6, third column of the '*Nansen* summer' and '*Nansen* winter' rows). This suggests that the application of the swept-area methodology to the survey

results to provide biomass estimates in absolute terms results in underestimates of the biomass by about 60%. This could be due to escapement above and below the net, avoidance of the net and to the fact that a portion of the population is off the bottom when the surveys are being conducted.

The estimate of natural mortality  $M$  of  $0.76 \text{ yr}^{-1}$  is unrealistically high for a relatively long-lived species such as hake. Similarly, the value of the steepness parameter  $h$  (0.32) estimated by the model is surprisingly low. These estimates are cause for concern and are discussed in more detail in Chapter 9.

Fig. 5.5c plots the stock-recruitment curve – with the low  $h$  value, recruitment falls off rapidly as spawning biomass drops – while Fig. 5.5a shows the estimated residuals about this function. There does not seem to be any clear pattern in the recruitment residuals. Fig. 5.5b plots the time series of recruitment. Recruitment fell relatively steadily from the commencement of the fishery to the early 1980's. Again, the very strong recruitment of 1982 is clearly visible in this figure. Since 1990, recruitment is estimated to have steadily increased.

The sensitivity of the Reference Case assessment to the value of the  $\sigma_R$ -input has been tested and is illustrated in Fig. 5.6. Sensitivity to the  $\sigma_R$ -input is the only variant of the Reference Case considered here, as it is the cause of the largest uncertainty in the model. Fig. 5.6 illustrates the effect of varying the  $\sigma_R$ -input (the input standard deviation for the stock-recruitment residuals) on a) the  $\sigma_R$ -output (calculated from the maximum likelihood estimates for the stock-recruitment residuals), b) MSY and c) the present biomass (expressed in terms of the 2001 spawning biomass as a proportion of the pre-exploitation equilibrium level). These plots indicate that the estimates of quantities of key management importance depend heavily on the value input for  $\sigma_R$ . MSY, for example, can increase more than three fold, depending on the value of  $\sigma_R$ -input. In the Reference Case assessment, the input value used for  $\sigma_R$  is 0.25, in common with the South African assessments. The reason for this choice is that, roughly speaking, the highest value of  $\sigma_R$ -input which yields a similar value for  $\sigma_R$ -output. Teleosts generally show much greater levels of recruitment fluctuations, so that even the asymptote of some 0.45 for  $\sigma_R$ -output (Fig. 5.6a) is toward the lower end of the range (e.g., Beddington and Cooke, 1983, list 26 other gadoids for only 9 of which is  $\sigma_R$  less than 0.3). Fig. 5.7 plots the time series of spawning biomass for three values of  $\sigma_R$ -input (0.10, 0.25 and 0.40). This figure illustrates how sensitive the estimates of the 1982 year class and following mid 1980's recovery are to the input value for  $\sigma_R$ . The sensitivity of the model to the value input for  $\sigma_R$  is considered further in Chapter 11.

**Table 5.1:** Total annual landings, CPUE and survey abundance data for Namibian hake (ICSEAF Divisions 1.3, 1.4 and 1.5) for the period 1964 to 2001. The GLM CPUE series is from Brandão *et al.* (2001). Catches and survey biomass estimates are in thousand tons; the value for the 2001 catch is assumed to equal the TAC for that year. CPUE values shown in italics are considered to be of questionable reliability and are excluded from the Reference Case assessment (BENEFIT, 2000). The 2000 and 2001 “Nansen” summer surveys, shown in italics, were conducted by commercial trawlers. For these years, an additional variance (CV = 0.153) has been added to the survey sampling variances to make allowance for uncertainty in the relative catchability of the trawlers compared to the *Nansen* (Butterworth *et al.*, 2001). See main text for data sources.

Year	Catches	CPUE ICSEAF		CPUE GLM (kg/h)	Spanish winter survey	Spanish summer survey	<i>Nansen</i> survey	
		1.3 + 1.4 (tons/h)	1.5 (tons/h)				summer (CV)	winter (CV)
1964	47.852							
1965	193.200	1.78	2.24					
1966	334.627	1.31	2.62					
1967	394.445	0.91	1.47					
1968	630.392	0.96	1.38					
1969	526.657	0.88	1.15					
1970	627.198	0.90	1.10					
1971	595.215	0.87	1.44					
1972	820.110	0.72	1.00					
1973	667.965	0.57	1.00					
1974	514.558	0.45	0.70					
1975	488.208	0.42	0.82					
1976	601.045	0.42	0.58					
1977	431.483	0.49	0.69					
1978	379.390	0.43	0.56					
1979	310.175	0.40	0.74					
1980	171.848	0.45	0.71					
1981	211.534	0.55	0.85					
1982	307.078	0.53	0.84					
1983	339.590	0.58	0.90		708.500			
1984	364.993	0.64	0.93		2128.260	2187.600		
1985	386.184	0.66	1.03		1215.840			
1986	381.189	0.65	0.93		938.290	1018.610		
1987	300.249	0.61	0.88		721.020			
1988	336.000	0.63	0.84		562.590	532.550		
1989	309.329				485.680	1737.840		
1990	132.379					1957.130	586.771 (0.154)	725.893 (0.119)
1991	56.135						545.824 (0.212)	
1992	87.497			1.432			817.302 (0.110)	1005.620 (0.093)
1993	108.000			1.569			942.584 (0.128)	798.308 (0.112)
1994	112.206			1.197			750.374 (0.119)	964.510 (0.090)
1995	130.362			0.767			584.928 (0.121)	647.135 (0.104)
1996	129.102			0.666			819.415 (0.139)	729.610 (0.112)
1997	116.593			0.718			663.349 (0.123)	
1998	150.825			0.925			1572.86 (0.145)	
1999	160.690			0.962			1071.53 (0.129)	
2000	162.821			0.764			1357.19 (0.195)	
2001	200.000						586.726 (0.233)	

**Table 5.2:** Log CPUE ratios between the *Nansen* and commercial trawlers in calibration experiments (Butterworth *et al.*, 2001).

	log CPUE ratios	s.e.
<i>Nansen vs Oshakati</i>	-0.2237	0.0713
<i>Nansen vs Garoga</i>	+0.0567	0.0507
<i>Nansen vs Ribadeo</i>	-0.1900	0.0494

**Table 5.3:** Commercial catches-at-age (shown as proportions) for the Namibian hake fishery. Catches for the period 1968 to 1988 are from ICSEAF records for Divisions 1.3, 1.4 and 1.5 (ICSEAF, 1989), while those from 1997 to 1999 are from NatMIRC catch-at-length data for the fishery off Namibia, coupled to an age-length key for the 1999 season (Dealie, NatMIRC, pers. commn).

Age	Proportions caught at age: <i>Merluccius capensis</i> and <i>M. paradoxus</i> combined									
	0	1	2	3	4	5	6	7	8+	
1968	0.000	0.002	0.094	0.548	0.244	0.081	0.024	0.005	0.003	
1969	0.000	0.006	0.126	0.368	0.346	0.098	0.034	0.015	0.007	
1970	0.000	0.000	0.155	0.402	0.269	0.127	0.031	0.011	0.004	
1971	0.000	0.001	0.067	0.302	0.429	0.130	0.043	0.019	0.008	
1972	0.000	0.004	0.101	0.468	0.282	0.095	0.034	0.014	0.003	
1973	0.000	0.022	0.099	0.465	0.324	0.055	0.020	0.008	0.007	
1974	0.000	0.068	0.278	0.278	0.147	0.127	0.073	0.024	0.005	
1975	0.000	0.030	0.155	0.435	0.197	0.108	0.046	0.020	0.009	
1976	0.000	0.054	0.280	0.416	0.192	0.043	0.011	0.003	0.001	
1977	0.000	0.112	0.120	0.379	0.279	0.086	0.012	0.008	0.005	
1978	0.000	0.059	0.399	0.341	0.112	0.055	0.023	0.008	0.002	
1979	0.000	0.032	0.243	0.330	0.200	0.120	0.046	0.020	0.008	
1980	0.000	0.143	0.157	0.267	0.217	0.112	0.065	0.025	0.013	
1981	0.000	0.096	0.249	0.259	0.190	0.117	0.061	0.019	0.008	
1982	0.000	0.148	0.354	0.236	0.127	0.061	0.041	0.022	0.010	
1983	0.000	0.473	0.397	0.083	0.030	0.009	0.005	0.002	0.001	
1984	0.000	0.058	0.532	0.294	0.077	0.025	0.009	0.003	0.001	
1985	0.000	0.098	0.245	0.391	0.198	0.051	0.012	0.003	0.001	
1986	0.000	0.048	0.391	0.251	0.169	0.094	0.032	0.013	0.003	
1987	0.000	0.035	0.233	0.389	0.214	0.085	0.033	0.009	0.002	
1988	0.000	0.023	0.268	0.451	0.202	0.041	0.011	0.003	0.001	
1997	0.000	0.004	0.116	0.167	0.178	0.245	0.141	0.115	0.034	
1998	0.001	0.005	0.061	0.121	0.157	0.307	0.179	0.131	0.038	
1999	0.003	0.008	0.099	0.148	0.158	0.265	0.168	0.118	0.034	

**Table 5.4:** Summer survey catches-at-age (shown as proportions): *Merluccius capensis* and *M. paradoxus* combined, based upon a 1999 age-length key for each species (similarly to the 1997-1999 data in Table 5.3) (Dealie, NatMIRC, pers. commn).

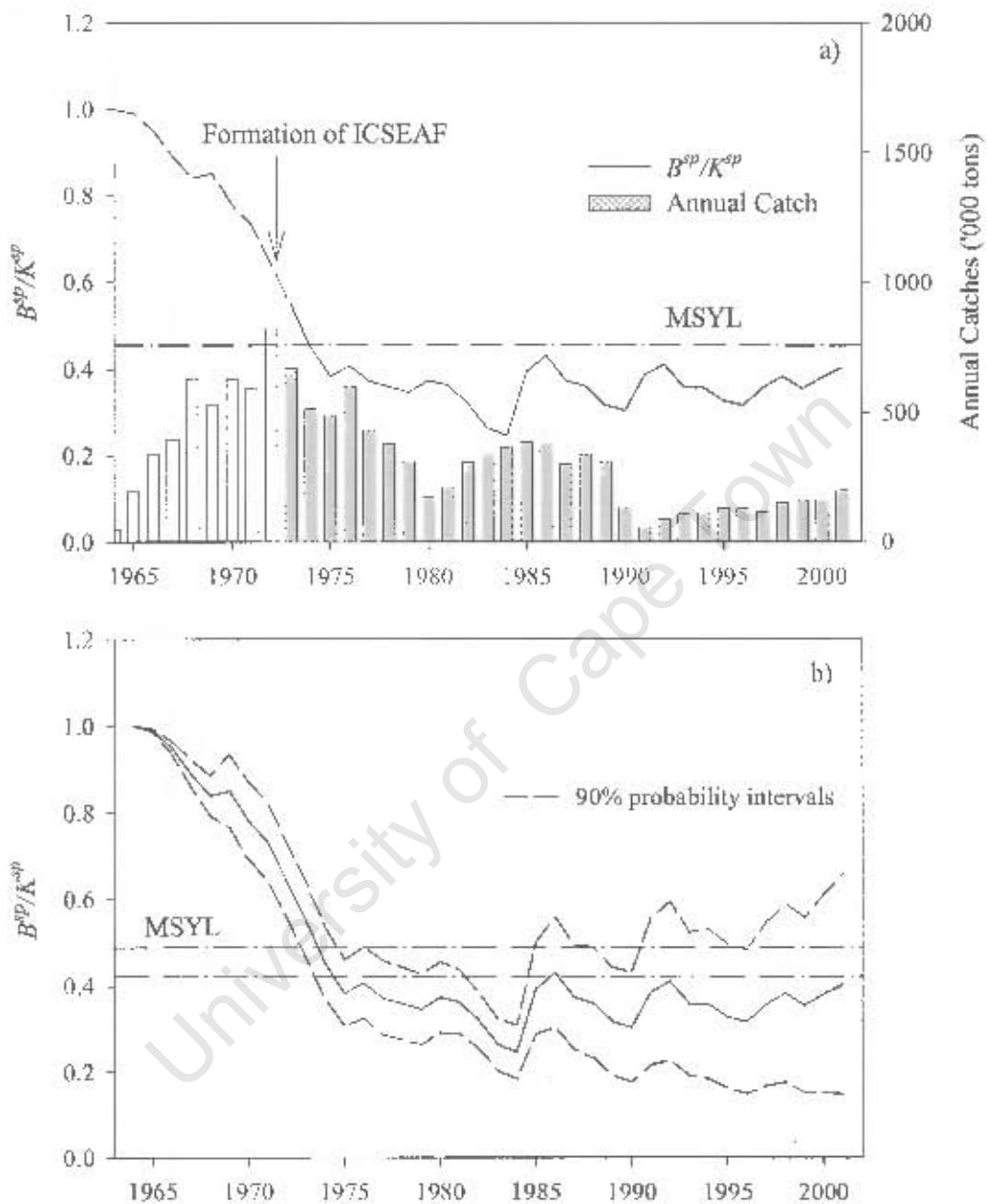
Age	Proportions caught at age: <i>Merluccius capensis</i> and <i>M. paradoxus</i> combined								
	0	1	2	3	4	5	6	7	8+
1990	0.156	0.228	0.152	0.330	0.115	0.014	0.005	0.002	0.000
1991	0.051	0.051	0.085	0.422	0.222	0.116	0.043	0.008	0.002
1992	0.249	0.204	0.153	0.195	0.083	0.069	0.033	0.010	0.002
1993	0.060	0.211	0.176	0.370	0.075	0.048	0.032	0.022	0.006
1994	0.159	0.225	0.186	0.250	0.081	0.043	0.029	0.020	0.006
1995	0.321	0.198	0.171	0.158	0.072	0.040	0.022	0.013	0.004
1996	0.128	0.204	0.178	0.289	0.106	0.049	0.025	0.017	0.005
1997	0.025	0.075	0.196	0.354	0.209	0.074	0.036	0.025	0.007
1998	0.169	0.297	0.166	0.227	0.068	0.046	0.016	0.008	0.002
1999	0.197	0.107	0.157	0.353	0.114	0.040	0.018	0.011	0.003
2000	0.051	0.270	0.225	0.346	0.060	0.029	0.011	0.006	0.002

**Table 5.5:** Winter survey catches-at-age (shown as proportions): *Merluccius capensis* and *M. paradoxus* combined, based upon a 1999 age-length key for each species (similarly to the 1997-1999 data in Table 5.3) (Dealie, NatMIRC, pers. commn).

Age	Proportions caught at age: <i>Merluccius capensis</i> and <i>M. paradoxus</i> combined								
	0	1	2	3	4	5	6	7	8+
1990	0.037	0.092	0.106	0.463	0.232	0.053	0.014	0.003	0.001
1991									
1992	0.046	0.152	0.156	0.348	0.141	0.078	0.050	0.024	0.006
1993	0.011	0.089	0.130	0.489	0.148	0.062	0.038	0.026	0.007
1994	0.056	0.119	0.189	0.337	0.143	0.080	0.042	0.027	0.008
1995	0.363	0.174	0.198	0.134	0.059	0.038	0.020	0.011	0.003
1996	0.212	0.200	0.248	0.217	0.069	0.029	0.013	0.009	0.003

**Table 5.6:** Estimates of management quantities for the Reference Case assessment of the Namibian hake. The first figure shown is the best estimate, followed by the Hessian-based CV in parenthesis.  $B^{ex}$  refers to the exploitable biomass as defined in equation 4.10 for the post-independence ( $S_{2001,a}$ ) selectivity function. The estimates of MSY and MSYL are also in terms of this post-independence selectivity function.

		Reference Case			
Total negative loglikelihood		-94.0			
-lnL : CPUE		-32.4			
-lnL: Survey		-14.1			
-lnL: CAA com.		-58.3			
-lnL: CAA surv		-8.9			
-lnL:SR Residuals		19.7			
$K^{sp}$		3640 (0.16)			
$K^{exp}$		3953 (0.18)			
$B^{sp}_{2001}$		1466 (0.31)			
$B^{ex}_{2001}$		411 (0.55)			
$h$		0.318 (0.19)			
$MSYL^{sp}$		1657 (0.20)			
$MSYL^{ex}$		476 (0.31)			
$MSY$		300 (0.25)			
$B^{sp}_{2001}/K^{sp}$		0.403 (0.39)			
$B^{ex}_{2001}/K^{ex}$		0.104 (0.63)			
$B^{sp}_{2001}/MSYL^{sp}$		0.885 (0.42)			
$B^{ex}_{2001}/MSYL^{ex}$		0.863 (0.67)			
$MSYL^{sp}/K^{sp}$		0.455 (0.04)			
$MSYL^{ex}/K^{ex}$		0.120 (0.20)			
$M$		0.76 (0.04)			
	Age	$S_{1968,a}$	$S_{1989,a}$	$S_{2001,a}$	$S_{surv,a}$
	0	0.00	0.00	0.00	0.00
	1	0.00	0.00	0.00	0.00
	2	0.09	0.63	0.01	0.77
	3	0.66	1.00	0.03	1.00
	4	0.97	1.00	0.12	1.00
	5	1.00	1.00	0.37	1.00
	6	1.00	1.00	0.72	1.00
	7	1.00	1.00	0.93	1.00
	8+	1.00	1.00	1.00	1.00
Commercial sigmas:					
CPUE ICSEAF (1.3+1.4)		0.171 (0.18)			
CPUE ICSEAF (1.5)		0.202 (0.12)			
CPUE GLM		0.211 (0.25)			
Commercial $q$ 's:					
CPUE ICSEAF (1.3+1.4)		$0.283 \times 10^3$ (0.21)			
CPUE ICSEAF (1.5)		$0.432 \times 10^3$ (0.21)			
CPUE GLM		$2.215 \times 10^3$ (0.42)			
Survey sigmas estimated:					
Spanish winter		0.391 (0.09)			
Spanish summer		0.503 (0.04)			
Survey $q$ 's:					
Spanish winter		0.401 (0.19)			
Spanish summer		0.557 (0.20)			
<i>Nansen</i> summer		0.367 (0.19)			
<i>Nansen</i> winter		0.418 (0.20)			
Commercial trawlers $q$ 's:					
		0.404 (0.25)			
Catches-at-age sigmas:					
commercial		0.110 (0.04)			
summer survey		0.114 (0.06)			
winter survey		0.161 (0.07)			
Additional sigma (survey)		0.225 (0.26)			



**Fig. 5.1:** The Reference Case ASPM assessment (which incorporates fluctuations about the stock-recruitment relationship) for the Namibian hake resource is shown in a), together with the estimated MSYL and the annual catches. The pre- and post-1972 periods are distinguished. b) shows the Hessian-based 90% probability intervals. The resource abundance is expressed in terms of spawning biomass as a proportion of its pre-exploitation equilibrium level ( $B^{sp}/K^{sp}$ ).

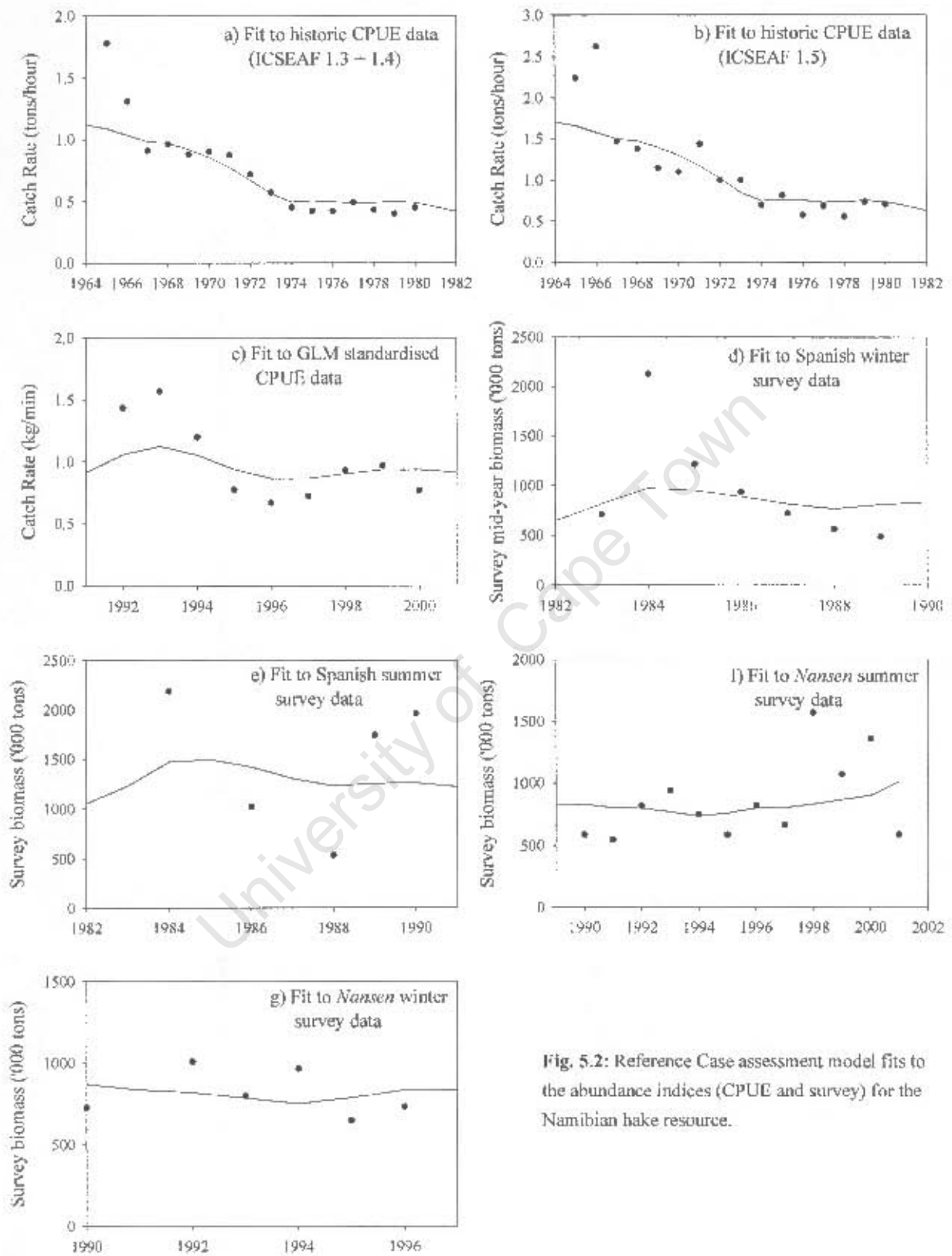


Fig. 5.2: Reference Case assessment model fits to the abundance indices (CPUE and survey) for the Namibian hake resource.



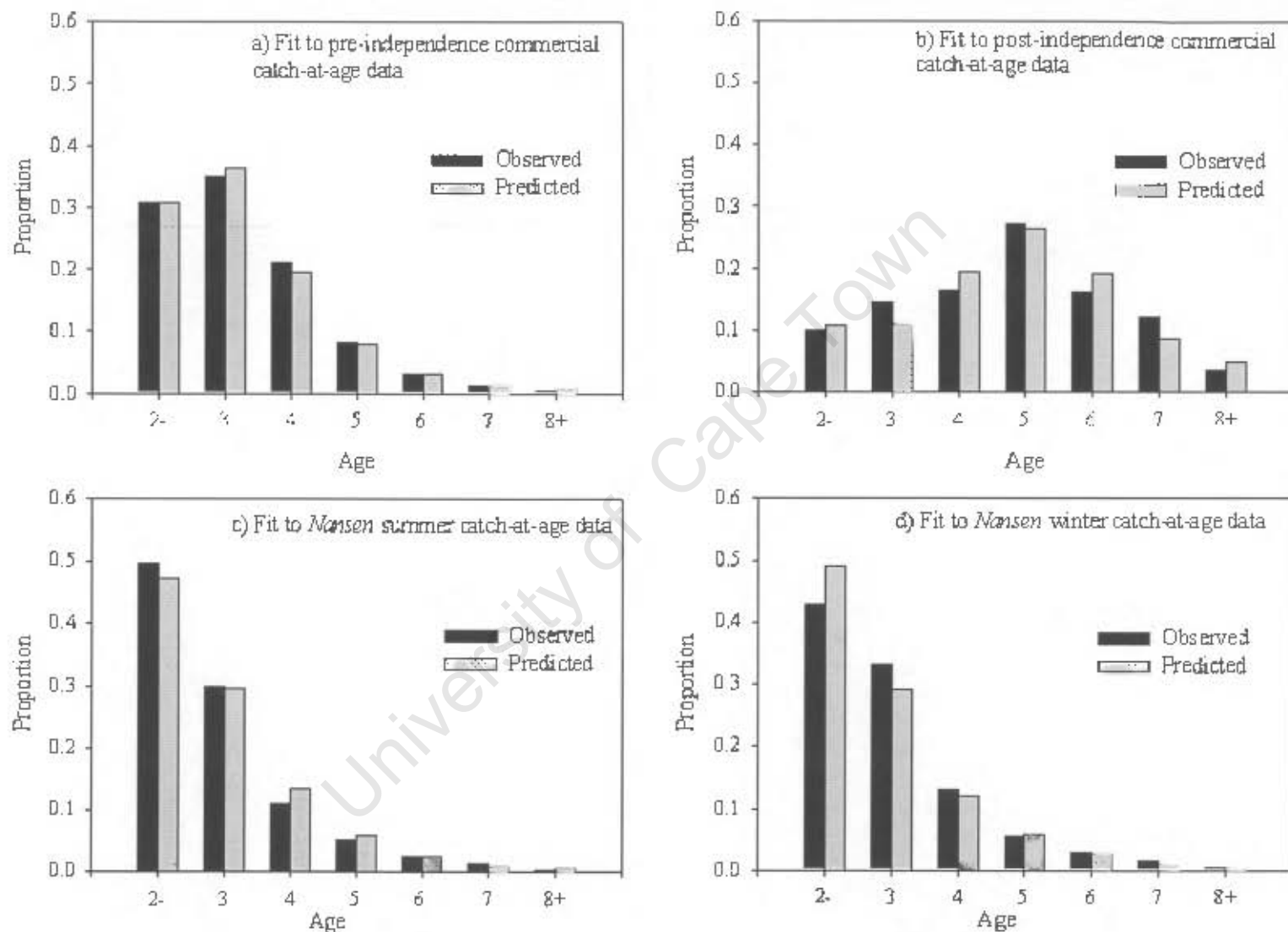


Fig. 5.3: Reference Case assessment model fits to catch-at-age data for the Namibian hake resource, as averaged over all the years with data for each data set. For the commercial data, the catches-at-age have been separated between pre- and post-independence periods.

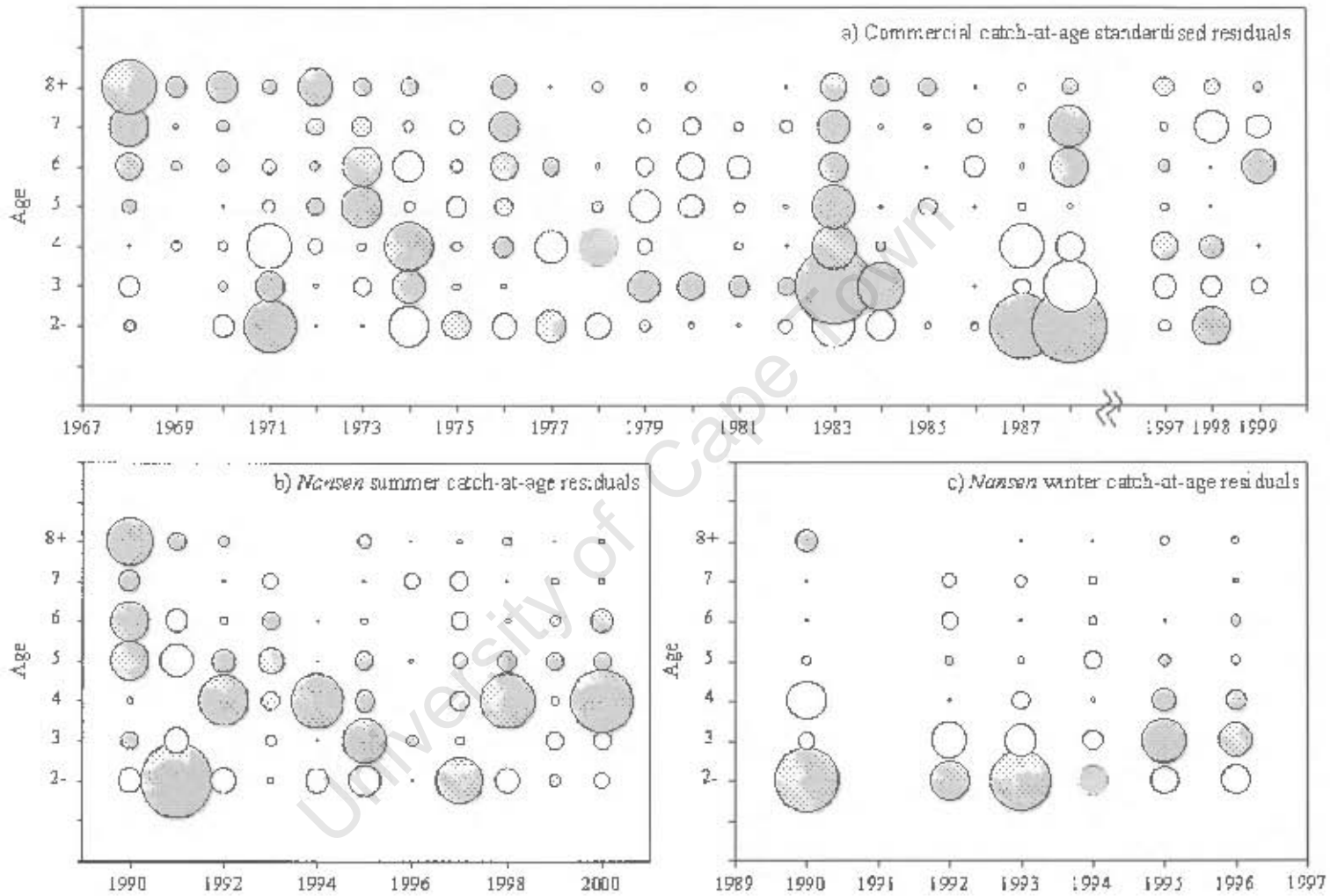
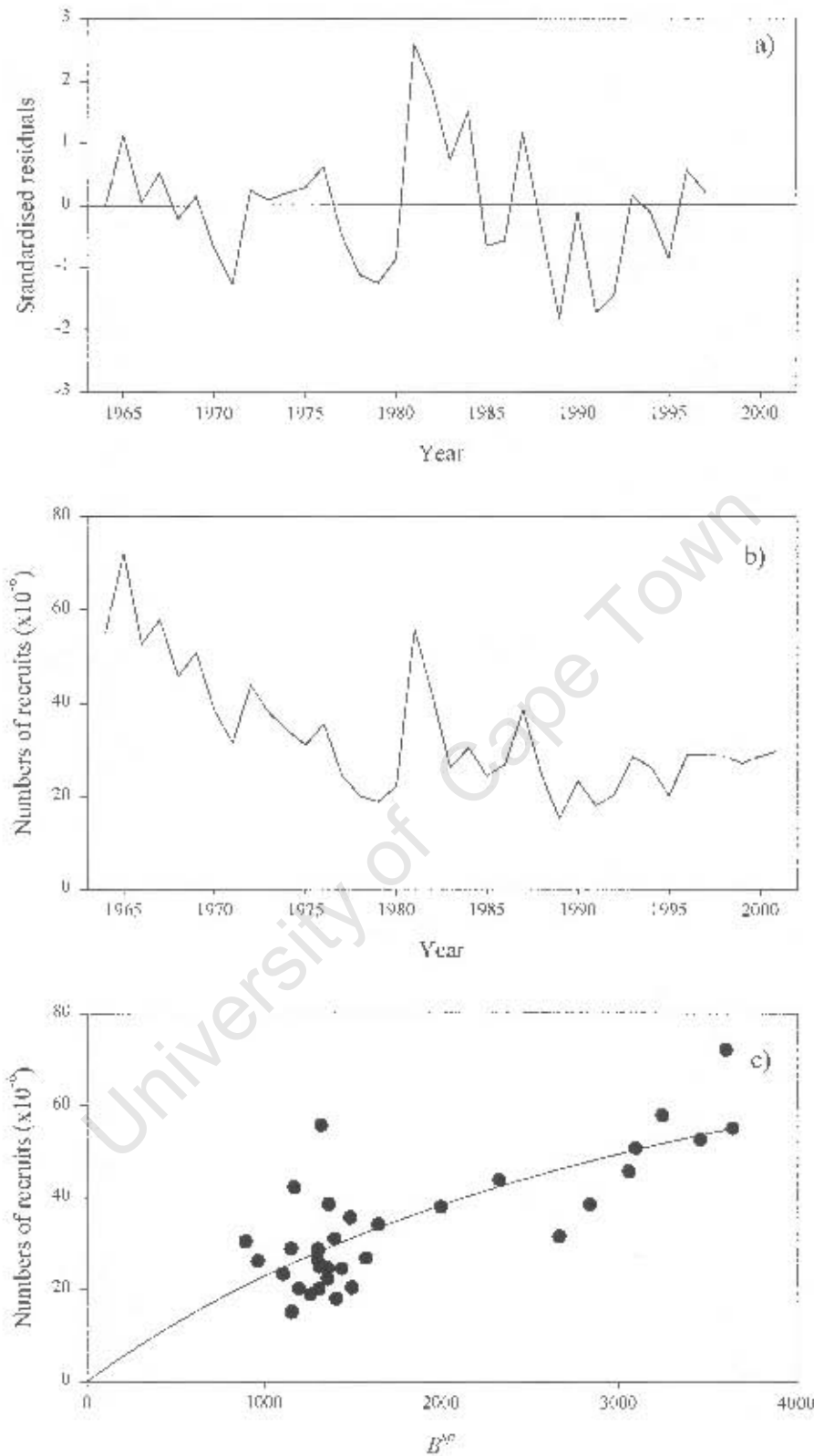
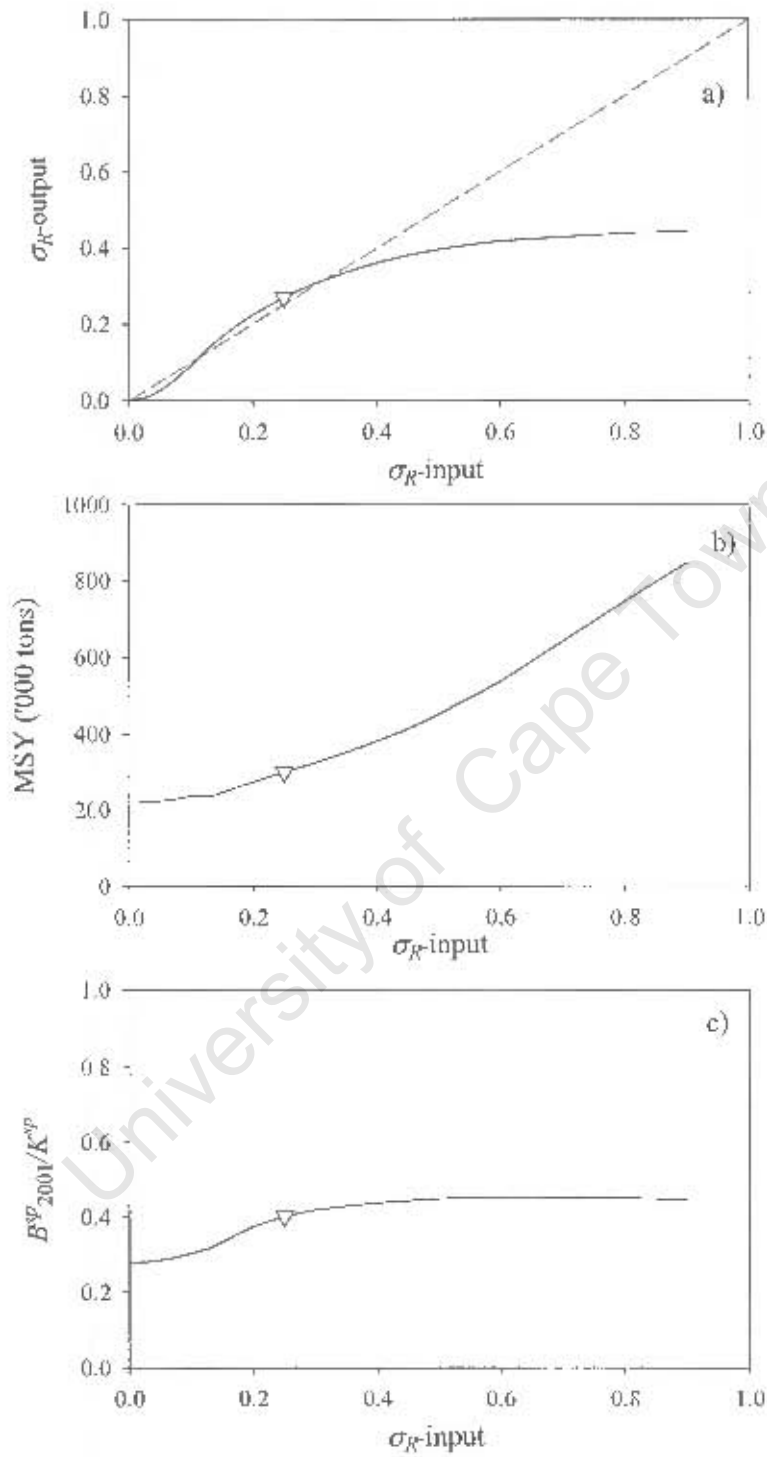


Fig 5.4: "Bubble plots" of the catch-at-age residuals for a) the commercial data, b) the *Nansen* summer data and c) the *Nansen* winter data. The size (radius) of the bubble is proportional to the corresponding standardized residual  $((\ln(\text{obs}) - \ln(\text{pred})) / (\sigma / \sqrt{\text{pred}}))$ . For positive residuals, the bubbles are white and for negative residuals, the bubbles are gray.



**Fig 5.5:** Time-series of a) estimated standardised stock-recruitment residuals and b) recruitment for the Reference Case assessment of the Namibian hake resource (the line is full only for years for which recruitment residuals are estimated). c) shows the estimated stock-recruitment relationship.



**Fig. 5.6:**  $\sigma_R$ -input vs. a)  $\sigma_R$ -output (the dashed line shows  $\sigma_R$ -output =  $\sigma_R$ -input), b) MSY and c)  $B_{200t}^{SP}/K^{SP}$ , for the Reference Case assessment of the Namibian hake resource.  $\nabla$  shows the case  $\sigma_R$ -input = 0.25 chosen for the Reference Case assessment.

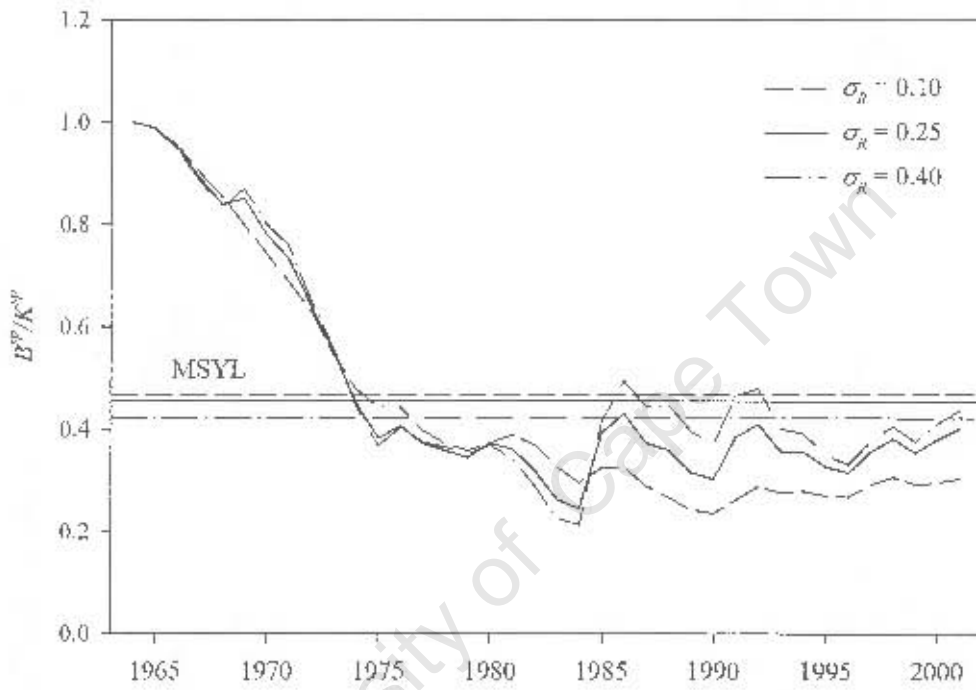


Fig. 5.7: Time-series of spawning biomass (in terms of its pre-exploitation equilibrium level) for three values of  $\sigma_R$ -input (0.10, 0.25 and 0.40), together with the estimated MSYL.

## 6 Assessment of the South African west coast hake resource

### 6.1 Data

The two species which compose the hake resource off the South African west coast remain for the moment assessed as one (Rademeyer and Butterworth, 2001b). The longlining fleet takes only a relatively small proportion of the total hake catch off the west coast, so that a species-disaggregated assessment has not yet been seen as a priority. Future assessments, however, will certainly distinguish the two species.

#### 6.1.1 Total catch

Leslie (1998a) describes the data available for the west coast hake assessment in detail. Annual total catches (by mass) are given in Table 6.1 (1917 to 1975, Chalmers, 1976; 1976 to 1988, ICSEAF, 1989; 1989 to 1997, Leslie, 1998a; 1998 to present, Leslie, MCM, pers. commn). Before the mid-1960's the geographical location of hake catches was not recorded, and for simplicity these have all been taken to have come from the west coast, though some would have come from the south coast.

Most of the hake taken off the west coast is caught by deep-sea bottom trawling, with only a relatively small fraction (a few percent) caught by longlining or handlining. The model therefore assumes a single fleet fishery, with the catches all assumed to come from the offshore trawl fleet. The longlining component has however increased in recent years and future assessments should take account of separate fleets with their different selectivity patterns. Catches are available from 1917 to 2001, with the 2001 value being the best estimate for that year at this stage as recent data capture awaits finalisation.

#### 6.1.2 Abundance indices

CPUE and survey abundance indices, along with the sampling standard errors for the survey abundance indices, are listed in Table 6.2. Both the CPUE index and survey biomass estimates are treated as indices of relative abundance in the Reference Case assessment. The CPUE index consists

## 6.3 Results and Discussion

Only results from the Reference Case assessment are provided in this Chapter; however, variants of this assessment, which deal with some of the uncertainties about the model-assumptions/structure, are described in Appendix A2. Management quantity estimates for the Reference Case assessment are given in Table 6.7, while Fig. 6.1 shows the resource abundance time-series estimated. It is evident that the substantial drop in the size of the resource in the 1960's and 1970's has been followed by a steady though slow recovery in the last three decades. This recovery is also seen in the lower 5% probability limit in Fig. 6.1b, particularly from the early 1990's, when an OMP was put into place as the basis for TAC recommendations. The resource is estimated to be currently at about 22% of its pre-exploitation level (in terms of both the mature and exploitable components). Although this seems relatively low, it is not very far from the level estimated to correspond to the MSY (31% of pre-exploitation abundance) for this resource. At this level, the resource is estimated to be able to yield 129 thousand tons per annum. In 2001, the intended west coast component of the overall TAC was 107 thousand tons, although only about 96 thousand tons were actually caught on the west coast in that year. The true state of the west coast hake resource is determined much more precisely than in the case of the Namibian hake (note the relatively narrow probability intervals for recent years in Fig. 6.1b compared to those in Fig. 5.1b). This is due to the increasing trend in recent abundance indices of the west coast hake, which is not evident for the Namibian case and which allows for a more precise estimation of the model parameters; i.e., it is not a 'one-way trip situation' (Hilborn, 1979, who showed that given a relative abundance index with a declining trend only, assessments would be unable to discriminate the values of productivity- and initial abundance-related parameters).

In the case of the west coast hake resource, there is sufficient information (for ages above 2) to allow for an age-dependent natural mortality,  $M_a$ , to be estimated. (Results from an assessment with age-independent  $M$  are shown in Appendix A2.) Although the age-dependency allows for a lower mortality at higher ages, the estimates for intermediate ages 3-5 still seem unrealistically high for a relatively long-lived species such as hake. This problem is discussed further in Chapter 9.

The multiplicative bias for the *Africana* surveys on the west coast are higher than those for the Namibian case, with  $q_{summer} = 0.79$  and  $q_{winter} = 0.90$ . Although the catching efficiency of the *Nansen* research vessel ( $q^{Nansen} = 0.64$ ) is estimated to be lower than that of the *Africana* on the west coast, differences in gear alone cannot explain the still greater negative bias off Namibia. Furthermore, the fishing selectivity pattern of the *Nansen* on the west coast and off Namibia differ substantially, with a greater proportion of small hake (age 2 and below) estimated to be caught off the South African west coast compared to off Namibia.

The variances on the two CPUE indices are unlikely to be as low as those estimated when fitting the population model (less than 0.1 for both the historic and GLM-standardised series), so that there is a case for imposing lower bounds on these variances in the fit so that these data do not receive undue weight. Indeed, with such low variance estimates, there is a danger than the model is to some extent tracking noise rather than a real trend in abundance.

Fig. 6.2 and Fig. 6.3 show the Reference Case assessment fit to the abundance indices and catch-at-age data respectively, comparing the observed values and the corresponding model predictions. The model shows broadly reasonable fits to all the indices. The model doesn't fit the observed decline in CPUE in the last two years of the series (1999 and 2000) because it estimates the population to still be recovering slowly (Fig 6.2b). This may be a consequence of assuming recruitments given exactly by the stock-recruit relationship from 1996 onwards. The model also struggles to reflect the full extent of the positive trend which is shown by the summer survey estimates over the last two decades (Fig. 6.2c).

The fits to the catch-at-age data are very good for both the commercial and the survey data (Fig. 6.3). Fig.6.4 plots the standardised catch-at-age residuals  $(\varepsilon_{y,a} \rightarrow \frac{(\ln \hat{p}_{y,a}^i - \ln \hat{p}_{y,a}^i)}{\sigma^i / \sqrt{\hat{p}_{y,a}^i}})$  for the

commercial and survey data. This plot allows one to identify potential yearly patterns in the residuals, which is not possible in Fig. 6.3 where the data are averaged over the years for which data are available. There are some indications of systematic effects in the residuals, which warrant further investigation of models for the fishing selectivities. For example, the model systematically predicts too many fish in the age classes 4 and above in the summer survey catch-at-age data (excluding the *Nansen* data). Similarly, from the mid 1980's the model is predicting systematically more fish in the 7+ group than is actually observed.

The time series of the stock-recruitment residuals and recruitments are shown in Fig. 6.5a and b respectively. It is clear that on average, the recruitment off the South African west coast, over the period for which stock-recruitment residuals can be estimated, doesn't vary as much as that off the Namibian coast. There are still however four years of recruitment evidently well below average (1978, 1984, 1992 and 1993). In Fig. 6.5b, it can be seen that recruitment is estimated to have stayed high (close to that at carrying capacity) from the commencement of the fishery to the late 1950's. The high level of exploitation in the 1960's and early 1970's resulted in a rapid decrease in recruitment. Since then however, recruitment has been increasing steadily and is estimated to be currently at about two thirds of that expected at carrying capacity level.

Fig. 6.5c plots the estimated stock-recruitment relationship. It is evident from this figure that this relationship extrapolates considerably beyond the range of the data used in the analysis. In the



Namibian case on the other hand, the recruitment data used reflects a greater range of the spawning biomass. Future assessments of the west coast hake resource should investigate the impact of different forms of stock-recruitment relationships on the estimates of stock status and other management quantities.

Fig. 6.6 shows the effect of varying the  $\sigma_R$ -input (the input standard deviation on the stock-recruitment residuals) on the  $\sigma_R$ -output (calculated from the maximum likelihood estimates for the stock-recruitment residuals), MSY and the biomass. The  $\sigma_R$ -output in Fig. 6.5a is consistently lower than the input values and never exceeds 0.2. Because the recruitment fluctuations are estimated to be relatively small in any case, varying  $\sigma_R$ -input doesn't have a marked effect on the MSY (Fig. 6.5b). Below an  $\sigma_R$ -input of about 0.5, the MSY estimate is relatively robust to changes in the  $\sigma_R$ -input. However, as  $\sigma_R$ -input is increased the status of the resource is estimated to be somewhat poorer (Fig. 6.5e). Fig. 6.7 plots the time series of spawning biomass for three values of  $\sigma_R$ -input (0.10, 0.25, and 0.40). Although the current spawning biomass is estimated to decrease as  $\sigma_R$ -input increases, the effect of varying the level of recruitment fluctuation is not nearly as dramatic as in the Namibian hake case (Fig. 5.7).

**Table 6.1:** Total annual landings of west coast hake (Division 1.6) for the period 1917 to 2001 (up to 1988, ICSEAF, 1989; 1989 to 1997, Leslie, 1998a; 1998 to present, Leslie, MCM, pers. commn). The catch assumed for 2001 is the current best estimate for that year, as data capture is still being finalised.

Year	Catch ('000 tons)	Year	Catch ('000 tons)	Year	Catch ('000 tons)
1917	1.000	1946	40.400	1975	89.617
1918	1.100	1947	41.400	1976	143.894
1919	1.900	1948	58.800	1977	102.328
1920	0.000	1949	57.400	1978	101.140
1921	1.300	1950	72.000	1979	92.704
1922	1.000	1951	89.500	1980	101.538
1923	2.500	1952	88.800	1981	100.678
1924	1.500	1953	93.500	1982	85.970
1925	1.900	1954	105.400	1983	73.677
1926	1.400	1955	115.400	1984	88.410
1927	0.800	1956	118.200	1985	99.590
1928	2.600	1957	126.400	1986	109.091
1929	3.800	1958	130.700	1987	104.010
1930	4.400	1959	146.000	1988	90.131
1931	2.800	1960	159.900	1989	84.896
1932	14.300	1961	148.700	1990	78.918
1933	11.100	1962	147.600	1991	85.521
1934	13.800	1963	169.500	1992	86.280
1935	15.000	1964	162.300	1993	98.110
1936	17.700	1965	203.000	1994	102.770
1937	20.200	1966	195.000	1995	94.716
1938	21.100	1967	176.700	1996	91.364
1939	20.000	1968	143.600	1997	92.328
1940	28.600	1969	165.100	1998	109.297
1941	30.600	1970	142.500	1999	86.489
1942	34.500	1971	202.000	2000	108.963
1943	37.900	1972	243.933	2001	95.730
1944	34.100	1973	157.782		
1945	29.200	1974	123.000		

**Table 6.2:** Historic (ICSEAF) (ICSEAF, 1989) and GLM-standardised CPUE series with ( $\rho = 0.5$ ) and without ( $\rho = 0$ ) (Glazer and Leslie, 2001a) correction for bycatch correlation (restricted to data for Irvin & Johnson, Sea Harvest and Atlantic Trawling) for the west coast hake resource, together with survey abundance data (and associated standard errors) (up to 1997, Leslie, 1998a; 1998 to present, Leslie, MCM, pers. commn). Biomass estimates for the survey (from the swept-area method) are in thousand tons.

Year	ICSEAF (Div. 1.6) CPUE (tons/day)	GLM CPUE (kg/min)		Summer survey		Winter survey		Nansen summer	
		$\rho = 0.5$	$\rho = 0$	Biomass	(s.e.)	Biomass	(s.e.)	Biomass	(s.e.)
1955	17.31								
1956	15.64								
1957	16.47								
1958	16.26								
1959	16.26								
1960	17.31								
1961	12.09								
1962	14.18								
1963	13.97								
1964	14.60								
1965	10.84								
1966	10.63								
1967	10.01								
1968	10.01								
1969	8.62								
1970	7.23								
1971	7.09								
1972	4.90								
1973	4.97								
1974	4.65								
1975	4.66								
1976	5.35								
1977	4.84								
1978		13.88	14.95						
1979		15.37	15.78						
1980		14.22	14.81						
1981		13.97	14.82						
1982		13.07	14.49						
1983		15.66	17.16						
1984		15.72	16.26						
1985		19.07	19.88	231.134	(38.629)	398.193	(53.557)		
1986		16.42	17.67	296.044	(42.744)	286.374	(32.737)		
1987		13.91	14.22	352.874	(57.004)	270.946	(46.409)		
1988		13.80	13.14	212.036	(31.640)	267.798	(64.461)		
1989		14.46	13.75			627.147	(134.761)		
1990		15.47	14.01	512.299	(98.448)	357.089	(55.307)		
1991		17.29	15.64	384.147	(83.393)				
1992		17.69	16.05	319.533	(37.493)				
1993		15.13	14.30	395.642	(51.976)				
1994		15.03	14.95	440.117	(68.667)				
1995		12.14	12.32	462.707	(86.365)				
1996		15.86	15.86	506.857	(84.235)				
1997		16.15	16.06	752.837	(115.622)				
1998		16.72	16.83						
1999		15.89	16.43	761.736	(123.905)				
2000		13.74	15.12					326.994	(36.816)
2001								466.131	(41.683)

**Table 6.3:** Commercial catches-at-age (shown as proportions of numbers) for the west coast hake fishery (up to 1988, Punt, 1989; 1989 to 1997, Leslie, 1998a; 1998 to present, Leslie, MCM, pers. commn).

Age	Proportions caught at age: <i>Merluccius capensis</i> and <i>M. paradoxus</i> combined							
	0	1	2	3	4	5	6	7+
1978	0.000	0.072	0.716	0.151	0.039	0.016	0.005	0.001
1979	0.000	0.114	0.545	0.215	0.063	0.046	0.013	0.003
1980	0.000	0.056	0.472	0.288	0.112	0.048	0.017	0.008
1981	0.004	0.235	0.492	0.158	0.068	0.026	0.011	0.006
1982	0.037	0.290	0.484	0.114	0.040	0.023	0.009	0.003
1983	0.001	0.121	0.488	0.238	0.085	0.044	0.016	0.007
1984	0.000	0.063	0.483	0.275	0.097	0.046	0.024	0.012
1985	0.000	0.008	0.350	0.395	0.133	0.069	0.030	0.015
1986	0.000	0.014	0.339	0.467	0.104	0.040	0.022	0.015
1987	0.000	0.023	0.524	0.276	0.103	0.048	0.016	0.009
1988	0.000	0.021	0.589	0.266	0.059	0.036	0.021	0.009
1989	0.000	0.014	0.434	0.402	0.090	0.036	0.018	0.006
1990	0.000	0.002	0.313	0.496	0.137	0.034	0.013	0.005
1991	0.000	0.002	0.253	0.357	0.233	0.087	0.048	0.019
1992	0.000	0.012	0.405	0.302	0.145	0.088	0.035	0.013
1993	0.000	0.003	0.146	0.378	0.307	0.128	0.029	0.009
1994	0.000	0.001	0.140	0.464	0.200	0.157	0.030	0.008
1995	0.000	0.001	0.109	0.552	0.207	0.075	0.044	0.012
1996	0.000	0.002	0.120	0.554	0.221	0.063	0.029	0.011
1997	0.000	0.012	0.201	0.500	0.187	0.059	0.033	0.008
1998	0.000	0.030	0.202	0.500	0.168	0.061	0.031	0.007
1999	0.001	0.056	0.256	0.462	0.128	0.057	0.031	0.009

**Table 6.4:** Winter survey catches-at-age (shown as proportions of numbers): *Merluccius capensis* and *M. paradoxus* combined, for the 100-500 m depth range for the west coast hake fishery (up to 1997, Leslie, 1998a; 1997 to present, Leslie, MCM, pers. commn).

Age	Proportions caught at age: <i>Merluccius capensis</i> and <i>M. paradoxus</i> combined							
	0	1	2	3	4	5	6	7+
1985	0.012	0.267	0.522	0.149	0.028	0.013	0.006	0.003
1986	0.009	0.398	0.376	0.162	0.027	0.014	0.009	0.005
1987	0.020	0.359	0.454	0.115	0.027	0.018	0.004	0.004
1988	0.031	0.321	0.484	0.107	0.036	0.013	0.004	0.002
1989	0.074	0.395	0.309	0.182	0.029	0.006	0.003	0.002
1990	0.016	0.378	0.386	0.119	0.054	0.030	0.011	0.005

**Table 6.5:** Summer survey catches-at-age (shown as proportions of numbers): *Merluccius capensis* and *M. paradoxus* combined, for the 100-500 m depth range for the west coast hake fishery (up to 1997, Leslie, 1998a; 1999, Leslie, MCM, pers. commn).

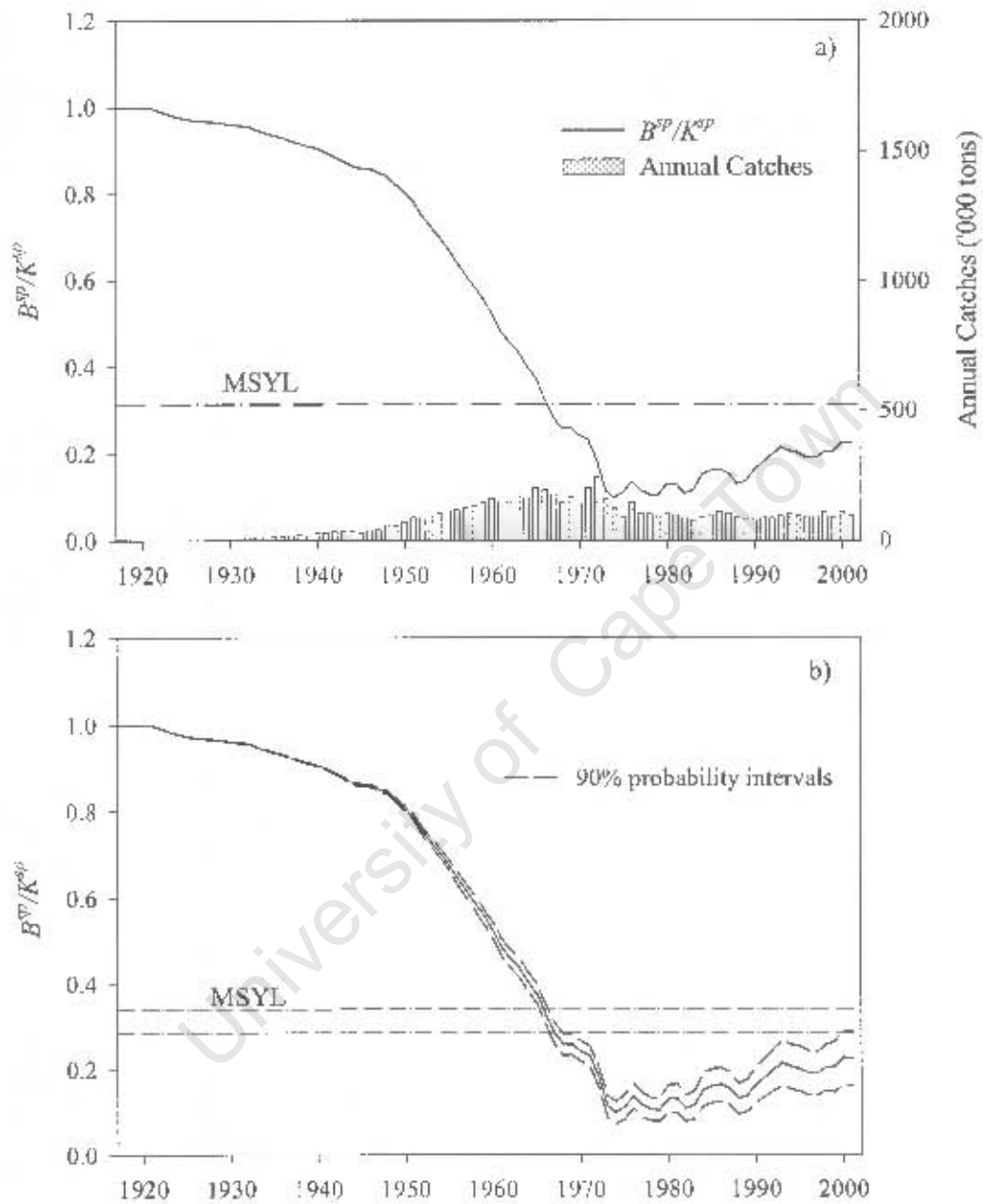
Age	Proportions caught at age: <i>Merluccius capensis</i> and <i>M. paradoxus</i> combined							
	0	1	2	3	4	5	6	7+
1985	0.015	0.340	0.448	0.146	0.030	0.014	0.005	0.003
1986	0.025	0.315	0.505	0.126	0.013	0.008	0.005	0.003
1987	0.006	0.409	0.462	0.089	0.026	0.005	0.002	0.002
1988	0.021	0.538	0.357	0.052	0.012	0.010	0.007	0.003
1989	-	-	-	-	-	-	-	-
1990	0.020	0.358	0.498	0.104	0.015	0.004	0.001	0.000
1991	0.022	0.247	0.584	0.106	0.026	0.010	0.004	0.002
1992	0.020	0.325	0.478	0.113	0.038	0.015	0.007	0.003
1993	0.004	0.177	0.549	0.203	0.045	0.015	0.005	0.002
1994	0.013	0.223	0.488	0.221	0.028	0.014	0.009	0.004
1995	0.084	0.494	0.308	0.079	0.021	0.009	0.003	0.001
1996	0.061	0.319	0.322	0.249	0.035	0.008	0.004	0.002
1997	0.025	0.189	0.497	0.262	0.018	0.005	0.002	0.001
1998	-	-	-	-	-	-	-	-
1999	0.084	0.251	0.376	0.209	0.052	0.017	0.008	0.002

**Table 6.6:** Nansen summer survey catches-at-age (shown as proportions of numbers): *Merluccius capensis* and *M. paradoxus* combined, for the 100-500 m depth range west coast hake fishery (Leslie, MCM, pers. commn).

Age	Proportions caught at age: <i>Merluccius capensis</i> and <i>M. paradoxus</i> combined							
	0	1	2	3	4	5	6	7+
2000	0.203	0.352	0.295	0.123	0.020	0.005	0.002	0.001
2001	0.239	0.285	0.255	0.157	0.049	0.009	0.004	0.002

**Table 6.7:** Estimates of management quantities for the Reference Case assessment for the west coast hake. The first figure shown is the best estimate, followed by the Hessian-based CV in parenthesis.

		Reference Case				
Total negative loglikelihood		-176.7				
-lnL : CPUE		-71.0				
-lnL: Survey		-16.0				
-lnL: CAA com.		-57.1				
-lnL: CAA surv		-35.7				
-lnL: SR Residuals		3.2				
$K^{SP}$		973 (0.06)				
$K^{EX}$		1386 (0.05)				
$B^{SP}_{2001}$		218 (0.13)				
$B^{EX}_{2001}$		298 (0.12)				
$h$		0.615 (0.08)				
$MSYL^{SP}$		304 (0.09)				
$MSYL^{EX}$		404 (0.09)				
$MSY$		129 (0.03)				
$B^{SP}_{2001}/K^{SP}$		0.224 (0.18)				
$B^{EX}_{2001}/K^{EX}$		0.215 (0.15)				
$B^{SP}_{2001}/MSYL^{SP}$		0.715 (0.19)				
$B^{EX}_{2001}/MSYL^{EX}$		0.738 (0.17)				
$MSYL^{SP}/K^{SP}$		0.313 (0.05)				
$MSYL^{EX}/K^{EX}$		0.291 (0.05)				
	Age	$M_a$	$S_{1984,a}$	$S_{1993,a}$	$S_{surv,a}$	$S_{Nansen,a}$
	0	1.06 (0.05)	0.00	0.00	0.01	0.09
	1	1.06 (0.05)	0.00	0.00	0.26	0.36
	2	1.06 (0.05)	0.73	0.10	1.00	1.00
	3	0.82 (0.05)	1.00	0.84	1.00	1.00
	4	0.67 (0.05)	1.00	1.00	1.00	1.00
	5	0.58 (0.05)	1.00	1.00	1.00	1.00
	6	0.51 (0.05)	1.00	1.00	1.00	1.00
	7+	0.46 (0.05)	1.00	1.00	1.00	1.00
Commercial sigmas:						
	CPUE ICSEAF (1.6)	0.349 (0.09)				
	CPUE GLM	0.182 (0.10)				
Commercial $q$ 's:						
	CPUE ICSEAF (1.6)	0.019 (0.07)				
	CPUE GLM	0.058 (0.11)				
Survey $q$ 's:						
	summer	0.793 (0.13)				
	winter	0.899 (0.11)				
	Nansen	0.643 (0.13)				
Catches-at-age sigmas:						
	commercial	0.107 (0.03)				
	summer survey	0.121 (0.03)				
	winter survey	0.069 (0.07)				
	Nansen survey	0.070 (0.05)				
Additional sigma (survey)		0.231 (0.24)				



**Fig. 6.1:** The Reference Case ASPM assessment (which incorporates fluctuations about the stock-recruitment relationship) for the South African west coast hake resource, is shown in a), together with the estimated MSYL and the annual catches; b) shows the Hessian-based 90% probability intervals. The resource abundance is expressed in terms of spawning biomass as a proportion of its pre-exploitation equilibrium level ( $B^{SP}/K^{SP}$ ).

