Southern blue whiting (*Micromesistius australis*) stock assessment for the Campbell Island Rise for 2009–10

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EXECUTIVE SUMMARY

This report documents the development of a stock assessment for the Campbell Island Rise stock of southern blue whiting for 1979–2009 using catch history, proportion-at-age, and acoustic survey data up to and including the 2009 season. The primary data sources on abundance were the R.V. *Tangaroa* wide area acoustic surveys carried out from 1993 to 2009 and proportion-at-age data from 1979 to 2009. The main information on recent stock size came from the 2009 survey, which had the highest adult biomass and second highest estimate of immature fish from the entire series.

Two base case models were considered for the assessment, one using age-based fishing selectivities and the second using length-based fishing selectivities. MCMC estimates of initial (equilibrium) spawning stock biomass (B_0) were estimated at 375 500 t (95% C.I.s 323 760–456 830 t) for the age-based model and 334 230 t (291 510–409 910 t) for the length-based model. The corresponding estimates of B_{2009} (%B_0) were 40% (28–54%) and 41% (27–56%). These median estimates of B_0 are about 50% higher than previous estimates of B_0 from this stock. This is primarily due to the strong 2006 and 2007 year classes which are about to enter the fishery. There is little doubt that these year classes are strong, and possibly similar in strength to the previous strong 1991 year class, but at present they are poorly estimated by the model. An acoustic survey of this stock is taking place in September 2011 and the strength of these year classes will be better known after the results have been analysed.

Two sensitivities were also carried out for the assessment. The first modelled the acoustic biomass estimates as categories rather than as decomposed biomass at age. Here, we assumed that the immature and adult biomass categories from the acoustic surveys are a compound estimate comprising one selectivity pattern for the immature biomass estimates and a separate selectivity pattern for the adult biomass estimates, where the latter selectivity was constrained to be equal to the commercial fishery selectivity. Estimates of key model parameters such as B_0, B_{2009}, and B_{2009} (%B_0) were similar, but slightly lower than, the comparable base case model. However, the fits to the acoustic indices appeared substantially worse. The main problem appears to be that the fishery targets different length classes in different areas in different years. By creating a single "one-size fits all" selectivity ogive for each acoustic category some of this finer detail is lost and the fits are consequently worse. While there are several other ways in which this could potentially be implemented in the model, none of them are likely to be entirely satisfactory and may not result in model improvement.

The second sensitivity modelled observations from the sub-Antarctic trawl survey biomass and age frequencies time series. Although the fits suggested some consistency in biomass estimates between the summer series and the model estimates, in general the trawl survey underestimated biomass at low stock sizes and overestimated biomass at high stock sizes. We therefore conclude that the time series is not particularly useful for monitoring abundance in its present form.

1. INTRODUCTION

Southern blue whiting (SBW) are almost entirely restricted in distribution to sub-Antarctic waters. They are dispersed throughout the Campbell Plateau and Bounty Platform for much of the year, but during August and September they aggregate to spawn near the Campbell Islands, on Pukaki Rise, on Bounty Platform, and near Auckland Islands over depths of 250–

600 m (Figure 1). During most years fish in the spawning fishery range between 35–50 cm fork length (FL), although occasionally smaller length classes of males (29–32 cm FL) have been observed in the catch (Hanchet & Dunn 2010).

Commercial fishing has been concentrated on the Campbell Island Rise and, to a lesser extent, the Bounty Platform. The Pukaki Rise and Auckland Islands have been generally smaller fisheries, with much lower annual catches than the Campbell Island Rise and Bounty Platform fisheries (Hanchet & Dunn 2010).

Acoustic surveys using R.V. *Tangaroa* and assessments of the Campbell Island Rise stock have been carried out, typically every two to three years, since 1993 (e.g., Hanchet 1991, 1992, Hanchet & Haist 1994, Hanchet & Ingerson 1995, Hanchet & Ingerson 1996, Hanchet 1997, Hanchet et al. 1998, Hanchet 2000, Hanchet et al. 2003). The most recent assessment was reported by Hanchet et al. (2006) for the 2005–06 fishing year. They identified several areas of future work including alternative parameterisations of the selectivity ogive for the acoustic surveys, length-based rather than age-based fishing selectivity, and fitting to sub-Antarctic trawl survey results.

This report documents the assessment of the Campbell Island Rise stock using data up to and including the 2009 season. We update the assessment using the R.V. *Tangaroa* acoustic indices for 1993–2009 and commercial catch proportions-at-age data from the years 1979–2009. We consider the implications to the model of using either the acoustic indices by age (2, 3, and 4+ fish) or category (immature and mature). Trawl survey indices from the sub-Antarctic in areas near the Campbell Island Rise are briefly evaluated as indices of abundance. A review and summary of the input data available for the Campbell Island Rise was given by Hanchet & Dunn (2010).

This report is in fulfilment of the Ministry of Fisheries Project SBW2009/01 objective 2: To update the stock assessment of the Campbell Island Rise stock, including estimating biomass and sustainable yields.
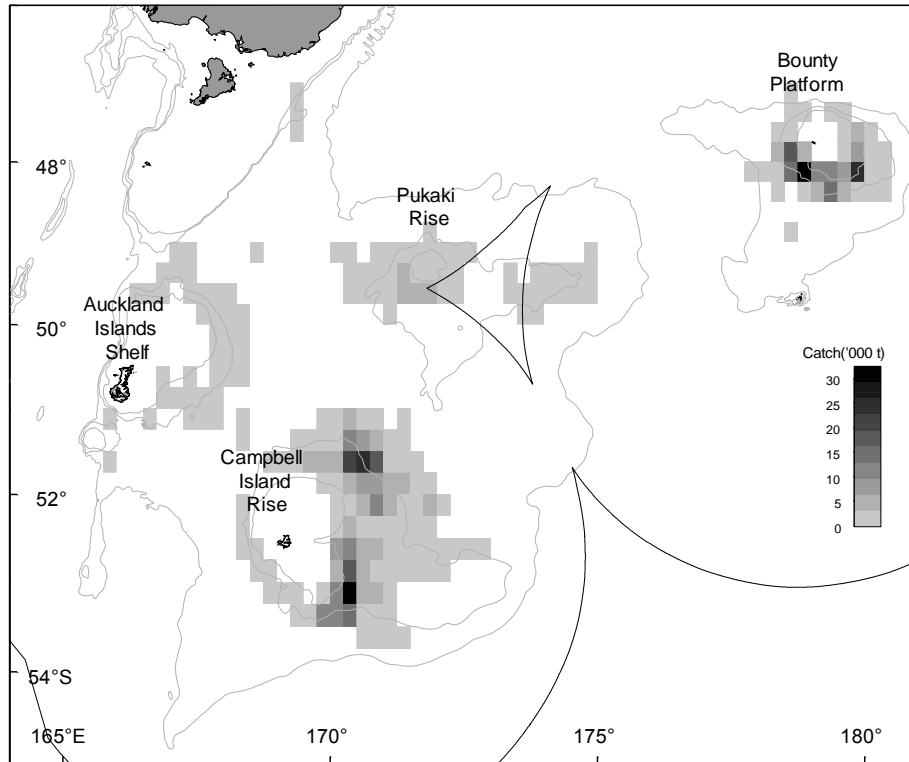
Figure 1: Relative total density of the commercial catch of southern blue whiting by location, TCEPR data 1990–2009.

2. METHODS

2.1 Population dynamics

A two-sex, single stock and area Bayesian statistical catch-at-age model for the Campbell Island Rise southern blue whiting stock was implemented in CASAL (Bull et al. 2011) following a similar approach to that used in previous assessments of this stock (e.g., Hanchet et al. 2006). The model partitioned the stock into two sexes with age groups 2–11, with a plus group at age 11, and was run for the years 1979 to 2009. Five year projections were run for the years 2010–2014. The annual cycle was partitioned into two time steps (Table 1). In the first time step (nominally the non-spawning season), 90% of natural mortality was assumed to have taken place. In the second time step (spawning season), fish ages were incremented; the 2-year-olds were recruited to the population, which were then subjected to fishing mortality and the remaining 10% of natural mortality. A two sex model was used because there are significant differences observed between males and females in both the proportions at age in the commercial catch for fish aged 2–4 (see later) and their mean length at age (Hanchet & Dunn 2010).

Catches for southern blue whiting have been recorded since 1971 (Hanchet & Dunn 2010), with an average of 25 000 t annual catch between 1971 and 1977 (Figure 2). However, the locations and hence stock associated with the catch in this period is not well known. In addition, age and length sampling of the population from 1979 showed evidence of a very high proportion (greater than 50% by number in the catch proportions-at-age) of old fish (11+) in the Campbell Island Rise population, with the age data suggesting that there was at least one very strong year class spawned in or around 1965 that remained a significant part of the population until the mid 1980s (see also Hanchet et al. (1998)).

Without knowledge of the actual catch before 1978 and strong evidence that the population was not at an equilibrium age structure, we assume a non-equilibrium age structure as the initial state. Hence, the population model was initialised with a starting state, labelled $C_{initial}$, in 1979. The numbers of individuals in the population at the start of the model were estimated for each age group as independent parameters (see Cinitial in Bull et al. 2009 for details). Although the fishing selectivity on southern blue whiting differs at ages 2–4 between males and females, and the values of natural mortality may differ slightly between sexes, we assume that these differences will have little effect on the relative proportions of males and females in each age class in the population in 1979. Hence, we constrained the estimates of the initial age structure so that the number of males and females within each age class were equal.

The stock recruitment relationship was assumed to be Beverton-Holt with a steepness of 0.9, with the proportion of males at recruitment (at age 2) assumed to be 0.5 of all recruits. Year class strengths for the years 1977–2007 were parameterised in the model such that the mean for the years 1977–2007 was assumed to equal one.

Southern blue whiting exhibit large inter-annual differences in growth, presumably caused by local environmental factors, that are closely correlated with the occurrence of the strong and weak year classes. Hence, we do not use a standard von Bertalanffy growth curve to determine the mean length at age of fish in the model, but rather an empirical length-at-age matrix (See Appendix). The length-at-age matrix was derived by qualitatively reviewing the empirically estimated mean lengths-at-age from the commercial catch-at-length and -age data (Hanchet & Dunn 2010). Missing estimated mean lengths in the matrix were inferred from the relative size of their cohort and the mean growth of similar ages in other years; and cohorts with unusually small or large increments were similarly adjusted.

The mean length-at-ages in the future years were required for projections and calculated as follows. The mean length in 2010 was calculated by adding the observed mean growth increment from 1979–2009 to each age class in 2009 to determine their expected lengths in 2010, with the mean length of age 2 fish in 2010 assumed to be equal to the mean of the annual mean lengths of age 2 fish from 1979–2009. By iteratively applying the above algorithm, the mean lengths for the years 2011–2014 were determined (See Appendix).

Lengths-at-age were converted to weights-at-age in the model using the length-weight relationship given by Hanchet (1991), i.e., assuming the relationship weight $= a \times \text{length}^b$ for length in centimetres and weight in kilograms. The parameters $a= 0.00515$ and 0.00407, and $b = 3.092$ and 3.152 were assumed for males and females respectively.

In general, southern blue whiting are assumed to be fully or almost fully selected by the fishery at either age four or five and not vulnerable to fishing at age one. We assumed that fishing selectivities were logistic by sex, and that the maximum exploitation rate (U_{max}) was 0.7. Further, in order to include potential changes in selectivity either as a function of age or sex, we investigated both age-based selectivities with an annual shift parameter, or length-based selectivities with an annual shift parameter.

In previous models of southern blue whiting on the Campbell Island Rise, fish available to the fishery were all assumed to be mature and spawning, with all of these fish equally likely to be vulnerable to fishing (i.e., a fishing selectivity was assumed that was equal to one for all mature fish). In the models presented here, we disentangled the estimates of the maturity ogive from the fishing selectivity. Hence, we assume a fixed proportion of fish at age and sex mature (Figure 3), and estimate a logistic shaped fishing selectivity for males and females respectively.

Table 1: Annual cycle of the stock model, showing the processes taking place at each step, and the available observations. Fishing mortality (*F*) and natural mortality (*M*) that occur within a time step occur after all other processes. Column headed *M* is the proportion of *M* occurring in that time step.

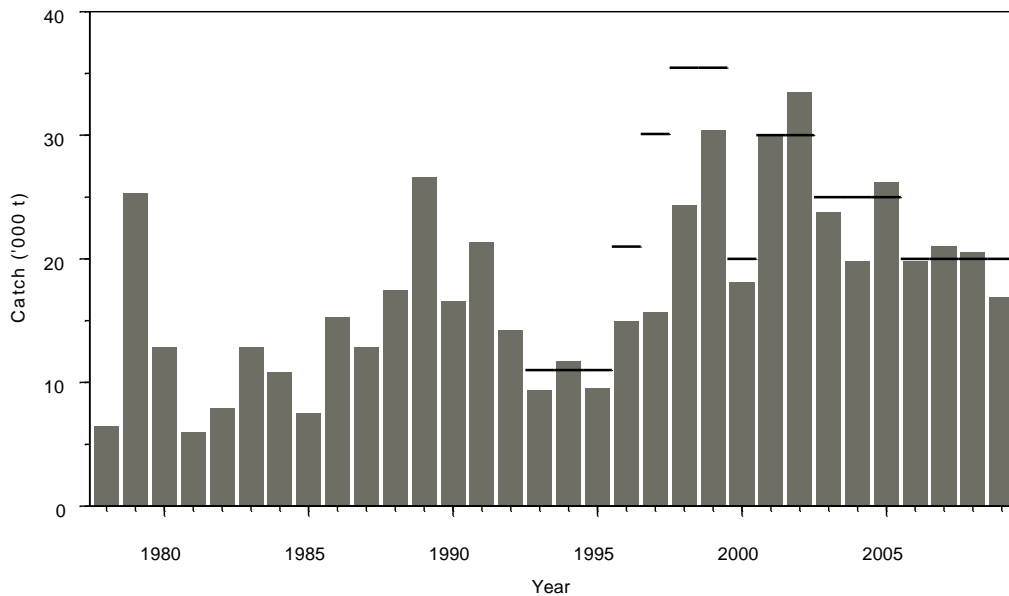| Period	Process	M	Length at age	Observations
1. Nov–Aug	Natural mortality (*M*)	0.9	–	Summer trawl survey
2. Sep–Oct	Age, recruitment, fishing mortality (*F*), and *M*	0.1	Growth matrix	Proportions at age
				Acoustic abundance indices
				Autumn trawl survey

