Report on progress with refined hake assessment

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Work is in progress on developing refined Operating Models for the hake resource to form the basis for the simulation testing of the next OMP due for adoption late in 2010. The primary form of model used is likely to be an extension of the area-specific selectivity-based approach used in 2006 (i.e. using changes in selectivity by area rather than explicit movement models to reflect changes in hake distribution with age). Two key new features, as recommended by the International Stock Assessment Workshop held in December 2008, are accounting for gender differences (because male and female hake grow at different rates, confounding the interpretation of length distribution data if this is not taken into account), and fitting directly to age-length data rather than to derived age distributions to account properly for biases that otherwise enter evaluations.

We attach a **DRAFT** on the associated assessment paper currently under development. Note that this is **NOT final**, either in terms of editing or (preliminary) results shown, but is provided now to **FACILITATE FEEDBACK**. The primary task of the international stock assessment workshop taking place over November 30 to December 4 will be to review progress with the development of Operating Models and make recommendations for their finalisation early in the new year. Towards this end, work must now be sharply focussed to ensure that results of analyses to be tabled at the start of that workshop are as informative as possible. Accordingly feedback is requested from DWG members and observers (and will also be requested of the three-person international panel) on the following:

A) Selection of a provisional base case

Comments on any suggested changes to data used or assumptions made in the draft document attached are requested **BY FRIDAY 23 OCTOBER.**

Lest there be any misconceptions, this does **not** involve commitment to final selections in this regard. The model developed takes about a day's computer time to run. Clearly therefore it will **not** be possible to run every combination of every possible selections from alternatives for a number of data choices and assumptions. Rather only single factor variations around a provisional base case are viable to explore as sensitivities. **That** is the reason why such a provisional base case needs rapid agreement.

B) Prioritisation of sensitivities

For the reasons given above, the number of sensitivities that can be explored before the end November workshop is not limitless. Some initial possibilities for sensitivities are listed below. Feedback is requested **BY FRIDAY 6 NOVEMBER** on these sensitivities and their relative priority. In making suggestions on this, please have regard to the numerous sensitivities explored for the previous set of Operating Models. Aspects to which results for those were found to be insensitive are rather unlikely to have major impacts on results for these refined models.

Data input options

Catches

- Inshore trawl catches – are they all *M. capensis*? – T Fairweather
- Update of species-split algorithm given data for the last few years – OLRAC

CPUE

- Downweighting or elimination of spatial strata with currently little fishing (e.g. north of 31°S) from area-weighted offshore trawl CPUE index – J Glazer and T Fairweather (also OLRAC and R Leslie)

- Alternative depth stratification of offshore trawl CPUE index to take deeper strata into account explicitly – J Glazer and T Fairweather

- Alternative choices for the δ parameter included in the log-normally based CPUE standardisation be able to incorporate zero CPUE observations (including omitting such data and setting δ to zero) – J Glazer

- Alternatives to the approach to GLM3 (Fairweather *et al*., 2009) in regard to commercial size distribution estimation by depth – realistic at this stage?

- Longline CPUE data for model fitting – unrealistic at this stage?

- Plausible estimates for the extent to which catchability might decrease with depth – awaited from industry/OLRAC.

- Inshore trawl CPUE series – unrealistic at this stage.

- Possible impact on CPUE through introduction of navigational aides.

- Include all offshore companies (or offshore vessels) in CPUE standardisation rather than only those companies operating since 1994.

Note that the assessment would not be repeated for all these options. Rather CPUE trends for a number of them might be derived and compared, with assessments conducted only for the more extreme to bound sensitivity to this selection.

Surveys

- Sub-stratification of one south coast stratum for lower variance estimates – T Fairweather

- Adjust survey estimates to take account of environmental co-variates – unrealistic at this stage?

- Include recent *Nansen* surveys (the SA portion of the trans-boundary cruises) – unrealistic at this stage?

Age and length data

- Further ageing data from Durholtz and colleagues – rather consider the guillotine to have dropped – could take more on board in January when Operating Models are finalised

- Further longline length distribution data - unrealistic at this stage.

Sensitivities

- Alternative upper bounds on natural mortality at age
  OMP-2006 options considered:
    1) upper bounds of 0.5 and 0.3 on ages 2 and 5 respectively are implemented; and
    2) upper bounds of 1.0 and 0.5 on ages 2 and 5 respectively are implemented)

- Alternative choices for the central year of the period when the fishery changed from primarily *M. capensis* to primarily *M. paradoxus* (to consider also years later than the range considered for OMP-06 testing)
  OMP-2006 options considered:
    1) 1950;
    2) 1940; and
    3) 1957

- Fixed rather than estimated steepness values
  OMP-2006 options considered:
    1) *h* for both *M. capensis* and *M. paradoxus* are estimated in the minimisation process;
    2) for *M. paradoxus*, *h* is fixed at 0.8, while this parameter is estimated for *M. capensis*;
    3) for *M. capensis*, *h* is fixed at 0.7, while this parameter is estimated for *M. paradoxus*; and
    4) for *M. paradoxus*, *h* is fixed at 0.8 and for *M. capensis*, *h* is fixed at 0.7

- Alternative selectivity assumptions (focussing on trends at larger lengths)

- Ricker stock-recruitment function
  OMP-2006 option considered:
    1) the stock-recruit curve for each species is constrained so that maximum recruitment occurs when the spawning biomass is at 45% of the pristine level

- Discard pattern changes
  OMP-2006 option considered:
    1) Discarding for both inshore and offshore trawl fleets is modelled by increasing in commercial selectivity by 0.2 for ages 1 and 2 for catches of both *M. capensis* and *M. paradoxus*. The loss of fish (to discarding as well as to theft by predators) from longlines is also included by doubling the fishing mortality from this fleet. All discarding components of this are assumed to occur from the beginning of the fishery to the present but is not carried through to the projections.

- Changes in past *K* values over time
  OMP-2006 option considered:
    1) K of both species assumed to have decreased linearly by 30% over the 1980 to 2000 period.

- Assessments commencing in (about) 1970

- Forced rather than estimated current depletions
  OMP-2006 options considered:
    1) Current spawning biomass of *M. paradoxus* is forced upwards to 40% of pre-exploitation level, while spawning biomass of *M. capensis* forced downwards to 30% of its pre-exploitation level;
    2) Current spawning biomass of *M. paradoxus* is forced upwards to 30% of pre-exploitation level;
    3) Current spawning biomass of *M. capensis* is forced downwards to 30% of pre-exploitation level;
    4) Current spawning biomass of *M. capensis* is forced downwards to 20% of pre-exploitation level;
    5) Current spawning biomass of both species forced to 30% of pre-exploitation levels; and
    6) Current spawning biomass of *M. capensis* is forced downwards to 20% of pre-exploitation level and the steepness parameter for this species if fixed at 0.7

DRAFT UNDER DEVELOPMENT

A Gender-Disaggregated Assessment for the South African Hake Resource, Fitting Directly to Age-Length Keys

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INTRODUCTION

There are very clear gender-specific differences in somatic growth for both *M. paradoxus* and *M. capensis*, in fact more so than between species (see Fig. 1). Routine application of age-length keys to obtain catch-at-age proportions is conducted without attention to gender-specific differences, but gender-differential growth means that larger sized males are not well represented in the catch. This could confound estimates based on catch-at-age data developed from a gender-aggregated age-length key, which might consequently under-represent the number of older hake present (and therefore affect estimates of natural mortality as well as distort estimates of year-class strength – the comparatively low variability of previous estimates of the latter has been a puzzle and concern, which might be resolved by gender differentiation of the assessments). Furthermore there is a sex-imbalance in certain components of the fishery: for example Geromont *et al*. (1995) estimated a female proportion in the south coast longline catches of 83%.

In the light of these considerations, the assessment of the hake resource is now being refined to incorporate gender- as well as species-differentiation. Thus in this analysis, the genders are modelled separately. In part because of this, the model is also fit directly to age-length keys (ALKs) and length frequencies (as e.g. in Punt *et al*. 2006), rather than to the age frequency information which multiplying the two would provide. There are three reasons for this:

a) ALKs are not available for all years and surveys or fisheries, so that length distribution data have to be fitted directly in those cases.

b) The fishery selectivity is essentially length- rather than age-specific; age-specific selectivities as assumed when fitting to age-distribution data will lead to mis-fitting of length distribution data in these circumstances (e.g. the lower tails of the length distributions of younger fish are not present in catches, but an age-specific selectivity requires them to be).

c) The feature of the data described in b) leads to a bias in the estimation of hake growth curves if estimated directly from hake age data, leading to the lengths at younger ages being positively biased; growth curve parameters need to be estimated within the assessment to correct for this bias.

DATA and METHODS

Appendix I details the data used in this analysis, while the specifications and equations of the overall model are set out in Appendix II.

RESULTS

Notes

Commercial proportions-at-length not calculated in the same way as survey PAL?

Need to compute MSY, etc.

Fit to the commercial proportion-at-length for longline and west coast offshore trawl is poor given the model's propensity to suggest greater numbers of larger fish than observed Work to resolve this is continuing.

REFERENCES

BENEFIT, 2004

Beverton and Holt, 1957

Brandão *et al*., 2004

Fairweather, 2008, mass-at-length

Fairweather and Leslie, 2008. Length at maturity.

Fairweather T. 2009. Updated abundance estimates for Merluccius capensis & M. paradoxus. Unpublished report, Marine and Coastal Management. MCM/2009/JUN/SWG-DEM/47. 4pp.

Glazer JP. 2009. New GLM paper. Unpublished report, Marine and Coastal Management. MCM/2009/..

Gaylard JD and Bergh MO. 2004. A species splitting mechanism for application to the commercial hake catch data 1978 to 2003. Unpublished report, Marine and Coastal Management. WG/09/04/D:H:21. 8pp.

Leslie RW. 2009. Survey length frequencies paper. Unpublished report, Marine and Coastal Management. MCM/2009/..

Punt et al. 2006

Rademeyer RA. 2009. Age-reading error matrices.

Table 1: Estimates of management quantities.