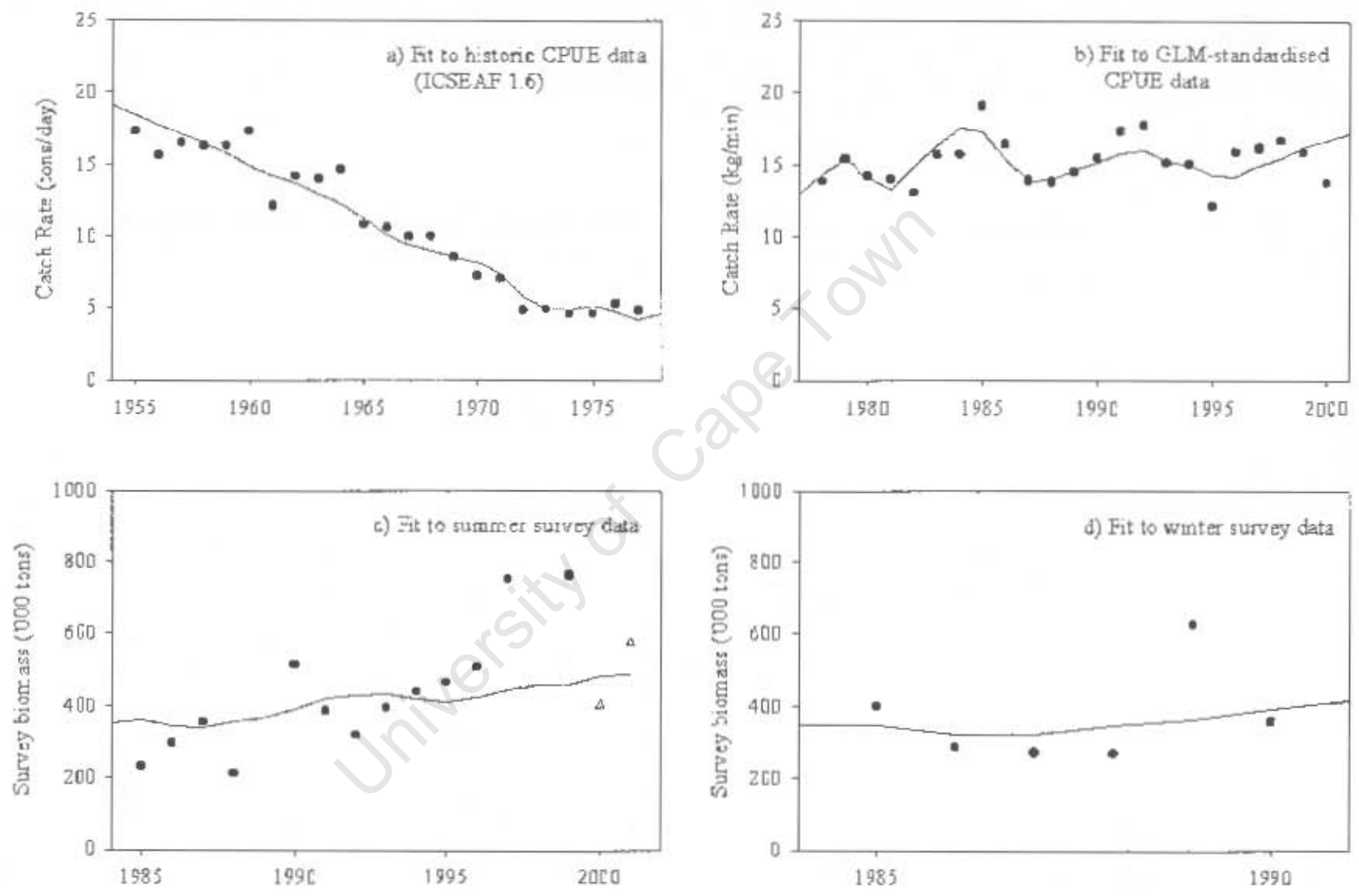


Fig. 6.2: Reference Case assessment model fit to the abundance indices (CPUE and survey) for the South African west coast hake resource. The *Nansen* survey estimates for 2000-2001, shown by  $\Delta$  in c), have been rescaled by the ratio of the estimated  $q$ 's for those and the standard (*Africana*) summer surveys.



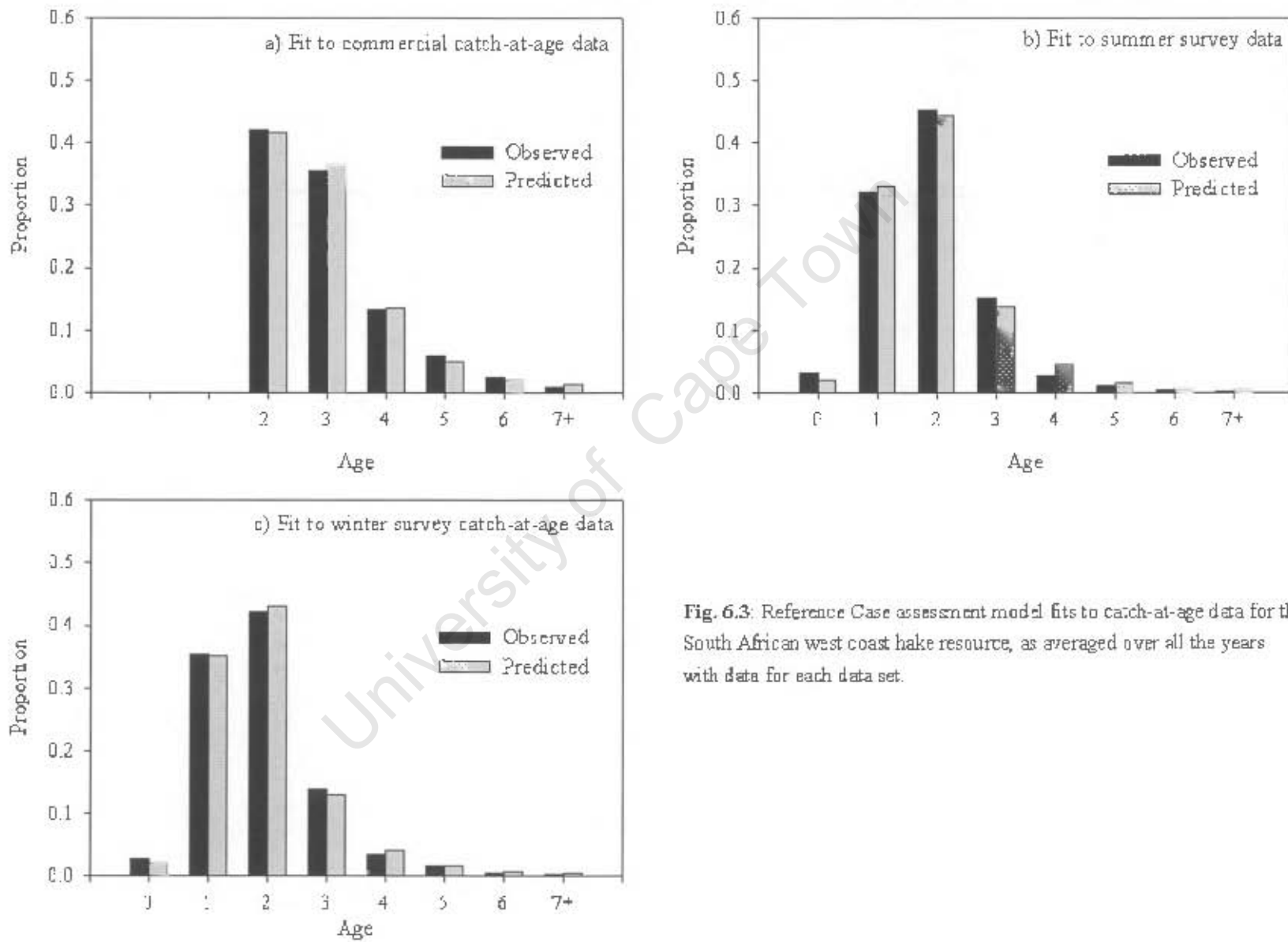


Fig. 6.3: Reference Case assessment model fits to catch-at-age data for the South African west coast hake resource, as averaged over all the years with data for each data set.

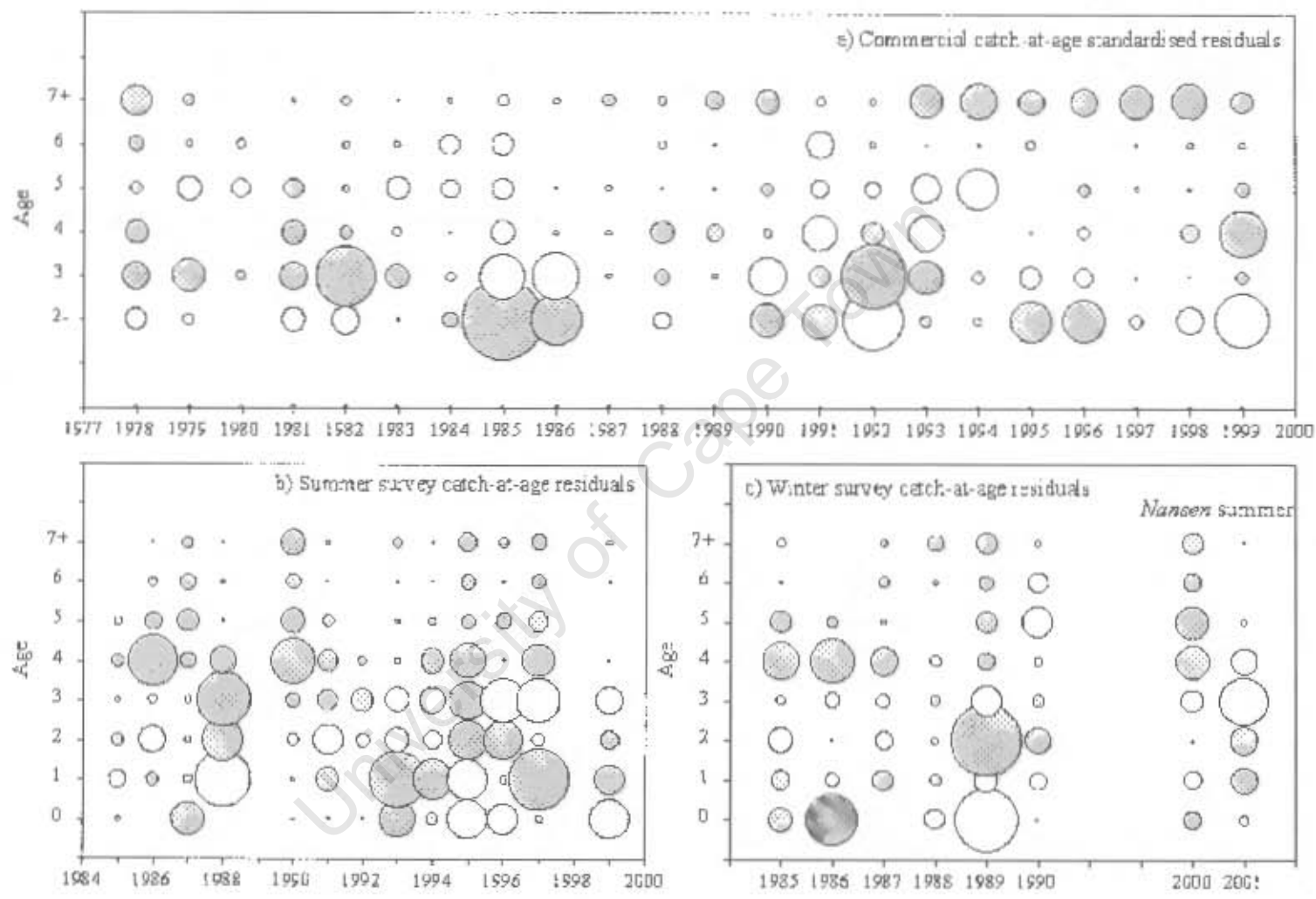
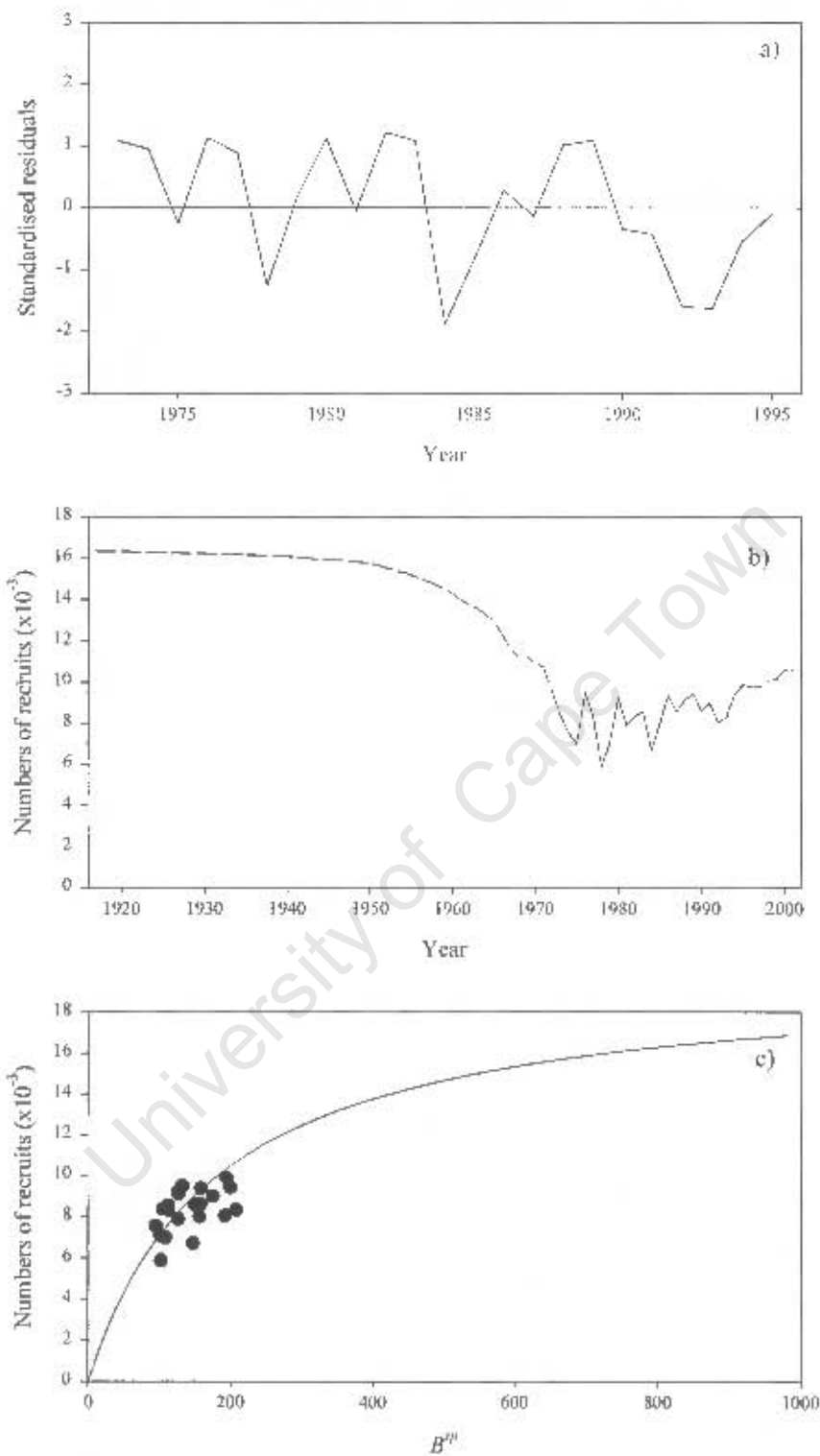


Fig 6.4: "Bubble plots" of the catch-at-age residuals for a) the commercial data, b) the summer survey data and c) the winter survey data, with the Nansen 2000 and 2001 summer survey data. The size (radius) of the bubble is proportional to the corresponding standardized residual  $(\ln(\text{obs}) - \ln(\text{pred})) / (\text{sigma} / \sqrt{\text{pred}})$ . For positive residuals, the bubbles are white and for negative residuals, the bubbles are gray.



**Fig 6.5:** Time-series of a) estimated standardised stock-recruitment residuals and b) recruitment for the Reference Case assessment of the west coast hake resource (the line is full only for years for which recruitment residuals are estimated). c) shows the estimated stock-recruitment relationship.

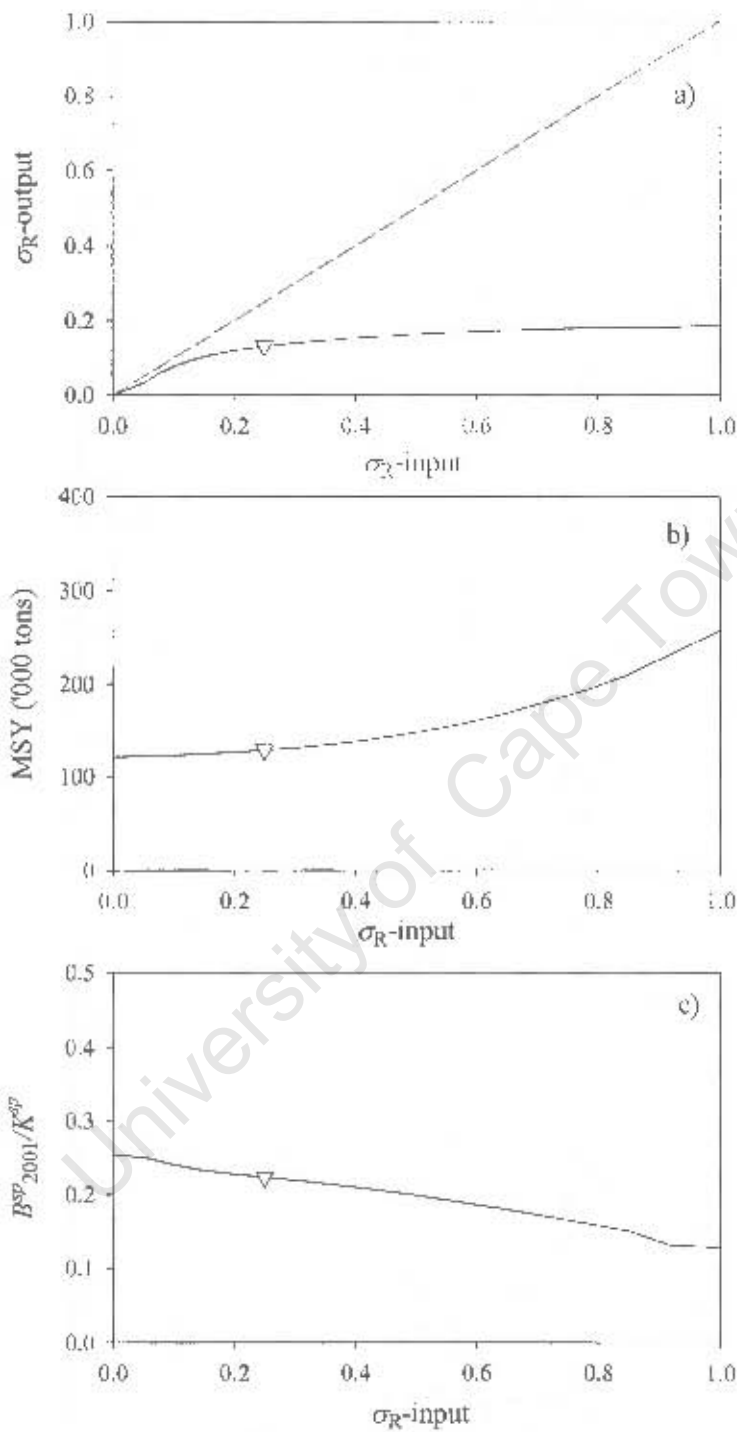


Fig. 6.6:  $\sigma_R$ -input vs a)  $\sigma_R$ -output (the dashed line shows  $\sigma_R$ -output =  $\sigma_R$ -input), b) MSY and c)  $B_{2001}^{SP}/K^{SP}$ , for the Reference Case assessment of the west coast hake resource.  $\nabla$  shows the case  $\sigma_R$ -input = 0.25 chosen for the Reference Case assessment.

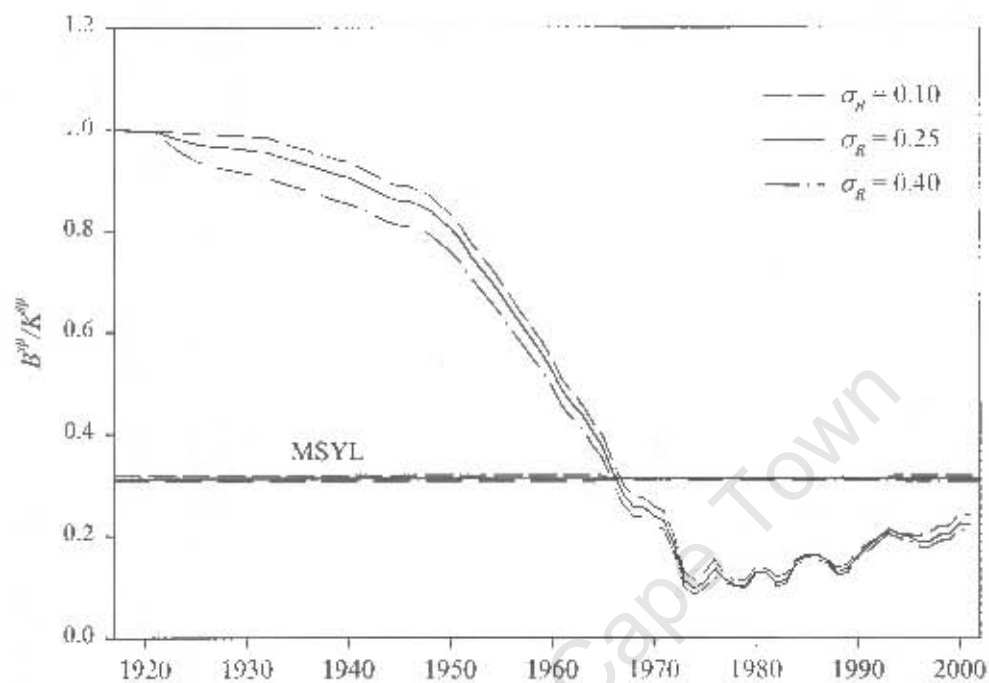


Fig. 6.7: Time-series of spawning biomass (in terms of its pre-exploitation equilibrium level) for three values of  $\sigma_R$ -input (0.10, 0.25 and 0.40), together with the estimated MSYL.

## 7 Assessment of the South African south coast *M. capensis* resource

Until recently, the two hake species off the south coast of South Africa were assessed as a single stock exploited by a single fleet, as it is still the case for the South African west coast and Namibian stocks. The justification for aggregating the two species of hake in this way was based upon simulation studies by Punt (1993), which suggested that managing two such stocks as if they were a single one was not problematic, provided that the species composition and age-selectivity of the fishery remained unchanged. The development of a longline fishery for hake, proportionately greater on the south coast and targeting principally the shallow water hake *M. capensis*, brought about the need to modify this practice. The south coast *M. capensis* stock has been assessed as a single stock since 1999 (Geromont and Butterworth, 1999a).

### 7.1 Data

#### 7.1.1 Total catch

Leslie (1998b) describes the data available for the south coast hake assessment in detail. The south coast *M. capensis* hake stock is fished by three fleets: the offshore and inshore trawl fleets and the longline/handline fleet. The annual catches by mass assumed for each fleet are given in Table 7.1 for the period 1967 to 2001 (data sources: up to 1997, Geromont and Butterworth, 1999a; 1998 to present, Glazer, MCM, pers. commn). The 2001 values are the current best estimates for that year as recent data capture awaits finalisation.

For simplicity, the catches of hake made by the inshore trawl and handline/longline fleets are assumed to consist of *M. capensis* only. This assumption is considered to be reasonable because they are restricted to relatively shallow water (Leslie, MCM, pers. commn). The catches made by the offshore trawl fleet have been split by species by applying the species proportion-by-depth relationship for the south coast developed by Geromont *et al.* (1995b), which was estimated by stratifying the south coast research survey catches by depth. Prior to 1978, there is no depth information recorded for the landings so that the proportion of *M. capensis* caught cannot be estimated using this method. Consequently, the catch data for the 1967-1977 period are split by species by

assuming that the average proportion of *M. capensis* in the offshore catch over the 1978-1982 period (45%) applies to the earlier data. This assumption has, however, recently been questioned as trawling was concentrated in inshore area around Cape Town and in bays along the south coast when the fishery began. Future assessments will need to test sensitivity to different assumptions about this split.

Furthermore, because fleet-disaggregated catch data are not available prior to 1974, the assumption has had to be made that the annual catch of the inshore fleet from 1967 to 1974 was equal to its 1974 value of 10 thousand tons, and that the balance of the total catch recorded was taken by the offshore fleet.

### 7.1.2 Abundance indices

CPUE and survey abundance indices, along with the sampling standard errors for the survey abundance indices, are listed in Table 7.2. Both the CPUE indices and survey biomass estimates are treated as indices of relative abundance in the Reference Case assessment. The CPUE index consists of two separate series, the first from ICSEAF for 1969 to 1977 (ICSEAF, 1989) and the second from 1978 to 2000 (Glazer and Leslie, 2001b), corresponding to the historic (“old”) and the GLM-standardised catch rates respectively. Both CPUE series are for the offshore trawl fleet. As mentioned above, there are no effort-by-depth data available prior to 1978 so that the historic CPUE data for the offshore fleet cannot be disaggregated by species. However, since information on the CPUE trend over this period is important for the assessment, the assumption is made that these combined-species data are also reflective of trends in the *M. capensis* stock alone. The CPUE data for the inshore fleet are not used in this analysis due to their unreliability (Leslie, 1998b). Although the total landed catch is known (measured at discharge), there are some concerns about the accuracy of the data recorded in the logbooks, such as trawl duration. Further investigation of the inshore CPUE data should be carried out, to ascertain if a subset might be of sufficient reliability to provide a CPUE series for use in future assessments.

Due to problems in capturing and validating the data at a drag level in 2001, the GLM-standardised CPUE series is restricted to data for the three biggest companies (Irvin & Johnson, Sea Harvest and Atlantic Trawling) (see Glazer and Leslie, 2001b, for more information). Because these three companies account for the greatest majority of the catch, using these restricted data should not affect the assessment appreciably.

Research surveys have been conducted bi-annually in spring and autumn from 1986 on board of the FRS *Africana* (estimates up to 1997, Geromont and Butterworth, 1999a; 1998 to present, Leslie, MCM, pers. commn). Survey biomass estimates are available for two depth ranges. The 0-200 m

depth range excludes estimates for waters deeper than the 200 m isobath, while the biomass indices for the 0-500 m depth range reflect the biomass for the whole survey area and are more representative of the entire stock. Despite the fact that estimates for the 0-500 m depth range are not available for all surveys (such as the 1989 and 1990 autumn surveys), the Reference Case assessment uses this series of estimates as an index of relative abundance, because they reflect wider coverage of the resource.

### 7.1.3 Catches-at-age

Commercial catch-at-age data are given as proportions in Table 7.3 for the inshore fleet. Data for the longline/handline fleet are given in Table 7.4 (up to 1996, Geromont and Butterworth, 1999a; 1997 to present, Leslie, MCM, pers. commn). It is assumed that these two fleets catch only *M. capensis*. It is not possible to disaggregate the commercial catch-at-age data at a species level so that the catch-at-age data for the offshore fleet for *M. capensis* only are therefore not available. The catch-at-age information obtained from the autumn survey for the 0-500 m depth range is shown in Table 7.5 (up to 1994, Geromont and Butterworth, 1999b; 1995 to present, Leslie, MCM, pers. commn). The plus-group age for both commercial and survey data is chosen as 7. The commercial minus-group is taken as 3 for the offshore and inshore trawl fleets and 4 for the longline fleet, which targets older fish. There is no minus group for the surveys.

## 7.2 Reference Case assessment specifications

The following assumptions have been made for the Reference Case assessment of the *M. capensis* hake stock off the south coast of South Africa (rationale has not been repeated below when it duplicates that given for Namibian hake in Section 5.2):

- 1)  $B_{1967}^{sp} = K^{sp}$ : The model assumes that the stock was at its pristine level when the fishery commenced.
- 2) *Natural mortality*:  $M_a$  is taken to be age-independent ( $M$ ), as there is not enough information in the data to allow for the estimation of an age-dependent  $M$ .
- 3) *Commercial selectivity-at-age*: Each fleet is characterised by a different selectivity pattern. The selectivity takes on the form of a logistic curve (equation 4.25). Due to the depth distribution of the hake (with older fish found at a greater depth than younger ones) the inshore fleet does not fully select older fish and a slope parameter  $s$  (see equation 4.26) is therefore estimated for this fleet. On the other hand, the longline fleet targets principally older fish so that the slope parameter  $s$  for that



fleet is set to zero. As there are no catch-at-age data available to estimate a selectivity vector for the offshore fleet, the selectivity for this fleet is assumed to be the same as for the inshore fleet (i.e.,  $a_c^f$  and  $\delta^f$  for the offshore fleet are set to the same values as estimated for the inshore fleet), but with a zero slope. For the longline fleet, the selectivity for ages  $\leq 4$  indicated by a logistic curve is multiplied by a factor  $\lambda$ . Indeed, the selectivity for this fleet and these ages is so low that it is not adequately represented by a logistic curve. The parameter  $\lambda$  is treated as another estimable parameter in the likelihood maximisation process.

- 4) *Survey selectivity-at-age*: The survey selectivity is estimated separately for each age and is assumed to be the same for the spring and autumn surveys. Attempts to use a logistic form for the survey selectivity led to model mis-specification; catch-at-age residuals were particularly large for ages 1 to 4 when using the logistic form.
- 5) *Stock-recruitment residuals*:  $\sigma_R$  is fixed at 0.25. The residuals are assumed not to be serially correlated, i.e.,  $\rho = 0$ . They are estimated from year 1984 to 1995 ( $y_1$  and  $y_2$  in equation 4.22).
- 6) *Lower bound on the variance on the CPUE data*: Minima for these  $\sigma^{f,i}$  estimates corresponding to the GLM-based and ‘historic’ series are 0.1 and 0.25 respectively.
- 7) *Additional variance on surveys*: An additional variance is estimated for the surveys conducted by the *Africana*.

## 7.3 Results and Discussion

Only results from the Reference Case assessment are provided in this Chapter. For variants of this assessment which deal with some of the uncertainties about the model-assumptions/structure see Appendix A3. Management quantity estimates for the Reference Case assessment are given in Table 7.6, whereas Fig. 7.1 shows the resource abundance time-series estimated. In the *M. capensis* south coast assessment, which distinguishes three different fishing fleets, the exploitable biomass and associated quantities (such as MSY) have been estimated for each fleet separately. These estimates, which are different for each fleet because each fleet has a particular fishing selectivity-at-age pattern, are shown in Table 7.6 under the ‘Offshore’, ‘Inshore’ and ‘Longline’ headings. In order to make comments about the fishery as a whole, an average selectivity (and resulting exploitable biomass and associated quantities) has been computed by assuming the same proportion of the catch as was made by each fleet in 2001. These ‘average selectivity’ estimates are shown in the first column in Table 7.6.

As with the Namibian and west coast hake stocks, the *M. capensis* resource on the south coast shows a decline from the beginning of the fishery to the mid-1970's. The resource on the south coast has, however, not been exploited to the same extent as the larger stocks off the west coast of southern Africa. The lowest the biomass is estimated to have reached was in 1976 when it fell to approximately 34% of its pre-exploitation level. By comparison, the west coast stock fell to less than 10% of its pre-exploitation level. This can be explained by the fact that the south coast fishery only really took off in the mid-1960's relatively soon before the creation of ICSEAF and the implementation of more stringent management policies. In addition, a large portion of the south coast grounds is untrawlable as the area is too rocky, and could therefore provide a refuge for a part of the population.

The initial decline in the south coast *M. capensis* stock was followed by a rapid recovery period that lasted until the early 1980's. Since then the stock has remained fairly stable, at around 50% of its pre-exploitation biomass. This is well above the 'average selectivity' MSYL of 0.376. The 'average selectivity' MSY for the south coast *M. capensis* stock is 33 thousand tons. Surprisingly, the probability intervals on the spawning biomass (Fig. 7.1b) are not widening with time as is the case for the Namibian and South African west coast hake resources. A possible reason is that the proportionate recovery of the south coast *M. capensis* resource is better than in the other two cases.

A number of the management quantities associated with the inshore and longline fleets are very poorly estimated. This results in the average-selectivity estimates having very large CVs (Table 7.6). For example the 90% probability intervals for the average-selectivity MSYL are extremely large (Fig. 7.1b).

The natural mortality  $M$  is taken to be independent of age and is estimated to be  $0.55 \text{ yr}^{-1}$ . Although this is the lowest of the  $M$  estimates for the various hake stocks off southern Africa, it is still higher than what would be expected for a relatively long-lived fish such as hake. One of the reasons why  $M$  is estimated to be lower for this stock is the unrealistically high value estimated for the steepness  $h$  (1.0), which would suggest an extremely productive stock, for which no correlation exists between recruitment and biomass. The estimate for the CV (0.01) on the steepness parameter is also unrealistically low. This can be explained by the fact that this estimate is Hessian-based and, as the steepness parameter is hitting an upper boundary at 1, is not accurate as the log-likelihood will not be quadratic in  $h$  close to this point. These estimates are cause for concern and are discussed in more detail in Chapter 9.

Somewhat unexpectedly, this assessment suggests that the research survey swept area biomass estimates overestimate the stock size on average by more than 100% (the proportional bias coefficients for the spring and autumn surveys are 2.2 and 2.5 respectively). Again, a plausible explanation is that a large portion of the south coast grounds is untrawlable (R. Leslie, MCM, pers. commn). Indeed, because the swept-area methodology used for the surveys assumes that the fish are homogeneously

distributed within the whole area surveyed, if hake densities in the untrawlable area are actually lower than in the area trawled by the survey vessel, this would lead to an overestimation of the biomass, as is suggested by the assessment model. The issue of survey bias is discussed further in Chapter 9.

The Reference Case assessment fits to the abundance indices and catch-at-age data are shown in Fig. 7.2 and Fig. 7.3 respectively. These figures compare the observed values and the corresponding model predictions. Although the model shows a reasonable fit to all the indices, the GLM-standardised CPUE series seems to show some pattern in the residuals, with a profusion of positive values in the middle of the series and mainly negative values on either side. The reason for this pattern should be investigated further. The general fit to the historic CPUE data is good although, similarly to the west coast case, the model does not mimic the initial steep drop in abundance suggested by the CPUE series.

The model fit to the catch-at-age data (Fig. 7.3) also seems reasonable for the commercial data. There is however a particularly large difference between the observed and predicted catch of 0 year olds in the autumn survey data. This is due to the data for the 1999 survey which have an unusually large proportion of 0 year olds (16% compared to, on average, less than 3%). This might suggest that an extremely good recruitment occurred in that year, but there are no subsequent years' data available as yet to confirm this. The catch-at-age data in Fig. 7.3 also show four very different patterns depending on the fleet. To aid comparison, the predicted catch-at-age values for the offshore fleet are also shown, although actual data are not available for this fleet. The majority of fish caught by the inshore fleet are 4 years old or younger; in contrast the greatest proportion caught by the longline fleet consists of fish older than 6 years. The offshore fleet is assumed to have a similar catch-at-age pattern to that of the inshore fleet, although not catching small fish to the same extent. Due to the size gradation by depth, small *M. capensis* are not generally available to the offshore fleet. By contrast, the survey data show a more uniform catch with age. These differences in the catches-at-age are reflected in the different selectivities for the fleets, as can be seen in Table 7.6.

The catch-at-age data obtained from the survey show a rather different pattern to that observed for surveys off Namibia and off the South African west coast, where a larger proportion of small fish are caught. On the south coast, the proportions-at-age caught by the survey are very widely spread over the ages (Table 7.5) and consequently the estimated survey selectivity pattern shows a steady increasing trend up to age 5. Possible explanations for these different patterns might be related to the hypothesis of Le Clus (MCM, pers. commn), which suggests that *M. capensis* might be moving to the south as they grow older. Furthermore, the west and south coasts have very different seabed topographies, with a very narrow continental slope on the west coast and the wide Agulhas Bank on the south coast, which affects the distribution of the two hake species and possibly the survey catch-at-age pattern. The greater proportion of untrawlable grounds on the south coast compared to the west

coast could contain differentially more of the smaller *M. capensis* and so bias the survey results. The question of differing selectivity functions from area to area is discussed in more detail in Chapter 9.

Fig. 7.4 plots the standardised catch-at-age residuals for the commercial (inshore and longline fleets) and survey data. There are no clear systematic effects in the residuals, although Fig. 7.4c shows two years (1992 and 1999) with systematically smaller catches of fish aged 3 years and above than expected in terms of the model.

Fig. 7.5c plots the stock-recruitment curve. With the estimated high  $h$  value, recruitment does not decrease with the spawning biomass, but rather stays high until the resource is close to collapse. Fig. 7.5a shows the estimated residuals about this stock-recruitment function. These residuals show a consistent negative trend with time, which corresponds to poor recruitment in the last decade compared to that in the 1980's. During the period for which recruitment residuals are estimated, the spawning biomass stayed relatively stable so that the estimated decrease in recruitment cannot be linked to a decrease in biomass. The reason for this pattern need to be investigated further. Fig. 7.5b plots the time series of recruitment. Again, because of an  $h$  value of 1, the recruitment is constant over the periods for which recruitment residuals are set to zero rather than estimated.

Fig. 7.6 shows the effect of varying the  $\sigma_R$ -input (the input standard deviation for the stock-recruitment residuals) on the  $\sigma_R$ -output (calculated from the maximum likelihood estimates for the stock-recruitment residuals), MSY (for each fleet) and the spawning biomass. The model fit did not converge for values of  $\sigma_R$ -input greater than 0.45. The  $\sigma_R$ -output in Fig. 7.6a is consistently lower than the input values and never exceeds 0.2. Not surprisingly therefore, the estimated MSYs and current resource depletion are not greatly influenced by the value input for  $\sigma_R$ , certainly for  $\sigma_R$ -input  $> 0.1$ .

Fig. 7.7 plots the time series of spawning biomass for three values of  $\sigma_R$ -input (0.10, 0.25 and 0.40). Both the estimated spawning biomass and MSYL are more affected by a decrease in the scale of the recruitment fluctuations than by an increase. With an  $\sigma_R$ -input of 0.1, the south coast *M. capensis* resource abundance shows a virtually flat trend over the last two decades and is estimated to be currently at more than double the MSY level, which constitutes an even more optimistic appraisal of the resource than the Reference Case with  $\sigma_R$ -input of 0.25. This is because the recruitment is 'forced' to stay closer to the values indicated by the stock-recruitment curve and the decrease in recruitment in the mid-1990's is not as evident. Increasing the  $\sigma_R$ -input to 0.4 did not affect the estimates as dramatically as decreasing it by the same amount, although the resource status is estimated to be somewhat poorer. The sensitivity of the model to the value input for  $\sigma_R$  is discussed further in Chapter 11.

**Table 7.1:** Assumed total annual catches by fleet for the south coast (east of 20°E) of *M. capensis* for the period 1967 to 2001 (up to 1997, Geromont and Butterworth, 1999a; 1998 to present, Glazer, MCM, pers. commn). The catch assumed for 2001 is the present best estimate for that year, as data capture is still being finalised. Note that longline component of the line catches is relatively well known, but that the handline component is only a rather coarse estimate obtained from a combination of reported catch, factory figures and export figures (Sims, MCM, pers. commn).

Year	Offshore	Inshore	Longline/ Handline	Total
1967	3.302	10.000		13.302
1968	9.614	10.000		19.614
1969	14.202	10.000		24.202
1970	8.008	10.000		18.008
1971	11.023	10.000		21.023
1972	21.320	10.000		31.320
1973	30.303	10.000		40.303
1974	40.875	10.056		50.931
1975	30.352	6.372		36.724
1976	23.363	5.740		29.103
1977	16.634	3.500		20.134
1978	15.340	4.931		20.271
1979	18.299	4.931		23.230
1980	16.594	4.931		21.525
1981	12.470	9.400		21.870
1982	19.025	8.089		27.114
1983	16.544	7.672		24.216
1984	14.587	9.035	0.016	23.638
1985	21.940	9.203	0.357	31.500
1986	16.975	8.724	0.386	26.085
1987	16.357	8.607	0.449	25.413
1988	17.973	8.417	0.402	26.792
1989	24.298	10.038	0.169	34.505
1990	25.656	10.012	0.348	36.016
1991	18.600	8.206	4.270	31.076
1992	15.106	9.252	2.599	26.957
1993	11.560	8.870	0.278	20.708
1994	11.729	9.569	1.129	22.427
1995	10.010	10.630	1.447	22.087
1996	14.046	11.062	3.354	28.462
1997	10.420	8.834	3.979	23.233
1998	6.554	8.283	3.209	18.046
1999	7.385	8.595	6.893	22.873
2000	11.801	10.740	7.026	29.567
2001	13.575	10.165	6.900	30.640

**Table 7.2:** Historic (ICSEAF - 1969 to 1977) and GLM-standardised (1978 to 2001) CPUE data (restricted to data for Irvin & Johnson, Sea Harvest and Atlantic Trawling; see Glazer and Leslie, 2001b), and spring and autumn surveys abundance estimates with associated standard errors in thousand tons for south coast *M. capensis* for the 0-500 m depth range (up to 1997, Geromont and Butterworth, 1999; 1998 to 2000, Leslie, MCM, pers. commn). The historic CPUE series is for *M. capensis* and *M. paradoxus* combined (ICSEAF, 1989). The autumn surveys did not take place in 1998, 2000 and 2001 because of technical problems with the survey vessel, the *Africana*.

Year	ICSEAF Div. 2.1+2.2 CPUE (tons/hr)	GLM CPUE (kg/min)	Spring Survey (0-500 m)		Autumn Survey (0-500 m)	
			Biomass	(s.e.)	Biomass	(s.e.)
1969	1.23					
1970	1.22					
1971	1.14					
1972	0.64					
1973	0.56					
1974	0.54					
1975	0.37					
1976	0.40					
1977	0.42					
1978		4.59				
1979		5.09				
1980		5.33				
1981		4.77				
1982		6.23				
1983		7.24				
1984		7.60				
1985		10.20				
1986		8.39	202.871	(278.450)		
1987		7.50	162.282	(17.512)		
1988		7.38			165.184	(21.358)
1989		7.96				
1990		9.55				
1991		10.11			273.897	(44.363)
1992		8.35			137.798	(15.317)
1993		6.46			156.533	(13.628)
1994		7.57			158.243	(23.607)
1995		7.59			233.359	(31.862)
1996		6.08			243.934	(25.035)
1997		5.20			182.157	(18.601)
1998		6.40				
1999		5.80			190.864	(14.929)
2000		6.67				

**Table 7.3:** Inshore fleet catches-at-age (proportions of numbers) for *M. capensis* on the south coast (up to 1996, Geromont and Butterworth, 1999b; 1997 to present, Leslie, MCM, pers. commn).

Age	Proportions caught at age: <i>Merluccius capensis</i>						
	1	2	3	4	5	6	7+
1989	0.000	0.081	0.478	0.285	0.109	0.039	0.008
1990	0.000	0.055	0.279	0.439	0.171	0.045	0.011
1991	0.000	0.053	0.281	0.367	0.219	0.067	0.014
1992	0.001	0.151	0.371	0.237	0.184	0.048	0.009
1993	0.000	0.026	0.332	0.457	0.139	0.039	0.006
1994	0.000	0.060	0.380	0.304	0.183	0.067	0.007
1995	0.000	0.015	0.232	0.455	0.209	0.072	0.018
1996	0.000	0.024	0.327	0.457	0.140	0.043	0.008
1997	0.000	0.034	0.369	0.394	0.159	0.034	0.011
1998	0.008	0.166	0.377	0.284	0.116	0.034	0.015
1999	0.012	0.190	0.365	0.248	0.116	0.044	0.024
2000	0.000	0.022	0.244	0.476	0.196	0.034	0.028

**Table 7.4:** Longline/handline catches-at-age (proportions of numbers) for *M. capensis* on the south coast (up to 1996, Geromont and Butterworth, 1999b; 1997 to present, Leslie, MCM, pers. commn).

Age	Proportions caught at age: <i>Merluccius capensis</i>						
	1	2	3	4	5	6	7+
1994	0.000	0.000	0.001	0.030	0.248	0.404	0.318
1995	0.000	0.000	0.000	0.006	0.093	0.262	0.638
1996	0.000	0.000	0.000	0.007	0.134	0.297	0.561
1997	0.000	0.000	0.002	0.036	0.201	0.298	0.464
1998							
1999							
2000	0.000	0.001	0.003	0.020	0.148	0.203	0.626

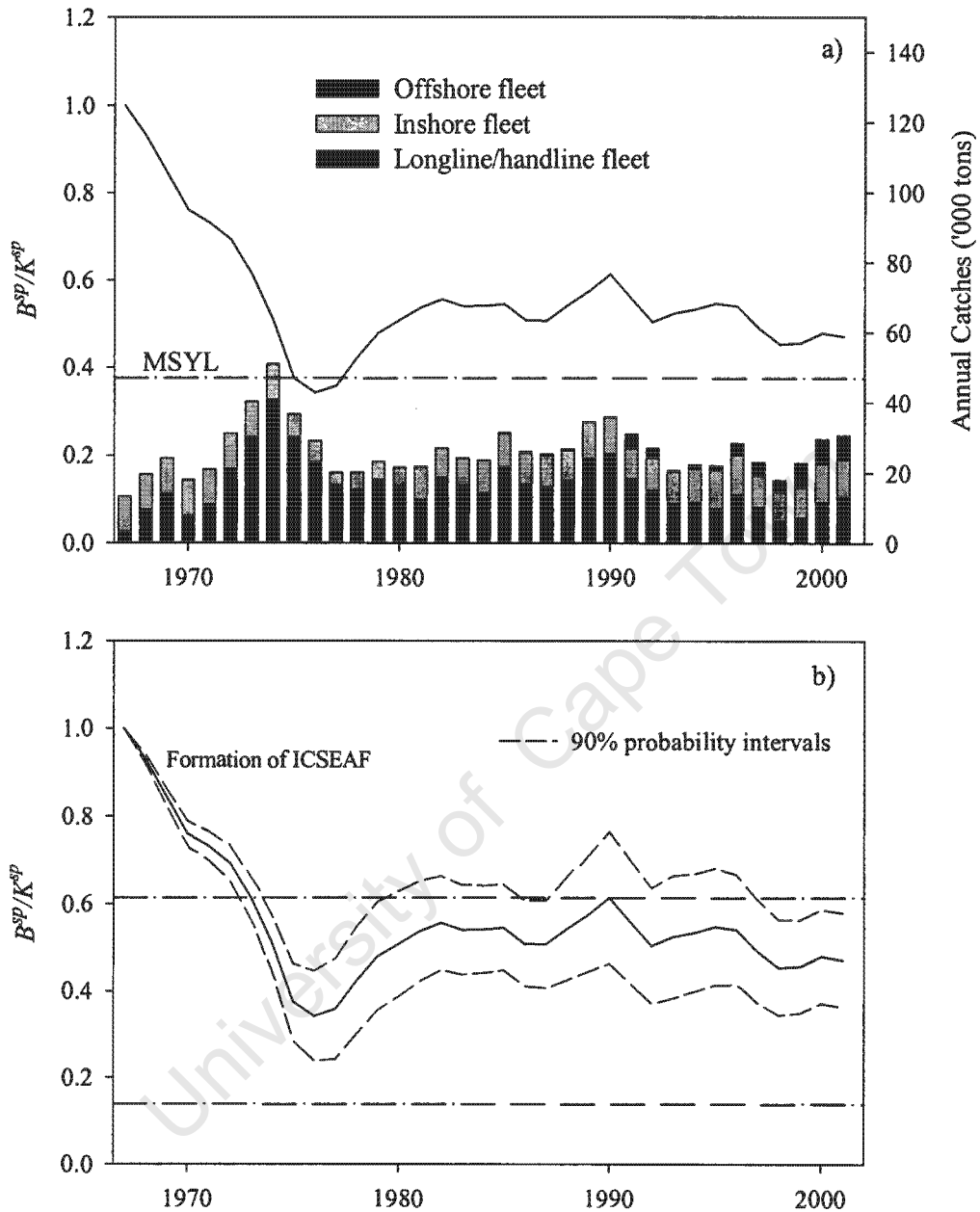
**Table 7.5:** Autumn survey catches-at-age (proportions of numbers for the 0-500 m depth range for south coast *M. capensis* (up to 1994, Geromont and Butterworth, 1999b; 1995 to present, Leslie, MCM, pers. commn).

Age	Proportions caught at age: <i>Merluccius capensis</i>							
	0	1	2	3	4	5	6	7+
1991	0.011	0.111	0.126	0.173	0.215	0.181	0.112	0.073
1992	0.015	0.203	0.358	0.145	0.118	0.110	0.038	0.014
1993	0.001	0.083	0.120	0.171	0.373	0.143	0.068	0.042
1994	0.061	0.140	0.123	0.219	0.137	0.159	0.116	0.045
1995	0.019	0.121	0.225	0.189	0.202	0.149	0.066	0.029
1996	0.005	0.104	0.188	0.192	0.288	0.131	0.061	0.031
1997	0.064	0.134	0.105	0.187	0.216	0.175	0.067	0.052
1998								
1999	0.159	0.140	0.281	0.145	0.117	0.087	0.040	0.030



**Table 7.6:** Estimates of management quantities for the Reference Case assessment for south coast *M. capensis*: the first figure shown is the best estimate, followed by the Hessian-based CV in parenthesis (note that the Hessian-based CV for  $h$  is unreliable as this parameter is estimated at a bound). Exploitable biomass and associated quantities are estimated for each fleet (assuming that this particular fleet is the only one operating) and for an ‘average-selectivity’ in the first column (see text for details).

		Reference Case			
Total -lnL		-116.6			
-lnL : CPUE		-36.7			
-lnL: Survey		-10.7			
-lnL: CAA com.		-50.4			
-lnL: CAA surv		-21.8			
-lnL: SR Residuals		3.1			
		Offshore	Inshore	Longline	
$K^{SP}$		170 (0.13)			
$K^{SA}$		142 (0.15)	121 (0.11)	75 (0.40)	
$B^{SP}_{2001}$		80 (0.17)			
$B^{SA}_{2001}$		58 (0.16)	77 (0.15)	13 (0.79)	
$h$		1.000 (0.01)			
$MSYL^{SP}$		49 (0.21)	21 (0.23)	117 (0.08)	
$MSYL^{SA}$		26 (0.10)	24 (0.16)	20 (0.23)	
$MSY$		35 (0.09)	35 (0.15)	27 (0.22)	
$B^{SP}_{2001}/K^{SP}$		0.471 (0.14)			
$B^{SA}_{2001}/K^{SA}$		0.406 (0.16)	0.639 (0.10)	0.180 (0.47)	
$B^{SP}_{2001}/MSYL^{SP}$		1.646 (0.12)	3.904 (0.26)	0.685 (0.13)	
$B^{SA}_{2001}/MSYL^{SA}$		2.224 (0.14)	3.209 (0.08)	0.678 (0.57)	
$MSYL^{SP}/K^{SP}$		0.286 (0.19)	0.121 (0.33)	0.687 (0.15)	
$MSYL^{SA}/K^{SA}$		0.182 (0.21)	0.199 (0.10)	0.265 (0.17)	
$M$		0.546 (0.19)			
	Age	$S_{off,a}$	$S_{in,a}$	$S_{ll,a}$	
	0	0.00	0.00	0.00	
	1	0.07	0.00	0.01	
	2	0.15	0.02	0.07	
	3	0.29	0.13	0.44	
	4	0.60	0.53	1.00	
	5	0.96	0.89	0.96	
	6	1.00	0.99	0.60	
	7+	0.91	1.00	0.35	
Commercial sigma's:					
	historic CPUE	0.251 (0.31)			
	GLM CPUE	0.267 (0.14)			
Commercial $q$ 's:					
	historic CPUE	0.010 (0.20)			
	GLM CPUE	0.107 (0.16)			
Survey $q$ 's:					
	spring	2.157 (0.31)			
	autumn	2.511 (0.31)			
Catches-at-age sigma's:					
	inshore	0.102 (0.04)			
	longline	0.147 (0.09)			
	autumn survey	0.130 (0.03)			
Additional sigma (survey)		0.165 (0.37)			



**Fig. 7.1:** The Reference Case ASPM assessment (which incorporates fluctuations about the stock-recruitment relationship) for the South African south coast hake *M. capensis* resource is shown in a), together with the estimated 'average-selectivity' MSYL (see text for details) and the annual catches (distinguishing the catches made by the offshore, inshore and longline/handline fleets); b) shows the Hessian-based 90% confidence intervals. The resource abundance is expressed in terms of spawning biomass as a proportion of its pre-exploitation equilibrium level ( $B^{sp}/K^{sp}$ ).

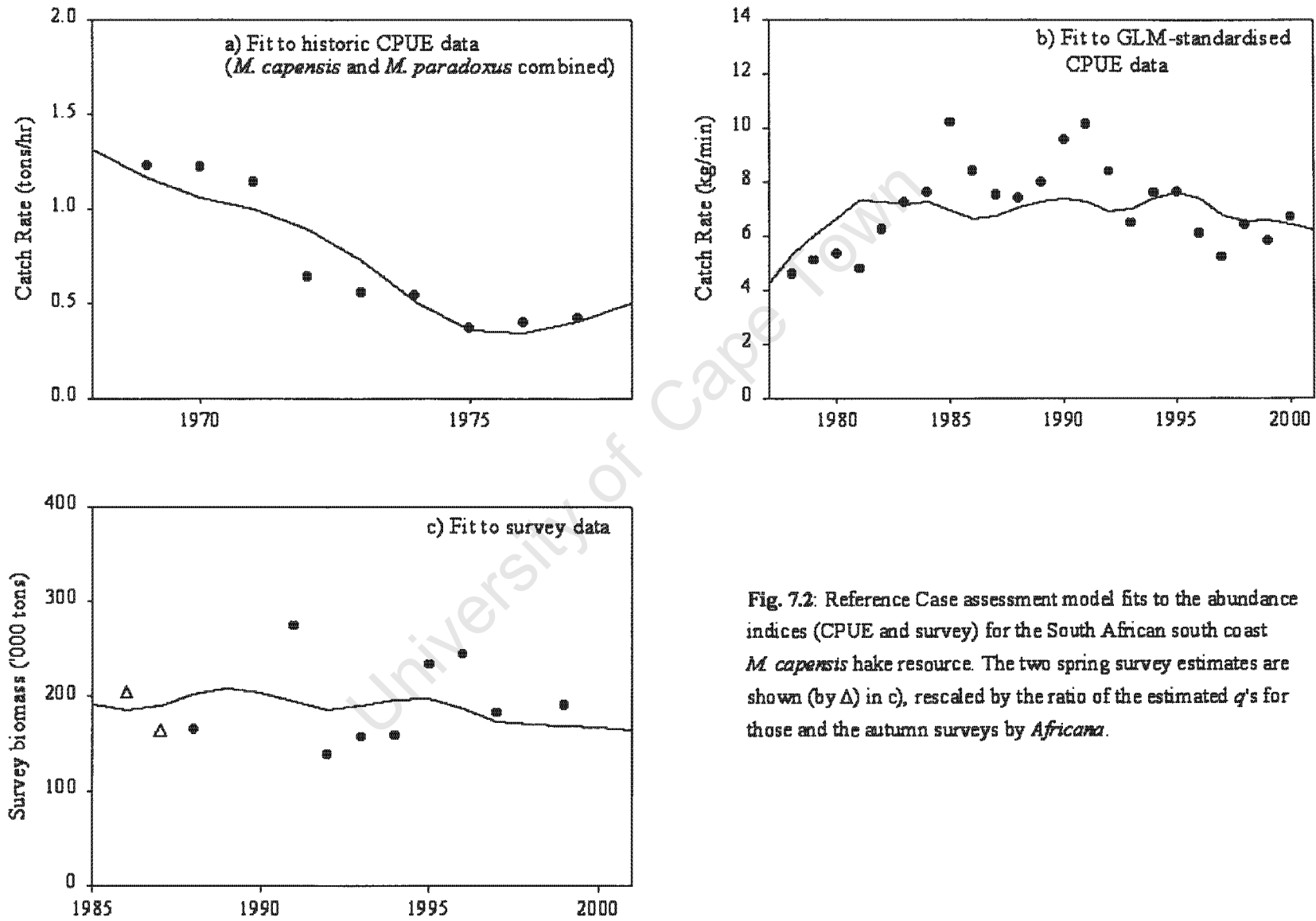


Fig. 7.2: Reference Case assessment model fits to the abundance indices (CPUE and survey) for the South African south coast *M. capensis* hake resource. The two spring survey estimates are shown (by  $\Delta$ ) in c), rescaled by the ratio of the estimated  $q$ 's for those and the autumn surveys by *Africana*.

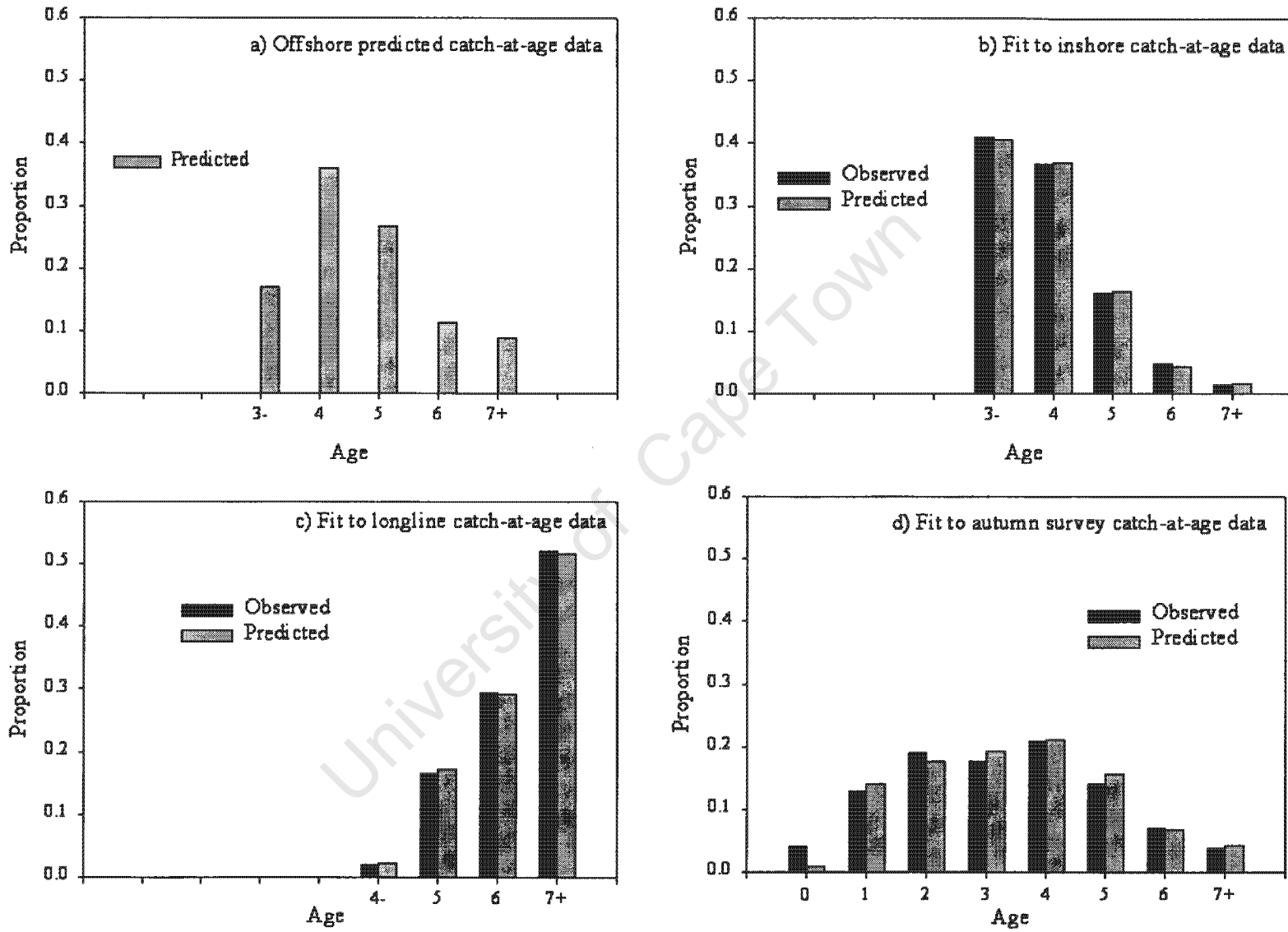


Fig. 7.3: Reference Case assessment model fits to catch-at-age data for the South African south coast *M. capensis* hake resource, as averaged over all the years with data for each data set. Catch-at-age information for *M. capensis* only is not available for the offshore fleet, but for comparison purposes, the predicted values are shown a).

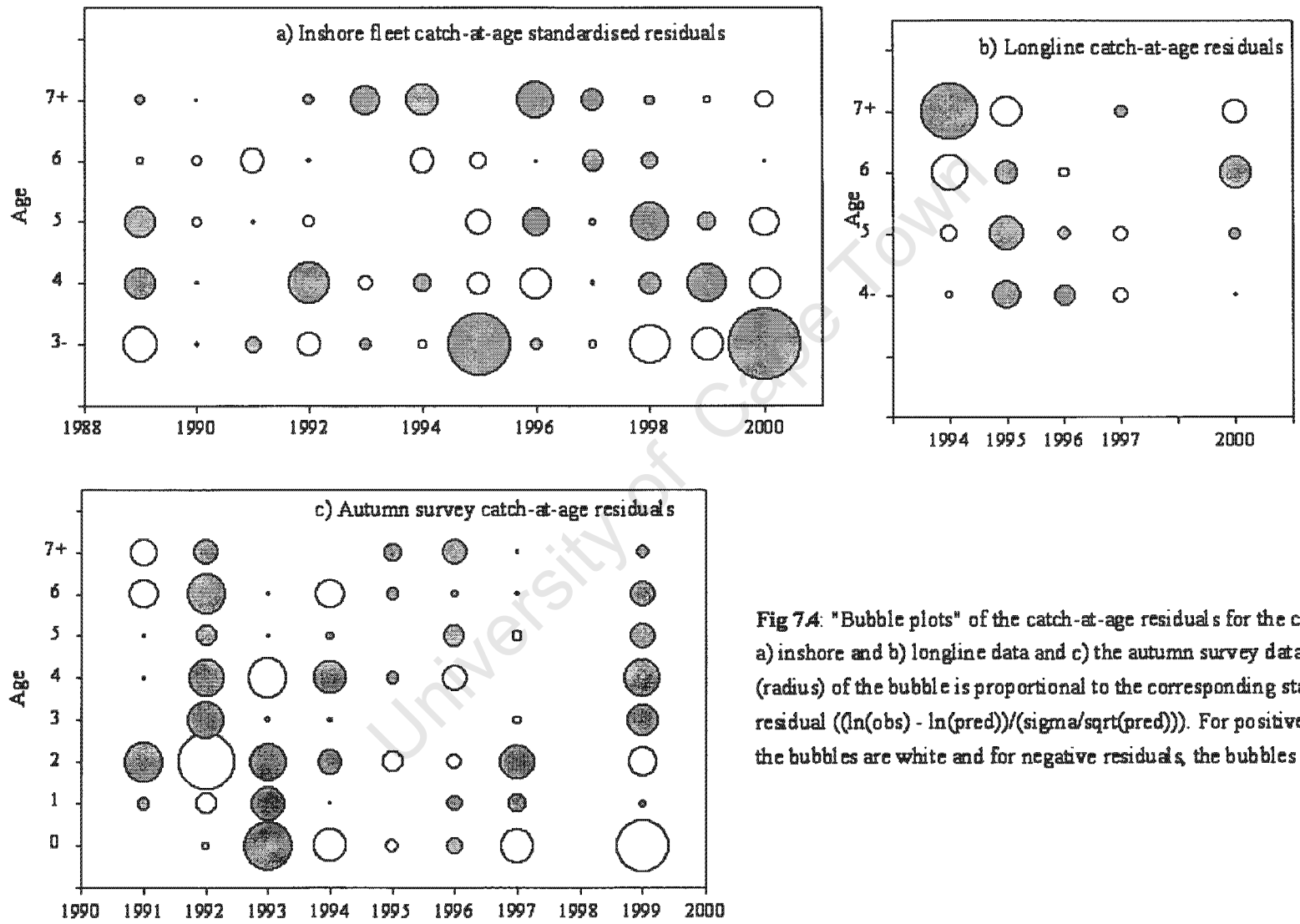


Fig 7A: "Bubble plots" of the catch-at-age residuals for the commercial a) inshore and b) longline data and c) the autumn survey data. The size (radius) of the bubble is proportional to the corresponding standardized residual  $((\ln(\text{obs}) - \ln(\text{pred})) / (\sigma / \sqrt{\text{pred}}))$ . For positive residuals, the bubbles are white and for negative residuals, the bubbles are gray.