Figure 2: Reported landings of southern blue whiting on the Campbell Island Rise, 1978–2009. Horizontal lines indicate the TACC since 1993.
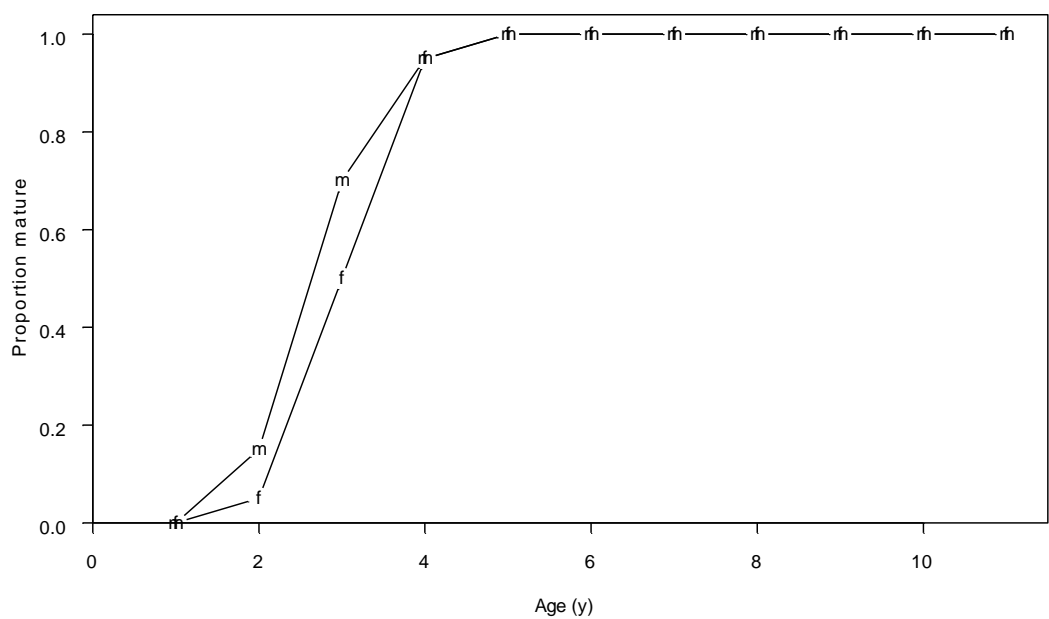

Figure 3: Assumed proportions mature for males (m) and females (f) for the Campbell Island Rise.

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2.2 Observations

2.2.1 Wide area acoustic surveys

Acoustic biomass estimates of southern blue whiting available on Campbell Island Rise during the fishing season were available from a wide area survey series conducted by the R.V. *Tangaroa* in the years 1993–1995, 1998, 2000, 2002, 2004, 2006 and 2009 (Hanchet & Dunn 2010).

Southern blue whiting acoustic marks were identified as one of three categories of fish; juvenile, immature, and adult. The categories were broadly defined as adult (also known as mature) that consisted mainly of adult fish which were going to spawn that year; immature that consisted mainly of 2 year olds; and juvenile that consisted mainly of 1 year olds. Identification of each mark to a category was typically made based on an assessment of the acoustic 'shape' of the mark or its location (for example, shallow or deep). These categories were then decomposed into biomass estimates of age classes, consisting of 1, 2, 3 and 4+ aged fish using the methods documented in Hanchet et al. (2000). Marks in the northern and southern fishing grounds around Campbell Island were decomposed using scaled length frequencies corresponding to each ground. The mature fish (adults) were usually decomposed using the scaled adult commercial length frequency distribution for that ground and year; while the immature and juvenile categories were decomposed using the length frequency distributions obtained from targeted research trawling for that ground and year (Hanchet et al. 2000).

For the base case assessment models we used the wide area survey acoustic biomass estimates of southern blue whiting by age (aged 2, 3, and 4+ — see Table 2), and assumed that these were relative estimates of mid-season biomass (i.e., after half the catch for that season has been removed), with a c.v. equal to sampling c.v. estimated from the survey (Table 2).

In a sensitivity run, we considered the model fit to the wide area survey acoustic biomass estimates of southern blue whiting by categories (juvenile, immature, and adult — see Table 3). In these models we ignore the juvenile category because biomass estimates of the juvenile (almost exclusively one year olds) were highly variable, inconsistent between years, and are not likely to be a good index of abundance. Hence, only the biomass estimates for immature and adult fish were used.

For these models, the overall survey selectivity ogive was split into two size categories using a 'compound' selectivity ogive. Here, the selectivity of immature fish was assumed to be the product of some (estimated) overall selectivity and an inverse logistic ogive. The selectivity of the adult fish was assumed to be the product of that same overall selectivity and a standard logistic ogive. Further, values for parameters of the respective selectivities for immature and adult fish were constrained so that they shared common values, i.e., the decline in the immature selectivity with age is defined so that it exactly matches the increase in the adult selectivity. The selectivity is defined so that,

$$f_{Overall}\ x\ =\ 1 - a_{min}\ \bigg/ \bigg[1 + 19^{\ a_{50} - x\ /a_{to95}} \bigg] + a_{min}$$

$$f_{immature}\ x\ =\ f_{Overall}\ x\ \times\ 1 - 1 \bigg/ \bigg[1 + 19^{\ b_{50} - x\ /b_{to95}} \bigg]$$

$$f_{adult}\ x\ =\ f_{Overall}\ x\ \times 1 \bigg/ \bigg[1 + 19^{\ b_{50} - x\ /b_{to95}} \bigg]$$

where a_{50} is the value of the 50% selectivity of the overall logistic curve, a_{to95} describes its slope, and a_{min} is the minimum value of the curve; b_{50} is the 50% selectivity of both the left

(immature) inverse logistic curve and the right (adult) logistic curve; and b_{to95} describes their equal (but opposite) slopes.

For both the age and category models, the acoustic biomass observations were fitted using a lognormal likelihood,

$$-\log L = \sum_{i=1}^{n} \left(\log \sigma_i + 0.5 \left(\frac{\log O_i / qE_i}{\sigma_i} + 0.5\sigma_i \right)^2 \right)$$

$$\text{where } \sigma_i = \sqrt{\log 1 + c_i^2}$$

where O_i are the observed biomass estimates at time i with c.v.s c_i, E_i are the model expected biomasses at time i and q is the catchability constant for the biomass series.

Table 2: Acoustic biomass estimates (t) of age 1, 2, 3 and 4+ southern blue whiting on the Campbell Island Rise using the revised target strength and sound absorption coefficient, 1993–2009 (Gauthier et al. 2011).

Year	Age 1 Biomass	c.v.	Age 2 Biomass	c.v.	Age 3 Biomass	c.v.	Age 4+ Biomass	c.v.
1993	206	1.76	107 192	0.28	13 396	0.23	16 784	0.25
1994	699	0.57	19 634	0.29	168 006	0.32	23 213	0.28
1995	0	–	17 269	0.27	27 952	0.21	124 892	0.25
1998	8 678	0.25	20 895	0.15	35 579	0.12	139 388	0.18
2000	2 443	0.38	15 606	0.16	8 785	0.16	110 931	0.17
2002	13 436	0.38	4 609	0.65	10 632	0.64	103 422	0.68
2004	3 144	0.65	24 380	0.15	36 683	0.30	39 007	0.39
2006	2 230	0.32	27 933	0.23	10 199	0.34	56 206	0.32
2009	0	–	110 250	0.22	115 944	0.26	92 598	0.27

Table 3: Acoustic biomass estimates (t) of juvenile, immature, and adult southern blue whiting on the Campbell Island Rise using the revised target strength and sound absorption coefficient, 1993–2009 (Gauthier et al. 2011).

Year	Juvenile Biomass	c.v.	Immature Biomass	c.v.	Adult Biomass	c.v.
1993	0	–	129 380	0.25	28 649	0.24
1994	0	–	26 280	0.38	180 439	0.34
1995	0	–	48 844	0.29	123 124	0.30
1998	2 103	0.45	26 987	0.20	171 199	0.14
2000	2 468	0.39	6 074	0.24	138 196	0.17
2002	13 228	0.39	681	0.76	116 178	0.68
2004	3 090	0.67	16 833	0.16	79 074	0.35
2006	2 200	0.38	10 892	0.24	81 628	0.32
2009	0	–	98 098	0.28	204 539	0.27

2.2.2 Trawl research survey biomass estimates

Sub-Antarctic trawl surveys targeting hoki, hake, and ling have been carried out using R.V. *Tangaroa* since 1991 (e.g., O'Driscoll & Bagley 2009) in two time series, summer and autumn. Although southern blue whiting have not been a target species of these surveys, they are often caught in moderate numbers — particularly on the Pukaki Rise and Campbell Island Rise. Hanchet & Stevenson (2006) reanalysed biomass estimates and scaled length frequency distributions for southern blue whiting from the Sub-Antarctic summer and autumn survey

series for each of three sub-areas, Pukaki Rise, Campbell Island Rise, and Auckland Island Shelf. They defined the three areas as follows: Pukaki Rise (strata 11, 12); Campbell Island Rise (10, 13, 14, 15, and 9S); Auckland Island Shelf (3, 4, 5, 6, 7, 8, 9N) (see Figure 5 in Hanchet & Dunn 2010).

The c.v.s of the trawl survey biomass estimates for the Campbell Island Rise area were mainly 25–40%, possibly making them marginally useful as an index to monitor abundance (Table 4). Qualitative evaluation of the survey biomass estimates suggested some consistency in biomass estimates between the summer and autumn series, between adjacent surveys, and with the acoustic estimates of the Campbell Island stock. However, while Hanchet & Stevenson (2006) noted that the trend in the trawl survey abundance indices on the Campbell Island Rise was generally similar to estimates of biomass from the population model, they noted that the trawl survey typically appeared to underestimate biomass at low stock sizes and overestimate biomass at high stock sizes.

In a sensitivity run, we considered a model with data from the sub-Antarctic summer trawl survey series. Data from the autumn series was not considered because (i) the series consisted of only four points and has not been updated since 1998, and (ii) otolith data collected from the survey has not been aged and no commercial catch-at-age data were available for that time of the year.

When used, the summer trawl survey biomass observations were fitted using a lognormal likelihood, i.e.,

$$-\log L = \sum_{i=1}^{n} \left(\log \sigma_i + 0.5 \left(\frac{\log O_i / q E_i}{\sigma_i} + 0.5 \sigma_i \right)^2 \right)$$

$$\text{where } \sigma_i = \sqrt{\log 1 + c_i^2}$$

where O_i are the observed biomass estimates at time i with c.v.s c_i, E_i are the model expected biomasses at time i and q is the catchability constant for the biomass series.

Table 4: R.V. *Tangaroa* trawl survey biomass estimates for selected strata for the Campbell Island Rise (data for 1991–2005 from Hanchet & Stevenson (2006)).

			Summer					Autumn	
Year	Trip	Biomass (t)	c.v.	N	Year	Trip	Biomass (t)	c.v.	N
1991	TAN9105	2 328	0.53	52	1992	TAN9211	5 942	0.58	39
1992	TAN9204	5 013	0.31	54	1993	TAN9310	1 714	0.29	34
1993	TAN9304	2 472	0.25	52	1996[1]	TAN9605	31 203	0.36	19
2000	TAN0012	10 738	0.14	23	1998	TAN9805	10 321	0.37	17
2001	TAN0118	6 393	0.40	23					
2002	TAN0219	3 198	0.45	20					
2003	TAN0317	1 047	0.56	19					
2004	TAN0414	778	0.26	21					
2005	TAN0515	1 502	0.27	17					
2006	TAN0617	4 729	0.73	16					
2007	TAN0714	2 631	0.53	19					
2008	TAN0813	5 870	0.29	17					
2009	TAN0911	4 884	0.31	15					

1. Only 1 station for TAN9605 was in stratum 0009S (see Figure 5 in Hanchet & Dunn 2010). This was supplemented with a second station taken from 0009N to allow the stratum biomass and variance to be calculated. The contribution of stratum 0009S to the total biomass was ~64 t, and hence the impact of this correction on the estimated biomass was negligible.

2.2.3 Proportions-at-age for the wide-area acoustic surveys

Length and age frequency data used for the decomposition of the wide-area acoustic biomass estimates were derived from length frequencies of fish caught in target identification tows by the R.V. *Tangaroa* (typically juvenile and immature fish), combined with length frequency data from the commercial catch of the adult biomass. These length data were combined with the age-length key for that year (made up from age-length data collected from both acoustic research and commercial catch data). Here, sampled fish caught from the juvenile or immature marks (from the acoustic target identification and other research tows from the acoustic surveys) were assumed to be a simple random sample of the length frequency of juvenile or immature fish respectively. These were converted to estimates of the age frequencies, with associated c.v.s by age estimated using the NIWA catch-at-age software by bootstrap (Bull & Dunn 2002). The resulting age frequencies for juvenile and immature fish are given in Figure 4 and Figure 5 respectively.

Data for juvenile categories were ignored as the survey sampling was not believed to index their abundance. Hence only the data for immature fish were used in the sensitivity models with acoustic category data as proportions-at-age observations to inform the shape of the compound selectivity.