	Both		
-lnL total	923.3		
CPUE historic	-37.4		
CPUE GLM	-132.7		
Survey	-34.0		
Commercial CAL	20.3		
Survey CAL	60.0		
ALK	1020.0		
Recruitment penalty	11.5		
Selectivity smoothing penalty	10.5		
Negpen	0.0		
	Both	**Males**	**Females**
M. paradoxus K^{sp}	1526	656	870
h	0.78		
Bsp_{2009}	131	33	98
B^{sp}_{2009}/K^{sp}	0.09	0.05	0.11
M. capensis K^{sp}	853	399	454
h	0.98		
B^{sp}_{2008}	497	232	264
B^{sp}_{2008}/K^{sp}	0.58	0.58	0.58
2009 species ratio B^{sp}	3.79	7.03	2.69
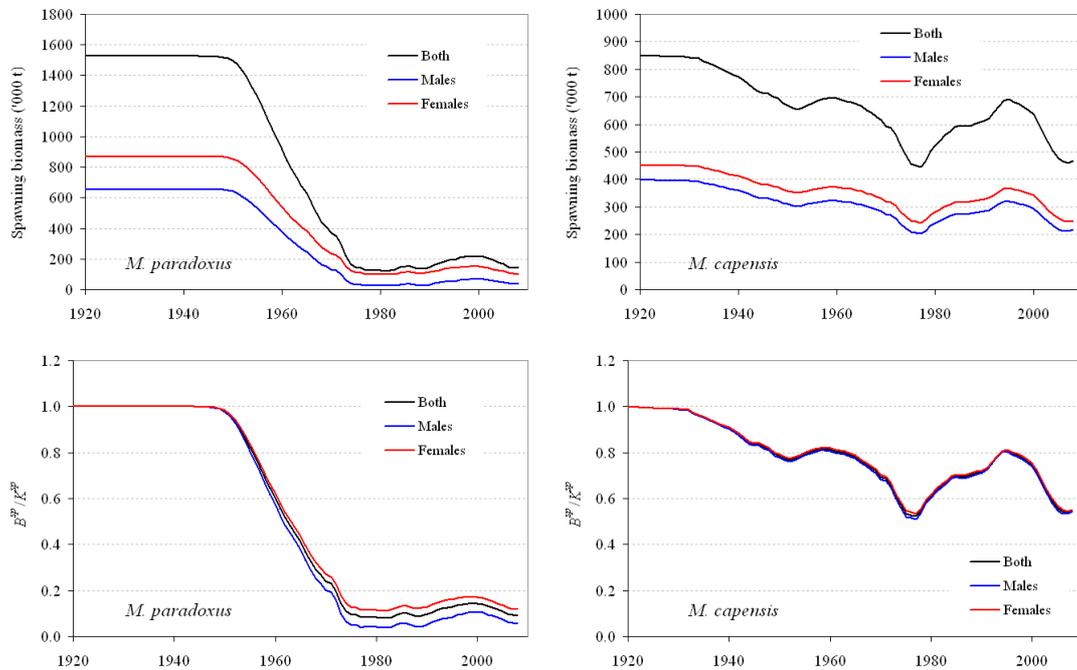
Fig. 1: Estimated spawning biomass trajectories for males and females *M. paradoxus* and *M. capensis*, both in absolute terms and relative to pre-exploitation level.
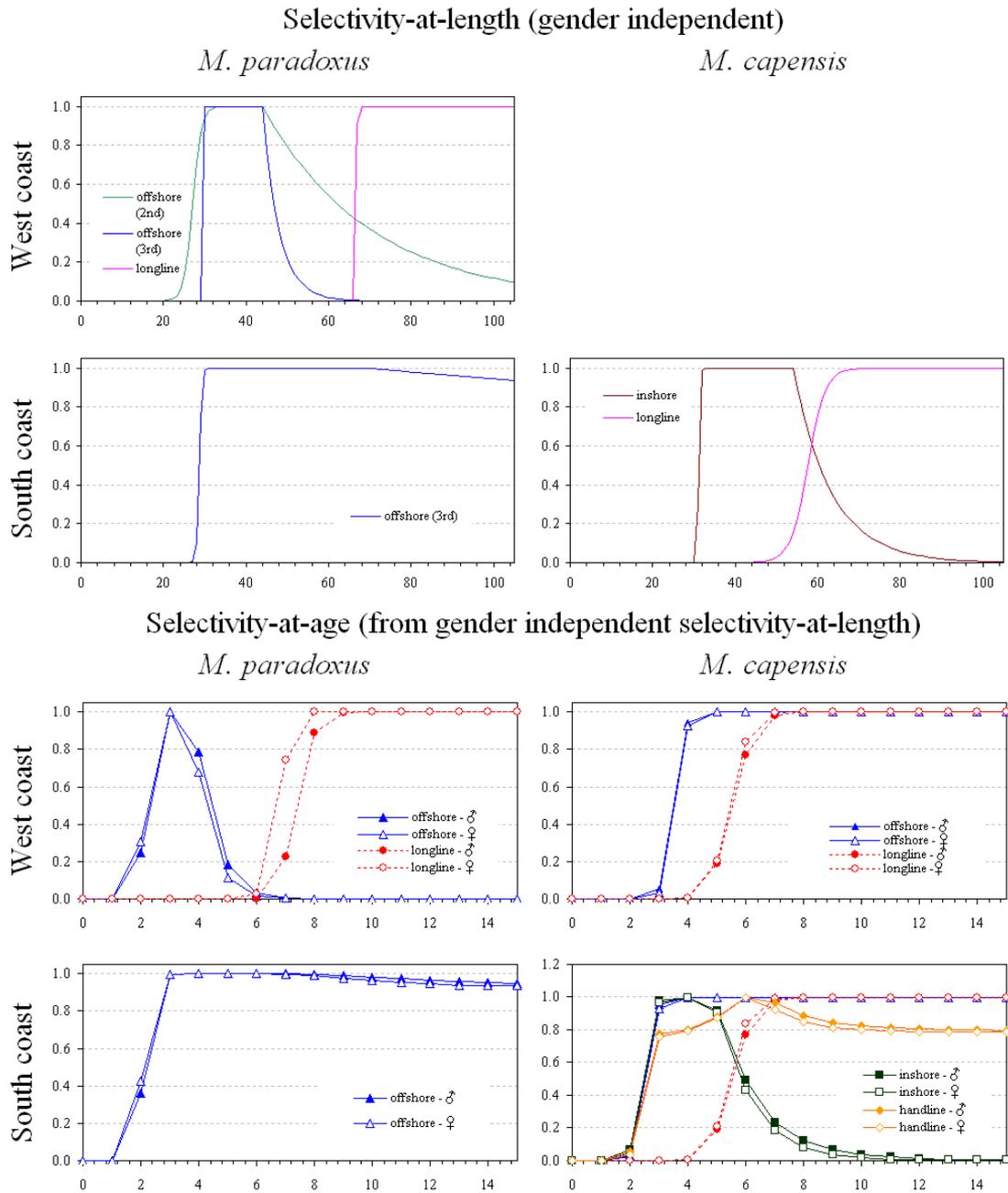
Fig. 2: Commercial gender-independent selectivities-at-length estimated directly in the model-fitting (the other selectivities-at-length (West Ccoast: *M. paradoxus* offshore 1st period and, *M. capensis* offshore and longline; South Coast:, *M. paradoxus* longline and *M. capensis* offshore and handline) are based on various assumptions (see text)) and commercial gender-dependent selectivities-at-age that follows from those.
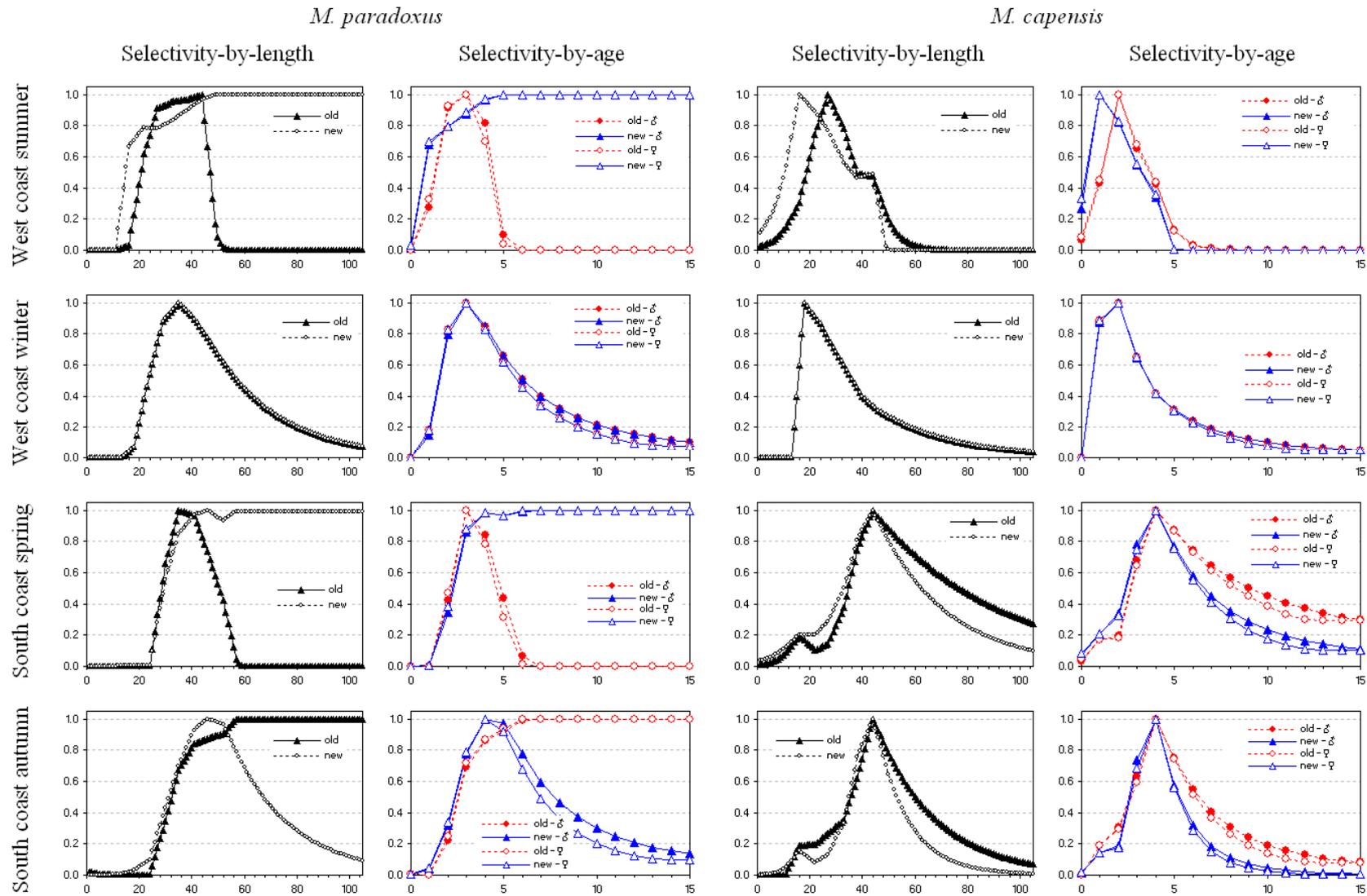
Fig. 3: Gender-independent survey selectivity-at-length (estimated) for the 'old' and 'new' *Africana* gear and derived gender-dependent survey selectivity-at-age for each of the four surveys for *M. paradoxus* and *M. capensis*.
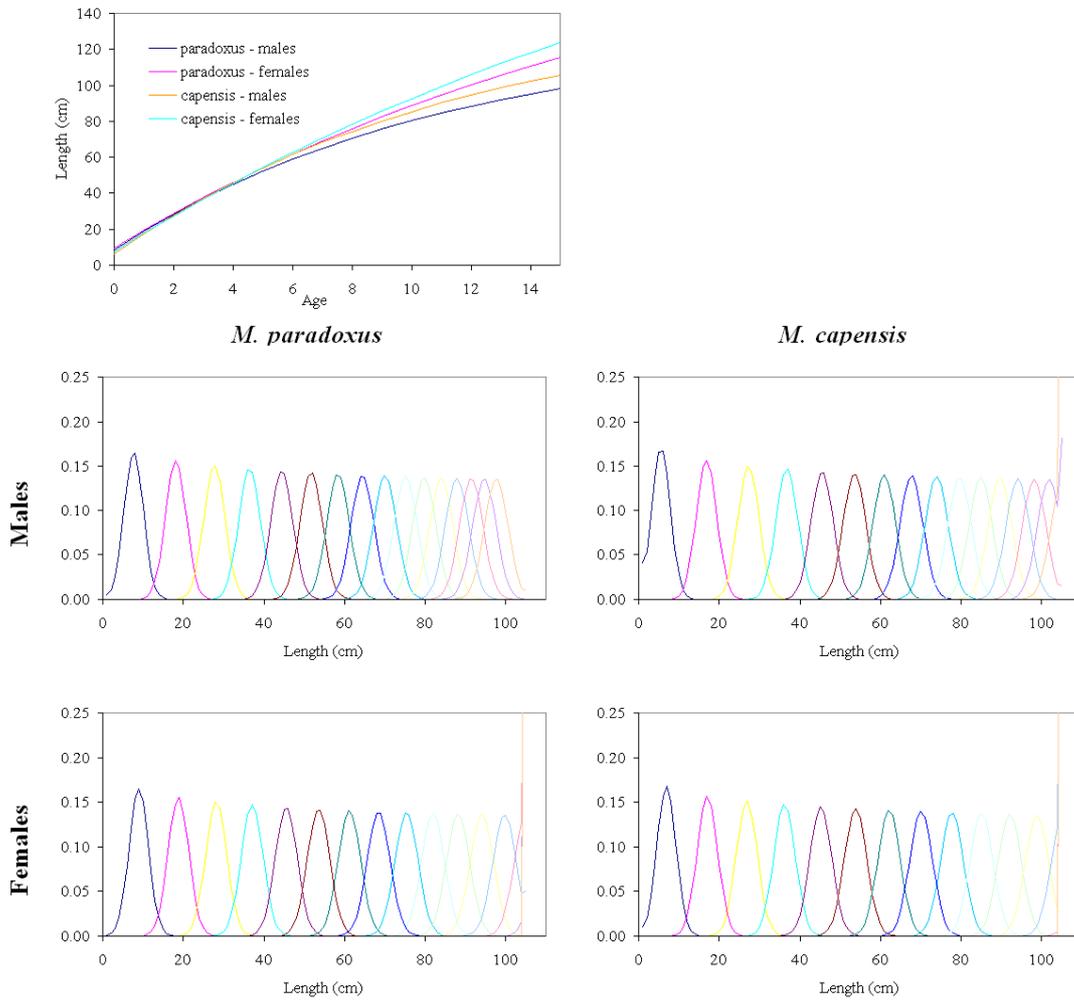
Fig. 4: Estimated length-at-age relationship and resulting length-at-age distributions for males and females *M. paradoxus* and *M. capensis*. In the lower plots the distributions, starting from the left, correspond to ages 0, 1, 2, …