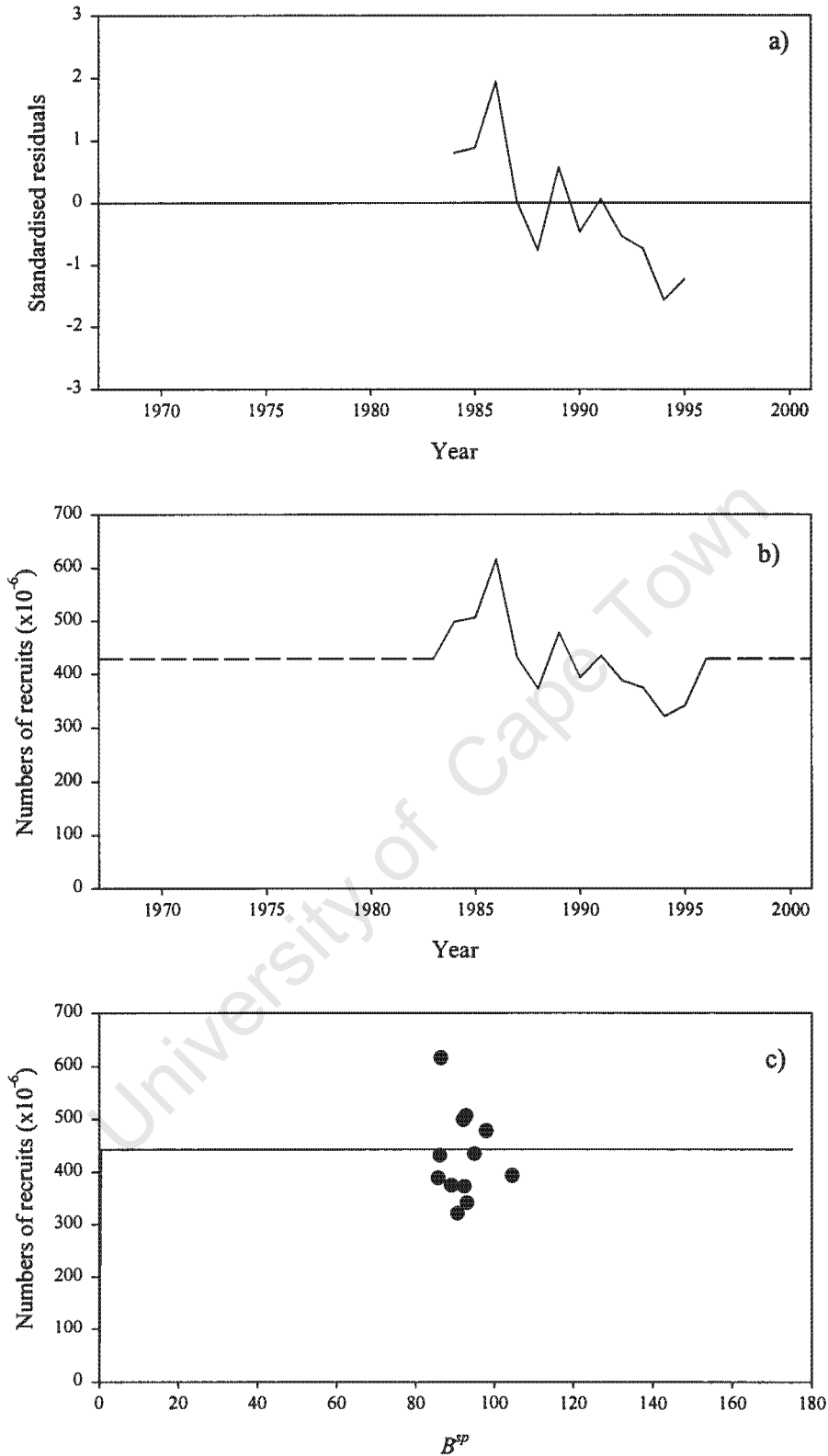


Fig 7.5: Time-series of a) estimated standardised stock-recruitment residuals and b) recruitment for the Reference Case assessment of the south coast *M. capensis* resource. c) shows the stock-recruitment relationship.

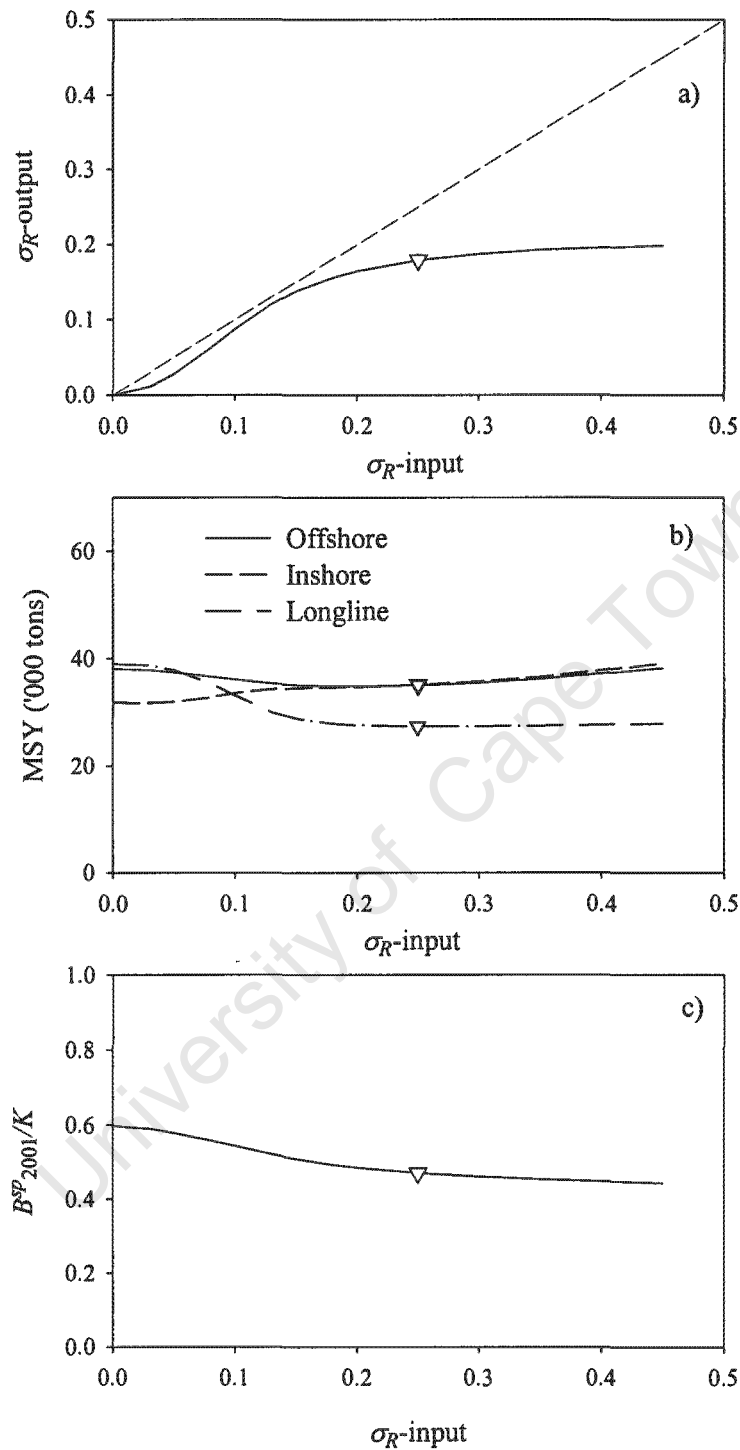


Fig. 7.6:  $\sigma_R$ -input vs. a)  $\sigma_R$ -output (the dashed line shows  $\sigma_R$ -output =  $\sigma_R$ -input), b) MSY (for each fleet) and c)  $B^{SP}_{2001}/K^{SP}$ , for the Reference Case assessment with fluctuations in the stock-recruitment relationship.  $\nabla$  shows the case  $\sigma_R$ -input = 0.25 used in the Reference Case assessment.

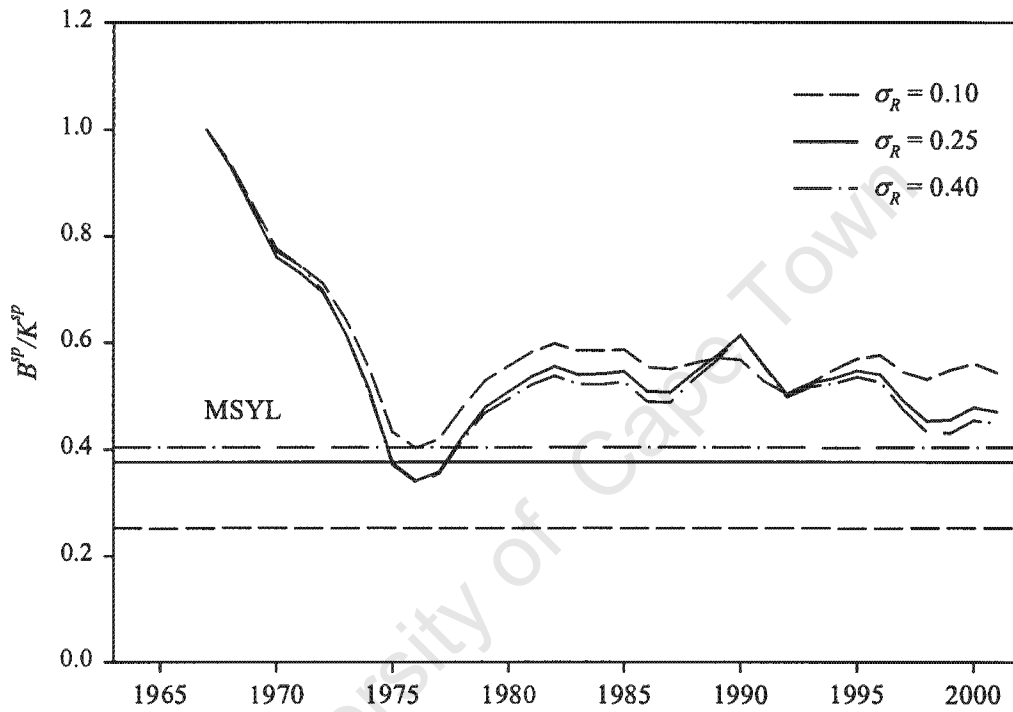


Fig. 7.7: Time-series of spawning biomass (in terms of its pre-exploitation equilibrium level) for three values of input- $\sigma_R$  (0.10, 0.25 and 0.40), together with the estimated MSYL.



## 8 Assessment of the South African *M. paradoxus* resource

Previous attempted assessments of the south coast *M. paradoxus* resource did not yield sensible results, probably because it is not a separate stock, independent of the west coast stock, and so does not react in the standard manner implicit in stock dynamics equations in response to what is in fact only localised and hence partial exploitation levels (Geromont and Butterworth, 1999a). This Chapter describes assessments of the *M. paradoxus* resource off South Africa, both for the west coast only and for the south and west coasts combined (Rademeyer and Butterworth, 2002b). The purpose of this work is primarily to compare the relative productivities of the south coast *M. paradoxus* stock with the entire South African (west and south coasts combined) *M. paradoxus* stock, in order to better estimate a sustainable catch for the south coast component of the *M. paradoxus* stock, currently not included in the OMPs. Estimating the current status of the resource is therefore not the main aim of this exercise and this is why it is considered adequate to use data up to 1999 only, which are readily available.

### 8.1 Data

#### 8.1.1 Total catch

The total annual catches of *M. paradoxus* assumed for this analysis are shown in Table 8.1 for the south and west coasts separately, from the beginning of the fishery to 1999. Despite the fact that a proportion of *M. paradoxus* are caught by the longline fleet, both on the south and west coasts, this assessment is fleet-aggregated, as there is no information immediately available on the species-structure of the longline catches. All the catches are therefore assumed to have been made by the offshore trawl fleet.

The catches have been split by species by applying the species proportion-by-depth relationships for the west and south coasts developed by Geromont *et al.* (1995b) (Glazer, MCM, pers. commn), which were estimated by stratifying the research survey catches for each coast by depth. Prior to 1978, there is no depth information recorded for the landings so that the proportion of *M. paradoxus* cannot be estimated by this method. Consequently, the catch data for the 1917-1977 period

have been split by species by assuming that the average proportion of *M. paradoxus* in the offshore fleet catch over the 1978-1982 period applies to this earlier data. These proportions are 55% and 92% for the south and west coasts respectively. As with the south coast *M. capensis* assessment, this assumption has been questioned because when the fishery commenced, trawlers operated in inshore areas close to Cape Town, so that future assessments should consider other assumptions.

### 8.1.2 Abundance Indices

Historic and GLM standardised CPUE data are given in Table 8.2. The historic CPUE data for south coast from 1969 to 1977 and for west coast from 1955 to 1977 are for *M. capensis* and *M. paradoxus* combined (ICSEAF, 1989). They cannot be disaggregated by species, as there are no effort-by-depth data available for this period. However, since information on the CPUE trend over this period is important for the assessment, the assumption is made that these combined-species data are also reflective of trends in the separate *M. paradoxus* stock alone. The GLM standardised CPUE data from 1978 to 1999 are from Glazer (MCM, pers. commn); these are for *M. paradoxus* only (and based also on the estimated species-proportion vs. depth relationship).

Survey biomass estimates for *M. paradoxus* for the depth range 0-500m, along with their associated standard errors, are given in Table 8.3 (Leslie, MCM, pers. commn). The combined estimates were obtained by adding the south coast autumn survey biomass estimates to the west coast summer survey estimates and using them as an index of begin-year abundance (as the west coast contribution dominates). This is not ideal because of the different time of the year when these surveys take place, but achieves the longest time series.

### 8.1.3 Catches-at-age

Commercial catches are not split by species and therefore catch-at-age information for *M. paradoxus* only is not available for the commercial catches. Hopefully in the future, on-board observers will be able to provide a basis to estimate commercial catches-at-age by species in South Africa, as is currently the case in Namibia.

Survey catch-at-age data (expressed as proportions) are given in Tables 8.4, 8.5 and 8.6 for the south coast, west coast and the two coasts combined respectively (Leslie, MCM, pers. commn). Because of the very low proportions of older fish, a 5+ plus-group is adopted. The south coast catches-at-age have been calculated from length frequency data using an age-length key for fish caught on the

west coast. Indeed, there are not enough *M. paradoxus* caught and aged during the surveys on the south coast to be able to reliably estimate a separate age-length key for that area.

To obtain the survey catches-at-age of *M. paradoxus* for the west and south coasts combined, the catches in numbers in each age class were added for the south coast autumn survey and the west coast summer survey (0-500m depth range), and then converted to proportions.

## 8.2 Reference Cases assessment specifications

The *M. paradoxus* resource is assessed in two ways, the west coast component only ('West Coast only') and the stock as a whole ('Both Coasts'); the reasons for proceeding in this way are discussed in Chapter 12. Three variants of the assessment model are presented for each of the two cases. The difference between the three variants is only in the shape of the selectivity function (for both the commercial and the survey selectivities) at older ages.

The age-structured production model used is exactly the same in both assessments, only the data inputs change. The following assumptions have been made in the assessments of the *M. paradoxus* hake stock off the south and west coasts of South Africa (rational as not been repeated below when it duplicates that given for Namibian hake in Section 5.2):

- 1)  $B_{1917}^{sp} = K^{sp}$ : The model assumes that the stock was at its pristine level when the fishery commenced.
- 2) *Natural mortality*:  $M_a$  is taken to be age-dependent ( $M_a$ ) (with the form of equation 4.23).
- 3) *Commercial selectivity-at-age*: As there is no information on the age-structure of the commercial catches of *M. paradoxus*, commercial selectivity-at-age cannot be directly estimated.  $S_{y,a}^{com}$  is therefore estimated by assuming that the ratios of the survey to commercial selectivities-at-age from the combined-species west coast assessment (Chapter 6) apply here too. Similarly, the periods of fixed and changing selectivity used in the combined species west coast assessment (to take account for the change in the selectivity pattern at low ages over time in the commercial catches) have also been used in this assessment. The first selectivity period is from 1917 to 1984 and the second from 1993 to the present, with the selectivities in the intervening period assumed to vary linearly between these 1984 and 1993 values. The proportions of the survey selectivity used for the commercial selectivity are as follow:

Ages	1917-1984	1993-1999
0	0.0	0.0
1	0.0	0.0
2	0.7	0.25
3	1.0	1.0
4	1.0	1.0
5+	1.0	1.0

- 4) *Survey selectivity-at-age*: The survey selectivity is estimated directly by the model for ages 0 and 1 and set to 1 for ages above 1, as for the combined-species west coast assessment. However, both the survey and the commercial selectivities can be modified by including a downward slope for  $a > a_{slope}$ , which measures the rate of decrease in selectivity with age for fish older than  $a_{slope}$ . Three variants on the assessment are reported in this Chapter; they vary only in the value of this selectivity slope. These variants are: a) 'no slope', b) 'slope of 0.2' ( $s = 0.2 \text{ yr}^{-1}$ ) and c) 'slope of 0.4' ( $s = 0.4 \text{ yr}^{-1}$ ). The slope is taken to be the same for the survey and the commercial selectivities. The analysis with slope  $> 0$  assumes the age from which the decrease commences,  $a_{slope} = 3$ . A decreasing selectivity at large ages for *M. paradoxus* seems quite plausible, as the older animals may be preferentially in deeper waters than are customarily trawled.
- 5) *Stock-recruitment residuals*:  $\sigma_R$  is fixed at 0.25. The residuals are assumed not to be serially correlated, i.e.,  $\rho = 0$ . They are estimated from year 1985 to 1996 for the west coast only assessments and from year 1986 to 1993 for the coasts combined assessments.
- 6) *Lower bound on the variance on the CPUE data*: Minima for these  $\sigma^{f,i}$  estimates corresponding to the GLM-based and 'historic' series are 0.1 and 0.25 respectively.
- 7) *Additional variance on surveys*: A common additional variance is estimated for the surveys conducted by the *Africana* and the *Nansen*.
- 8) *CPUE series used*: The 'Both Coasts' assessment is fitted to both the south and west coasts historic CPUE series.

### 8.3 Results and Discussion

Estimates of management quantities for the three variants of the model, for both the 'West Coast only' and the 'Both Coasts' cases are given in Tables 8.7 and 8.8 respectively, whereas Figs. 8.1

and 8.5 show the resource abundance time-series for each of the three selectivity slopes. The differences are minimal between the two cases with a positive selectivity slope, but they differ markedly from the 'No slope' case in terms of spawning biomass trajectories. In both the 'West Coast only' and the 'Both Coasts' cases, the fit is slightly better when the selectivity on the older fish is allowed to decrease (see Tables 8.7 and 8.8); this arises primarily because of a better fit to the survey catch-at-age data. A slope of 0.4 fits the 'West Coast only' data the best, while the 'Slope of 0.2' case gives the best fit (of the three variants considered) for the 'Both Coasts' assessment. Figs. 8.2 and 8.5 show how these two models fit the abundance indices. In both cases, the model shows broadly reasonable fits to the CPUE indices. The model does not however fit the clear positive trend shown by the survey biomass estimates, particularly in the 'West Coast only' case, because very little recovery is observed over the last 20 years in the catch rates. The reason for such different trends in the CPUE and survey data should be investigated further.

Figs. 8.3 and 8.7 show the fit of these models to the survey catch-at-age data. The fits to the catch-at-age data are good, although in both cases, despite the fact that selectivity is assumed to decrease for older ages, the model predicts too large a proportion of fish of age 4 and above. This pattern of too many large fish predicted in the catches-at-age is also clear in the 'bubble' plots of the standardised catch-at-age residuals (Figs. 8.4 and 8.8), where the residuals are systematically negative for ages 4 and above. Furthermore, the model seems to underestimate the proportion of 0 year old in the 'West Coast only' case, though this might be due to the large recruitment observed in 1999.

Having a decreasing selectivity at older ages results in a more pessimistic estimate of the status of the resource in 1999, compared to the case with a flat selectivity at older ages, but the estimates of  $M_a$  seem more realistic (not as high as for the 'No slope' case), particularly for older ages. In the 'Slope of 0.4' case, the stock in 1999 is estimated to be at about 17% of the pre-exploitation spawning biomass. In the 'No slope' case, the 1999 spawning biomass is estimated to be in a better condition, at about 27% of the pre-exploitation level. There has been a steady recovery in the South African *M. paradoxus* stock since the sharp decline in biomass in the late 1960's and 1970's; however, in the models with a positive selectivity slope, this recovery is estimated to be small and the current spawning biomass is still well below its MSYL of approximately 0.26 – 0.30 (depending whether or not the south coast is included in the assessment).

In all cases, the difference in the MSY estimates between the 'West Coast only' and the 'Both Coasts' assessments is approximately 19 thousand tons. Suggesting that the effective MSY for the south coast portion of the *M. paradoxus* stock is close to this value.

**Table 8.1:** Assumed total annual catches by coast for *M. paradoxus* for the period 1917 to 1999. Catches are given in thousand tons. Refer to the text for details on the assumptions made and the sources for the data.

Year	South coast	West coast	Total	Year	South coast	West coast	Total
1917		0.920	0.920	1959		134.251	134.251
1918		1.011	1.011	1960		147.032	147.032
1919		1.747	1.747	1961		136.733	136.733
1920		0.000	0.000	1962		135.722	135.722
1921		1.195	1.195	1963		155.859	155.859
1922		0.920	0.920	1964		149.239	149.239
1923		2.299	2.299	1965		186.663	186.663
1924		1.379	1.379	1966		179.307	179.307
1925		1.747	1.747	1967	2.657	162.480	165.137
1926		1.287	1.287	1968	7.735	132.044	139.779
1927		0.736	0.736	1969	11.475	151.813	163.289
1928		2.391	2.391	1970	6.444	131.032	137.476
1929		3.494	3.494	1971	8.869	185.744	194.613
1930		4.046	4.046	1972	19.825	224.302	244.127
1931		2.575	2.575	1973	24.382	145.084	169.466
1932		13.149	13.149	1974	32.888	113.101	145.989
1933		10.207	10.207	1975	24.421	82.405	106.826
1934		12.689	12.689	1976	18.798	132.314	151.112
1935		13.793	13.793	1977	13.383	94.093	107.477
1936		16.276	16.276	1978	13.947	95.335	109.281
1937		18.574	18.574	1979	15.475	84.400	99.874
1938		19.402	19.402	1980	15.328	93.762	109.091
1939		18.390	18.390	1981	7.880	91.704	99.584
1940		26.298	26.298	1982	14.051	78.260	92.312
1941		28.137	28.137	1983	12.447	68.938	81.385
1942		31.724	31.724	1984	13.960	81.354	95.314
1943		34.850	34.850	1985	18.651	95.089	113.740
1944		31.356	31.356	1986	21.071	104.435	125.506
1945		26.850	26.850	1987	13.801	100.118	113.919
1946		37.149	37.149	1988	14.767	86.409	101.176
1947		38.068	38.068	1989	14.112	81.341	95.453
1948		54.068	54.068	1990	17.335	76.573	93.908
1949		52.781	52.781	1991	20.999	84.260	105.258
1950		66.206	66.206	1992	24.446	84.660	109.106
1951		82.297	82.297	1993	19.451	96.745	116.196
1952		81.654	81.654	1994	16.622	101.836	118.458
1953		85.975	85.975	1995	19.536	93.874	113.409
1954		96.918	96.918	1996	34.451	90.201	124.652
1955		106.113	106.113	1997	29.290	91.480	120.770
1956		108.688	108.688	1998	21.450	107.388	128.837
1957		116.228	116.228	1999	29.096	85.593	114.689
1958		120.182	120.182				

**Table 8.2:** Historic ICSEAF (1969 to 1977 and 1955 to 1977) (ICSEAF, 1989) and GLM standardised (1978 to 1999) (Glazer, MCM, pers. commn) CPUE data for *M. paradoxus*. The historic CPUE series is for *M. capensis* and *M. paradoxus* combined, while the GLM-standardised CPUE series is for *M. paradoxus* only.

Year	South coast		West coast		Combined GLM CPUE kg/min
	ICSEAF CPUE tons/hr	GLM CPUE kg/min	ICSEAF CPUE tons/day	GLM CPUE kg/min	
1955			17.31		
1956			15.64		
1957			16.47		
1958			16.26		
1959			16.26		
1960			17.31		
1961			12.09		
1962			14.18		
1963			13.97		
1964			14.60		
1965			10.84		
1966			10.63		
1967			10.01		
1968			10.01		
1969	1.28		8.62		
1970	1.22		7.23		
1971	1.14		7.09		
1972	0.64		4.90		
1973	0.56		4.97		
1974	0.54		4.65		
1975	0.37		4.66		
1976	0.40		5.35		
1977	0.42		4.84		
1978		2.172		10.166	12.338
1979		1.889		10.721	12.610
1980		2.640		10.148	12.787
1981		1.688		10.008	11.696
1982		2.520		9.443	11.963
1983		2.736		10.797	13.533
1984		3.160		11.271	14.430
1985		4.151		13.052	17.202
1986		4.679		11.435	16.113
1987		3.788		9.552	13.340
1988		3.260		8.971	12.231
1989		2.964		9.686	12.651
1990		3.497		9.568	13.065
1991		4.725		11.483	16.209
1992		5.040		10.966	16.006
1993		4.967		10.156	15.123
1994		4.393		10.801	15.194
1995		4.372		10.318	14.689
1996		6.574		11.070	17.644
1997		6.127		10.601	16.728
1998		5.640		12.243	17.883
1999		6.687		10.045	16.732

**Table 8.3:** Survey abundance estimates and associated standard errors in thousand tons for *M. paradoxus* for the depth range 0-500 m for the south and west coasts (Leslie, MCM, pers. commn). The combined estimates are obtained by adding the south coast autumn estimates to the west coast summer estimates.

Year	South Coast				West Coast				Combined	
	Spring		Autumn		Summer		Winter		Autumn/Summer	
	Biomass	(s.e.)	Biomass	(s.e.)	Biomass	(s.e.)	Biomass	(s.e.)	Biomass	(s.e.)
1985					168.139	(36.607)	264.916	(52.968)		
1986	23.049	(5.946)			196.151	(36.366)	172.522	(24.129)		
1987	21.545	(4.601)			284.859	(53.108)	195.530	(44.425)		
1988			30.236	(11.084)	158.796	(27.390)	233.103	(64.016)	189.032	(29.547)
1989							468.928	(124.878)		
1990					282.225	(78.956)	226.910	(46.016)		
1991			26.604	(10.431)	327.105	(82.209)			353.709	(82.868)
1992			24.305	(15.197)	234.699	(33.963)			259.004	(37.208)
1993			198.403	(98.423)	321.782	(48.799)			520.185	(109.856)
1994			111.354	(34.622)	329.927	(58.332)			441.281	(67.833)
1995			44.618	(19.823)	324.626	(80.370)			369.244	(82.778)
1996			85.530	(25.485)	430.971	(80.614)			516.501	(84.547)
1997			134.656	(50.922)	570.091	(108.230)			704.747	(119.611)
1998										
1999					562.988	(116.322)				
2000										

**Table 8.4:** Autumn survey catches-at-age (proportions of numbers) of *M. paradoxus* on the south coast for the 0-500 m depth range (estimated from unpublished MCM records of catch-at-length and age-length keys).

Age	Proportions caught at age: <i>Merluccius paradoxus</i>					
	0	1	2	3	4	5+
1991	0.0038	0.0099	0.5219	0.2920	0.1162	0.0563
1992	0.0000	0.0006	0.3698	0.5407	0.0653	0.0236
1993	0.0000	0.0047	0.4157	0.5439	0.0260	0.0097
1994	0.0054	0.0898	0.6558	0.1857	0.0170	0.0463
1995	0.0002	0.0002	0.1241	0.7729	0.0886	0.0139
1996	0.0000	0.0000	0.0968	0.7494	0.0999	0.0539
1997	0.0002	0.0012	0.1108	0.5806	0.1055	0.2016



**Table 8.5:** Summer survey catches-at-age (proportions of numbers) of *M. paradoxus* on the west coast for the 0-500 m depth range (estimated from unpublished MCM records of catch-at-length and age-length keys).

Age	Proportions caught at age: <i>Merluccius paradoxus</i>					
	0	1	2	3	4	5+
1990	0.0285	0.3098	0.4918	0.1583	0.0088	0.0017
1991	0.0182	0.2777	0.5608	0.1069	0.024	0.0079
1992	0.0098	0.3834	0.4847	0.0824	0.0231	0.0118
1993	0.0089	0.1995	0.5469	0.1866	0.0439	0.0097
1994	0.0107	0.2441	0.5508	0.1656	0.0174	0.0078
1995	0.0651	0.1905	0.4435	0.2583	0.0282	0.0096
1996	0.0572	0.3939	0.3018	0.2096	0.0298	0.005
1997	0.0055	0.1708	0.5459	0.2564	0.0164	0.0032
1998						
1999	0.1613	0.4099	0.3358	0.0808	0.0084	0.0026

**Table 8.6:** Autumn/summer survey catches-at-age (proportions of numbers) for *M. paradoxus* for the two coasts combined for the 0-500 m depth range. Catches in numbers in each age class were added for the south coast autumn survey and the west coast summer survey and then converted to proportions.

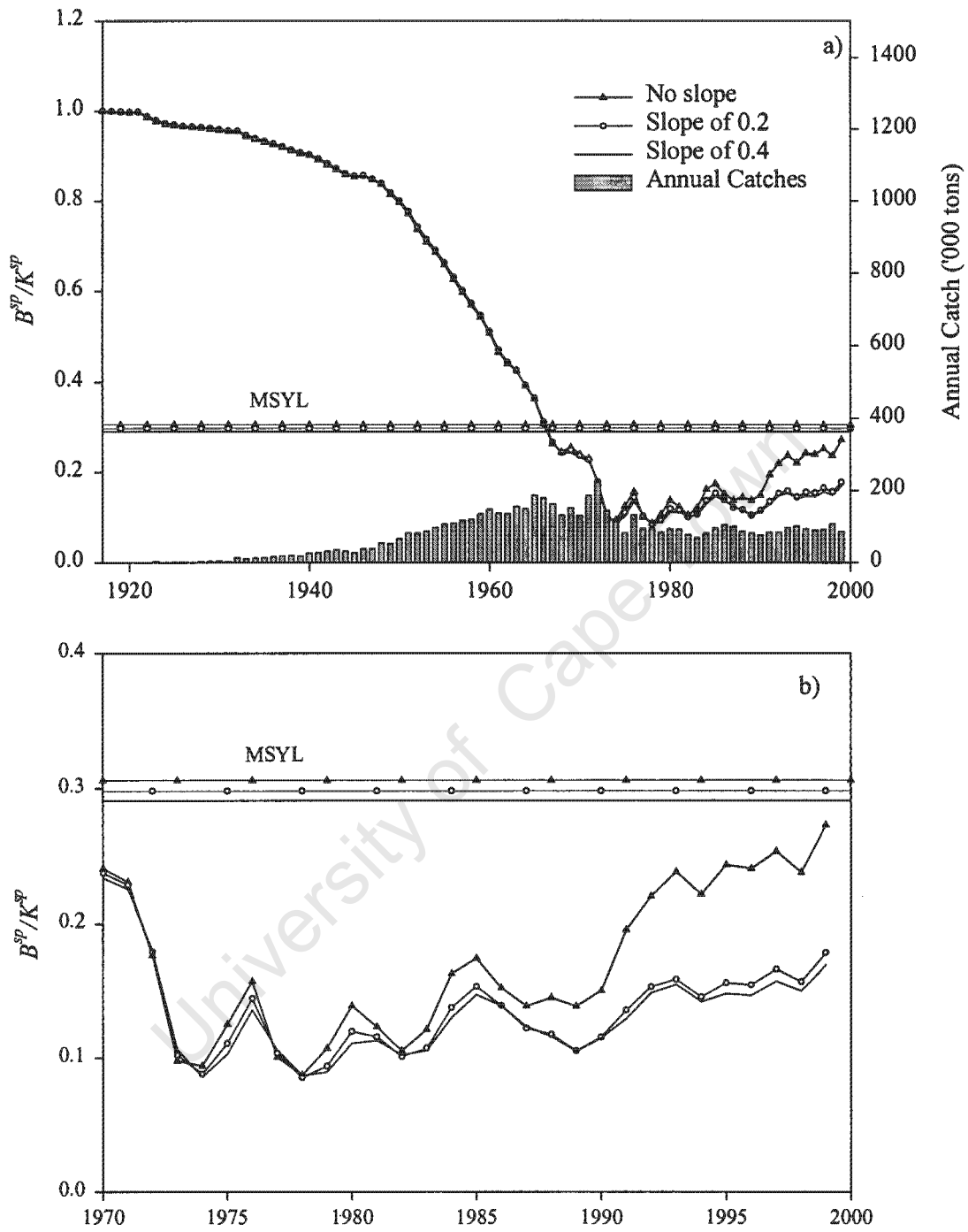
Age	Proportions caught at age: <i>Merluccius paradoxus</i>					
	0	1	2	3	4	5+
1991	0.0177	0.2679	0.5594	0.1137	0.0274	0.0140
1992	0.0093	0.3653	0.4793	0.1039	0.0251	0.0170
1993	0.0064	0.1442	0.5097	0.2881	0.0388	0.0129
1994	0.0098	0.2174	0.5690	0.1691	0.0173	0.0175
1995	0.0605	0.1769	0.4206	0.2951	0.0325	0.0145
1996	0.0529	0.3642	0.2863	0.2503	0.0351	0.0112
1997	0.0052	0.1611	0.5212	0.2748	0.0215	0.0162

Table 8.7: Estimates of management quantities for the west coast component of the *M. paradoxus* resource, for three different shapes for the selectivity function (see text for details). The first figure shown is the best estimate, followed by the Hessian-based CV in parenthesis.

	West Coast only											
	No slope				Slope of 0.2				Slope of 0.4			
Total -lnL	-109.02				-112.85				-113.90			
-lnL : CPUE	-89.58				-93.55				-94.26			
-lnL: Survey	-14.15				-12.20				-11.94			
-lnL: CAA com.	-				-				-			
-lnL: CAA surv	-7.92				-9.87				-10.66			
-lnL: SR Residuals	2.64				2.77				2.96			
$K^{SP}$	559 (0.08)				698 (0.08)				801 (0.09)			
$K^{AA}$	973 (0.05)				904 (0.04)				813 (0.04)			
$B^{SP}_{1999}$	153 (0.13)				125 (0.14)				136 (0.14)			
$B^{AA}_{1999}$	201 (0.12)				171 (0.12)				155 (0.12)			
$h$	0.620 (0.06)				0.645 (0.06)				0.661 (0.06)			
$MSYL^{SP}$	171 (0.05)				208 (0.06)				233 (0.07)			
$MSYL^{AA}$	262 (0.03)				314 (0.03)				297 (0.03)			
$MSY$	123 (0.03)				129 (0.03)				131 (0.03)			
$B^{SP}_{1999}/K^{SP}$	0.273 (0.14)				0.179 (0.16)				0.169 (0.17)			
$B^{AA}_{1999}/K^{AA}$	0.207 (0.11)				0.189 (0.11)				0.190 (0.11)			
$B^{SP}_{1999}/MSYL^{SP}$	0.891 (0.16)				0.599 (0.18)				0.582 (0.19)			
$B^{AA}_{1999}/MSYL^{AA}$	0.768 (0.14)				0.544 (0.14)				0.521 (0.15)			
$MSYL^{SP}/K^{SP}$	0.306 (0.05)				0.298 (0.05)				0.291 (0.05)			
$MSYL^{AA}/K^{AA}$	0.270 (0.05)				0.348 (0.05)				0.365 (0.05)			
Age	$M_a$	$S^{surv}$	$S^{com}_{1917}$	$S^{com}_{1999}$	$M_a$	$S^{surv}$	$S^{com}_{1917}$	$S^{com}_{1999}$	$M_a$	$S^{surv}$	$S^{com}_{1917}$	$S^{com}_{1999}$
0	1.185	0.004	0.000	0.000	0.998	0.006	0.000	0.000	0.900	0.504	0.000	0.000
1	1.185	0.192	0.000	0.000	0.998	0.239	0.000	0.000	0.900	0.267	0.000	0.000
2	1.185	1.000	0.700	0.100	0.998	1.000	0.700	0.122	0.900	1.000	0.700	0.125
3	0.891	1.000	1.000	0.800	0.751	1.000	1.000	0.977	0.678	1.000	1.000	1.000
4	0.715	1.000	1.000	1.000	0.603	0.819	0.819	1.000	0.544	0.670	0.670	0.838
5+	0.597	1.000	1.000	1.000	0.504	0.670	0.670	0.819	0.455	0.449	0.449	0.562
Commercial $q$ 's:												
SC ICSEAF CPUE												
WC ICSEAF CPUE	0.026 (0.06)				0.028 (0.06)				0.031 (0.06)			
GLM CPUE	0.053 (0.10)				0.061 (0.11)				0.066 (0.11)			
Commercial sigma's:												
SC ICSEAF CPUE												
WC ICSEAF CPUE	0.113 (0.03)				0.112 (0.02)				0.114 (0.03)			
GLM CPUE	0.060 (0.09)				0.050 (0.10)				0.048 (0.10)			
Survey $q$ 's:												
Summer/Autumn	0.610 (0.12)				0.851 (0.12)				0.957 (0.13)			
Winter	0.724 (0.10)				0.899 (0.10)				0.964 (0.11)			
Catches-at-age sigma's:	0.148 (0.06)				0.141 (0.06)				0.138 (0.06)			
Addnl sigma (survey)	0.208 (0.31)				0.247 (0.27)				0.253 (0.26)			

**Table 8.8:** Estimates of management quantities for the whole ('Both Coasts') component of the *M. paradoxus* resource, for three different shapes for the selectivity function (see text for details). The first figure shown is the best estimate, followed by the Hessian-based CV in parenthesis.

	Both Coasts											
	No slope				Slope of 0.2				Slope of 0.4			
Total -lnL	-109.02				-111.16				-110.60			
-lnL : CPUE	-96.16				-96.91				-95.93			
-lnL: Survey	-6.72				-6.11				-5.97			
-lnL: CAA com.	-				-				-			
-lnL: CAA surv	-7.20				-9.21				-9.67			
-lnL:SR Residuals	1.06				1.07				0.97			
$K^{SP}$	655 (0.08)				841 (0.08)				997 (0.10)			
$K^{SA}$	1020 (0.05)				959 (0.05)				862 (0.05)			
$B^{SP}_{1999}$	178 (0.11)				143 (0.14)				163 (0.15)			
$B^{SA}_{1999}$	260 (0.09)				226 (0.10)				211 (0.10)			
$h$	0.743 (0.04)				0.767 (0.05)				0.780 (0.05)			
$MSYL^{SP}$	174 (0.04)				217 (0.04)				251 (0.05)			
$MSYL^{SA}$	259 (0.02)				315 (0.02)				301 (0.02)			
$MSY$	142 (0.02)				147 (0.02)				150 (0.02)			
$B^{SP}_{1999}/K^{SP}$	0.271 (0.11)				0.171 (0.15)				0.164 (0.16)			
$B^{SA}_{1999}/K^{SA}$	0.254 (0.08)				0.236 (0.10)				0.245 (0.10)			
$B^{SP}_{1999}/MSYL^{SP}$	1.023 (0.12)				0.661 (0.16)				0.650 (0.17)			
$B^{SA}_{1999}/MSYL^{SA}$	1.002 (0.10)				0.717 (0.12)				0.701 (0.12)			
$MSYL^{SP}/K^{SP}$	0.265 (0.05)				0.258 (0.05)				0.252 (0.05)			
$MSYL^{SA}/K^{SA}$	0.254 (0.05)				0.329 (0.04)				0.350 (0.04)			
Age	$M_a$	$S^{surv}$	$S^{com}_{1917}$	$S^{com}_{1999}$	$M_a$	$S^{surv}$	$S^{com}_{1917}$	$S^{com}_{1999}$	$M_a$	$S^{surv}$	$S^{com}_{1917}$	$S^{com}_{1999}$
0	0.985	0.005	0.000	0.000	0.800	0.007	0.000	0.000	0.701	0.009	0.000	0.000
1	0.985	0.181	0.000	0.000	0.800	0.220	0.000	0.000	0.701	0.246	0.000	0.000
2	0.985	1.000	0.700	0.100	0.800	1.000	0.700	0.122	0.701	1.000	0.700	0.125
3	0.741	1.000	1.000	0.800	0.603	1.000	1.000	0.977	0.528	1.000	1.000	1.000
4	0.595	1.000	1.000	1.000	0.484	0.819	0.819	1.000	0.425	0.670	0.670	0.838
5+	0.408	1.000	1.000	1.000	0.405	0.670	0.670	0.819	0.356	0.449	0.449	0.562
Commercial $q$ 's:												
SC ICSEAF CPUE	0.003 (0.07)				0.003 (0.07)				0.003 (0.07)			
WC ICSEAF CPUE	0.025 (0.06)				0.027 (0.06)				0.030 (0.06)			
GLM CPUE	0.069 (0.10)				0.080 (0.10)				0.086 (0.10)			
Commercial sigma's:												
SC ICSEAF CPUE	0.210 (0.06)				0.208 (0.07)				0.217 (0.06)			
WC ICSEAF CPUE	0.119 (0.03)				0.116 (0.03)				0.111 (0.02)			
GLM CPUE	0.065 (0.07)				0.065 (0.08)				0.070 (0.09)			
Survey $q$ 's:												
Summer/Autumn	0.777 (0.10)				1.101 (0.10)				1.234 (0.10)			
Winter												
Catches-at-age sigma's:	0.152 (0.06)				0.142 (0.06)				0.140 (0.06)			
Addnl sigma (survey)	0.231 (0.36)				0.256 (0.34)				0.262 (0.33)			



**Fig. 8.1:** Estimated spawning biomass (as a proportion of the pre-exploitation level) for the west coast component of the *M. paradoxus* hake resource, for each of the three variants of the assessment (see text for details). MSYL is also shown for each of the variants.

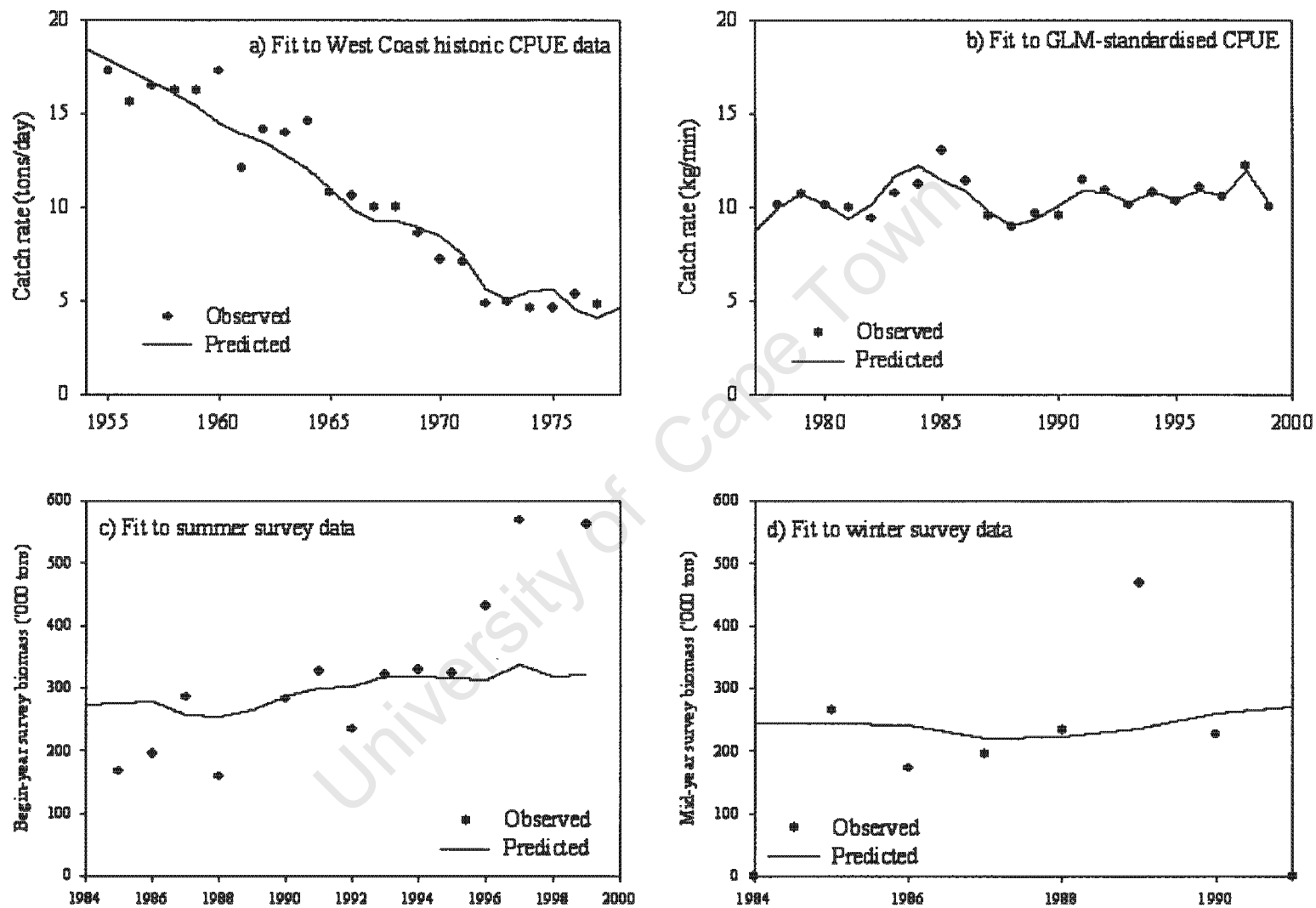


Fig. 8.2: Assessment model fits for *M. paradoxus* to the abundance indices for the 'west coast only', 'Slope of 0.4' case. The historic (pre-1978) CPUE data are for both *M. capensis* and *M. paradoxus* combined.

Fig. 8.4: "Bubble plots" of the survey catch-at-age residuals for the 'West Coast only' and standardized residuals  $((\ln(\text{obs}) - \ln(\text{pred})) / (\sigma \sqrt{t}))$ . For positive residuals, the slope of 0.4 case. The size (radius) of the bubble is proportional to the corresponding, the bubbles are white and for negative residuals, the bubbles are gray.

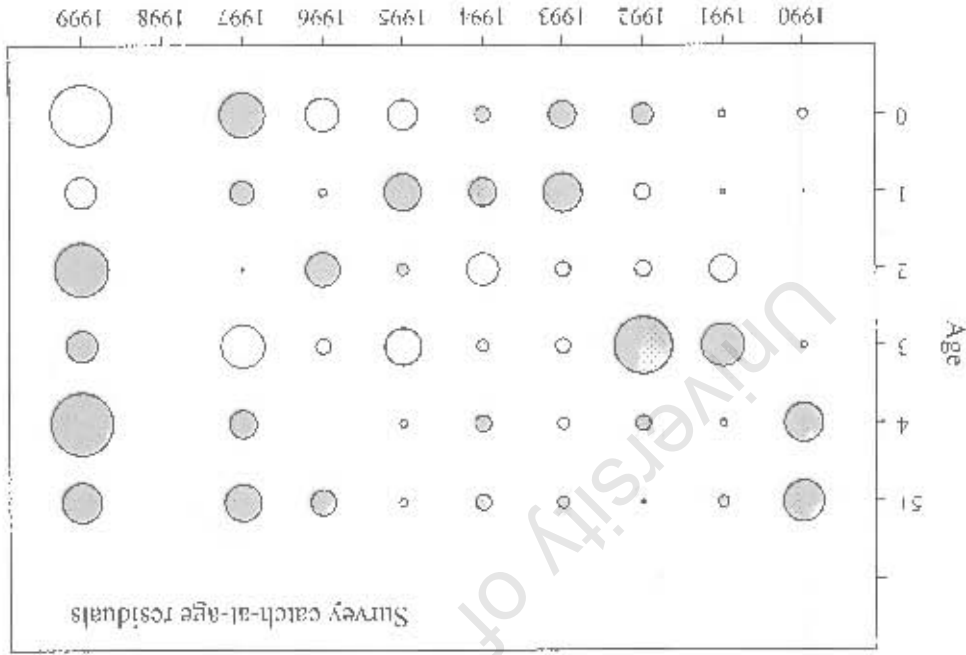
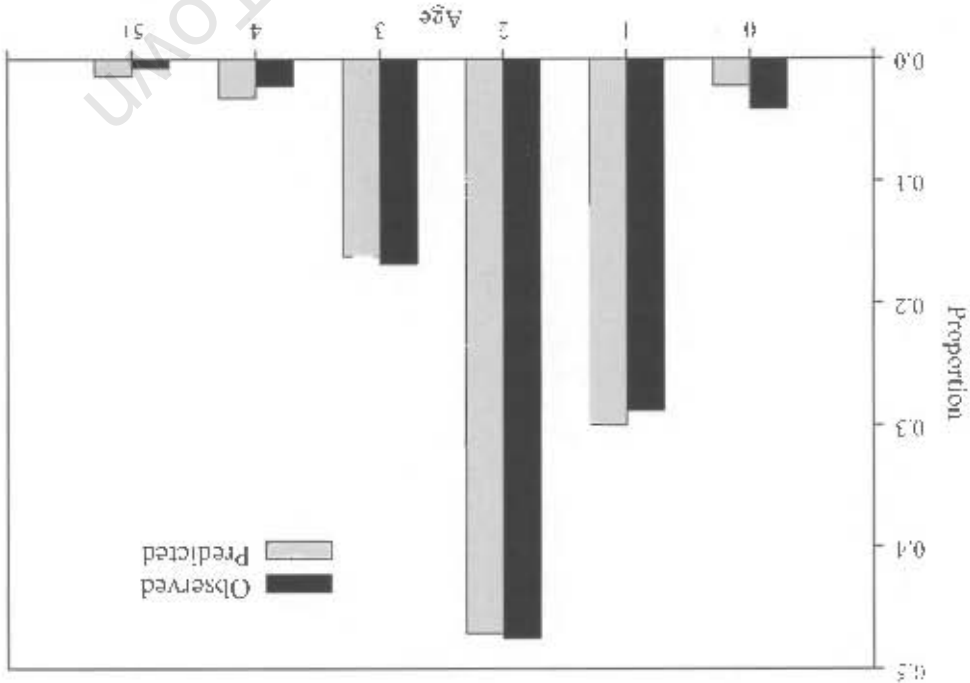
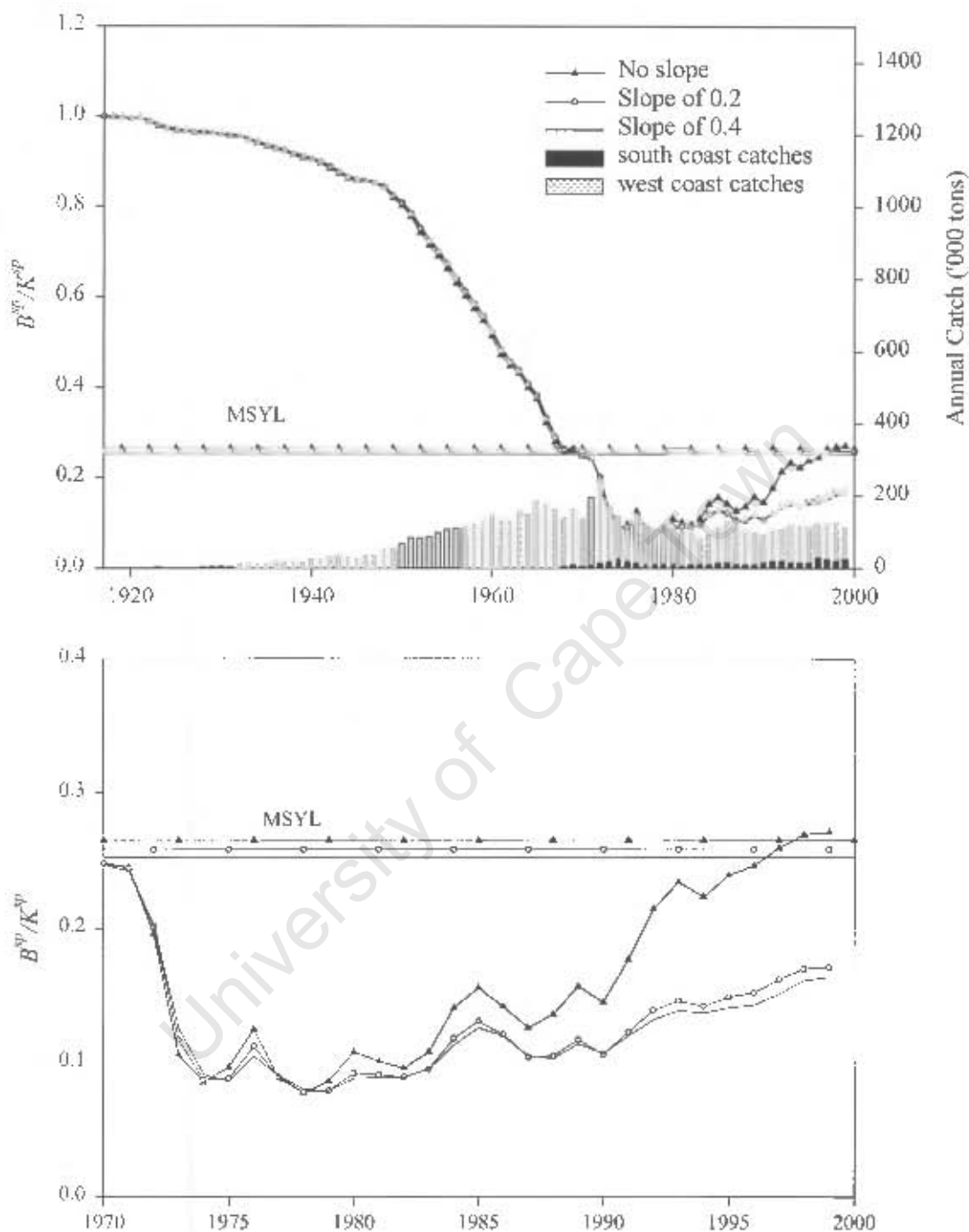


Fig. 8.3: Model fit to catches-at-age, as averaged over all the years with data, for the 'West Coast only' and 'Slope of 0.4' case.





**Fig. 8.5:** Estimated spawning biomass (as a proportion of the pre-exploitation level) for the whole ('Both Coasts') *M. paradoxus* hake resource, for each of the three variants of the assessment (see text for details). MSYL is also shown for each of the variants.

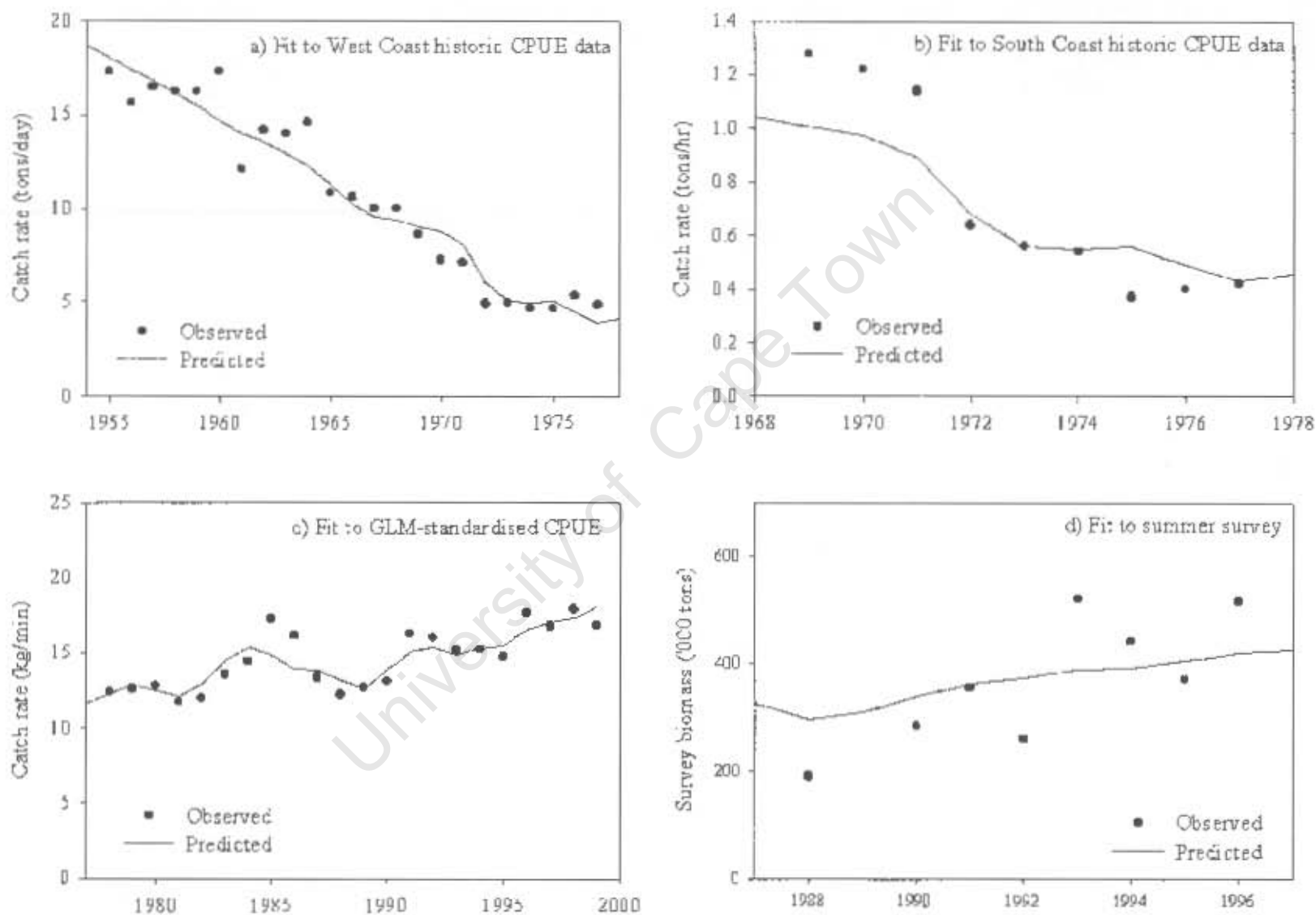


Fig. 8.6 Assessment model fits for *M. paradoxus* to the abundance indices for the 'Both Coasts', 'Slope of 0.2' case. The historic (pre 1978) CPUE data are for both *M. capensis* and *M. paradoxus* combined.



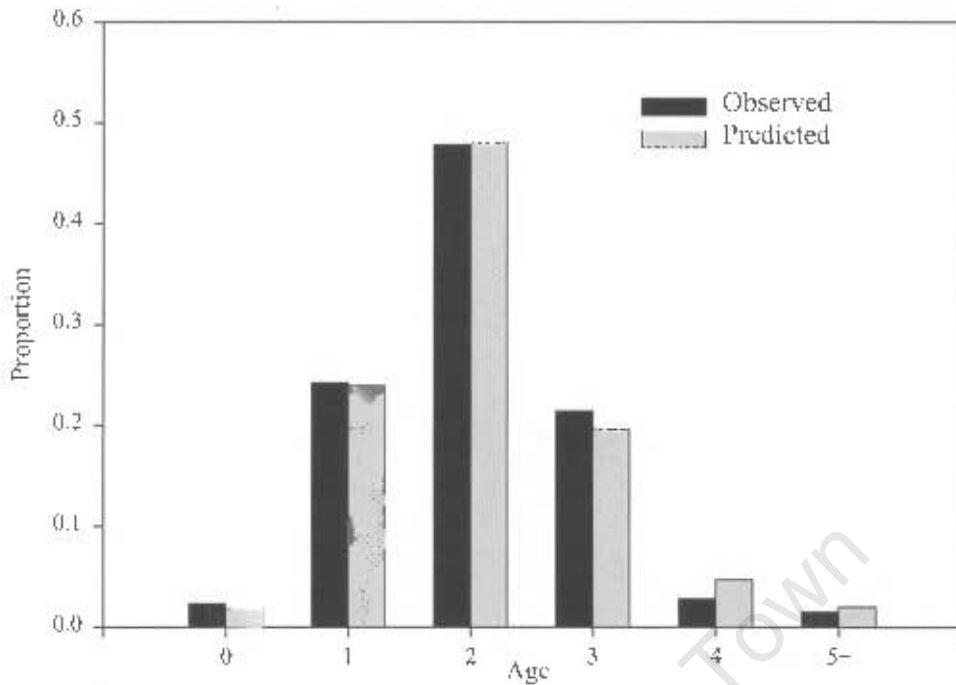


Fig. 8.7: Model fit to survey catches-at-age for *M. paradoxus*, as averaged over all the years with data, for the 'Both Coasts' and 'Slope of 0.2' case.

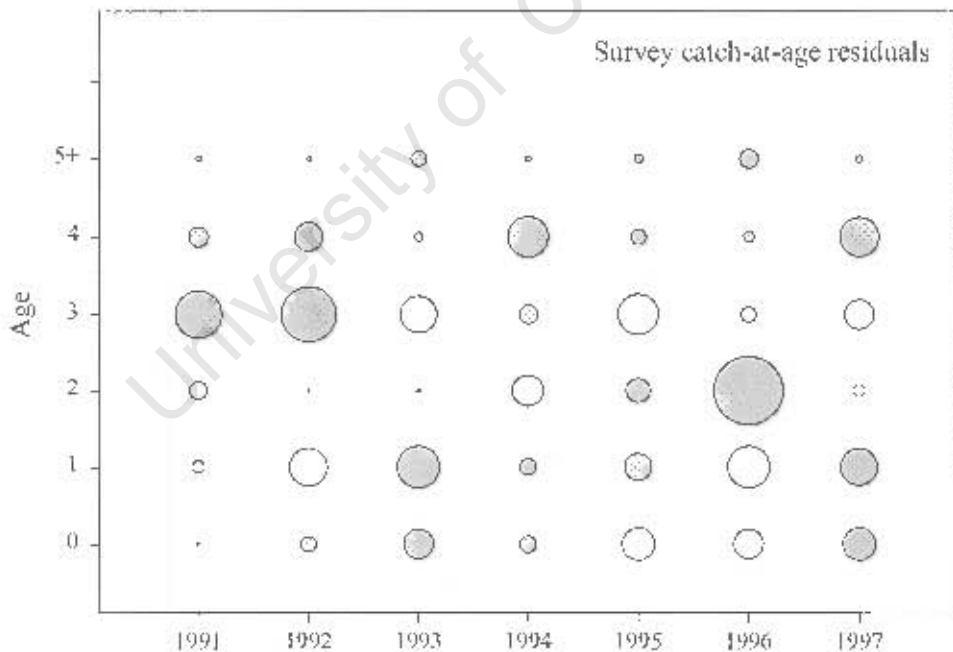


Fig 8.8: "Bubble plots" of the survey catch-at-age residuals for the 'Both Coasts' and 'Slope of 0.2' case. The size (radius) of the bubble is proportional to the corresponding standardized residual  $((\ln(\text{obs}) - \ln(\text{pred})) / (\sigma \cdot \sqrt{\text{pred}}))$ . For positive residuals, the bubbles are white and for negative residuals, the bubbles are gray.

## 9 General discussion and comparison between stocks

This Chapter is based on a paper by Butterworth and Rademeyer (in press) presented at a Conference on the Scientific and Technical Basis for the Sustainability of Fisheries, University of Miami, 26-30 November 2001.