The catch proportions-at-age data were fitted to the modelled proportions-at-age composition using a multinomial likelihood,

$$-\log L = -\log N! + \sum_i \left[\log NO_i! - NO_i \log E_i \right]$$

where O_i are the observed proportions-at-age i, E_i are the model expected proportions-at-age i, and N is the effective sample size. The derivation of the assumed multinomial sample sizes for the proportions-at-age data was the same as described for the commercial catch-at-age data, described below.
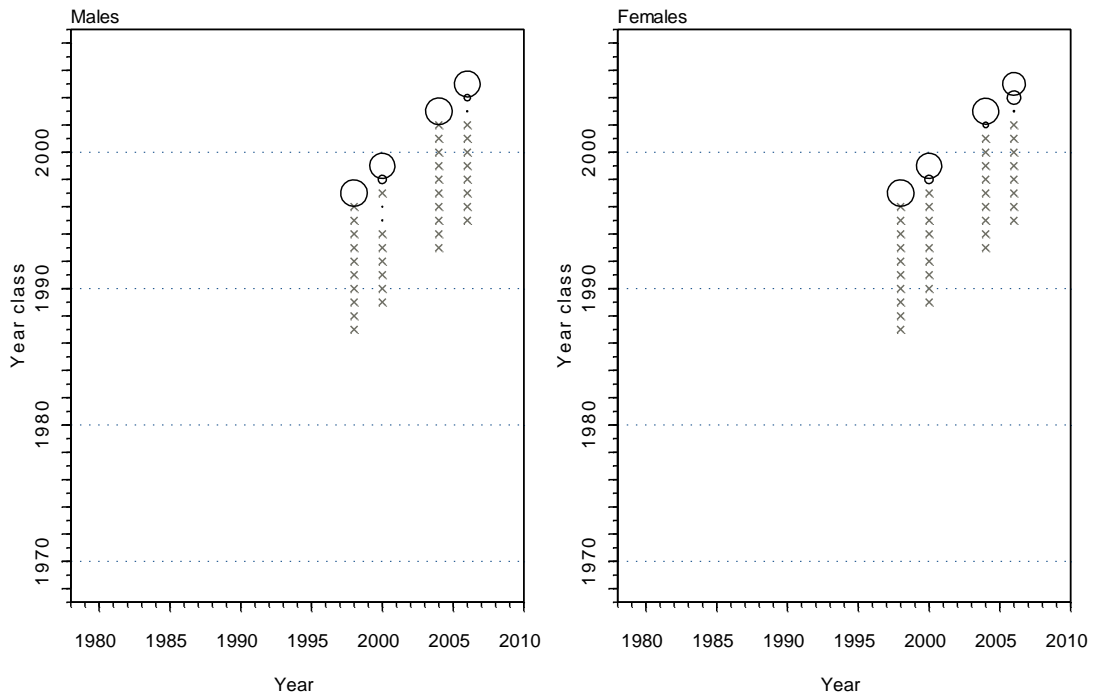
Figure 4: Acoustic juvenile proportions at age for the Campbell Island stock by sex and year class, 1993–2009 for ages 2–11+. Symbol area proportional to the proportions-at-age within the sampling event.
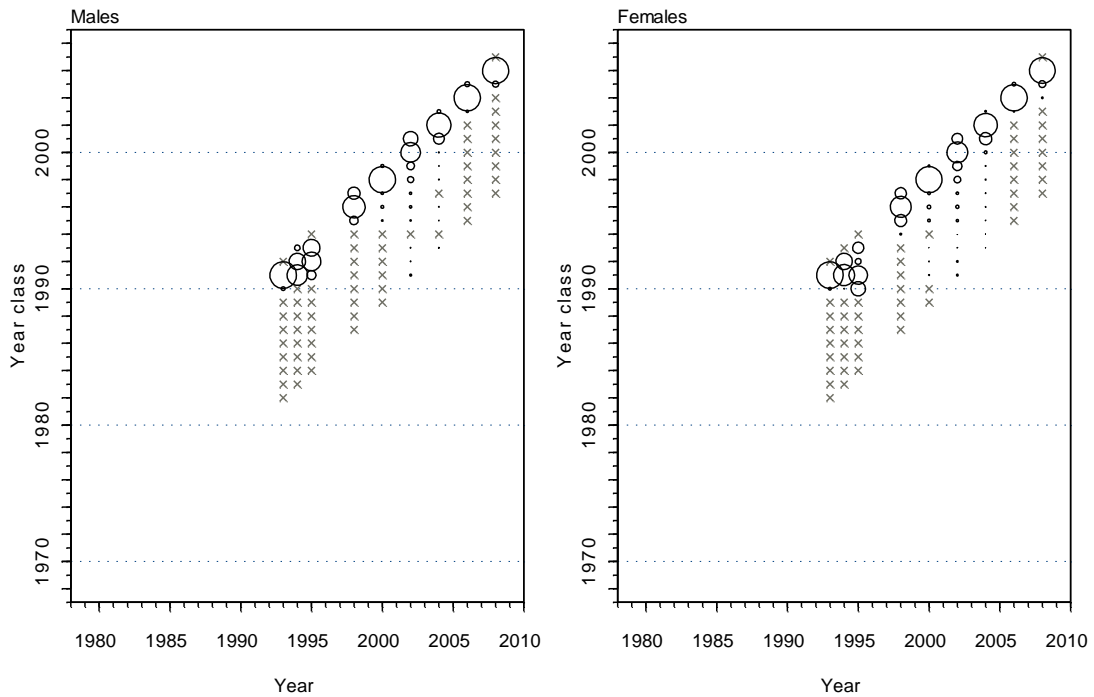

Figure 5: Acoustic immature proportions at age for the Campbell Island stock by sex and year class, 1993–2009 for ages 2–11+. Symbol area proportional to the proportions-at-age within the sampling event.

2.2.4 Trawl survey proportions-at-age

Length frequency data from the summer trawl surveys were calculated by scaling length samples to the tow catch and then the stratum area. These length data were combined with the

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age-length key from that year (made up from age-length data collected from both acoustic research and commercial catch data) using the NIWA catch-at-age software by bootstrap (Bull & Dunn 2002). Note that the otoliths were mainly collected during September, whilst the summer trawl surveys were carried out in November/December. Although the fish may grow slightly during this period, it was unlikely to have significantly biased the results. Age frequencies for the trawl surveys are given in Figure 6. Age data were not available from the autumn trawl survey series, and hence catch-at-age frequencies were not calculated.

The catch proportions-at-age data were fitted to the modelled proportions-at-age composition using a multinomial likelihood,

$$-\log L = -\log N! + \sum_i \left[\log NO_i! - NO_i \log E_i \right]$$

where O_i are the observed proportions-at-age i, E_i are the model expected proportions-at-age i, and N is the effective sample size. The derivation of the assumed multinomial sample sizes for the proportions-at-age data was the same as described for the commercial catch-at-age data, described below.
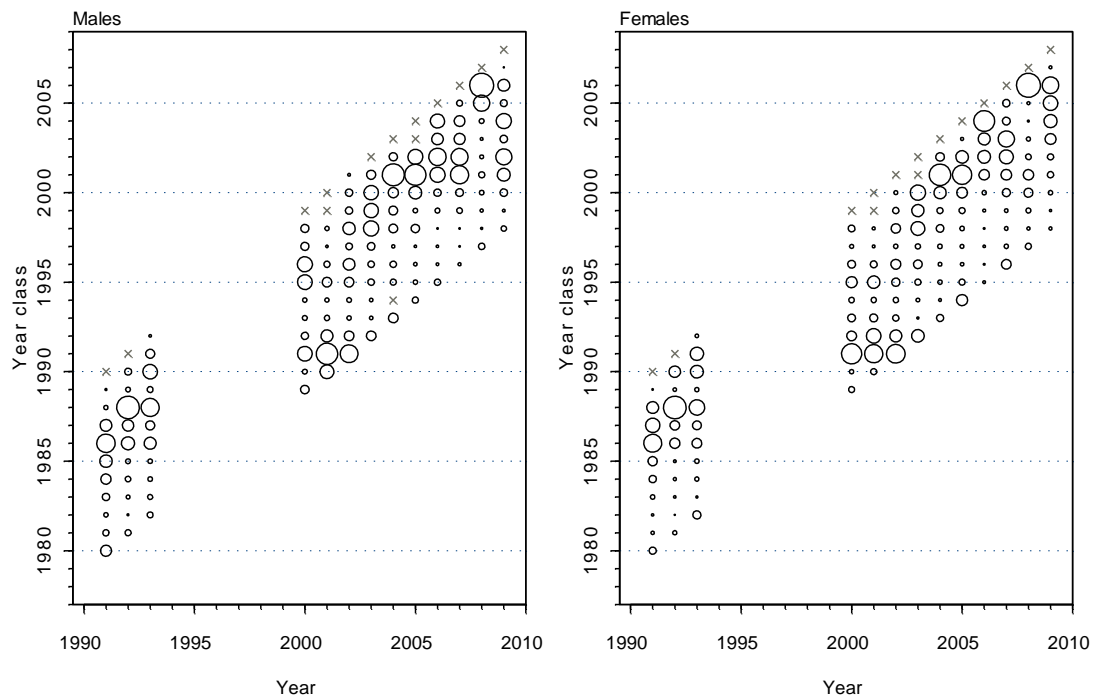

Figure 6: Summer trawl survey proportions at age for the Campbell Island stock by sex and year class, 1991–2009 for ages 2–11+. Symbol area proportional to the proportions-at-age within the sampling event.

2.2.5 Proportions-at-age in the commercial catch

Catch-at-age observations by sex were available from the commercial fishery for 1979 to 2009 from observer data, excluding 1987 (Figure 7). While length data were available for 1987, there were no otoliths aged from 1987 and hence we ignore these data in this analysis. Commercial catch-at-age data were fitted to the model as proportions-at-age by sex, where associated c.v.s by age were estimated using the NIWA catch-at-age software by bootstrap (Bull & Dunn 2002). The catch proportions-at-age data were fitted to the modelled proportions-at-age composition using a multinomial likelihood,

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$$-\log L = -\log N! + \sum_i \left[\log NO_i! - NO_i \log E_i\right]$$

where O_i are the observed proportions-at-age i, E_i are the model expected proportions-at-age i, and N is the effective sample size. Proportions-at-age data were derived from the aged otoliths collected by observers and the length frequency of the catch. Hanchet & Dunn (2010) described the catch-at-age data available for the assessment models from 1990, and data before 1990 was described by Hanchet et al. (2006). The derivation of the assumed multinomial sample sizes for the proportions-at-age data is described below.

Ageing error was ignored in the proportions-at-age data as errors in ageing for southern blue whiting are believed to be very low.
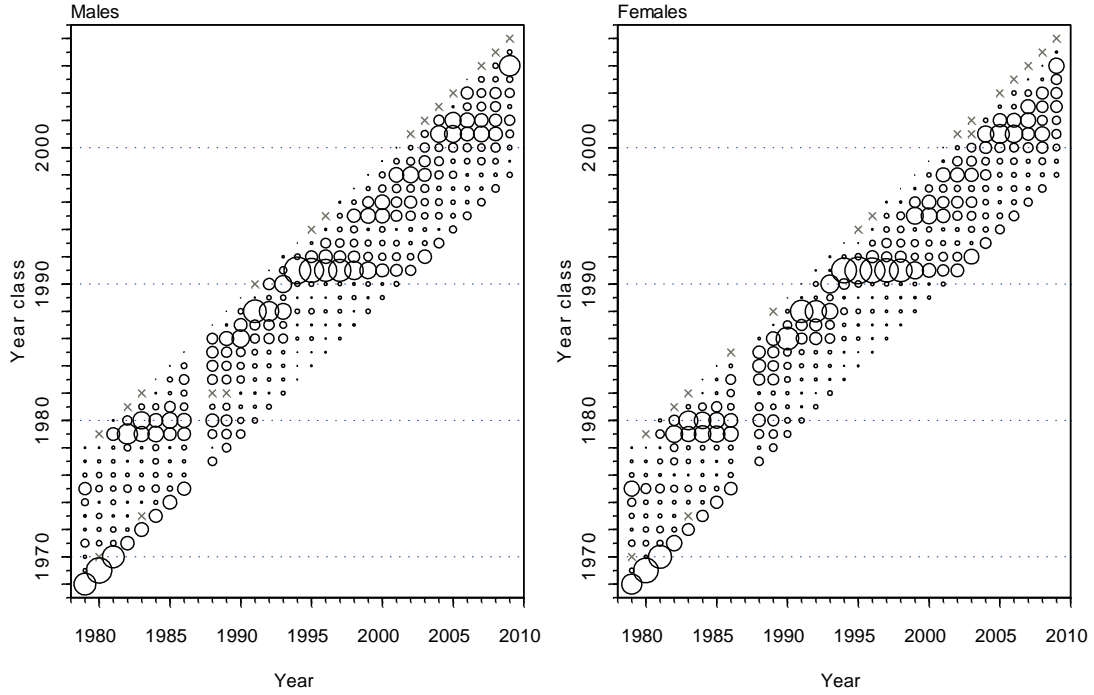

Figure 7: Commercial catch proportions at age for the Campbell Island stock by sex and year class, 1978–2009 for ages 2–11+. Symbol area proportional to the proportions-at-age within the sampling event.

2.3 Model estimation

The model parameters were estimated by minimising an objective function, which is the sum of the negative log-likelihoods from the data, negative-log priors (in a Bayesian analysis), and penalties that constrain the parameterisations, i.e., the objective function in a Bayesian analysis for **p**, the vector of the free parameters, L the likelihood function, and O_i the ith observation was

$$\text{Objective}(\mathbf{p}) = -\sum_i \log\left[L\left(\mathbf{p}\mid O_i\right)\right] - \log\left[\theta\left(\mathbf{p}\right)\right]$$

Where θ is the joint prior (and penalty) density of the parameters **p**. The observations, likelihoods, penalties, and priors are described later.

Initial model fits were evaluated at the maximum of the posterior density (MPD), MPD profile distributions (i.e., by evaluating the minimum objective function while fixing one

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parameter and allowing all other parameters to vary), and model fits and residuals. At the MPD, the approximate covariance matrix of the free parameters was calculated as the inverse of the approximation to the Hessian, and the corresponding correlation matrix also calculated.

To estimate the joint posterior distribution of the parameters in a Bayesian analysis, CASAL uses a straightforward implementation of the Metropolis algorithm (Gelman et al. 1995, Gilks et al. 1998) to execute the Monte Carlo Markov Chain (MCMC). The Metropolis algorithm attempts to draw a sample from a Bayesian posterior distribution, and calculates the posterior density π, scaled by an unknown constant. The algorithm generates a 'chain' or sequence of values. Typically the beginning of the chain is discarded and every nth element of the remainder is taken as the posterior sample. The chain is produced by taking an initial point x_0 and repeatedly applying the following rule, where x_i is the current point; (i) draw a candidate step s from a proposal distribution J, which should be symmetric i.e., $J(-s)=J(s)$, (ii) calculate $r=\min(\pi(x_i+s)/\pi(x_i),1)$, and (iii) let $x_{i+1}=x_i+s$ with probability r, or x_i with probability $1-r$.

A point estimate (i.e., the MPD) was produced, along with the approximate covariance matrix of the parameters (as the inverse Hessian) (see Bull et al. 2008 for more detail), and used as the starting point for the chain.

MCMCs were estimated using a burn-in length of 1×10^6 iterations, with every $10\,000^{th}$ sample taken from the next 1×10^7 iterations (i.e., a systematic sample of length 1000 was taken from the Bayesian posterior). Chain diagnostic plots, autocorrelation estimates, and single chain convergence tests of Geweke (1992) and Heidelberger & Welch (1983) stationarity and half-width were used to determine evidence of non-convergence. The tests used a significance level of 0.05 and the diagnostics were calculated using the Bayesian Output Analysis software (Smith 2003).

2.3.1 Prior distributions and penalties

In general, the assumed prior distributions used in the assessment were intended to be non-informative with wide bounds (Table 5). The exceptions to this were the priors and penalties on biomass catchability coefficients for fish aged 4+ and on the relative year class strengths. The prior assumed for the relative year class strengths was lognormal, with mean 1.0 and c.v. 1.3, for all year classes.