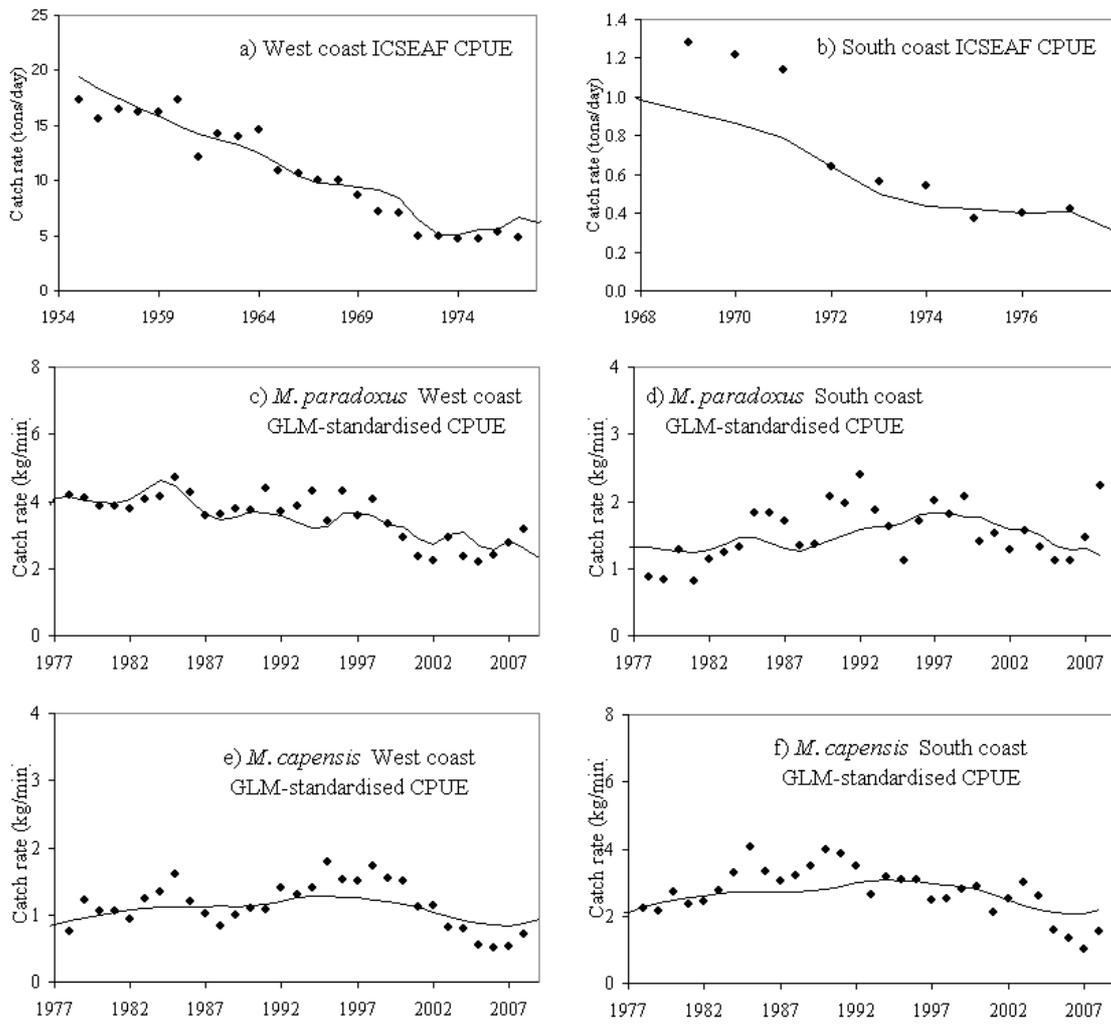
Fig. 5: Fit of the model to the CPUE data.
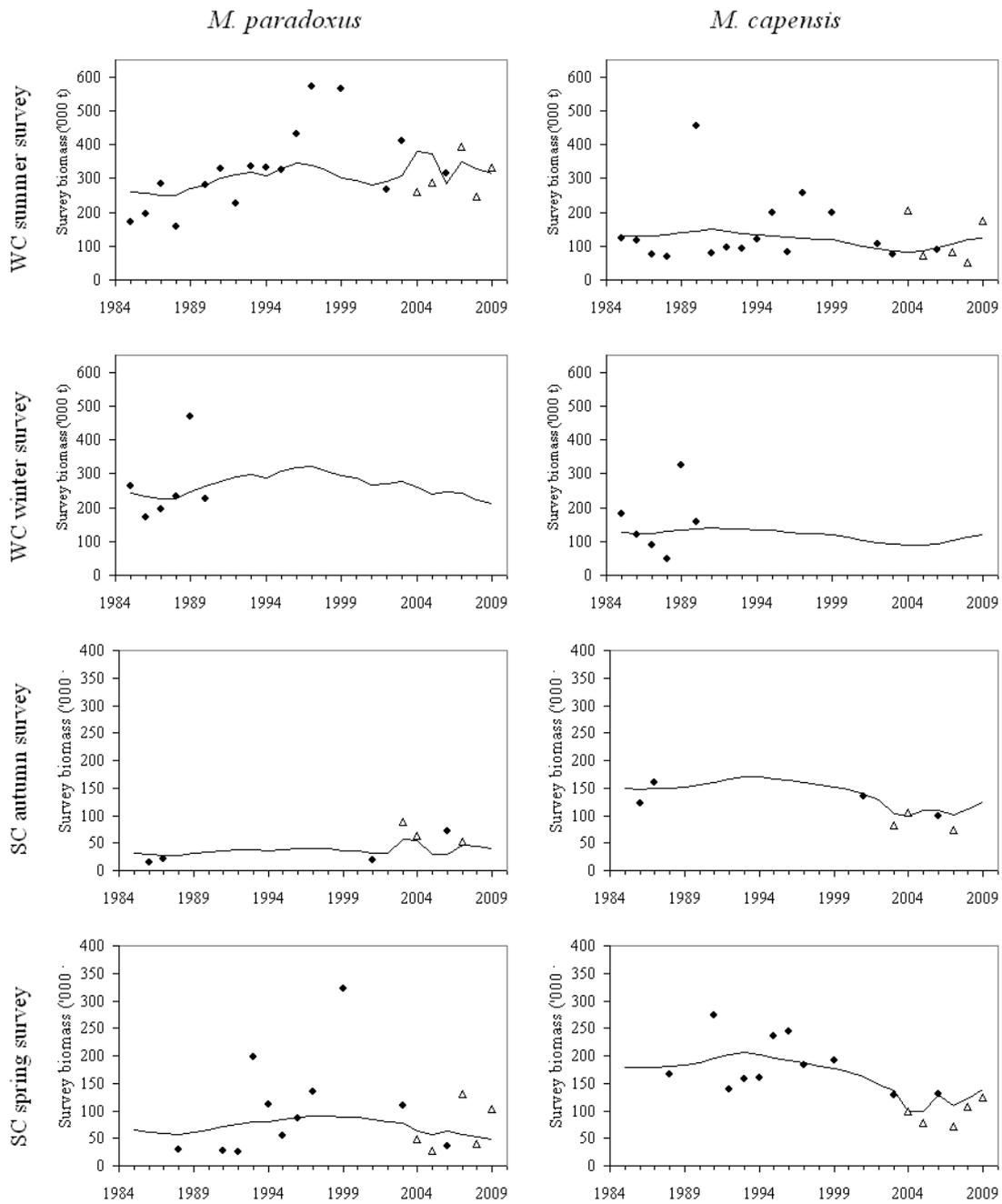
Fig. 6: Fit of the model to the survey abundance indices. The triangles represent surveys that have been conducted with the new gear on the *Africana*. These are rescaled by the calibration factor for the species concerned to make them comparable to the others.
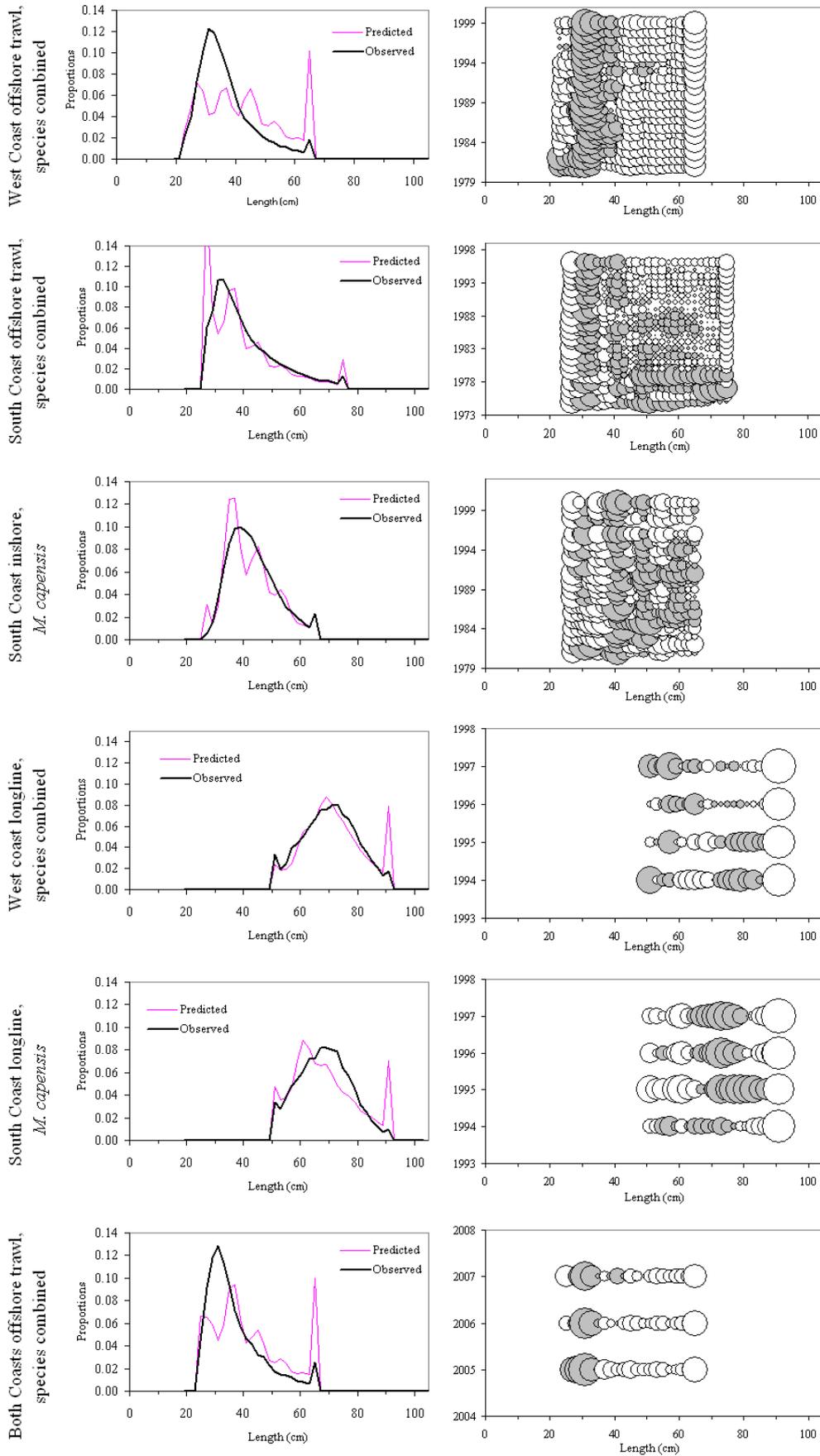
Fig. 7: Fit of the model to the commercial proportion-at-length data, aggregated over years for which data is available for the plots on the left.
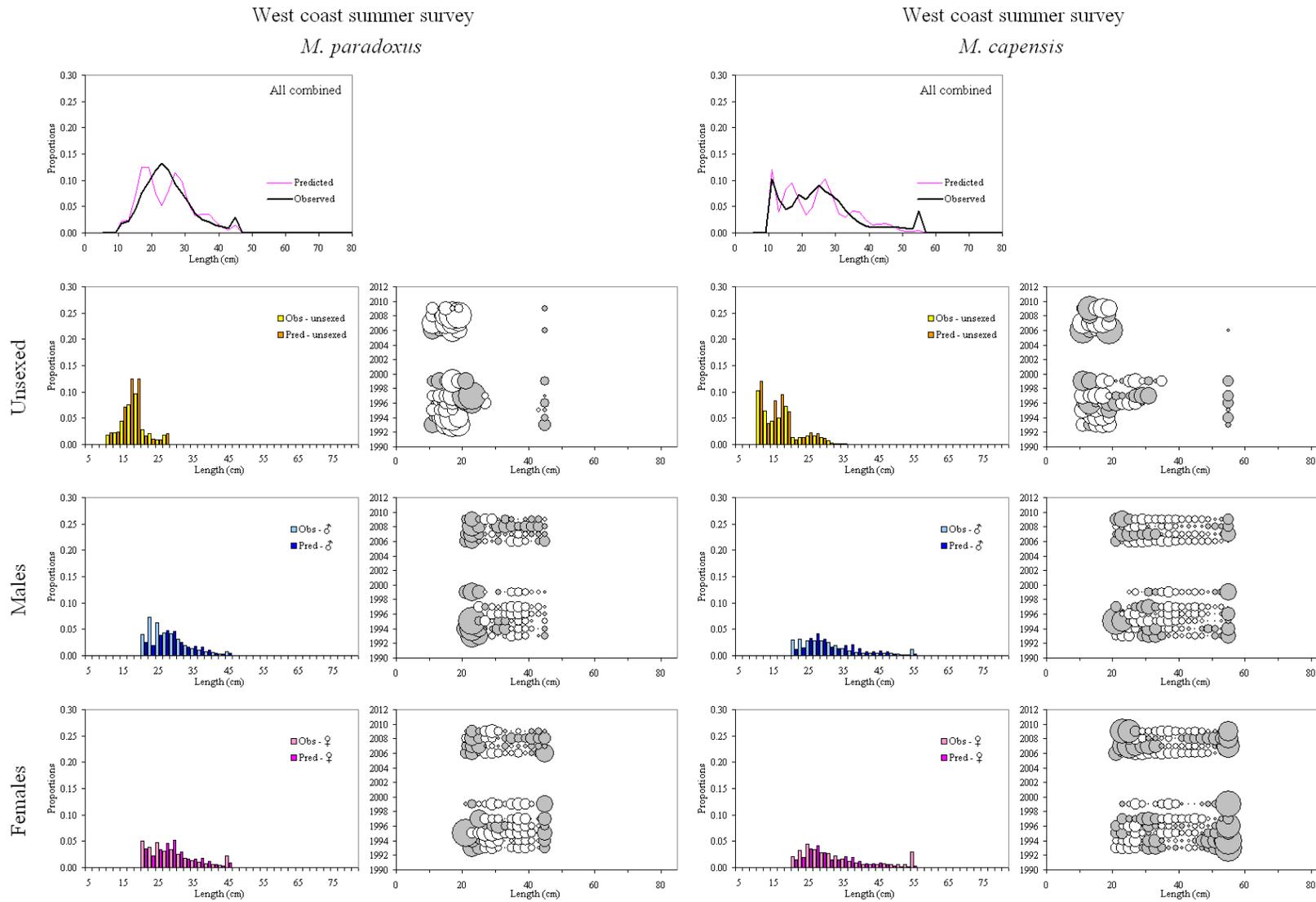
Fig. 8: Fit of the model to the survey gender-aggregated surveys proportion-at-length data. (in some plots, aggregated over years for which data is available).
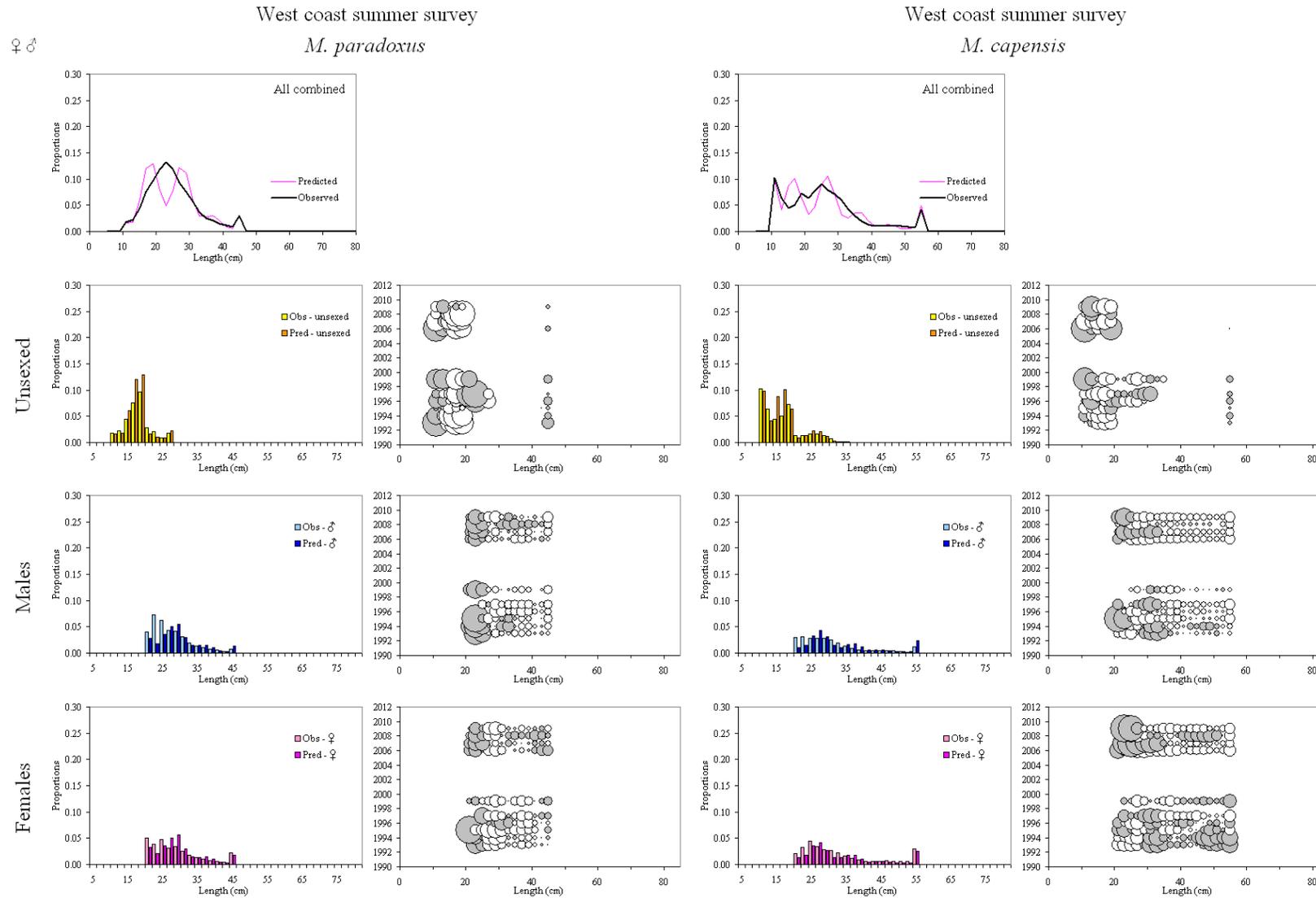
Fig. 9a: Fit of the model to the west coast summer survey gender- disaggregated proportion-at-length data (in some plots, aggregated over years for which data is available).
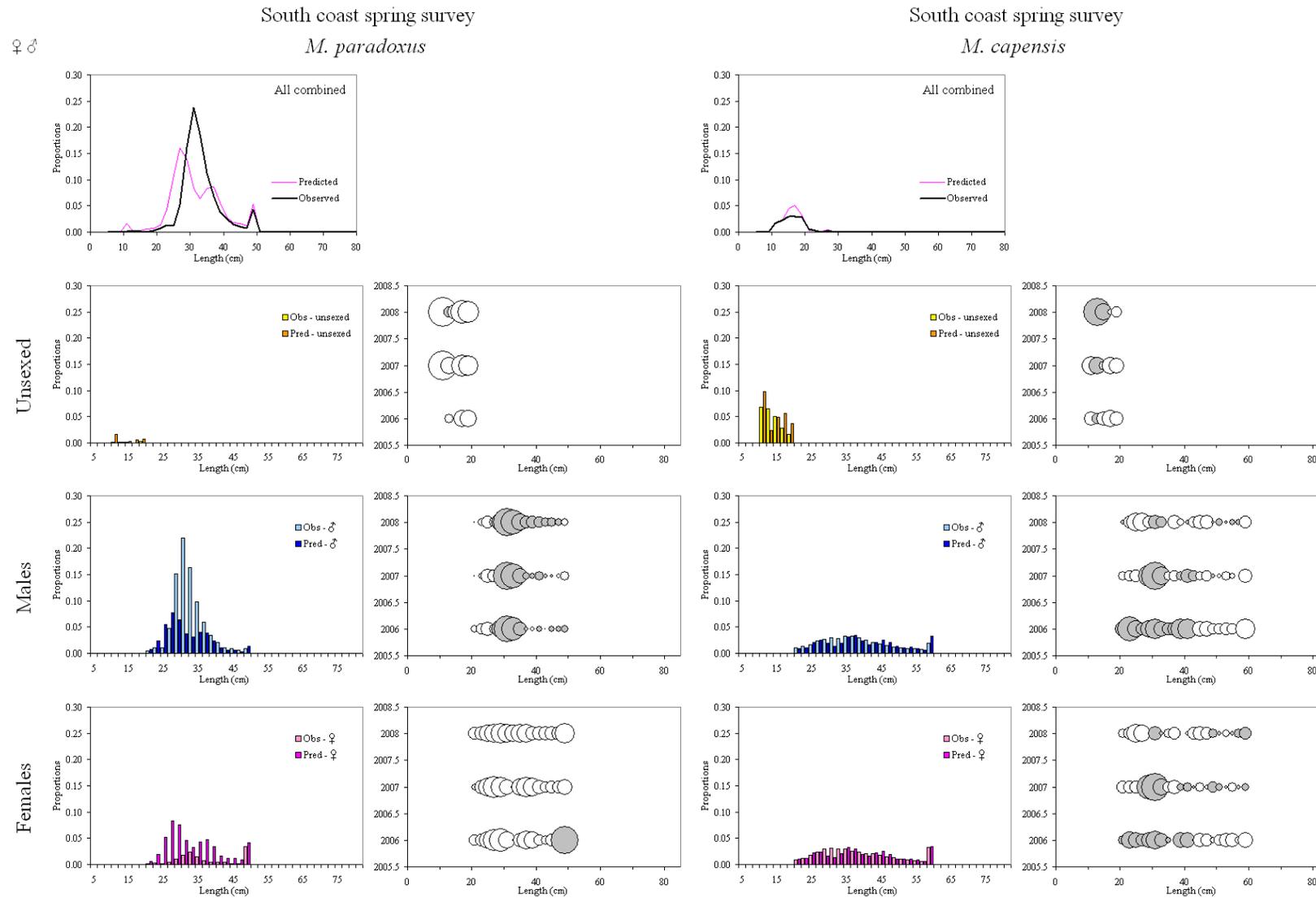
Fig. 9b: Fit of the model to the south coast spring survey gender- disaggregated proportion-at-length data (in some plots, aggregated over years for which data is available).
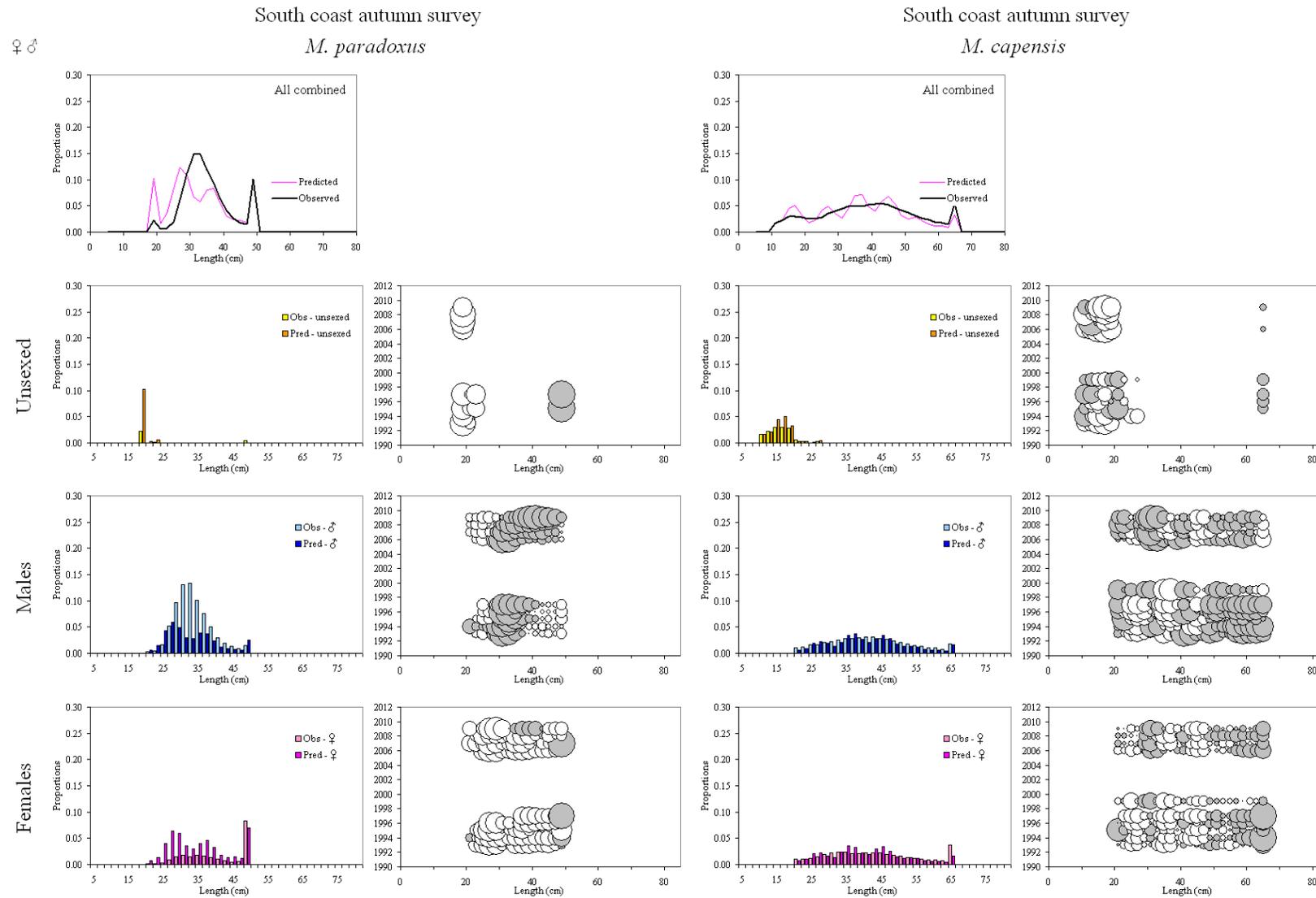
Fig. 9c: Fit of the model to the south coast autumn survey gender- disaggregated proportion-at-length data (in some plots, aggregated over years for which data is available).
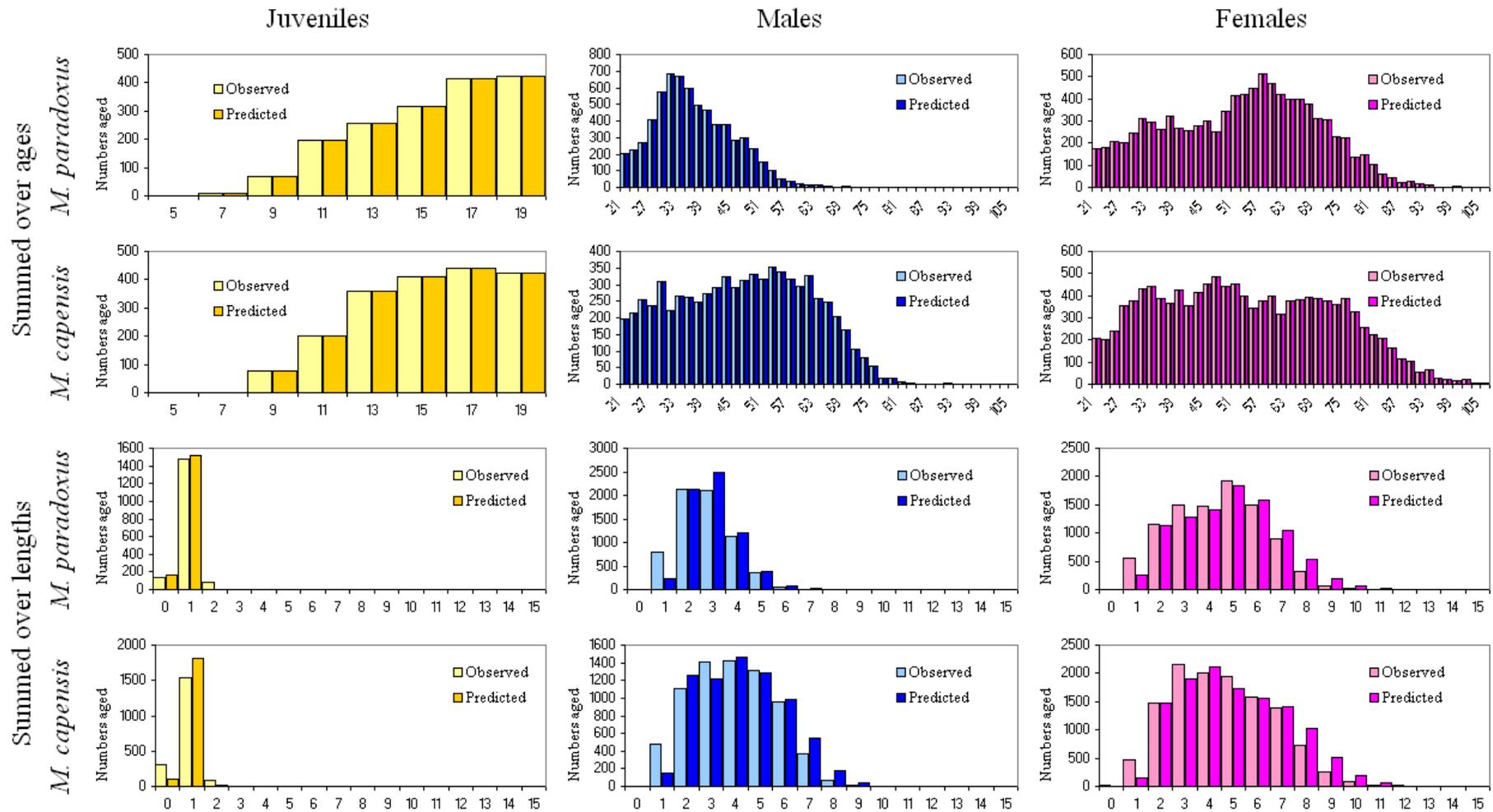
Fig. 10: Fit of the model to the ALKs, aggregated over all ALKs, first two rows summed over ages (should be exactly equal) and second two rows summed over lengths.