### 9.1 Resource recoveries? A retrospective analysis

In the 1960's and 1970's, the southern African hake stocks were severely depleted, principally because of the rapidly increasing foreign fishing effort in the region during this period. One of the questions raised in this Chapter is to what extent the management initiatives of the past three decades have facilitated a recovery in the hake resource. With the declaration of the 200 nm EEZ in South Africa in 1977 and Namibia's independence in 1990 came substantial reductions in the total catch off both countries. The results of the assessments presented in the previous Chapters indicate that some resource recovery has been achieved over the last three decades, but how did the situation appear as this period progressed?

Fig. 9.1 compares the estimated biomass trajectories (as proportions of their pre-exploitation levels) for the current Namibian and west coast assessments (Chapters 5 and 6 respectively), with assessments carried out in earlier years. The earlier assessment results shown are from Punt (1989) for the 1988 assessments and Butterworth *et al.* (1986) for the 1984 assessments for both the Namibian and west coast hake stocks. For the west coast, the 1992 assessment results are from Punt (1994) and the 1994 assessment results are from Geromont and Butterworth (1996). The plots in Fig. 9.1 also show biomass projections, under the catches that were subsequently taken, for the earlier assessments, and the MSY values estimated in each case.

It must be noted that the results from the different assessments are not exactly comparable. Indeed, the earlier assessments were carried out by means of an age-aggregated production model, the dynamic Schaefer model (see Chapter 3), for which the MSYL is at half of the pre-exploitation level ( $B/K = 0.5$ ). For those assessments, the biomass shown is the total biomass, while for the more recent assessments, it is the trajectory of the spawning biomass which is plotted (in all cases in terms of pre-exploitation levels). Furthermore, the results shown here for Namibia combine Divisions 1.3 + 1.4 and 1.5, though these were assessed separately prior to 1990.

Nevertheless, even admitting the lack of precise comparability over time because of changed assessment methods, these plots show a clear retrospective pattern. As time progressed, estimates of the extent and rate of recovery declined, and estimated sustainable yield levels also dropped below previous expectations. In the Namibian case, MSY estimates have dropped by more than 100 thousand tons over the last two decades, and the biomass is currently still estimated to be below MSYL. In the case of the west coast hake, the differences in the estimates of MSY (a decrease of less than 20 thousand tons over the 20-year period) are not as great as in the Namibian case, but the view on the extent of recovery of the stock has changed substantially. What are the reasons underlying these patterns?

The differences between the estimated extent of recovery and MSY from the different assessments are particularly large in the Namibian case and can for the most part be accounted for by the CPUE data used in the different assessments. Fig. 9.2 compares the observed and predicted trends of the CPUE index of abundance. The observed data are the CPUE data provided to ICSEAF (Table 5.1), while the predicted values are those obtained from the ASPM currently used to assess the Namibian hake resource (Chapter 5). The ICSEAF CPUE data show an upturn in the 1980's, and these data are the primary reason for the optimistic assessments during that period, as shown in Fig. 9.1a. In line with these optimistic assessments, ICSEAF allowed the catches to rise during this period (Table 5.1, Chapter 5). However, these 1980's CPUE data are now regarded with scepticism. It is now known that there was misreporting of catches over this period (Anon., 1997), and furthermore the reported rising CPUE hardly seems consistent with the fact that towards the end of the 1980's, some of the foreign fishing vessels were leaving Namibian waters to fish elsewhere. Current assessments (as in Chapter 5) disregard these post-1980 ICSEAF CPUE data, with the consequent major impact on estimated resource trends and productivity levels that is evident in Fig. 9.1a.

The reason underlying the retrospective pattern in Fig. 9.1b for the west coast hake stock is different, although it also involves the trend in the CPUE data. Over the late 1980's and 1990's, CPUE did not increase as rapidly as predicted by the dynamic Schaefer model used for assessments at the time, resulting in increasingly less optimistic appraisals of the resource. Before 1995, the nominal CPUE was adjusted only by using coarsely estimated power factors for vessel classes. When a thorough GLM-based standardisation exercise was undertaken in 1995, the trend in the CPUE series changed substantially, as shown in Fig. 9.3. The nominal upward trend in CPUE of 3.4% p.a. (Fig. 9.3a) remained positive at 1.2% after accounting for the change in the fleet towards more powerful vessels (Fig. 9.3b). However, when allowance was also made for bycatch, depth and latitude factors, the evidence for any increasing trend disappeared (Fig. 9.3c). This further adjustment was a consequence of a movement of the fleet towards deeper water where catch rates were higher, and possibly also a shift in the hake distributional pattern towards deeper water. Even after refining the

GLM to take account of positive correlations in hake and bycatch CPUE measures, such upward trend as remained was rather small (only 0.6% p.a. – Fig. 9.3d) (Glazer and Butterworth, 2002).

The industry however, argued that a lack of any catch rate increase over the previous two decades (indicating no recovery at all of the resource) was contrary to their experience. They furthermore pointed to the upward trend in the abundance estimates from research surveys (5.8% p.a.; s.e. 2.6%), though large variability meant that his trend estimate was not statistically inconsistent with that for the GLM-standardised CPUE data.

In off-the-record discussions with industry, the likely real explanation for these results became apparent. The first conservation measure taken by ICSEAF, in 1975, had been to increase the mesh size to 110 mm for the hake trawl fishery. However, this had rendered catch rates uneconomical, so that vessels had (illegally) inserted small mesh-liners in their nets. As catch rates later improved as the stock recovered, use of these liners had been phased out. Thus recorded catch rates did not increase as fast as abundance, because CPUE was indexing an increasingly smaller proportion of the biomass over time (unlike the research surveys which were comparable over time). The length distribution of the hake catches provides independent confirmation of this, with a decreasing proportion of the two year old fish in the catch as the 1980's progressed (Table 6.3).

Current assessments (as in Chapter 6) therefore make allowance for a decrease in selectivity for younger fish over the period liners are assumed to have been phased out (see Fig. 9.4). This is why the ASPM model predicts a lesser increasing trend for CPUE than for research survey results over the last two decades (see Figs. 6.2b and 6.2c respectively), and also why (despite only a small increasing trend in the standardised CPUE of Fig. 9.3d) the west coast hake stock is considered to have made a reasonable recovery over the last 30 years.

Even so, if the current ASPM methodology (from Chapter 6) is applied omitting data for the last three years, the results shown in Fig. 9.5 are obtained, i.e., a retrospective pattern remains. The reason for this trend in estimates is that even with liners presumably not in use for some time, CPUE has not shown a recent increasing trend as the model predicts (see Fig. 9.4). This is a matter of some concern, which might be partly related to the increase in the proportion of the total catch made by the longline fleet in recent years. Indeed, longlining targets the older hake in the population, but the ASPM used to model the west coast population is not disaggregated by fleet and therefore does not specifically take this recent change in the overall selectivity pattern into consideration.

## 9.2 Outstanding key assessment questions

The assessment results presented in Chapters 5, 6, 7 and 8 cannot be viewed with complete confidence because of some important questions which arise from certain features of these analyses.

### 9.2.1 Recruitment variability

A somewhat unsatisfactory aspect of the maximum-likelihood-based assessment methodology applied to incorporate recruitment fluctuations (refer specifically to equations 4.4 and 4.22, in Chapter 4) is that the value of  $\sigma_R$  cannot be estimated from the data but must be independently specified. This is problematic particularly in cases such as that for the Namibian hake (see Fig. 9.6) where estimates of stock status and productivity are strongly dependent on the value chosen for  $\sigma_R$ -input.

From an assessment with a particular  $\sigma_R$ -input, a corresponding  $\sigma_R$ -output value can be computed in each case from the maximum likelihood estimates for the recruitment residuals. Fig. 9.7 shows the relationship between the  $\sigma_R$ -output and  $\sigma_R$ -input values for the four stocks considered. The similarity of the two values is not an argument to indicate a more appropriate choice of  $\sigma_R$ -input, as the penalised likelihood formulation used will always yield a maximum for the deterministic limit of  $\sigma_R \rightarrow 0$ . One would need to adopt fully Bayesian methodology, together with a prior for  $\sigma_R$ -input to deal properly with this difficulty. In the interests of inter-stock consistency, a common baseline value of  $\sigma_R$ -input (0.25) was used for the ASPM assessment results reported in the previous Chapters.

An intriguing feature of these plots is that for the South African stocks, whatever the value of  $\sigma_R$ -input specified,  $\sigma_R$ -output does not exceed 0.25. The low level of recruitment variability that this indicates for the South African stocks in particular scarcely seems credible. Teleosts generally show much greater levels of recruitment fluctuations, so that even the Namibian asymptote of some 0.45 is towards the lower end of the range (Beddington and Cooke, 1983)

It could be that recruitment fluctuations are moderated by the heavy degree of cannibalism and inter-species predation on younger hake, *M. paradoxus* in particular. Fish younger than 2 years of age are hardly captured either in surveys or commercially; the assessments' estimates of recruitment therefore really refer to the proportion of recruits that survive their first two years of life. However, it might also be that there are errors in hake ageing, which could confound the detection of stronger and weaker cohorts. In the Namibian case for example, recent catch-at-age data are based on a single age-length key only.

## 9.2.2 Natural mortality

Fig. 9.8 shows the estimates of natural mortality  $M$  for each of the four stocks obtained when fitting the ASPM. In the case of the west coast and *M. paradoxus* stocks, there is sufficient information (for ages above 2) to move beyond the assumption that  $M$  is independent of age  $a$ . What is of concern is how high these estimates are. Values in excess of  $0.5 \text{ yr}^{-1}$  for mature hake (age 4 and above), which are little affected by cannibalism or predation by the other hake species, seem unrealistically large.

Postulating decreasing selectivity-at-age for the older fish (either as a result of greater net avoidance or occurrence in deeper waters than covered by fishing operations and surveys) would seem to have potential to secure compensating reductions in these natural mortality estimates towards more realistic levels. However, maximum likelihood estimation supports this only in the case of the *M. paradoxus* stock. In the other cases, difficulties arise for the models to fit the historic decline in CPUE and the catch-at-age data (see “Selectivity down” in Table 11.1 for Namibian hake and “Selectivity slope of 0.2” in Appendix A2, Table A2.1. for west coast hake), likely related to the fact that a decreasing selectivity at large age implies a largish cryptic biomass not available to the fishery.

Essentially, the high  $M$  estimates arise because ageing (both commercial and research survey samples) suggests the presence of only very few hake of ages 7 and above. As with recruitment variability therefore, some questions about systematic errors in ageing must arise.

## 9.2.3 Steepness

Natural mortality aside, the parameter upon which productivity of a stock (as a proportion of its average pre-exploitation biomass) most depends is the stock-recruitment curve steepness  $h$ . Fig. 9.9 shows the stock–recruitment relationships estimated for the Reference Case assessments described in the previous Chapters. These plots also show replacement lines, and reflect the definition of  $h$  as the proportion of the average pre-exploitation recruitment level to be expected when spawning biomass falls to 20% of its average unexploited value ( $K^{\text{sp}}$ ). The sustainable yield capability of the stock is roughly indicated by the difference between the stock-recruitment curve and the replacement line, so that lower  $h$  values mean smaller stock productivity.

The surprising aspect of these results is the marked difference in the  $h$  estimates for the four stocks. This is not simply a chance outcome for imprecise estimates: the likelihood profiles for  $h$  in Fig. 9.10 show that some of the differences are statistically significant. While the estimated values of  $h = 0.615$  for the west coast and  $h = 0.767$  for the south and west coasts *M. paradoxus* are similar to

what is typical for other fish stocks (Myers *et al.*, 1999, report a median estimate for gadoids of 0.79 with a lower 20%-ile of 0.67 and upper 20%-ile of 0.87), the best estimate for south coast *M. capensis* of  $h = 1.0$  is unrealistically high. At the other extreme, an  $h = 0.318$  estimate for Namibian hake is extremely low (sensitivity of the model to a higher  $h$  value is shown in Appendix A1). Possible reasons for poorer estimated hake productivity off Namibia compared to South Africa are the greater variability of the environment off Namibia (Shannon *et al.*, 1992), and a possible ecosystem change related to the major reduction in the 1970's of the previously large sardine (*Sardinops sagax*) resource off Namibia, which has remained at low levels since (Boyer *et al.*, 2001).

Both steepness and natural mortality related to population productivity. A number of data issues could affect the estimates of these parameters. For example, ignoring discards, combining sex and species and errors in catch-at-age might be interpreted by the model by modifying estimates of  $M$  and/or  $h$  from their true values, and may be playing a role in the surprising estimates obtained from some of the hake assessments.

#### 9.2.4 Selectivity functions

The age-specific selectivity functions for each of the four stocks are estimated in the model either directly or in terms of a logistic curve (see equations 4.24 and 4.25, Chapter 4), with a possible decrease at larger ages (equation 4.26), for both the commercial fishery and the research surveys (conducted for the most part by the *Nansen* in Namibia and by the *Africana* in South Africa). The selectivities for each stock obtained from the current assessments are shown in Fig. 9.11. This estimation is made possible through the availability of catch-at-age data for both commercial and research catches.

The surprising feature of these plots is how different some of these estimated relationships are. The lesser selectivity for younger hake in the commercial fishery off Namibia is understandable because of regulations there that restrict fishing to deeper than 200 m to protect juvenile hake. Similarly, the low commercial selectivity for younger shallow-water *M. capensis* on the south coast may be attributable to the fact that the catch-at-age data are from the inshore trawl fleet which may be avoiding the shallow depths at which these fish are to be found, but that does not explain the similar under-representation of younger *M. capensis* in the research survey catches, as these are intended to cover the full distributional range of the resource. Le Clus (MCM, pers. commn) suggests that medium-sized *M. capensis* migrate to the Agulhas Bank when they reach maturity, while juveniles and small shallow-water Cape hake concentrate on the west coast. This different availability of the small hakes on the two coasts might therefore explain why they are not seen on the south coast and the resulting different survey selectivities, but this Le Clus hypothesis needs to be reconciled with

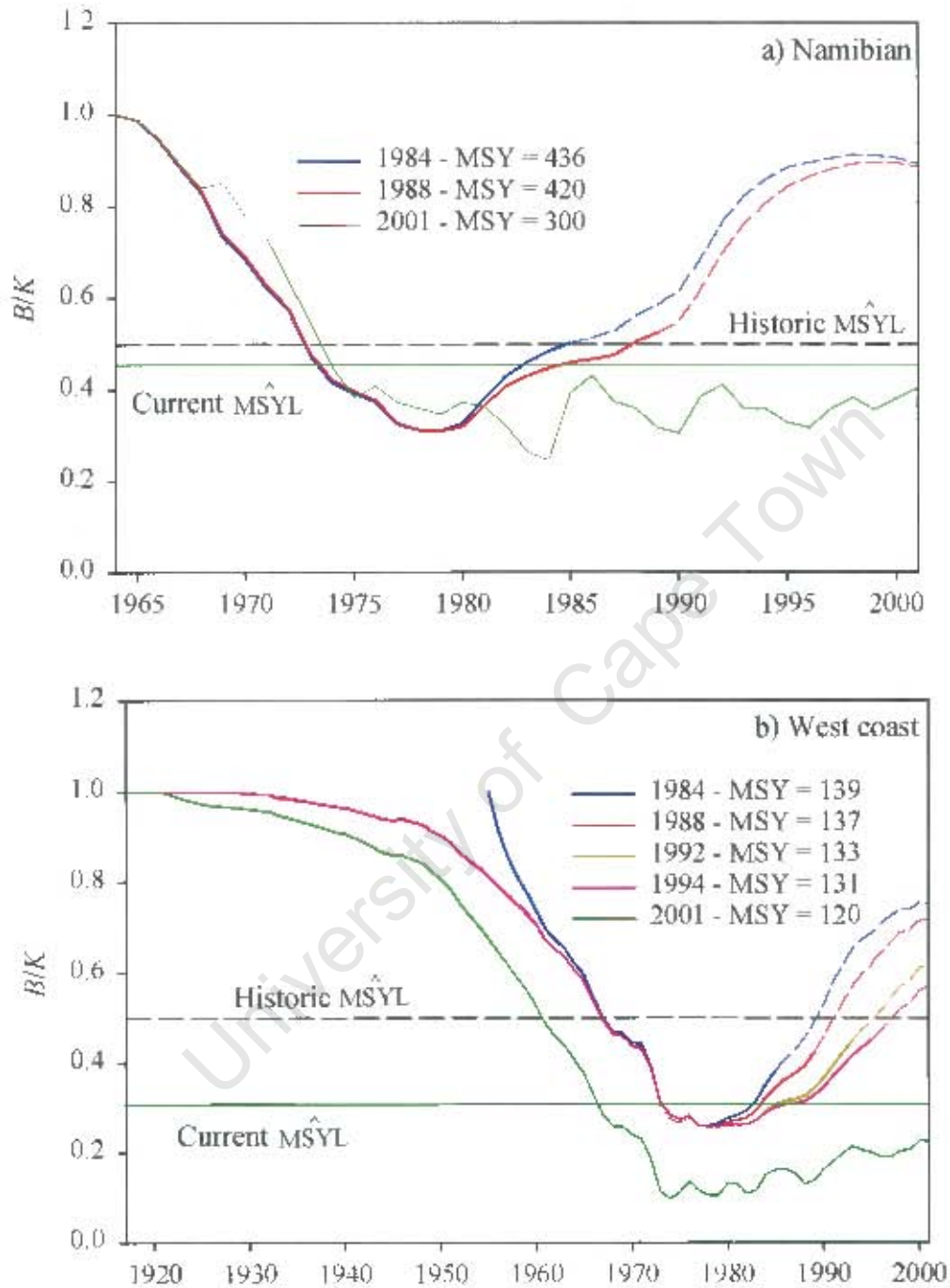
differing estimates of *M. capensis* biological parameters for the west and south coasts (see Section 1.1.2). If this migration is real, then the *M. capensis* stocks off the South African west and south coasts should actually be assessed as one.

### 9.2.5 Survey bias

Although hake abundance estimates from research surveys are available in absolute terms, based upon swept-area methodology, they are treated as relative indices in fitting the ASPMs, which consequently estimate a multiplicative bias parameter  $q$  for these surveys for each vessel and area. The results, together with estimates of 90% confidence intervals for these biases, are shown in Fig. 9.12.

Once again the surprising result is how different these estimated biases are from area to area. It is, of course, possible that these differences are artefacts of mis-estimation of  $M$  or of selectivity functions as a consequence of some errors in ageing. If the differences are real, however, one likely needs to look towards differences in substrates to explain these results. A  $q$  estimate well in excess of 1 suggests that there may be considerable underestimation of the productivity of which the south coast *M. capensis* resource is capable. Alternatively, however, the explanation may be that a large portion of the south coast region is untrawlable, and hake densities in such areas may be lower than in the trawlable areas sampled by the research surveys (the swept-area methodology assumes these densities to be equal) (R. Leslie, MCM, pers. commn). The estimates for the *Africana* and *Nansen* on the west coast do not differ greatly, and the direction of the difference is as would be expected from likely greater escapement of fish underneath the *Nansen*'s net (R. Leslie, MCM, pers. commn).





**Fig. 9.1.** Current and historic assessments (with projections (dashed) under catches subsequently taken) for a) Namibian and b) west coast hake. Estimated MSY values are in thousands of tons.

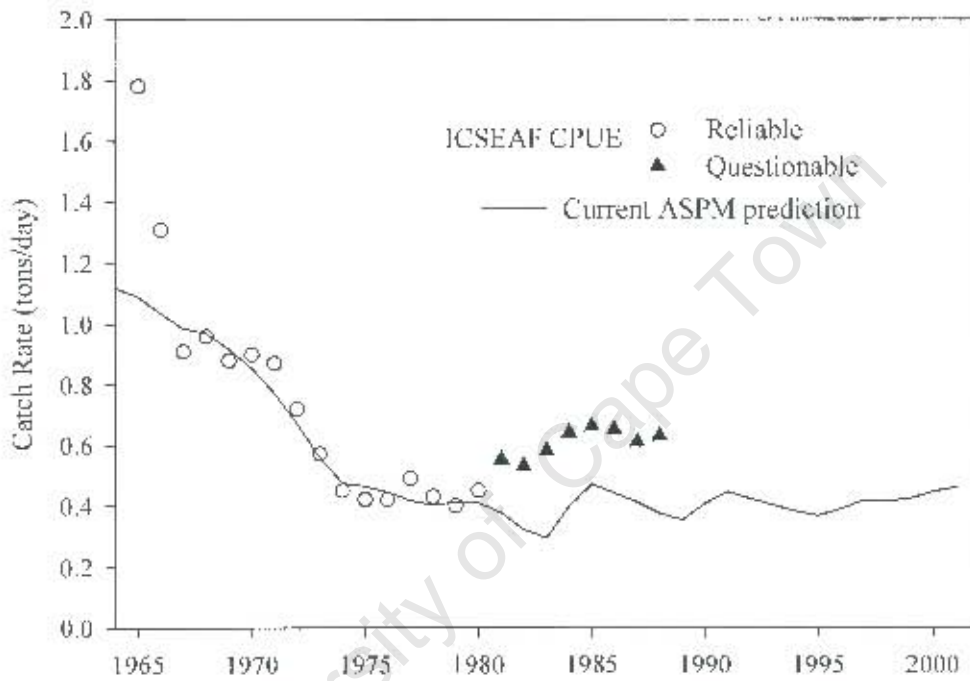


Fig. 9.2: ICSEAF CPUE data for the Namibian hake, showing the period over which these data are considered questionable, and the current ASPM prediction for the CPUE trend.

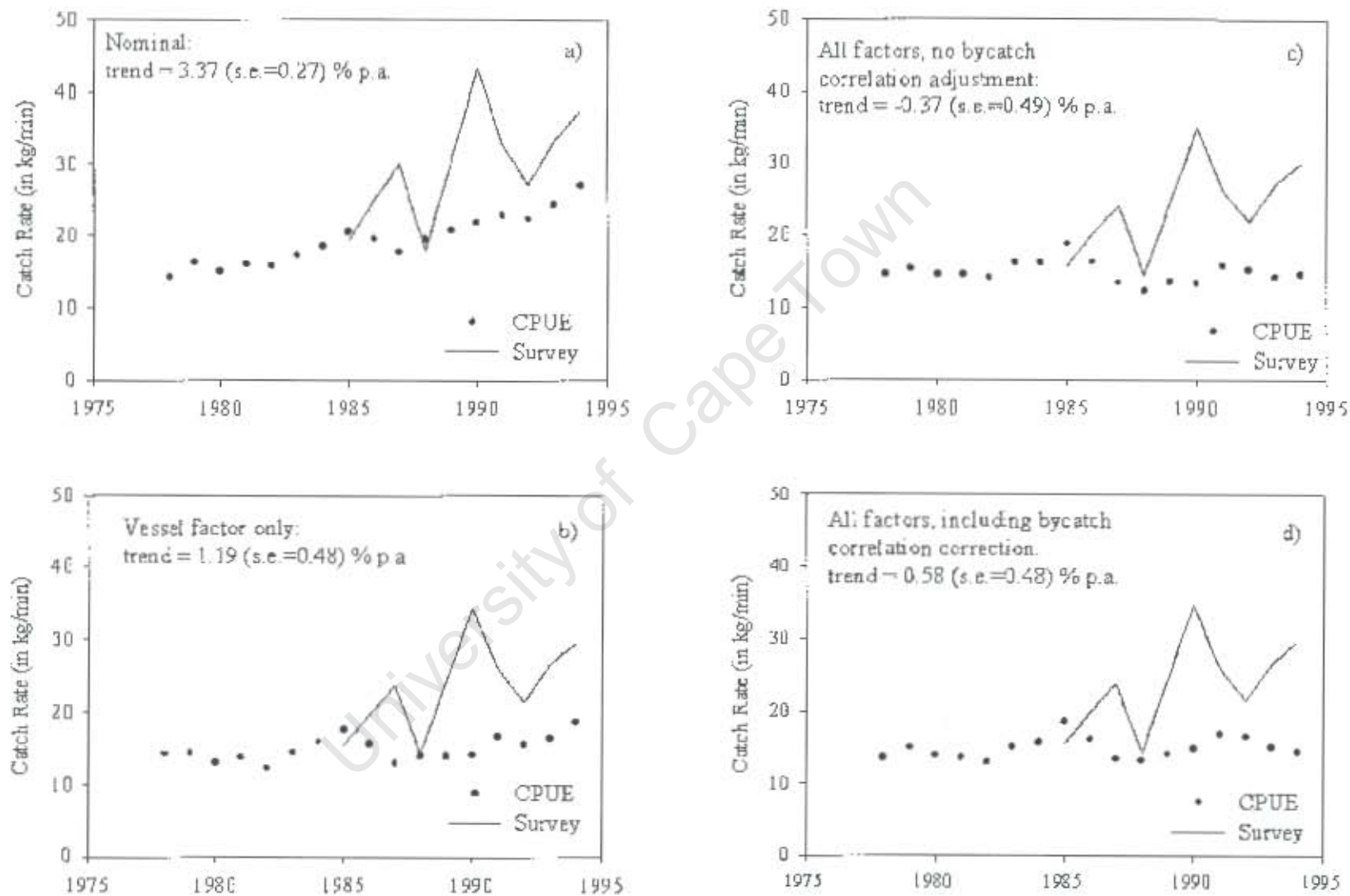


Fig. 9.3 Comparison of research survey and GLM standardised CPUE trends for west coast hake.

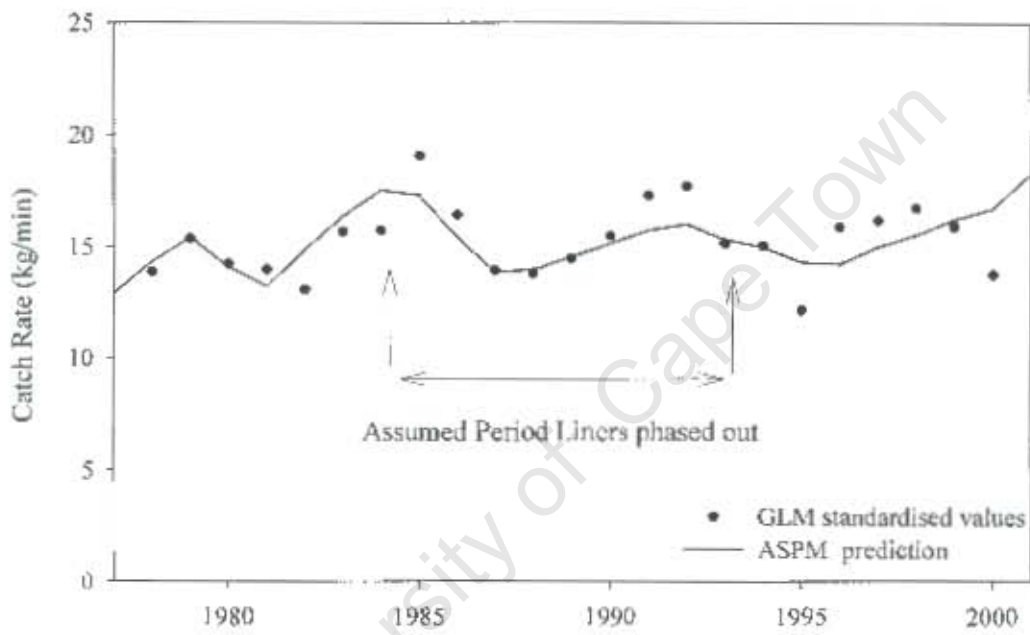


Fig. 9.4: Time series of CPUE for west coast hake, showing the period during which net liners are assumed to have been phased out.

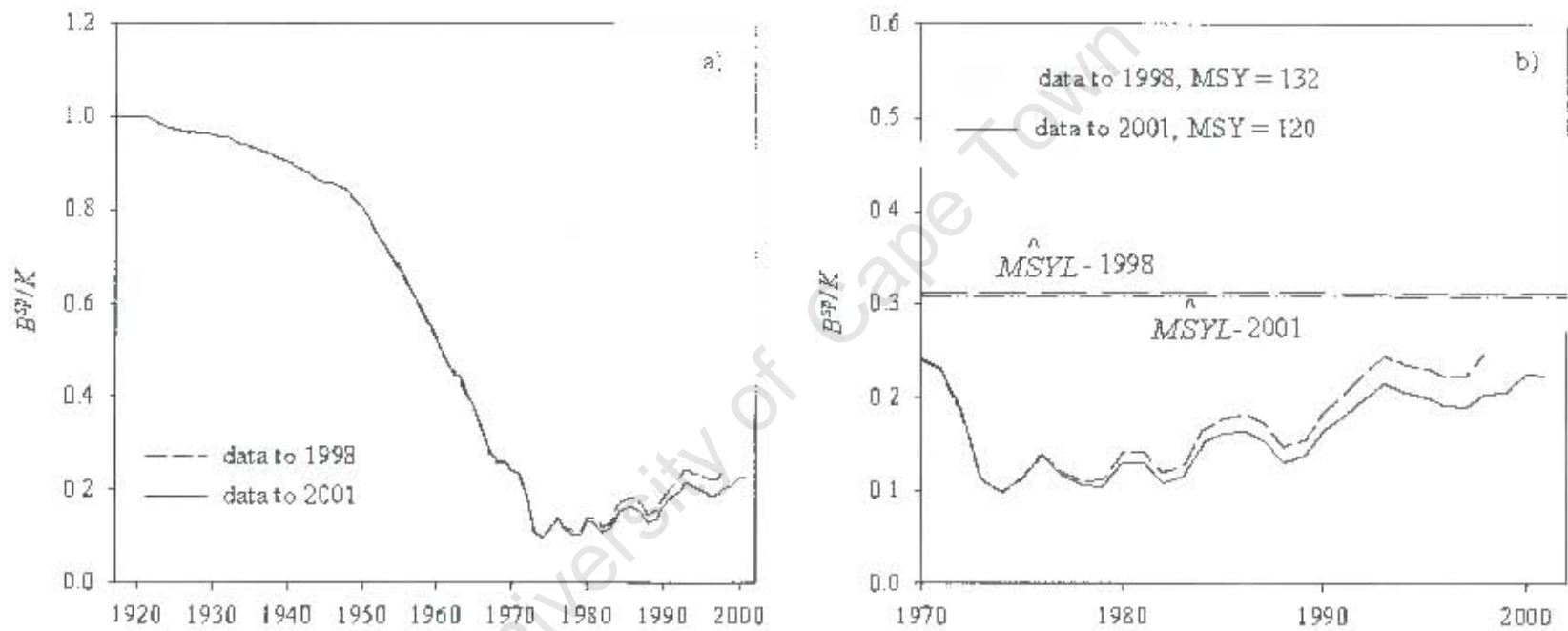


Fig. 9.5: Retrospective ASPM for west coast hake. Estimated MSY values are in thousands of tons.

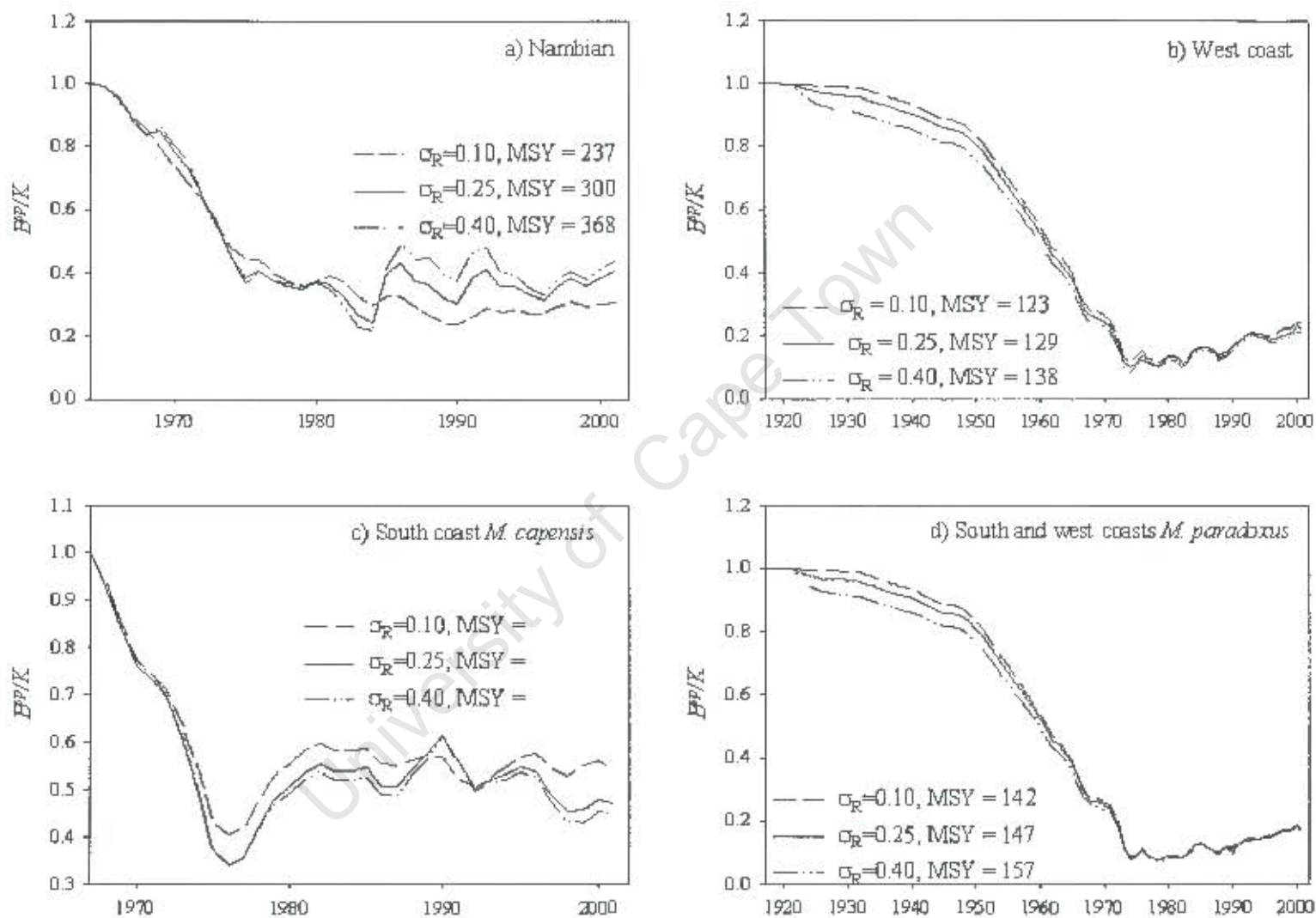


Fig. 9.6: Effect of various level of stock-recruitment fluctuations in ASPM assessments for (a) Namibian and (b) west coast hake, (c) south coast *M. capensis* and (d) south and west coasts *M. paradoxus*.

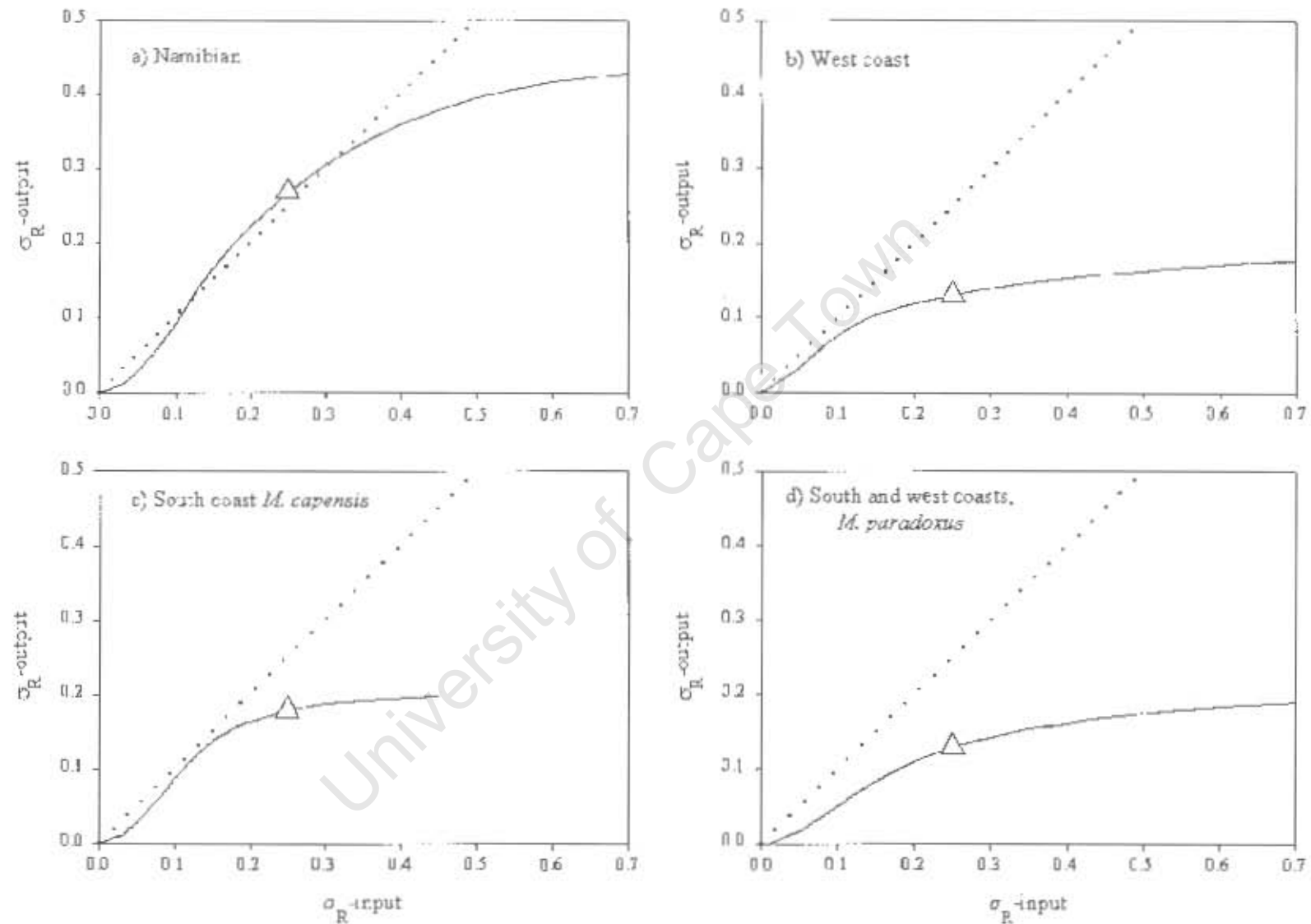
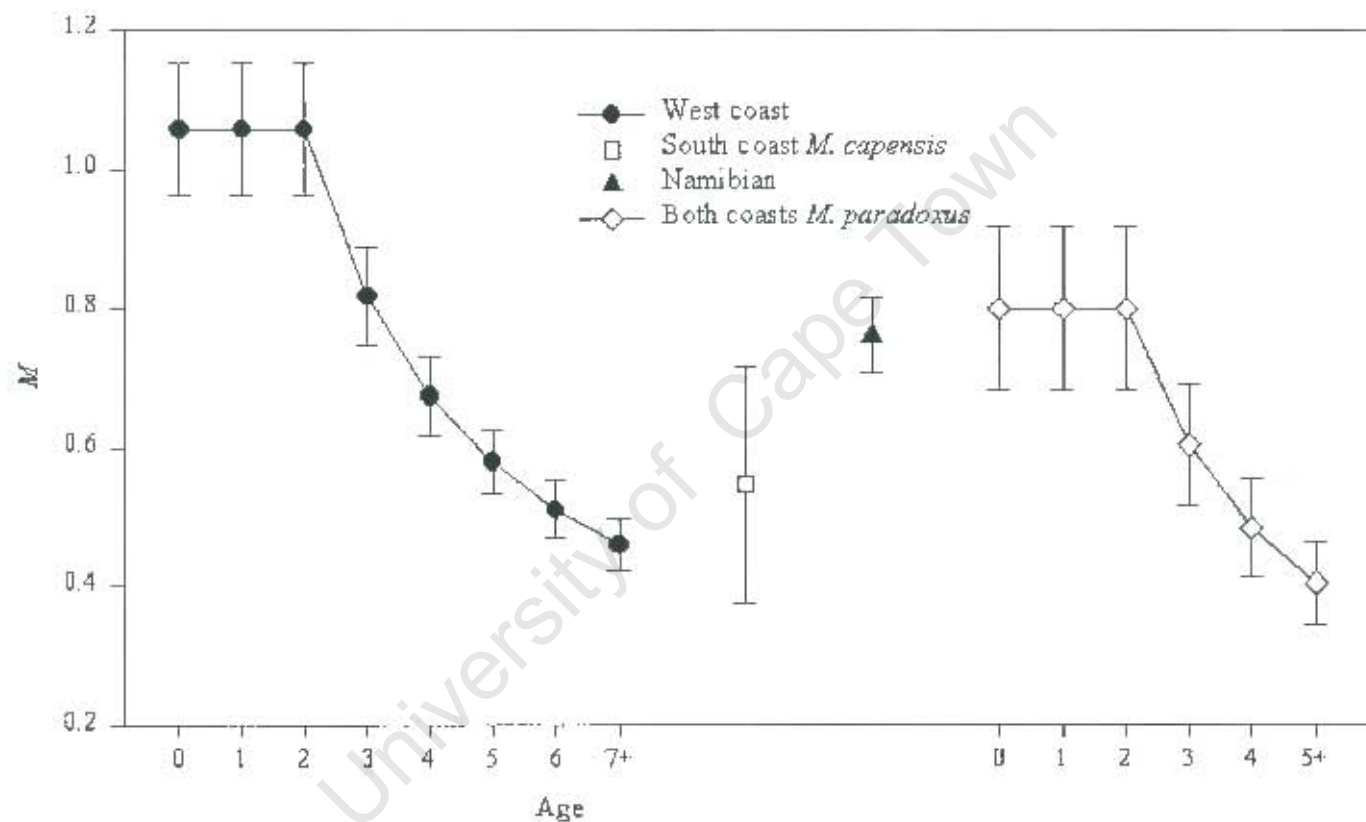


Fig. 9.7.  $\sigma_R$ -input vs  $\sigma_R$ -output for a) Namibian and b) west coast hake, c) south coast *M. capensis* and d) south and west coast *M. paradoxus* (Slope of 0.2)  $\Delta$  shows the Reference Case assessment assumption. The dotted line reflects  $\sigma_R$ -output equal to  $\sigma_R$ -input.



**Fig. 9.8** Estimates of natural mortality  $M$  for each of the four southern African hake stocks, shown together with 90% confidence intervals. An age-dependent form for  $M$  is estimated for the west coast stock, as well as for the *M. paradoxus* stock for both coasts combined (Slope of 0.2).



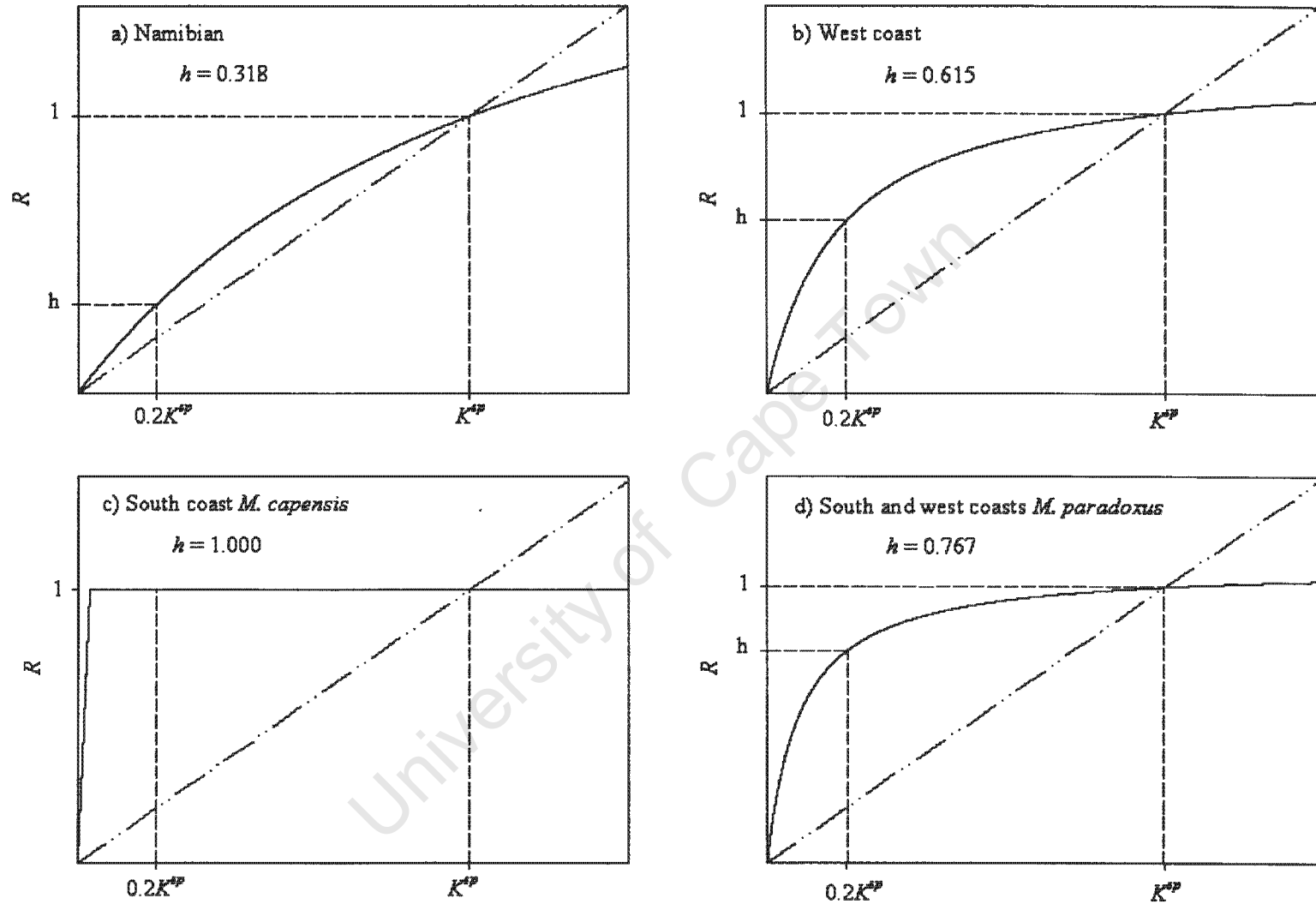
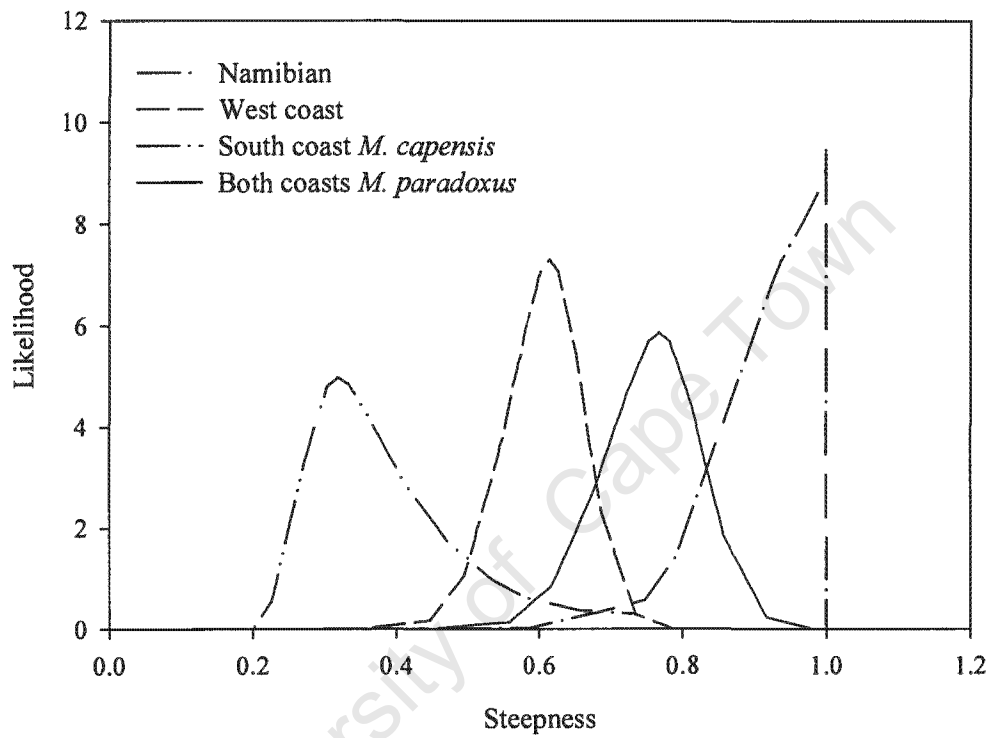
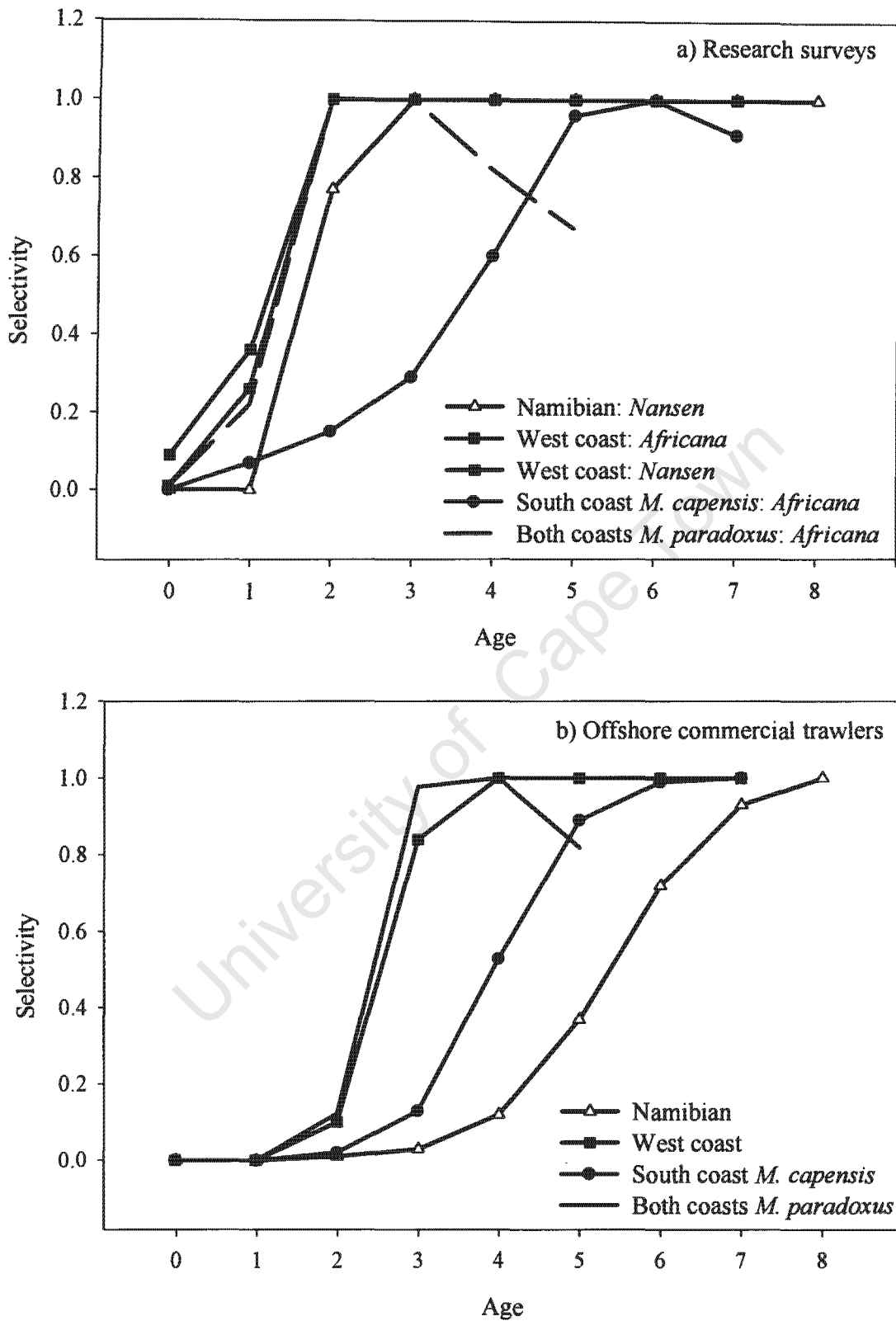


Fig 9.9: Estimated stock-recruitment relationships, characterised by the steepness  $h$ , for a) Namibian and b) west coast hake, and c) south coast *M. capensis* and d) *M. paradoxus*, south and west coasts combined (Slope of 0.2). Recruitment  $R$  is shown relative to its pre-exploitation equilibrium level. The straight lines through the origin are replacement lines, for which annual numbers of recruits would exactly balance the number of deaths in the absence of exploitation.



**Fig. 9.10:** Likelihood profiles for steepness  $h$  for the Reference Case assessments for the four hake stocks. The curves have been scaled so that the area under each is the same.



**Fig. 9.11:** Current selectivity functions for a) research surveys and b) offshore commercial trawlers. Note: for south coast *M. capensis*, the offshore commercial trawlers are assumed to show the same pattern as the inshore trawlers, for which catch-at-age data are available, at lower ages.

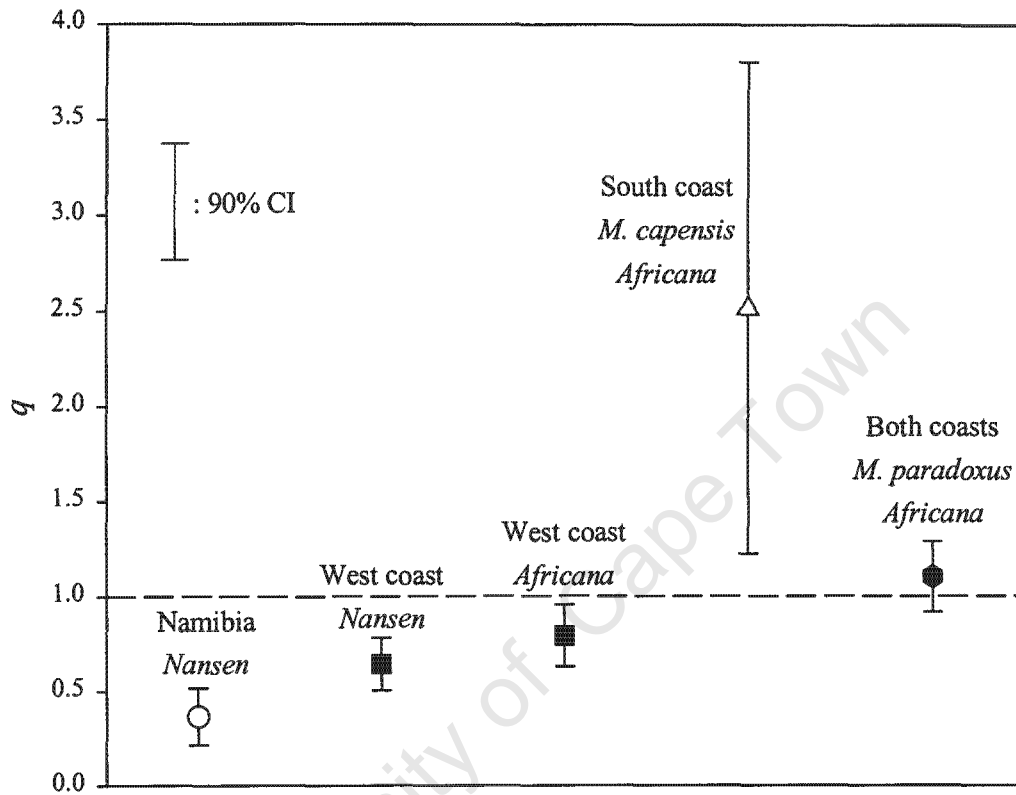


Fig. 9.12: Swept area survey multiplicative bias coefficients  $q$  (with respect to the most highly selected age group).

## **SECTION II: MANAGEMENT**

University of Cape Town

# 10 Overview of Operational Management Procedures

Since 1990 in South Africa and 1998 in Namibia, the primary basis for scientific TAC recommendations for the hake fisheries has been the “Operational Management Procedure” or “OMP” approach (Butterworth *et al.*, 1997; Butterworth and Punt, 1999; Geromont *et al.*, 1999). Other than hake, the South African pilchard-anchovy pelagic and west coast rock lobster fisheries are also managed using this approach, making South Africa one of the world leaders in putting this process into practice. In Namibia, seals are also managed on this basis.

An OMP is a set of rules which specify exactly how the regulatory mechanism (e.g., a TAC or allowable fishing effort) is to be computed each year, from specified stock-monitoring data such as commercial CPUE and/or abundance indices from research surveys (Butterworth and Punt, 1999). This approach is not necessarily related to a fairly complex assessment process. In the case of the South African and Namibian hake, these rules are based on fitting a population model, but the approach can also be empirical, based primarily on recent trends in abundance indices. The empirical approach has the advantage of simplicity; however, the population model-based procedures, which generally take more data into account, seem to perform better than empirical approaches, by showing less inter-annual variability in, for example, TAC levels (Butterworth and Punt, 1999). Indeed, the model-based procedures incorporate a more developed form of feedback control, with the model parameters automatically adjusted each year as further data become available (Butterworth *et al.*, 1997).

An OMP should be agreed upon by all involved parties (scientists, industry, managers) and put into place for a number of years (typically 3 to 5 years), after which it could be revised as necessary (Cochrane *et al.*, 1997). The selection of a particular OMP should be based upon the comparison of performance across a range of candidate OMPs.

The performance of a particular candidate OMP is assessed by simulation. A model of the stock is constructed and each simulation involves projecting the biomass trajectory forward for a fixed period (such as 10 or 20 years) with the future catches determined by the candidate OMP. This model is called an ‘operating model’; it describes the true underlying dynamics of the resource and fishery, but its details are unknown to the process used to calculate the TAC recommendations. The historic catch data used in the model remain unchanged from one simulation to the next (unless potential errors in such catches is under consideration); however, future catches can vary due to stochastic effects – both recruitment variability and noise in future CPUE and survey abundance indices, as well as

imprecision associated with the estimates of parameters describing the stock's dynamics (Punt, 1993). The simulated performance of each candidate OMP is then evaluated in terms of the projected risks and rewards, as different candidate OMPs will involve differing trade-offs (Cochrane *et al.*, 1997). Performance is generally assessed in terms of the conflicting objectives of higher average annual catch, lower risk of unintended depletion and low inter-annual variability in catches (Punt, 1993). It is for the decision-makers to select their preferred risk/reward trade-off.

Another component of key importance in the OMP approach is that the candidate OMPs must be shown to be adequately robust to a key range of uncertainties (alternative defensible assumptions and hypothesis) about the stock and its dynamics. Such uncertainties can include concerns about the validity of the data used, possible future environmental changes, recruitment variations, values assumed for natural mortality-at-age, etc. (Geromont *et al.*, 1999). The robustness of the candidate OMPs is tested by assuming that each of a series of alternative assessments, in turn, reflects the 'true' situation of the fishery and resource (Punt and Butterworth, 1991). In the future, the range of uncertainties should be reduced with research and new data; OMPs could then be made more 'efficient' (for example, take greater catches for the same perceived risk). This approach links closely to the Precautionary Principle advocated by WSSD and by the FAO for fisheries, which states that: "where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation" (UNCED, 1992).

The advantages of the OMP approach to management are potentially considerable. An OMP should run, unrevised, over a number of years, considerably reducing the time spent otherwise on agreeing to annual "best" assessments as the basis for annual TAC recommendations, as these are often based on complex models and involve lengthy related debates and bureaucratic processes (Geromont *et al.*, 1999). Furthermore, the OMP approach provides a transparent and objective basis for setting TACs; the rules are understood and agreed by all as part of the "management game". This enhances credibility between fishery scientists and members of the industry, and renders the demarcation between scientific and policy responsibilities clearer: the anticipated performance of different candidate OMPs is calculated by the scientists, while the managers select one of the procedures based on their preferred risk/reward trade-off, and the TAC is then calculated automatically over the next few years (Butterworth *et al.*, 1997). The longer-term objectives of the OMP approach are also consistent with the fact that risk in fisheries management cannot be sensibly evaluated for short-term actions, but only for the medium term (Cochrane *et al.*, 1997). This longer-term approach of the OMP, combined with the results from the simulated projections, also gives the industry a better basis for future planning, both in the short- and the longer-term (Butterworth *et al.*, 1997). Finally, one of the greatest advantages of the OMP approach is that it automatically takes account of uncertainties through the robustness testing approach.

# 11 An Operational Management Procedure for Namibian hake

## 11.1 Introduction

Over the immediate post-independence period, from 1991 to 1997, hake TACs in Namibia were recommended as approximately 20% (an *ad hoc* choice) of the swept-area-based survey estimates of biomass of fish above 35cm in length (the ‘fishable’ component of the resource). From the severely reduced TAC of 56 thousand tons in 1991 (the first year following independence), the hake TAC rose to some 120 thousand tons in 1997. A substantial drop in both the *Nansen* survey results and in particular in the commercial CPUE (see Table 5.1), led the local Namibian scientists in 1997 to recommend a TAC reduction of about 50%, an action which would have had severe repercussions on the nation’s economy as the hake fishery makes an appreciable contribution to Namibia’s GDP.

However, during an international scientific workshop on hake held in October 1997 (Anon., 1997), it became clear that estimates of the status of the hake stock and associated management advice were highly dependent on whether or not the *Nansen* survey abundance estimates were to be regarded as reliable in absolute (as distinct from only relative) terms in assessments. Assuming that the *Nansen* surveys provided reliable values for the resource biomass in absolute terms, the resource was evaluated as heavily depleted with large reductions in the TAC needed to avoid further depletion. On the other hand, if the *Nansen* results were considered as indices only of relative abundance, the assessments indicated the resource to be well above its MSYL, with large increases in TAC being possible without endangering the future of the fishery (Butterworth and Geromont, 2001).

This deadlock was resolved with the adoption of a simple Interim Management Procedure (IMP) developed by Butterworth and Geromont (2001). The aim of this IMP was to provide TAC recommendations that would be robust to the key uncertainty regarding the reliability or otherwise of the *Nansen* survey abundance estimates in absolute terms. A relatively simple approach was chosen for this IMP because of the limited time available to develop it. Its aim was essentially to decrease catches if further abundance monitoring data indicated the resource to be dangerously depleted, but to increase them if instead such data indicated the resource to be in a healthy state.



The IMP did not have a specific longer-term target (such as moving the resource to an abundance that could provide MSY). Furthermore, the IMP was tested over a limited range of operating models of the possible underlying resource dynamics; these concentrated mainly upon the uncertainty regarding the value assumed for  $q$ , the Nansen survey multiplicative bias factor. Since 1997 this uncertainty has diminished and it is now accepted that Nansen survey estimates are reliable indices of abundance in relative terms only. It also became recognised that the IMP had played its required role and was due for replacement. This Chapter describes a range of candidate Management Procedures for the Namibian hake resource, presented to a meeting of the Namibian Hake Working Group in February 2002. In collaboration with the industry and the NatMIRC scientists, an OMP was chosen and applied to recommend a TAC in 2002.

## 11.2 Methods

[Note: The Namibian hake assessment presented in this thesis is not fleet-disaggregated. For clarity therefore, the equations below will ignore the fleet superscript  $f$ .]

### 11.2.1 The operating model

The operating model used to describe the underlying resource dynamics in the simulation testing process is an ASPM (see Chapter 4). The Reference Case operating model is detailed in Chapter 5. To test the robustness of the OMP to the assumptions made, the different candidate OMPs have been tested for a series of different model specifications and these are described in section 11.2.3.3. The model is fitted to commercial CPUE data, survey abundance estimates and catch-at-age data. It treats *Merluccius capensis* and *M. paradoxus* in combination, and includes stock-recruitment fluctuations.

### 11.2.2 The candidate OMPs considered

The model used as the basis for setting the future TAC is an ASPM of the same form as the operating model (described in Chapter 4). However, only two parameters are estimated at each application of the OMP: the pre-exploitation spawning biomass,  $K^sp$ , and the steepness parameter  $h$ . The natural mortality, the selectivity parameters, the additional variance and the historic stock-recruitment residuals are all fixed to the values estimated for the Reference Case operating model.

The parameters of the ASPM model ( $K^{sp}$  and  $h$ ) are estimated by maximising a likelihood of exactly the same form as for the operating model, i.e., the indices of abundance provided by the commercial CPUE data and by the scientific surveys are included, as well as the historic catch-at-age data.