A log-normal prior was used for the acoustic survey catchability coefficient of adults ages 4+ with mean 1.0 and c.v. 0.2. The prior for ages 2 and 3 was assumed to be uniform. The prior used for the wide area acoustic survey catchability coefficient for ages 4+ was originally obtained using the approach of Cordue (1996), and was detailed by Hanchet (2002). Uncertainty over various factors, including mean target strength, acoustic system calibration, target identification, shadow or dead zone correction, and areal availability were included within the derivation of the prior. That approach suggested a mean of 1.4 and c.v. 0.2 with bounds 0.1–2.8. Following the recalibration of the acoustic estimates with revised estimates of the target strength relationship and sound absorption coefficients, the Middle Depths Fisheries Assessment Working Group revised the prior parameters but retained their bounds.

Natural mortality was estimated to be 0.2 y^{-1} by Hanchet (1991). The prior on natural mortality was determined by assuming that the true value could differ from the current value by about 0.05 y^{-1}, and not more than 0.1 y^{-1}. Natural mortality was parameterised by the average of male and female, with the difference estimated with an associated normal prior with mean zero and bounds of 0.05 y^{-1}.

Penalty functions were used to constrain the model so that any combinations of parameters that did not allow the historical catch to be taken were strongly penalised. A small penalty was applied to encourage the estimates of year class strengths to have mean equal to one.

Table 5: The parameters, number of degrees of freedom (N), selectivity shape (shape), priors (including distributions, and means and c.v.s for the lognormal), and bounds assumed for estimated parameters.

Parameter	Shape	N	Distribution	Mean	c.v.	Lower	Upper
							Priors
					Values		Bounds
B_0		1	Uniform-log	–	–	30 000	800 000
Initial population (by sex)		10	Uniform	–	–	5e5	1e10
Male fishing selectivity							
Age-based	Logistic	2	Uniform	–	–	1	20
Length-based	Logistic	2	Uniform	–	–	20	50
Female fishing selectivity							
Age-based	Logistic	2	Uniform	–	–	1	20
Length-based	Logistic	2	Uniform	–	–	20	50
Selectivity shift parameters		3	Uniform	–	–	-10	10
Year class strength		31	Lognormal	1.0	1.3	0.001	100
Acoustic catchability q							
Age model (2+)		1	Uniform	–	–	0.1	2.8
Age model (3+)		1	Uniform	–	–	0.1	2.8
Age model (4+)		1	Lognormal	1.0	0.2	0.1	2.8
Category model		1	Lognormal	1.0	0.2	0.1	2.8
Trawl selectivity							
Male	Logistic	2	Uniform	–	–	1	20
Female	Logistic	2	Uniform	–	–	1	20
Trawl catchability q		1	Uniform	–	–	0.01	1.0
Natural mortality (average)			lognormal	0.2	0.2	0.075	0.325
Natural mortality (difference)			Normal	0.0	0.05	-0.05	0.05

2.3.2 Process error and data weighting

Lognormal errors, with known c.v.s, were assumed for the relative biomass and proportions-at-age data. The c.v.s available for these data allow for sampling error only. However, additional variance, assumed to arise from differences between model simplifications and real world variation, was added to the sampling variance. The additional variance, termed process error, was estimated in each of the initial runs (MPDs) using all the available data. Process errors were estimated separately for the proportion-at-age data, and for the acoustic estimates from the wide area and local area aggregation surveys.

Estimates of the sample size for the proportions-at-age observations were made via a two-step process. First, the sample sizes were derived by assuming the relationship between the observed proportions, E_i, and estimated c.v.s, c_i, followed that for a multinomial distribution with unknown sample size N_j. The estimated sample size was then derived using a robust non-linear least squares fit of $\log(c_i) \sim \log(P_i)$. Second, estimates of the effective sample size, N_j', were obtained by adding additional process error, N_{PE}, to the sample size calculated in (a) above, where,

$$N_j' = 1 \Big/ \left(\frac{1}{N_j} + \frac{1}{N_{PE}} \right)$$

i.e., from an initial MPD model fit, an estimate of the additional process error was made by solving the following equation for N_{PE},

$$n = \sum_{ij} \frac{{O_{ij} - E_{ij}}^2}{E_{ij}\left({1}\Big/{N_j} + {1}\Big/{N_{PE}}\right)}$$

where n was the number of multinomial cells, O_{ij} was the observed proportions for age class i in year j, E_{ij} was the expected proportions, N_j was the effective sample size estimated in (a) above, and N_{PE} was the associated process error for that class of observations. Estimates of the additional process error for the models are described below.

Estimates of the process error c.v. for the biomass observations were made by fitting the process error within each MPD run, where the applied c.v. c_i' was determined from the process error c_{PE} and the observed c.v.s c_i by,

$$c_i' = \sqrt{c_i^2 + c_{PE}^2} \ .$$

However, in all models the estimated additional process error for the acoustic biomass estimates was zero.

3. RESULTS

3.1 Exploratory models, and the sensitivity and final model runs

Several exploratory model runs were investigated in order to determine the key aspects of the models that would need further investigation. Initially, we discuss three models using the acoustic indices by age class. The first (labelled model 1.2) assumed a constant age-based fishing selectivity for the catch history; the second assumed a constant length-based selectivity (model 1.3); and the third (model 1.4) assumed age-based selectivities with an annual shift parameter. The models are summarised in Table 6.

In the initial exploratory models, MPD estimates of natural mortality were thought to be unusually low (typically, M less than 0.15 y^{-1}) compared with estimates obtained from MCMC runs (typically approximately 0.18–0.20 y^{-1}). Hence, we fixed $M{=}0.2$ y^{-1} for the exploratory runs (but note we free this parameter for the final models). In considering the exploratory models, we focused on the fits to the acoustic biomass time series, fits to the proportions-at-age data, and the estimated relative year class strengths. The additional process error for the commercial catch-at-age proportions and the acoustic indices was estimated for all models (see Table 7), although the estimate for the acoustic indices was always zero.

All three models suggested strong relative year classes in 1991, and again in 2006 and 2007. Evidence for the 2006 year class was in both the acoustic data and in the recent commercial catch proportions-at-age, while the 2007 year class has yet to appear in the commercial catch.

Model fits for the acoustic data were reasonable (Figure 8–Figure 10), except that there was a consistent deviation for the 2004 and 2006 acoustic indices for age 4+. An exploratory model based on model 1.3 with the relative sample size of the commercial catch proportions-at-age data set very low ($N_{PE}{=}5$) suggested that the poor fit was due to a conflict between the proportions-at-age data and the acoustic indices. However, even with the relative weight of the age data set low, the model was only slightly better at fitting the 4+ acoustic indices data and the tradeoffs was a much poorer fit to the age data.

For all exploratory models, the fits to most of the age data appeared reasonable (Figure 8–Figure 10). However, there was a discrepancy in the model fits to the proportions-at-age data

in the two most recent years of data (2008 and 2009) for models 1.2 and 1.3. In these two years, the age-based selectivity model (model 1.2) suggested that the fishery had managed to avoid a small proportion of the smaller than average sized age two to four year old fish in the population.

In order to model an assumption that the fishing selectivity had changed so that these fish were not available to the fishery, we considered an 'selectivity shift' extension to both models. Here we introduced an annual shift parameter into the fishing selectivity. The annual shift parameter maintained the same shape selectivity, but allowed the model to shift the selectivity to the right to reduce the expected proportion of each year class available to the fishery. The age-based model with annual shifts suggested that this amounted to a shift equivalent to about one year in both 2008 and 2009. However, the likelihood values and fits to the individual age data (not shown) suggested that while the model with annual shift parameters visually appeared to have a better fit (see Figure 10) it did not result in a statistically significant improvement based on AIC criteria.

As a result of these investigations, we considered two main scenarios for modelling the Campbell Island Rise stock. The first assumed a constant age-based selectivity ogive for the fishery, while the second made the same assumptions for the model population structure, but assumed that the fishing selectivities were length-based (Table 6).

Two sensitivity models were also considered. The first (model 4.2) modelled the acoustic biomass estimates as categories rather than as decomposed biomass at age (see also Section 2.2.1). The second (model 5.2) sensitivity modelled observations from sub-Antarctic trawl survey biomass and age frequencies time series. Both sensitivities used age-based fishing selectivity and estimated M. The results from these two sensitivities are discussed later.

Table 6: Model run labels and descriptions for the model runs.

Model type	Model label	Description
Exploratory models	1.2	Age-based fishing selectivity
	1.3	Length-based fishing selectivity
	1.4	Age-based fishing selectivity with annual selectivity shifts
Final models	3.2	Age-based fishing selectivity with estimated M
	3.3	Length-based fishing selectivity with estimated M
Sensitivity models	4.2	Run 3.2 but with acoustic categories
	5.2	Run 3.2 but with the summer trawl survey indices

Table 7: Process error estimates for catch-at-age (N_{PE}) and acoustic survey (cv_{PE}) observations for the exploratory and final models.

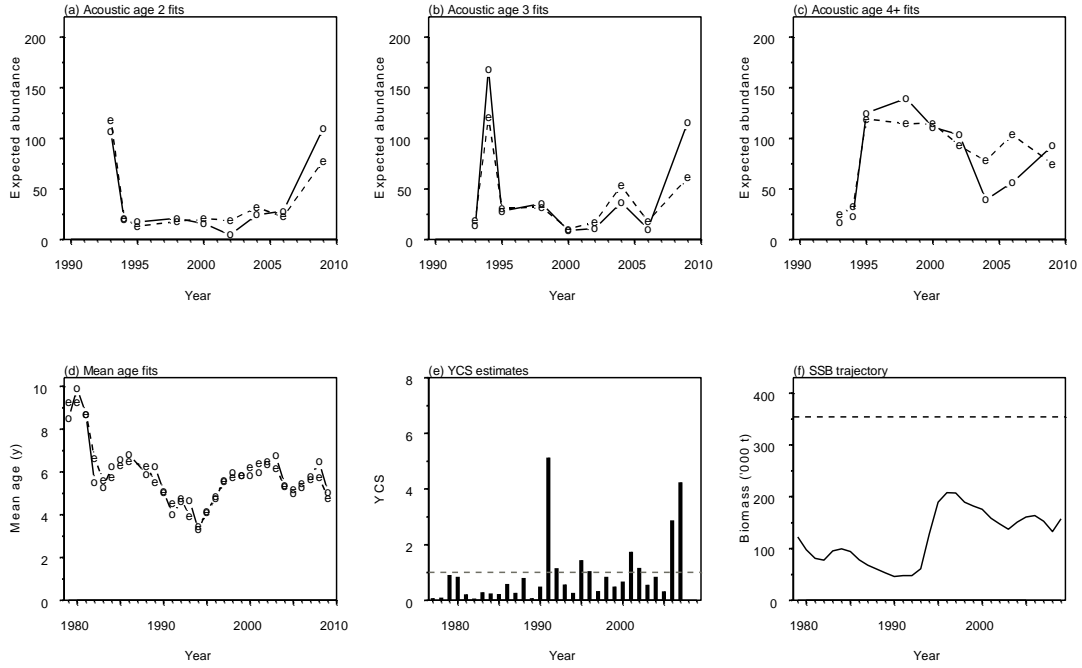| Model type	Model label	N_{PE}	Cv_{PE}
Exploratory Models	1.2	113	0.00
	1.3	89	0.00
	1.4	113	0.00

Figure 8: Observed (o) and expected (e) fits for (a) age 2, (b) age 3, and (c) age 4+ acoustic biomass indices; (d) observed (o) and expected (e) mean age fits for the commercial catch-at-age data; (e) estimated relative year class strength (with the average of one shown as a dashed line); and (f) estimated SSB trajectory (with B_0 shown as a dashed line) 1979–2009 for the exploratory model 1.2.
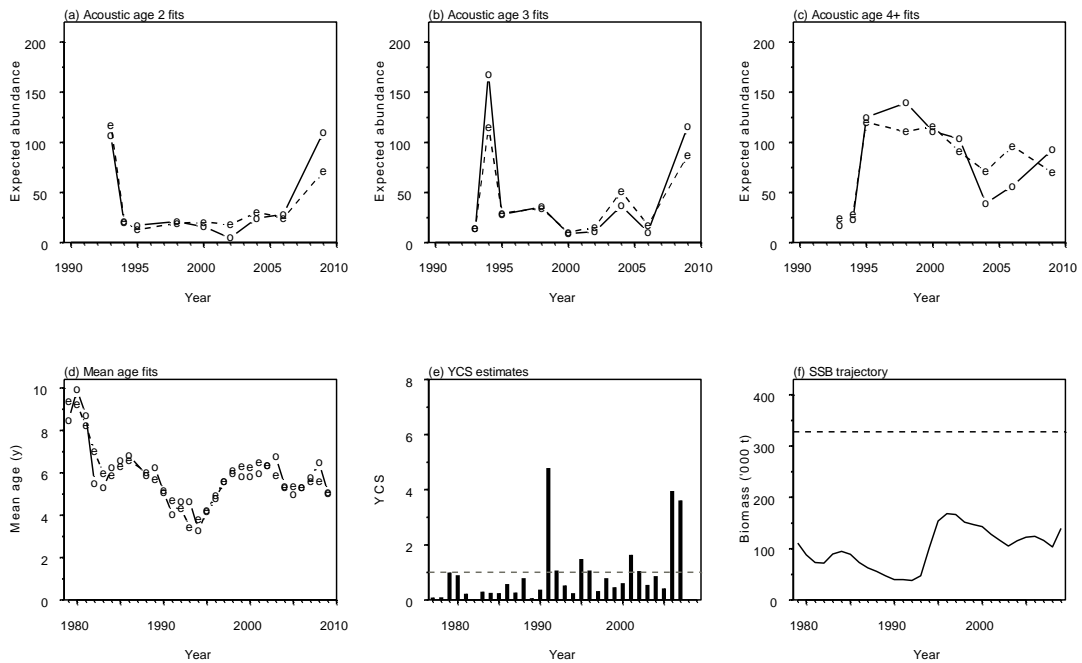

