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Tini a Tangaroa

## Southern blue whiting (*Micromesistius australis*) stock assessment for the Campbell Island Rise for data up to 2018–19

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## EXECUTIVE SUMMARY

**Doonan, I.J. (2020). Southern blue whiting (*Micromesistius australis*) stock assessment for the Campbell Island Rise for data up to 2018–19.**

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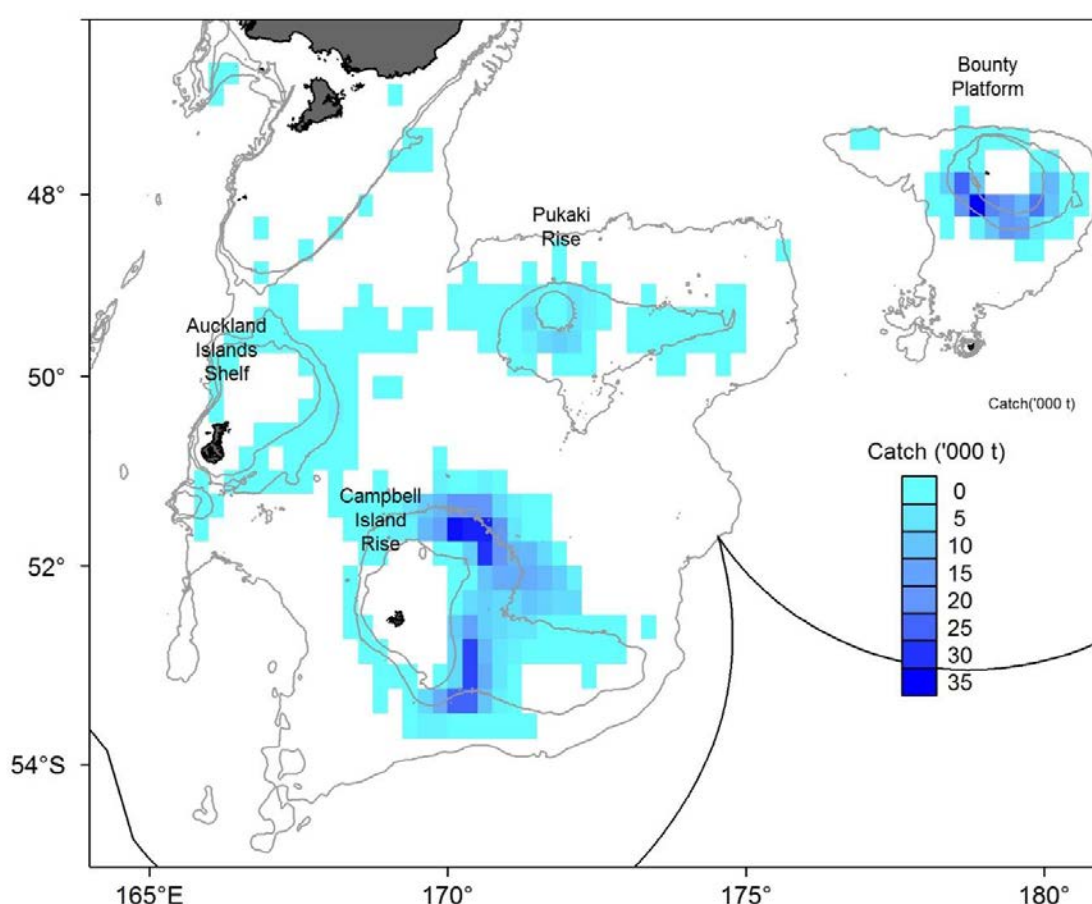
This report documents the stock assessment for the Campbell Island Rise stock of southern blue whiting, using a model informed by catch history, proportion-at-age, and acoustic survey biomass estimates up to and including the 2019 fishing season (2018–19 fishing year). This assessment updates the previous assessment in 2016–17. The primary data sources were the relative abundance index from the R.V. *Tangaroa* wide-area acoustic biomass surveys carried out from 1993 to 2019, and commercial trawl proportion-at-age data from 1979 to 2019.