Future projections based upon an OMP require the simulation of the future data to be used in evaluating a TAC. For the OMP presented here, it is assumed that the current commercial CPUE data (with one year availability lag, as at present) and the *Nansen* summer surveys (though conducted by a trawler which may change from year to year) continue. Catch-at-age data on the other hand are not included for future years because their regular availability is uncertain at present. The commercial CPUE and survey data are generated from operating model-predicted estimates of the appropriate biomass component and catchability with noise added (see section 12.2.3.1). For the CPUE data, the variance of this noise is as estimated in the associated assessment. For the survey data, an average of historic sampling CVs (0.125) is used together with the estimated additional variance, and also the further added variance with CV = 0.153 which accounts for different trawlers being used from year to year.

Given estimates of the MSY level ( $\hat{MSY}^{ex}$ ) and of the current exploitable biomass ( $\hat{B}_y^{ex}$ ), where  $y$  is the year for which the TAC is to be set, the TAC ( $TAC_y$ ), corresponding to a generalisation of a constant proportion harvesting strategy, is computed as follows:

$$TAC_y = (1 - \omega) \cdot TAC_{y-1} + \omega \cdot Q_y^{\beta, \lambda} \quad 11.1$$

where

$$\hat{Q}_y^{\beta, \lambda} = \lambda \cdot \left( \frac{\hat{B}_{y-1}^{ex}}{\hat{MSY}^{ex}} \right)^{\beta} \cdot \hat{MSY} \quad 11.2$$

The  $\beta$  parameter is adjusted to modify the extent of TAC variations with changes in estimated abundance – as  $\beta$  is decreased below 1, these variations drop in size. The  $\lambda$  parameter effectively selects the target equilibrium biomass – for  $\lambda = 1$ , this is the MSY level; higher or lower values of  $\lambda$  target lower or higher biomasses respectively. The basis of this harvesting strategy is therefore equivalent to a standard  $F_{MSY}$  management policy, which is damped to reduce fluctuations ( $\beta$ ) and modified by a precautionary factor ( $\lambda$ ).

Further rules which were considered were:

- i) the TAC could not decrease before year  $y_{no\ decr}$ ;
- ii) any TAC increase was limited to  $x\%$  per year;

iii) any TAC decrease (from  $y_{no\ decr}$  onwards) was limited to  $y\%$  per year.

These further rules provided a basis to set limits on the extent by which the TAC might change from one year to the next without exposing the resource to the danger of overfishing, thereby facilitating improved socio-economic stability in the industry.

For the baseline OMP, the following values were used:  $\omega = 0.5$ ,  $\beta = 0.7$ ,  $\lambda = 1.0$ ,  $y_{no\ decr} = 2001$  (i.e., effectively this constraint did not apply), any TAC increase was limited to 5% per year and any decrease in TAC was limited to 15% per year.

Other structurally different OMPs were investigated and included a ‘trend’ OMP (which sets the future TAC as a function of the trend in the CPUE data), a Fox model fitted to abundance information only (i.e., ignoring catch-at-age data) (similar to that used for South African west coast hake – see Section 12.1) and an ‘amended’ Fox model (in which older CPUE data were downweighted). However, none of these showed a satisfactory adaptive behaviour (i.e., adequate TAC adjustment to resource abundance trends), and so are not discussed in detail here). The problem with the Fox model approach arose from multimodality of the associated likelihood function.

## 11.2.3 The process used to test the candidate OMPs

### 11.2.3.1 Projection Methodology

Projections into the future under a specific OMP were evaluated using the following steps.

#### Step 1:

From an assessment of the resource, the components of the numbers-at-age vector for the start of year  $y_1$  ( $N_{y_1,a} : a = 1, \dots, m$ ) are estimated by application of equations 4.1 to 4.3 (the operating model), where  $y_1$  is the year the projections start, 2002 in this case. This requires specification of how the catch is disaggregated by age to obtain the  $C_{y_1,a}$ , and how future recruitments are specified.

The  $C_{y_1,a}$  values follow from equation 4.9, under the assumption that the commercial selectivity function remains unchanged at its post-independence form ( $S_{y_1,a} \rightarrow S_a^{post}$ ). From this it follows that:

$$F_{y_1} = C_{y_1} / \sum_{a=0}^m w_{a+1/2} N_{y_1,a} e^{-M_a/2} S_a^{post} \quad 11.1$$

and hence that:

$$C_{y_1,a} = N_{y_1,a} e^{-M_a/2} S_a^{post} F_{y_1} \quad 11.2$$

Future recruitments are provided by application of the stock-recruitment relationship of equation 4.4. Future recruitments will not be exactly determined by the stock-recruitment relationship, but will be subject to fluctuation about the levels indicated by that relationship. Log-normal fluctuations are introduced by generating  $\zeta_y$  factors from  $N(0, \sigma_R^2)$  where  $\sigma_R = 0.25$  for the Reference Case assessment. Furthermore, so that such fluctuations affect the spawning biomass “immediately”, and not only after a 4-year lag until new recruits become mature, projections “commence” in 1995 rather than 2001, based upon the actual catches made over the 1995-2000 period.

Step 2:

The information obtained in Step 1 is used to generate values of the abundance indices  $I_{y_1-1}^{CPUE}$  and  $I_{y_1}^{surv}$ . Indices of abundance in future years will not be exactly proportional to true abundance, but also subject to observation error. Log-normal observation error is therefore added to the expected value of the abundance index evaluated, i.e.:

$$I_y^i = q^i B_y^i e^{\varepsilon_y^i} \quad \varepsilon_y^i \text{ from } N\left(0, (\sigma^i)^2\right) \quad 11.3$$

where

- $B_y^i$  is determined from equations 4.10 – 4.12 as appropriate,
- $I$  reflects commercial CPUE or the surveys, and
- $q^i$  is as estimated (equation 4.16) for that assessment.

Furthermore, it is assumed that:

$\sigma^{CPUE}$  is as estimated (equation 4.15) for that assessment, and

$$(\sigma^{surv})^2 = (\sigma_{av})^2 + (\sigma_A)^2 + (\sigma_{trawl})^2$$

where

- $\sigma_{av} = 0.125$  is the average of the historic sampling CVs for that survey,
- $\sigma_A$  is the square root of the survey additional variance as estimated for that assessment, and
- $\sigma_{trawl} = 0.153$  is the extra CV corresponding to the inter-trawler variability (see Chapter 5).

Step 3:

From these abundance indices, the OMP's ASPM is used, with the estimates of natural mortality, selectivities-at-age, additional variance and stock-recruitment residuals of the Reference Case assessment, to estimate the pre-exploitation spawning biomass  $K^{sp}$  and the steepness parameter  $h$ .

Step 4:

The OMP model-predicted exploitable biomass for year  $y_1-1$  ( $\hat{B}_{y_1-1}^{ex}$ ) is then calculated, using equation 4.10.

Step 5:

Given estimates of MSY, MSY level ( $\widehat{MSYL}^{ex}$ ) and of the current exploitable biomass ( $\hat{B}_{y_1-1}^{ex}$ ) from the OMP's ASPM, equations 11.1 and 11.2 are used to compute  $TAC_{y_1}$ .

Step 6:

The numbers-at-age  $N_{y_1,a}$  are projected forward under a catch  $TAC_{y_1}$  by means of the operating model to determine  $N_{y_1+1,a}$  (in this process, it is assumed that the recent commercial age-specific selectivity pattern estimated in step 1 remains unchanged).

Steps 1-6 are repeated for each future year in turn for as long a period as desired, and at the end of that period the performance of the candidate OMP under review is assessed by considering statistics such as the average catch taken over the period and the final spawning biomass of the resource (as described in the next section).

### 11.2.3.2 Performance statistics

The choice of an OMP depends on it being best able to achieve a desired trade-off between the conflicting objectives of higher catches on average, lower inter-annual TAC variability, and lower risks of unintended resource depletion. The measures which were chosen in this study to quantify these management objectives were as follows:

**Catch-related:**

- The average annual catch over a twenty year projection period:  $\frac{1}{20} \sum_{y=2002}^{2021} C_y$

- The Average Annual Variation (AAV) in TAC from one year to the next (expressed as a proportion of the average annual catch):  $\left[ \frac{1}{20} \sum_{y=2002}^{2021} |C_y - C_{y-1}| / C_{y-1} \right] \cdot 100$ . This statistic gives an indication of the industrial stability associated with a particular candidate OMP, and is expressed as a percentage.

**Risk-related** (in terms of undesired biomass reduction):

- Final compared to initial depletion:  $B_{2021}^{SP} / K^{SP} - B_{2001}^{SP} / K^{SP}$

Once stochastic effects (e.g., future errors in indices of abundance, “observation errors”, and recruitment fluctuations, “process errors”) are taken into account, the results for each of these quantities when testing a particular candidate OMP is a distribution arising from alternative realisations of these stochastic effects (see Appendix B2). Results are reported in the form of medians and 90%-iles of these distributions.

### 11.2.3.3 Robustness tests

The Reference Case operating model is the current “best guess” for representing the actual dynamics of the Namibian hake resource. There are however some uncertainties (in the data for example, as well as in some of the assumptions made in the model) that need to be taken into account when testing the performance of candidate OMPs. A list of the associated robustness tests is given below. This list was developed from discussions (with NatMIRC scientists in particular) in the Namibian Hake Working Group. Ideally, the performance statistics for a candidate OMP should be ‘robust’ across this range, i.e., show acceptable results whatever the assumptions made in the operating model.

- a) Bias in historical CPUE series (“*Bias in historic CPUE*”) The ICSEAF CPUE data (see Table 5.1) are modified in the following way to reflect a changed trend:

$$CPUE_y^{bias} = CPUE_y \cdot e^{\delta(y-1964)} \quad 11.4$$

For this variant, the value of  $\delta=0.03$  was chosen to be positive (i.e., a positive bias) because this resulted in an increase in the log-likelihood (i.e., a better model fit); a negative  $\delta$  leads to the reverse effect.

- b) Weighing recent CPUE data more heavily than historical CPUE data (survey data were not similarly weighted) (“*More weight on recent data*”): Because of the possibly greater reliability of more recent data, the CPUE likelihood is modified from equation 4.14 as follows:

$$-\ln L = \sum_i w^i \left[ \sum_y \ln \sqrt{(\sigma_y^i)^2 + (\sigma_A)^2} + \frac{(\varepsilon_y^i)^2 e^{-\omega^*(y-2001)}}{2((\sigma_y^i)^2 + (\sigma_A)^2)} \right] \quad 11.5$$

where  $\omega^* = 0.2$ .

- c) Nansen survey estimates treated as unbiased absolute indices of abundance (“Survey  $q=1$ ”): Although it is now accepted that the swept-area computations from the Nansen surveys do underestimate the hake biomass in absolute terms, there is still scepticism amongst some scientists as to the reliability of the estimates of  $q$  from the ASPM fit to the data, so that this test was included to reflect a bound on possibilities. Furthermore, this assessment variant is useful because it provides a more pessimistic dynamics model upon which to test the candidate OMPs.
- d) Regime shift scenarios (“Regime shift”): Two regime shift scenarios have been considered. In both cases, the shift is assumed to have taken place between 1970 and 1975, which corresponds to the period of a substantial decrease in pilchard biomass, a major food source for hake (D. Boyer, NatMIRC, pers. commn). In the first scenario (“ $K^{sp*}$  est”), the new carrying capacity is estimated in the model fitting process, while in the second scenario the new carrying capacity is fixed at 80% of the original.
- e) Higher variability for stock-recruitment fluctuations (“Higher  $\sigma_R$ -input”): For the Reference Case operating model,  $\sigma_R = 0.25$  was chosen on an *ad hoc* basis, as there is no clear basis to fix  $\sigma_R$ -input. However, it is clear that the estimates of management quantities are very dependent on the value assumed for  $\sigma_R$ -input. In this variant assessment,  $\sigma_R$ -input = 0.40.
- f) Lower variability for stock-recruitment fluctuations (“Lower  $\sigma_R$  - input”): In this variant,  $\sigma_R$ -input = 0.10.
- g) A decrease in selectivity for the older ages (“Selectivity down”): Because of the concern over the very high value estimated for natural mortality in most other cases, a negative selectivity slope  $s$  of 0.2 has been included from age 4 (equation 4.26). Indeed, the natural mortality is high because the older age classes are not well represented in the catch-at-age data, but this could also be due to a lower selectivity on older fish.
- h) Assessment model fitted to survey fishable biomass instead of total abundance (“Fit to fishable biomass”): For each survey, the survey fishable biomasses (provided by T. Illende, NatMIRC, pers. commn) were multiplied by the ratio of total biomass used in the Reference Case (from E. Johnson, NatMIRC, using the stratification method of Burmeister (2000b)) over the total biomass from Illende (NatMIRC, pers. commn). The survey fishable biomasses were rescaled for comparability because these values were obtained from a different method to Burmeister’s, which is used in the other cases. The fishable biomass is the biomass of fish larger than 35 cm (i.e., approximately older

than 3.5 years) and therefore only age classes 4 and above were considered when defining  $B_y^{ex}$  for equation 4.10.

## 11.3 Results and Discussion

### 11.3.1 Reference Case and Robustness test Operating Models

Management quantities estimates for the current Reference Case assessment and each of the robustness test operating models are shown in Table 11.1. The values given below are the best estimates followed by Hessian-based CVs in parenthesis.

#### *“Reference Case”:*

For the Reference Case assessment, the current depletion in terms of spawning biomass ( $B_{2001}^{sp}/K^{sp}$ ) is 0.40 (0.39). MSY is 300 (0.25) thousand tons at a MSY level of 46% (0.04) of the pre-exploitation level. In terms of this model the resource is estimated to be in a relatively good state, slightly below MSYL.

#### *“Bias in historic CPUE”:*

This assessment (with  $\delta = 0.03$ ) is more optimistic than the Reference Case assessment because it suggests that the historic drop in abundance was not as large as these historic CPUE data suggest. In this case, the current depletion (0.70 (0.42)) is estimated to be well above the MSYL of 42% (0.12) of the pre-exploitation level. The MSY is estimated to be 406 (0.43) thousand tons.

#### *“More weight on recent data”:*

The log-likelihood for the case weighting recent CPUE data more heavily than historical data ( $\omega^* = 0.2$ ) cannot be compared with the other cases because the log-likelihood contribution of the CPUE abundance indices is different (with the weights added). The management quantities estimated are fairly insensitive to the weighting, but this assessment does give a slightly worse appraisal of the resource compared to the Reference Case.

#### *“Survey $q = 1$ ”:*

For  $q$  fixed at 1, the log-likelihood decreases by the considerable amount of some 35 points, which indicates very strongly that the *Nansen* survey data are indices of abundance in relative terms



only. In this case, MSY decreases to 261 (0.13) thousand tons and the current spawning biomass is estimated to be at about only 21% (0.18) of its pre-exploitation level.

*“Regime shift”:*

In the first scenario (“ $K^{sp*}$  est”), the new carrying capacity is estimated to be about half of the original carrying capacity. The fit is improved, but the very high value for the steepness ( $h = 1.0$ ) is cause for concern regarding realism and hence reliability. In the second scenario (“ $K^{sp*} = 0.8K^{sp}$ ”), the steepness  $h$  is estimated at a seemingly more reasonable 0.55 (0.41). In both cases, the resource is estimated to be in a healthy state.

*“Higher  $\sigma_R$ -input”:*

With a  $\sigma_R$ -input of 0.40 (compared to 0.25 in the Reference Case), the resource is estimated to be in a slightly better state than with a lower  $\sigma_R$ -input because the effect of the good recruitment in the mid-1980’s is accentuated. Note again that the log-likelihood is not comparable to the Reference Case. The current spawning biomass is estimated to be about 46% (0.38) of its pre-exploitation level, which is just above the MSYL of 44% (0.06). The MSY is also raised substantially to 368 (0.28) thousand tons compared to 300 (0.25) thousand tons in the Reference Case.

*“Lower  $\sigma_R$ -input”:*

On the other hand, lowering  $\sigma_R$ -input (0.10) gives a more pessimistic appraisal of the resource, with the current spawning biomass at only 31% (0.34) of its pre-exploitation level. The reason to consider different  $\sigma_R$ -input values is to reflect a trade-off: higher  $\sigma_R$ -input values than 0.25, such as 0.40, seem more realistic; however, they also suggest a marked improvement in the resource in the mid-1980’s as a result of particularly good recruitment at that time – a result based on limited historic age data of doubtful reliability, which, consequently, seems questionable. The choice of  $\sigma_R$ -input = 0.10 is to show the opposite effect.

*“Selectivity down”:*

Despite the forced decrease in selectivity of older fish, the estimated natural mortality is only slightly lower in this case ( $M = 0.67$  (0.04) compared to  $0.76 \text{ yr}^{-1}$  in the Reference Case). The fit is also much worse, essentially because of poor representation of the survey catch-at-age data. This assessment gives a very pessimistic view of the resource, with the current  $B_y^{sp} / K^{sp}$  at 0.18 (0.20) and a MSY of only 255 (0.22) thousand tons.

*“Fit to fishable biomass”:*

Fitting to the survey fishable biomass rather than the total biomass results in a slightly more pessimistic view of the resource in terms of current spawning biomass (estimated at 34% (0.20) of its

pre-exploitation level), but a potentially slightly more productive stock, with MSY at 306 (0.11) thousand tons compared to the 300 thousand tons for the Reference Case operating model.

### 11.3.2 Management Procedures

#### *Baseline OMP*

Figs. 11.1 to 11.4 compare the performance of the baseline OMP for the Reference Case and the nine alternative robustness test operating models. Fig. 11.1 shows the initial (2001) depletion ( $B_{2001}^{sp}/K^{sp}$ ) and the depletion at the end of the 20-year projection period ( $B_{2021}^{sp}/K^{sp}$ ), with 90% probability intervals. For each case, the estimated MSYL and its 90% probability intervals are also shown. The values presented in this and the following Figures are the bootstrap medians and 90% probability intervals. The former may differ slightly from the best estimates given in Table 11.1. Fig. 11.2 gives a measure of the variability in TAC over the projection period, while Fig. 11.3 shows the expected average annual catch. Time-series of TAC (median) for each robustness test operating model are given in Fig. 11.4. These results are for fully stochastic scenarios, i.e., including uncertainty in parameter estimates, errors in future data, and allowing for past and future recruitment variability.

Fig. 11.1, which compares the current and projected depletions under the baseline OMP, does not give the complete picture in terms of the effectiveness of the OMP in regards to depletion status. Indeed, even if the lower 90% probability limit for the projected depletion shows an increase compared to that for the current depletion, it is still possible that for some of the realisations, the spawning biomass actually decreased during the projection period. Furthermore, an increase/decrease in the resource abundance is not always good/bad, but depends on where the biomass starts and finishes relative to MSYL. If the current biomass is below MSYL, an appropriate OMP would lead to an increase in the size of the resource. Conversely, if the current biomass is above the level at which MSY is produced, one would want the size of the resource to decrease so that a higher yield can be produced. Fig. 11.5 makes an attempt at capturing these two factors. In this figure the pie charts come in pairs, the right-hand one showing the proportion of occasions (for 100 bootstrap replicates) that the resource starts below MSYL in light and above MSYL in dark. The left-hand one is divided into five scenarios, the proportions of which are represented by a slice of the pie.

Case 1: The resource starts below MSYL in 2001 and increases over the 20-year projection period (“Very Good”).

Case 2: The resource starts above MSYL, decreases over the 20-year projection period, and is still above MSYL in 2021 (“Good”).

Case 3: The resource starts above MSYL in 2001 and increases (“Middle”). This is not really satisfactory in terms of yield, but it will not result in a risk to the resource.

Case 4: As Case 2, but the resource is below MSYL at the end of the projection period (“Bad”).

Case 5: The resource starts below MSYL and decreases (“Very Bad”).

It is clear that the “Very Bad” and “Bad” cases do not occur often, except for the case for which the selectivity decreases at older ages.

The time-series of depletion for the spawning biomass with 90% probability intervals for the Reference Case is shown in Fig. 11.6, with the 20-year projection into the future, under the baseline OMP. The MSYL with its 90% probability intervals is also shown. Figs. 11.7 and 11.8 are “worm” plots of annual catch and depletion respectively for the Reference Case projected under the baseline OMP (a “worm” plot shows a number of possible realisations, rather than a distribution or confidence band).

The results described above indicate that the baseline OMP shows the adaptive behaviour desired, securing an abundance increase (in median terms) in all cases with an initial (2001) biomass below MSYL, and allowing for an increase in catch in the more optimistic cases. Negative features include the drop in the lower 5%-ile for depletion in the “Selectivity down” case, and unnecessary catch reductions for the cases where carrying capacity has declined, because the OMP does not “realise” that abundance is above MSYL (given an assumption of an unchanged  $K^{sp}$ , it interprets little increase in CPUE and surveys as a need to reduce catches to secure better – but in fact unnecessary – recovery).

#### **Other candidate OMPs**

Figs. 11.9 to 11.12 compare the performance of six alternative OMPs (see Table 11.2 for a list of the control parameter values for each OMP), and of the baseline OMP in the case of two implementation uncertainties. The cases with implementation uncertainties are used to test the performance of the baseline OMP when the OMP's TAC outputs are not applied in practice exactly. The first implementation uncertainty case is denoted “incr only”: if the OMP indicates a decrease in the TAC, the actual TAC implemented is decreased only if a decrease was also indicated the previous year, otherwise it is kept constant. In the second case of implementation uncertainty (“uni. random”), the TAC is increased or decreased at random by a percentage drawn from a uniform distribution [0.05; 0.05]. Scenarios with no catch, and with annual catch fixed at 200 thousand tons are also shown for comparative purposes. Each of these scenarios is furthermore compared for the Reference Case, and the “higher  $\sigma_R$ ” and “lower  $\sigma_R$ ” operating models. As it becomes difficult to present the results from each candidate OMP for each of the robustness test operating models, the “higher  $\sigma_R$ ” and “lower  $\sigma_R$ ” were chosen as reflective of the more optimistic and more pessimistic resource status scenarios.

In terms of depletion (Fig. 11.9), only changes in the  $\beta$  and  $\lambda$  parameters seems to make a noticeable difference to the final depletion. Lower values of  $\beta$  lead to more catch on average (Fig. 11.11) and therefore result in a slightly lower final depletion. A lower  $\beta$  also means slightly less variability in catches (Fig. 11.10). On the other hand, a lower value of  $\lambda$  leads to less catch on average but results in a slightly higher final depletion.

The implementation uncertainties considered do not result in any marked deterioration in performance.

The spread of the final depletion distribution is narrower (and in particular the lower limit is higher) for all the OMP variants compared to the constant catch case, showing the value of adaptive management which adjusts TAC's in response to signals concerning resource status.

## 11.4 Conclusions

Apart from the cases where carrying capacity has decreased over time (resource under-utilisation), and when selectivity decreases at large age (risk of further depletion), the candidate OMPs examined all provide reasonable performance. The primary selection choice is that of the control parameter  $\beta$ : greater recovery for higher  $\beta$ , versus larger catches and less catch variability for lower  $\beta$ .

At a Namibian Hake Working Group meeting in February 2002 in Swakopmund, this work was presented (Rademeyer and Butterworth, 2002a) and discussions which followed with the NatMIRC scientists and representatives of the Namibian hake industry led to the recommendation for a new OMP (to replace the IMP), which was subsequently used to recommend the hake TAC for that year. For the OMP adopted, the following control parameters values were used: as for the baseline OMP,  $\omega = 0.5$ ,  $\beta = 0.7$ ,  $y_{no\ decr}$  is 2001 and any TAC increase is limited to 5% per year; the changes from the baseline OMP are the choice of  $\lambda = 0.9$  (to rather target for a spawning biomass slightly above MSYL as another safety measure) and a limit on any decrease in TAC of 10% per year, rather than 15% (as a restriction to 10% did not appear to lead to any appreciable increase in risk). The choice of  $\lambda = 0.9$  will mean lower catches in the short to medium term, but eventually catch rates that are about 10% higher. Some management quantity estimates and catch projections under the adopted OMP are given in Table 11.3, both for the Reference Case model, and also for the 'higher  $\sigma_R$ ' and 'lower  $\sigma_R$ ' robustness test operating models.

Table 11.1: Management quantity estimates for the Namibian hake operating models for OMP robustness tests: the first figure shown is the best estimate, followed by the Hessian-based CV in parenthesis (except for selectivities).

	1) Reference Case				2) Bias in historic CPUE CPUE <sub>t</sub> e <sup>δ(t-1964)</sup> δ = 0.03				3) More weight on recent data ω* = 0.2				4) Survey q = 1			
Total negative loglikelihood	-94.0				-100.2				-163.3				-69.3			
-lnL: CPUE	-32.4				-35.1				-104.0				-37.5			
-lnL: Survey	-14.1				-14.2				-14.2				2.0			
-lnL: CAA com.	-58.3				-61.1				-56.7				-50.6			
-lnL: CAA surv	-8.9				-9.7				-8.4				-3.0			
-lnL: SR Residuals	19.7				19.8				19.9				19.8			
$K^{SP}$	3640 (0.16)				3226 (0.17)				3719 (0.15)				3265 (0.10)			
$K^{SA}$	3953 (0.18)				3433 (0.18)				4076 (0.16)				3556 (0.11)			
$B^{SP}_{2001}$	1466 (0.31)				2244 (0.35)				1367 (0.27)				697 (0.16)			
$B^{SA}_{2001}$	411 (0.55)				787 (0.51)				378 (0.48)				136 (0.32)			
$h$	0.318 (0.19)				0.414 (0.43)				0.312 (0.16)				0.329 (0.11)			
$MSYL^{SP}$	1657 (0.20)				1365 (0.28)				1701 (0.18)				1473 (0.12)			
$MSYL^{SA}$	476 (0.31)				345 (0.54)				508 (0.28)				484 (0.23)			
$MSY$	300 (0.25)				406 (0.43)				291 (0.22)				261 (0.13)			
$B^{SP}_{2001}/K^{SP}$	0.403 (0.39)				0.696 (0.42)				0.367 (0.33)				0.214 (0.18)			
$B^{SA}_{2001}/K^{SA}$	0.104 (0.63)				0.229 (0.60)				0.093 (0.54)				0.038 (0.35)			
$B^{SP}_{2001}/MSYL^{SP}$	0.885 (0.42)				1.643 (0.54)				0.804 (0.36)				0.473 (0.19)			
$B^{SA}_{2001}/MSYL^{SA}$	0.843 (0.67)				2.281 (0.93)				0.744 (0.56)				0.281 (0.34)			
$MSYL^{SP}/K^{SP}$	0.455 (0.04)				0.423 (0.12)				0.457 (0.04)				0.451 (0.03)			
$MSYL^{SA}/K^{SA}$	0.120 (0.20)				0.101 (0.40)				0.125 (0.19)				0.136 (0.18)			
$M$	0.76 (0.04)				0.77 (0.04)				0.75 (0.04)				0.69 (0.04)			
Age	$S_{1968,a}$	$S_{1989,a}$	$S_{2001,a}$	$S_{surv}$	$S_{1968,a}$	$S_{1989,a}$	$S_{2001,a}$	$S_{surv}$	$S_{1968,a}$	$S_{1989,a}$	$S_{2001,a}$	$S_{surv}$	$S_{1968,a}$	$S_{1989,a}$	$S_{2001,a}$	$S_{surv}$
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.09	0.63	0.01	0.77	0.08	0.62	0.01	0.76	0.09	0.63	0.01	0.77	0.10	0.68	0.01	0.83
3	0.66	1.00	0.03	1.00	0.61	1.00	0.04	1.00	0.68	1.00	0.03	1.00	0.70	1.00	0.04	1.00
4	0.97	1.00	0.12	1.00	0.97	1.00	0.15	1.00	0.98	1.00	0.12	1.00	0.98	1.00	0.13	1.00
5	1.00	1.00	0.37	1.00	1.00	1.00	0.44	1.00	1.00	1.00	0.38	1.00	1.00	1.00	0.37	1.00
6	1.00	1.00	0.72	1.00	1.00	1.00	0.78	1.00	1.00	1.00	0.73	1.00	1.00	1.00	0.71	1.00
7	1.00	1.00	0.93	1.00	1.00	1.00	0.95	1.00	1.00	1.00	0.93	1.00	1.00	1.00	0.92	1.00
8+	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Commercial sigmas:																
CPUE ICSEAF (1.3+1.4)	0.171 (0.18)				0.126 (0.14)				0.008 (0.17)				0.144 (0.12)			
CPUE ICSEAF (1.5)	0.202 (0.12)				0.173 (0.08)				0.010 (0.09)				0.183 (0.07)			
CPUE GLM	0.211 (0.25)				0.238 (0.15)				0.118 (0.21)				0.162 (0.18)			
Commercial q 's: ( $\times 10^3$ )																
CPUE ICSEAF (1.3+1.4)	0.283 (0.21)				0.391 (0.21)				0.000 (0.19)				0.337 (0.13)			
CPUE ICSEAF (1.5)	0.432 (0.21)				0.596 (0.21)				0.000 (0.19)				0.513 (0.13)			
CPUE GLM	2.215 (0.42)				1.287 (0.49)				0.002 (0.36)				4.982 (0.21)			
Survey sigmas:																
Spanish winter	0.391 (0.09)				0.432 (0.13)				0.087 (0.11)				0.339 (0.06)			
Spanish summer	0.503 (0.04)				0.503 (0.04)				0.138 (0.05)				0.543 (0.03)			
Survey q 's:																
Spanish winter	0.401 (0.19)		Commercial		0.314 (0.28)		Commercial		0.431 (0.16)		Commercial		0.628 (0.12)		Commercial	
Spanish summer	0.557 (0.20)		trawlers q 's:		0.424 (0.30)		trawlers q 's:		0.601 (0.17)		trawlers q 's:		0.932 (0.13)		trawlers q 's:	
Nansen summer	0.367 (0.19)		0.404 (0.25)		0.252 (0.34)		0.277 (0.34)		0.395 (0.21)		0.434 (0.21)		1.000 -		1.000 -	
Nansen winter	0.418 (0.20)		0.462 (0.24)		0.290 (0.35)		0.321 (0.35)		0.450 (0.20)		0.497 (0.20)		1.000 -		1.000 -	
Catches-at-age sigmas:																
commercial	0.110 (0.04)				0.107 (0.04)				0.112 (0.04)				0.118 (0.05)			
summer survey	0.114 (0.06)				0.113 (0.06)				0.112 (0.06)				0.119 (0.07)			
winter survey	0.161 (0.07)				0.161 (0.07)				0.162 (0.06)				0.160 (0.07)			
Additional sigma (survey)	0.225 (0.26)				0.222 (0.25)				0.224 (0.26)				0.362 (0.35)			

Table 11.1: continued

	5) Change in $K$ $K_{sp}^* \text{ est}$ (1970-1975)				6) Change in $K$ $fix K_{sp}^* = 0.80 K_{sp}$ (1970-1975)				7) $\sigma_R = 0.40$				
Total negative loglikelihood	-98.3				-94.9				-110.1				
-lnL : CPUE	-32.2				-30.1				-33.4				
-lnL: Survey	-13.3				-14.2				-13.2				
-lnL: CAA com.	-65.9				-61.7				-66.6				
-lnL: CAA surv	-9.0				-9.8				-10.7				
-lnL:SR Residuals	22.1				20.9				13.8				
	In terms of the new $K^{SP}$ :				In terms of the new $K^{SP}$ :								
$K^{SP}$	3469 (0.15)		1873 (0.13)		3142 (0.13)		2513 (0.13)		3461 (0.19)				
$K^{SA}$	3733 (0.16)				3354 (0.15)				3731 (0.20)				
$B^{SP}_{1001}$	1586 (0.19)				1974 (0.21)				1581 (0.32)				
$B^{SA}_{1001}$	461 (0.29)				684 (0.29)				433 (0.53)				
$h$	1.000 (0.00)				0.554 (0.41)				0.365 (0.26)				
$MSYL^{SP}$	785 (0.16)				1025 (0.16)				1535 (0.23)				
$MSYL^{SA}$	110 (0.15)				213 (0.42)				371 (0.39)				
$MSY$	339 (0.16)				429 (0.33)				368 (0.28)				
$B^{SP}_{1001}/K^{SP}$	0.457 (0.18)		0.846 (0.11)		0.628 (0.21)		0.785 (0.21)		0.457 (0.38)				
$B^{SA}_{1001}/K^{SA}$	0.123 (0.30)				0.204 (0.31)				0.116 (0.60)				
$B^{SP}_{1001}/MSYL^{SP}$	2.020 (0.27)				1.927 (0.28)				1.030 (0.43)				
$B^{SA}_{1001}/MSYL^{SA}$	4.186 (0.49)				3.216 (0.51)				1.166 (0.72)				
$MSYL^{SP}/K^{SP}$	0.467 (0.10)		0.864 (0.13)		0.326 (0.06)		0.408 (0.07)		0.444 (0.06)				
$MSYL^{SA}/K^{SA}$	0.029 (0.25)				0.063 (0.31)				0.100 (0.26)				
$M$	0.77 (0.04)				0.76 (0.04)				0.77 (0.05)				
Age	$S_{1968,a}$	$S_{1989,a}$	$S_{2001,a}$	$S_{surv}$	$S_{1968,a}$	$S_{1989,a}$	$S_{2001,a}$	$S_{surv}$	$S_{1968,a}$	$S_{1989,a}$	$S_{2001,a}$	$S_{surv}$	
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
2	0.08	0.61	0.01	0.76	0.08	0.62	0.01	0.78	0.08	0.62	0.01	0.77	
3	0.63	1.00	0.03	1.00	0.62	1.00	0.04	1.00	0.64	1.00	0.03	1.00	
4	0.97	1.00	0.12	1.00	0.97	1.00	0.15	1.00	0.97	1.00	0.12	1.00	
5	1.00	1.00	0.39	1.00	1.00	1.00	0.43	1.00	1.00	1.00	0.37	1.00	
6	1.00	1.00	0.74	1.00	1.00	1.00	0.78	1.00	1.00	1.00	0.73	1.00	
7	1.00	1.00	0.94	1.00	1.00	1.00	0.95	1.00	1.00	1.00	0.94	1.00	
8+	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Commercial sigmas:													
CPUE ICSEAF (1.3+1.4)	0.175 (0.19)				0.185 (0.29)				0.169 (0.19)				
CPUE ICSEAF (1.5)	0.209 (0.12)				0.214 (0.20)				0.207 (0.12)				
CPUE GLM	0.189 (0.17)				0.228 (0.17)				0.177 (0.24)				
Commercial $q$ 's: ( $\times 10^3$ )													
CPUE ICSEAF (1.3+1.4)	0.296 (0.20)				0.329 (0.17)				0.299 (0.22)				
CPUE ICSEAF (1.5)	0.451 (0.20)				0.502 (0.17)				0.456 (0.22)				
CPUE GLM	1.962 (0.26)				1.444 (0.29)				2.150 (0.43)				
Survey sigmas:													
Spanish winter	0.433 (0.07)				0.441 (0.09)				0.419 (0.11)				
Spanish summer	0.523 (0.04)				0.511 (0.04)				0.520 (0.04)				
Survey $q$ 's:													
Spanish winter	0.363 (0.20)	Commercial			0.349 (0.25)	Commercial			0.368 (0.22)	Commercial			
Spanish summer	0.491 (0.20)	trawlers $q$ 's:			0.470 (0.26)	trawlers $q$ 's:			0.501 (0.24)	trawlers $q$ 's:			
Nansen summer	0.331 (0.19)	0.364 (0.19)			0.284 (0.23)	0.312 (0.23)			0.345 (0.27)	0.379 (0.27)			
Nansen winter	0.377 (0.19)	0.416 (0.19)			0.325 (0.23)	0.359 (0.23)			0.398 (0.27)	0.440 (0.27)			
Catches-at-age sigmas:													
commercial	0.104 (0.04)				0.106 (0.05)				0.103 (0.04)				
summer survey	0.115 (0.06)				0.115 (0.06)				0.112 (0.06)				
winter survey	0.157 (0.07)				0.161 (0.07)				0.157 (0.07)				
Additional sigma (survey)	0.235 (0.25)				0.222 (0.26)				0.237 (0.26)				

Table 11.1: continued

	8) $\sigma_M = 0.10$				9) Selectivity down Sel slope = 0.2 from age 4				10) Fit to fishable biomass			
Total negative loglikelihood	-57.2				-81.0				-146.0			
-lnL: CPUE	-30.5				-38.7				-34.3			
-lnL: Survey	-14.8				-13.3				-11.1			
-lnL: CAA com.	-28.7				-59.3				-30.6			
-lnL: CAA surv	2.7				10.0				-84.2			
-lnL:SR Residuals	14.2				20.3				14.2			
$K^{SP}$	4085 (0.11)				4634 (0.12)				3009 (0.09)			
$K^{SA}$	4507 (0.13)				4105 (0.13)				3210 (0.11)			
$B^{SP}_{2001}$	1245 (0.28)				811 (0.15)				1030 (0.18)			
$B^{SA}_{2001}$	354 (0.51)				84 (0.14)				176 (0.31)			
$h$	0.277 (0.13)				0.276 (0.10)				0.366 (0.11)			
$MSYL^{SP}$	1913 (0.14)				2199 (0.14)				1229 (0.11)			
$MSYL^{SA}$	646 (0.25)				458 (0.25)				206 (0.31)			
$MSY$	237 (0.27)				255 (0.22)				306 (0.11)			
$B^{SP}_{2001}/K^{SP}$	0.305 (0.34)				0.175 (0.20)				0.342 (0.20)			
$B^{SA}_{2001}/K^{SA}$	0.079 (0.57)				0.020 (0.22)				0.055 (0.35)			
$B^{SP}_{2001}/MSYL^{SP}$	0.651 (0.36)				0.369 (0.22)				0.838 (0.22)			
$B^{SA}_{2001}/MSYL^{SA}$	0.548 (0.57)				0.184 (0.31)				0.852 (0.40)			
$MSYL^{SP}/K^{SP}$	0.468 (0.03)				0.474 (0.03)				0.409 (0.03)			
$MSYL^{SA}/K^{SA}$	0.143 (0.18)				0.111 (0.18)				0.064 (0.27)			
$M$	0.75 (0.04)				0.67 (0.04)				0.73 (0.05)			
Age	$S_{1968,A}$	$S_{1989,A}$	$S_{2001,A}$	$S_{surv}$	$S_{1968,A}$	$S_{1989,A}$	$S_{2001,A}$	$S_{surv}$	$S_{1968,A}$	$S_{1989,A}$	$S_{2001,A}$	$S_{surv}$
0	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
1	0.00	0.08	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.07	0.00	0.00
2	0.10	0.40	0.01	0.73	0.11	0.72	0.01	0.83	0.09	0.24	0.01	0.00
3	0.70	0.84	0.04	1.00	0.71	1.00	0.02	1.00	0.63	0.60	0.02	0.00
4	0.98	0.97	0.13	1.00	1.00	1.00	0.05	1.00	0.97	0.87	0.07	0.60
5	1.00	1.00	0.38	1.00	0.84	0.82	0.13	0.82	1.00	0.97	0.22	0.69
6	1.00	1.00	0.72	1.00	0.69	0.67	0.32	0.67	1.00	0.99	0.52	0.79
7	1.00	1.00	0.93	1.00	0.56	0.55	0.66	0.55	1.00	1.00	0.83	0.89
8+	1.00	1.00	1.00	1.00	0.46	0.45	1.00	0.45	1.00	1.00	1.00	1.00
Commercial sigmas:												
CPUE ICSEAF (1.3+1.4)	0.176 (0.17)				0.161 (0.13)				0.124 (0.08)			
CPUE ICSEAF (1.5)	0.194 (0.12)				0.197 (0.09)				0.172 (0.07)			
CPUE GLM	0.265 (0.20)				0.168 (0.22)				0.212 (0.14)			
Commercial $q$ 's: ( $\times 10^{-3}$ )												
CPUE ICSEAF (1.3+1.4)	0.250 (0.18)				0.276 (0.14)				0.405 (0.12)			
CPUE ICSEAF (1.5)	0.381 (0.18)				0.420 (0.14)				0.617 (0.12)			
CPUE GLM	2.517 (0.36)				9.713 (0.21)				4.975 (0.21)			
Survey sigmas:												
Spanish winter	0.379 (0.06)				0.310 (0.06)				0.478 (0.09)			
Spanish summer	0.522 (0.03)				0.575 (0.03)				0.556 (0.05)			
Survey $q$ 's:												
Spanish winter	0.454 (0.17)		Commercial		0.577 (0.10)		Commercial		2.510 (0.15)		Commercial	
Spanish summer	0.652 (0.17)		trawlers $q$ 's:		0.916 (0.11)		trawlers $q$ 's:		2.838 (0.14)		trawlers $q$ 's:	
Nansen summer	0.423 (0.20)		0.465 (0.21)		0.767 (0.11)		0.843 (0.11)		0.582 (0.14)		0.640 (0.14)	
Nansen winter	0.480 (0.19)		0.531 (0.19)		0.845 (0.10)		0.934 (0.10)		0.875 (0.14)		0.967 (0.14)	
Catches-at-age sigmas:												
commercial	0.137 (0.04)				0.109 (0.04)				0.130 (0.04)			
summer survey	0.130 (0.06)				0.122 (0.07)				0.077 (0.06)			
winter survey	0.168 (0.05)				0.160 (0.07)				0.066 (0.07)			
Additional sigma (survey)	0.215 (0.26)				0.230 (0.24)				0.290 (0.21)			

**Table 11.2:** Control parameter values for each of the six candidate OMPs presented. The values in bold reflect the changes from the baseline OMP.

	$\lambda$	$\beta$	$\omega$	$y_{no\ decr}$	max incr.	max decr.
a) Baseline	1.0	0.7	0.5	2001	5%	-15%
b) $\beta = 0.5$	1.0	<b>0.5</b>	0.5	2001	5%	-15%
c) $\beta = 1.0$	1.0	<b>1.0</b>	0.5	2001	5%	-15%
d) $\omega = 0.3$	1.0	0.7	<b>0.3</b>	2001	5%	-15%
e) max decr. -10%	1.0	0.7	0.5	2001	5%	<b>-10%</b>
f) adopted	<b>0.9</b>	0.7	0.5	2001	5%	<b>-10%</b>



**Table 11.3:** Management quantities estimates for the Reference Case, ‘higher  $\sigma_R$ ’ and ‘lower  $\sigma_R$ ’ robustness test operating models projected under the OMP ultimately adopted for Namibian hake. The quantities in parenthesis are bootstrap estimated 90% probability intervals.

	Reference Case	$\sigma_R = 0.40$	$\sigma_R = 0.10$
$B^{SP}_{2001}/K$	0.354 (0.212; 0.675)	0.428 (0.220; 0.757)	0.277 (0.190; 0.463)
$B^{SP}_{2004}/K$	0.354 (0.219; 0.737)	0.432 (0.223; 0.903)	0.275 (0.173; 0.481)
$B^{SP}_{2004}/B^{SP}_{2001}$	1.026 (0.793; 1.303)	1.021 (0.683; 1.570)	0.983 (0.876; 1.097)
$B^{SP}_{2011}/K$	0.415 (0.231; 0.748)	0.504 (0.241; 0.977)	0.299 (0.183; 0.580)
$B^{SP}_{2011}/B^{SP}_{2001}$	1.168 (0.800; 1.610)	1.196 (0.682; 2.136)	1.065 (0.850; 1.277)
$B^{SP}_{2021}/K$	0.490 (0.254; 0.844)	0.569 (0.282; 0.934)	0.340 (0.194; 0.565)
$B^{SP}_{2021}/B^{SP}_{2001}$	1.290 (0.869; 1.911)	1.326 (0.624; 2.452)	1.193 (0.940; 1.473)
MSYL	0.459 (0.408; 0.476)	0.432 (0.488; 0.470)	0.469 (0.450; 0.482)
$B^{SP}_{2021}/MSYL$	1.072 (0.553; 2.070)	1.310 (0.622; 2.218)	0.726 (0.404; 1.212)
AAV	4.1 (3.0; 5.8)	4.3 (3.3; 6.2)	4.4 (3.1; 6.1)
Average annual catch	197.2 (134.6; 286.0)	231.6 (143.7; 306.6)	165.7 (113.1; 261.5)
Catch - 2001	200.0 (200.0; 200.0)	200.0 (200.0; 200.0)	200.0 (200.0; 200.0)
Catch - 2002	209.4 (188.2; 210.0)	210.0 (210.0; 210.0)	197.4 (180.0; 210.0)
Catch - 2003	206.6 (169.5; 220.5)	220.5 (189.0; 220.5)	189.1 (162.0; 220.5)
Catch - 2004	198.0 (155.1; 231.5)	224.6 (170.1; 231.5)	174.8 (145.8; 231.5)
Catch - 2005	187.8 (139.6; 243.1)	228.9 (153.1; 243.1)	165.7 (131.2; 243.1)
Catch - 2006	178.3 (127.2; 255.3)	223.3 (137.8; 255.3)	153.4 (118.1; 247.5)
Catch - 2007	170.8 (117.2; 268.0)	221.2 (124.5; 268.0)	150.6 (106.3; 259.1)
Catch - 2008	175.9 (113.0; 281.4)	226.7 (123.2; 281.4)	150.4 (96.9; 266.6)
Catch - 2009	179.4 (102.1; 293.3)	229.7 (117.8; 295.5)	154.0 (91.3; 269.1)
Catch - 2010	182.9 (97.8; 307.6)	233.7 (112.6; 310.3)	153.1 (89.0; 282.4)
Catch - 2011	179.3 (102.7; 314.6)	234.8 (106.0; 325.8)	152.4 (85.8; 290.0)
Catch - 2012	186.4 (107.1; 327.6)	238.8 (109.6; 342.1)	155.4 (82.6; 290.2)
Catch - 2013	191.7 (106.2; 322.8)	237.8 (115.1; 359.2)	153.0 (82.3; 289.6)
Catch - 2014	192.1 (111.5; 330.4)	237.4 (120.9; 372.2)	152.7 (82.2; 295.9)
Catch - 2015	201.2 (111.5; 338.2)	235.6 (116.4; 371.6)	155.0 (83.8; 301.1)
Catch - 2016	201.9 (115.5; 331.3)	239.9 (122.2; 369.7)	153.9 (85.6; 292.3)
Catch - 2017	202.5 (121.2; 329.8)	247.0 (119.6; 365.9)	155.9 (89.9; 284.1)
Catch - 2018	205.0 (123.4; 328.2)	253.1 (125.4; 363.5)	161.4 (94.4; 287.1)
Catch - 2019	211.6 (121.7; 329.0)	261.4 (131.1; 361.3)	162.2 (96.4; 272.5)
Catch - 2020	214.9 (119.5; 324.8)	269.9 (132.7; 358.2)	163.8 (99.0; 283.8)
Catch - 2021	215.9 (118.9; 324.9)	277.8 (134.7; 361.4)	165.0 (101.2; 284.0)

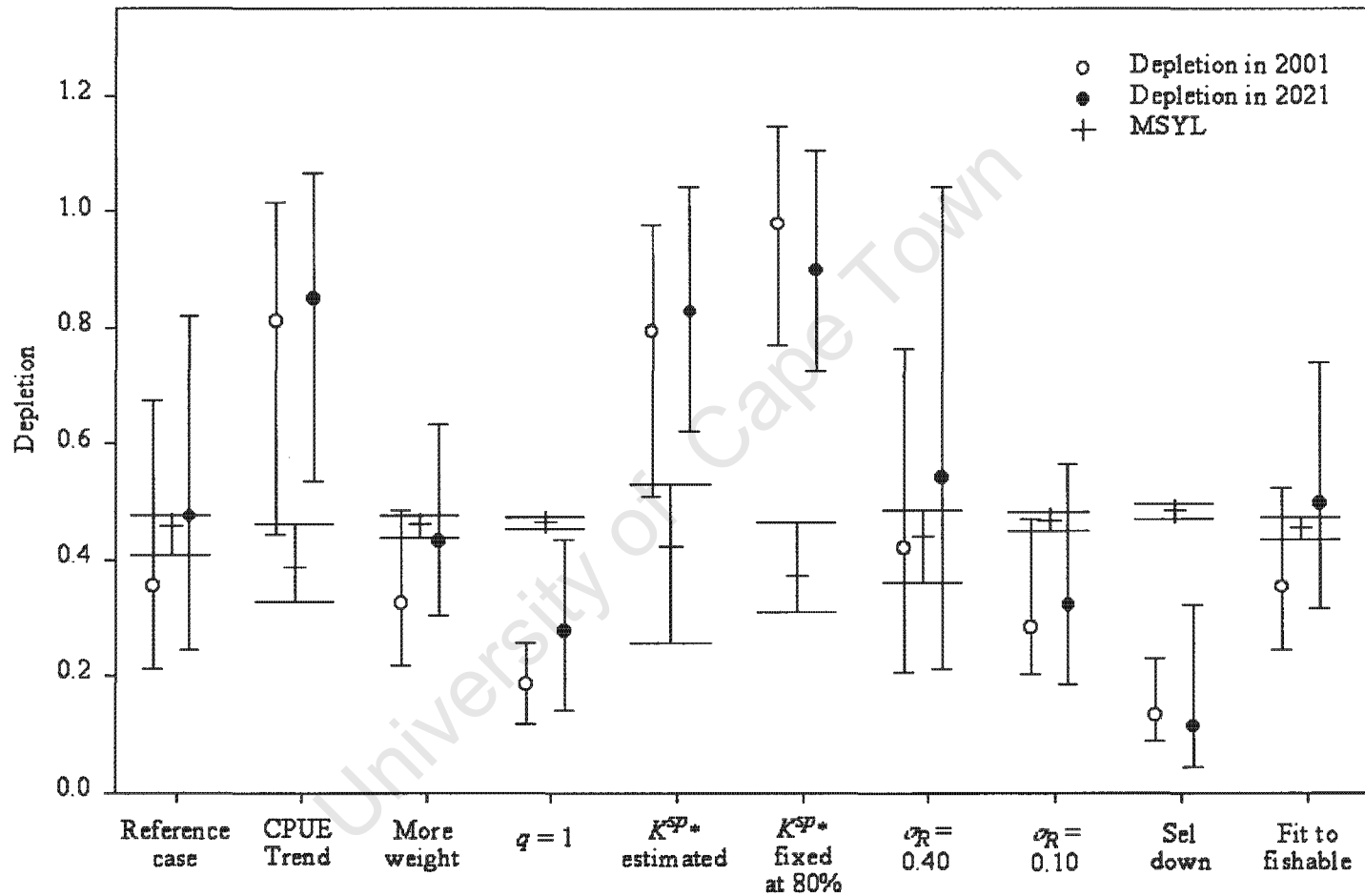


Fig. 11.1: Initial (2001) and projected final (2021) depletions under the baseline OMP, for the Reference Case and nine robustness test operating models. The estimated MSYL is also shown. The error bars show the 90% bootstrap probability or confidence intervals. For the regime shift scenarios (" $K^{SP*}$  est" and " $K^{SP*}$  80%"), the depletions are in terms of the new carrying capacity.

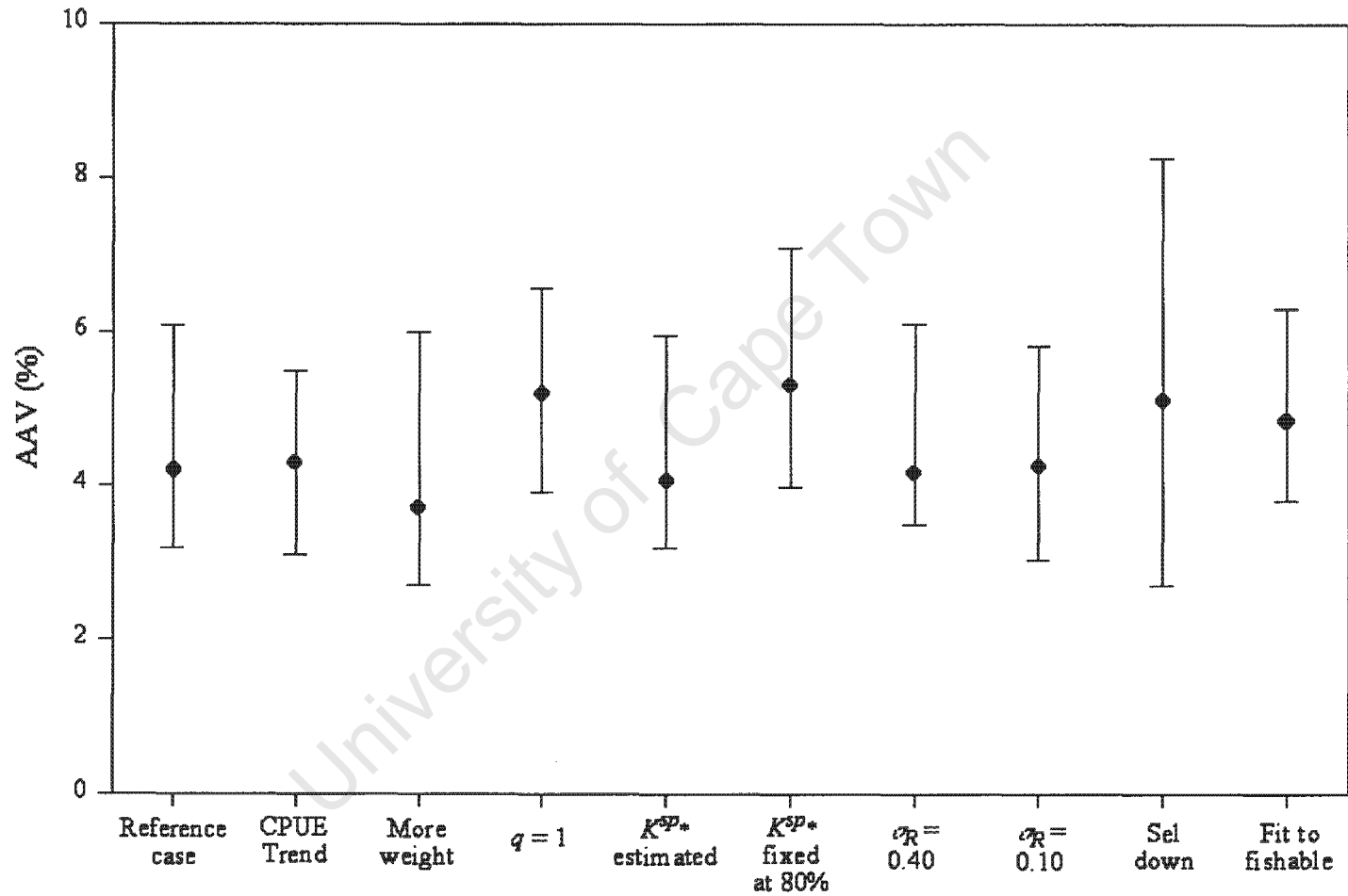


Fig. 11.2: Average Annual Variation (AAV) in catch for the 20 years projection period under the baseline OMP, for the Reference Case and nine robustness test operating models. The error bars show the 90% bootstrap probability intervals.

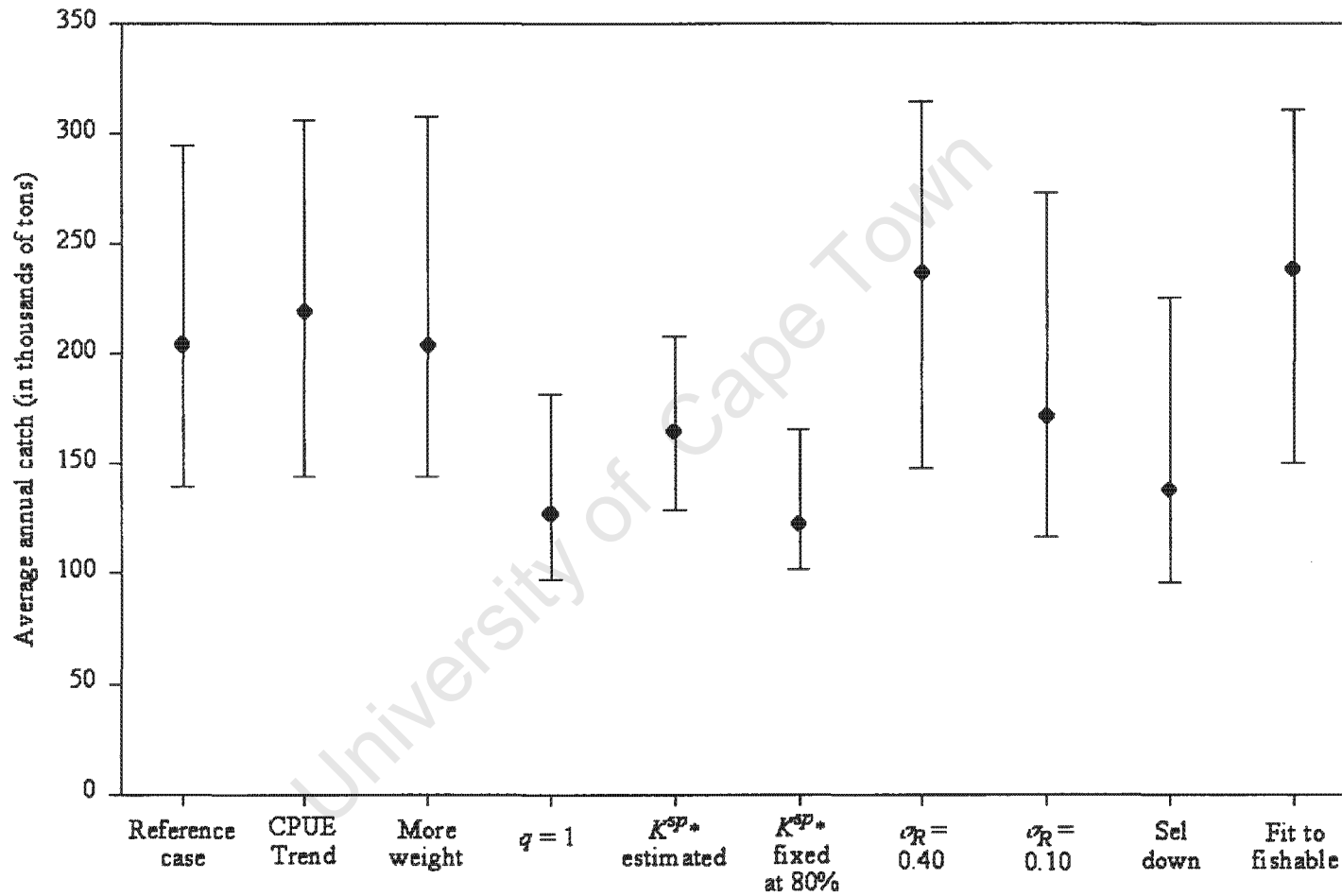


Fig. 11.3: Average Annual Catch for the 20-years projection period under the baseline OMP, for the Reference Case and nine robustness test operating models. The error bars show the 90% bootstrap probability intervals.

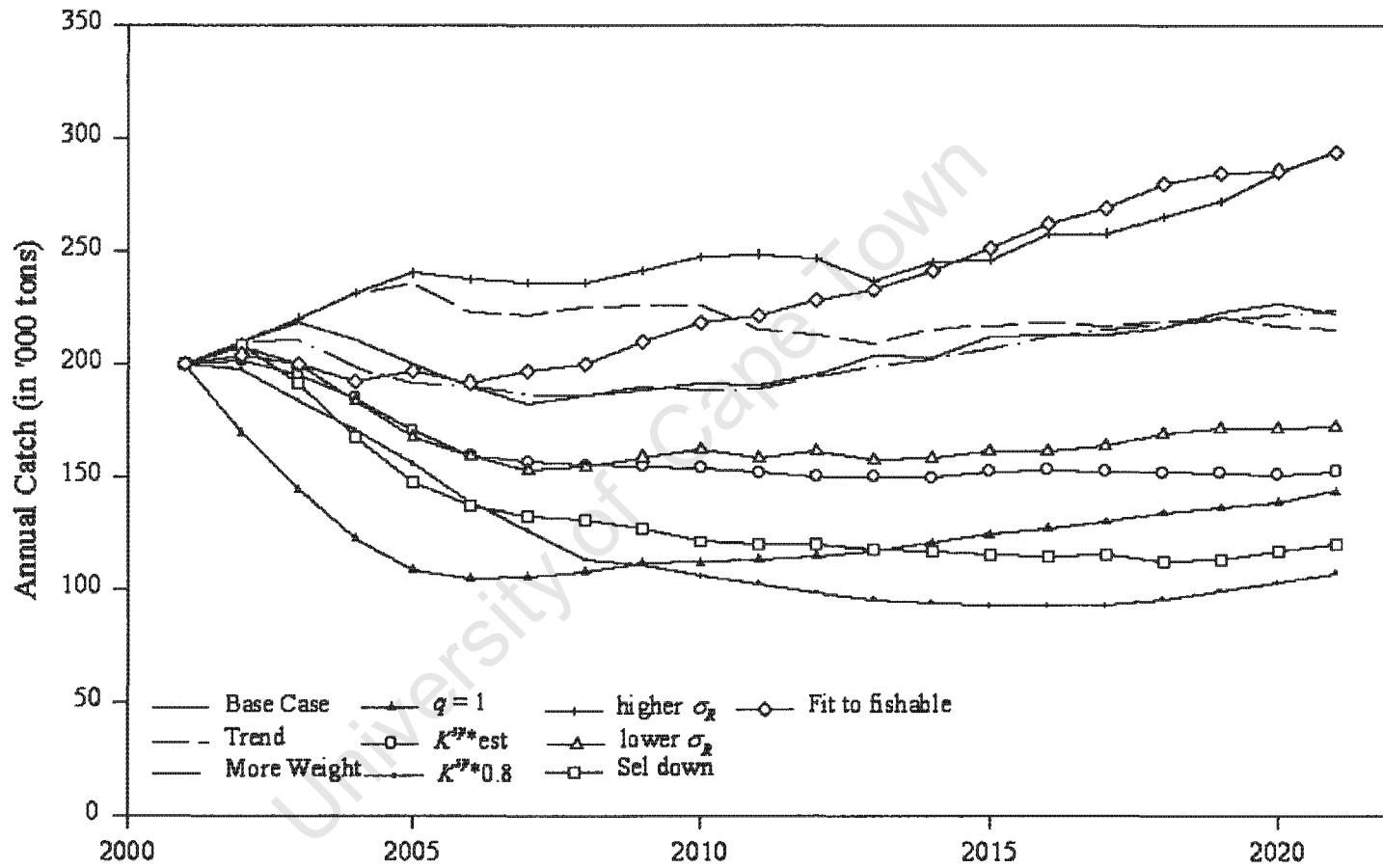
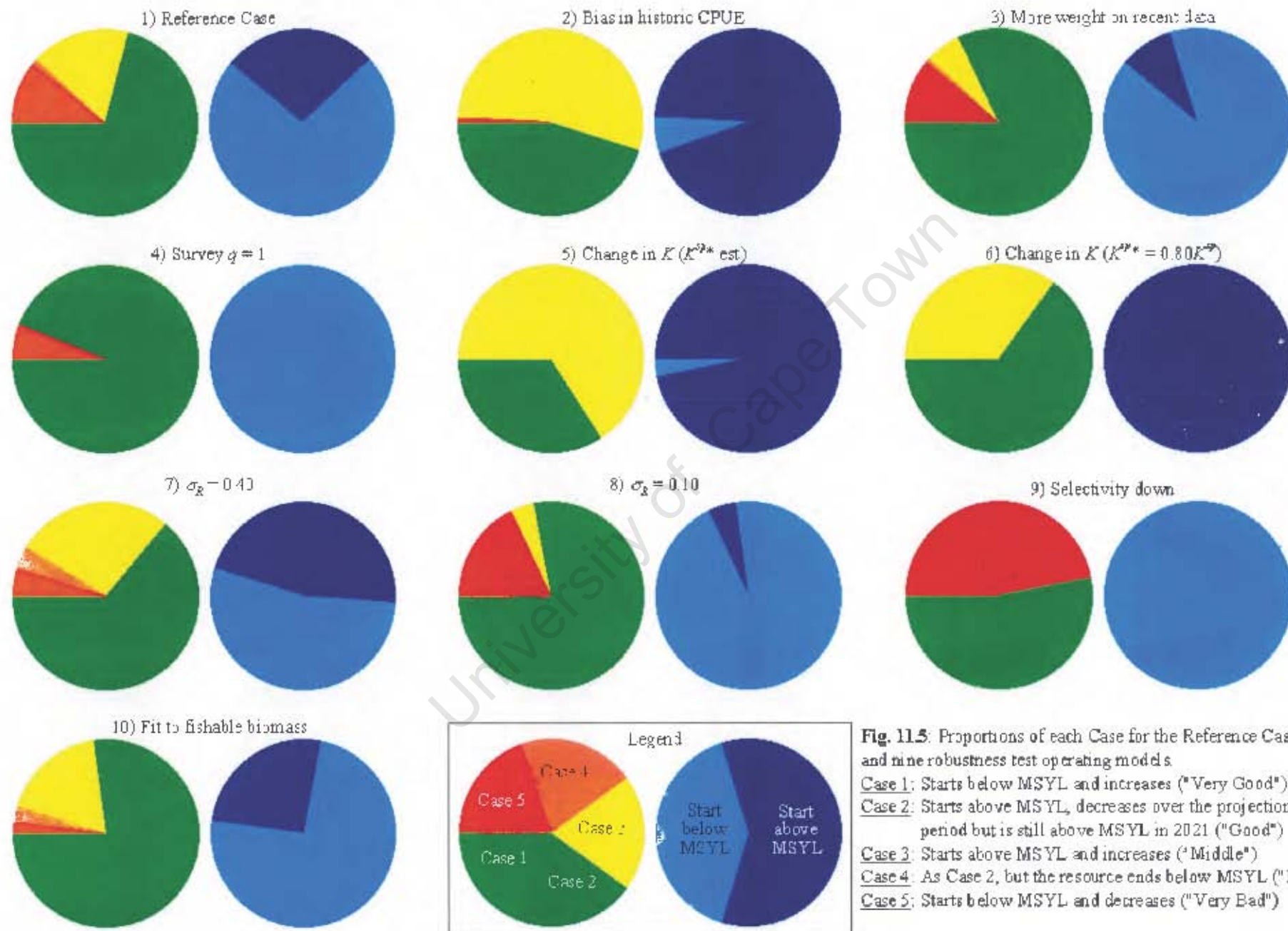


Fig. 11.4: Median Annual Catch for the 20 years projection period under the baseline OMP, for the Reference Case and nine robustness test operating models.