APPENDIX I – The Data Utilized

I.1 Annual catches

The species-split of the catches is carried out external to the model. A summary of the assumptions made to disaggregate the catches by species for the baseline assessment is given below. The reported or assumed catches by fleet and species are given in Table App.I.1 and plotted in Fig. App.I.1.

Offshore trawl fleet

From 1978 onwards, the catches made by the offshore trawl fleet have been split by species by applying the size-based species proportion-by-depth relationships for the west and south coasts which were developed by Gaylard and Bergh (2004) from research survey data.

Prior to 1978, there is no depth information recorded for the landings so that the proportion of *M. capensis* caught cannot be estimated using the method above. The catch data for the 1917-1977 period are split by assuming that the proportion of *M. capensis* caught follows a logistic function over this period, starting at 1 and then decreasing to stabilise at the 1978-1982 average value. As trawling was concentrated in inshore areas around Cape Town and to the east when the fishery began (i.e. probably catching *M. capensis* exclusively) and progressively moved offshore, this seems a more defensible approach. To reflect a change from a *M. capensis* only fishery to the species ratio in the catch in 1978, the changing proportion with year *y* of *M. capensis* in the offshore trawl catch on coast *c* is modelled by:

$$prop_{cy}^{prop} = \frac{1 - \Delta_c}{1 + \exp[(y - P_1)/P_2]} + \Delta_c \qquad \text{(App.I.1)}$$

where

Δ_c is the average proportion of *M. capensis* in the offshore catch over the 1978-1982 period for coast *c* (24% and 60% for the west and south coasts respectively), and

P_1, P_2 are parameters of the logistic function; P_1 is the year in which the proportion of *M. capensis* in the catch is mid-way between 100% and Δ_c, while P_2 determines how rapidly this change in proportion occurs.

For the baseline assessment assumes: P_1=1950 and P_2=1.5.

Inshore trawl and handline fleets

Catches made by these fleets are assumed to consist of *M. capensis* only, as they operate in relatively shallow water on the south coast.

Longline fleet

Longline catches on the west coast are assumed to consist of 30% *M. capensis* for the whole period, while on the south coast, catches by this fleet are assumed to consist of *M. capensis* exclusively (Andrew Penney, PISCES, pers. commn).

The total catch in 2009 is assumed equal to the TAC for that year (118 500 t); it is split between the different fleets and species assuming the same proportions as in 2008.

I.2 Abundance indices

Six CPUE time-series are available for assessing the status of the resource (Table App.I.2): a CPUE series for each of the south and west coasts developed by the International Commission for South East Atlantic Fisheries (ICSEAF, 1989) and a GLM-standardised CPUE series for each coast, for each of *M. paradoxus* and *M. capensis* (Table App.I.2) from the offshore trawl fleet (Glazer, 2009). The two historical CPUE series cannot be disaggregated by species, as there are no effort-by-depth data available for this pre-1978 period. The GLM standardized CPUE indices are species-specific (the catch data being based on the Gaylard and Bergh (2004) algorithm).

Research surveys have been conducted on board the FRS *Africana* from 1986 in spring and/or autumn on the south coast and from 1985 in summer and/or winter on the west coast, and provide fully species-specific information. Since 2003, new fishing gear has occasionally been used on the *Africana*, for which a calibration factor is available. Survey biomass estimates and their estimated (sampling) standard errors are listed in Tables App.I.3-4 (Fairweather, 2009). Only surveys extending to the deepest depth (500m) normally included in the survey design are considered for reasons of comparability.

I.3 Length frequencies

Survey length frequencies are available disaggregated by species and in some years disaggregated by gender (Table App.I.5) (Fairweather, 2009).

Sex-aggregated proportions-at-length for each survey stratum ($p_{yl}^{surv,i}$) are provided in 1cm length classes (Fairweather, 2009). In some instances, the proportions of males and females for a particular survey stratum and length class are available ($q_{yl}^{g,surv,i}$, where $\sum_{g} q_{yl}^{g,surv,i} = 1$). These are converted to survey specific (i.e. aggregated over all strata for a particular cruise) proportions-at-lengths for males (g=1), females (g=2) and unsexed (g=0) (with $\sum_{g=0}^{2} p_{yl}^{g,surv,i} = 1$) as follows:

a. For all length classes < 21 cm, the proportions-at-length are assumed to be unsexed;

b. The proportions-at-length are grouped into 2cm length classes. For length classes > 20 cm:

- If there is no sex-information for either of the two 1 cm length classes to group (i.e. $\sum_{g} q_{yl}^{g,surv,i} = 0$ and $\sum_{g} q_{y,l+1}^{g,surv,i} = 0$), then the proportion for the resulting 2 cm length class is assumed to be unsexed:

$$p_{yL}^{g,surv,i} = \begin{cases} p_{yl}^{surv,i} + p_{y,l+1}^{surv,i} & \text{for } g = 0 \\ 0 & \text{for } g = 1/2 \end{cases} \qquad \text{(App.I.1)}$$

- If there is sex-information for one of the two 1 cm length classes to group (i.e. if $\sum_{g} q_{yl}^{g,surv,i} = 1$ or $\sum_{g} q_{y,l+1}^{g,surv,i} = 1$), then the sex-information from the one length class is used for both:

$$p_{yL}^{g,surv,i} = \begin{cases} 0 & \text{for } g = 0 \\ q_{yl}^{g,surv,i} \left(p_{yl}^{surv,i} + p_{y,l+1}^{surv,i} \right) & \text{for } g = 1/2 \end{cases} \qquad \text{(App.I.2)}$$

- If there is sex-information for both of the two 1 cm length classes to group (i.e. if $\sum_{g} q_{yl}^{g,surv,i} = 1$ and $\sum_{g} q_{y,l+1}^{g,surv,i} = 1$), then the sex-information is used directly:

$$p_{yL}^{g,surv,i} = \begin{cases} 0 & \text{for } g = 0 \\ q_{yl}^{g,surv,i} p_{yl}^{surv,i} + q_{y,l+1}^{g,surv,i} p_{y,l+1}^{surv,i} & \text{for } g = 1/2 \end{cases} \qquad \text{(App.I.3)}$$

c. The strata proportions-at-length are weighted by the estimated total number in the strata to obtain a survey specific gender-disaggregated proportions-at-length ($p_{yl}^{g,surv}$). The estimated total number in each stratum is calculated as:

$$N_y^{surv,i} = B_y^{surv,i} \Big/ \overline{W}_y^{surv,i} \qquad \text{(App.I.4)}$$

where

$B_y^{surv,i}$ is the survey biomass estimate for stratum i in survey *surv*, and

$\overline{W}_y^{surv,i}$ is the mean weight of fish for stratum i in survey *surv*, with

$$\overline{W}_y^{surv,i} = \sum_L \left(p_{yL}^{surv,i} \alpha L^\beta \right) \qquad \text{(App.I.5)}$$

d. For each 2 cm length class, if the unsexed proportion is less than 20% of the total proportion in that length class, the sexed proportion is used to split the unsexed proportion into males and females.

Figs. App.I.2-3 plot the survey length frequencies available.

Length frequency information from the commercial catch is not available by species, the reason being that it is often based on cleaned (headed and gutted) fish, which cannot be easily identified by species. As a result it is not possible to disaggregate the commercial length frequencies by species. A species-aggregated annual age-length key has been developed and applied to the length distribution data for the two species combined to obtain the species-aggregated catches-at-age (Leslie, 1998). Commercial catches-at-age for the offshore (both coasts combined) and for the inshore and longline (south coast only) fleets are shown in Tables App.II.10-12. The south coast inshore and longline fleet catches are assumed to consist of *M. capensis* only.

I.4 Age-Length Keys

Table App.I.6 lists the age-length keys available. Data from animals with frills on gills (FOG) have been discarded. All aged animals less or equal to 20cm in length are assumed to be juveniles, i.e. of unknown gender. The few unsexed data from animals greater than 20cm have been discarded (<1% of the total).

The 'unknown reader' is in fact a combination of data from two or three readers. When the data from the two or three readers are available directly, these are used rather than the aggregated data.