Figure 9: Observed (o) and expected (e) fits for (a) age 2, (b) age 3, and (c) age 4+ acoustic biomass indices; (d) observed (o) and expected (e) mean age fits for the commercial catch-at-age data; (e) estimated relative year class strength (with the average of one shown as a dashed line); and (f) estimated SSB trajectory (with B_0 shown as a dashed line) 1979–2009 for the exploratory model 1.3.
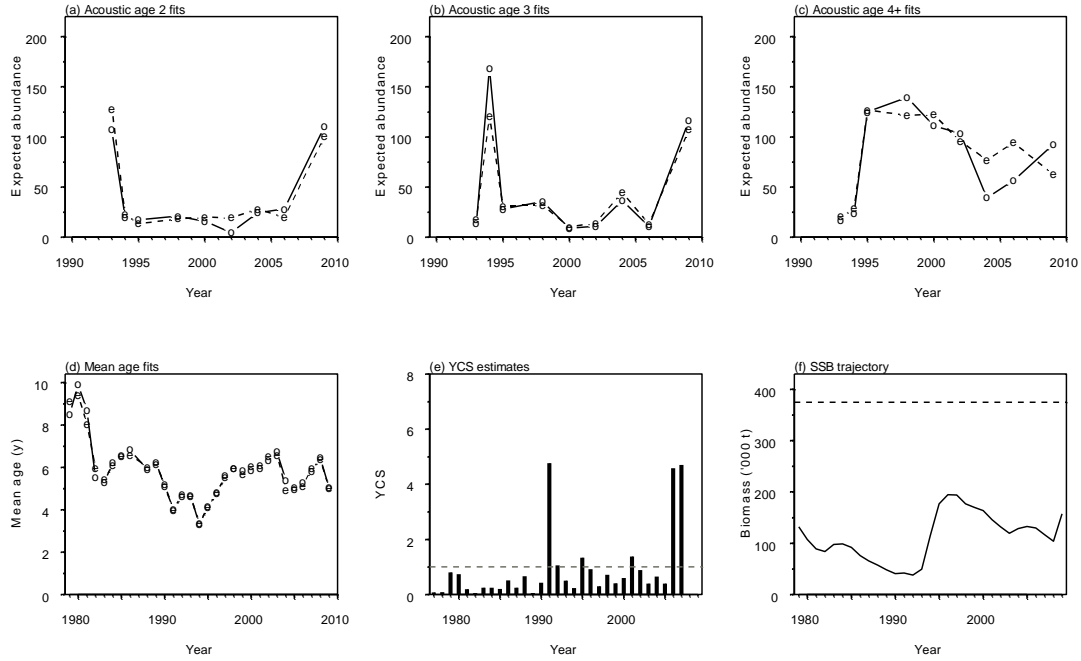
Figure 10: Observed (o) and expected (e) fits for (a) age 2, (b) age 3, and (c) age 4+ acoustic biomass indices; (d) observed (o) and expected (e) mean age fits for the commercial catch-at-age data; (e) estimated relative year class strength (with the average of one shown as a dashed line); and (f) estimated SSB trajectory (with B_0 shown as a dashed line) 1979–2009 for the exploratory model 1.4.

3.2 Final model runs

The age-based selectivity and length-based selectivity models were used as the basis for the final model runs. In each case, natural mortality (M) was estimated and MPD and MCMC runs carried out. The additional process error for the commercial catch-at-age proportions and the acoustic indices was assumed equal to that estimated for the equivalent exploratory model (see Table 7 above).

MPD model fits for models 3.2 and 3.3 were virtually identical to those for models 1.2. and 1.3 and have not been repeated here. Estimated MPD parameter values for selected variables are given in Table 8 and Table 9, and the objective function values for the final models in Table 10.

Table 8: MPD estimates of the catchability coefficients (q) and natural mortality (y^{-1}) parameters for the wide area acoustic biomass indices for model 3.2 and model 3.3.

Model	Catchability			Natural mortality	
	Age 2	Age 3	Age 4	Male	Female
3.2	1.25	1.23	0.86	0.165	0.121
3.3	1.37	1.28	1.00	0.168	0.130

Table 9: MPD estimates of equilibrium (B_0), initial (B_{1979}), and current biomass for model 3.2 and model 3.3.

Model	B_0	B_{1979l}	B_{2009}	B_{2009} (%B_0)
3.2	418 160	89 620	128 010	30.6
3.3	385 940	86 890	113 860	29.5

20

Table 10: MPD objective function values, likelihoods, and number of estimated parameters for models 3.2 and 3.3.

Objective function Component	Model 3.2	Model 3.3
Commercial catch proportions-at-age	950.0	939.0
Tangaroa acoustic biomass (age 2)	-4.1	-4.9
Tangaroa acoustic biomass (age 3)	-4.4	-8.5
Tangaroa acoustic biomass (age 4)	-6.2	-6.6
Sub-total (observations)	935.3	919.1
Penalties	0.9	0.9
B_0 prior	12.9	12.9
All other priors	-40.3	-41.1
Total objective function	908.8	891.8
Number of free parameters	51	51

3.3 MCMC results

3.3.1 MCMC Diagnostics

MCMC traces for B_0 and B_{2009} (%B_0) for each model run were reasonably good (Figure 11, and Figure 12). Plots of relative jump size suggested that the parameters ages seven and nine in the initial population ($C_{initial}$) performed poorly and may be poorly estimated by the models (Figure 13, Figure 14). There was also some evidence of autocorrelation in estimates of B_0, with the age-based selectivity model performing slightly better than the length-based selectivity model (Figure 13, Figure 14).
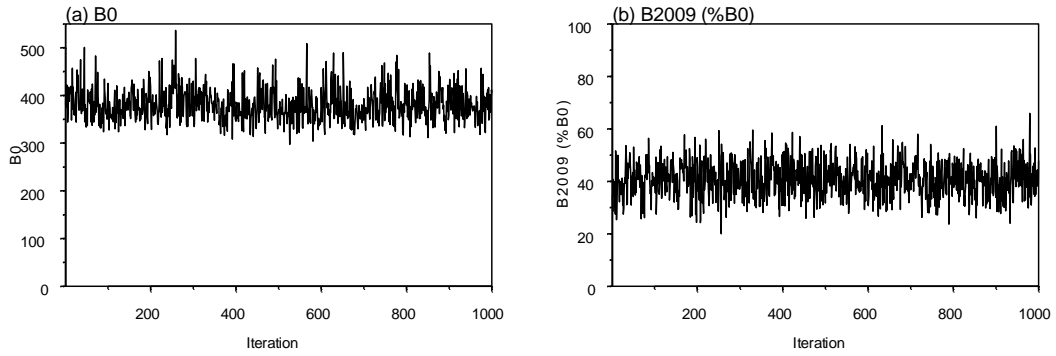
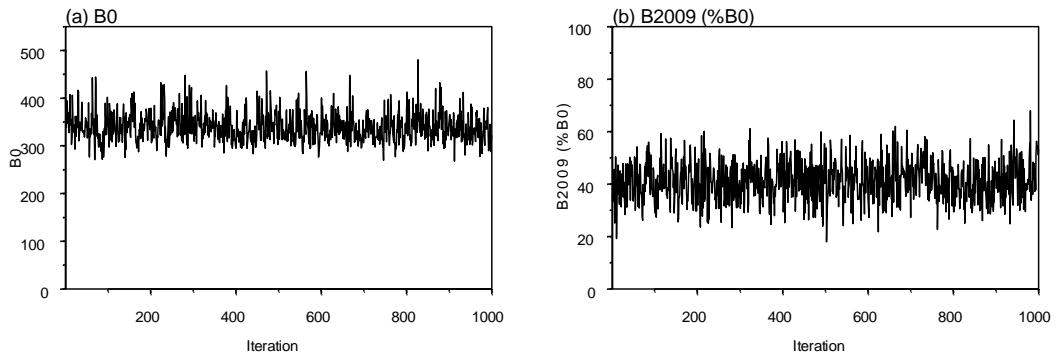**Figure 11: MCMC posterior trace plots for (a) B_0 and (b) current biomass ($\%B_{2009}/B_0$) for model 3.2.**

Figure 12: MCMC posterior trace plots for (a) B_0 and (b) current biomass ($\%B_{2009}/B_0$) for model 3.3.

Figure 13: MCMC posterior diagnostic plots for model 3.2, showing (left) median relative jump size for all parameters (x-axis, labelled 1–37), and (right) autocorrelation lag plot for B_0.
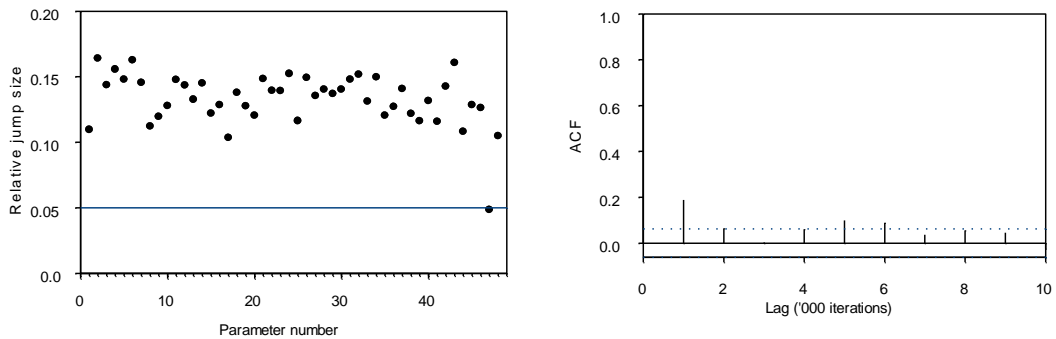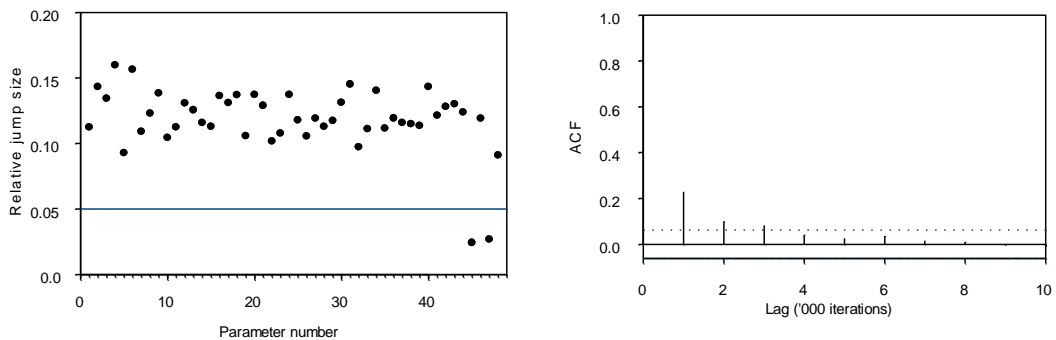

Figure 14: MCMC posterior diagnostic plots for model 3.3, showing (left) median relative jump size for all parameters (x-axis, labelled 1–37), and (right) autocorrelation lag plot for B_0.

3.3.2 MCMC estimates

MCMC posterior plots of the biomass trajectories, B_0, and B_{2009} (%B_0) were very similar for the two models (Figure 15–18). All biomass estimates including B_0 and B_{2009} were about 10% higher for model 3.2 compared to model 3.3, but B_{2009} (%B_0) were about the same for both models at about 40% (Table 11). The results suggest that stock biomass showed a steady decline from the early 1980s until 1993 followed by a large increase to 1996, followed by a gradual decline to 2009.

Year class strength has been highly variable over the course of the fishery (Figure 19). The 1991 year class was about four times stronger than any year classes until at least 2006, and gave rise to the large increase in biomass seen during the mid 1990s. There were several above average year classes during the mid to late 1990s and in early 2000, but these contributed to only a small proportion of the catch (see also Figure 7) and have probably been largely removed from the population. The 2006 and 2007 year classes were estimated to be at a similar level to the 1991 year class, with large numbers of the 2006 year class caught in the 2009 fishery and large numbers of both year classes seen by the 2009 acoustic survey. MCMC posterior plots of the initial age structure suggested that the initial population was dominated by fish of age 10 and older, but that the proportions of each were poorly estimated (Figure 20).

The key difference between the two models was that model 3.2 had an age-based fishing selectivity, whilst model 3.3 had a length-based selectivity. In the age-based model the fishery selected significantly more males than females at ages two and three, but by age four fish of both sexes were selected equally and were almost fully selected (Figure 21). In the length-based model males were again selected at slightly smaller sizes than females but neither sex was fully selected until a length of about 50 cm (Figure 22).

The median estimates of the adult (4+) acoustic q were 0.73 for model 3.2 and 0.86 for model 3.3 (Table 12), and the posterior distributions were shifted well to the left of the prior (Figure 23). This would suggest that the acoustic surveys are substantially underestimating the adult biomass, but it is unclear how this could have occurred. The median estimates of natural mortality ranged between 0.18 and 0.20 for the two sexes and models which is consistent with previous estimates.

Table 11: MCMC estimates of equilibrium (B_0), B_{1991}, and current biomass for the model runs

Model	B_0	B_{1991} (%B_0)	B_{2009}	B_{2009} (%B_0)
3.2	375 500 (323 760–456 830)	11.9 (8.2–16.6)	151 060 (108 620–212 910)	40 (28–54)
3.3	334 230 (291 510–409 910)	11.6 (8.0–16.2)	136 310 (95 420–188 990)	41 (27–56)

Table 12: MCMC estimates of the catchability coefficients (q) and natural mortality (y^{-1}) parameters for the wide area acoustic biomass indices for the model runs

Model	Catchability			Natural mortality	
	Age 2	Age 3	Age 4	Male	Female
3.2	1.00 (0.73–1.34)	1.00 (0.76–1.30)	0.73 (0.58–0.90)	0.18 (0.14–0.21)	0.18 (0.15–0.22)
3.3	1.08 (0.78–1.45)	1.04 (0.79–1.35)	0.86 (0.70–1.03)	0.19 (0.14–0.23)	0.20 (0.16–0.24)

Figure 15: MCMC posterior plots of the trajectory of (a) biomass and (b) biomass (%B_0) for model 3.2.