**Fig. 11.5:** Proportions of each Case for the Reference Case and nine robustness test operating models

**Case 1:** Starts below MSYL and increases ("Very Good")

**Case 2:** Starts above MSYL, decreases over the projection period but is still above MSYL in 2021 ("Good")

**Case 3:** Starts above MSYL and increases ("Middle")

**Case 4:** As Case 2, but the resource ends below MSYL ("Bad")

**Case 5:** Starts below MSYL and decreases ("Very Bad")

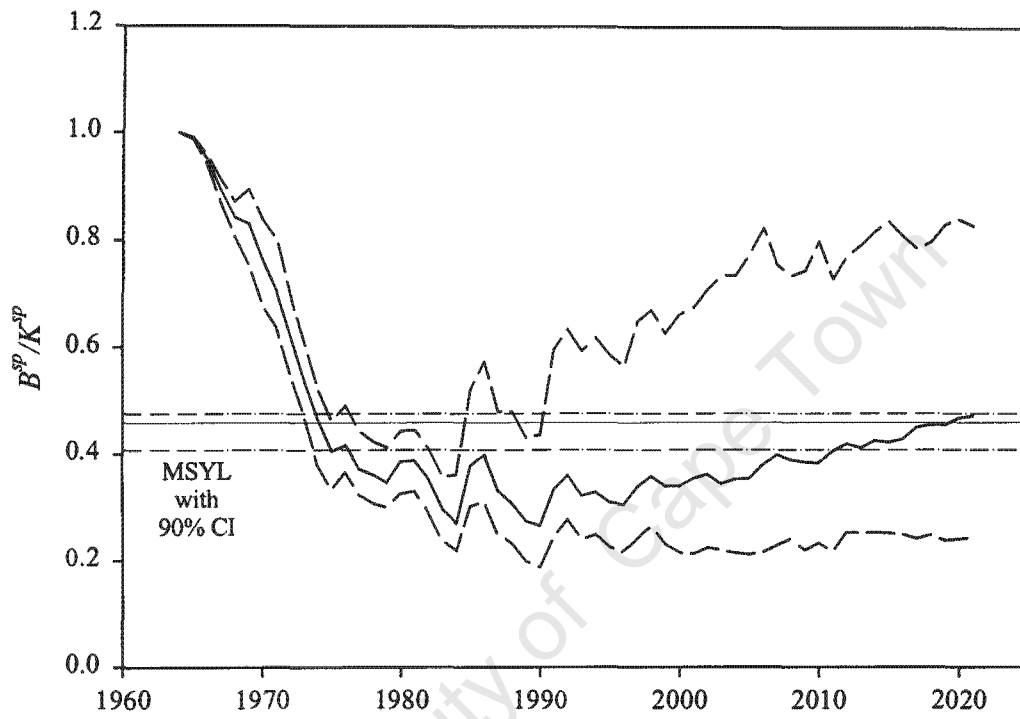


Fig. 11.6:  $B_y^{sp}/K^{sp}$  with 90% bootstrap probability intervals for the Reference Case assessment projected 20 years into the future under the baseline OMP. MSYL with its 90% probability intervals is also shown.

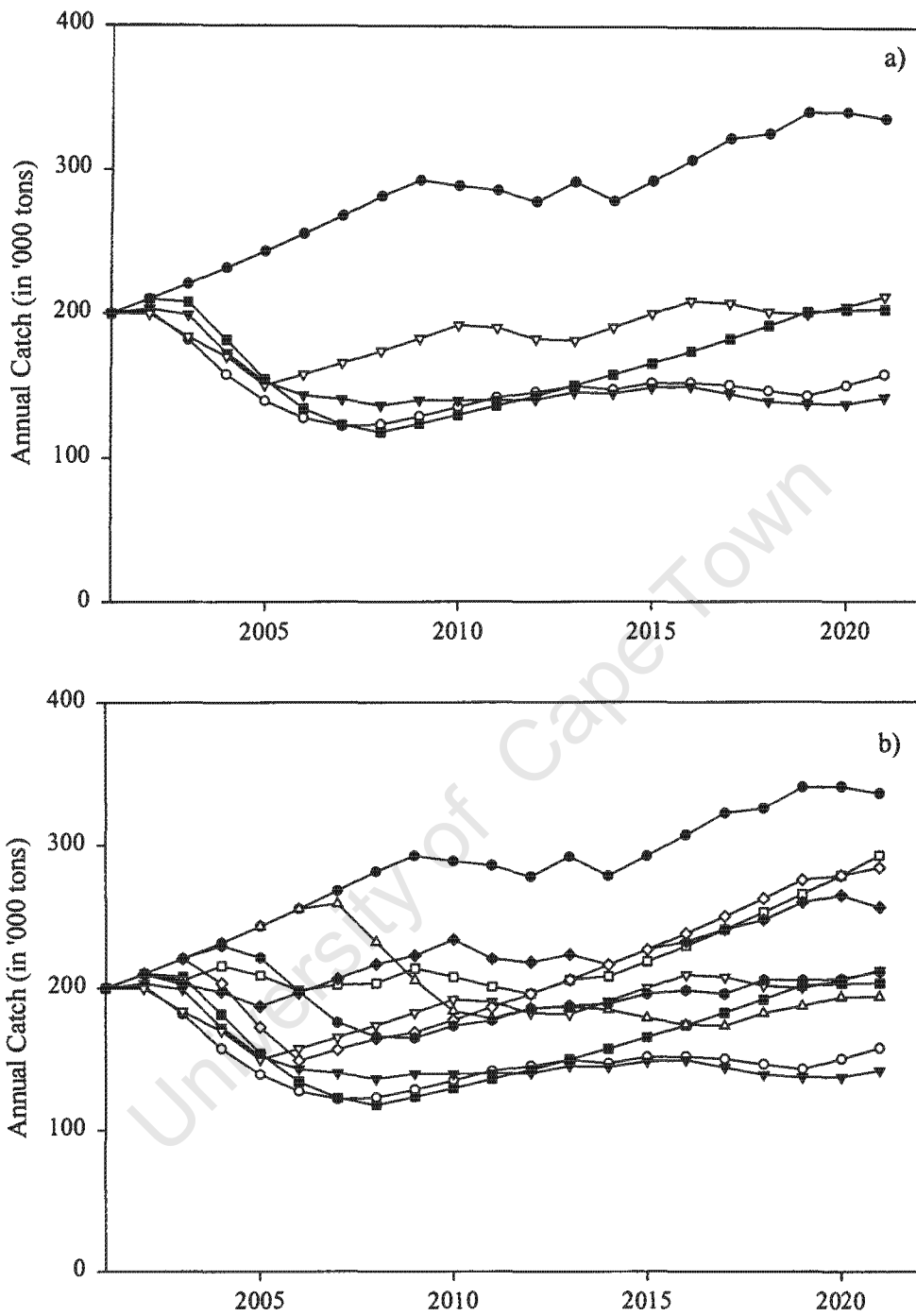


Fig. 11.7: "Worm" plots of annual catch, showing a) the first 5 and b) the first 10 bootstrap replicates, for the Reference Case operating model under the baseline OMP.



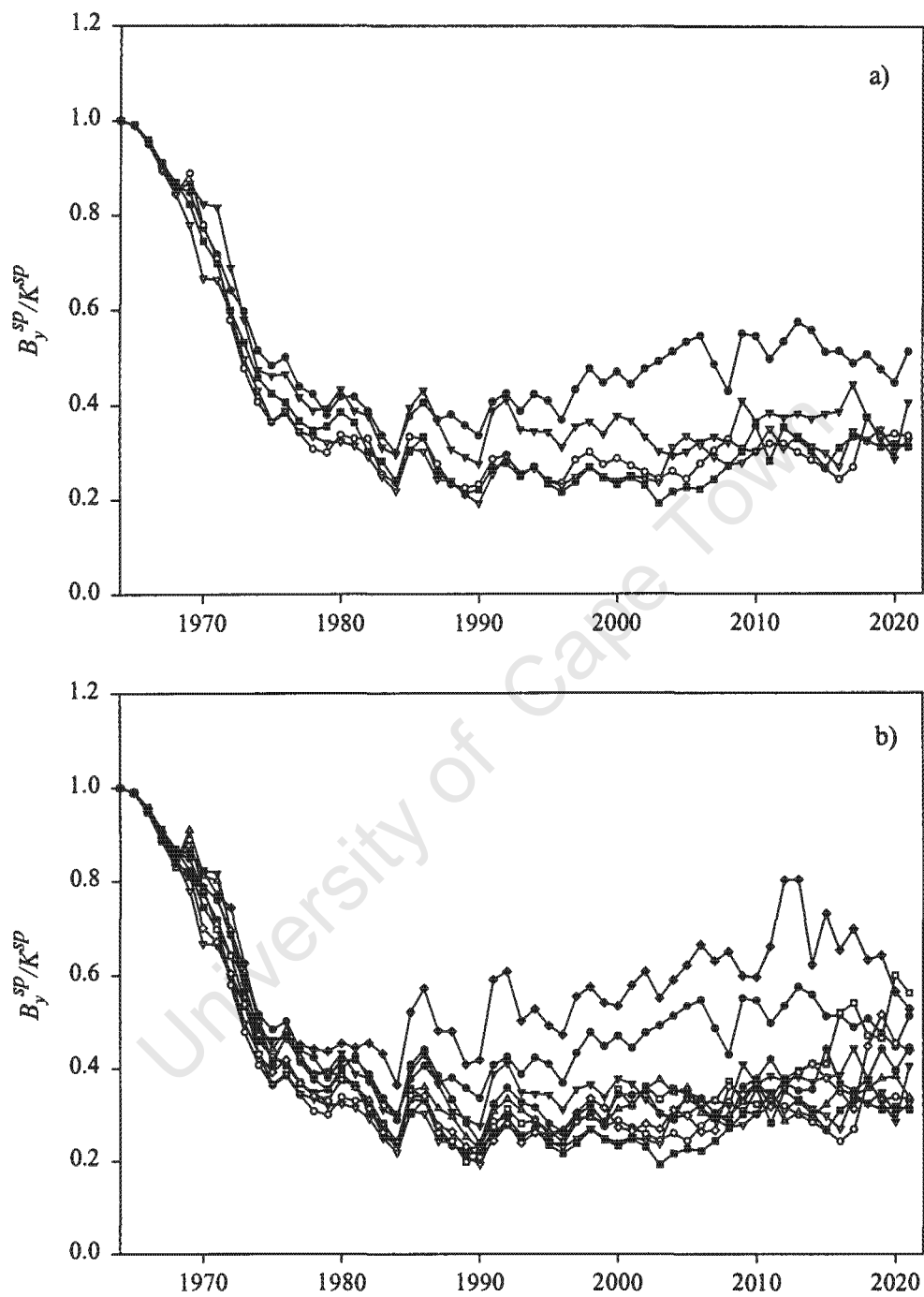


Fig.11.8: "Worm" plots of  $B_y^{sp}/K^{sp}$ , showing a) the first 5 and b) the first 10 bootstrap replicates, for the Reference Case operating model under the baseline OMP.

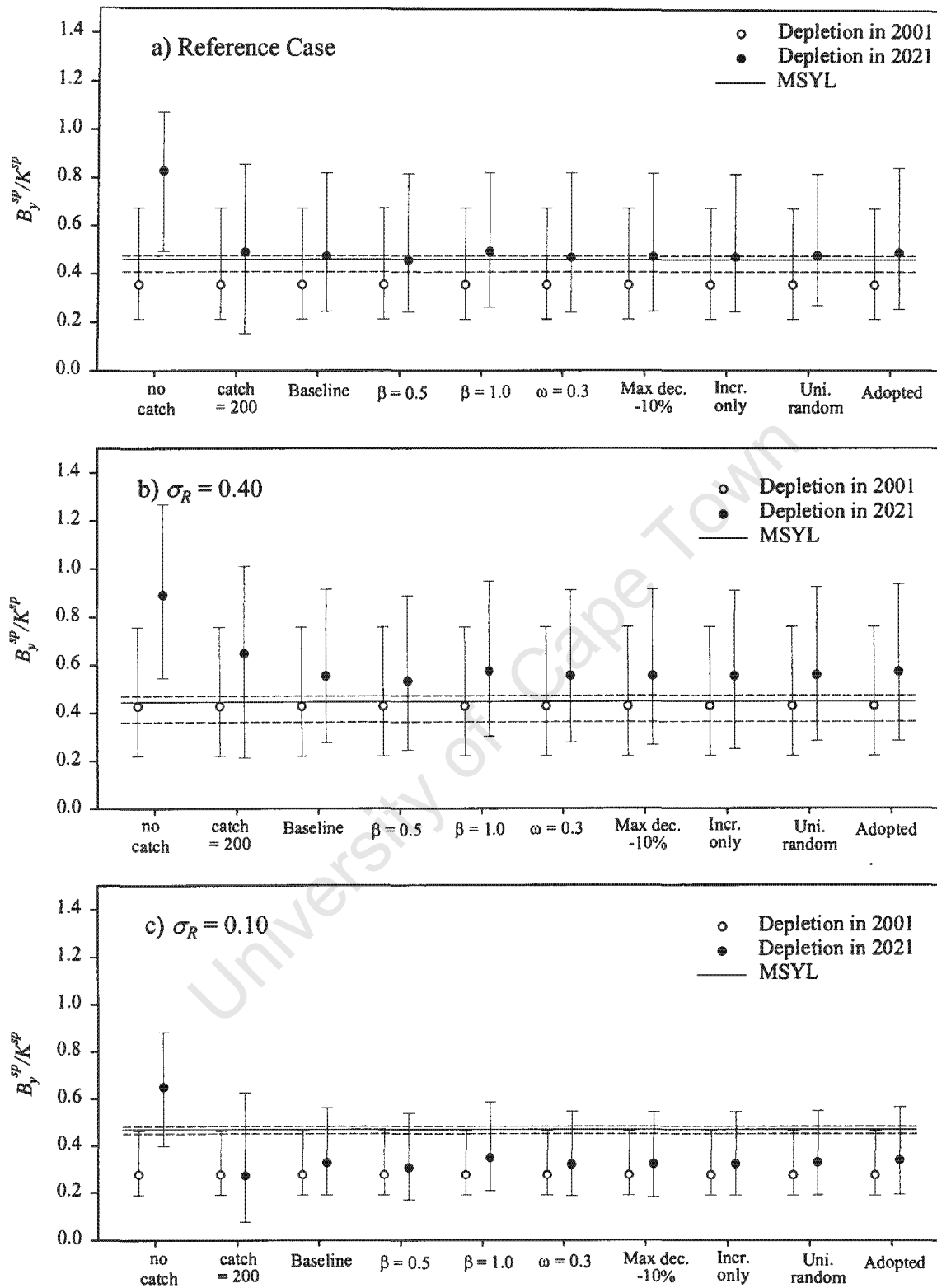


Fig. 11.9: Initial (2001) and projected final (2021) depletions under: no catch, a constant catch of 200 thousand tons, six different candidate OMPs and two cases of implementation uncertainty, for a) the Reference Case operating model, b) the operating model with higher  $\sigma_R$  and c) the operating model with lower  $\sigma_R$ . The estimated value of MSYL is also shown. The error bars show the 90% probability intervals.

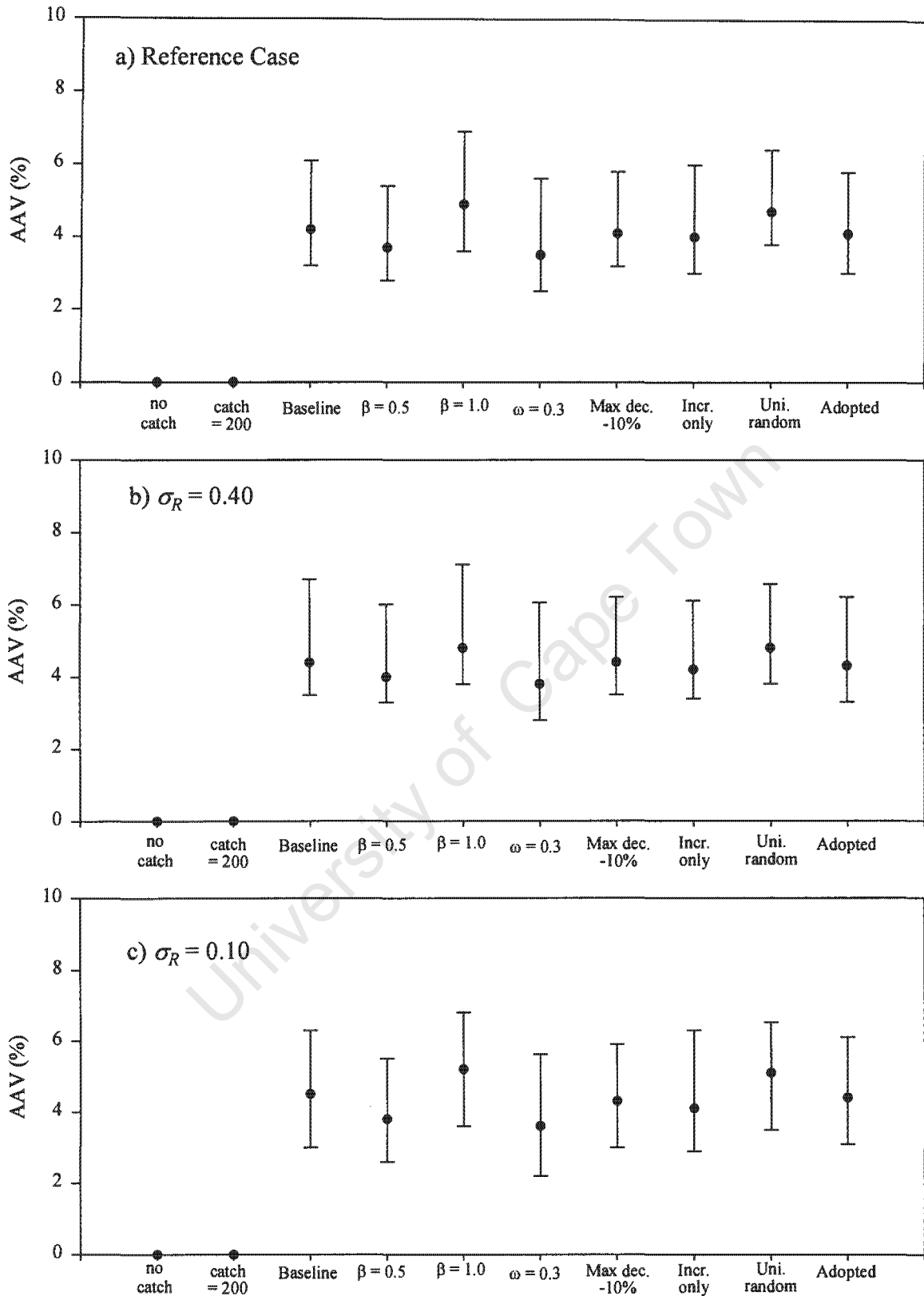


Fig. 11.10: Average Annual Variation (AAV) in catch for the 20-year projection period under: no catch, a constant catch of 200 thousand tons, six different candidate OMPs and two cases of implementation uncertainty for a) the Reference Case operating model, b) the operating model with higher  $\sigma_R$  and c) the operating model with lower  $\sigma_R$ . The error bars show the 90% probability intervals.

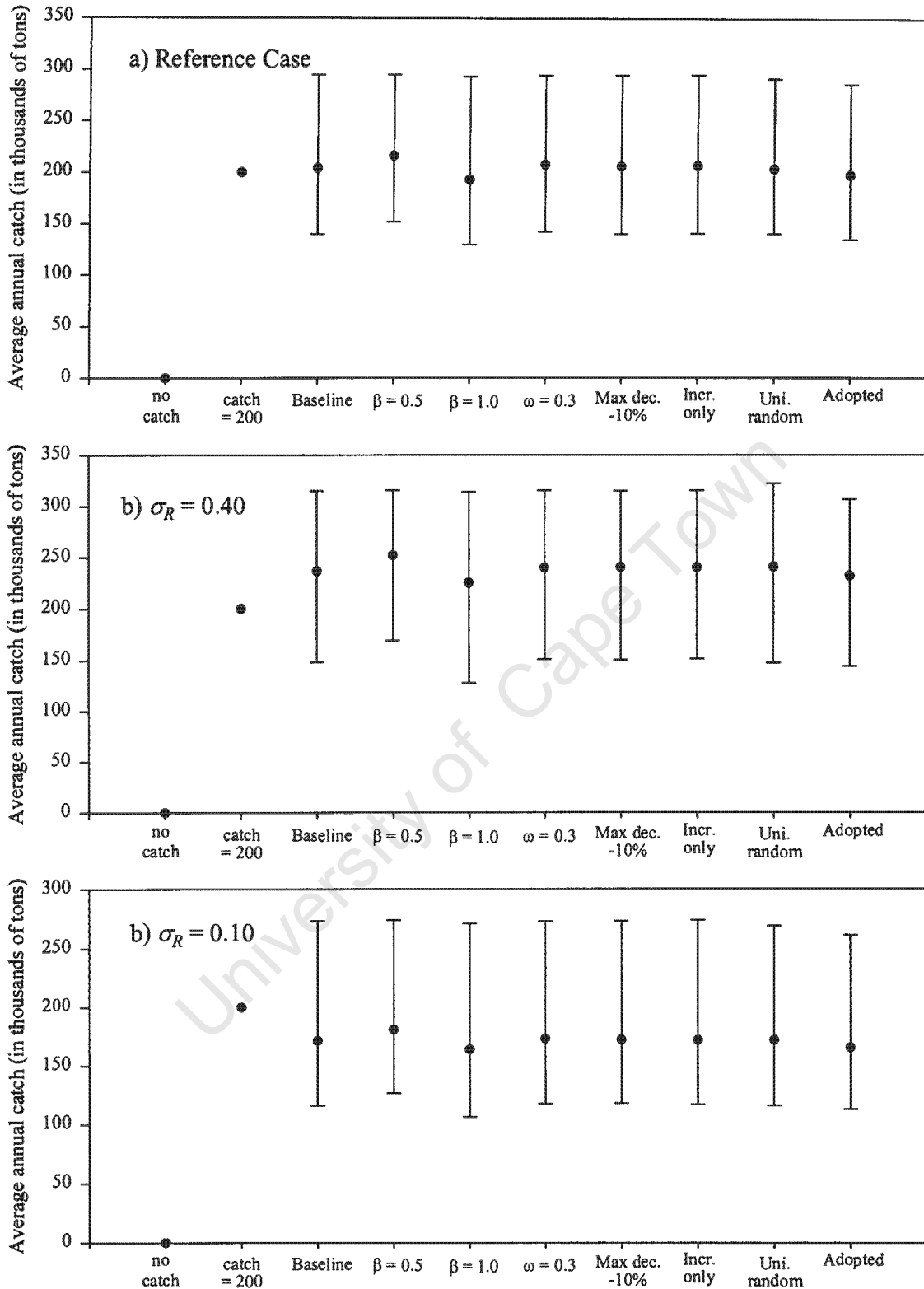


Fig. 11.11: Average Annual Catch for the 20 years projection period under: no catch, a constant catch of 200 thousand tons, six different candidate OMPs and two cases of implementation uncertainty for a) the Reference Case operating model, b) the operating model with higher  $\sigma_R$  and c) the operating model with lower  $\sigma_R$ . The error bars show the 90% probability intervals.

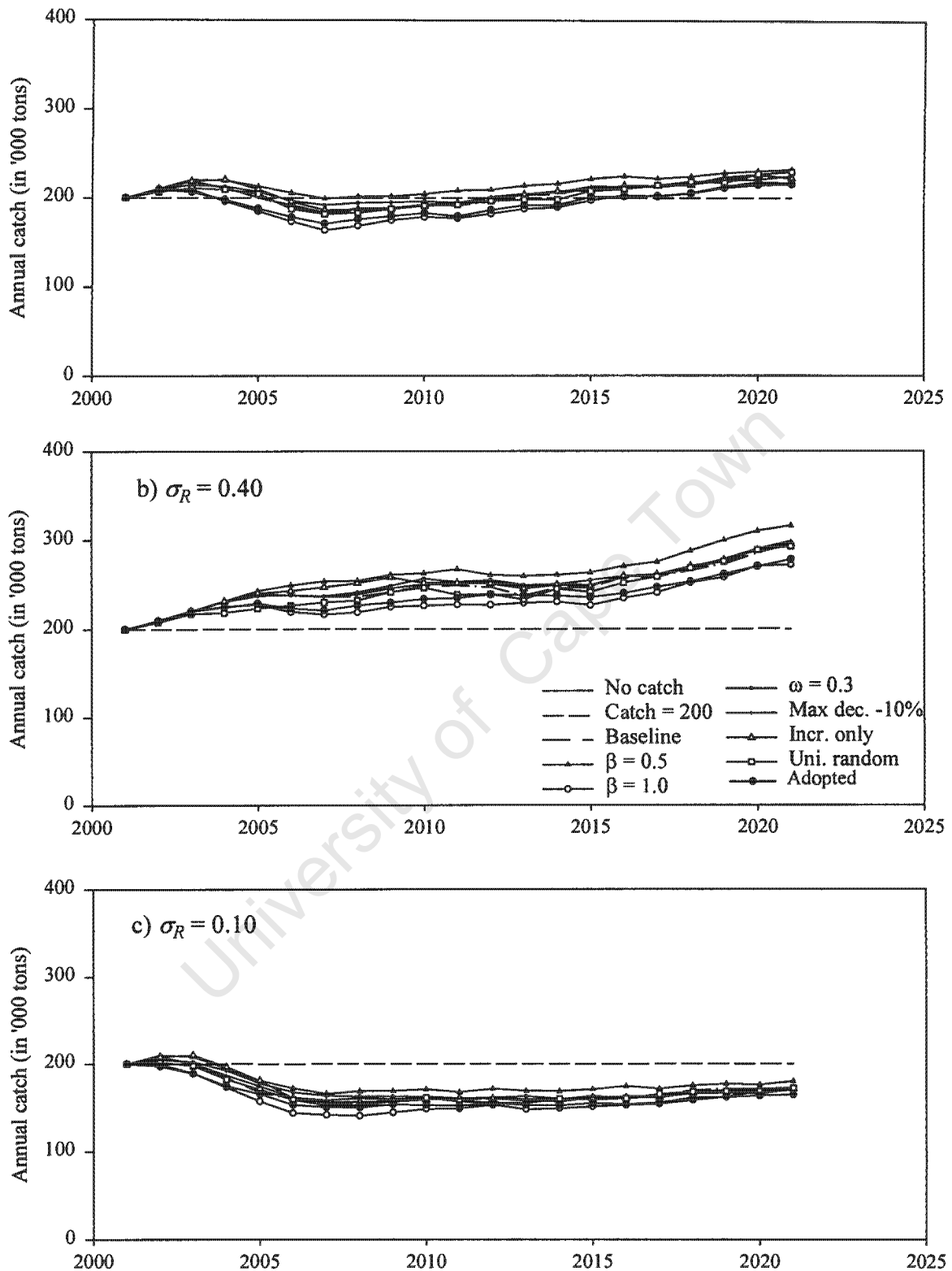


Fig. 11.12: Median Annual Catch for the 20-year projection period under: no catch, a constant catch of 200 thousand tons, six different candidate OMPs and two cases of implementation uncertainty for a) the Reference Case operating model, b) the operating model with higher  $\sigma_R$  and c) the operating model with lower  $\sigma_R$ .

## 12 Operational Management Procedures for the South African hake resources

### 12.1 West coast OMP (species combined)

An OMP was first used as the basis for hake TAC scientific recommendations in South Africa in 1990. This OMP, which was applied from 1990 to 1995 to provide recommendations for the years from 1991 to 1996 for both the west and south coasts hake resources, was based on an  $f_{0.2}$  harvesting strategy coupled to the Schaefer form of a dynamic age-aggregated production model. This production model, the Butterworth-Andrew observation error estimator (Butterworth and Andrew, 1984), was fitted to biomass estimates obtained from research surveys as well as the abundance index obtained from commercial catch rates (CPUE). Because the production model does not take the potentially important catch-at-age information into consideration, an *ad hoc* tuned VPA (Virtual Population Analysis) based on the Laurec-Shepherd tuning algorithm (Pope and Shepherd, 1985) was used in addition to age-aggregated production models for simulation testing of alternative candidate OMPs (Punt, 1993). However, the results obtained from an age-aggregated model were applied to provide TAC recommendations, because it was found that the VPA-based OMPs responded more to the noise than only to trend in the data, and therefore showed substantially larger inter-annual variability in catches with no compensatory gains in terms of either average catch or decreased risk (Punt, 1993).

This OMP had been chosen following thorough prior simulation testing (Punt, 1992, 1993), but in 1995 it became apparent that it was in need of revision, for two main reasons. First, the commercial CPUE on the west coast had not increased as much as predicted five years earlier, suggesting some mis-specification in the base case operating model which had been chosen in 1990 as the most appropriate representation of the hake resource dynamics (Geromont and Butterworth, 1997). The matter of changes in the fishing selectivity over time (as a result of the phasing out the illegal use of small-mesh net-liners in the late 1980's) was brought to light and needed to be taken into account (Geromont and Butterworth, 1998a), as this resulted in the CPUE series not providing a comparable index over the full 1978-1995 period for which detailed data had been collected from the local trawl fleet, and the Schaefer model no longer providing adequate predictions of resource trends. Secondly, general linear modelling (GLM) techniques applied to standardise the CPUE series suggested a lesser rate of recovery of the resource over recent decades than had coarser methods used earlier.

For these reasons, the hake TAC was held fixed for the years 1997 and 1998, while a revised OMP was being developed. In August 1998, the Sea Fishery Advisory Council (SFAC) adopted a revised OMP to provide recommendations for the west coast component of the hake TAC. This OMP is still in use. It is based on an  $f_{0.075}$  harvesting strategy coupled to a Fox production model (Geromont and Glazer, 1998). Although the OMP's Fox model is age-aggregated, the model used to assess the resource and provide the basis for testing the candidate OMPs was an age-structured production model which, in addition to commercial CPUE and survey abundance indices, was also fitted to commercial and survey catch-at-age data. To avoid the problems associated with the non-comparability of the CPUE series over time, the OMP omits the period during which the fishing selectivity is believed to have changed (i.e., over which net-liners were phased out) and uses only the pre-1984 and post-1991 CPUE data, treating them as independent series.

A Schaefer-based and an ASPM-based OMP were also tested during the initial development of this revised OMP. The Schaefer option was discarded because it did not perform satisfactorily, with initial catches rising too rapidly, causing resource depletion, followed by a drastic cut in TACs as a correction measure. The Fox-based OMP was chosen over the ASPM option because, although both performed satisfactorily and in a similar way, the high computation time required by the ASPM option would have limited the number of robustness tests performed.

The basis of the OMP evaluations that led to the choice of the current OMP for west coast hake are summarised in Appendix C1, the scientific document submitted to the SFAC in August 1998. This document, which contrasted alternative candidate OMPs, recommended that three main objectives be considered when deciding between the candidate OMPs:

- 1) a high probability for the resource to recover to MSYL within the next 10 years;
- 2) a low probability of a net decline in the spawning biomass over this 10-year period; and
- 3) a low probability of a decrease in TAC early in the 10-year period.

The Fox-model-based OMPs proposed were linked to harvesting strategies ranging from  $f_{0.05}$  to  $f_{0.15}$ , which provided different trade-offs between immediate TAC levels and longer-term improvements in resource abundance. At one extreme, the  $f_{0.05}$  option provided the largest short-term increase in catch, but the least longer-term increase in resource abundance; while at the other extreme, an  $f_{0.15}$  option resulted in a slight decrease in the TAC in the short-term, and allowed for the largest longer-term increase in resource abundance.

It was also shown that these candidate OMPs were relatively robust to a range of uncertainties in both the model structure and in the data (Geromont and Butterworth, 1998b, 1998c, 1998d). The robustness tests performed on the candidate OMPs are listed in Appendix C1. The factors with the greatest impact on anticipated performance of the candidate OMPs were a) the extent of variability in future hake recruitment, and b) future positive bias in CPUE coupled with an absence of future

research surveys. It was noted that in case b), the candidate OMPs could lead to a marked decrease in resource abundance over the next 10 years. Due to technical problems, research surveys on-board the *Africana* have taken place in only one year (1999) since the adoption of this OMP, although the surveys were subsequently conducted on-board the *Nansen* in 2000 and 2001 (these two data points are treated as a separate series, with a separate  $q$ , when implementing the OMP). It is therefore very important that the analysis of CPUE data does not overlook any factor that may be leading to enhanced fishing efficiency.

The data input to the OMP (see Tables 6.1 and 6.2) include (with year  $y$  being the year for which the TAC recommendation is made):

- i) the historic annual catches up to year  $y-1$ ,
- ii) the historic CPUE series from 1955 to 1977 (treated as an index of relative abundance),
- iii) the GLM-standardised (case  $\rho = 0.5$ ) CPUE series up to year  $y-2$  (updated annually), omitting the period in the 1980's during which the fishing selectivity is taken to have changed from smaller to larger fish and treating the resulting CPUE data (from 1978 to 1984 and from 1993 to year  $y-2$ ) as two separate indices of relative abundance,
- iv) the summer (from 1985 to year  $y-1$ ) and winter (from 1985 to 1990) research survey data, treated as relative abundance indices.

The formula which provides the TAC recommendation for the 1998 revised OMP is as follows (Geromont and Butterworth, 1998a; Geromont and Glazer, 1998):

$$TAC_y = \Delta TAC_{y-1} + (1 - \Delta) FOX_{y, f_{0.075}} \quad 12.1$$

where  $TAC_y$  is the TAC recommended for year  $y$ ,  $\Delta = 0.5$  is a control parameter which moderates the extent of the TAC annual variations and  $FOX_{y, f_{0.075}}$  is the estimated catch for year  $y$  corresponding to an  $f_{0.075}$  harvesting strategy according to the Fox surplus production model (Fox, 1970; see Fig. 1.4).

The  $\Delta$  of 0.5 was chosen to ensure relatively fast reaction to trends in recent data, while still keeping changes in TAC from one year to the next relatively small. The  $f_{0.075}$  harvesting strategy was chosen by the SFAC as constituting an appropriate trade-off between average annual catches and resource recovery.



### 12.1.1 TAC recommendation for 2003

From 100 000 tons in 1999, the west coast component of the hake TAC under the revised OMP has increased steadily up to 110 000 tons in 2002. The data input for the 2003 TAC recommendation are shown in Table 12.1, with the new or modified data (compared to the assessment in Chapter 6) in bold. In 2000, the *Africana*, the vessel normally used in the South African hake surveys, broke down. This is why the *Nansen* was used for the 2000 and 2001 west coast surveys. The OMP treats these two data points as a separate abundance index series and hence estimates a separate  $q$  for this *Nansen* series. The GLM-standardised CPUE is not, as for the series in the assessment in Chapter 6, for the three biggest companies only, but now includes data for all the companies. The catch in 2002 is assumed to be 107 thousand tons, and not the 2002 OMP's TAC recommendation of 110 000 tons. Indeed, for reasons discussed later, the overall TAC recommendation for 2002 was not increased as suggested by the OMP but maintained at its 2001 level for which the west coast component was 107 thousand tons. Thus 107 000 tons has been kept as the assumed catch level for 2002, but the application of the OMP formula for a recommendation for 2003 assumed a 2002 TAC equal to that recommended by the OMP application a year previously.

Computation of  $FOX_{2003,0.075}$  as set out above yields 105 292 tons. Thus, in terms of the revised OMP of equation 12.1 (after rounding to the nearest 1000 tons as is conventional), the 2003 TAC recommended for west coast hake is 108 000 tons, a decrease of about 2% compared to 2002 (MCM, 2002). This decrease follows from the downward trend in the CPUE index over the last four years (the 2001 CPUE value is the lowest over the whole 1978-2001 CPUE series), combined with the rather low 2002 survey biomass estimate.

To get an idea of what recommendations the OMP will likely provide in the near future, 'theoretical' 2004 and 2005 TAC recommendations were computed as follows. Given no further information in terms of CPUE and survey data (i.e., the observed CPUE and survey biomass estimates are set equal to the values predicted by the OMP's assessment model), and using the recommended  $TAC_{2003}$  as the catch for 2003, the TAC in 2004 is projected to be 107 000 tons. Similarly, if this TAC is taken to be the catch in 2004, the TAC in 2005 is projected to remain unchanged at 107 000 tons.

## 12.2 South coast *M. capensis* OMP

The need for a revised OMP for hake on the South African south coast arose with the development, in this region principally (relative to the total hake catch off this coast), of a longline

fishery for hake. Previously, the management of hake on the south coast was based upon aggregating over the two hake species (as it is still done for the west coast and Namibian stocks), with the justification for aggregating the two species based upon simulations which assumed that the species and age-selectivity of the fishery remained unchanged (Punt, 1992). These assumptions became invalidated on the south coast with the development of the longline fishery for hake which targets mainly older *M. capensis*.

The revised OMP for the south coast *M. capensis* component of the hake resource was adopted by the Consultative Advisory Forum (or CAF, the body that replaced the Sea Fishery Advisory Council in terms of a new Act of Parliament) in June 2000. It is of the same form as the one used for the west coast, based on a Fox-form age-aggregated production model but incorporating a  $f_{0.3}$  harvesting strategy (the smoothing parameter  $\Delta$  is kept at 0.5 as for the west coast hake OMP) (Geromont and Butterworth, 2000b). It is implemented by using the offshore fleet CPUE data (for *M. capensis* only, based on splitting the catch by species according to depth) and research survey biomass estimates of *M. capensis* (i.e., the assessment model within the OMP ignores the mixed-fleet nature of the fishery).

The objectives of the OMP for the south coast *M. capensis* resource were somewhat different than in the case of the west coast hake resource. Indeed, the south coast shallow-water Cape hake resource was (and still is – see Chapter 7) estimated to be in a healthy state, well above the level estimated to yield MSY, and a resource ‘rebuilding to MSY level’ strategy was not required for this component of the overall hake resource. The choice of a candidate OMP, therefore, involved a trade-off between catch and catch rate, rather than a trade-off between the average annual catch and the extent of resource recovery, as had been the case for the west coast OMP.

Representatives of the hake fishing associations indicated that economic viability required CPUE levels to be maintained at their average value over the 1990’s; this entailed keeping the resource abundance somewhat high, with a consequent reduction in the risks associated with other uncertainties when making recommendations for TACs for this fishery. The main consideration therefore in selecting an OMP for the south coast *M. capensis* resource became trying to keep catch rates relatively stable over the next few years. The  $f_{0.3}$  harvesting strategy option was chosen as it projected roughly steady levels of both catch and catch rate over the next few years. The basis of the OMP evaluations that led to this choice of OMP are summarised in more detail in Appendix C2, which includes two documents presented to the CAF and a list of robustness tests performed.

### 12.2.1 TAC recommendation for 2003

Table 12.2 shows the data input to the OMP, with new or modified data (compared to the assessment in Chapter 7) in bold. The data include i) the series of annual catches (from 1967 to 2002), with the 2002 catch assumed equal to the TAC for that year, ii) the historic offshore CPUE series (from 1969 to 1977), iii) the GLM-standardised CPUE data (from 1978 to 2001) and the spring and autumn survey biomass estimates for the 0-500 m depth range. The GLM-standardised CPUE is not, as for the series in the assessment in Chapter 7, for the three biggest companies only, but now includes all the data. Unlike the more recent data, the historic CPUE data correspond to both *M. capensis* and *M. paradoxus* combined, as these data cannot be disaggregated by species.

Computation of  $FOX_{2003,0.3}$  yields 24 003 tons. Thus, the 2003 TAC recommended for south coast *M. capensis* is 25 000 tons, which is the same as for 2002 (MCM, 2002).

In the same manner as for the west coast, to get an idea of what recommendations the OMP might provide in the near future, 'theoretical' 2004 and 2005 TAC recommendations were computed as follows. Given no further information in terms of CPUE and survey data (i.e., the observed CPUE and survey biomass estimates are set equal to the values predicted by the OMP's assessment model), and using the recommended  $TAC_{2003}$  as the catch for 2003, the TAC in 2004 is projected to be 25 000 tons. Similarly, if this TAC is taken to be the catch in 2004, the TAC in 2005 is projected to remain unchanged at 25 000 tons.

### 12.3 South coast *M. paradoxus*

As mentioned in Chapter 8, an attempted separate assessment for *M. paradoxus* on the south coast did not yield sensible results, given that the *M. paradoxus* on the south coast is likely a component of the west coast *M. paradoxus* stock (Geromont and Butterworth, 1999a). In the absence of an OMP for this component of the resource, the TAC contribution for south coast *M. paradoxus* for 2000 was computed as an *ad hoc* proportional addition to the west coast OMP output; this assumes that changes in the south coast *M. paradoxus* allowable catch should match trends in west coast hake abundance. This proportion was based upon the average ratio of the catches from these two components of the overall resource for the preceding five years (see Appendix C2). This method was presented to, and accepted by, the CAF at its June 2000 meeting, and was meant to be applied for the following three years (or until a possible earlier OMP revision).

In 2001, however, some concerns arose about this method, as this averaged proportion was noted to be appreciably higher for the five most recent years compared to the previous ten years (Fig. 12.1). For this reason, the TAC in 2001 was kept fixed at the 2000 level and not increased by 3 thousand tons as the OMP outputs at that time suggested (the increase arising from the OMP-based recommendation for the combined-species west coast component of the resource).

Fig. 12.2 shows the *M. paradoxus* spawning biomass projected for 20 years under a selection of constant catch strategies for six scenarios. These are the 'West Coast only' and the 'Both Coasts' assessments, for each of the three shapes of the selectivity function (see Chapter 8). For each of the cases, the catches were selected (to the nearest thousand tons) as a) the one keeping the spawning biomass constant over the last 10 years of the projection period, b) 5 thousand tons above this value and c) 5 thousand tons below this value. These (case a)) longer-term replacement yield values are some 20, 28 and 28 thousand tons larger for the 'Both Coasts' than for the 'West Coast only' assessments for the 'No slope', 'Slope of 0.2' and 'Slope of 0.4' cases respectively.

Probably these longer-term replacement yield estimates provide the most appropriate guidance (until the development of an OMP for the *M. paradoxus* stock) as to what extent the west coast OMP output for the TAC should be increased to take account of *M. paradoxus* on the south coast. The results vary from 20 to 28 thousand tons, being larger for greater values of selectivity slope. Since this slope seems likely to be greater than zero, both because older fish tend to be found deeper (and beyond trawlers' range) and because this results in more realistic *M* values (see Table 8.7), one might conclude that the appropriate correction is closer to the upper rather than the lower value bounding this range.

### 12.3.1 TAC recommendation for 2003

As indicated above, the assessment models for the South African *M. paradoxus* resource suggest that the south coast component of the total sustainable yield of the *M. paradoxus* resource probably lies towards the upper end of the 20 000 – 28 000 tons range. The MCM Demersal Working Group therefore recommended that the 2003 TAC for the west coast should be adjusted by 25 000 tons to incorporate the portion of the *M. paradoxus* resource on the south coast (MCM, 2002).

## 12.4 Summary of TAC recommendations for 2003

The direct applications of the adopted OMPs for the west coast *Merluccius* species and south coast *M. capensis* components for 2003 suggest a relatively small decrease of 2 000 tons in the contribution of those two components to the global TAC compared to 2002. However, the *ad hoc* adjustment for south coast *M. paradoxus* used in 2000 and 2001 appears to have been too large, and the MCM Demersal Working Group recommended that the contribution of this component to the global TAC be reduced by 6 000 tons from the 2002 value of 31 000 tons. This would have resulted in the global TAC for 2003 being decreased by 8 000 tons, a reduction that would have been disruptive to the hake industry. Because projections (given no further information in terms of CPUE and survey data) indicate that the global TAC recommendations from the OMPs are expected to be stable over the next three years, it was recommended by the Working Group that the reduction be spread over the next three years to lessen the negative impact on the industry, unless further data forthcoming over that period indicate to the contrary (MCM, 2002). The global TAC for 2003 subsequently approved by the Minister of Environmental Affairs and Tourism reflected a decrease by 2 000 tons to 164 000 tons.

**Table 12.1:** Total annual catches for the period 1955 to 2002, together with historic ('old') and GLM-standardised CPUE series with ( $\rho=0.5$ ) correction for by catch correlation (Glazer, 2002a) and survey abundance data (with associated standard errors) for west coast hake (Div. 1.6). Data in bold have been updated from those used in the assessment in Chapter 6 (see Chapter 6 for data sources).

Year	Total annual catch	CPUE	CPUE GLM	Summer survey		Winter survey		Nansen summer survey	
		ICSEAF 1.6 (tons/day)	$\rho = 0$ (kg/min)	Biomass	(s.e.)	Biomass	(s.e.)	Biomass	(s.e.)
1955	115.400	17.31							
1956	118.200	15.64							
1957	126.400	16.47							
1958	130.700	16.26							
1959	146.000	16.26							
1960	159.900	17.31							
1961	148.700	12.09							
1962	147.600	14.18							
1963	169.500	13.97							
1964	162.300	14.60							
1965	203.000	10.84							
1966	195.000	10.63							
1967	176.700	10.01							
1968	143.600	10.01							
1969	165.100	8.62							
1970	142.500	7.23							
1971	202.000	7.09							
1972	243.933	4.90							
1973	157.782	4.97							
1974	123.000	4.65							
1975	89.617	4.66							
1976	143.894	5.35							
1977	102.328	4.84							
1978	101.140		<b>12.877</b>						
1979	92.704		<b>14.156</b>						
1980	101.538		<b>13.224</b>						
1981	100.678		<b>12.908</b>						
1982	85.970		<b>12.324</b>						
1983	73.677		<b>14.235</b>						
1984	88.410		<b>14.944</b>						
1985	99.590			231.134	(38.629)	398.193	(53.557)		
1986	109.091			296.044	(42.744)	286.374	(32.737)		
1987	104.010			352.874	(57.004)	270.946	(46.409)		
1988	90.131			212.036	(31.640)	267.798	(64.461)		
1989	84.896					627.147	(134.761)		
1990	78.918			512.299	(98.448)	357.089	(55.307)		
1991	85.521			384.147	(83.393)				
1992	86.280			319.533	(37.493)				
1993	98.110		<b>14.490</b>	395.642	(51.976)				
1994	102.770		<b>13.800</b>	440.117	(68.667)				
1995	94.716		<b>12.646</b>	462.707	(86.365)				
1996	91.364		<b>13.745</b>	506.857	(84.235)				
1997	92.328		<b>13.411</b>	752.837	(115.622)				
1998	109.297		<b>16.496</b>						
1999	86.489		<b>12.464</b>	761.736	(123.905)				
2000	<b>101.714</b>		<b>13.070</b>					326.994	(36.816)
2001	<b>93.940</b>		<b>11.650</b>					466.131	(41.683)
2002	<b>107.000</b>			<b>380.202</b>	<b>(38.701)</b>				

**Table 12.2:** Total annual catches for the period 1967 to 2002, together with historic (ICSEAF Div. 2.1+2.2) and GLM-standardised CPUE series (Glazer, 2002b) and survey abundance data (with associated standard errors) for south coast *M. capensis*. The historic CPUE series (1969-1977) is for *M. capensis* and *M. paradoxus* combined. Data in bold have been updated from those used in the assessment in Chapter 7 (see Chapter 7 for data sources).

Year	Total annual catch	ICSEAF	GLM CPUE	Spring survey		Autumn survey	
		CPUE Div. 2.1+2.1 (tons/hr)	(kg/min)	(0-500m) Biomass	(s.e.)	(0-500m) Biomass	(s.e.)
1967	13.302						
1968	19.614						
1969	24.202	1.23					
1970	18.008	1.22					
1971	21.023	1.14					
1972	31.320	0.64					
1973	40.303	0.56					
1974	50.931	0.54					
1975	36.724	0.37					
1976	29.103	0.40					
1977	20.134	0.42					
1978	20.271		4.264				
1979	23.230		4.747				
1980	21.525		5.262				
1981	21.870		4.857				
1982	27.114		5.578				
1983	24.216		6.523				
1984	23.638		7.189				
1985	31.500		9.050				
1986	26.085		7.727	202.871	(278.450)		
1987	25.413		7.482	162.282	(17.512)		
1988	26.792		7.056			165.184	(21.358)
1989	34.505		7.842				
1990	36.016		9.329				
1991	31.076		8.739			273.897	(44.363)
1992	26.957		7.700			137.798	(15.317)
1993	20.708		6.240			156.533	(13.628)
1994	22.427		7.320			158.243	(23.607)
1995	22.087		6.509			233.359	(31.862)
1996	28.462		7.173			243.934	(25.035)
1997	23.233		6.012			182.157	(18.601)
1998	18.046		5.479				
1999	22.873		5.889			190.864	(14.929)
2000	30.798		7.724				
2001	28.887		7.888	133.533	(20.845)		
2002	25.000						

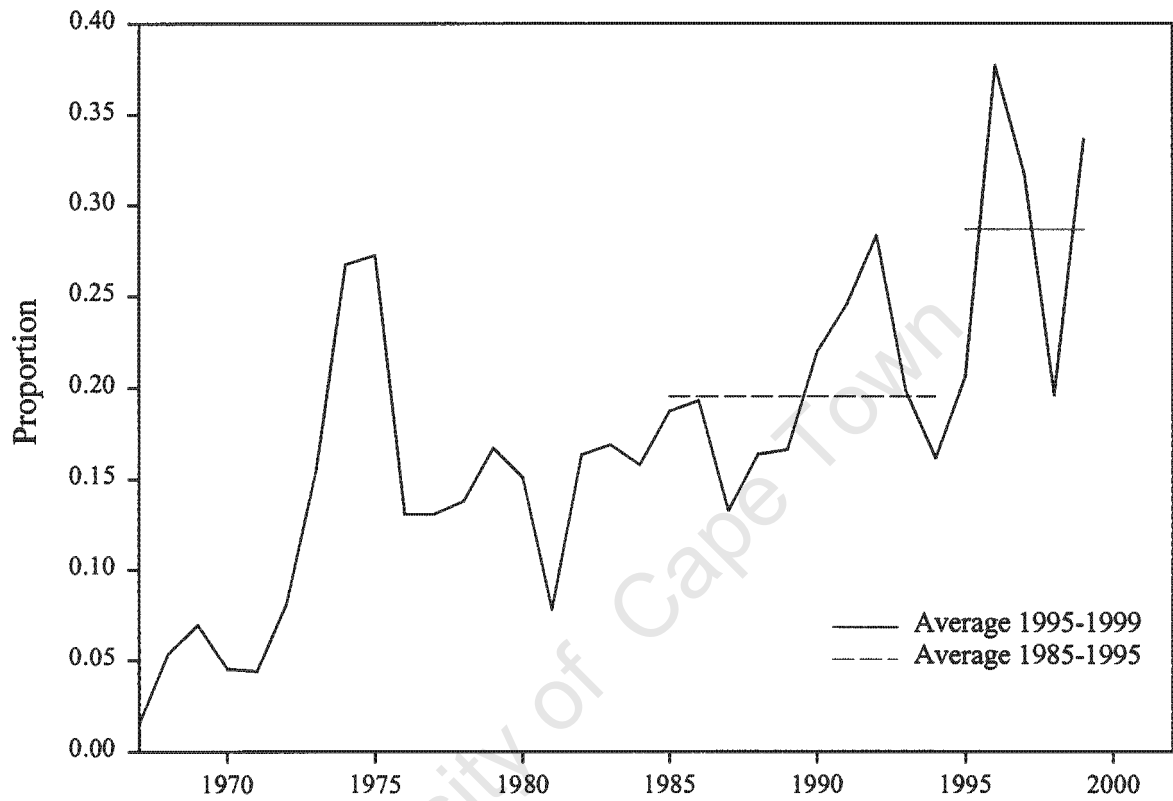
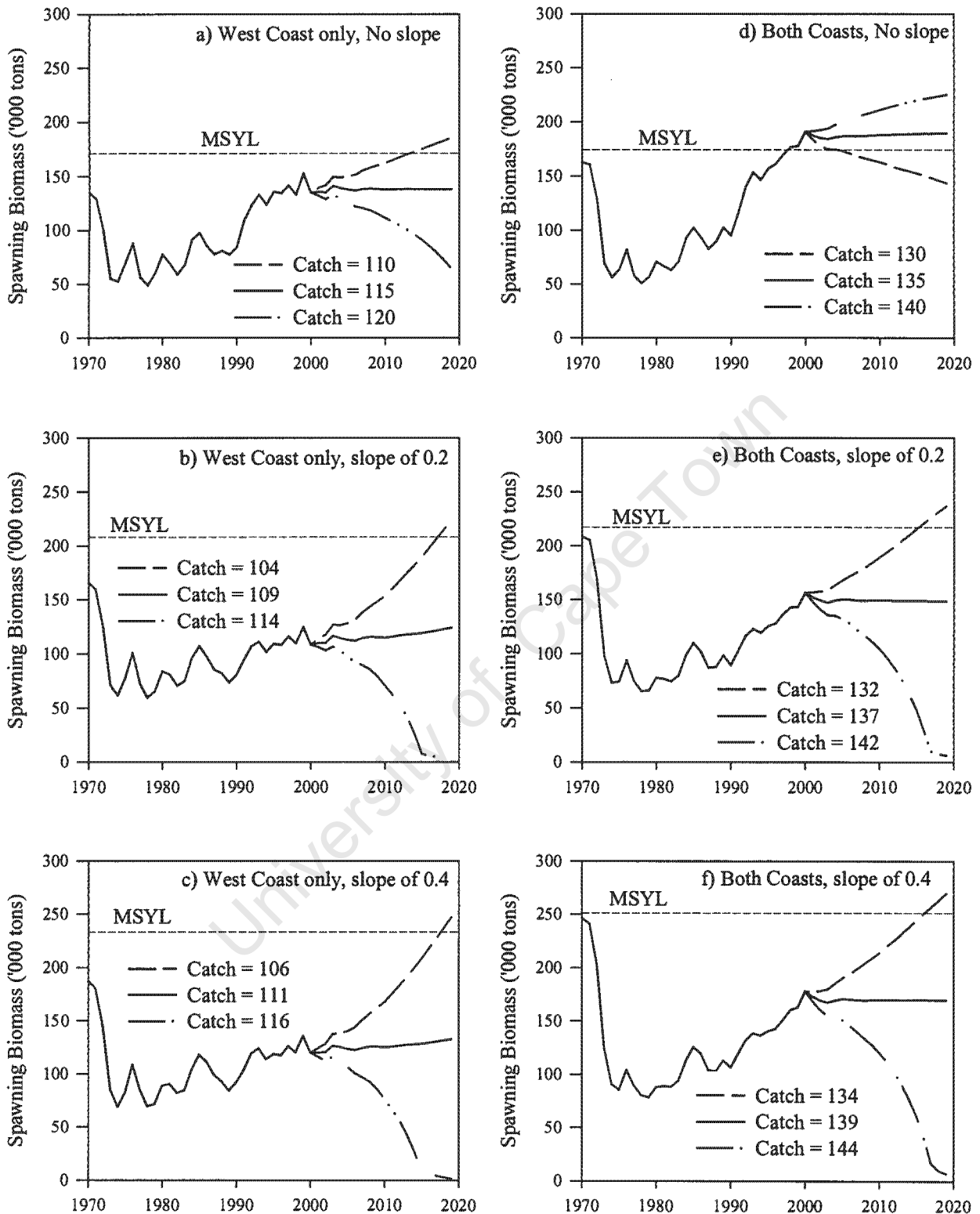


Fig. 12.1: Annual trend in south coast *M. paradoxus* catch as a proportion of the total west coast hake catch.





**Fig. 12.2:** Projected spawning biomass under selected constant catch strategies, for the 'West Coast only' component of the *M. paradoxus* resource (a-c) and 'Both Coasts' (d-f), for each of the three cases described in the text. The catches are in thousands of tons. MSYL is also shown.

## 13 Overall conclusions and future research

Over the last three decades, management has achieved some recovery in the hake stocks off Namibia and South Africa, although this recovery has proved to be less rapid than had been predicted earlier, and the stocks are less productive than previously thought (see Chapter 9).

Some key questions concerning the assessments of these resources remain: why is recruitment variability estimated to be so low, natural mortality to be so high, and steepness, selectivity and the multiplicative bias for survey estimates of abundance to be so different for the different stocks? Possible bias in age readings might provide an explanation for some of these features of the assessments. Also the Namibian and the South African west coast assessments still ignore the fact that the hake resource consists of two species. Given their potentially different dynamics and varying contributions to the overall catch over time, separating the two species in future assessments might lead to more realistic parameter estimates and maybe more consistency throughout the resource.

The current assessments and operational management procedures for the southern African hake provide a reliable basis to manage this resource for the near future. The OMP basis used to provide TAC recommendations for this resource over recent years has demonstrated its intended adaptive behaviour in responding to new data forthcoming over time. However, some important questions have been raised (see Chapter 9), which future research will need to attempt to solve. Some recommendations to address these problems, as well as suggestions to improve the current assessments and management of the resource are listed below.

### 13.1 Assessments and their uncertainties

#### 13.1.1 Fit the model to length distribution data

One of the first aims for future assessments of the southern African hake resource is to move towards length-based, rather than age-based, fitting of the models. The reason for attempting to use the length data directly is that regular ageing of the hake otoliths has not occurred because of staffing difficulties at governmental agencies and, in some cases, ageing data are available for only a very few years. Furthermore, errors in ageing are postulated as one of possible causes for the unrealistic values estimated in some cases for natural mortality, as well as the surprisingly low levels of recruitment fluctuations observed (by confounding the detection of stronger and weaker year-classes in the age-

composition data). Furthermore, age data might not be available in the future due to diminished scientific capacity at governmental agencies.

Thus, to take account of as much data as possible as may relate to the age structure of the population, one desirably wants to try to utilise the catch-at-length data directly for both surveys and commercial catches. This will involve fitting the assessment model to the length, rather than the age distribution of commercial and survey catches. Appendix B1 sets out how catch-at-length information from the fishery can be taken into account in estimating the population model parameters (Brandão *et al.*, 2002). Initially, and unless there is evidence to the contrary, the somatic growth curve and the extent of variability about it would be assumed not to change over time for this approach.

Models using spatially disaggregated (or not) length-based assessment methods, such as MULTIFAN-CL (for example, Fournier *et al.*, 1998), would be useful to consider.

### 13.1.2 Move to species-disaggregated assessment and management

Another problem of the current assessment and management of the hake resource is that in some cases (off the Namibian and South African west coasts) *M. capensis* and *M. paradoxus* are still treated as a single species. Treating the two species as a single stock could confuse the interpretation of the data and lead to management problems, such as over-harvesting of one species and under-utilisation of the other, and it is therefore of high priority to first assess the two species separately and then develop separate OMPs for these species. This is becoming of particular consequence due to the growing longline component of the fishery which targets large *M. capensis* preferentially, in contrast to the trawl fishery which utilises both species.

For the South African stock, it is planned to replace the current hake TAC recommendation process (a species-combined west coast OMP, an *M. capensis* south coast OMP, and an *ad hoc* adjustment for south coast *M. paradoxus*) by OMPs for *M. capensis* on the south and west coasts separately, and an OMP for *M. paradoxus* for both south and west coast combined. Similarly, separate OMPs for *M. capensis* and *M. paradoxus* are planned for the Namibian resource.

The major problem in conducting species-disaggregated assessments of hake is that although the two species are distinguished in the research survey trawls, they are not in the commercial catches. In Namibia, however, some species-disaggregated data have been collected by observers on-board commercial vessels since 1997, and hopefully such a program might be instituted by MCM in the future for the South African fishery.

Currently for the South African stocks, the split by species of the historic catches is pre-specified externally to the model, based on the depth distribution of the catches (Geromont *et al.*,

1995b). For years when depth information is not available, a constant proportion of the two species in the catches is assumed. This method, however, does not allow for the effect of a possible differential exploitation on the two species. Indeed, one species might have been exploited more heavily than the other, possibly affecting recruitment and resulting in the proportion of the two species in the catches changing over time. It has therefore been suggested (BENEFIT, 2000) that historic catches should rather be split by species internally within the assessment model, assuming a constant relative selectivity of the two species over time, i.e., keeping the ratio of fishing mortality (rather than catch) for each species constant, by assuming that the fishery didn't change its (distributional) behaviour over time. A problem arises with this method in the Namibian case because, since independence in 1990, vessels have been restricted to waters deeper than 200 m, which would have an effect on the relative selectivity of the two species. Sensitivity to different assumptions will have to be tested in this case.

### **13.1.3 Use Bayesian approach to estimate assessment precision**

Currently, the uncertainty in the parameters estimated in the hake assessments is Hessian-based (therefore approximate only), while bootstrapping is used to quantify the uncertainty of the projected parameters in the Namibian hake OMP tests. Some sensitivity tests have also been conducted (particularly in the Namibian hake OMP context) to investigate the implications of uncertainty associated with the model structure. However, the use of the Bayesian approach, implemented in ADMB via the Markov Chain Monte Carlo method, would facilitate representing and taking fuller account of the uncertainties related to parameter estimation and perhaps also model structure (Punt and Hilborn, 2001).

A major advantage of this approach is the ability to incorporate prior information on the parameter estimates, such as for  $M$  or  $h$  for which some current estimates seem unrealistic. In this way, information obtained from historical experience with other stocks, as well as from expert knowledge about the biological parameters and processes can be taken into account. This approach would also resolve the  $\sigma_R$ -input problem (though only partially, as a prior for  $\sigma_R$ -input would need specification), and also allow recruitment variability across the full time series.

### **13.1.4 Allow for time-series modelling of selectivity-at-age**

To date, only simple deterministic trends in selectivity have been included in the southern African hake assessments. In the Namibian case for example, the selectivity is simply taken to differ pre- and post-independence (due to the exclusion of vessels in waters shallower than 200 m after

1990), with a trend over time (towards selecting younger fish) in the first period. Future assessments should allow for the behaviour of the fishers to vary over time as regard to selectivity, for marketing and other reasons. Butterworth, Ianelli and Hilborn (in press) present a time-series methodology to incorporate a temporal variability in the selectivity-at-age in ASPM assessments. This approach would allow a more objective basis for accounting for selectivity changes, where at the moment, the choices of periods for constant and then linearly changing selectivity are somewhat arbitrary. This approach could be implemented using the ADMB package.

### **13.1.5 Incorporate temporal changes in somatic growth**

For some species, the weight-at-age relationship can vary considerably from one cohort to the next. This can potentially have an important impact on the assessments, for example if the selectivity is assumed to be a function of age (in case where it is actually a function of length).

Sampling data from the various commercial fisheries for hake need to be examined to check whether it is justified to assume that the somatic growth curve is constant over time. If the results indicate that the level of variability is of sufficient magnitude to make an appreciable impact on the assessment results, this will have to be taken into account in future assessments.

### **13.1.6 Explanation for different multiplicative biases for swept-area survey estimates of abundance**

A further surprising feature of existing hake assessments (as discussed in Chapter 9) is the appreciable differences, from area to area, in the estimated survey multiplicative bias coefficients  $q$ . The models suggest that swept-area estimated from the research surveys substantially underestimate the resource abundance off Namibia, while overestimating it off the South African south coast. If these differences are real, rather than artefacts of mis-estimation of  $M$  or the selectivity functions related to ageing errors (i.e., indicative of perhaps substantial bias in some of the current assessments), it is possible that differences in substrates between the different areas could explain these results. An examination of possible changes in substrate proportions and hence in the trawlable portion of each area needs to be conducted.