Table App.I.1: Species-disaggregated catches (in thousand tons) of South African hake from the south and west coasts (see text for details).

| | M. paradoxus | | | M. capensis | | | | | |
| | Offshore | | Longline | Offshore | | Inshore | Longline | | Handline |
	West coast	South coast	West coast	West coast	South coast	South coast	West coast	South coast	South coast
1917				1.000					
1918				1.100					
1919				1.900					
1920				0.000					
1921				1.300					
1922				1.000					
1923				2.500					
1924				1.500					
1925				1.900					
1926				1.400					
1927				0.800					
1928				2.600					
1929				3.800					
1930				4.400					
1931				2.800					
1932				14.300					
1933				11.100					
1934				13.800					
1935	0.001			14.999					
1936	0.001			17.699					
1937	0.003			20.197					
1938	0.005			21.095					
1939	0.010			19.990					
1940	0.028			28.572					
1941	0.057			30.543					
1942	0.126			34.374					
1943	0.268			37.632					
1944	0.465			33.635					
1945	0.763			28.437					
1946	1.991			38.409					
1947	3.743			37.657					
1948	9.304			49.496					
1949	14.770			42.630					
1950	27.306			44.694					
1951	44.856			44.644					
1952	53.304			35.496					
1953	62.466			31.034					
1954	74.752			30.648					
1955	84.517			30.883					
1956	88.043			30.157					
1957	94.982			31.418					
1958	98.660			32.040					
1959	110.468			35.532					
1960	121.131			38.769		1.000			
1961	112.716			35.984		1.308			
1962	111.918			35.682		1.615			
1963	128.545			40.955		1.923			
1964	123.095			39.205		2.231			
1965	153.970			49.030		2.538			
1966	147.905			47.095		2.846			
1967	134.026	5.661		42.674	8.525	3.154			
1968	108.921	11.136		34.679	16.772	3.462			
1969	125.229	15.136		39.871	22.795	3.769			
1970	108.087	9.466		34.413	14.257	4.077			
1971	153.218	12.017		48.782	18.098	4.385			
1972	185.025	18.633		58.908	28.062	4.692			
1973	119.679	28.873		38.103	43.483	5.000			
1974	93.296	36.254		29.704	54.599	10.056			
1975	67.975	26.920		21.642	40.543	6.372			
1976	109.144	20.722		34.750	31.208	5.740			
1977	77.616	14.753		24.712	22.219	3.500			
1978	104.101	4.018		23.411	3.568	4.931			
1979	95.374	2.759		38.149	4.161	6.093			
1980	100.779	2.950		32.749	3.510	9.121			
1981	91.624	1.302		29.306	4.184	9.400			
1982	84.990	4.240		28.359	7.118	8.089			
1983	71.202	6.124	0.161	23.231	6.392	7.672	0.069		
1984	81.804	4.843	0.256	29.451	6.092	9.035	0.110	0.016	
1985	91.096	10.442	0.817	33.974	9.574	9.203	0.350	0.292	0.065
1986	103.494	10.214	0.965	30.311	5.751	8.724	0.413	0.302	0.084
1987	94.742	9.269	2.500	22.783	6.415	8.607	1.071	0.353	0.096
1988	83.041	7.430	3.628	23.541	7.086	8.417	1.555	0.331	0.071
1989	82.592	7.640	0.203	24.667	11.272	10.038	0.087	0.032	0.137
1990	76.754	12.028	0.270	26.882	10.764	10.012	0.116		0.348
1991	86.172	14.004		20.278	8.070	8.206		3.000	1.270
1992	81.812	20.023		21.475	6.439	9.252		1.500	1.099
1993	101.982	11.086		16.083	3.175	8.870			0.278
1994	104.347	7.601	1.130	19.520	3.451	9.569	0.484	0.626	0.449
1995	93.332	4.552	0.670	27.564	2.598	10.630	0.287	0.650	0.756
1996	109.831	9.759	1.676	19.344	3.530	11.062	0.718	1.828	1.515
1997	99.881	11.904	1.806	17.273	3.932	8.834	0.774	1.872	1.404
1998	110.856	10.796	0.647	16.797	3.357	8.283	0.277	1.471	1.738
1999	87.509	12.435	1.963	16.252	2.911	8.595	0.841	4.144	2.749
2000	95.020	8.586	3.456	22.629	4.997	10.906	1.481	2.077	5.500
2001	100.610	9.520	2.793	17.265	6.358	11.836	1.197	1.688	7.300
2002	87.837	14.147	4.772	17.513	4.018	9.581	2.045	3.945	3.500
2003	97.043	18.887	4.668	10.294	4.186	9.883	2.000	4.878	3.000
2004	89.480	27.663	3.758	11.265	4.594	10.004	1.611	4.429	1.600
2005	91.148	22.594	4.172	7.136	3.634	7.881	1.788	4.559	0.700
2006	88.571	16.556	3.592	9.525	3.473	5.524	1.539	4.032	0.400
2007	98.212	12.573	3.151	13.427	1.902	6.350	1.350	3.834	0.400
2008	91.957	13.788	2.170	9.969	1.168	5.496	0.930	2.740	0.231
2009	84.906	12.731	2.004	9.205	1.078	5.075	0.859	2.530	0.213

Table App.I.2: South and west coast historic (ICSEAF, 1989) and GLM standardized CPUE data (GLM3 of Glazer, 2009) for *M. paradoxus* and *M. capensis*. The historic CPUE series are for *M. capensis* and *M. paradoxus* combined.

| | ICSEAF CPUE (t hr^{-1}) | | | GLM CPUE (kg min^{-1}) | | | |
| | Species-aggregated | | | *M. paradoxus* | | *M. capensis* | |
Year	West Coast	South Coast	Year	West Coast	South Coast	West Coast	South Coast
1955	17.31		1978	4.18	0.88	0.76	2.22
1956	15.64		1979	4.11	0.83	1.22	2.17
1957	16.47		1980	3.85	1.28	1.06	2.71
1958	16.26		1981	3.85	0.81	1.06	2.34
1959	16.26		1982	3.79	1.13	0.94	2.42
1960	17.31		1983	4.05	1.25	1.25	2.77
1961	12.09		1984	4.14	1.32	1.34	3.28
1962	14.18		1985	4.70	1.84	1.60	4.08
1963	13.97		1986	4.26	1.83	1.20	3.34
1964	14.60		1987	3.56	1.70	1.01	3.05
1965	10.84		1988	3.60	1.34	0.84	3.21
1966	10.63		1989	3.79	1.36	1.00	3.49
1967	10.01		1990	3.75	2.07	1.10	4.00
1968	10.01		1991	4.40	1.97	1.08	3.87
1969	8.62	1.28	1992	3.71	2.39	1.39	3.50
1970	7.23	1.22	1993	3.85	1.87	1.29	2.65
1971	7.09	1.14	1994	4.30	1.63	1.41	3.18
1972	4.90	0.64	1995	3.41	1.12	1.78	3.10
1973	4.97	0.56	1996	4.31	1.71	1.52	3.08
1974	4.65	0.54	1997	3.57	2.00	1.50	2.48
1975	4.66	0.37	1998	4.07	1.80	1.73	2.52
1976	5.35	0.40	1999	3.32	2.07	1.53	2.79
1977	4.84	0.42	2000	2.91	1.40	1.50	2.87
			2001	2.34	1.52	1.11	2.12
			2002	2.24	1.28	1.13	2.53
			2003	2.92	1.56	0.81	3.01
			2004	2.34	1.33	0.80	2.61
			2005	2.18	1.12	0.56	1.59
			2006	2.41	1.12	0.51	1.36
			2007	2.74	1.47	0.54	1.01
			2008	3.16	2.22	0.70	1.52

Table App.I.3: Survey abundance estimates and associated standard errors in thousand tons for *M. paradoxus* for the depth range 0-500m for the south coast and for the west coast. Values in bold are for the surveys conducted by the *Africana* with the new gear.

| | West coast | | | | South coast | | | |
| Year | Summer | | Winter | | Spring (Sept) | | Autumn (Apr/May) | |
	Biomass	(s.e.)	Biomass	(s.e.)	Biomass	(s.e.)	Biomass	(s.e.)
1985	169.959	(36.680)	264.839	(52.949)	-	-	-	-
1986	196.111	(36.358)	172.477	(24.122)	13.758	(3.554)	-	-
1987	284.805	(53.101)	195.482	(44.415)	21.554	(4.605)	-	-
1988	158.758	(27.383)	233.041	(64.003)	-	-	30.316	(11.104)
1989	-	-	468.780	(124.830)	-	-	-	-
1990	282.174	(78.945)	226.862	(46.007)	-	-	-	-
1991	327.020	(82.180)	-	-	-	-	26.638	(10.460)
1992	226.687	(32.990)	-	-	-	-	24.304	(15.195)
1993	334.151	(50.234)	-	-	-	-	198.849	(98.452)
1994	330.270	(58.319)	-	-	-	-	111.469	(34.627)
1995	324.554	(80.357)	-	-	-	-	55.068	(22.380)
1996	430.908	(80.604)	-	-	-	-	85.546	(25.484)
1997	569.957	(108.200)	-	-	-	-	135.192	(51.031)
1998	-	-	-	-	-	-	-	-
1999	562.859	(116.302)	-	-	-	-	321.478	(113.557)
2000	-	-	-	-	-	-	-	-
2001	-	-	-	-	19.929	(9.956)	-	-
2002	267.487	(35.068)	-	-	-	-	-	-
2003	411.177	(69.431)	-	-	**88.442**	(36.051)	108.857	(37.528)
2004	**259.527**	(56.021)	-	-	**63.900**	(17.894)	**48.898**	(20.343)
2005	**286.416**	(39.849)	-	-	-	-	**26.605**	(7.952)
2006	315.310	(49.490)	-	-	72.415	(15.500)	34.799	(8.325)
2007	**392.812**	(70.043)	-	-	**52.287**	(19.231)	**129.646**	(60.661)
2008	246.542	(51.973)	-	-	**24.816**	(8.775)	39.505	(11.408)
2009	**330.235**	(28.526)	-	-	-	-	**102.834**	(28.670)

Table App.I.4: Survey abundance estimates and associated standard errors in thousand tons for *M. capensis* for the depth range 0-500m for the south coast and for the west coast. Values in bold are for the surveys conducted by the *Africana* with the new gear.

| | West coast | | | | South coast | | | |
| Year | Summer | | Winter | | Spring (Sept) | | Autumn (Apr/May) | |
	Biomass	(s.e.)	Biomass	(s.e.)	Biomass	(s.e.)	Biomass	(s.e.)
1985	124.647	(22.707)	181.487	(27.476)	-	-	-	-
1986	117.810	(23.636)	119.587	(18.489)	121.197	(16.625)	-	-
1987	75.693	(10.241)	87.391	(11.198)	159.088	(17.233)	-	-
1988	66.725	(10.765)	47.120	(9.568)	-	-	165.939	(21.871)
1989	-	-	323.833	(67.295)	-	-	-	-
1990	455.798	(135.237)	157.800	(23.561)	-	-	-	-
1991	77.357	(14.995)	-	-	-	-	274.298	(44.395)
1992	95.407	(11.744)	-	-	-	-	138.085	(15.357)
1993	92.598	(14.589)	-	-	-	-	158.340	(13.733)
1994	121.257	(35.951)	-	-	-	-	160.555	(23.701)
1995	199.142	(26.812)	-	-	-	-	236.025	(31.840)
1996	83.337	(9.285)	-	-	-	-	244.410	(25.107)
1997	257.293	(46.056)	-	-	-	-	183.087	(18.906)
1998	-	-	-	-	-	-	-	-
1999	198.716	(32.467)	-	-	-	-	191.203	(14.952)
2000	-	-	-	-	-	-	-	-
2001	-	-	-	-	133.793	(20.858)	-	-
2002	106.253	(15.813)	-	-	-	-	-	-
2003	75.960	(13.314)	-	-	**82.928**	(9.010)	128.450	(20.062)
2004	**205.939**	(33.216)	-	-	106.119	(15.596)	**99.902**	(12.027)
2005	**70.983**	(13.845)	-	-	-	-	**76.932**	(5.965)
2006	88.420	(22.851)	-	-	99.867	(9.803)	130.900	(14.816)
2007	**82.270**	(11.441)	-	-	**74.615**	(7.383)	**70.940**	(5.615)
2008	**50.877**	(5.355)	-	-	**94.232**	(11.456)	**108.195**	(9.978)
2009	**175.289**	(39.920)	-	-	-	-	**124.004**	(11.808)

Table App. I.5: Survey length frequencies currently available.

| | West coast | | | | South coast | | | |
| Year | Summer | | Winter | | Spring (Sept) | | Autumn (Apr/May) | |
	Sex-aggr.	By sex	Sex-aggr.	By sex	Sex-aggr.	By sex	Sex-aggr.	By sex
1985	†		†		-	-	-	-
1986	†		†		†		-	-
1987	†		†		†		-	-
1988	†		†		-	-	†	
1989	-	-	†		-	-	-	-
1990	†		†		-	-	-	-
1991	†		-	-	-	-	†	
1992	†		-	-	-	-	†	
1993	†	†	-	-	-	-	†	†
1994	†	†	-	-	-	-	†	†
1995	†	†	-	-	-	-	†	†
1996	†	†	-	-	-	-	†	†
1997	†	†	-	-	-	-	†	†
1998	-	-	-	-	-	-	-	-
1999	†	†	-	-	-	-	†	†
2000	-	-	-	-	-	-	-	-
2001	-	-	-	-	†		-	-
2002	†	-	-	-	-	-	-	-
2003	†	-	-	-	†		†	-
2004	†	-	-	-	†		†	-
2005	†	-	-	-	-	-	†	-
2006	†	†	-	-	†	†	†	†
2007	†	†	-	-	†	†	†	†
2008	†	†	-	-	†	†	†	†
2009	†	†	-	-	-	-	†	†

TableApp. I.6: Species- and sex-disaggreagated age and length data currently available by reader.