Figure 16: MCMC posterior plots for (a) B_0 (solid line) and B_{2009} (dashed line) and (b) current biomass (%B_{2009}/B_0) for model 3.2.
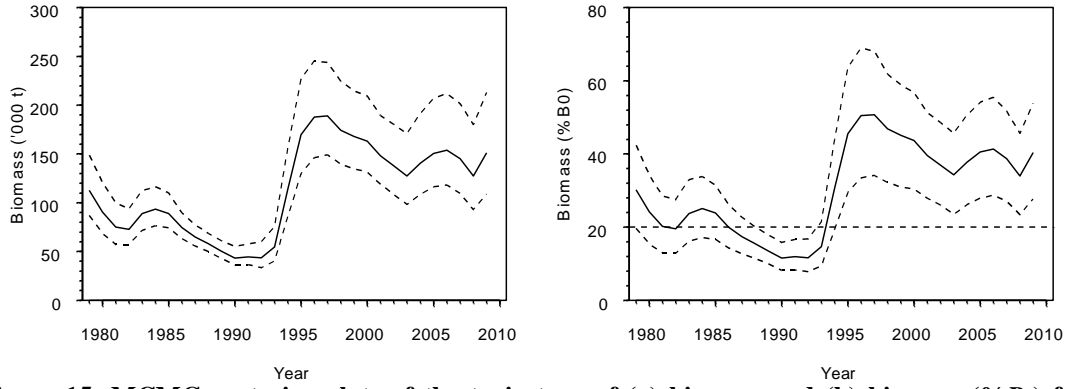

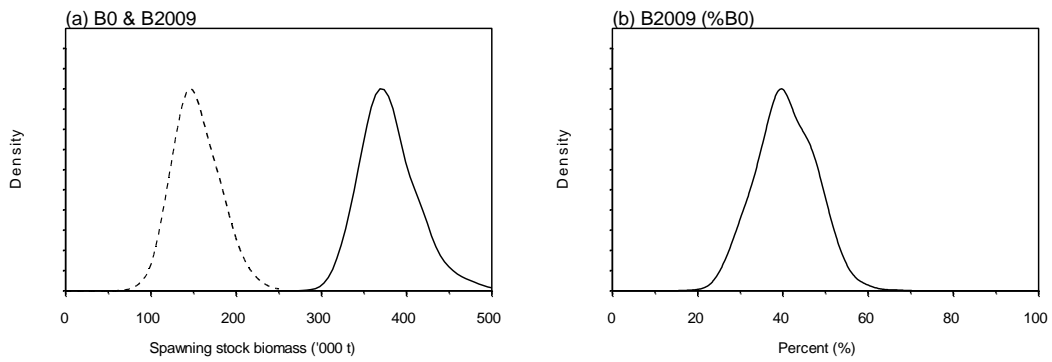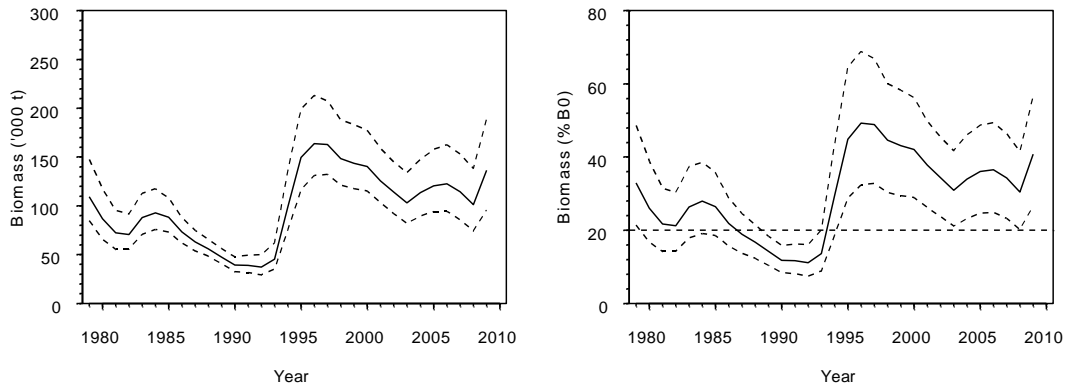**Figure 17: MCMC posterior plots of the trajectory of (a) biomass and (b) biomass (%B_0) for model 3.3.**
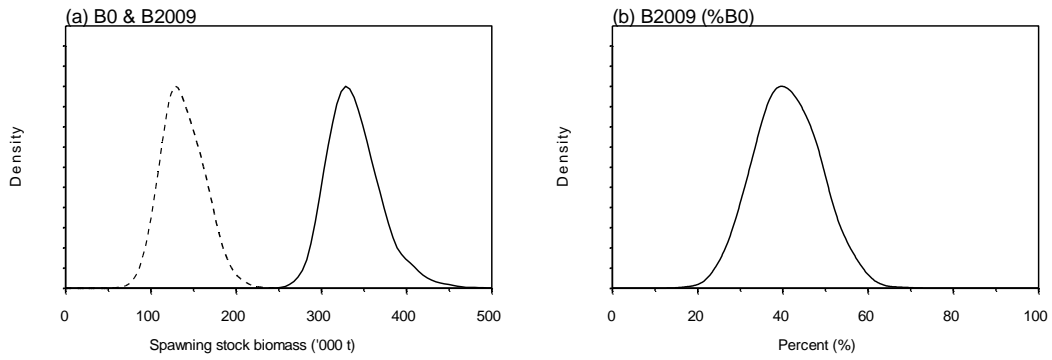
Figure 18: MCMC posterior plots for (a) B_0 (solid line) and B_{2009} (dashed line) and (b) current biomass ($\%B_{2009}/B_0$) for model 3.3.

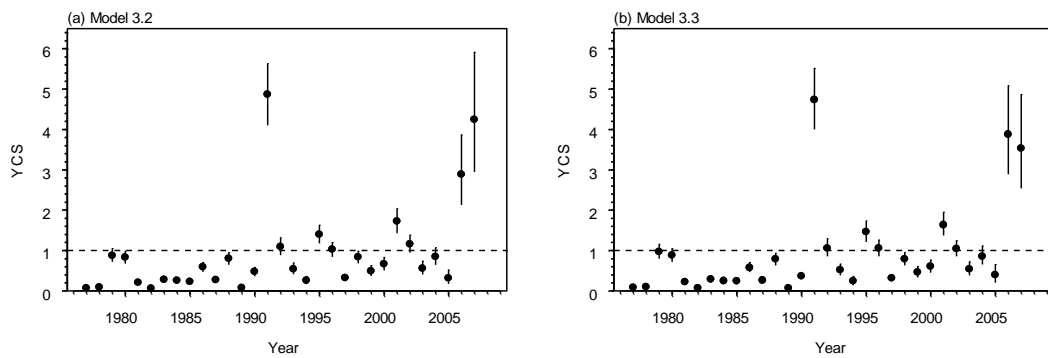**Figure 19: MCMC posterior plots of estimated year class strengths for (a) model 3.2 and (b) model 3.3.**
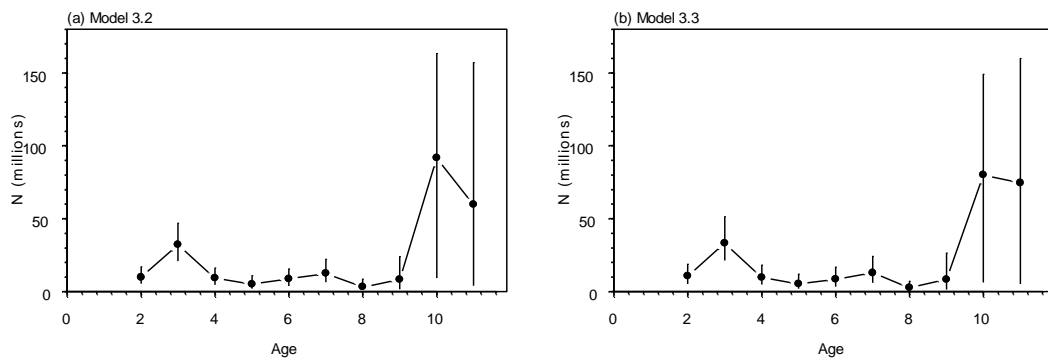

Figure 20: MCMC posterior plots of the estimated initial age structure ($C_{initial}$) for (a) model 3.2 and (b) model 3.3 (in numbers of fish for males and females combined).
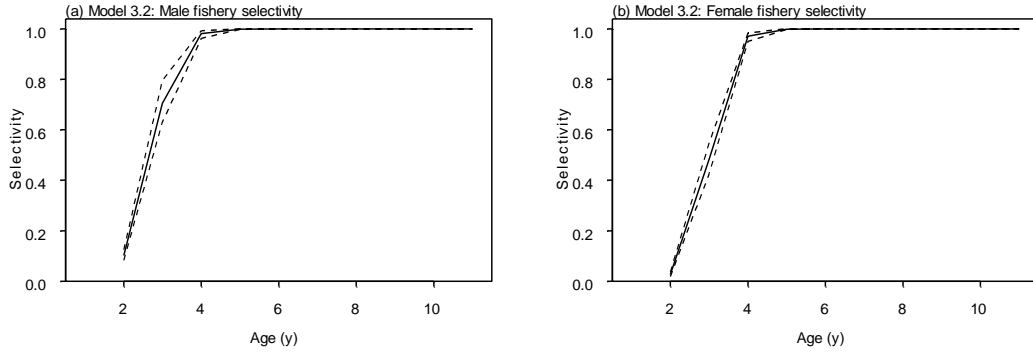
Figure 21: MCMC posterior plots of fishery selectivity by age for (a) males and (b) females for model 3.2.
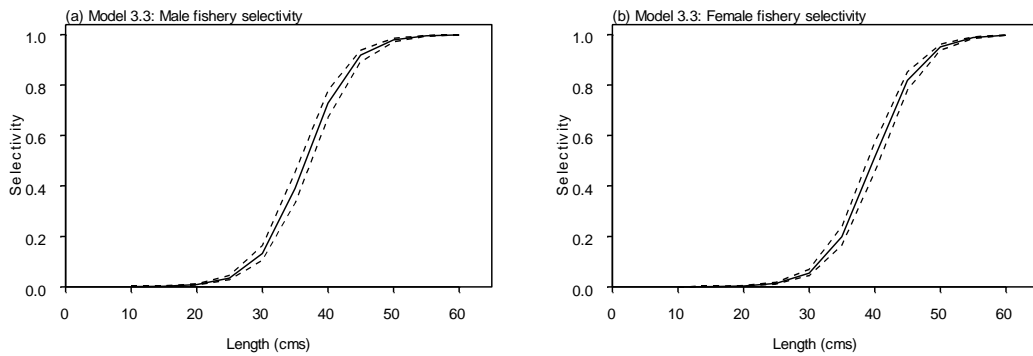
Figure 22: MCMC posterior plots of fishery selectivity by age for (a) males and (b) females for model 3.3.
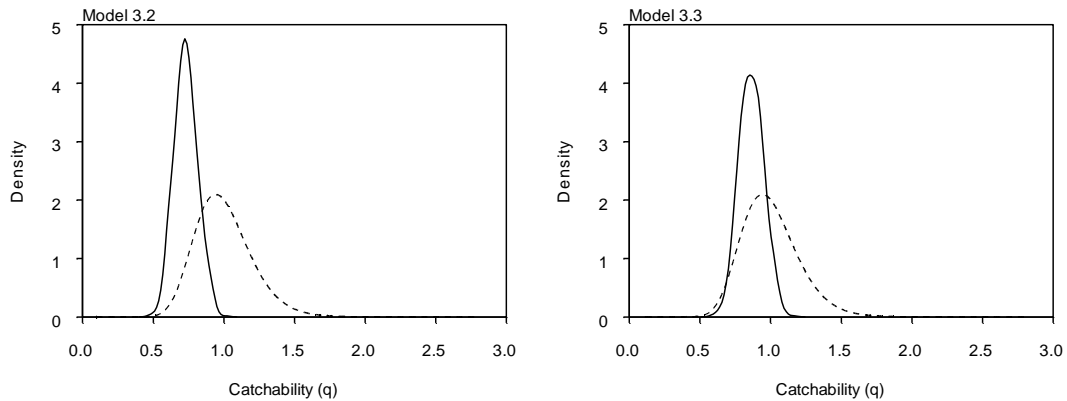
Figure 23: MCMC posterior plots of the acoustic 4+ catchability coefficients (solid lines) and the assumed prior (dashed lines) for (left) model 3.2 and (right) model 3.3.

3.4 Projections

Projections were made assuming fixed catch levels of (i) 23 000 t per year, (ii) 23 000 t for 2010 and 30 000 t thereafter, (iii) 23 000 t for 2010 and 35 000 t thereafter, and (iv) 23 000 t for 2010 and 40 000 t thereafter. Projections were made using the MCMC samples with future recruitment assumed by drawing randomly from the distribution of previous year class strengths estimated by the model. The probability that the mid-season biomass for the specified year will be less than the threshold level (20% B_0) is given in Table 13. The probability of dropping below the threshold biomass at catch levels of 23 000 t is less than 10% for all models and all years. Under average recruitment conditions the biomass is expected to increase in the few years immediately after 2009 in all models, then begin to

decline. Plots of the biomass trajectories for the current catch (23 000 t) for models 3.2 and 3.3 are given in Figures 24 and 25. respectively.

Table 13: Probability that the projected mid-season vulnerable biomass for 2010–2015 will be less than 20% B_0, and the median projected biomass (%B_0), at a projected catch of 23 000 t, 30 000 t, 35 000 t, and 40 000 t for models 3.2 and 3.3.

Catch	Model	Pr ($SSB < 0.2B_0$)						Median SSB (%B_0)					
		2010	2011	2012	2013	2014	2015	2010	2011	2012	2013	2014	2015
23 000 t	3.2	0.00	0.00	0.00	0.00	0.00	0.00	57.6	69.4	71.0	69.7	66.7	65.0
	3.3	0.00	0.00	0.00	0.00	0.00	0.00	59.9	70.8	70.7	69.0	66.3	63.2
30 000 t	3.2	0.00	0.00	0.00	0.00	0.00	0.00	57.6	68.5	68.4	65.4	60.8	57.8
	3.3	0.00	0.00	0.00	0.00	0.00	0.01	59.9	69.9	67.8	64.3	60.1	55.4
35 000 t	3.2	0.00	0.00	0.00	0.00	0.00	0.01	57.6	67.9	66.5	62.2	56.7	52.6
	3.3	0.00	0.00	0.00	0.00	0.00	0.02	59.9	69.2	65.6	60.9	55.4	50.0
40 000 t	3.2	0.00	0.00	0.00	0.00	0.01	0.04	57.6	67.2	64.5	59.1	52.5	47.7
	3.3	0.00	0.00	0.00	0.00	0.01	0.07	59.9	68.5	63.4	57.4	50.9	44.5

Figure 24: MCMC posterior plots for the median (solid line) and 95% credible intervals (dashed lines) for (a) SSB and (b) current biomass (%B_{2009}/B_0) for a catch of 23 000 t for model 3.2. Horizontal lines indicate 50% and 20% B_0, and the vertical line represents the beginning of the projection period (2010–2013).