### 13.1.7 Include additional CPUE information

Hake assessment models are at present fitted only to offshore trawl CPUE information. Consideration needs to be given to the possibilities of using CPUE data for the trawl fleet operating inshore on the south coast, as well as CPUE data for the longlining fleet on both the south and west coasts and off Namibia. It is possible that these series will give a different perspective on the status of the resource, because each fleet has a different selectivity and target different areas.

### 13.1.8 Develop multi-species models

It has been shown (for example Payne *et al.*, 1987; Punt *et al.*, 1992) that the most important form of predation on Cape hakes is interspecific (hake-on-hake) predation and to a lesser extent cannibalism. For that reason, inter- and intraspecific predations are considered to be a very important factors in regulating hake abundance off Namibia and South Africa and a multi-species model-estimation procedure which takes explicit account of the high levels of interspecific predation and cannibalism should be developed, perhaps by updating and extending the type of models developed by Punt and Hilborn (1994) and Punt and Butterworth (1995).

### 13.1.9 Sex-disaggregation of assessments

Geromont *et al.* (1995a) noted that, on the south coast, the estimated female proportion in the longline catches greatly exceeds that for the trawl catch; in contrast, on the west coast, similar proportions of females were caught by the longline and the trawl fleets. This differential selectivity might affect the sex-structure of the population, which could have consequences for recruitment as this would likely depend primarily on egg production and hence the female component of the spawning biomass. Furthermore, Punt and Leslie (1991) note that as the estimates of age and size at maturity for males and females are so different, there is no clear justification for pooling the data for males and females for assessment purposes, except that commercial catch information is not readily available in a sex-disaggregated form. Although of lesser priority than some of the other points mentioned above, sex-disaggregated assessments should be pursued to examine the effect of this sex-specific selectivity.

Fig. 1.2 shows that there are appreciable differences in growth between males and females, especially at older ages, in fact more so than between species. Routine application of age-length keys to obtain catch-at-age proportions is conducted without attention to difference in growth between sexes; but sex-differential growth means that larger sizes of males are not well represented in the

catch. This could confound estimates based on catch-at-age data developed from a sex-aggregated age-length key, which might consequently underrepresent the number of older hake present, and this may have some effect on the estimates of  $M$ .

### 13.1.10 Allow for interchange between stocks

It has been suggested that populations of *M. paradoxus* off Namibia and South Africa actually form a single stock (Burmeister, 2000a). This hypothesis is based on the facts that no genetic differences between the two stocks have been observed (Grant *et al.*, 1987, 1988; Becker *et al.*, 1988) and that *M. paradoxus* spawning has not been recorded off Namibia (Gordoa *et al.*, 1995). Similarly, Le Clus (MCM, pers. comm) suggests that *M. capensis* on the South African west and south coasts, which are currently treated as two different stocks, actually form a single stock. Future assessments should investigate the effect of a possible interchange between what are currently treated as separate stocks.

A natural step in future work would be to formally link the different hake stocks via some form of meta-analysis. Information about the different stocks would be related via some distribution rather than treating each stock as a completely isolated and independent unit. Migration could also be build into such an analysis. However, before carrying such a joint assessment with common parameters, the differences between the stocks must be explored carefully in order to understand whether these differences are real or rather reflect different area-specific biases. A meta-analysis would not be appropriate if such biases are appreciable because it rests on the assumption that differences arise only from real natural variability.

## 13.2 Operational Management Procedures

The first priority in terms of the future management of the hake stocks is, once the appropriate operating models have been constructed, to develop species-split OMPs: for the South African stock, OMPs for *M. capensis* on the south and west coasts separately, and an OMP for *M. paradoxus* for both south and west coast combined; and for the Namibian stock, separate OMPs for *M. capensis* and *M. paradoxus*. These OMPs will have to be robust to the key uncertainties about the model structure and the data, as with the current OMPs. The associated operating models, which would be used in testing the candidate OMPs, might incorporate some of the features discussed above.

As mentioned above, species-split OMPs are a priority in terms of the management of the hake resource, but how practical would species-split TACs be? It would be very difficult to manage the fishery using separate species-specific TACs, but a “pseudo species-specific” management could be implemented by balancing allocation among sectors with the productivity of the component of the resource they target. In this light, the effects of greater flexibility in implementation, such as allowing TACs each year to be over- or under-caught by up to  $x\%$ , should be investigated. Also, consideration should be given as to what extent monitoring data on the catch species-composition (from on-board observers) should be an input to the OMPs. Indeed, at the moment for the south coast *M. capensis* OMP, the splitting of the catch by species is based on the depth distribution of the species, and the use of direct observational data from on-board observers should be discussed.

Furthermore, future OMPs should:

### **13.2.1 Incorporate socio-economic factors**

The comparison of alternative candidate OMPs for scientific advice for the management of the hake resource off southern Africa is in terms of performance statistics. To date these performance statistics have, so far as the hake resources off southern Africa are concerned, been based only on biological and ‘operational’ measures, such as expected catches and projected depletion levels. These measures need to be extended to incorporate economic parameters. The existing process to test candidate OMP already provides the necessary framework for this, so that including economic considerations should be straightforward if the pertinent quantitative inputs are made available. Examples of economic factors which could be taken into consideration include the proportion of the TAC caught by trawling vs. longlining, and the appropriate number of vessels in the fishery.

### **13.2.2 Incorporate age data**

The two South African OMPs in use at the moment for hake are both based on a dynamic age-aggregated production model, i.e., they do not take catch-at-age information into consideration as is the case with the current Namibian OMP, based on an ASPM (see Chapter 11). Consideration should be given to include at least some age-data in the future South African OMPs.



### 13.2.3 Consider increasing the weight of recent data

A concern with the current OMPs is that they work with considerable historic data, so that each new year's data has a proportionately lesser effect on the estimates and resulting TAC recommendations. Upweighting of recent data needs to be considered to ensure that the OMP will react in time to possible sudden changes in resource dynamics (e.g., a series of poor year classes). On the other hand, more weight on the more recent data will increase the likelihood of greater inter-annual fluctuations in the TAC and might result in a procedure adjusting more to noise in the data than to true underlying trends.

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## References

- Anon. 1997. Proceedings of an International Workshop on the Research and Management of Hake in Namibian Waters, Swakopmund, Namibia, 13-17 October 1997. Namibian Ministry of Fisheries and Marine Resources internal report. 233pp.
- Andrew P.A. 1986. Dynamic catch-effort models for the southern African hake populations. *Rep. Benguela Ecol. Program. S. Afr.* 10. 248pp.
- Andronov V.N. 1987. Daily feeding rhythm and daily rations of Cape hakes *Merluccius capensis* Castelnau in the Namibian area. *Colln scient. Pap. int. Commn SE. Atl. Fish.* 14(1): 39-50.
- Babayan V.K., Dubrovin B.I., Kolarov P., Prodanov K., Vaske B. and Wysokiński A. 1985. Assessment of the total allowable catch of Cape hakes in Divisions 1.3 + 1.4 and 1.5. *Colln scient. Pap. int. Commn SE. Atl. Fish.* 12(1): 31-37.
- Babayan V.K., Kolarov P., Prodanov K., Vaske B. and Wysokiński A. 1986. Stock assessment and catch projection for Cape horse mackerel in ICSEAF Divisions 1.3 + 1.4 + 1.5. *Colln scient. Pap. int. Commn SE. Atl. Fish.* 13(1): 65-69.
- Babayan V.K., Kolarov P., Vaske B., Vasilyev D. and Wysokiński A. 1987. TAC estimates for 1987 for Cape hakes in Divisions 1.3 + 1.4 and 1.5. *Colln scient. Pap. int. Commn SE. Atl. Fish.* 14(1): 51-57.
- Badenhorst A. 1988. Aspects of the South African longline fishery for kingklip *Genypterus capensis* and the Cape hakes *Merluccius capensis* and *M. paradoxus*. *S. Afr. J. mar. Sci.* 6: 33-42.
- Badenhorst A. and Smale M.J. 1991. The distribution and abundance of seven commercial trawlfish from the Cape south coast of South Africa, 1986-1990. *S. Afr. J. mar. Sci.* 11: 377-393.
- Baranov F.T. 1918. On the question of the dynamics of the fishing industry. *Nauch. Issled. Ikhtiol. Inst. Izv.* 1: 81-128 (In Russian).
- Becker I.I., Grant W.S., Kirby R.W. and Robb F.T. 1988. Evolutionary divergence between sympatric species of southern African hakes, *Merluccius capensis* and *M. paradoxus*. 2. Restriction enzyme analyses of mitochondrial DNA. *Heredity.* 61: 21-30.

- Beddington J.R. and Cooke J.G. 1983. The potential yield of fish stocks. *FAO Fish. Tech. Rep.* 242. 47pp.
- BENEFIT 2000. Report of the BENEFIT stock assessment workshop. University of Cape Town. 20 – 24 November 2000. BENEFIT Programme, Swakopmund. 53pp.
- Beverton R.J.H. and Holt S.J. 1957. *On the dynamics of exploited fish populations*. Fisheries Investment Series 2, Vol. 19, U.K. Ministry of Agriculture and Fisheries, London. 533pp.
- Booth A.J. and Hecht T. 1998. Changes in the Eastern Cape demersal inshore trawl fishery between 1967 and 1995. In *Benguela Dynamics*. Pillar S.C., Moloney C.L., Payne A.I.L. and F.A. Shillington (Eds). *S. Afr. J. mar. Sci.* 19: 341-353.
- Botha L. 1971. Growth and otolith morphology of the Cape hakes *Merluccius capensis* Cast. and *M. paradoxus* Franca. *Investl Rep. Div. Sea Fish. S. Afr.* 97. 32pp.
- Botha L. 1973. Migrations and spawning behaviour of the Cape hakes. *S. Afr. Shipp. News Fishg Ind. Rev.* 28(4): 62-67.
- Botha L. 1980. The biology of the Cape hakes *Merluccius capensis* Cast. and *M. paradoxus* Franca in the Cape of Good Hope area. PhD thesis. University of Stellenbosch. 182pp.
- Botha L. 1985. Occurrence and distribution of Cape hakes *Merluccius capensis* Cast. and *M. paradoxus* Franca in the Cape of Good Hope area. *S. Afr. J. mar. Sci.* 9: 327-357.
- Botha L. 1986. Reproduction, sex ratio and rate of natural mortality of Cape hakes *Merluccius capensis* Cast. and *M. paradoxus* Franca in the Cape of Good Hope area. *S. Afr. J. mar. Sci.* 4: 23-35.
- Boyd P.A., Hewitson J.D., Kruger I. and Le Clus F. 1985. Temperature and salinity trends off Namibia from August 1982 to August 1984. *Colln scient. Pap. int. Commn SE Atl. Fish.* 12(1): 53-58.
- Boyer D.C., Boyer H.J., Fossen I. and Kreiner A. 2001. Changes in abundance of the northern Benguela sardine stock during the decade 1990-2000, with comments on the relative importance of fishing and the environment. In: *A Decade of Namibian Fisheries Science*. Payne, A.I.L., Pillar S.C. and Crawford R.J.M. (Eds.). *S. Afr. J. mar. Sci.* 23: 67-84.

- Brandão A. and Butterworth D.S. 2001. Effect of incorporation of vessel factors in the GLM analyses of the CPUE data for Namibian hake. Unpublished report, BENEFIT Programme, Swakopmund. BEN/NOV01/NH/1b. 9pp.
- Brandão A., Butterworth D.S. and Voges L. 2001. An updated application of GLM analyses to the CPUE data for Namibian hake. Unpublished report, NatMIRC, Namibia. HWG/WkShop/2001/Doc.4. 26pp.
- Brandão A., Butterworth D.S., Watkins B.P. and Staveres L. 2002. An updated assessment of the toothfish (*Dissostichus eleginoides*) resource in the Prince Edward Island vicinity and extensions taking commercial catch-at-length data into account. Unpublished report, CCAMLR. WG/FSA/02-76. 23pp.
- Burmeister L.-M. 2000a. A summary of the distribution of *M. paradoxus* in the Benguela. Unpublished report, BENEFIT Programme, Swakopmund. BEN/NOV01/NH/4a. 3pp.
- Burmeister L.-M. 2000b. Evaluation of efficiency of alternative stratification strategies of biomass estimates for the hake (*Merluccidae*) off Namibia. Unpublished report, BENEFIT Programme, Swakopmund. BEN/NOV00/NH/2a. 16pp.
- Burmeister L.-M. 2001. Depth-stratified density estimates and distribution of the Cape hake *Merluccius capensis* and *M. paradoxus* off Namibia deduced from survey data, 1990-1999. In: *A Decade of Namibian Fisheries Science*. Payne, A.I.L., Pillar S.C. and Crawford R.J.M. (Eds.). *S. Afr. J. mar. Sci.* **23**: 347-356.
- Butterworth D.S. and Andrew P.A. 1984. Dynamic catch-effort models for the hake stocks in ICSEAF Divisions 1.3-2.2. *Colln scient. Pap. int. Commn SE Atl. Fish.* **11**(1): 29-58.
- Butterworth D.S., Bergh M.O., Andrew P.A. 1986. A comparison of dynamic catch-effort model and VPA assessments for the hake stock in ICSEAF Divisions 1.3-1.6. *Colln scient. Pap. int. Commn SE. Atl. Fish.* **13**: 131-165.
- Butterworth D.S., Cochrane K.L. and De Oliveira J.A.A. 1997. Management procedures: a better way to manage fisheries? The South African experience. In *Global Trends: Fisheries Management*. Pikitch, E.K., Huppert D.D. & Sissenwine M.P. (Eds). American Fisheries Society Symposium **20**. Bethesda, Maryland, U.S.A.: 83-90.

- Butterworth D.S. and Geromont H.F. 2001. Evaluation of a class of possible Interim Management Procedures for the Namibian hake fishery. In: *A decade of Namibian Fisheries Science*. Payne, A.I.L., Pillar S.C. and Crawford R.J.M. (Eds). *S. Afr. J. mar. Sci.* **23**: 357-374.
- Butterworth D. S., Ianelli J. N. and Hilborn R. In press. A statistical model for stock assessment of southern bluefin tuna with temporal changes in selectivity. *S. Afr. J. mar. Sci.* **24**
- Butterworth D.S. and Punt A.E. 1999. Experiences in the evaluation and implementation of Management Procedures. *ICES J. Mar. Sci.* **56**: 985-998.
- Butterworth D.S., Punt A.E., Plaganyi E.E. and Rademeyer R.A. 2001. An updated assessment and projections for the Namibian hake resource. Unpublished report, NatMIRC, Namibia. HWG/WkShop/2001/04/Doc.1. 16pp.
- Butterworth D.S. and Rademeyer R.A. In press. Sustainable management initiatives for the southern African hake fisheries over recent years. Proceedings of a *Conference on the Scientific and Technical Bases for the Sustainability of Fisheries*. University of Miami, 26-30 November, 2001. 58pp.
- Chalmers D.S. 1976. Weight conversion factors, length/weight relationships and annual landings of some South African trawl-caught fish. *Fish. Bull. S. Afr.* **8**: 1-4.
- Cochrane K.L., Butterworth D.S. and Payne A.I.L. 1997. South Africa's offshore living marine resources: the scientific basis for management of the fisheries. *Trans. Roy. Soc. S. Afr.* **52**(1): 149-176.
- Cryer J.D. 1986. *Time series analysis*. Wadsworth Publishing, Boston, Massachusetts. 286pp.
- ESS. 2000. An Economic and Sectoral Study of the South African Fishing Industry, Vol. 3. <http://www.envirofishafrica.co.za/ess/ESS2000Website/>
- Fox W.W. 1970. An exponential surplus-yield model for optimizing exploited fish populations. *Trans. Am. Fish. Soc.* **99**(1): 80-88.
- Franca P. 1962. Considérations sur la taxonomie des *Merluccius* de l'Atlantique oriental. *Mems Jta Invest. Ultramar. Ser. 2*, **36**: 7-48.
- Geromont H.F. and Butterworth D.S. 1996. Some age-structured production model calculations for the South African west coast hake resource. Unpublished report, MCM, South Africa. WG/07/96/D:H:22: 10pp.

- Geromont H.F. and Butterworth D.S. 1997. Assessments of West Coast hake using an age-structured production model to provide a basis for simulation testing of a revised Operational Management Procedure. Unpublished report, MCM, South Africa. WG/08/97/D:H:35: 24pp.
- Geromont H.F. and Butterworth D.S. 1998a. Initial evaluation of a range of possible management procedures for west coast hake. Unpublished report, MCM, South Africa. WG/02/98/D:H:18. 26pp.
- Geromont H.F. and Butterworth D.S. 1998b. Initial management procedure robustness trials for west coast hake. Unpublished report, MCM, South Africa. WG/02/98/D:H:20. 7pp.
- Geromont H.F. and Butterworth D.S. 1998c. Management procedure robustness trials for west coast hake. Unpublished report, MCM, South Africa. WG/02/98/D:H:24. 17pp.
- Geromont H.F. and Butterworth D.S. 1998d. Addendum to: Management procedure robustness trials for west coast hake. Unpublished report, MCM, South Africa. WG/02/98/D:H:36. 13pp.
- Geromont H.F. and Butterworth D.S. 1999a. A fleet-disaggregated age-structured production model applied to the south coast hake fishery for *Merluccius capensis* and *M. paradoxus*. Unpublished report, MCM, South Africa. WG/05/99/D:H:01: 32pp.
- Geromont H.F. and Butterworth D.S. 1999b. Operating models proposed for south coast *Merluccius capensis* management procedure robustness trials. Unpublished report, MCM, South Africa. WG/11/99/D:H:46. 33pp.
- Geromont H.F. and Butterworth D.S. 2000a. Final set of operating models proposed for south coast *Merluccius capensis* management procedure robustness trials. Unpublished report, MCM, South Africa. WG/02/00/D:H:3. 29pp.
- Geromont H.F. and Butterworth D.S. 2000b. Candidate management procedures robustness trials for south coast *Merluccius capensis* east of 20°E. Unpublished report, MCM, South Africa. WG/06/00/D:H:12. 23pp.
- Geromont H.F. Butterworth D.S., Japp D. and Leslie R. 1995a. Preliminary assessment of longline experiment: south coast hake. Unpublished report, MCM, South Africa. WG/11/95/D:H:28. 12pp.
- Geromont H.F., De Oliveira J.A.A., Johnston S.J. and Cunningham C.L. 1999. Development and application of management procedures for fisheries in southern Africa. *ICES J. Mar. Sci.* 56: 952-966.

- Geromont H.F. and Glazer J.P. 1998. The 1998 Revised Management Procedure for the South African west coast hake resource. Unpublished report, MCM, South Africa. WG/11/98/D:H:49. 11pp.
- Geromont H.F. and Glazer J.P. 2000. The revised management procedure for the South African south coast *Merluccius capensis* resource. Unpublished report, MCM, South Africa. WG/06/00/D:H:20. 13pp.
- Geromont H.F., Leslie R.W. and Butterworth D.S. 1995b. Estimation of *Merluccius capensis* and *paradoxus* proportions in Cape hake catches. Unpublished report, MCM, South Africa. WG/03/95/D:H:2. 13pp.
- Glazer J.P. 1999. The application of General Linear Modelling methods to estimate trends in abundance of the hake and rock lobster stocks off South Africa. MSc thesis, University of Cape Town, South Africa. 239pp.
- Glazer J.P. 2002a. Standardised CPUE series for the west coast hake (1978-2001). Unpublished report, MCM, South Africa. WG/10/02/D:H:22. 10pp.
- Glazer J.P. 2002b. Standardised CPUE series (1978-2002) for the South Coast hake *M. capensis* east of 20°East. Unpublished report, MCM, South Africa. WG/10/02/D:H:21. 10pp.
- Glazer J.P. and Butterworth D.S. 2002. GLM-based standardization of the South African west coast hake catch per unit effort series, focusing on adjustments for targeting at other species. *S. Afr. J. mar. Sci.* **24**: 323-339.
- Glazer J.P. and Leslie R. 2001a. Provisional standardized CPUE series for the west coast hake (1978-2000). Unpublished report, MCM, South Africa. WG/09/01/D:H:12. 10pp.
- Glazer J.P. and Leslie R. 2001b. Provisional standardized CPUE series (1978-2000) for the south coast hake *Merluccius capensis* east of 20°E. Unpublished report, MCM, South Africa. WG/09/01/D:H:15. 10pp.
- Gordoa A. and Duarte C.M. 1991. Internal school density of Cape hakes (*Merluccius capensis*) *Can. J. Fish. Aquat. Sci.* **48**: 2095-2099.
- Gordoa A., Macpherson E. and Olivar M. P. 1995. Biology and fisheries of Namibian hakes (*M. paradoxus* and *M. capensis*). In *Hake: Fisheries, Ecology and Markets*. J. Alheit and T.J. Pitcher (Eds). London, Chapman and Hall: 49-88.



- Grant W.S., Becker I.I. and Leslie R.W. 1988. Evolutionary divergence between sympatric species of southern African hakes, *Merluccius capensis* and *M. paradoxus*. 1. Electrophoretic analysis of proteins. *Heredity* **61**: 13-20.
- Grant W.S., Leslie R.W. and Becker I.I. 1987. Genetic stock structure of the southern African hakes *Merluccius capensis* and *M. paradoxus*. *Mar. Ecol. Prog. Ser.* **41**: 9-20.
- Gulland J.A. 1961. Fishing and the stocks of fish at Iceland. *Fish. Invest. Minst. Agric. Fish. Food U.K.* (Ser. 2). **23**(4). 55pp.
- Gulland J.A. 1965. Estimation of mortality rates. Annex to *Rep. Artic Fish. Working Group, Int. Counc. Explor. Sea C.M.* 1965(3): 9pp. (mimeo).
- Hilborn R. 1979. Comparison of fisheries control systems that utilize catch and effort data. *J. Fish. Res. Board Can.* **36**: 1477-1489.
- Hilborn R. 1990. Estimating the parameters of full age-structured models from catch and abundance data. *Bull. int. N. Pac. Fish. Commn.* **50**: 207-213.
- Huse I., Hamukuaya H., Boyer D.C., Malan P.E. and Strømme T. 1998. The diurnal vertical dynamic of Cape hakes and their potential prey. In *Benguela Dynamics*. Pillar S.C., Moloney C.L., Payne A.I.L. and F.A. Shillington (Eds). *S. Afr. J. mar. Sci.* **19**: 365-376.
- Hutchings L., Beckley L.E., Griffiths M.H., Roberts M.J., Sundby S. and van der Lingen C. 2002. Spawning on the edge: spawning grounds and nursery areas around the southern African coastline. *Mar. Freshwater Res.* **53**: 307-318.
- ICSEAF. 1978 Proceedings and Reports of Meetings 1977. *Proc. Rep. Meet. int. Commn SE. Atl. Fish.* 1977. 165pp.
- ICSEAF. 1983. Proceedings and Reports of Meetings 1982. *Proc. Rep. Meet. int. Commn SE. Atl. Fish.* 1983(2). 147pp.
- ICSEAF. 1989. Historical series data selected for Cape hakes assessment. ICSEAF document. SAC/89/Doc./3. 10pp.
- Inada T. 1981. Studies on the merlucciid fishes. *Bull. Far Seas Fish. Res. Lab.* **18**. 172pp.

- Japp D.W. 1988. The status of the experimental demersal longline fishery for kingklip *Genypterus capensis* in Divisions 1.6, 2.1 and 2.2. *Colln scient. Pap. int. Commn SE. Atl. Fish.* 15(2): 35-39.
- Japp D.W., Sims P. and Smale M.J. 1994. A review of the fish resources of the Agulhas Bank. *S. Afr. J. Sci.* 90(3): 123-134.
- Jones B.W. 1974. World resources of hakes of the genus *Merluccius*. In *Sea Fisheries Research*. Harden-Jones, F.R. (Ed.). London, Elek Science. 139-166.
- Leslie R.W. 1998a. Final data document for west coast hake assessments. Unpublished report, MCM, South Africa. WG/03/98/D:H:12. 33pp.
- Leslie R.W. 1998b. Final data document for south coast hake assessments. Unpublished report, MCM, South Africa. WG/03/98/D:H:13. 26pp.
- Lleonart J. and Salat J. 1989. A dynamic approach to catch-effort data analysis using a new concept: the inertia of the stock. *Can. J. Fish. Aquat. Sci.* 46(8): 1367-1374.
- Lleonart J., Salat J. and Macpherson E. 1985. CVPA, an expanded VPA with cannibalism. Application to a hake population. *Fish. Res.* 3(1): 61-79.
- Mas-Riera J. 1991. Changes during growth in the retinal structure of three hakes, *Merluccius* spp. (Teleostei, Gadiformes), in relation to their depth distribution and feeding. *J. exp. mar. Biol. Ecol.* 152: 91-104.
- MCM. 1998. A revised OMP for the west coast hake resource and a recommended hake TAC for 1999. Unpublished report, MCM, South Africa. WG/06/98/D:H:37. 11pp.
- MCM. 2000a. Proposed revised Operational Management Procedures for south coast hake. Unpublished report, MCM, South Africa. WG/06/00/D:H:18. 4pp.
- MCM. 2000b. Recommendation to the consultative advisory forum for the hake TAC for 2001. Unpublished report, MCM, South Africa. WG/06/00/D:H:19. 8pp.
- MCM. 2002. Recommendation on the hake TAC for 2003. Unpublished report, MCM, South Africa. WG/11/02/D:H:27. 7pp.
- MFMR. 1999. *Annual Report 1999*. Namibia: Ministry of Fisheries and Marine Resources. 35pp.

- Myers R.A., Bowen K.G. and Barrowman N.J. 1999. Maximum reproductive rate of fish at low population sizes. *Can J. Fish. Aquat. Sci.* **56**: 2404-2419.
- Olivar M.-P., Rubiés P. and Salat J. 1988. Early life history and spawning of *Merluccius capensis* Castelnau in the northern Benguela Current. *S. Afr. J. mar. Sci.* **6**: 245-254.
- Osborne R.F., Melo Y.C., Hofmeyr M.D. and Japp D.W. 1999. Serial spawning and batch fecundity of *Merluccius capensis* and *M. paradoxus*. *S. Afr. J. mar. Sci.* **21**: 211-216.
- Payne A.I.L. 1986. Biology, stock integrity and trends in the commercial fishery for demersal fish on the south-east coast of South Africa. PhD thesis. University of Port Elizabeth, v + 368pp.
- Payne A.I.L. 1989. Cape hakes. In *Oceans of Life off Southern Africa*. Payne A.I.L. and Crawford R.J.M. (Eds). Vlaeberg Publishers, Cape Town. 136-147.
- Payne A.I.L., Badenhorst A., Augustyn C.J. and Leslie R.W. 1989. Biomass indices for Cape hakes and other demersal fish species in South African waters in 1988 and earlier. *Colln Scient. Pap. int. Commn SE. Atl. Fish.* **16**(2): 25-62.
- Payne A.I.L. and Punt A.E. 1995. Biology and fisheries of South African hakes. In *Hake: Fisheries, Ecology and Markets*. J. Alheit and T.J. Pitcher (Eds). London, Chapman and Hall: 15-47.
- Payne A.I.L., Rose B. and Leslie R.W. 1987. Feeding of hake and a first attempt at determining their trophic role in the South African west coast marine environment. In *The Benguela and Comparable Ecosystems*. Payne A.I.L., Gulland J.A. and K.H. Brink (Eds). *S. Afr. J. mar. Sci.* **5**: 471-501.
- Pella J.S. and Tomlinson P.K. 1969. A generalized stock production model. *Bull. Inter-Am. Trop. Tuna Commn.* **13**: 421-496.
- Pillar S.C. and Barange M. 1993. Feeding selectivity of juvenile Cape hakes *Merluccius capensis* in the southern Benguela. *S. Afr. J. mar. Sci.* **13**: 255-268.
- Pillar S.C., Stuart V., Barange M. and Gibbons M.J. 1992. Community structure and trophic ecology of euphausiids in the Benguela ecosystem. In *Benguela Trophic Functioning*. Payne A.I.L., Brink K.H., Mann K.H. and Hilborn R. (Eds). *S. Afr. J. mar. Sci.* **12**: 393-409.
- Pillar S.C. and Wilkinson I.S. 1995. The diet of Cape hakes *Merluccius capensis* on the south coast of South Africa. *S. Afr. J. mar. Sci.* **15**: 225-239.

- 
- Pope J.G. 1984. The performance of short cut methods for catch forecasts. *ICES Document CM 1984/D:3*. 12pp.
- Pope J.G. and Shepherd J.G. 1985. A comparison of the performance of various methods for tuning VPAs using effort data. *J. Cons. perm. int. Explor. Mer.* **42**: 129-151.
- Punt A.E. 1989. Production model TAC estimates for 1990 for the hake resources in ICSEAF Divisions 1.3 to 2.2. ICSEAF document. SAC/89/S.P./25. 99pp.
- Punt A.E. 1992. Management procedures for Cape hakes and baleen whale resources. PhD thesis, University of Cape Town. 875pp.
- Punt A.E. 1993. The comparative performance of production-model and *ad hoc* tuned VPA based feedback-control management procedures for the stock of Cape hakes off the west coast of South Africa. In: *Risk evaluation and biological reference points for fisheries management*. Smith S.J., Hunt J.J. and Rivard D. (Eds). *Can. Spec. Publ. Fish. Aquat. Sci.* **120**: 283-299.
- Punt A.E. 1994. Assessments of the stocks of Cape hakes (*Merluccius* spp.) off South Africa. *S. Afr. J. Mar. Sci.* **14**: 159-186.
- Punt A.E. and Butterworth D.S. 1991. On an approach for comparing the implications of alternative fish stock assessments, with application to the stock of Cape hakes *Merluccius* spp. off northern Namibia. *S. Afr. J. mar. Sci.* **10**: 219-240.
- Punt A.E. and Butterworth D.S. 1995. The effects of future consumption by the Cape fur seal on catches and catch rates of the Cape hakes. 4. Modelling the biological interaction between Cape fur seals *Arctocephalus pusillus pusillus* and the Cape hakes *Merluccius capensis* and *M. paradoxus*. *S. Afr. J. mar. Sci.* **16**: 255-285.
- Punt A.E. and Hilborn R. 1994. A comparison of fisheries models with and without cannibalism with implications for the management of the Cape hake resource off southern Africa. *ICES J. Mar. Sci.* **51**: 19-29.
- Punt A.E. and Hilborn R. 2001. BAYES-SA: Bayesian stock assessment methods in fisheries. User's manual. *FAO Computerized Information Series (Fisheries)*. No 12. Rome, FAO. 56pp.
- Punt A.E. and Japp D.W. 1994. Stock assessment of the kingklip *Genypterus capensis* off South Africa. *S. Afr. J. mar. Sci.* **14**: 133-149.

- Punt A.E. and Leslie R.W. 1991. Estimates of some biological parameters for the Cape hakes off the South African west coast. *S. Afr. J. mar. Sci.* 10: 271-284.
- Punt A.E., Leslie R.W. and Du Plessis S.E. 1992. Estimation of the annual consumption of food by Cape hakes *Merluccius capensis* and *M. paradoxus* off the South African west coast. In *Benguela Trophic Functioning*. Payne A.I.L., Brink K.H., Mann K.H. and Hilborn R. (Eds). *S. Afr. J. mar. Sci.* 12: 611-634.
- Rademeyer R.A. and Butterworth D.S. 2001a. Management procedure development for the Namibian hake resource. Unpublished report, NatMIRC, Namibia. HWG/WkShop/2002/02/Doc.1. 41pp.
- Rademeyer R.A. and Butterworth D.S. 2001b. An updated assessment for the West Coast Hake resource. Unpublished document, MCM, South Africa. WG/09/01/D:H:19. 21pp.
- Rademeyer R.A. and Butterworth D.S. 2002a. Management procedure development for the Namibian hake resource. Unpublished document, NatMIRC, Namibia. WG/WkShop/02/00/Doc. 2. 40pp.
- Rademeyer R.A. and Butterworth D.S. 2002b. An Age-Structure Production Model applied to the *Merluccius paradoxus* Hake resource off the South and West Coasts. Unpublished report, MCM, South Africa. WG/10/02/D:H:16. 42pp.
- Rice J.A. 1995. *Mathematical statistics and data analysis* (2<sup>nd</sup> ed.). Wadsworth Publishing, Belmont, California. 602pp.
- Ricker W.E. 1954. Stock and recruitment. *J. Fish. Res. Bd. Can.* 11: 559-623.
- Roel B.A. and Macpherson E. 1988. Feeding of *Merluccius capensis* and *M. paradoxus* off Namibia. *S. Afr. J. mar. Sci.* 6: 227-243.
- Schaefer M.B. 1954. Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. *Bull. inter-Am. Trop. Tuna Commn.* 1(2): 25-56.
- Shannon L.V, Crawford R.J.M., Pollock D.E., Hutchings L., Boyd A.J., Tauton-Clark J., Badenhorst A., Melville-Smith R., Augustyn C.J., Cochrane K.L., Hampton I., Nelson G., Japp D.W. and Tarr R.J.Q. 1992. The 1980's – a decade of change in the Benguela ecosystem. In: *Benguela Trophic Functioning*. Payne A.I.L., Brink K.H., Mann K.H. and Hilborn R. (Eds). *S. Afr. J. mar. Sci.* 12: 271-296.

- Smith S.J., Hunt J.J. and Rivard D. 1993. Introduction In: Risk evaluation and biological reference points for fisheries management. *Can. Spec. Publ. Fish. Aquat. Sci.* 120: viii + 442pp.
- Strogalev V.D. 1984. Environmental aspects of estimating year class strength for Cape hakes in ICSEAF Divisions 1.3 and 1.4. *Colln scient. Pap. int. Commn SE Atl. Fish.* 11(2): 55-60.
- UNCED. 1992. Principles of Agenda 21. <http://www.un.org/esa/sustdev/agenda21.htm>
- Van Eck T.H. 1969. The South African hake: "*Merluccius capensis*" or "*Merluccius paradoxus*"? *S. Afr. Shipp. News Fish. Ind. Rev.* 24(5): 95-97.

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## Appendix A1 – Sensitivity tests to the Reference Case assessment of the Namibian hake resource

Table A1.1 compares management quantity estimates for the Namibian hake Reference Case assessment (Chapter 5) with those for five key variations of this assessment. The changes to the Reference Case assessment for the different sensitivities are motivated and described below, together with some discussion of the results.

### *“M fixed at 0.5”*

One of the concerns with the Namibian hake Reference Case assessment in Chapter 5 is the unrealistically high estimate for the natural mortality  $M$ . In this sensitivity test,  $M$  is fixed at  $0.5 \text{ yr}^{-1}$ , a value which is more in the line of what would be expected for a relatively long-lived fish such as hake. This results in a slightly more optimistic appraisal of the stock status. The stock is estimated to be currently above MSYL and to be able to yield a maximum of 316 thousand tons. In this case, the value of the steepness parameter  $h$  is 0.593, a value which seems also more credible than the extremely low value of 0.318 in the Reference Case assessment. The CVs also decrease considerably, suggesting that the estimation of  $M$  is a major cause for uncertainty in the assessment of the Namibian hake resource. The model fit to the catch-at-age data (both commercial and survey) deteriorates enormously compared to the Reference Case.

### *“h fixed at 0.623”*

As mentioned in Chapter 9, the steepness estimate of 0.318 of the Reference Case assessment is extremely low. In this assessment, the steepness has been fixed to 0.623, which corresponds to the upper 95% end probability interval obtained from the likelihood profile for  $h$ . In this case, the stock is estimated to be extremely productive (the estimated MSY – 570 thousand tons – is nearly double that for the Reference Case assessment) and in a very healthy state. This is due to the fact that, surprisingly, the estimated value of  $M$  does not decrease compared to the Reference Case assessment. The combination of a high natural mortality and a high steepness leads to this view of a very productive stock. The fit of the model to the catch-at-age data actually improves compared to the Reference Case, but there is an appreciable deterioration in the fit to the CPUE trends.

*“incl. 81-88 ICSEAF CPUE data”*

The historic ICSEAF CPUE data from 1981 to 1988 are ignored in the current assessments. Indeed, they show a clear positive trend, which is regarded with scepticism, and it is now known that there was misreporting of catches over this period (Anon., 1997). This sensitivity test includes the full ICSEAF CPUE series. As expected from the positive trend in these data in the late 1980's, their inclusion results in a more optimistic appraisal of the stock (currently slightly above rather slightly below MSYL).

*“80-89 catches up by 25%”*

As mentioned above, it is known that there was some misreporting of catches in the 1980's. The sensitivity of the model to an increase of 25% in the catches over the 1980 to 1989 period is tested here. The results are only slightly affected by this change in the data. The stock is estimated to be slightly more productive.

*“no last 3 years of data”*

Excluding the last 3 years of data results in a more optimistic view of the stock, as this excludes recent low CPUE and survey biomass estimates. This shows that these recent data are responsible for current estimates that the resource is below rather than above MSYL.



Table A1.1: Estimates of management quantities for the Reference Case assessment and five variants thereof, for the Namibian hake. The first figure shown is the best estimate, followed by the Hessian-based CV in parenthesis. See Table 5.6 for clarification of some of the notation.

	Reference Case				a) M fixed at 0.5				b) h fixed at 0.623				c) incl. 81-88 ICSEAF CPUE data				d) 80-89 catches up by 2.5%				e) no last 3 years of data																											
Total negative loglikelihood	-94.0				-48.8				-91.6				-106.6				-92.6				-83.0																											
-lnL: CPUE	-32.4				-32.6				-25.6				-45.3				-30.8				-29.9																											
-lnL: Survey	-14.1				-14.8				-13.9				-14.4				-14.1				-14.3																											
-lnL: CAA com	-58.3				-32.0				-63.4				-55.4				-58.4				-50.9																											
-lnL: CAA surv	-8.9				-0.2				-10.3				-9.6				-9.3				-7.9																											
-lnL: SR Residuals	19.7				30.9				21.5				18.1				20.0				20.0																											
K <sup>SP</sup>	3640 (0.16)				2561 (0.08)				2986 (0.15)				3474 (0.13)				3966 (0.19)				3409 (0.17)																											
K <sup>SP</sup>	3953 (0.18)				2764 (0.09)				3159 (0.16)				3748 (0.14)				4341 (0.21)				3688 (0.18)																											
B <sup>SP</sup> 2001	1466 (0.31)				1014 (0.26)				2452 (0.22)				1584 (0.23)				1543 (0.34)				1646 (0.44)																											
B <sup>SP</sup> 2001	411 (0.55)				461 (0.43)				912 (0.23)				479 (0.39)				437 (0.58)				467 (0.80)																											
h	0.318 (0.19)				0.593 (0.13)				0.623				0.343 (0.16)				0.309 (0.22)				0.348 (0.26)																											
MSYL <sup>SP</sup>	1657 (0.20)				978 (0.11)				1242 (0.21)				1563 (0.15)				1817 (0.23)				1532 (0.22)																											
MSYL <sup>SP</sup>	476 (0.31)				422 (0.19)				258 (0.16)				446 (0.25)				529 (0.35)				378 (0.35)																											
MSY	300 (0.25)				316 (0.07)				570 (0.20)				326 (0.18)				311 (0.31)				326 (0.28)																											
B <sup>SP</sup> 2001/K <sup>SP</sup>	0.403 (0.39)				0.396 (0.30)				0.821 (0.12)				0.456 (0.24)				0.389 (0.44)				0.483 (0.55)																											
B <sup>SP</sup> 2001/K <sup>SP</sup>	0.104 (0.63)				0.167 (0.47)				0.289 (0.17)				0.128 (0.41)				0.101 (0.69)				0.127 (0.92)																											
B <sup>SP</sup> 2001/MSYL <sup>SP</sup>	0.885 (0.42)				1.036 (0.34)				1.974 (0.13)				1.013 (0.27)				0.849 (0.49)				1.074 (0.61)																											
B <sup>SP</sup> 2001/MSYL <sup>SP</sup>	0.863 (0.67)				1.094 (0.48)				3.533 (0.13)				1.075 (0.42)				0.827 (0.76)				1.233 (0.98)																											
MSYL <sup>SP</sup> /K <sup>SP</sup>	0.455 (0.04)				0.382 (0.05)				0.416 (0.08)				0.450 (0.04)				0.458 (0.05)				0.449 (0.07)																											
MSYL <sup>SP</sup> /K <sup>SP</sup>	0.120 (0.20)				0.153 (0.14)				0.082 (0.11)				0.119 (0.18)				0.122 (0.20)				0.103 (0.24)																											
M	0.76 (0.04)				0.50 (0.00)				0.77 (0.06)				0.75 (0.04)				0.77 (0.05)				0.74 (0.05)																											
Age	S <sub>1968,A</sub>	S <sub>1985,A</sub>	S <sub>2001,A</sub>	S <sub>surv</sub>	S <sub>1968,A</sub>	S <sub>1985,A</sub>	S <sub>2001,A</sub>	S <sub>surv</sub>	S <sub>1968,A</sub>	S <sub>1985,A</sub>	S <sub>2001,A</sub>	S <sub>surv</sub>	S <sub>1968,A</sub>	S <sub>1985,A</sub>	S <sub>2001,A</sub>	S <sub>surv</sub>	S <sub>1968,A</sub>	S <sub>1985,A</sub>	S <sub>2001,A</sub>	S <sub>surv</sub>	S <sub>1968,A</sub>	S <sub>1985,A</sub>	S <sub>2001,A</sub>	S <sub>surv</sub>																								
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00																								
1	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00																								
2	0.09	0.63	0.01	0.77	0.14	0.75	0.02	1.00	0.08	0.62	0.01	0.78	0.09	0.63	0.01	0.78	0.09	0.63	0.01	0.76	0.09	0.64	0.01	0.74																								
3	0.66	1.00	0.03	1.00	0.77	1.00	0.07	1.00	0.60	1.00	0.04	1.00	0.65	1.00	0.03	1.00	0.67	1.00	0.03	1.00	0.66	1.00	0.03	1.00																								
4	0.97	1.00	0.12	1.00	0.99	1.00	0.23	1.00	0.96	1.00	0.16	1.00	0.97	1.00	0.13	1.00	0.98	1.00	0.12	1.00	0.97	1.00	0.10	1.00																								
5	1.00	1.00	0.37	1.00	1.00	1.00	0.52	1.00	1.00	1.00	0.46	1.00	1.00	1.00	0.39	1.00	1.00	1.00	0.38	1.00	1.00	1.00	0.33	1.00																								
6	1.00	1.00	0.72	1.00	1.00	1.00	0.81	1.00	1.00	1.00	0.80	1.00	1.00	1.00	0.74	1.00	1.00	1.00	0.73	1.00	1.00	1.00	0.69	1.00																								
7	1.00	1.00	0.93	1.00	1.00	1.00	0.95	1.00	1.00	1.00	0.96	1.00	1.00	1.00	0.94	1.00	1.00	1.00	0.93	1.00	1.00	1.00	0.92	1.00																								
8+	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00																								
Commercial sigmas:																																																
CPUE ICSEAF (1.3+1.4)	0.171 (0.18)				0.115 (0.09)				0.245 (0.40)				0.143 (0.13)				0.199 (0.20)				0.161 (0.17)																											
CPUE ICSEAF (1.5)	0.202 (0.12)				0.165 (0.06)				0.265 (0.32)				0.170 (0.09)				0.223 (0.15)				0.195 (0.11)																											
CPUE GLM	0.211 (0.25)				0.360 (0.18)				0.223 (0.17)				0.225 (0.21)				0.212 (0.27)				0.246 (0.30)																											
Commercial q's:																																																
CPUE ICSEAF (1.3+1.4)	0.283 x10 <sup>3</sup> (0.21)				0.489 x10 <sup>3</sup>				0.324 x10 <sup>3</sup> (0.28)				0.313 x10 <sup>3</sup>				0.244 x10 <sup>3</sup> (0.24)				0.312 x10 <sup>3</sup> (0.21)																											
CPUE ICSEAF (1.5)	0.432 x10 <sup>3</sup> (0.21)				0.749 x10 <sup>3</sup>				0.493 x10 <sup>3</sup> (0.28)				0.472 x10 <sup>3</sup>				0.372 x10 <sup>3</sup> (0.24)				0.475 x10 <sup>3</sup> (0.21)																											
CPUE GLM	2.215 x10 <sup>3</sup> (0.42)				2.800 x10 <sup>3</sup>				1.056 x10 <sup>3</sup> (0.25)				1.990 x10 <sup>3</sup>				2.089 x10 <sup>3</sup> (0.44)				2.473 x10 <sup>3</sup> (0.61)																											
Survey sigmas:																																																
Spanish winter	0.391 (0.09)				0.353 (0.07)				0.461 (0.07)				0.402 (0.07)				0.367 (0.10)				0.394 (0.13)																											
Spanish summer	0.503 (0.04)				0.564 (0.04)				0.517 (0.04)				0.500 (0.03)				0.510 (0.04)				0.506 (0.04)																											
Survey q's:																																																
Spanish winter	0.401 (0.19)				Commercial trawlers q's: 0.920 (0.05)				Commercial trawlers q's: 0.270 (0.35)				Commercial trawlers q's: 0.405 (0.16)				Commercial trawlers q's: 0.354 (0.19)				Commercial trawlers q's: 0.443 (0.18)																											
Spanish summer	0.557 (0.20)				q's: 1.423 (0.06)				q's: 0.361 (0.35)				q's: 0.559 (0.16)				q's: 0.498 (0.21)				q's: 0.614 (0.20)																											
Naoson summer	0.367 (0.19)				0.404 (0.25)				0.823 (0.17)				0.902 (0.17)				0.222 (0.27)				0.244 (0.27)				0.352 (0.19)				0.387 (0.19)				0.346 (0.26)				0.381 (0.26)				0.372 (0.32)				0.411 (0.32)			
Naoson winter	0.418 (0.20)				0.462 (0.24)				0.952 (0.16)				1.052 (0.16)				0.250 (0.27)				0.276 (0.27)				0.403 (0.18)				0.445 (0.18)				0.394 (0.26)				0.436 (0.26)				0.439 (0.32)				0.485 (0.32)			
Catches-at-age sigmas:																																																
commercial	0.110 (0.04)				0.136 (0.05)				0.104 (0.04)				0.112 (0.04)				0.111 (0.04)				0.112 (0.04)																											
summer survey	0.114 (0.06)				0.148 (0.05)				0.118 (0.06)				0.114 (0.06)				0.117 (0.06)				0.117 (0.06)																											
winter survey	0.161 (0.07)				0.164 (0.06)				0.162 (0.07)				0.161 (0.07)				0.161 (0.07)				0.151 (0.08)																											
Additional sigma (survey)	0.225 (0.26)				0.212 (0.27)				0.230 (0.26)				0.220 (0.26)				0.226 (0.26)				0.193 (0.28)																											

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## Appendix A2 – Sensitivity tests to the Reference Case assessment of the South African west coast hake resource

Table A2.1 compares management quantity estimates for the South African west coast hake Reference Case assessment (Chapter 6) with those for two variations to this assessment. The changes to the Reference Case assessment for the different sensitivities are motivated and described below, together with some discussion of the results.

### *“M age-independent”*

Keeping the natural mortality  $M$  constant over the ages, results in an estimate for  $M$  (0.80) which is unrealistically high, and gives a slightly more optimistic view of the current status of the resource. The fit to the data, however, is much worse, essentially because of poor representation of the survey catch-at-age data.

### *“Selectivity slope of 0.2”*

Because of the concern over the relatively high value estimated for natural mortality, a negative selectivity slope  $s$  of 0.2 has been included from age 4 (equation 4.26) in this sensitivity test. Indeed, the estimated  $M$  for the Reference Case is high because the older age classes are not well represented in the catch-at-age data, but this could also be due to a lower selectivity on older fish. A lower selectivity on older fish could reflect a cryptic biomass of this component of the resource, if for example older fish were found preferentially on untrawlable grounds. However, the estimated  $M$  vector hardly changes at all and the fit to both the commercial and survey catch-at-age data is worse. Other management quantity estimates are fairly insensitive to this change, although it does give a slightly more optimistic view of the current status of the resource.

**Table A2.1:** Estimates of management quantities for the Reference Case and two key variants of this assessment for the South African west coast hake. The first figure shown is the best estimate followed by the Hessian-based CV in parenthesis.

	Reference Case						a) $M$ age independent					b) Selectivity slope of 0.2					
Total -lnL:	-179.9						-157.7					-170.6					
-lnL: CPUE	-71.0						-70.1					-70.8					
-lnL: Survey	-16.0						-16.5					-16.2					
-lnL: CAA com.	-57.1						-54.3					-50.7					
-lnL: CAA surv	-35.7						-16.8					-32.8					
-lnL:SR Residuals	3.2						3.4					3.2					
$K^W$	973 (0.06)						920 (0.09)					1092 (0.07)					
$K^{st}$	1386 (0.05)						1450 (0.09)					1270 (0.06)					
$B^W_{2001}$	218 (0.13)						325 (0.16)					297 (0.16)					
$B^{st}_{2001}$	298 (0.12)						435 (0.15)					339 (0.14)					
$h$	0.615 (0.08)						0.471 (0.11)					0.566 (0.09)					
$MSYL^W$	304 (0.09)						338 (0.13)					355 (0.11)					
$MSYL^{st}$	404 (0.09)						454 (0.13)					406 (0.10)					
$MSY$	129 (0.03)						130 (0.05)					126 (0.04)					
$B^W_{2001}/K^W$	0.224 (0.18)						0.353 (0.20)					0.272 (0.20)					
$B^{st}_{2001}/K^{st}$	0.215 (0.15)						0.300 (0.16)					0.267 (0.16)					
$B^W_{2001}/MSYL^W$	0.715 (0.19)						0.963 (0.22)					0.836 (0.21)					
$B^{st}_{2001}/MSYL^{st}$	0.738 (0.17)						0.960 (0.19)					0.836 (0.18)					
$MSYL^W/K^W$	0.313 (0.05)						0.367 (0.06)					0.325 (0.06)					
$MSYL^{st}/K^{st}$	0.291 (0.05)						0.313 (0.05)					0.319 (0.04)					
Age	$M_a$	$S_{1984,a}$	$S_{1993,a}$	$S_{surv,a}$	$S_{Nansen,a}$		$M_a$	$S_{1984,a}$	$S_{1993,a}$	$S_{surv,a}$	$S_{Nansen,a}$		$M_a$	$S_{1984,a}$	$S_{1993,a}$	$S_{surv,a}$	$S_{Nansen,a}$
0	1.06	0.00	0.00	0.01	0.09		0.80	0.00	0.00	0.01	0.16		1.04	0.00	0.00	0.01	0.09
1	1.06	0.00	0.00	0.26	0.36		0.80	0.00	0.00	0.37	0.53		1.04	0.00	0.00	0.26	0.37
2	1.06	0.73	0.10	1.00	1.00		0.80	0.88	0.12	1.00	1.00		1.04	0.76	0.11	1.00	1.00
3	0.82	1.00	0.84	1.00	1.00		0.80	1.00	0.85	1.00	1.00		0.80	1.00	0.86	1.00	1.00
4	0.67	1.00	1.00	1.00	1.00		0.80	1.00	1.00	1.00	1.00		0.66	1.00	1.00	1.00	1.00
5	0.58	1.00	1.00	1.00	1.00		0.80	1.00	1.00	1.00	1.00		0.57	0.82	0.82	0.82	0.82
6	0.51	1.00	1.00	1.00	1.00		0.80	1.00	1.00	1.00	1.00		0.50	0.67	0.67	0.67	0.67
7+	0.46	1.00	1.00	1.00	1.00		0.80	1.00	1.00	1.00	1.00		0.45	0.55	0.55	0.55	0.55
Commercial sigmas:																	
CPUE ICSEAF	0.099 (0.09)						0.080 (0.10)					0.082 (0.10)					
CPUE GLM	0.082 (0.10)						0.085 (0.13)					0.082 (0.13)					
Commercial $q$ 's:																	
CPUE ICSEAF	0.019 (0.07)						0.039 (0.16)					0.050 (0.14)					
CPUE GLM	0.058 (0.11)						0.039 (0.16)					0.051 (0.14)					
Survey $q$ 's:																	
summer	0.793 (0.13)						0.591 (0.18)					0.715 (0.16)					
winter	0.899 (0.11)						0.650 (0.17)					0.795 (0.15)					
Nansen	0.643 (0.13)						0.482 (0.17)					0.585 (0.15)					
Catches-at-age sigmas:																	
commercial	0.107 (0.03)						0.104 (0.03)					0.109 (0.03)					
summer survey	0.121 (0.03)						0.146 (0.04)					0.123 (0.03)					
winter survey	0.069 (0.07)						0.076 (0.08)					0.071 (0.07)					
Nansen survey	0.070 (0.05)						0.072 (0.07)					0.069 (0.04)					
Addnl sigma (survey)	0.231 (0.24)						0.223 (0.24)					0.238 (0.25)					

## Appendix A3 – Sensitivity tests to the Reference Case assessment of the South African south coast *M. capensis* resource

Table A3.1 compares management quantity estimates for the South African south coast *M. capensis* Reference Case assessment (Chapter 7) with those for two key variations to this assessment. The changes to the Reference Case assessment for the different sensitivities are motivated and described below, together with some discussion of the results.

### “Steepness fixed at 0.8”

Because of the concern over the unrealistically high value estimated for the steepness parameter  $h$  (1.0) in the Reference Case assessment, this parameter has been fixed to 0.8 in this sensitivity test. Although a value of 0.8 for  $h$  is outside its Hessian-based 90% probability interval for the Reference Case assessment, the negative log-likelihood is hardly affected by this change. Here, however, the Hessian-based CV estimate for  $h$  is unreliable, likely because  $h$  is estimated at a bound of its range. The likelihood profile for  $h$  (see Fig. 9.10) indicates that  $h = 0.8$  falls within the 90% probability interval. As expected, the estimate for the natural mortality  $M$  is increased slightly compared to the Reference Case assessment. The appraisal of the stock status is slightly less optimistic, although the resource is still estimated to be well above its MSYL. Broadly speaking, the management quantity estimates are not greatly affected by an  $h$  fixed at 0.8.

$$“B_{1967}^{SP} = 0.7K^{SP}”$$

For the Reference Case assessment, the resource is assumed to be at its pre-exploitation equilibrium level ( $K^{SP}$ ) in 1967; in other words, the hake fishery on the south coast is assumed to have commenced only in the mid-1960's. However, there were trawlers operating from Mossel Bay, East London and Port Elizabeth during the first quarter of the 20<sup>th</sup> century. Although they principally targeted sole, they would have caught some hake, and more specifically *M. capensis* as these were inshore trawlers. This sensitivity test therefore assumes that the spawning biomass in 1967 was already reduced to 70% of its pristine level (with an equilibrium age-structure, taken for simplicity to be that for  $F = 0$ ). With this assumption, the model fit improves slightly, particularly to the CPUE data. The decrease in the value of the sigma for the GLM-standardised CPUE series (but not the

historic CPUE) from the Reference Case assessment suggests that smaller negative log-likelihood is due mostly to a better fit of the GLM-standardised CPUE data. This assessment gives a slightly more pessimistic appraisal of the resource in terms of current biomass; indeed, the estimated current size of the spawning biomass is similar to that in the Reference Case assessment but  $K^{sp}$  is now increased by about 15%. The current depletion is therefore estimated to be 0.41.

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Table A3.1: Estimates of management quantities for the Reference Case model and two variants thereof, for the south coast *M. capensis* resource. The first figure shown is the best estimate, followed by the Hessian-based CV in parenthesis.

	Reference Case				a) Steepness fixed at 0.8				b) $B^{1967} = 70\%K^{SP}$			
Total -lnL	-116.6				-115.6				-119.5			
-lnL: CPUE	-36.7				-35.6				-39.6			
-lnL: Survey	-10.7				-10.9				-10.5			
-lnL: CAA com	-50.4				-50.6				-50.9			
-lnL: CAA surv	-21.8				-21.6				-21.9			
-lnL:SR Residuals	3.1				3.1				3.3			
		Offshore	Inshore	Longline		Offshore	Inshore	Longline		Offshore	Inshore	Longline
$K^{SP}$	170 (0.13)				170 (0.12)				196 (0.16)			
$K^{AA}$	115 (0.36)	142 (0.15)	121 (0.11)	75 (0.40)	98 (0.37)	137 (0.13)	131 (0.08)	62 (0.37)	154 (0.28)	167 (0.14)	117 (0.11)	105 (0.32)
$B^{SP}_{1001}$	80 (0.17)				82 (0.18)				81 (0.18)			
$B^{AA}_{1001}$	46 (0.45)	58 (0.16)	77 (0.15)	13 (0.79)	38 (0.49)	58 (0.17)	80 (0.17)	9 (0.88)	57 (0.52)	58 (0.18)	73 (0.11)	19 (0.90)
$h$	1.000 (0.01)				0.800 -				0.907 (0.14)			
$MSYL^{SP}$	64 (0.27)	49 (0.21)	21 (0.23)	117 (0.08)	74 (0.25)	46 (0.25)	17 (0.62)	125 (0.07)	57 (0.37)	48 (0.22)	39 (0.14)	116 (0.09)
$MSYL^{AA}$	27 (0.08)	26 (0.10)	24 (0.16)	20 (0.23)	26 (0.10)	25 (0.13)	18 (0.41)	18 (0.25)	29 (0.08)	24 (0.10)	37 (0.13)	24 (0.21)
$MSY$	33 (0.10)	35 (0.09)	35 (0.15)	27 (0.22)	31 (0.12)	33 (0.12)	26 (0.37)	25 (0.23)	33 (0.07)	33 (0.10)	29 (0.14)	32 (0.21)
$B^{SP}_{1001}/K^{SP}$	0.471 (0.14)				0.481 (0.14)				0.413 (0.20)			
$B^{AA}_{1001}/K^{AA}$	0.401 (0.17)	0.406 (0.16)	0.639 (0.10)	0.180 (0.47)	0.389 (0.20)	0.419 (0.16)	0.608 (0.12)	0.152 (0.59)	0.368 (0.27)	0.348 (0.22)	0.624 (0.19)	0.185 (0.70)
$B^{SP}_{1001}/MSYL^{SP}$	1.251 (0.34)	1.646 (0.12)	3.904 (0.26)	0.685 (0.13)	1.107 (0.32)	1.779 (0.15)	4.771 (0.65)	0.655 (0.13)	1.419 (0.50)	1.696 (0.13)	2.091 (0.15)	0.698 (0.23)
$B^{AA}_{1001}/MSYL^{AA}$	1.710 (0.40)	2.224 (0.14)	3.209 (0.08)	0.678 (0.57)	1.454 (0.41)	2.333 (0.15)	4.381 (0.47)	0.526 (0.66)	1.948 (0.55)	2.398 (0.17)	1.998 (0.11)	0.824 (0.70)
$MSYL^{SP}/K^{SP}$	0.376 (0.38)	0.286 (0.19)	0.121 (0.33)	0.687 (0.15)	0.434 (0.34)	0.270 (0.22)	0.101 (0.71)	0.735 (0.12)	0.291 (0.53)	0.244 (0.20)	0.198 (0.20)	0.592 (0.24)
$MSYL^{AA}/K^{AA}$	0.235 (0.35)	0.182 (0.21)	0.199 (0.10)	0.265 (0.17)	0.267 (0.32)	0.180 (0.21)	0.139 (0.45)	0.288 (0.14)	0.189 (0.41)	0.145 (0.62)	0.312 (1.67)	0.224 (0.88)
$M$	0.546 (0.19)				0.618 (0.16)				0.468 (0.24)			
Age	$S_{surv}$	$S_{off,A}$	$S_{in,A}$	$S_{ll,A}$	$S_{surv}$	$S_{off,A}$	$S_{in,A}$	$S_{ll,A}$	$S_{surv}$	$S_{off,A}$	$S_{in,A}$	$S_{ll,A}$
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.07	0.00	0.01	0.00	0.05	0.00	0.01	0.00	0.10	0.00	0.01	0.00
2	0.15	0.02	0.07	0.00	0.11	0.02	0.06	0.00	0.20	0.02	0.08	0.00
3	0.29	0.13	0.44	0.00	0.22	0.14	0.39	0.00	0.35	0.11	0.49	0.00
4	0.60	0.53	1.00	0.00	0.49	0.55	0.97	0.00	0.68	0.47	1.00	0.01
5	0.96	0.89	0.96	0.10	0.83	0.90	1.00	0.08	1.00	0.87	0.89	0.13
6	1.00	0.99	0.60	0.42	0.93	0.99	0.69	0.35	0.96	0.98	0.49	0.50
7+	0.91	1.00	0.35	1.00	1.00	1.00	0.44	1.00	0.72	1.00	0.25	1.00
Commercial sigma's:												
historic CPUE	0.251 (0.31)				0.251 (0.31)				0.251 (0.31)			
GLM CPUE	0.267 (0.14)				0.279 (0.14)				0.238 (0.16)			
Commercial q's:												
historic CPUE	0.010 (0.20)				0.010 (0.18)				0.014 (0.23)			
GLM CPUE	0.107 (0.16)				0.109 (0.17)				0.108 (0.21)			
Survey q's:												
spring	2.157 (0.31)				2.548 (0.59)				1.983 (0.19)			
autumn	2.511 (0.31)				2.911 (0.59)				2.428 (0.20)			
Catches-at-age sigma's:												
inshore	0.102 (0.04)				0.102 (0.04)				0.102 (0.05)			
longline	0.147 (0.09)				0.149 (0.10)				0.147 (0.09)			
autumn survey	0.130 (0.03)				0.130 (0.03)				0.130 (0.03)			
Addnl sigma (survey)	0.165 (0.37)				0.161 (0.38)				0.172 (0.35)			

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## Appendix B1 – Incorporation of catch-at-length information in fitting an ASPM

The ASPM-predicted annual catches-at-age (by number) made by each fleet ( $\widehat{C}_{y,a}^f$ ) are given in equation 4.18 (Chapter 4). These are converted into predicted proportions of catch of age  $a$ :

$$\widehat{p}_{y,a}^f = \widehat{C}_{y,a}^f / \sum_{a'} \widehat{C}_{y,a'}^f \quad \text{B1.1}$$

The proportions-at-age are then converted into proportions-at-length using the von Bertalanffy growth equation (equation 1.1, Chapter 1), assuming that the length-at-age distribution remains constant over time:

$$\widehat{p}_{y,l}^f = \sum_a \widehat{p}_{y,a}^f A_{a,l}^f \quad \text{B1.2}$$

where  $A_{a,l}^f$  is the proportion of fish of age  $a$  that fall in the length group  $l$  for fleet  $f$  (i.e.,  $\sum_l A_{a,l}^f = 1$  for all ages  $a$  for fleet  $f$ ).

The matrix  $A$  is calculated under the assumption that length-at-age is normally distributed about a mean given by the von Bertalanffy equation, i.e.:

$$L_a \sim N \left[ L_\infty \left( 1 - e^{-\kappa(a-t_0)} \right); \theta_a^2 \right] \quad \text{B1.3}$$

where

$N$  is the normal distribution, and

$\theta_a$  is the standard deviation of length-at-age  $a$ , which is modelled to be proportional to the expected length at age  $a$ , i.e.:

$$\theta_a = \beta L_\infty \left( 1 - e^{-\kappa(a-t_0)} \right) \quad \text{B1.4}$$

with  $\beta$  a parameter estimated in the model fitting process.

Note that since the model of the population's dynamics is based upon a one-year time step, the value of  $\beta$  and hence the  $\theta(a)$ 's estimated will reflected the real variability of the length-at-age as well as the 'spread' that arises from the fact that fish in the same annual cohort are not all spawned at

exactly the same time, and that catching takes place throughout the year so that there are differences in the age (in terms of fractions of a year) of fish allocated to the same cohort.

The following term (replacing equation 4.17, Chapter 4) is then added to the negative log-likelihood:

$$-\ln L^{\text{length}} = w_{\text{len}} \sum_f \sum_y \sum_l \left[ \ln \left( \sigma_{\text{len}}^f / \sqrt{\hat{p}_{y,l}^f} \right) + \hat{p}_{y,l}^f \left( \ln p_{y,l}^f - \ln \hat{p}_{y,l}^f \right)^2 / 2 \left( \sigma_{\text{len}}^f \right)^2 \right] \quad \text{B1.5}$$

where

$p_{y,l}^f$  is the observed proportion (by number) in length group  $l$  in the catch in year  $y$  for fleet  $f$ , and

$\sigma_{\text{len}}^f$  is the standard deviation associated with the length-at-age data for fleet  $f$ , which is estimated in the fitting procedure by:

$$\hat{\sigma}_{\text{len}}^f = \sqrt{\sum_y \sum_l \hat{p}_{y,l}^f \left( \ln p_{y,l}^f - \ln \hat{p}_{y,l}^f \right)^2 / \sum_y \sum_l 1} \quad \text{B1.6}$$

Equation B1.5 makes the assumption that proportion-at-length data are log-normally distributed about their model-predicted values. The associated variance is taken to be inversely proportional to  $\hat{p}_{y,l}^f$  to downweight contributions from expected small proportions which will correspond to small observed sample sizes (A. Punt, University of Washington, pers. commn).