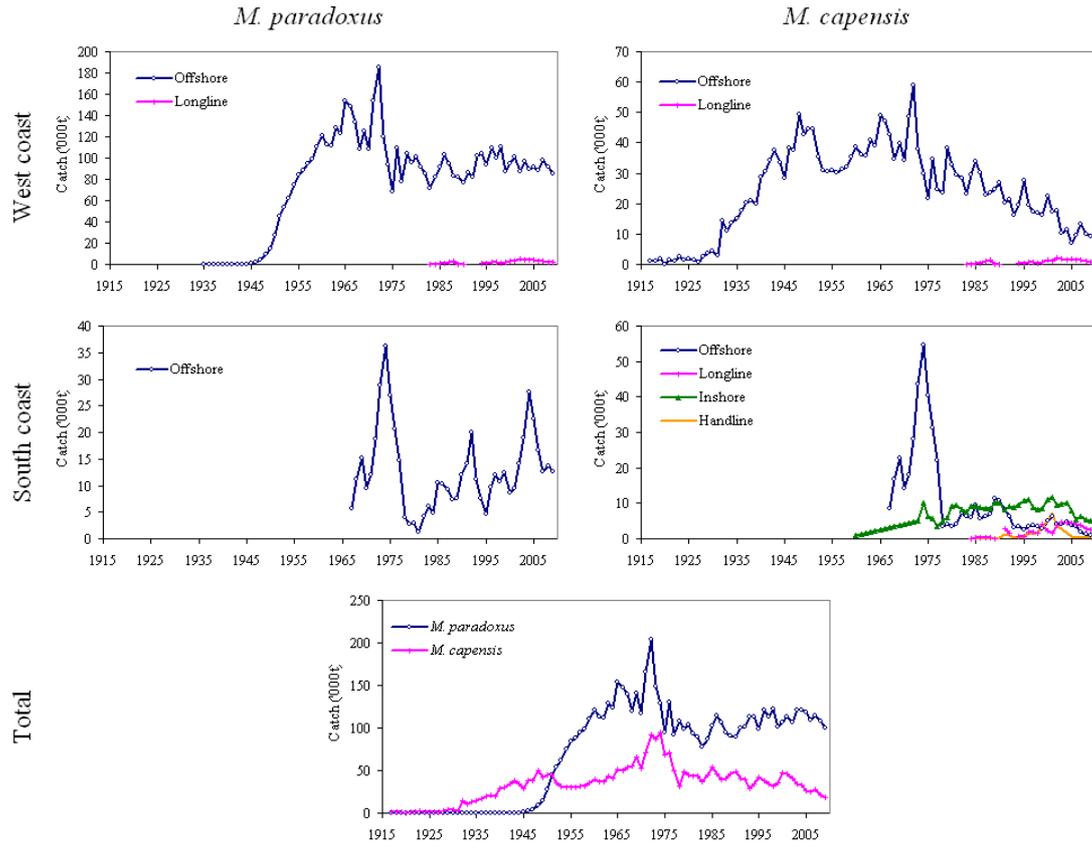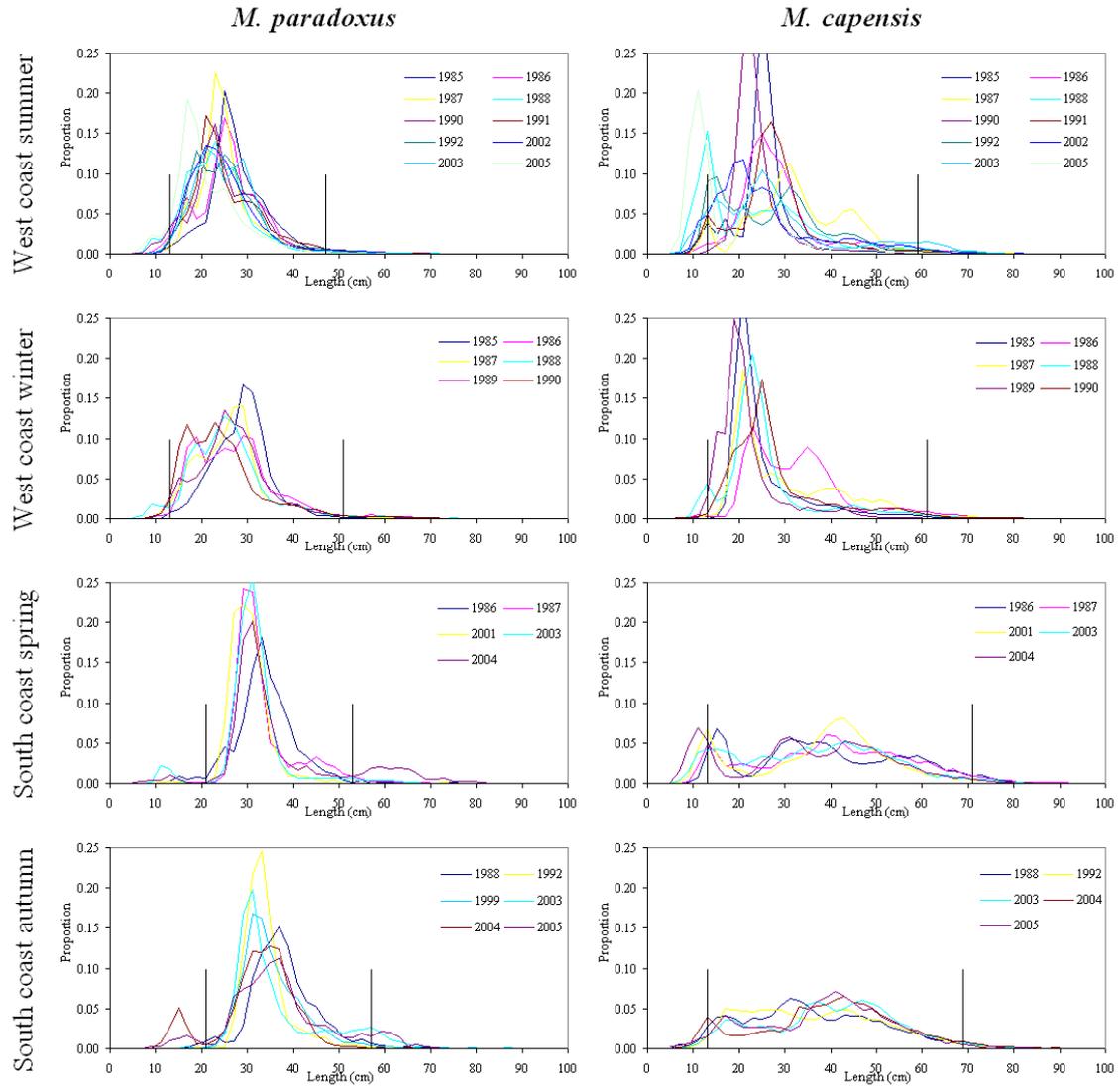|	Year	*M. paradoxus*										*M. capensis*									
		UR	AD	LB	KG	JP	AP	DJ	PM	TA	KB	UR	AD	LB	KG	JP	AP	DJ	PM	TA	KB
West coast summer survey	1990	351										354									
	1991	349										384									
	1992				310	310	44								390	389	33				
	1993				313	311		49				2			353	352		62			
	1994				290	290		4							282	282		6			
	1995					303					303					368					368
	1996	292										365									
	1997	333		334								334									
	1999	268	307	299								319	352	359							
	2004			506																	
	2005			354									340								
	2006		465	468									163								
	2007		557	554									369	372							
	2008		412	409									475	453							
West coast winter survey	1988	471										354									
	1990	303																			
South coast spring survey	1994	10																			
	2004												808	808							
	2006		489	243									512								
	2007		116										441								
	2008		149										127								
South coast autumn survey	1991	109										421									
	1992				40	40	5								329	329	91				
	1993				95	95		23							407	407		40			
	1994				95	69		27				5			390	391		83			
	1995	95										404									
	1996	60										373									
	1997	85										387									
	1999		139	139					140	140	140		266	264					408	406	400
	2004												508								
	2005		194	193																	
	2006		444	358										740							
	2007		215	214									629	626							
	2008		137										643	643							
Offshore commercial	1992				521	521	46								260	260	28				
	1993				645	646		75							115	115		17			
	1994				330	330		38				5									
Longline comm.	1994				314	314		9							131	126		5			

Fig. App.I.1: Annual catches, see text for detail.

Fig. App.I.2: Sex-aggregated survey catch-at-length information. The vertical bars show the minus and plus group used.

West coast summer survey

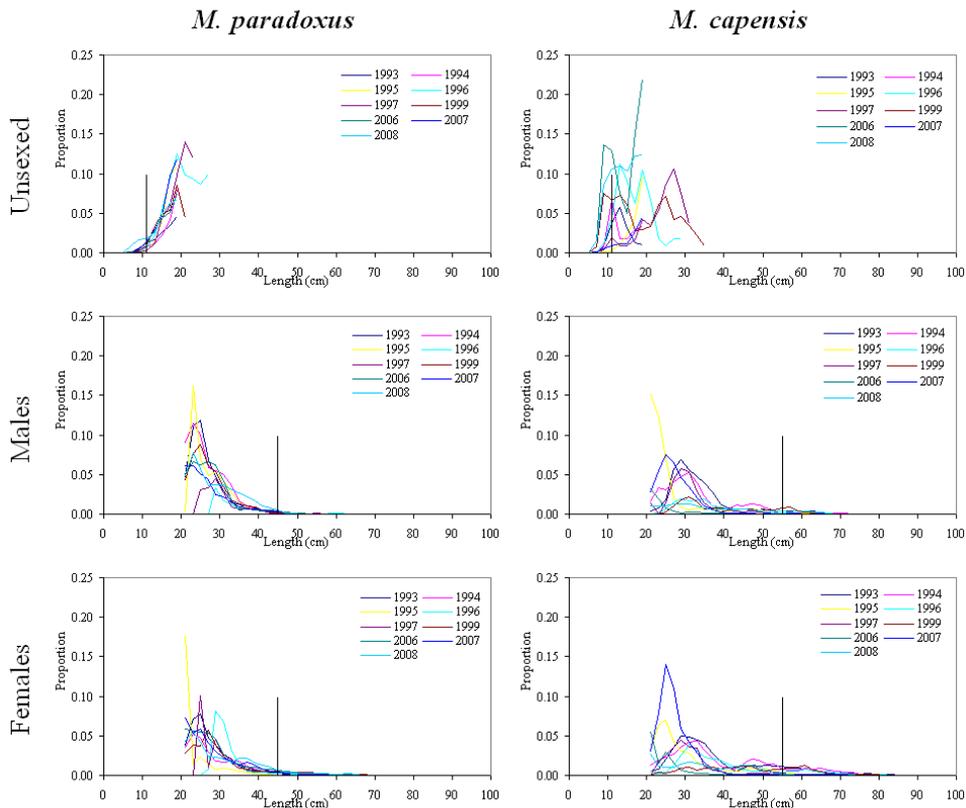### *M. paradoxus*   *M. capensis*

Fig App.I.3a: West coast summer gender-disaggregated survey catch-at-length information. The vertical bars show the minus and plus group used.
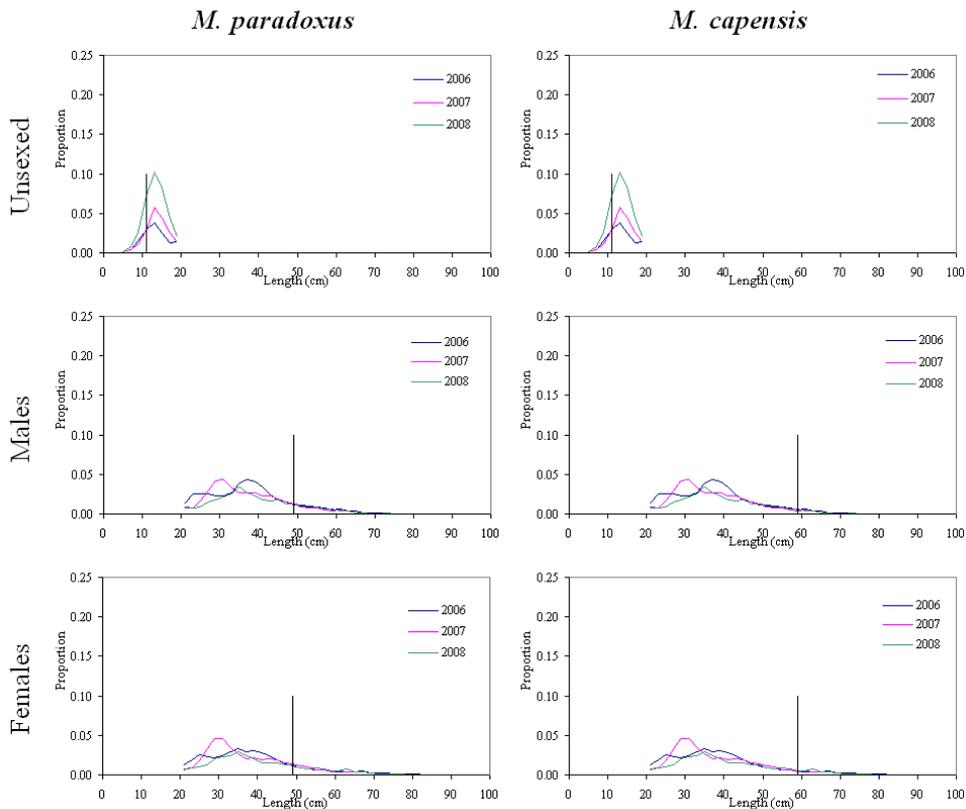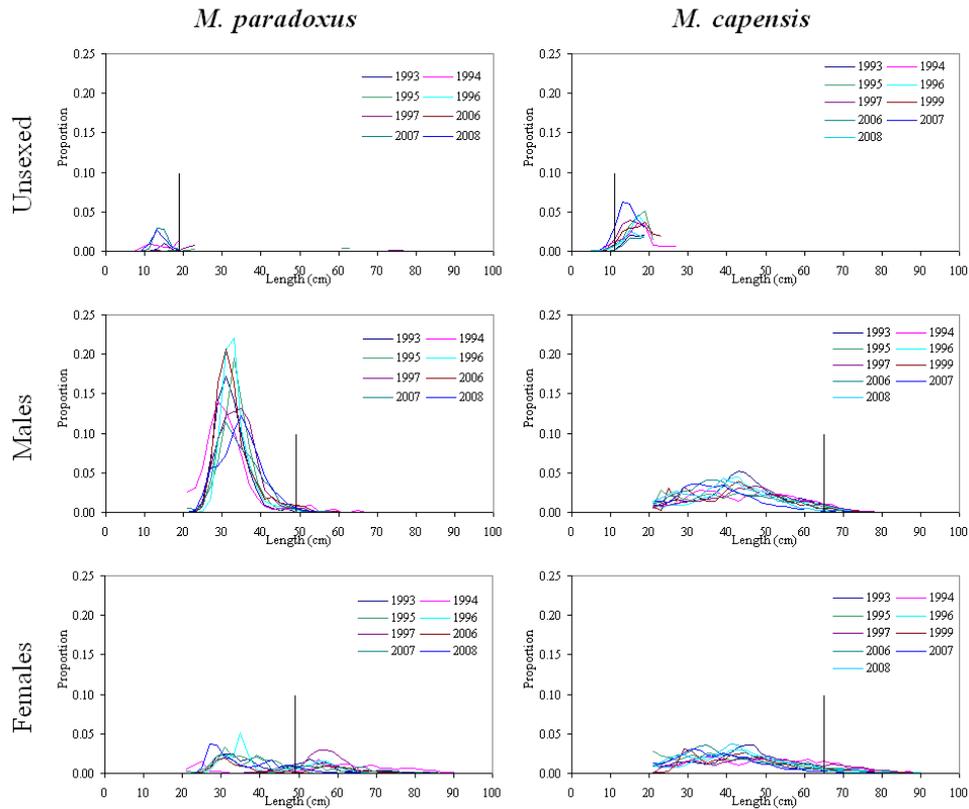
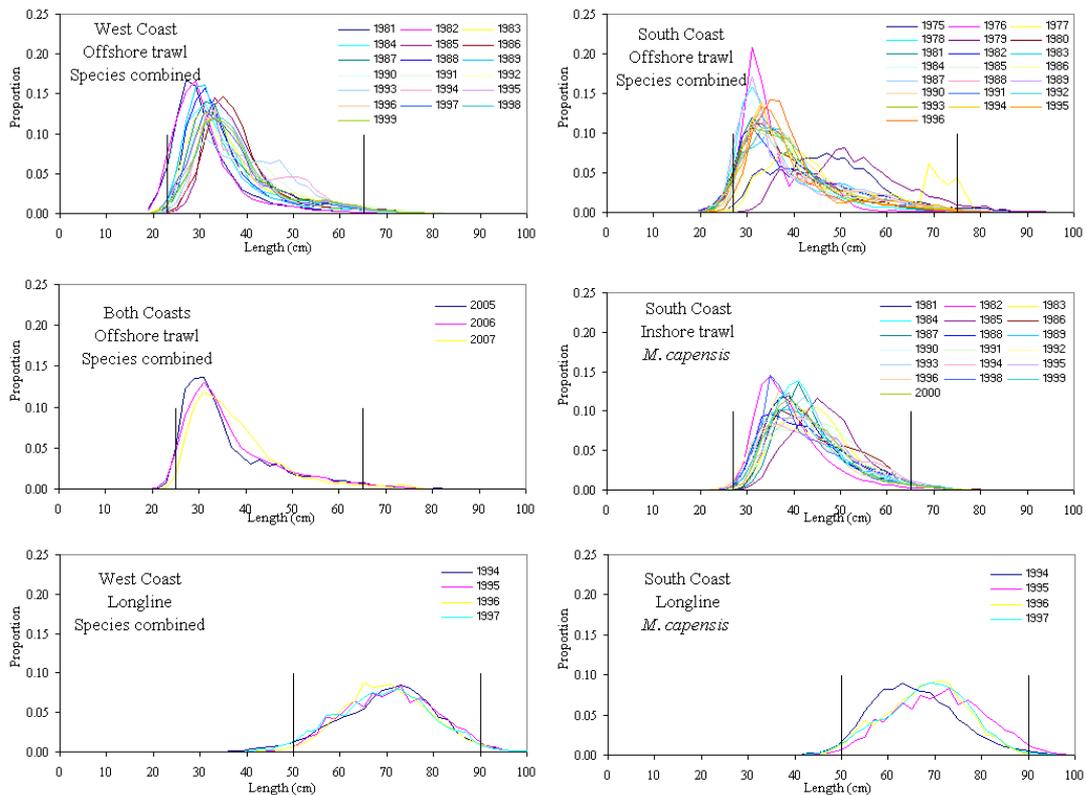## South coast spring survey

M. paradoxus   *M. capensis*

Fig App.I.3b: South coast spring gender-disaggregated survey catch-at-length information. The vertical bars show the minus and plus group used.