The results of the base case assessment model run suggested that the biomass of the Campbell Island Rise stock in 2019 was at 58%  $B_0$  (95% CI 42–76%). Projections out to 2025 used resampled projected recruitment from the 1958 to 2016 estimates. When using a projected constant catch equal to the average over 2013 to 2019 fishing seasons, 21 500 t, the biomass was expected to decline to 41%  $B_0$  by 2025. The biomass was expected to decline to 20%  $B_0$  by 2025 under an assumption of a constant catch equal to the current TACC in 2019 (39 200 t).

## 1. INTRODUCTION

In New Zealand waters, southern blue whiting (*Micromesistius australis*) 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, where they are targeted by commercial trawl fisheries (Figure 1). During most years fish in the spawning fishery are 35–50 cm fork length (FL), although occasionally smaller length classes of males (29–32 cm FL) have been observed in the catch (Large in press).

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 generally been smaller fisheries, with much lower annual catches than the Campbell Island Rise and Bounty Platform fisheries (Large in press).



**Figure 1: Relative total density of the commercial catch of southern blue whiting by location, TCEPR data 1990–2019 (reproduced from Large in press).**

Acoustic biomass surveys of the Campbell Island Rise stock using R.V. *Tangaroa* have been carried out approximately every two to three years since 1993 and the most recent survey was carried out in 2019 (Ladroit et al. 2020). Stock assessments of the Campbell Island Rise stock have been carried out every one or two years since 1991 with the most recent assessment completed for the 2016–17 fishing year (Roberts & Hanchet 2019).

The 2017 assessment model (Roberts & Hanchet 2019) was changed to use an initial equilibrium age distribution, with the model starting in 1960, which also required estimates of catch history from 1960 to 1978. Previously, the initial age distribution was a non-equilibrium one (*C<sub>initial</sub>*) for 1979 (Dunn &

Hanchet 2017), but this model was unstable when natural mortality ( $M$ ) was estimated in the model using MCMC. Because the 2017 model (Roberts & Hanchet 2019) when estimating  $M$  was stable, it was preferred by the Deepwater Working Group (DWWG). However, even with this change in the assumptions over the initial state, the model was still unable to provide an unbiased estimate of  $M$  using MCMC, as revealed in simulations by Roberts & Dunn (2017); they recommended that the assessment continue to use an assumed value for  $M$  of 0.2 with sensitivity analyses at 0.15 and 0.25.

This report documents the assessment of the Campbell Island Rise stock using data up to and including the 2019–20 fishing year (2019 season), building upon the 2017 assessment model (Roberts & Hanchet 2019). The assessment used the R.V. *Tangaroa* acoustic biomass indices for 1993–2019 and commercial catch proportions-at-age data from the years 1979–2019. A comprehensive summary of available data used for the assessments of southern blue whiting was described by Large (in press).

This report is in fulfilment of the Fisheries New Zealand Project SBW201903 (To carry out stock assessments of southern blue whiting (*Micromesistius australis*) including estimating biomass and sustainable yields) Objective 1 (To update the stock assessment of the Campbell Island stock, including estimating biomass and sustainable yields).

## 2. METHODS

### 2.1 Population dynamics

For the current assessment, a two-sex, single stock and single area Bayesian statistical catch-at-age model for the Campbell Island Rise southern blue whiting stock was implemented in CASAL (Bull et al. 2012) following a similar approach to that used in previous assessments of this stock (e.g., Dunn & Hanchet 2017, Roberts & Hanchet 2019). The model partitioned the stock into immature and mature fish with two sexes and age groups 2–15, with a plus group at age 15. The model was run for the years 1960 to 2019, with five-year projections run for the years 2020–2025. 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 take place. In the second time step (spawning season), fish matured, ages were incremented, and the 2-year-olds were recruited to the population. These were then subjected to fishing mortality and the remaining 10% of natural mortality. A two-sex model was assumed because there are sex-based differences in both the proportions-at-age in the commercial catch for fish aged 2–4 (Large in press).

**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. The 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 | –             |  |
| 2. Sep–Oct | Age, recruitment, fishing mortality ( $F$ ), and $M$ | 0.1 | Growth matrix | Proportions at age<br>Acoustic abundance indices |

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 two) assumed to be 0.5 of all recruits. Relative year class strengths were parameterised in the model such that the mean was equal to one.