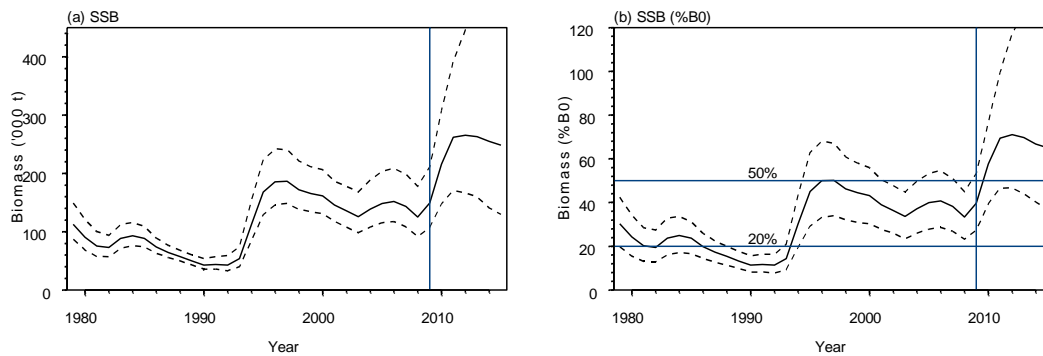**Figure 25: MCMC posterior plots for the median (solid line) and 95% credible intervals (dashed lines) for (a) SSB and (b) current biomass (%B_{2009}/B_0) for a catch of 23 000 t for model 3.3. Horizontal lines indicate 50% and 20% B_0, and the vertical line represents the beginning of the projection period (2010–2013).**

3.5 Sensitivity runs

3.5.1 Acoustic categories

Sensitivity run 4.2 used the acoustic biomass estimates as categories (immature and mature) rather than as decomposed biomass at age (e.g., age 2, 3, and 4+ — see also Section 2.2.1). This sensitivity reduced the use of the age data from the commercial fishery to being used only once within the model instead of using it twice, once as proportions-at-age in the commercial fishery and again as an age frequency used to decompose the adult acoustic biomass estimates into biomass at age. Here, we assumed that the immature and adult biomass categories from the acoustic surveys were a compound estimate comprising one selectivity pattern for the immature biomass estimates and a separate selectivity pattern for the adult biomass estimates, and combined such that they add to a total survey selectivity for the population. Further, we constrained the selectivity for the adult biomass to equal the commercial fishery selectivity, and used the proportions-at-age data available from survey target identification tows of the immature category to fit the selectivity for the immature fish.

MPD estimates of B_0, B_{2009} and B_{2009} (%B_0) were slightly lower than estimates from the comparable base case model 3.2 (Table 14). The biomass trajectory, year class strengths and fits to the indices are summarised in Figure 26 and objective function values for the final models in Table 15. MCMC estimates of B_0, B_{2009} and B_{2009} (%B_0) are given in Table 17, and for the catchability and natural mortality parameters in Table 18. Although the biomass trajectory was similar to that from the base case model, the fits to the acoustic indices were worse. The model was unable to fit closely the immature indices, and the fits to the 1994 and 2009 acoustic indices were poor. Model fits to mean age were generally good, whilst the year class strength estimates were similar to that for the base case except that the 2006 year class was estimated to be substantially weaker than in the base case. The compound selectivity ogives suggested that females were fully selected by age two whereas males were 85% selected at age two and were not fully selected until age eleven (Figure 27). The reason for this is unclear but could be related to the differential natural mortality between the sexes (Table 16). The estimated acoustic q of 0.73 was identical to the estimated adult 4+ q from the comparable base case model.

Table 14: MPD estimates of equilibrium (B_0), B_{1979}, and current biomass for model 3.2 and the sensitivity model runs.

Model	B_0	B_{1979}	B_{2009}	B_{2009} (%B_0)
3.2	418 160	89 620	128 010	30.6
4.2	346 420	98 200	95 590	27.6
5.2	376 790	92 100	104 950	27.9

Table 15: MPD objective function values, likelihoods, and number of estimated parameters for models 3.2, 4.2, and 5.2.

Objective function Component	3.2	4.2	Model 5.2
Acoustic immature proportions-at-age	-	159.3	-
Commercial catch proportions-at-age	950.0	986.8	966.5
Sub-Antarctic trawl survey biomass	-	-	31.0
Tangaroa acoustic biomass (age 2)	-4.1	-	-2.7
Tangaroa acoustic biomass (age 3)	-4.4	-	-5.2
Tangaroa acoustic biomass (age 4)	-6.2	-	-4.1
Tangaroa acoustic biomass (adult)	-	0.9	-
Tangaroa acoustic biomass (immature)	-	31.2	-
Trawl survey proportions-at-age	-	-	349.8

Sub-total (observations)	935.3	1178.3	1335.3
Penalties	0.9	0.9	0.9
B_0 prior	12.9	12.8	12.8
All other priors	-40.3	-33.3	-41.9
Total objective function	908.8	1158.6	1307.2
Number of free parameters	51	58	55

Table 16: MPD estimates of the catchability coefficients (q, for the acoustic decomposed indices at age 2, 3, and 4+; the acoustic category indices; and the summer trawl survey indices) and natural mortality parameters for the wide area acoustic biomass indices for model 3.2 and the sensitivity model runs.

Model				Catchability		Natural mortality	
	Age 2	Age 3	Age 4	Category	Trawl	Male	Female
3.2	1.25	1.23	0.86	–	–	0.165	0.121
4.2	–	–	–	0.88	–	0.138	0.185
5.2	1.45	1.33	0.89	–	0.06	0.147	0.148

Table 17: MCMC estimates of equilibrium (B_0), B_{1991}, and current biomass for model runs 3.2, 4.2, and 5.2.

Model	B_0	B_{1991} (%B_0)	B_{2009}	B_{2009} (%B_0)
3.2	375 500 (323 760–456 830)	11.9 (8.2–16.6)	151 060 (108 620–212 910)	40 (28–54)
4.2	314 900 (278 910–367 270)	18.4 (12.3–27.0)	117 280 (80 380–175 370)	37 (27-50)
5.2	334 480 (297 040–398 510)	16.1 (11.1–22.8)	122 960 (94 078–169 896)	37 (27–50)

Table 18: MCMC estimates of the catchability coefficients (q) and natural mortality (y^{-1}) parameters for the wide area acoustic biomass indices for the model runs.

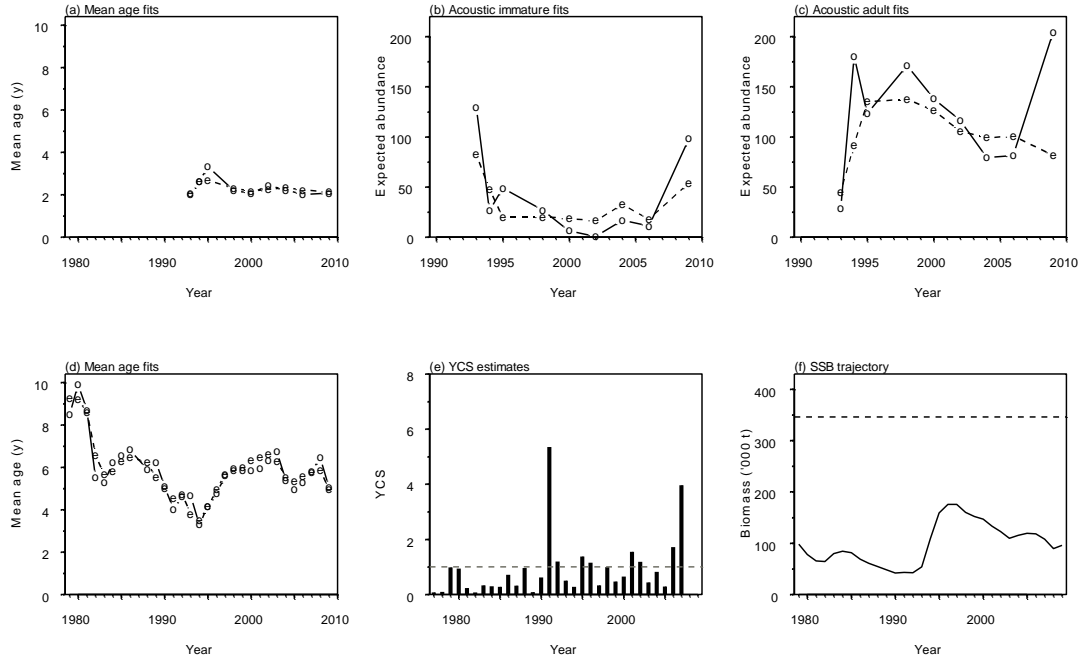| Model	Catchability		Natural mortality	
	Category	Value	Sex	Value
3.2	Age 2	1.00 (0.73–1.34)	Male	0.18 (0.14–0.21)
	Age 3	1.00 (0.76–1.30)	Female	0.18 (0.15–0.22)
	Age 4	0.73 (0.58–0.90)		
4.2	Adult	0.73 (0.55–0.96)	Male	0.21 (0.16–0.26)
			Female	0.22 (0.17–0.27)
5.2	Age 2	1.17 (0.87–1.50)	Male	0.19 (0.14–0.24)
	Age 3	1.10 (0.83–1.38)	Female	0.18 (0.14–0.23)
	Age 4	0.77 (0.61–0.91)		
	Trawl	0.05 (0.04–0.07)		

Figure 26: Observed (o) and expected (e) fits for (a) mean age for the immature age frequency; (b) immature and (c) adult acoustic biomass indices; (d) observed (o) and expected (e) mean age fits for the commercial catch-at-age data; (e) estimated relative year class strength (with the average of one shown as a dashed line); and (f) estimated SSB trajectory (with B_0 shown as a dashed line) 1979–2009 for model 4.2.
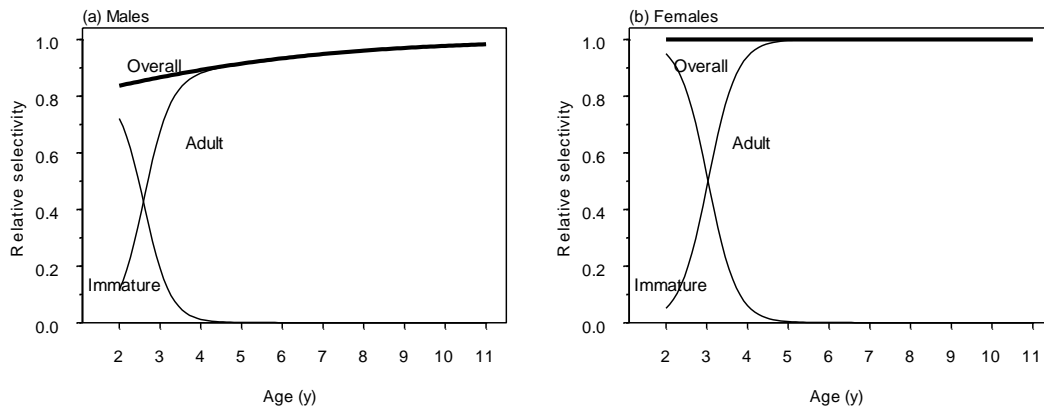
Figure 27: MPD estimates of the compound acoustic selectivity ogives for (a) males and (b) females for model 4.2.

3.5.2 Trawl survey biomass indices

Sensitivity run 5.2 modelled observations from the time series of sub-Antarctic trawl survey biomass estimates and age frequencies. MPD estimates of B_0, B_{2009} and B_{2009} (%B_0) were slightly lower than estimates from the comparable base case model 3.2 (Table 14). The biomass trajectory, year class strengths and fits to the indices are summarised in Figure 28 and objective function values for the final models in Table 15. MCMC estimates of B_0, B_{2009} and B_{2009} (%B_0) are given in Table 17, and for the catchability and natural mortality parameters in Table 18. The fits suggested some consistency in biomass estimates between the summer series and the model estimates. However, in general the series of trawl surveys underestimated biomass at low stock sizes and overestimated biomass at high stock sizes. The fits to the proportions-at-age from the trawl survey showed a similar pattern, and in general

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were unable to match the higher and lower observed mean ages. The trawl survey selectivity pattern was shallower than the fishing selectivity pattern suggesting that younger fish were less selected by trawl surveys than by the fishery (Figure 28). To investigate this further we tried fitting the trawl survey selectivity with a double normal ogive. The female selectivity pattern was very similar to that shown in Figure 29, whereas the males reached full selectivity at age six and dropped to 70% selectivity by age 11+, but other results were substantially unchanged.
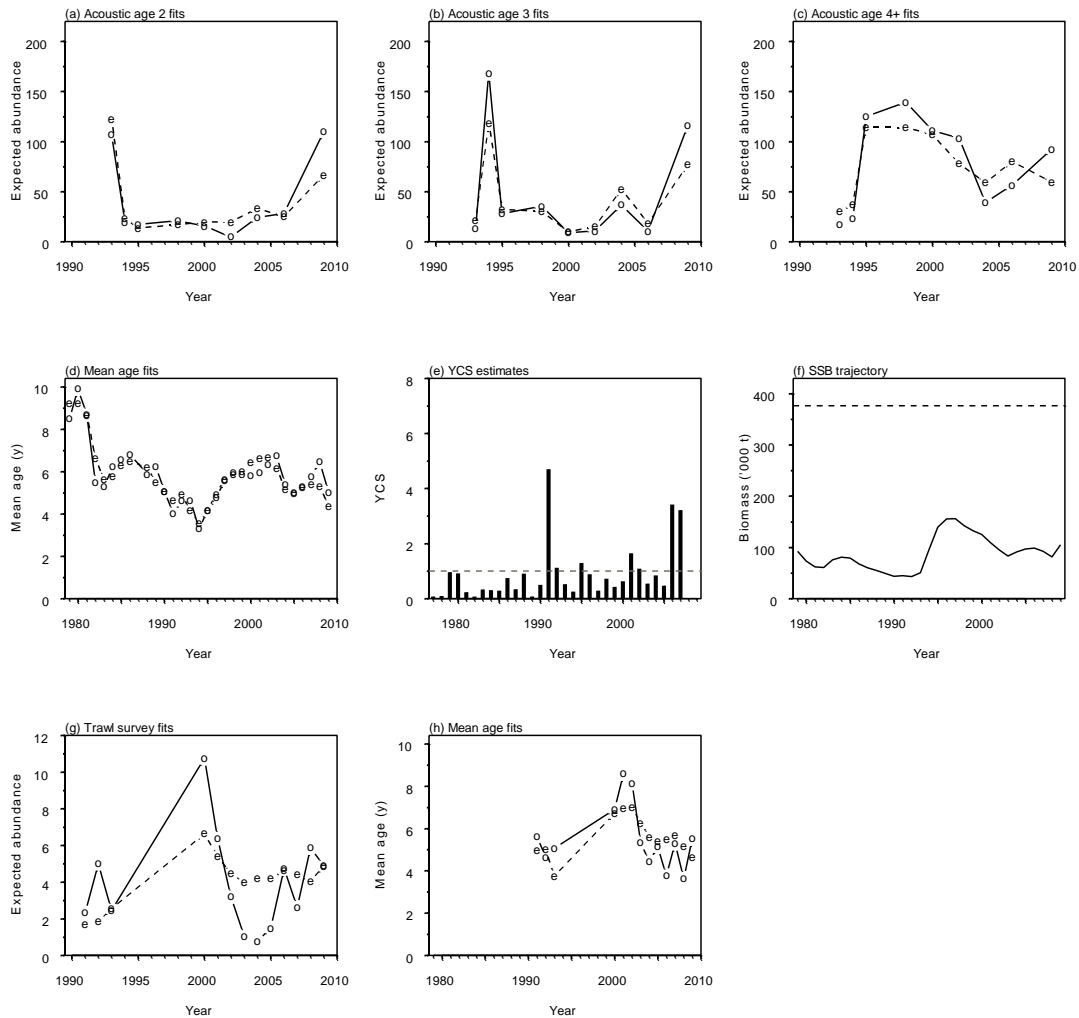
Figure 28: Observed (o) and expected (e) fits for (a) age 2, (b) age 3, and (c) age 4+ acoustic biomass indices; (d) observed (o) and expected (e) mean age fits for the commercial catch-at-age data; (e) estimated relative year class strength (with the average of one shown as a dashed line); (f) estimated SSB trajectory (with B_0 shown as a dashed line) 1979–2009; (g) fits to the trawl survey biomass indices, and (h) mean age fits to the trawl survey proportions-at-age data for model 5.2.