South coast autumn survey

Fig App.I.3c: South coast autumn gender-disaggregated survey catch-at-length information. The vertical bars show the minus and plus group used.

Fig App.I.4: Commercial catch-at-length information. The vertical bars show the minus and plus group used. Need to revise

APPENDIX II – Gender-disaggregated, Age-Structured Production Model fitting to Age-Length Keys

The model used is a gender-disaggregated Age-Structured Production Model (ASPM), which requires fitting directly to age-length keys (ALKs) and length frequencies. The model also involves assessing the two species as two independent stocks and it is fitted to species-disaggregated data as well as species-combined data. The general specifications and equations of the overall model are set out below together with some key choices in the implementation of the methodology. Details of the contributions to the log-likelihood function from the different data considered are also given. Quasi-Newton minimisation is used to minimise the total negative log-likelihood function (implemented using AD Model Builder^{TM}, Otter Research, Ltd.).

Population Dynamics

Numbers-at-age

The resource dynamics of the two populations (*M. capensis* and *M. paradoxus*) of the South African hake are modelled by the following set of equations:

Note: for ease of reading, the 'species' subscript *s* has been omitted below where not relevant.

$$N_{y+1,0}^g = R_{y+1}^g \qquad\qquad\qquad\qquad (\text{App.II.1})$$

$$N_{y+1,a+1}^g = \left(N_{ya}^g e^{-M_a/2} - \sum_f C_{fya}^g \right) e^{-M_a^g/2} \qquad\qquad \text{for } 0 \le a \le m-2 \qquad (\text{App.II.2})$$

$$N_{y+1,m}^g = \left(N_{y,m-1}^g e^{-M_{m-1}/2} - \sum_f C_{f,y,m-1}^g \right) e^{-M_{m-1}/2} + \left(N_{ym}^g e^{-M_m/2} - \sum_f C_{fym}^g \right) e^{-M_m/2} \; (\text{App.II.3})$$

where

N_{ya}^g is the number of fish of gender *g* and age *a* at the start of year *y*[1],

R_y^g is the recruitment (number of 0-year-old fish) of fish of gender *g* at the start of year *y*,

m is the maximum age considered (taken to be a plus-group),

M_a denotes the natural mortality rate on fish of age *a* (gender independent for the moment), and

C_{fya}^g is the number of hake of gender *g* and age *a* caught in year *y* by fleet *f*.

Recruitment

The number of recruits (i.e. new zero-year old fish) at the start of year *y* is assumed to be related to the corresponding female spawning stock size (i.e., the biomass of mature female fish) by means of the Beverton-Holt (Beverton and Holt, 1957) stock-recruitment relationship, parameterized in terms of the "steepness" of the stock-recruitment relationship, h, and the pre-exploitation equilibrium female spawning biomass, $K^{\female sp}$, and pre-exploitation recruitment, R_0 and assuming a 50:50 sex-split at recruitment.

---

[1] In the interests of less cumbersome notation, subscripts have been separated by commas only when this is necessary for clarity.

$$R_y^g = \frac{4hR_0 B_y^{\female,sp}}{K^{\female,sp}(1-h) + (5h-1)B_y^{\female,sp}} e^{(\varsigma_y - \sigma_R^2/2)}$$

(App.II.4)

where

ς_y reflects fluctuation about the expected recruitment in year y;

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

$$B_y^{\female,sp} = \sum_{a=1}^{m} f_a w_a^{\female} N_{ya}^{\female}$$

(App.II.5)

where

w_a^g is the begin-year mass of fish of gender g and age a, and

f_a is the proportion of fish of age a that are mature, and

$$.R_0 = K^{\female,sp} / \left[\sum_{a=1}^{m-1} f_a w_a^{\female} e^{-\sum_{a'=0}^{a-1} M_{a'}} + f_m w_m^{\female} \frac{e^{-\sum_{a'=0}^{m-1} M_{a'}}}{1-e^{-M_m}} \right]$$

(App.II.6)

Total catch and catches-at-age

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

$$C_{fy} = \sum_{g} \sum_{a=0}^{m} w_{a+1/2}^g \; C_{fya}^g = \sum_{g} \sum_{a=0}^{m} w_{a+1/2}^g \; N_{ya}^g e^{-M_a/2} F_{fy} S_{fya}^g$$

(App.II.7)

where

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

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

F_{fy} is the fishing mortality of a fully selected age class, for fleet f in year y (independent of g), and

S_{fya}^g is the 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) of gender g at age a for year y, and fleet f; when $S_{fya}^g = 1$[2], the age-class a is said to be fully selected.

As it is not possible to estimate a sex-specific commercial selectivity-at-age, it is rather assumed that the selectivity-at-length is the same for both males and females. The selectivity-at-length is converted to selectivity-at-age as follows:

$$S_{fya}^g = \sum_{l} S_{fyl} P_{a,l}^g$$

(App.II.8)

Where

---

[2] Such specification is provided for all sfy combinations to avoid confounding with F.

$P_{a,l}^g$ is the proportion of fish of age a and gender g that fall in the length group l (i.e., $\sum_l P_{a,l}^g = 1$ for

all ages a).

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

$$L_a \sim N\left[L_\infty\left(1 - e^{-\kappa(a-t_0)}\right); \theta_a^2\right] \tag{App.II.9}$$

where θ_a is the standard deviation of length-at-age a, which is modelled as a function of the expected length at age a, i.e.:

$$\theta_a = \beta\left[L_\infty\left(1 - e^{-\kappa(a-t_0)}\right)\right]^\gamma \tag{App.II.10}$$

The model estimate of the mid-year exploitable ("available") component of biomass for each species and 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:

$$B_{fy}^{ex} = \sum_g \sum_{a=0}^m w_{a+1/2}^g S_{fya}^g N_{ya}^g e^{-M_a/2}\left(1 - \sum_f S_{fya}^g F_{fy}\Big/2\right) \tag{App.II.11}$$

The model estimate of the survey biomass at the start of the year (summer) for each species is given by:

$$B_y^{surv} = \sum_g \sum_{a=0}^{m_s} w_a^g S_a^{g,surv,sum} N_{ya}^g \tag{App.II.12}$$

and in mid-year (winter):

$$B_y^{surv} = \sum_g \sum_{a=0}^m w_{a+1/2}^g S_a^{g,surv,win} N_{ya}^g e^{-M_a/2}\left(1 - \sum_f S_{fya}^g F_{fy}\Big/2\right) \tag{App.II.13}$$

where

$S_a^{g,surv,sum/win}$ is the survey selectivity for age a for gender g, converted from survey selectivity-at-length in the same manner as for the commercial selectivity (see eqn App.II.8).

Survey selectivity-at-length has been assumed to be the same for males and females.

Note that both the spring and autumn surveys are taken to correspond to winter (mid-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., $B_1^{g,sp} = K^{g,sp}$, and year $y=1$ corresponds to 1917 when catches are taken to commence.

The likelihood function

The model is fit to CPUE and survey abundance indices, commercial and survey length frequencies, survey age-length keys, 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[3].

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[3] Strictly it is a penalised log-likelihood which is maximised in the fitting process, as some contributions that would correspond to log-priors in a Bayesian estimation process are added.

CPUE relative abundance data

The likelihood is calculated by assuming that the observed abundance index (here CPUE) is log-normally distributed about its expected value:

$$I_y^i = \hat{I}_y^i e^{\varepsilon_y^i} \quad \text{or} \quad \varepsilon_y^i = \ell n\left(I_y^i\right) - \ell n\left(\hat{I}_y^i\right) \tag{App.II.14}$$

where

I_y^i is the abundance index for year y and series i (which corresponds to a specified species and fleet)

$\hat{I}_y^i = \hat{q}^i \hat{B}_{fy}^{ex}$ is the corresponding model estimate, where $\hat{B}_{fy}^{ex}$ is the model estimate of exploitable resource biomass, given by equation App.II.11,

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

ε_y^i from $N\left(0, \left(\sigma_y^i\right)^2\right)$.

In cases where the CPUE series are based upon species-aggregated catches (as available pre-1978), the corresponding model estimate is derived by assuming two types of fishing zones: z1) an "*M. capensis* only zone", corresponding to shallow water and z2) a "mixed zone" (Fig. App.II.1).

The total catch of hake of both species (*BS*) by fleet f in year y ($C_{BS,fy}$) can be written as:

$$C_{BS,fy} = C_{C,fy}^{z1} + C_{C,fy}^{z2} + C_{P,fy} \tag{App.II.15}$$

where

$C_{C,fy}^{z1}$ is the *M. capensis* catch by fleet f in year y in the *M. capensis* only zone (z1),

$C_{C,fy}^{z2}$ is the *M. capensis* catch by fleet f in year y in the mixed zone (z2), and

$C_{P,fy}$ is the *M. paradoxus* catch by fleet f in year y in the mixed zone.

Catch rate is assumed to be proportional to exploitable biomass. Furthermore, let γ be the proportion of the *M. capensis* exploitable biomass in the mixed zone ($\gamma = B_{C,fy}^{ex,z2} / B_{C,fy}^{ex}$) (assumed to be constant throughout the period for simplicity) and ψ_{fy} be the proportion of the effort of fleet f in the mixed zone in year y ($\psi_{fy} = E_{fy}^{z2} / E_{fy}$), so that:

$$C_{C,fy}^{z1} = q_C^{i,z1} B_{Cfy}^{ex,z1} E_{fy}^{z1} = q_C^{i,z1}\left(1 - \gamma\right) B_{C,fy}^{ex}\left(1 - \psi_{fy}\right) E_{fy} \tag{App.II.16}$$

$$C_{C,fy}^{z2} = q_C^{i,z2} B_{C,fy}^{ex,z2} E_{fy}^{z2} = q_C^{i,z2} \gamma B_{C,fy}^{ex} \psi_{fy} E_{fy} \quad \text{and} \tag{App.II.17}$$

$$C_{P,fy} = q_P^i B_{P,fy}^{ex} E_{fy}^{z2} = q_P^i B_{P,fy}^{ex} \psi_{fy} E_{fy} \tag{App.II.18}$$

where

$E_{fy} = E_{fy}^{z1} + E_{fy}^{z2}$ is the total effort of fleet f, corresponding to combined-species CPUE series i which consists of the effort in the *M. capensis* only zone (E_{fy}^{z1}) and the effort in the mixed zone (E_{fy}^{z2}), and

$q_C^{i,zj}$ is the catchability for *M. capensis* (*C*) for abundance series i, and zone zj, and

q_P^i is the catchability for *M. paradoxus* (*P*) for abundance series i.

It follows that:

$$C_{C,fy} = B_{C,fy}^{ex} E_{fy} \left[q_C^{i,z1}(1-\gamma)(1-\psi_{fy}) + q_C^{i,z2}\gamma\psi_{fy} \right]$$ (App.II.19)

$$C_{P,fy} = B_{P,fy}^{ex} E_{fy} q_P^i \psi_{fy}$$ (App.II.20)

From solving equations App.II.19 and App.II.20:

$$s_{fy} = \frac{q_C^{i,z1}(1-\gamma)}{\left\{ \dfrac{C_{C,fy} B_{P,fy}^{ex} q_P^i}{B_{C,fy}^{ex} C_{P,fy}} - q_C^{i,z2}\gamma + q_C^{i,z1}(1-\gamma) \right\}}$$ (App.II.21)

and:

$$\hat{I}_y^i = \frac{C_{fy}}{E_{fy}} = \frac{C_{fy} B_{P,fy}^{ex} q_P^i \psi_{fy}}{C_{P,fy}}$$ (App.II.22)

Zone 1 (z1): *M. capensis* only	Zone 2 (z2): Mixed zone
M. capensis: biomass (B_C^{z1}), catch(C_C^{z1})	*M. capensis*: biomass (B_C^{z2}), catch(C_C^{z2}) *M. paradoxus*: biomass (B_P), catch(C_P)
Effort in zone 1 (E^{z1})	Effort in zone 2 (E^{z2})

Fig. App.II.1: Diagrammatic representation of the two theoretical fishing zones.

Two species-aggregated CPUE indices are available: the ICSEAF west coast and the ICSEAF south coast series. For consistency, q's for each species (and zone) are forced to be in the same proportion:

$$q_s^{SC} = r q_s^{WC}$$ (App.II.23)

To correct for possible negative bias in estimates of variance $\left(\sigma_y^i \right)$ and to avoid according unrealistically high precision (and so giving inappropriately high weight) to the CPUE data, lower bounds on the standard deviations of the residuals for the logarithm of the CPUE series have been enforced; for the historic ICSEAF CPUE series (separate west coast and south coast series) the lower bound is set to 0.25, and to 0.15 for the recent GLM-standardised CPUE series, i.e.: $\sigma^{ICSEAF} \geq 0.25$ and $\sigma^{GLM} \geq 0.15$.

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

$$-\ell n\, L^{CPUE} = \sum_i \sum_y \left[\ell n\left(\sigma_y^i \right) + \left(\varepsilon_y^i \right)^2 / 2\left(\sigma_y^i \right)^2 \right]$$ (App.II.24)

where

σ_y^i is the standard deviation of the residuals for the logarithms of index i in year y.

Homoscedasticity of residuals for CPUE series is customarily assumed[4], so that $\sigma_y^i = \sigma^i$ is estimated in the fitting procedure by its maximum likelihood value:

$$\hat{\sigma}^i = \sqrt{1/n_i \sum_y \left(\ell n(I_y^i) - \ell n(\hat{I}_y^i) \right)^2} \qquad \text{(App.II.25)}$$

where n_i is the number of data points for abundance index i.

In the case of the species-disaggregated CPUE series, the catchability coefficient q^i for abundance index i is estimated by its maximum likelihood value, which in the more general case of heteroscedastic residuals, is given by:

$$\ln \hat{q}^i = \frac{\sum_y \left(\ln I_y^i - \ln \hat{B}_{srfy}^{ex} \right) / \left(\sigma_y^i \right)^2}{\sum_y 1 / \left(\sigma_y^i \right)^2} \qquad \text{(App.II.26)}$$

In the case of the species-combined CPUE, $q_C^{i,z1}$, $q_C^{i,z2}$, q_P^i and γ are directly estimated in the fitting procedure.

Survey abundance data

Data from the research surveys are treated as relative abundance indices in a similar manner to the species-disaggregated CPUE series above, with survey selectivity function $S_a^{surv,sum/win}$ replacing the commercial selectivity S_{fya} (see equations App.II.12 and App.II.13 above, which also take account of the begin- or mid-year nature of the survey).

An estimate of sampling variance is available for most surveys and the associated σ_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 App.II.24). The procedure adopted takes into account an additional variance $\left(\sigma_A^i \right)^2$ which is treated as another estimable parameter in the minimisation process. This procedure is carried out enforcing the constraint that $\left(\sigma_A^i \right)^2 > 0$, i.e. the overall variance cannot be less than its externally input component.

In June 2003, the trawl gear on the *Africana* was changed and a different value for the multiplicative bias factor q is taken to apply to the surveys conducted with the new gear. Calibration experiments have been conducted between the *Africana* with the old gear (hereafter referred to as the "old *Africana*") and the *Nansen*, and between the *Africana* with the new gear ("new *Africana*") and the *Nansen*, in order to provide a basis to relate the multiplicative biases of the *Africana* with the two types of gear (q_{old} and q_{new}). A GLM analysis assuming negative binomial distributions for the catches made (Brandão *et al.*, 2004) provided the following estimates:

$\Delta \ell n q^{capensis} = -0.494$ with $\sigma_{\Delta \ell n q^{capensis}} = 0.141$ i.e. $\left(q^{new} / q^{old} \right)^{capensis} = 0.610$ and

$\Delta \ell n q^{paradoxus} = -0.053$ with $\sigma_{\Delta \ell n q^{paradoxus}} = 0.117$ i.e. $\left(q^{new} / q^{old} \right)^{paradoxus} = 0.948$

where

$\ell n q_{new}^s = \ell n q_{old}^s + \Delta \ell n q^s$ with $s = capensis$ or $paradoxus$ (App.II.27)

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[4] There are insufficient data in any series to enable this to be tested with meaningful power.