Southern blue whiting on the Campbell Island Rise are assumed to be mature when on the fishing ground, because they are fished during spawning (Large in press). Hence, it was assumed that all mature fish were equally selected by fishing. The maximum exploitation rate ( $U_{\max}$ ) was assumed to be 0.99. The proportion of immature fish that mature in each year was estimated for ages 2–5, with fish aged 6

and above assumed to be fully mature (see Roberts & Hanchet 2019, Dunn & Hanchet 2017, and previous assessments). In a sensitivity run, annual adjustments to the proportions that mature by age were also estimated. Annual adjustments ( $m_{year}$ ) alter the maturity rate at age  $a$  in year  $year$  by

$$A_{a,year} = A_{a,0}e^{m_{year}}$$

where both  $A_{a,0}$  and  $m_{year}$  are estimated. When  $m_{year}$  is zero there is no effect; if  $m_{year} = -0.5$ , the base rate is decreased to  $0.61 A_{a,0}$ . Annual adjustments were restricted to the range -5 to 0, where zero represents “usual” recruitment and so  $m_{year}$  defines retarded maturity due to, e.g., a large cohort (which also slows growth). This formulation was used because the  $m_{year}$  are only estimated from 1990 because age data are collected from 1979 and the 22 recruitments prior to 1991 were low, but with three years where it was average, i.e., a lack of strong cohorts which are known to slow growth and cause maturation to be delayed.

Southern blue whiting exhibit large inter-annual differences in growth, presumably caused by local environmental factors, closely correlated with the occurrence of strong and weak year classes (Large in press). Hence, a standard von Bertalanffy growth curve was not used to determine the mean length at age of fish in the model, but rather an empirical length-at-age matrix. The length-at-age matrix used the empirically estimated mean lengths-at-age from the commercial catch data (Large in press). 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.

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  $weight = a \times length^b$  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, for all model years.

Catches for southern blue whiting have been recorded since 1971 (Large in press), with an average of 25 000 t annual catch between 1971 and 1977. However, the locations of the catches, and, hence, the stock associated with the catch in this period, are not well known. Also, 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).

This required estimation of the catch history in years 1971–1978, described in Section 2.2.

## 2.2 Observations

Available observations for the Campbell Island Rise stock are described by Large (in press). They include a time series of catches from 1979 to 2019; wide area acoustic biomass estimates, survey age frequency data for immature fish; and proportions-at-age from the commercial catch.

Previous stock assessments have begun from the year 1979 and have used catches for the Campbell Island stock taken from QMRs and MHRs. However, to start the model from 1960, catch estimates were required from the start of the fishery. It is known that the Russian fleet fished throughout the New Zealand EEZ from 1971 to 1977, and estimates of the total annual catch are available, but the proportion of the catch taken from the Campbell Island stock could not be determined (Hanchet 1998). For the purposes of the stock assessment it was assumed that the proportion of the catch taken from the Campbell Island stock in the period 1971–1977 equalled the proportion of the catch across the period since 1978 following Hanchet (1998) and Roberts & Dunn (2017). For the period 1978 to 2016–2017 this proportion equalled 0.70 and the resulting estimates for 1971–1977 are given in Table 2.



Previous models have also considered CPUE indices and trawl survey biomass indices. Standardised CPUE indices were last updated by Hanchet et al. (2006) but were not considered to be a useful index of abundance by the Middle Depths Working Group. Hence, these data are not used in this assessment.

Dunn & Hanchet (2011) modelled observations from the sub-Antarctic trawl survey biomass and age frequencies time series. They found that, although the model fits suggested some consistency with the summer series biomass estimates, in general the trawl survey underestimated biomass at low stock sizes and overestimated biomass at high stock sizes. They concluded that the time series was not particularly useful for monitoring abundance in its present form. Hence, these data are ignored for this assessment.

**Table 2: Estimated catches and catch limits (TACCs) (t) of southern blue whiting at the Campbell Island Rise for 1971 to 2016–17 (source: QMRs, MHRs, Roberts & Dunn 2017; italicised catch figures from 1971 to 1977 were estimated by applying the proportion of the catch taken from the Campbell Island stock since 1978 to the period 1971–1977, following Hanchet 1998 and Roberts & Dunn 2017 ; ‘–’ denotes no catch limit in place).**