The  $w_{\text{len}}$  weighting factor may be set at a value less than 1 to downweight the contribution of the catch-at-length data to the overall negative log-likelihood compared to that of the CPUE and survey data. The reason that this factor is introduced is that the  $p_{y,l}^f$  data for a given year frequently show evidence of strong positive correlation, and so are not as informative as the independence assumption underlying the form of equation B1.5 would otherwise suggest.



## Appendix B2 – Estimation of precision for the projections for Namibian hake OMP tests

The calculation of the probability intervals, as reported in Table 11.3 and some of the figures of Chapter 11, is effected by a parametric bootstrap procedure. Standard terminology for bootstrap methods as used in fisheries may be found in Smith *et al.* (1993).

[Note: The Namibian hake assessment presented in this thesis is not fleet-disaggregated. For clarity therefore, the equations below will ignore the fleet superscript  $f$ .]

### B2.1 Abundance data

Bootstrap samples are generated from the predicted abundance series obtained by fitting the model to the data. Error is then added to the predicted abundance indices according to the formula:

$$I_y^{i,U} = \hat{I}_y^i \exp(\varepsilon_y^{i,U}) \quad \text{where } \varepsilon_y^{i,U} \sim N\left(0, (\sigma_y^i)^2\right) \quad \text{B2.1}$$

when  $\sigma_y^i$  is provided or input, or:

$$I_y^{i,U} = \hat{I}_y^i \exp(\varepsilon_y^{i,U}) \quad \text{where } \varepsilon_y^{i,U} \sim N\left(0, (\hat{\sigma}^i)^2\right) \quad \text{B2.2}$$

when  $\sigma^i$  is estimated when fitting the model to the data, where:

$I_y^{i,U}$  is the abundance index for year  $y$  and series  $i$  in bootstrap data set  $U$ ,

$\hat{I}_y^i$  is the estimate of the abundance index for year  $y$  and series  $i$  obtained by fitting the model to the data,

$\sigma_y^i$  is the input value of the standard error for year  $y$  for survey abundance index  $i$ , adjusted as necessary to allow for estimated additional variance and inter-trawler variance in  $\ell nq$ , and

$\hat{\sigma}^i$  is the estimate of this standard error for index  $i$  (see equation 4.15).

Imprecision in the calibration factor between  $\ell nq_{Nansen}$  and  $\ell nq_{trawler}$  could be taken into account by replacing the estimate  $\Delta \ell nq = 0.100$  by  $\Delta \ell nq^U$  where:

$$\Delta \ell nq^U = \Delta \ell nq + \varepsilon - \sigma_{\Delta \ell nq}^2 / 2 \quad \varepsilon \text{ from } N\left(0, \sigma_{\Delta \ell nq}^2\right). \quad \text{B2.3}$$

but in the code actually implemented  $\Delta \ln q$  was treated as “data” in the interests of simplicity, i.e.,  $\Delta \ln q^U = 0.100$ .

## B2.2 Commercial catches-at-age

For the catch-at-age data, the bootstrap replicate process assumes an adjusted log-normal error distribution, and that these errors occur only in the assignment of the ages of the fish, rather than real fluctuations in selectivity at age from year to year. Bootstrap samples are generated from the model-fitted catches-at-age as follows:

$$C_{y,a}^U = \hat{C}_{y,a} \exp(\varepsilon_{y,a}^U) \quad \text{where } \varepsilon_{y,a}^U \sim N(0, \hat{\sigma}_{com}^2 / \hat{p}_{y,a}) \quad \text{B2.4}$$

where

$C_{y,a}^U$  is the number of fish caught of age  $a$  in year  $y$  in bootstrap sample  $U$ ,

$\hat{C}_{y,a}$  is the corresponding model estimate given in equation 4.18, and

$\hat{\sigma}_{com}$  is the associated estimate of standard deviation given by equation 4.19.

The pseudo catches-at-age are then scaled so that  $\sum_a w_{a+1/2} C_{y,a}^U = \sum_a w_{a+1/2} C_{y,a}$  for each year  $y$  (i.e., the total mass caught each year is assumed to be known without error). [Note that this is in any case implicit in equation 4.17, in which information on catches-at-age is used in the form of proportions.]

## B2.3 Survey catches-at-age

For the survey catch-at-age data, the bootstrap samples are generated in exactly the same manner as the commercial catches-at-age when assuming an adjusted log-normal error distribution.

# Appendix C1 – West coast hake OMP evaluations

## C1.1 Paper presented to the SAFC – June 1998 (MCM, 1998)

WG/06/98/D:H:37

### DEPARTMENT OF ENVIRONMENTAL AFFAIRS AND TOURISM SEA FISHERIES RESEARCH INSTITUTE

#### A REVISED OMP FOR THE WEST COAST HAKE RESOURCE AND A RECOMMENDED HAKE TAC FOR 1999

#### 1. SUMMARY

The results of robustness tests carried out for candidate OMPs for the West Coast hake resource are described. Adoption of a Fox-model-based OMP for this resource is recommended. Within the range of associated harvesting strategies from  $f_{0.05}$  to  $f_{0.15}$  investigated, it is the Institute's view that a choice close to  $f_{0.1}$  strategy be made for the OMP, which will then serve as the basis for West Coast hake TAC recommendations for at least the next three years. The overall TAC for hake for 1999 is the sum of contributions for the West and South Coasts. Calculation of the West Coast component awaits both a decision by the SFAC on their choice between OMP options, and evaluation of hake CPUE data for the 1997 season. However, in terms of the rules of the candidate OMPs suggested, the West Coast component for 1999 will not be less than 100 thousand tons. OMP testing for the South Coast hake resource is still in progress, and final selections for that resource will not be possible before 1999. Thus, and in the absence of any negative indicators for this resource, it is recommended that the South Coast contribution to the overall hake TAC for 1999 remain 51 000 tons. Hence, the overall TAC for hake (for all fisheries together) for 1999 would not be less than 151 thousand tons.

#### 2. OMP REVISION

Progress with revision of the OMP for the West Coast hake resource was reported in detail to the last meeting of the SFAC, so that this material will not be repeated here. That report provided 10-year projections of catch and spawning biomass under a variety of candidate OMPs. Note that to a good approximation, trends in spawning biomass mimic those to be anticipated in future catch rates (CPUE).

In considering the trade-offs between immediate TAC levels and longer-term improvements in CPUE, the SFAC indicated that it wished to see further computations focus on the range of OMP option that gave trade-offs corresponding to Fox-model-based OMPs linked to harvesting strategies from  $f_{0.05}$  to  $f_{0.15}$ . It further indicated that

the extent of TAC change from one year to the next should be limited to a maximum of 10%. Subsequent work has indicated that the average TAC change anticipated for the candidate OMP's under consideration is typically only 1-2%. This is so far below the 10% limit suggested, that it was considered unnecessary to formally include such a restriction on the OMP candidates as tested.

Results presented to the last SFAC meeting were for “deterministic” scenarios. These assume that current estimates of the status and productivity of the hake resource are exactly correct, and that information to be collected in future (both CPUE and scientific survey data) will be similarly perfect. Naturally this is unrealistically optimistic, and the “stochastic” analyses that have since been conducted make allowance for the presence of noise in the data and the consequent uncertainties.

Figure 1 shows 10-year projections for the TAC and the spawning biomass computed on this basis for the Fox-model-based candidate OMP's with linked  $f_{0.05}$ ,  $f_{0.10}$ ,  $f_{0.15}$  harvesting strategies. The solid lines in these plots show the central (median) predictions, while the dashed lines show the associated envelopes of uncertainty about these predictions (strictly, these are 90% probability intervals). Note that at the one extreme, the  $f_{0.05}$  option the largest short term catch increases, but the least longer-term increase in spawning biomass (and hence CPUE); at the other extreme, an  $f_{0.15}$  choice achieves the largest longer-term CPUE increase, but would likely see a slight decline in the TAC in the short term.

Figure 2 provides a clearer basis to summarise the differences between the three options. It plots likely levels with their ranges of uncertainty for three measures of anticipated performance over the next ten years for these three candidate OMPs: the average annual catch, the final spawning biomass level, and the increase in spawning biomass.

It is recommended that the SFAC focus on three objectives in deciding between these OMP options:

- 1) a high probability of achieving recovery to the biomass level which provides MSY (shown by the dotted line marked MSYL in the central block in Figure 2) within the next 10 years – the greater the proportion of the range shown above the dotted line in this Figure, the better this objective is achieved;
- 2) a low probability of a net spawning biomass decline over this 10-year period – the lesser the proportion of the range below the solid line in the right hand block in Figure 2, the better this objective is achieved; and
- 3) a low probability of a reduction in TAC early in the 10 year period – as evident from the TAC projection envelopes in Figure 1.

The  $f_{0.05}$  option best satisfies objective (3), but is poor for objectives (1) and (2). In contrast,  $f_{0.15}$  satisfies (1) and (2) well, but is poor with regard to (3). On balance, it seems that a choice of  $f_{0.1}$  (or a harvesting strategy close to this) would achieve the best compromise.

The results quoted above all presume that the underlying “base case” model of the West Coast hake population dynamics and its associated assumptions are exactly

correct. It is also important to check that if this is not the case, the OMP will (as far as possible) self-correct for this as further data become available over time, so that the resultant performance of the fishery over the next 10 years will remain close to the predictions of Figures 1 and 2, i.e. to check that the OMP is adequately “robust” to such uncertainties.

The Fox-model-based  $f_{0.1}$  candidate OMP has been subjected to most of the large number of such robustness tests listed in the previous report. The factors tested have been:

- A1: A different level of variability (0.2 instead of 0.45) in future hake recruitment.
- A2: Future changes in fishing efficiency which fail to be detected, so that CPUE data are not corrected to compensate:
  - a) positive: +2% pa
  - b) negative: -1% pa.
- A3: There are no future research surveys.
- A5: Carrying capacity drops by 50% due to some ecosystem change. Correspondingly, future average recruitment would also drop by 50%.
- B1: The commercial CPUE data are split into two separate series for small and for medium + large fish.
- B2: Natural mortalities-at-age are fixed at lower values than those estimated by an age-structures model – these values being surprisingly high.
- B3: Allowance is made for post-1990 variation of recruitments about the deterministic stock-recruitment relationship of the age-structured assessment model.
- B5: Discards (both past and future) are taken into account.
- B7: Results from the CPUE analysis which ignores the bycatch CPUE correlation effect are used.

Furthermore, some of these factors have been tested in combination.

In the interests of brevity, only results for those factors which were found to have the greatest impact on anticipated performance are reported here:

- a) the extent of variability in future hake recruitment: this value is poorly known for West Coast hake – the “base case” results assume a fairly large value for this variability which, roughly speaking, corresponds to an average variation of 45% pre year, whereas test A1 assumes a lower value of 20% (the value used also for the results shown in Figures 1 and 2);
- b) future positive bias in CPUE coupled with an absence of future research surveys (test A2a + A3): note that summer surveys did not take place in 1997 and 1998, there are questions about their resumption, and even if they do resume, possible gear change may lead to problems of comparability in the short term, so that it is both (regrettably) realistic and important to consider the implication of a possible absence of future surveys.

Figure 3 contrasts results for these various robustness tests for the Fox-model-based  $f_{0.1}$  candidate OMP by presenting results in a similar style to those in Figure 2. These

results give rise to some concern in the event of the combination of the circumstances envisaged in (b) above, which could lead to a marked spawning biomass reduction over the next 10 years. Hence, if the  $f_{0.1}$  option I adopted but surveys do not continue, particular care will need to be given to ensuring that the analysis of CPUE data does not overlook any factor that may be leading to enhance fishing efficiency.

Figure 3 also includes results for test B2, for which hake natural mortalities-at-age are set lower than the present best estimates. There is considerable concern that these estimate (which follow from the hake age composition data provided by the research surveys) may be too high, but it is comforting to note that the OMP does manifest considerable robustness to this source of uncertainty.

The Fox age-aggregated production model is not the only possible approach to link some  $f_{0.n}$  harvesting strategy in formulating a candidate OMP. An age-structured production model (ASPM) could also be used, and this approach was thoroughly investigated for a similar range of trade-offs between immediate TAC levels and longer-term spawning biomass recovery as for the Fox-model-based procedures described above. These calculations suggested that there was very little to choose between these approaches in terms of anticipated performance. However, the Fox-model-based procedures are simpler to define, more reliably tested and easier to implement, and are accordingly recommended.

### 3. WET COAST CONTRIBUTION TO THE 1999 OVERALL HAKE TAC

This contribution can be computed once the SFAC has chosen between the OMP options advised, and CPUE data for 1997 have been analysed. It should be noted that the rules for the OMP suggested include the provision that this contribution not be less than its level since 1995 of 100 thousand tons.

### 4. SOUTH COAST CONTRIBUTION TO THE 1999 OVERALL HAKE TAC

Separate evaluations for a revised OMP for the South Coast hake resource are still in progress, and are unlikely to be finalised before 1999. The South Coast situation differs in many respects from that for the West Coast fishery, particularly given the diversity of fisheries there, and this has to be taken into account. Therefore, it does not necessarily follow that the OMP chosen for West Coast hake will also turn out to be the most appropriate for South Coast hake.

In these circumstances, and noting that no negative indications regarding the status of this resource have become evident, it is recommended that the South Coast contribution to the overall hake TAC for 1999 be kept at its level since 1995 of 51 thousand tons (so that the overall hake TAC for 1999 will not be less than 151 thousand tons).

### 5. RECOMMENDATIONS

- i) A Fox-model-based OMP should be adopted to provide TAC recommendations for the West Coast hake resource for at least the next three years. Given the results above, the choice of the harvesting strategy component of this OMP should probably be close to  $f_{0.1}$ .
- ii) The West Coast contribution to the overall hake TAC for 1999 should be finalised by application of the OMP chosen as soon as analysis of the 1997 hake CPUE data has

been completed, though it should be noted that the OMP rules suggested preclude this contribution being less than 100 thousand tons.

- iii) The South Coast contribution to the overall hake TAC for 1999 should remain 51 000 tons.
- iv) The guideline division of the overall hake catches for 1999 between West and South Coasts should be the ratio 2:1.
- v) The overall TAC should apply to all forms of hake fishing in combination (i.e. all sources of fishing mortality on hake should be accounted for).

Dr A. Badenhorst  
Chairman: Demersal Working Group  
Sea Fisheries Research Institute  
18 June 1998

University of Cape Town

## West Coast Hake Revised Management Procedure

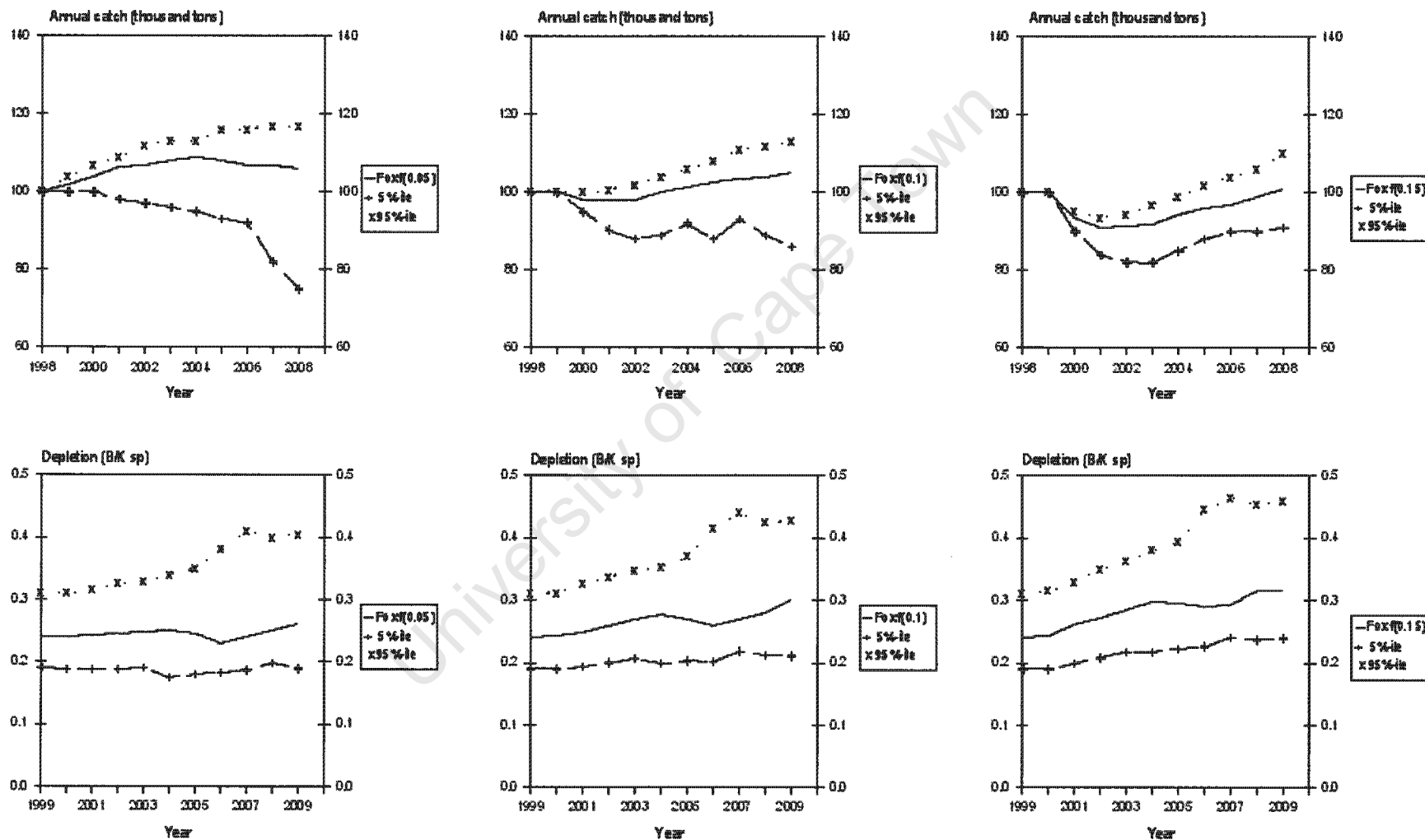


Figure 1: Stochastic projections (recruitment variability of 0.2) for Fox  $f(0.n)$  strategies.



## West Coast Hake Revised Management Procedure

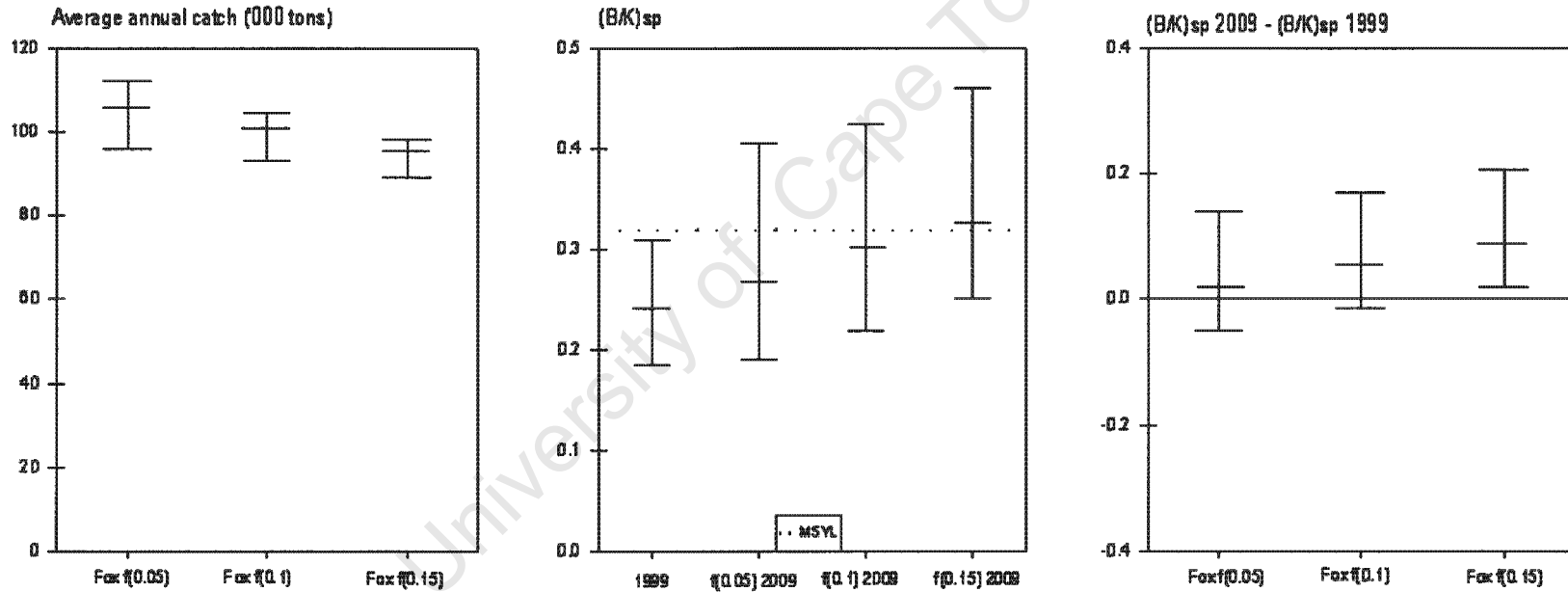


Figure 2: Graphical comparison of stochastic results (recruitment variability of 0.2) for Fox f(0.n) strategies.

## West Coast Hake Revised Management Procedure

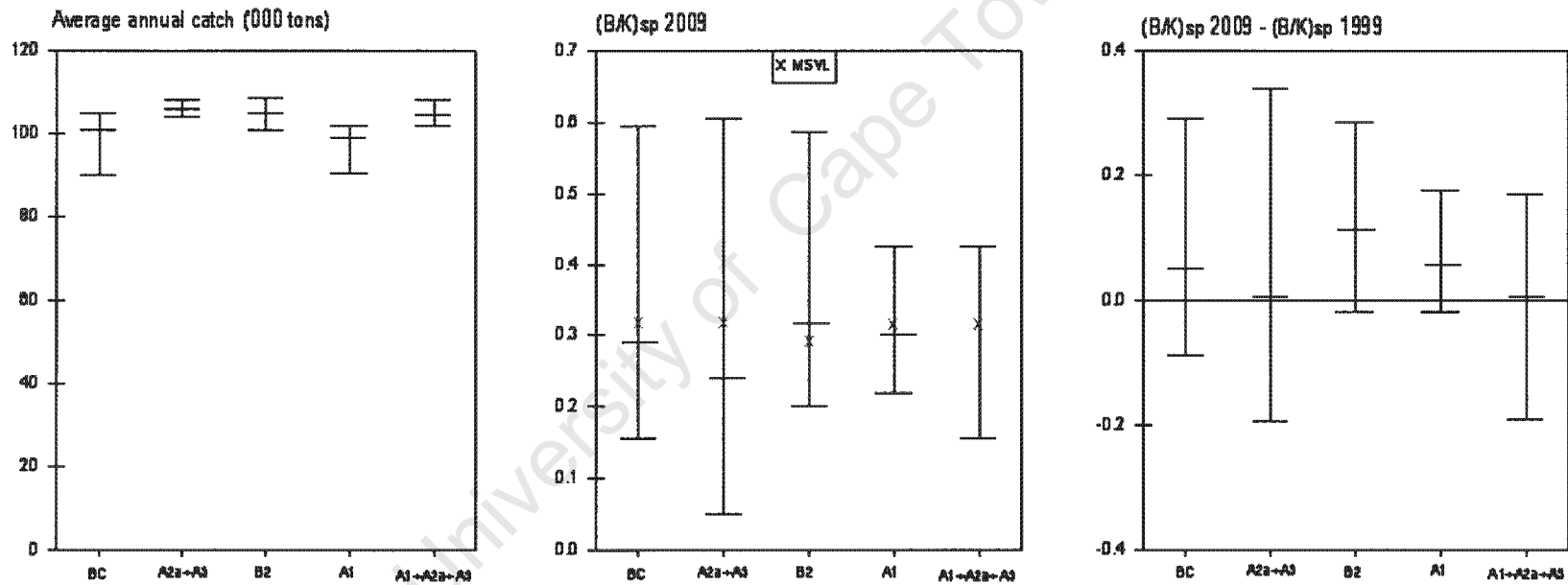


Figure 3: Graphical comparison of stochastic results for robustness tests A1 (recruitment variability of 0.2), A2a+A3 (future CPUE +2% pa, no future survey) and B2 (lower M) for Fox  $f(0.1)$  strategy.

## ADDENDUM

## SOME QUESTIONS (AND ANSWERS) ABOUT THE OMP FOR THE WEST COAST HAKE RESOURCE

- 1) Since the South Coast hake OMP is delayed until 1999, why not wait the West Coast one until then too, to be able to do more work on it?

Considerable time and effort has already been expended on the West Coast hake OMP development. Little further benefit is likely from devoting further resources to this exercise, i.e. a situation of diminishing returns. Resources are now better directed towards the South Coast hake OMP finalisation. Further work on the West Coast should rather be focused towards initiating the next revision, likely in about three years time, which is planned to take account, amongst other factors, of the two-species nature and sex-structure of the resource – extensions which will require some time to develop.

- 2) When natural mortality  $M$  is set lower than estimated from survey data, doesn't the OMP overshoot the biomass target too much, thereby unnecessarily depriving the industry of additional catch?

Test B2 in Figure 3 shows the anticipated results under the OMP when  $M$  is lower than currently thought, corresponding to a more productive resource. The OMP achieves automatic self-correction to a large extent, likely increasing TACs to 115 rather than 106 thousand tons over the next ten years. The biomass also rises further than anticipated under the base-case test, but the difference is only some 3% of  $K$ , which is not substantial. The OMP could of course be set to give larger TACs in this case, but this would simultaneously increase the probability of causing a resource decline if the base-case assumptions for  $M$  are correct – and one must keep in mind that resolution of the question of whether or not the base-case estimates of  $M$  are too high will likely take some year yet.

- 3) Shouldn't greater weight be given to the more recent data in the OMP, so that it is able to react faster to recent trends? (and hence be more robust?)

This would carry an increased likelihood of greater inter-annual fluctuations in the TAC, with up and down adjustments that are not necessary or desirable, and reflect the procedure adjusting more to noise in the data than to true underlying trends.

- 4) Could the TAC drop fast under some choices for an  $f_{0,n}$  strategy?

Of the options considered,  $f_{0.15}$  carries the greatest likelihood of a short-term drop in TAC. The most likely scenario under this choice would be a drop from the present level by a total of some 10% by 2001, following which a slow increase in TAC would follow (see Fig. 1).

- 5) Isn't the Fox model too simple to be reliable?

Greater complexity does not necessarily guarantee greater reliability. This is because of the danger that more complex models are often more likely to follow what is noise in the data rather than true underlying trends, thereby leading to unnecessary inter-annual fluctuations in the TAC. Tests of an OMP based on a more realistic, but also more complicated, age-structured production model which is fully updated from one year to the next given new data, showed precisely this poorer behaviour compared to the simple Fox model.

- 6) Shouldn't future surveys receive much more weight than CPUE in the OMP, given likely problems in interpreting the latter (because of potential problems allowing for bycatch effort direction, etc.)?

In the OMP as proposed, survey results are slightly over-weighted compared to CPUE data anyway, because the weighting of the former assumes that survey sampling error is the only contribution to noise in the survey results as an index of the underlying abundance. In reality, there are additional sources of noise in such data, such as variation from year to year in the proportion of the overall stock in the area surveyed. More complex weighting procedures seem unlikely to bring any large benefits, and could be complicated further by the need to perhaps try to make allowances for the possible short-term absence of surveys.

- 7) Is the OMP, once adopted by the SFAC and Minister, "cast in stone" for a minimum of three years?

No – should clear evidence come to light at any time that the assumptions underlying the basis on which the OMP was tested were seriously in error, review would commence immediately. A past example of a similar occurrence was the near-disappearance of anchovy at the end of 1996, a circumstance not foreseen in the development of the pelagic (pilchard-anchovy) OMP, which led to an immediate revision of the pilchard component of that OMP. Certain assumptions of the testing process could well be in error, e.g. the assumption made for the value of natural mortality  $M$  as discussed above. But it is also unlikely that evidence clearly favouring another value will become available before some extensive experimental work has first been conducted.

## C1.2 Additional information concerning the robustness tests

MCM (1998), reproduced above, lists the robustness tests performed on the west coast OMP. However, some details were omitted in that report so that more information on these tests is provided here.

The robustness tests were divided into two main groups. The first group (A) concerned the future data generated by the operating model, while the second group (B) tested the effect of alternative choices or assumptions concerning past data on the assessment results.

B2: The natural mortalities-at-age,  $M_a$ , were fixed at lower values than those estimated by the ASPM (Geromont and Butterworth, 1998a) – these values, which follow from the signal provided by the survey catch-at-age data, being surprisingly high. Thus, in conjunction with fixing  $M_a$  at lower values (0.7, 0.7, 0.7, 0.6, 0.5, 0.4, 0.3, 0.3) and assuming a negative slope of  $-0.2$  at older ages for both commercial and survey selectivities, the survey data were excluded from the likelihood function in the assessment for this case.

B5: Discards (both past and future) are taken into account by inflating the total annual catch by 25% and distributing these discards between the 1- and 2-year old fish by increasing the reported numbers caught each year by an 8:1 ratio for these two ages.

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## Appendix C2 – South coast *M. capensis* OMP evaluations

### C2.1 Paper presented to the CAF – June 2000 (MCM, 2000a)

WG/06/00/D:H:18

DEPARTMENT OF ENVIRONMENTAL AFFAIRS AND TOURISM  
MARINE AND COASTAL MANAGEMENT

#### PROPOSED REVISED OPERATIONAL MANAGEMENT PROCEDURES FOR SOUTH COAST HAKE

June 2000

##### Summary

Proposals are made for OMPs to provide the basis for recommending South Coast hake *TACs* for the next two to three years. These proposals treat shallow water *Merluccius capensis* and deepwater *M. paradoxus* Cape hakes separately. This is necessary because, unlike the offshore trawlers, the developing longline and handline fisheries on the South Coast take *M. capensis* almost exclusively. For *M. capensis*, three options for an OMP are presented. All are based on the Fox age-aggregated production model, and differ in the harvesting strategies applied:  $f_{0.25}$ ,  $f_{0.3}$  and  $f_{0.35}$ . The choice between these involves a trade-off between increases in catch and decreases in catch rate (CPUE), or vice versa. The  $f_{0.3}$  option is recommended as it is anticipated to keep both catch and CPUE fairly steady over the next few years. Industrial input has emphasised the importance of maintaining catch rates near recent levels for the economic viability of the fishery. The South Coast *M. paradoxus* resource appears likely to be a component of the West Coast *M. paradoxus* stock. Pending later development of a combined West and South Coast OMP for *M. paradoxus*, it is recommended that the South Coast *M. paradoxus* component of the overall hake *TAC* be set as a defined proportion (calculated from past trends in the fishery) of the *TAC* recommendation provided by the current OMP for West Coast hake.

##### Background

Throughout the early 1990's, the *TACs* recommended for the West and South Coast hake resources were calculated by means of OMPs based on the Schaefer age-aggregated production model for both species combined, coupled to an  $f_{0.2}$  harvesting strategy. However, in the mid-1990s it became necessary to keep catches constant for an interim period while these OMPs were revised. The reasons were linked to necessary revisions of the processes used to refine CPUE data; inappropriate previous interpretations of these data had led to the Schaefer model no longer providing adequate predictions of resource trends.

In 1998, following resolution of these problems, a revised OMP for West Coast hake was adopted, and has been used to provide the associated *TAC* recommendations since then. A key change from the previous OMP was to move to the Fox form of the age-aggregated production model. However, *ad hoc* approaches continued to be used to develop recommendations for the South Coast component of the *TAC*. The reason for this was the rapidly changing nature of this fishery, with an increasing and substantial component of the catch being taken by longlining and handlining. Unlike offshore trawling, these methods of fishing take essentially only *M. capensis*. In addition, line fishing selects older fish than does trawling. It therefore became evident that a South Coast hake OMP for both species combined was no longer viable. Instead, the two species would need to be assessed separately, requiring the development of separate OMPs for each. Naturally, this more complicated process, which involves splitting the historic catches by species, and consideration of the associated uncertainties, has taken longer than was the case for the West Coast (where longlining, as a proportion of the overall catch, is not nearly as substantial).

## Assessments

### *M. capensis*

The line and inshore trawl fisheries for hake on the South Coast take *M. capensis* virtually exclusively (only the offshore trawl fishery reflects a substantial component of *M. paradoxus* in its catch). Fig. 1 shows a recent decrease in the estimated historic spawning biomass trend for this resource, apparently as a result of a period of weaker recruitment, following a period of stronger-than-average recruitment. Despite the recent downward trend in CPUE that underlies this interpretation, the resource is estimated to be in a healthy state, well above the level estimated to yield MSY. It should, however, be noted that the resource is estimated to be relatively small in absolute terms (compared to hake on the West Coast), with a current spawning biomass of some 60 thousand tons.

### *M. paradoxus*

Attempts to conduct a separate assessment for *M. paradoxus* on the South Coast have not yielded sensible results. The most likely reason for this is that this is not an isolated stock, but rather a component of a single *M. paradoxus* stock that extends continuously from the West to the South Coast. As such, *M. paradoxus* is more sensibly assessed for both the West and South Coasts combined.

No further work on developing a separate OMP for South Coast *M. paradoxus* has therefore been pursued. Rather, in the longer term, it is intended to develop an OMP for West and South Coast *M. paradoxus* combined. Development of this new *M. paradoxus* OMP, together with new separate OMPs for the more discrete West Coast and South Coast *M. capensis* stocks will commence once an interim OMP for South Coast *M. capensis* has been accepted. These OMPs are scheduled for implementation in 2-3 years time, then replacing the current West Coast hake OMP and the (interim) South Coast *M. capensis* OMP proposed below. This leaves a temporary void in the basis for South Coast *M. paradoxus* *TAC* recommendations. A proposal to address this issue until the combined West and South coast *M. paradoxus* OMP becomes available is also made below.

## OMP Proposals for South Coast hake

### *M. capensis*

A wide range of simulation tests of candidate OMPs for the South Coast *M. capensis* resource has been carried out. These include consideration of the consequences of uncertainties about: the species-split for the earlier catches in the fishery; the value for natural mortality; the continued availability of information from fishery-independent research surveys; and possible changes in the relative magnitudes of the longline- and the trawl-based components of the fishery.

A particularly important consideration is that economic viability requires CPUE levels to be maintained at the average value over the 1990s. This is based on information provided by representatives the hake fishing associations. Maintaining the CPUE level requires that resource abundance be kept somewhat high, with a consequent reduction in the risks associated with other uncertainties when making recommendations for *TACs* for this fishery. For this reason, and also because this OMP is anticipated to be utilised for the next 2-3 years only, before revision as described above, it is not seen as necessary to go into details on the quantitative evaluations of the consequences of the uncertainties listed above. The candidate OMPs put forward here have been shown to demonstrate adequate robustness to these uncertainties. Thus the key consideration in selecting an OMP for the South Coast *M. capensis* resource becomes the trade-off between catches and catch-rates (CPUE) over the next few years.

Fig. 2 indicates the anticipated trends in catches and spawning biomass for South Coast *M. capensis* under three alternative OMP candidates. The spawning biomass trends indicated are essentially equivalent to the CPUE trends to be expected. The form of the OMP applied is as at present for the West Coast hake. This is an age-aggregated Fox production model, implemented in this case by making use of both offshore fleet CPUE data (for *M. capensis*, based on splitting the catch by species according to depth) and research survey biomass estimates for *M. capensis* for the 0-500 metre depth range. What distinguishes the three curves shown in the plots in Fig. 2 is the harvesting strategy applied to calculate the *TAC* - results are shown for  $f_{0.25}$ ,  $f_{0.3}$  and  $f_{0.35}$  options. As for the West Coast hake OMP, the smoothing parameter  $\delta$  in the *TAC* formula, introduced to limit the extent of *TAC* fluctuations from year to year, is kept at 0.5.

Note that the  $f_{0.25}$  option projects increased catches, but at the expense of a fall in the spawning biomass and hence the catch rate. On the other hand,  $f_{0.35}$  predicts a catch rate increase, but at the expense of a reduction in the current catch level. The intermediate option,  $f_{0.3}$ , is anticipated to achieve roughly steady levels of both catch and catch rate over the next few years.

On the basis of these results, it is recommended that the CAF adopt the  $f_{0.3}$  OMP option for recommending *TACs* for South Coast *M. capensis* for the next three years, with re-evaluation anticipated to occur at or shortly before the end of that period.

### *M. paradoxus*

Given that the *M. paradoxus* on the South Coast is likely a component of the West Coast *M. paradoxus* stock, and that most of the West Coast hake catch is comprised of *M. paradoxus*, it seems reasonable that changes in the allowed catch of South Coast *M. paradoxus* should



match trends in West Coast hake abundance, as reflected in the *TACs* provided by the West Coast hake OMP.

It is therefore **recommended** that the CAF agree that for the next three years (or until possible earlier OMP revision is effected), the South Coast *M. paradoxus* *TAC* be set as a proportion of the West Coast *TAC* as evaluated by the present West Coast hake OMP. The proportion is defined as the ratio of the average catch of *M. paradoxus* on the South Coast over the preceding five years, to a similar average for the total West Coast hake catch.

C.J. Augustyn  
Acting Director: Offshore Resources  
June 2000

## **C2.2 Paper presented to the CAF – August 2000 (MCM, 2000b)**

WG/06/D:H:19

### **DEPARTMENT OF ENVIRONMENTAL AFFAIRS AND TOURISM MARINE AND COASTAL MANAGEMENT**

#### **RECOMMENDATION TO THE CONSULTATIVE ADVISORY FORUM FOR THE HAKE *TAC* FOR 2001**

August 2000

#### **Summary**

A global Total Allowable Catch (*TAC*) for the Cape hakes (*Merluccius capensis* and *M. paradoxus*) of 166 000 t is recommended. Although there are three components to the assessment, viz. a West Coast component and two South Coast components, one for *M. capensis* and the other for *M. paradoxus*, a global *TAC* is recommended because of the difficulties involved in managing and policing separate *TACs*. Nevertheless, the relative magnitudes of the three separate components of the global *TAC* must be considered when access rights are allocated, to ensure that fishing effort distribution matches that of the resource. To achieve this goal, rights allocations to longline, handline and inshore trawl on the South Coast must not exceed the capacity of the South Coast *M. capensis* resource. It must also be remembered that the offshore trawl fishery on the South Coast, although taking mostly *M. paradoxus*, will also take some *M. capensis*.

A procedure to apportion the *TAC* among the four sectors of the hake fishery is presented. This procedure will balance the exploitation of the three components of the hake resource with the estimated productivity of each component. It is considered that this approach will be almost as effective as formal resource-specific *TACs*, but easier to implement and manage.

## Background

The hake fishery off South Africa is based on two hake species, the shallow-water and deep-water Cape hakes (*Merluccius capensis* and *M. paradoxus*), that differ mainly in their biology and distribution. They are similar in appearance and it is not possible to distinguish them in cleaned or processed form without using time-consuming molecular techniques. There is very little difference in quality, and no difference in market value between the two species for trawl-caught hake. Trawl-caught hake are marketed as a single commodity and it is not possible to obtain species-disaggregated commercial catch statistics.

Consequently, the assessment methods applied in the past have, of necessity, had to treat the two Cape hakes as a single species. In terms of the Operational Management Procedure (OMP) applied during the early 1990s, the hake resources on the West and South Coasts were assessed separately, but a global *TAC* was set. Allocations to smaller, inshore operators were generally taken close to their base of operations, and the offshore operators were requested to manage their fishing activities such that the global *TAC* was apportioned between the West and South Coasts in a 2:1 ratio. This arrangement was easier to manage than, applying formal, area-specific *TACs*.

With the advent of a line fishery (including both handline and longline) that targets mainly *M. capensis*, it has become necessary to assess the two species separately to ensure balanced exploitation of the two species. In addition, a balance between the catches taken on the West and South Coasts equivalent to the productivity of the respective resources must be maintained.

## West Coast contribution to the *TAC*

In terms of the revised OMP for the West Coast (ICSEAF division 1.6) component of the hake resource which was accepted and implemented in 1998, the recommended contribution to the *TAC* by this component is 107 000 t (Table 1). This OMP defines the selection of input data and calculates the recommended *TAC* based on those data. The input data are: annual nominal catch for 1917-2000 (fig 1a); historical catch per unit effort (CPUE), standardised by power factors for 1955-1977 (fig. 2a); post 1977 CPUE series standardised by General Linear Modelling (GLM), split into two series (1978-1986 and 1993-1999) to account for changes in fishing selectivity (fig 2a); and relative biomass indices with associated standard errors for summer (1985-1999) and winter surveys (1985-1990) (fig 3).

Due to technical problems, there were no direct biomass surveys by the FRS *Africana* in 2000. The GLM-standardised CPUE in 1999 is estimated to be the lowest since 1995. This arises partly from a changed distribution pattern of the fish, but may also reflect variations in environmental factors beyond those that can be taken into account in the GLM. This emphasises the importance of the fishery-independent biomass indices as they would provide

additional evidence to aid in deciding whether the change in CPUE reflects a change in abundance or simply random effects. However, it should also be emphasised that the OMP selected has been tested for robustness in the face of fluctuations of this nature, and will, over time, adjust *TACs* to compensate if necessary.

Table 1. Contributions to the global *TAC* by the three components of the assessment of the Cape hake resource

Component of the assessment	Contribution
West Coast - both species combined (ICSEAF Div. 1.6)	107 000
South Coast <i>Merluccius paradoxus</i> (ICSEAF Div. 2.1/2.2)	34 000
South Coast <i>Merluccius capensis</i> (east of 20°E)	25 000
<b>Global <i>TAC</i></b>	<b>166 000</b>

### South Coast contribution to the *TAC*

Unlike for the West Coast, the longline and handline catches taken on the South Coast are a substantial portion of the hake catch. These “line” fisheries target *M. capensis* almost exclusively, and select older, larger fish (predominantly large, highly fecund females) than do the trawlers. In addition, the inshore trawl fleet targets exclusively *M. capensis*. These differences in selectivity between the sectors in the fishery means that the two species have to be assessed separately to ensure that an increase in line fishing does not put the *M. capensis* resource at risk.

#### a) *M. capensis*

Three candidate OMPs for the *M. capensis* resource on the South Coast were presented to the previous meeting, in June 2000, of the Consultative Advisory Forum (CAF). The CAF selected an OMP that implements an  $f_{0.3}$  harvesting strategy and the following input data: annual nominal catch for 1967-2000 (fig 1b); historical CPUE (1969-1977) for both the offshore fleet (both hake species combined), standardised by power factors (fig 2b); GLM-standardised CPUE for the offshore fleet for *M. capensis* (fig 2b); and relative biomass indices with associated standard errors for spring and autumn surveys (fig 4). In terms of this OMP the recommended contribution to the *TAC* by this component of the resource is 25 000 t (Table 1).

#### b) *M. paradoxus*

Model fits obtained to date are unrealistic, quite possibly because these fish are a component of the West Coast stock of this species, and migration occurs between the two regions. A mechanism to adjust the *TAC* from the West Coast OMP to incorporate the portion of the *M. paradoxus* stock on the South Coast was presented to, and accepted by, the CAF at the June 2000 meeting. The recommended contribution to the *TAC* by this component is 34 000 t (Table 1).

### Associated issues

Some important issues related to allocation arise from the OMP revision process

#### 1. Handline catches on the South Coast

Uncontrolled growth in the informal handline fishery on the South Coast continued during 1999 and the first half of 2000. The landings from this sector have increased to an

estimated 2740 - 3500 tons in 1999. This sector is fast becoming a major component of the South Coast hake fishery, and urgent action is required to control the escalating catches.

## 2. Effort limitation

It is important to stress that the approach underlying both the West Coast hake and South Coast *M. capensis* OMPs, is a **constant fishing effort** strategy. This means that when the resource size increases (or decreases), the *TAC* is moved up (or down) **in proportion**, with the aim that the same number of vessel-fishing-hours as the previous year will be required to take the catch. In other words, a change in abundance is accompanied by a proportional change in catch rate and *TAC* so that the adjusted *TAC* will be taken without adjusting the amount of fishing effort. Thus, if increases in *TAC* are allocated to new entrants with new vessels, not only must the percentage shares of existing quota holders in the fishery be reduced, **BUT ALSO** their fleets must be reduced in the same proportions. Unless this is done, an excess of fishing capacity will develop. Overcapitalisation is an unnecessary waste of the country's resources, and will lead to a greater concentration of fishing effort by the fleet as a whole on bycatch species, to the probable long-term detriment of sustainable utilisation of these other resources.

## 3. Apportioning the *TAC* among fishing sectors and regions

The following points must be considered when the global *TAC* is apportioned among the different fishing sectors and regions. See Appendix A for a worked example based on the *TAC* recommendation for 2001, and the allocations made to the Inshore and "Line" sectors for 2000.

- ◆ Allocations to the inshore trawl fleet, to the informal handline fishery, and to the longliners based on the south coast must not exceed the productivity of the South Coast *M. capensis* resource.
- ◆ Although the offshore trawl fleet takes mainly *M. paradoxus*, it will take some *M. capensis*.
- ◆ Increases or decreases in the global *TAC* as a result of changes in the abundance of *M. paradoxus* should be absorbed by the offshore trawl sector so that undue pressure is not placed on the *M. capensis* resource.

## Recommendations

A global *TAC* for the Cape hakes (*M. capensis* and *M. paradoxus*) of 166 000 t for the year 2001 is recommended.

In addition, it is **strongly recommended** that those undertaking allocation decisions pursue calculations along the lines of those illustrated in Appendix A to ensure appropriate balance between allocations and the productivity of each component of the hake resource, and in particular, to protect the *M. capensis* resource on the South Coast. Judicious apportioning of the *TAC* among the different fishery sectors could be almost as effective as applying formal stock-specific *TACs*, but will be easier to implement and manage.

R.W. Leslie  
Chair: Demersal Working Group

## APPENDIX A

This Appendix serves to illustrate the concerns associated with apportioning the global *TAC* among the hake fishing sectors. It is based on the *TAC* recommendations for the year 2001, and on the allocations made to the Inshore and "Line" sectors in the year 2000. The allocations per sector used here ARE NOT intended as a recommendation, but merely serve to illustrate the factors that must be balanced when the global *TAC* is apportioned among the different hake fishing sectors.

**A. The components of the *TAC*<sub>2001</sub>.**

West Coast OMP <i>TAC</i> <sub>2001</sub>	107 000
Adjustment to the WC OMP <i>TAC</i> <sub>2001</sub> to account for <i>M. paradoxus</i> on the South Coast	34 000
South Coast <i>M. capensis</i> OMP <i>TAC</i> <sub>2001</sub>	25 000
Global <i>TAC</i>	166 000

**B. Allocations to sectors that exploit *M. capensis* on the South Coast.**

The catches taken by the handline, longline and inshore trawl sectors of the hake fishing industry are almost exclusively *M. capensis*. Therefore their allocations must be viewed in conjunction with the estimated *TAC* of 25 000 t for the South Coast *M. capensis* resource.

For the purposes of this example, the allocations for the inshore trawl and handline sectors for the year 2000, and 45% of the longline allocation (the proportion taken on the South Coast) are used as follows:

Inshore trawl	9 500
Handline	5 500
Longline (45% of the 10 000 t allocation)	4 500
Total	19 500

Therefore, in effect, an amount of 5 500 t (25 000 – 19 500) of *M. capensis* is available to the offshore trawl sector of the South Coast, east of 20°E, using the above scenario.

Note:

1. The handline reserve is presently under-utilized by an estimated 1 000 t.
2. There is likely to be pressure from the fishing industry to allow a greater proportion of the longline allocation to be caught on the South Coast.
3. The inshore trawl allocation has, in the past been maintained at approximately 6% of the *TAC*

**C. Allocations to sectors that exploit mainly *M. paradoxus*.**

The offshore trawl sector fishes in deeper water than the other three fishing sectors, and, therefore, takes mainly *M. paradoxus*. Nevertheless, over the past 5 years, catches taken by the offshore trawl sector on the South Coast, east of 20°E, have averaged 35% *M. capensis*, and 65% *M. paradoxus*.

If 35% of the hake catch is *M. capensis*, then a catch of 5 500 t of *M. capensis* equates to a total hake catch of 15 714 t. Therefore the offshore trawl sector should not catch more than 16 000 t of hake east of 20°E (the average catch over the past 5 years is 17 800 t).

**D. Implications**

1. The take of *M. paradoxus* east 20°E is limited by the amount of *M. capensis* available to the offshore trawl sector.
2. It may be possible for the offshore fleet to reduce the proportion of *M. capensis* in the catch by reducing the effort in the 200-300 m depth range, and increasing the effort in deeper water.
3. It is assumed that the *M. paradoxus* resource is a single stock, so it is not necessary for the "South Coast *M. paradoxus*" to be taken from the South Coast.

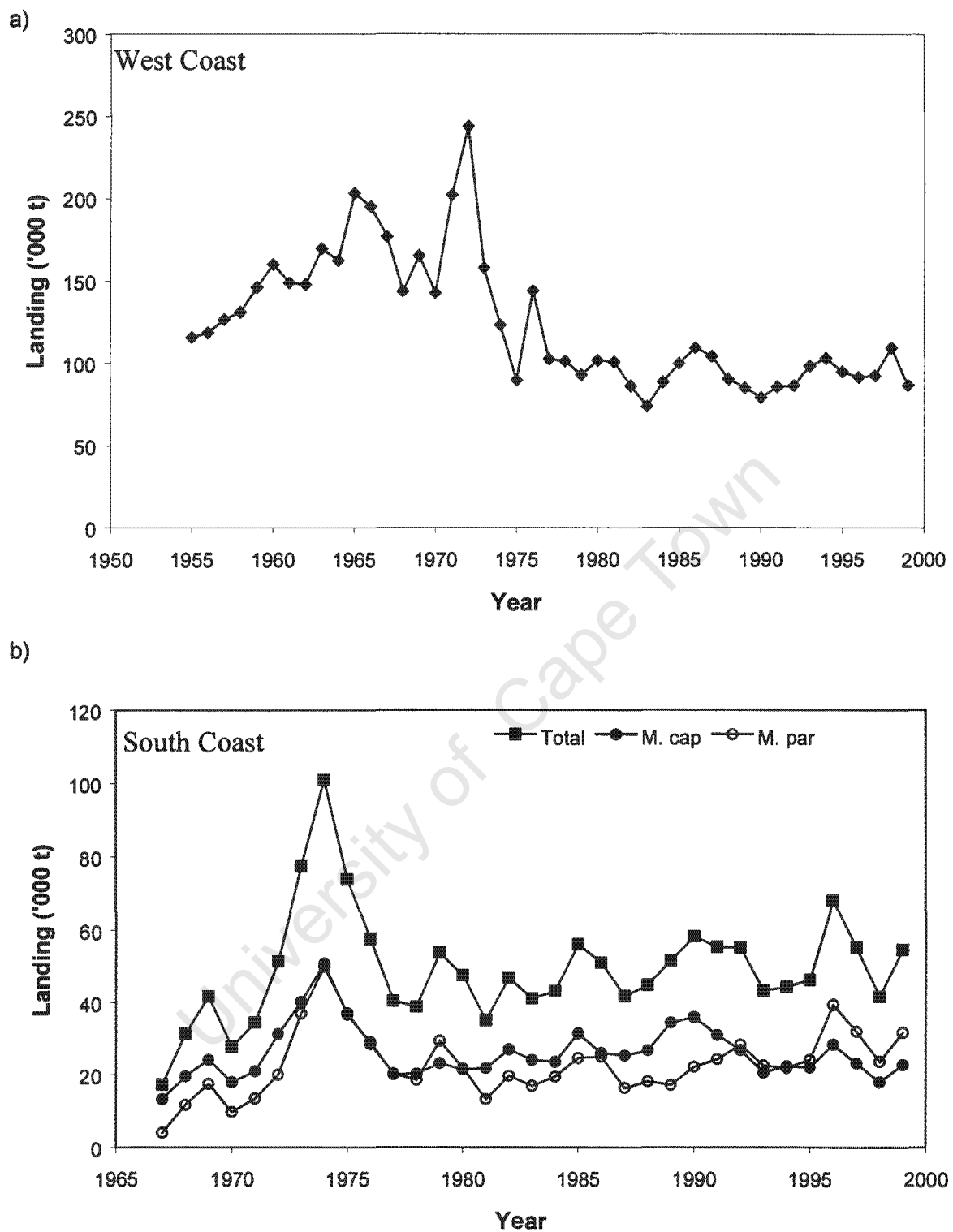


Figure 1. Annual landings of Cape hakes on the (a) West Coast and (b) South Coast.

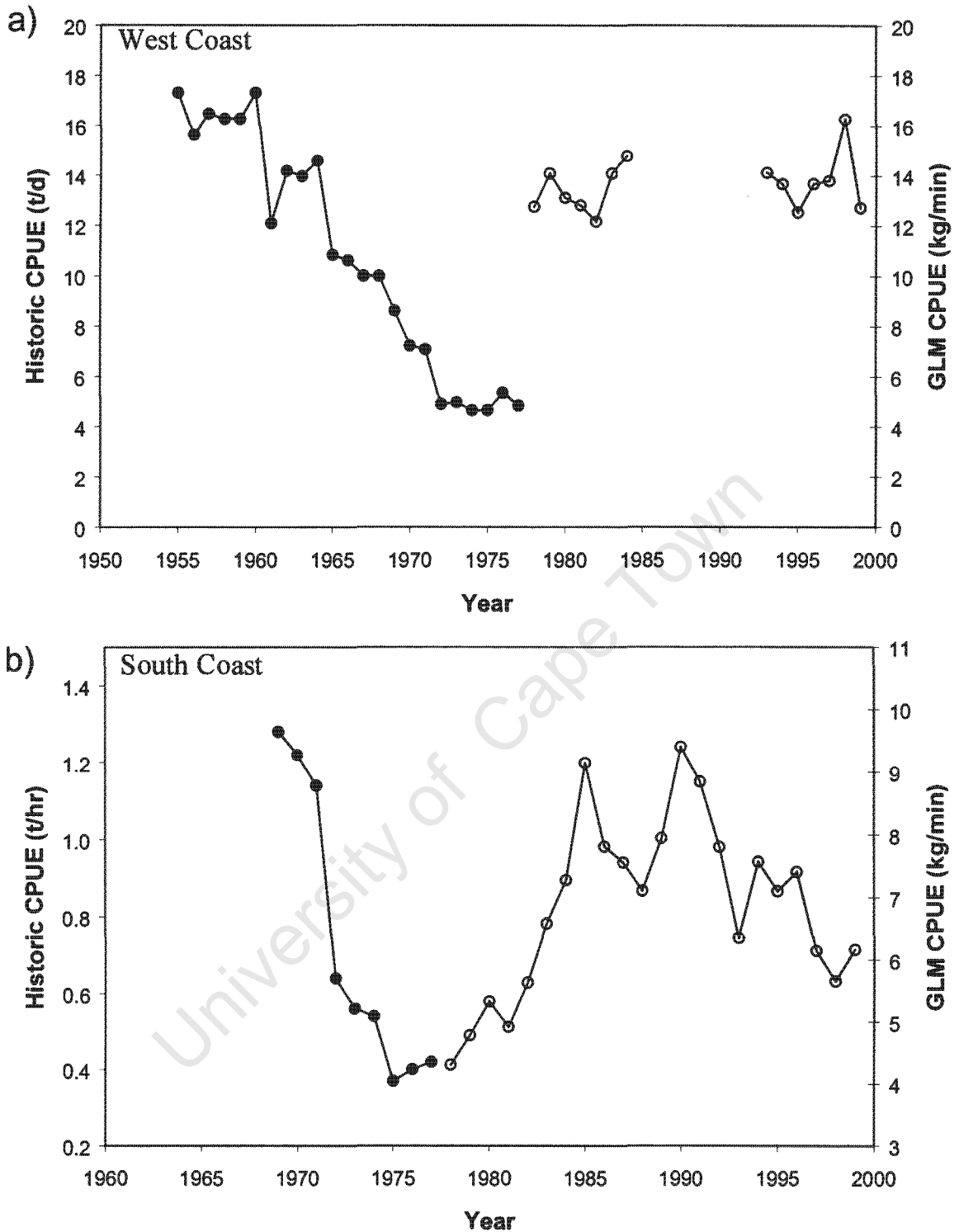


Figure 2: Historic CPUE series standardised by power factors (solid circles) and GLM-standardised CPUE (open circles) for the (a) West Coast and (b) South Coast. Note the historic and GLM CPUE series do not have the same units and are not directly comparable and that the GLM series for the South Coast is for *M. capensis* only.

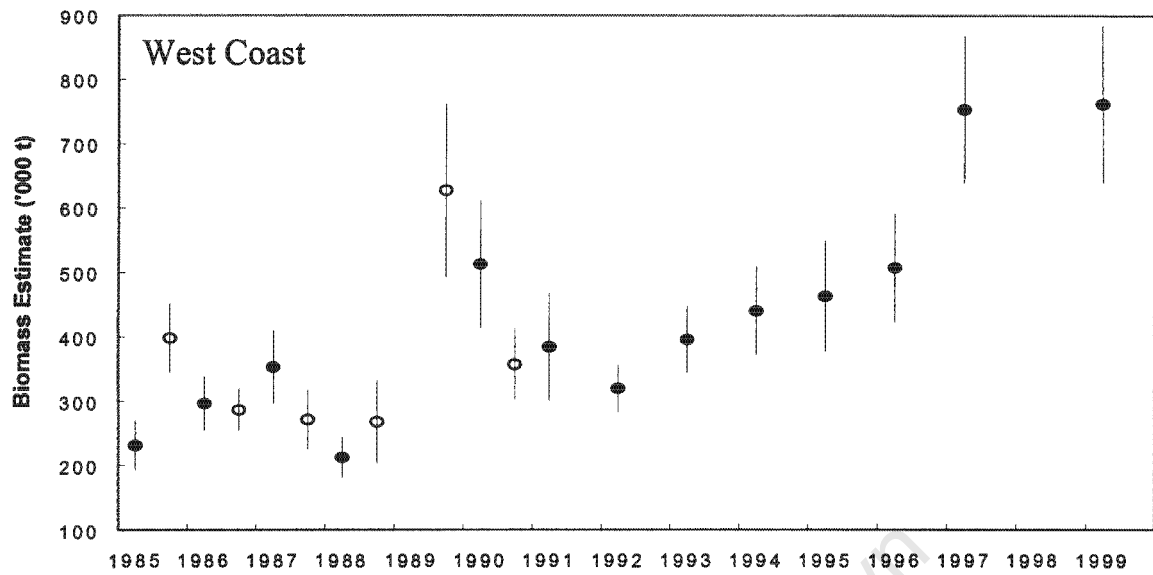


Figure 3: Direct survey biomass estimates for Cape hakes (0-500m) from summer (solid circles) and winter (open circles) surveys of the West Coast. Error bars represent one standard error

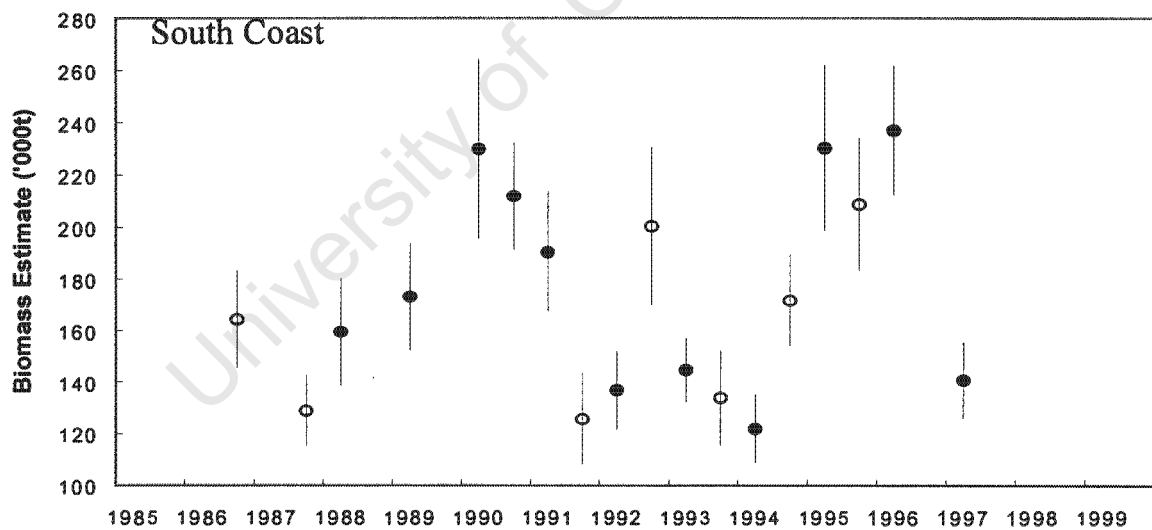


Figure 4: Direct survey biomass estimates of *M. capensis* (0-200m) for spring (open circles) and autumn (closed circles) surveys to the South Coast. Error bars represent one standard error.



## C2.3 List of robustness tests for the south coast *M. capensis* revised OMP

This list of robustness tests, developed by the MCM Demersal Working Group, is taken from Geromont and Butterworth (2000a, 2000b).

### A: Robustness tests related to the input data

- 1) Investigate sensitivity to alternative options for, or trends/biases in, the pre-1978 CPUE data (species-lumped data are fitted at present) by assuming a decline of a) 50% and b) 85% in the historic CPUE series.
- 2) a) Investigate sensitivity to the pre-1978 species split of the offshore catch (currently assumed 62% *M. capensis*), by assuming a *M. capensis* proportion of 82%.  
b) Investigate sensitivity to different proportions of *M. capensis* in the offshore catch from 1978 to 1998: *M. capensis* catches 25% lower.
- 3) Investigate sensitivity to pre-1974 inshore fleet catch levels by assuming catch levels of 6 000 tons (currently assumed equal to their 1974 level of some 10 000 tons).
- 4) Fit to survey abundance data for different depth ranges (0-200 instead of 0-500 m).
- 5) Take account of trawl discards and natural predator thefts from longlines. For this test, it is assumed that trawl discards constitute 10% of the annual landed trawl catch; to breakdown the discards by age the ratio of the numbers by age in the observer sampling of discards (approximately 0.1:0.5:0.4 for ages 1, 2 and 3 respectively) is used. Natural predator thefts from longline is assumed to constitute a 10% of the longline catch; the size composition of their catches is assumed identical to that of the fish finally landed.
- 6) Investigate sensitivity to omission of survey abundance data in model fit.

### B: Robustness tests related to the model

- 1) Investigate sensitivity to age-dependence in natural mortality,  $M$ , by a) estimating and b) fixing a separate  $M$  for younger ages ( $a < 7+$ ) and for the plus-group ( $a = 7+$ ).
- 2) Investigate the sensitivity to lower values of age-independent natural mortality ( $M=0.4, 0.5, 0.6$  and  $0.7$ ).
- 3) Investigate sensitivity to alternative assumptions for commercial (offshore) selectivities-at-age (increase the negative lobe at larger ages assumed for the inshore fleet selectivity from 0.3 to 0.4).

- 4) Extent period over which stock-recruitment residual are estimated (from 1967 instead 1978 in the Reference Case).
- 5) Explore fixing the “steepness” parameter,  $h$ , to 0.8 (estimated in the fit for the Reference Case).
- 6) Investigate sensitivity to relaxing the assumption that the resource was at its pre-exploitation equilibrium level in 1967 (assume  $B_{1967}^{SP} / K^{SP} = 0.7$ ).

### **C: Robustness tests related to projections**

- 1) Investigate the effect on projections if there were no future survey data.
- 2) Investigate the extent of fluctuation of future recruitments ( $\sigma_R = 0.25$  instead of  $\sigma_R = 0.45$  assumed in the Reference Case).
- 3) Investigate the effect of different level of fleet-disaggregated catches by assuming a fleet-disaggregated catch split of 1:4:5 for the offshore:inshore:longline fleets compared to the Reference Case split of 4:4:2.