No plausible explanation has yet been found for the particularly large extent to which catch efficiency for *M. capensis* is estimated to have decreased for the new research survey trawl net. It was therefore recommended (BENEFIT, 2004) that the ratio of the catchability of the new to the previous *Africana* net be below 1, but not as low as the ratio estimated from the calibration experiments. $\Delta\ell nq^{capensis}$ is therefore taken as -0.223, i.e. $\left(q^{new}/q^{old}\right)^{capensis} = 0.8$.

The following contribution is therefore added as a penalty (or a prior in a Bayesian context) to the negative log-likelihood in the assessment:

$$-\ell nL^{q-ch} = \left(\ell nq_{new} - \ell nq_{old} - \Delta\ell nq\right)^2 / 2\sigma^2_{\Delta\ell nq} \qquad \text{(App.II.28)}$$

A different length-specific selectivity is estimated for the "old *Africana*" and the "new *Africana*".

Commercial proportions at length

Commercial proportions at length cannot be disaggregated by species and gender. The model is therefore fit to the proportions at length as determined for both species and gender combined.

To be able to incorporate the proportion at length information, the proportions at age predicted by the model ($\widehat{p}^{g}_{sya}$) (which is based upon gender- and age-specific selectivity) for each species and gender are converted to proportions at length ($\widehat{p}^{g}_{syl}$) using the von Bertalanffy growth equation, assuming that the length-at-age distribution remains constant over time:

$$\widehat{p}^{g}_{syl} = \sum_{a} \widehat{p}^{g}_{sya} P^{g}_{sal} \qquad \text{(App.II.29)}$$

The contribution of the proportion at length data to the negative of the log-likelihood function when assuming an "adjusted" lognormal error distribution is given by:

$$-\ln L^{\text{length}} = 0.1 \sum_{y} \sum_{l} \left[\ell n\left(\sigma^{i}_{len} / \sqrt{p^{i}_{yl}}\right) + p^{i}_{yl}\left(\ell np^{i}_{yl} - \ell n\,\widehat{p}^{i}_{yl}\right)^2 / 2\left(\sigma^{i}_{len}\right)^2\right] \qquad \text{(App.II.30)}$$

where

the superscript '*i*' refers to a particular series of proportions at length data which reflect a specified fleet and coast, and species (or combination thereof) and

σ_{len} is the standard deviation associated with the proportion at length data, which is estimated in the fitting procedure by:

$$\hat{\sigma}^{i}_{len} = \sqrt{\sum_{y}\sum_{l} p^{i}_{yl}\left(\ln p^{i}_{yl} - \ln \hat{p}^{i}_{yl}\right)^2 / \sum_{y}\sum_{l} 1} \qquad \text{(App.II.31)}$$

The initial 0.1 multiplicative factor is a somewhat arbitrary downweighting to allow for correlation between proportions in adjacent length groups.

Commercial proportions at length are incorporated in the likelihood function using equation App.II.30, for which the summation over length *l* is taken from length l_{minus} (considered as a minus group) to l_{plus} (a plus group). The length for the minus- and plus-groups are fleet specific and are chosen so that typically a few percent, but no more, of the fish sampled fall into these two groups.

Survey proportions at length

The survey proportions at length 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 App.II.30). In this case however, data are disaggregated by species and for some surveys, further disaggregated by gender.

$$p_{syl}^{g,surv} = \frac{C_{syl}^{g,surv}}{\sum_{l} C_{syl}^{g,surv}}$$ is the observed proportion of fish of species s, gender g and length l from

survey $surv$ in year y,

$\hat{p}_{syl}^{g,surv}$ is the expected proportion of fish of species s, gender g and length l in year y in the survey $surv$, given by:

$$\hat{p}_{syl}^{g,surv} = \sum_{a} \hat{p}_{sya}^{g,surv} P_{sal}^{g} \qquad \text{(App.II.32)}$$

where

$$\hat{p}_{sya}^{g,surv} = \frac{S_{sa}^{g,surv,sum} N_{sya}^{g}}{\sum_{a'=0}^{m_s} S_{sa'}^{g,surv,sum} N_{sya'}^{g}} \qquad \text{(App.II.33)}$$

for begin-year (summer) surveys, or

$$\hat{p}_{sya}^{g,surv} = \frac{S_{sa}^{g,surv,win} N_{sya}^{g} e^{-M_a/2} \left(1 - \sum_{f} S_{fya}^{g} F_{fy} \Big/ 2 \right)}{\sum_{a'=0}^{m_s} S_{sa'}^{surv,win} N_{sya'} e^{-M_{a'}/2} \left(1 - \sum_{f} S_{fya'}^{g} F_{fy} \Big/ 2 \right)} \qquad \text{(App.II.34)}$$

for mid-year (autumn, winter or spring) surveys.

Age-length keys

Under the assumption that fish are sampled randomly with respect to age within each length-class, the contribution to the negative log-likelihood for the ALK data (ignoring constants) is:

$$-\ln L^{ALK} = -\sum_{i} \sum_{l} \sum_{a} \left[A_{i,l,a}^{obs} \ln\left(\hat{A}_{i,l,a}\right) - A_{i,l,a}^{obs} \ln\left(A_{i,l,a}^{obs}\right) \right] \qquad \text{(App.II.35)}$$

where

$A_{i,a,l}^{obs}$ is the observed number of fish of age a that fall in the length class l, for ALK i (a specific combination of survey, year, species and gender),

$\hat{A}_{i,a,l}$ is the model estimate of $A_{i,a,l}^{obs}$, computed as:

$$\hat{A}_{i,a,l} = W_{i,l} \frac{C_{i,l} A_{a,l}}{\sum_{a'} C_{i,l} A_{a',l}} \qquad \text{(App.II.36)}$$

where

$W_{i,l}$ is the number of fish in length class l that were aged for ALK i,.

$A_{a',l} = \sum_{a} P(a'|a) A_{a,l}$ is the ALK for age a and length l after accounting for age-reading error,

with.

$P(a'|a)$ the age-reading error matrix, representing the probability of an animal of true age a being aged to be that age or some other age a'.

Age-reading error matrices have been computed for each reader and for each species in Rademeyer (2009).

When multiple readers age the same fish, these data are considered to be independent information in the model fitting.

Stock-recruitment function residuals

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

$$- \ell n L^{SR} = \sum_{s} \sum_{y=y1}^{y2} \varsigma_{sy}^{2} \Big/ 2\sigma_{R}^{2} \qquad \text{(App.II.37)}$$

where

ς_{sy} is the recruitment residual for species s, and year y, which is assumed to be log-normally distributed with standard deviation σ_{R} and which is estimated for year $y1$ to $y2$ (see equation App.II.4) (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); and

σ_{R} is the standard deviation of the log-residuals, which is input.

The stock-recruitment residuals are estimated for years 1985 to 2006, with recruitment for other years being set deterministically (i.e. exactly as given by the estimated stock-recruitment curve) as there is insufficient catch-at-age information to allow reliable residual estimation for earlier years. A limit on the recent recruitment fluctuations is set by having the σ_{R} (which measures the extent of variability in recruitment – see equation – App.II.37) decreasing linearly from 0.25 in 2004 to 0.1 in 2009, effectively forcing recruitment over the last years to lie closer to the stock-recruitment relationship curve.

Model parameters

Estimable parameters

The primary parameters estimated are the species-specific female virgin spawning biomass $\left(K_{s}^{\varphi sp}\right)$ and "steepness" of the stock-recruitment relationship (h_{s}). The standard deviations σ^{i} for the CPUE series residuals (the species-combined as well as the GLM-standardised series) as well as the additional variance $\left(\sigma_{A}^{i}\right)^{2}$ for each survey abundance series are treated as estimable parameters in the minimisation process. Similarly, in the case of the species-combined CPUE, $q_{C}^{i,z1}$, $q_{C}^{i,z2}$, q_{P}^{i} and γ are directly estimated in the fitting procedure.

The species- and gender-specific von Bertalanffy growth curve parameters (L_{inf}, K and t_{0}) are estimated directly in the model fitting process, as well as b and g used to compute the standard deviation of the length-at-age a (App.II.10).

The following parameters are also estimated in the model fits undertaken (if not specifically indicated as fixed).

Natural mortality:

Natural mortality (M_{sa}) is assumed to be age-specific and is estimated using the following functional form:

$$M_{sa} = \begin{cases} M_{s2} & \text{for} \quad a \le 1 \\ \alpha_s^M + \dfrac{\beta_s^M}{a+1} & \text{for} \quad 2 \le a \le 5 \\ M_{s5} & \text{for} \quad a > 5 \end{cases}$$
(App.II.38)

M_{s0} and M_{s1} are set equal to M_{s2} ($= \alpha_s^M + \beta_s^M/3$) as there are no data (hake of ages younger than 2 are rare in catch and survey data) which would allow independent estimation of M_{s0} and M_{s1}.

Upper bounds of 1.0 and 0.5 on ages 2 and 5 respectively are implemented in the baseline assessment to maintain biological realism (likelihood maximisation prefers higher values for large ages in many cases, but this seems unlikely given there are few known predators of large hake).

Commercial fishing selectivity-at-length:

The fishing selectivity-at-length (gender independent) for each species and fleet, S_{sfl}, is estimated in terms of a logistic curve given by:

$$S_{sfl} = \left[1 + \exp\left(-\left(l - l_{sf}^c\right)/\delta_{sf}^c\right)\right]^{-1}$$
(App.II.39)

where

l_{sf}^c cm is the length-at-50% selectivity,

δ_{sf}^c cm^{-1} defines the steepness of the ascending limb of the selectivity curve.

The selectivity is sometimes modified to include a decrease in selectivity at larger lengths, as follows:

$$S_{sfl} \to S_{sfl} e^{-s_{sfl}\left(l - l_{slope}\right)} \quad \text{for } l > l_{slope},$$
(App.II.40)

where

s_{sfl} measures the rate of decrease in selectivity with length for fish longer than l_{slope} for the fleet concerned, and is referred to as the "selectivity slope".

Periods of fixed and changing selectivity have been assumed for the offshore trawl fleet to take account of the change in the selectivity at low ages over time in the commercial catches, likely due to the phasing out of the (illegal) use of net liners to enhance catch rates. Details of the fishing selectivities used in the assessment are shown in Table App.II.2 below.

Table App.II.2: Details for the commercial selectivity-at-length for each fleet and species combination, as well as indications of what data are available.

		M. paradoxus	*M. capensis*	data available
1. West coast offshore				
	1917-1976	set equal to 1989	set equal to 1989	
	1977-1984	two logistic + slope parameters estimated	same shift as paradoxus, zero slope	species combined
	1985-1992	linear change between 1984 and 1993 selectivity		species combined
	1993-2009	two logistic + slope parameters estimated	same as SC inshore but shifted to the right by 10 cm, zero slope	species combined
2. South coast offshore				
	1917-1976	set equal to 1989	set equal to 1989	
	1977-1984	two logistic + slope parameters estimated	same shift as paradoxus, zero slope	species combined
	1985-1992	linear change between 1984 and 1993 selectivity		species combined
	1993-2009	two logistic + slope parameters estimated	same as SC inshore but shifted to the right by 10 cm, zero slope	species combined
3. South coast inshore			two logistic + slope parameters estimated	capensis
4. West coast longline		two logistic parameters estimated, zero slope	same as South Coast longline	species combined
5. South coast longline			two logistic parameters estimated, zero slope	capensis
6. South coast handline			average of South Coast longline and inshore	

Survey fishing selectivity-at-length:

The survey selectivities are estimated directly for seven pre-determined lengths for *M. paradoxus* and *M. capensis*. When the model was fitted to proportion-at-age rather than proportion-at-length, survey selectivities were estimated directly for each ages (i.e. seven age classes); this is were the seven length come from. The lengths at which selectivity is estimated directly are survey specific (linear between the minus and plus groups) and are given in Table App.I.3 below. Between these lengths, selectivity is assumed to change linearly. The slope from lengths 16 to 15cm is assumed to continue exponentially to length 1 and similarly, the slope from lengths 57 and 58cm for *M. paradoxus* and from lengths 64 and 65 cm for *M. capensis* is assumed to continue exponentially to the maximum length considered (105cm)..

Table App.II.32: Lengths (in cm) at which survey selectivity is estimated directly.

M. paradoxus	West coast summer	11	16	22	27	33	38	44	49
	West coast winter	13	18	24	29	35	40	46	51
	South coast spring	19	24	30	35	41	46	52	57
	South coast autumn	19	24	30	35	41	46	52	57
M. capensis	West coast summer	11	16	22	27	33	38	44	49
	West coast winter	13	18	24	29	35	40	46	51
	South coast spring	11	16	22	27	33	38	44	49
	South coast autumn	11	16	22	27	33	38	44	49

Stock-recruitment residuals:

Stock-recruitment residuals ς_{sy} are estimable parameters in the model fitting process. They are estimated separately for each species, from 1985 to the present and set to zero pre-1985, because there are no catch-at-length data for that period to provide the necessary information.

Input parameters and other choice for application to hake

Age-at-maturity:

The proportion of female fish of species *s* and length *l* that are mature is assumed to follow a logistic curve with the parameter values given below (from Fairweather and Leslie, 2008, "stage 2, >40cm"):

	M. paradoxus	*M. capensis*
L50	43.43cm	43.64cm
Δ	4.33cm	6.23cm

Maturity-at-length is then converted to maturity-at-age as follows:

$$f_{sa}^{g} = \sum_{l} f_{sl}^{g} P_{a,l}^{g} \qquad\qquad (App.II.41)$$

Weight-at-length:

The weight-at-length for each species and gender is calculated from the mass-at-length function, with values of the parameters for this function listed below (from Fairweather, 2008, taking the average of the west and south coasts):

	M. paradoxus		*M. capensis*	
	Males	*Females*	*Males*	*Females*
α	0.007541	0.005836	0.006307	0.005786
β	2.9882	3.0653	3.0612	3.0851

Minus- and plus-groups

Because of a combination of gear selectivity and mortality, a relatively small number of fish in the smallest and largest length classes are caught. In consequence, there can be relatively larger errors (in terms of variance) associated with these data. To reduce this effect, the assessment is conducted with minus- and plus-groups obtained by summing the data over the lengths below and above l_{minus} and l_{plus} respectively. The minus- and plus-group used are given in Table App.II.43 (and plotted in Figs.I.2 and 3). Furthermore, the proportions at length data (both commercial and survey) are summed into 2cm length classes for the model fitting.

Table App.II.43: Minus- and plus-groups taken for the surveys and commercial proportion at length data.

SURVEY DATA		*M. paradoxus*		*M. capensis*	
		Minus	Plus	Minus	Plus
West coast summer					
Gender-aggregated data		13	47	13	59
Gender-disaggregated data	Unsexed	11	-	11	-
	Males	-	45	-	55
	Females	-	45	-	55
West coast winter					
Gender-aggregated data		13	51	13	61
Gender-disaggregated data	Unsexed	-	-	-	-
	Males	-	-	-	-
	Females	-	-	-	-
South coast spring					
Gender-aggregated data		21	53	13	71
Gender-disaggregated data	Unsexed	11	-	11	-
	Males	-	49	-	59
	Females	-	49	-	59
South coast autumn					
Gender-aggregated data		21	57	13	69
Gender-disaggregated data	Unsexed	19	-	11	-
	Males	-	49	-	65
	Females	-	49	-	65
COMMERCIAL DATA					
		Minus	Plus		
West coast offshore, species combined		23	65		
South coast offshore, species combined		27	75		
South coast inshore, *M. capensis*		27	65		
West coast longline, species combined		51	91		
South coast longline, *M. capensis*		51	91		
Both coasts offshore, species combined		25	65		