| Fishing year <sup>1</sup> | Estimated catch (t) <sup>2</sup> | Limit (t) | Fishing year <sup>1</sup> | Estimated catch (t) <sup>2</sup> | Limit (t) |
|---------------------------|----------------------------------|-----------|---------------------------|----------------------------------|-----------|
| 1971                      | <i>7 260</i>                     | –         | 1995–96                   | 14 959                           | 21 000    |
| 1972                      | <i>18 010</i>                    | –         | 1996–97                   | 15 685                           | 30 100    |
| 1973                      | <i>33 856</i>                    | –         | 1997–98                   | 24 273                           | 35 460    |
| 1974                      | <i>29 458</i>                    | –         | 1998–00                   | 30 386                           | 35 460    |
| 1975                      | <i>1 660</i>                     | –         | 2000–01                   | 18 049                           | 20 000    |
| 1976                      | <i>11 929</i>                    | –         | 2001–02                   | 29 999                           | 30 000    |
| 1977                      | <i>18 453</i>                    | –         | 2002–03                   | 33 445                           | 30 000    |
| 1978                      | <i>6 403</i>                     | –         | 2003–04                   | 23 718                           | 25 000    |
| 1978–79                   | 25 305                           | –         | 2004–05                   | 19 799                           | 25 000    |
| 1979–80                   | 12 828                           | –         | 2005–06                   | 26 190                           | 25 000    |
| 1980–81                   | 5 989                            | –         | 2006–07                   | 19 763                           | 20 000    |
| 1981–82                   | 7 915                            | –         | 2007–08                   | 20 996                           | 20 000    |
| 1982–83                   | 12 803                           | –         | 2008–09                   | 20 483                           | 20 000    |
| 1983–84                   | 10 777                           | –         | 2009–10                   | 19 040                           | 20 000    |
| 1984–85                   | 7 490                            | –         | 2010–11                   | 20 224                           | 23 000    |
| 1985–86                   | 15 252                           | –         | 2011–12                   | 30 982                           | 29 400    |
| 1986–87                   | 12 804                           | –         | 2012–13                   | 21 321                           | 29 400    |
| 1987–88                   | 17 422                           | –         | 2013–14                   | 28 606                           | 29 400    |
| 1988–89                   | 26 611                           | –         | 2014–15                   | 23 397                           | 39 200    |
| 1989–90                   | 16 542                           | –         | 2015–16                   | 22 100                           | 39 200    |
| 1990–91                   | 21 314                           | –         | 2016–17                   | 19 875                           | 39 200    |
| 1991–92                   | 14 208                           | –         | 2017–18                   | 18 334                           | 39 200    |
| 1992–93                   | 9 316                            | 11 000    | 2018–19                   | 15 147                           | 39 200    |
| 1993–94                   | 11 668                           | 11 000    | 2019–20                   | 26 308                           | 39 200    |
| 1994–95                   | 9 492                            | 11 000    |                           |                                  |           |

1. Fishing years defined as 1 April to 30 September for 1978; 1 October to 30 September for 1978–79 to 1997–98; 1 October 1998 to 31 March 2000 for 1998–2000; 1 April to 31 March for 2000–01 to current.
2. Estimated catch. Estimates for 1971 to 1977 are taken from Roberts & Dunn (2017).

## 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* from 1993 to 2019 (see Table 3 and Large in press for details). The primary objective of the acoustic surveys has been to estimate the relative biomass of the adult spawning stock by year. A secondary objective has been to provide biomass estimates of pre-recruit fish and therefore the survey transects extend into 300 m depths where the younger fish live.

Southern blue whiting acoustic marks were identified as one of three categories of fish: juvenile, immature, or adult. The categories were broadly defined as adult (also known as mature) which consisted mainly of adult fish that were going to spawn that year; immature which consisted mainly of two-year-olds; and juvenile which consisted mainly of one-year-olds. Identification of each mark to a category was typically made at the time based on the results of research tows, the acoustic ‘shape’ of the mark, and its depth and location.

Only the survey estimates of immature and mature southern blue whiting were used in this analysis and they were assumed to be relative estimates of mid-season biomass (i.e., after half the catch for that fishing season has been removed), with a CV equal to the sampling CV estimated from the survey. We ignore the juvenile category in the assessment because biomass estimates of the juvenile category (mainly two-year-olds) were generally low and inconsistent with subsequent estimates of those year classes, and so were unlikely to be a good index of abundance (Dunn & Hanchet 2011).

The acoustic biomass observations were fitted using a lognormal likelihood (Bull et al. 2012).