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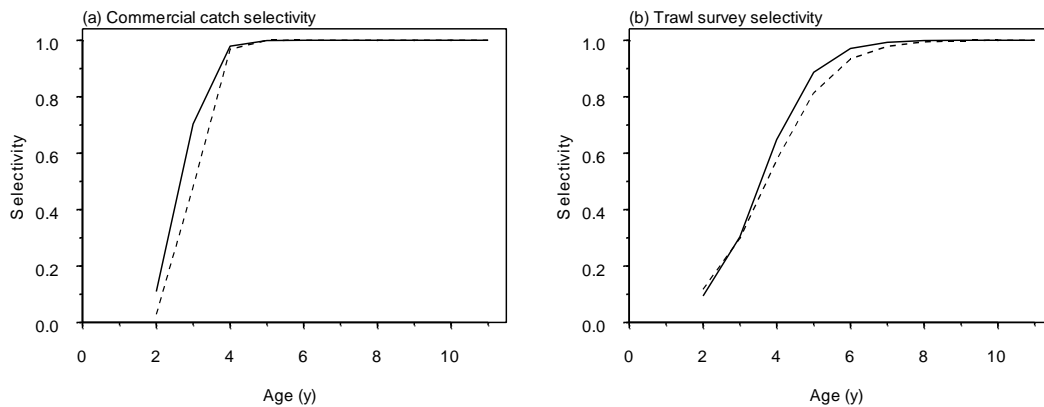
Figure 29: MPD estimates of (a) the commercial catch selectivity and (b) the trawl survey selectivity ogives for model 5.2.

4. DISCUSSION

The results of the assessment suggest that the biomass of the Campbell Island Rise stock in 2009 was 40%, rising to over 50% B_0 and likely to remain at that state over the short term under current and various projected increased catch levels. There was little difference in the results between the two base case models, with the age-based model being just a little bit more optimistic than the length-based model. The assessment is strongly influenced by the high biomass estimates from the 2009 acoustic survey. This survey estimated the highest adult biomass and second highest immature biomass since the survey series began in 1993. There is no reason to seriously doubt that the 2006 and 2007 year classes are likely to be strong, but the size of these year classes is not yet well estimated. At the time that the assessment was carried out the fish were not fully selected by the fishery and the relative proportions of these ages in the 2009 fishery could have been influenced by fleet behaviour. Interestingly, the relative strength of these two classes differed between the age-based and length-based models. In the length-based model the 2006 year class was estimated to be stronger, presumably because it took into account the delayed entry of these slower growing fish into the fishery.

The last stock assessment of the Campbell island Rise stock was carried out in 2005 (Hanchet et al. 2006). Estimates of B_{1979} and the stock trajectory up to 2005 were similar to the previous assessment, but the current model had two key differences: (i) higher biomass in 2005 and (ii) a much higher B_0. It is hard to compare acoustic qs directly between the two assessments because the current acoustic biomasses were calculated using a new target strength-fish length relationship and new absorption coefficient (Gauthier et al. 2011). However, even taking into account the revised biomass estimates the adult acoustic q estimated by the current model is much lower than in the 2005 model and so the biomass since mid-1990s has been consequently higher. As discussed above the main driver for this increase is probably the high estimate of adult biomass in the 2009 acoustic survey. A new survey is being conducted in September 2011, and we should have better idea of the biomass of older fish after the survey has been analysed. The other major difference between the previous assessment and this one is the much higher B_0. The high B_0 is the consequence of the two very strong 2006 and 2007 year classes estimated by the model. Again the main reason for this is the high biomass of age two and three year olds in the 2009 acoustic survey, although the 2006 year class was also seen in the proportion-at-age data from the fishery. At the time of the next assessment in 2011 there will be two new years of proportion-at-age data and an extra acoustic survey and the strength of these year classes should be much better estimated.

One of the criticisms of previous SBW assessments has been how the commercial catch proportions-at-age data have been used twice, once in the assessment and again to decompose the acoustic biomass indices into age specific biomass indices (Hanchet et al. 2006). The sensitivity model we examined fitted the adult acoustic index directly, and hence allowed for the decomposition of the acoustic biomass indices within the model. The model suggested that estimates of key model parameters such as B_0, B_{2009}, and B_{2009} (%B_0) were similar, but slightly lower than, the comparable model that used the decomposed biomass indices. However, the fits to the acoustic indices appeared substantially worse. The main problem appears to be that the fishery targets different length classes in different areas in different years. By creating a single "one-size fits all" selectivity ogive for each acoustic category some of this finer detail is lost and the fits are consequently worse. We note that this may need to be further investigated in future models so that the problem can be more fully resolved.

We also investigated fitting the sub-Antarctic summer trawl survey time series in the assessment model. Although the fits suggested some consistency in biomass estimates between the summer series and the model estimates, in general the trawl survey underestimated biomass at low stock sizes and overestimated biomass at high stock sizes as noted by Hanchet & Stevenson (2006). Like Hanchet & Stevenson (2006) we therefore conclude that the time series is not particularly useful for monitoring abundance in their present form.

5. ACKNOWLEDGMENTS

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APPENDIX A.

Table A1: Assumed mean length (cm) at age for male southern blue whiting aged 2–11+, 1990–2009, and the assumed mean length at age for projections, 2010–2014 (grey highlight).

Sex	Year	2	3	4	5	6	7	8	9	10	Age 11+
Male	1979	30.0	34.9	39.3	41.7	44.0	43.0	44.3	42.4	43.0	42.8
	1980	32.0	35.1	39.8	40.2	40.0	42.3	44.0	42.3	43.2	43.9
	1981	30.0	35.9	37.7	40.5	42.7	43.2	44.5	44.8	44.4	44.6
	1982	29.2	33.0	38.7	38.5	43.4	42.8	44.0	45.5	43.7	43.5
	1983	30.5	34.9	37.5	41.0	42.0	43.4	44.1	44.0	46.3	44.5
	1984	32.7	36.8	38.3	40.1	42.0	43.3	44.1	44.5	45.6	45.2
	1985	29.5	36.0	39.5	41.2	42.6	43.0	44.0	45.8	46.1	45.8
	1986	30.8	34.5	38.3	41.8	42.4	43.4	44.5	45.8	46.0	45.8
	1987	29.7	35.5	37.8	40.4	43.7	43.4	44.5	45.2	46.7	46.4
	1988	31.1	36.2	39.8	41.4	41.7	43.6	45.1	45.4	46.5	46.6
	1989	30.1	35.6	39.2	41.8	43.2	44.9	45.8	45.7	46.0	46.9
	1990	27.5	35.5	39.1	41.8	43.2	44.5	46.0	46.5	46.8	47.6
	1991	29.8	34.3	39.5	42.1	43.2	45.4	45.4	47.1	47.1	48.2
	1992	32.9	35.7	39.2	42.7	44.6	45.0	46.0	47.9	48.0	48.5
	1993	27.9	36.7	40.0	41.6	44.8	45.3	46.5	47.3	47.4	48.8
	1994	27.9	30.8	39.6	42.7	43.6	45.2	46.2	48.0	47.0	50.2
	1995	30.8	31.7	33.7	41.5	43.0	44.1	46.5	46.2	48.5	49.5
	1996	29.8	33.5	34.8	36.0	43.9	44.0	45.3	47.6	47.7	48.7
	1997	25.8	35.1	36.8	37.1	38.3	44.4	45.2	46.2	48.0	48.6
	1998	26.9	30.2	37.5	38.3	38.6	39.2	45.3	46.0	49.4	48.8
	1999	28.4	31.4	34.1	38.6	39.7	39.4	40.5	45.5	46.5	47.6
	2000	28.8	34.9	35.3	37.8	40.2	41.1	41.7	41.8	45.6	47.3
	2001	29.7	33.2	35.9	38.0	39.3	41.0	40.3	41.7	42.5	45.6
	2002	29.9	35.0	37.2	39.2	40.6	41.6	43.0	42.2	43.3	44.6
	2003	27.9	35.8	39.3	39.9	42.0	41.5	42.0	44.0	43.7	44.3
	2004	30.1	34.0	37.0	40.0	42.6	41.6	42.7	43.5	46.0	45.1
	2005	29.8	33.6	35.9	38.5	41.0	41.1	42.5	44.7	44.9	46.7
	2006	30.2	34.2	37.5	38.8	39.8	41.8	42.5	43.7	46.4	45.5
	2007	31.6	33.9	35.3	38.7	39.8	40.7	42.6	43.0	44.5	46.2
	2008	26.4	28.8	34.8	37.6	39.1	40.8	41.4	43.0	43.4	45.6
	2009	26.5	30.1	33.5	37.3	38.6	40.9	41.4	42.0	44.0	46.5
	2010	29.5	31.1	33.5	36.0	39.1	39.6	42.1	42.3	42.9	44.7
	2011	29.5	34.1	34.5	35.9	37.8	40.1	40.8	43.0	43.2	43.6
	2012	29.5	34.1	37.5	36.9	37.8	38.8	41.3	41.7	43.9	43.9
	2013	29.5	34.1	37.5	39.9	38.7	38.8	40.0	42.2	42.6	44.6
	2014	29.5	34.1	37.5	39.9	41.7	39.7	40.0	40.9	43.1	43.3

Table A2: Assumed mean length (cm) at age for female southern blue whiting aged 2–11+, 1990–2009, and the assumed mean length at age for projections, 2010–2014 (grey highlight).

Female										
1979	30.4	36.6	40.5	42.2	43.8	44.0	45.6	47.1	47.0	45.8
1980	34.0	36.0	41.2	43.4	43.1	47.4	46.4	47.1	48.0	48.1
1981	30.2	37.5	40.7	42.1	43.9	45.4	46.7	47.0	47.0	48.1
1982	30.4	34.4	40.0	42.4	45.6	45.0	46.5	46.9	47.2	47.2
1983	29.6	35.8	39.2	42.7	43.8	48.0	45.8	47.5	47.8	48.4
1984	32.7	37.6	40.7	42.5	44.5	47.0	47.0	47.3	47.6	48.1
1985	29.1	37.0	41.4	43.4	45.2	46.0	48.0	48.0	47.7	49.4
1986	31.2	35.9	39.5	41.9	44.5	45.6	47.4	47.9	48.5	48.9
1987	32.3	37.0	39.0	42.0	44.0	46.3	47.0	48.0	48.9	50.0
1988	31.5	38.2	41.6	42.8	44.0	47.0	47.2	47.7	49.4	50.4
1989	30.8	37.4	41.4	43.7	46.3	46.9	48.6	48.6	49.9	50.5
1990	27.7	37.1	41.0	44.3	45.6	46.9	47.5	49.5	50.3	51.2
1991	30.3	35.6	41.5	44.2	46.3	48.0	47.7	51.0	50.3	51.7
1992	34.0	39.6	41.0	44.0	46.0	48.3	50.4	48.9	52.0	51.9
1993	30.9	38.9	42.0	43.8	45.9	47.9	49.5	50.7	50.7	52.3
1994	27.0	32.8	40.9	44.6	45.4	48.2	49.0	49.5	51.0	53.6
1995	27.6	34.4	35.6	42.1	46.0	47.0	50.8	49.8	52.4	52.1
1996	31.3	34.2	37.2	38.2	46.8	47.4	48.5	50.8	50.4	52.0
1997	26.2	36.3	38.8	39.5	41.3	47.5	49.2	49.5	51.2	52.6
1998	26.4	32.3	38.1	41.1	41.3	42.2	47.8	50.4	50.5	51.1
1999	28.4	33.6	36.0	39.3	41.8	43.6	43.6	48.5	50.5	51.1
2000	31.1	35.2	37.0	39.5	42.1	43.9	43.9	45.0	49.0	50.9
2001	30.4	34.8	38.4	39.9	41.7	45.8	45.0	45.8	45.5	48.1
2002	32.7	37.3	39.1	40.4	43.0	43.8	47.2	46.9	46.4	47.5
2003	30.0	37.8	39.0	42.7	43.9	44.2	45.7	46.6	48.0	48.3
2004	32.0	35.5	39.0	42.0	44.0	46.1	46.6	47.4	48.5	49.3
2005	32.4	35.8	37.6	42.0	43.6	46.0	47.1	47.1	47.7	49.5
2006	31.4	36.2	39.1	40.7	43.2	45.0	46.6	47.5	48.3	50.1
2007	31.0	35.5	37.8	41.1	42.5	43.7	46.9	47.7	48.5	49.7
2008	28.2	34.2	36.6	39.0	40.9	43.2	45.0	45.0	48.0	50.9
2009	28.2	31.6	35.5	40.1	41.9	43.8	45.1	45.0	47.9	50.7
2010	30.3	33.8	35.0	38.1	42.2	43.8	45.0	45.9	46.0	49.0
2011	30.3	35.9	37.2	37.6	40.2	44.1	45.1	45.9	46.9	47.1
2012	30.3	35.9	39.2	39.8	39.6	42.1	45.3	45.9	46.9	48.0
2013	30.3	35.9	39.2	41.9	41.9	41.6	43.3	46.2	46.9	48.0
2014	30.3	35.9	39.2	41.9	43.9	43.8	42.8	44.2	47.1	48.0