**Table 3: R.V. *Tangaroa* juvenile, immature, and mature acoustic biomass estimates (t) and CV for the Campbell Island Rise 1993–2016 using the revised target strength derived by O’Driscoll et al. (2013).**

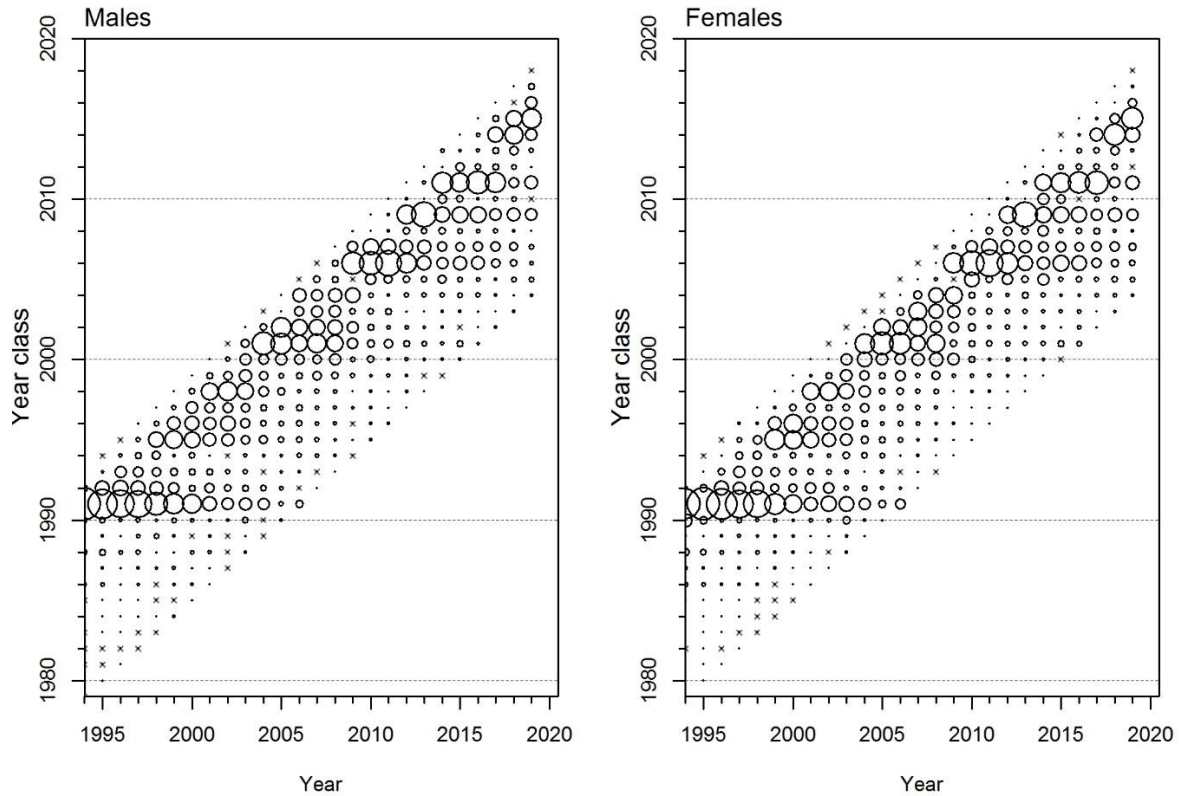
| Year | Juvenile |      | Immature |      | Mature  |      | Total<br>Biomass | Source                   |
|------|----------|------|----------|------|---------|------|------------------|--------------------------|
|      | Biomass  | CV   | Biomass  | CV   | Biomass | CV   |                  |                          |
| 1993 | 0        | 0.00 | 35 208   | 0.25 | 16 060  | 0.24 | 51 268           | (Fu et al. 2013)         |
| 1994 | 0        | 0.00 | 5 523    | 0.38 | 72 168  | 0.34 | 77 691           | (Fu et al. 2013)         |
| 1995 | 0        | 0.00 | 15 507   | 0.29 | 53 608  | 0.30 | 69 114           | (Fu et al. 2013)         |
| 1998 | 322      | 0.45 | 6 759    | 0.20 | 91 639  | 0.14 | 98 720           | (Fu et al. 2013)         |
| 2000 | 423      | 0.39 | 1 864    | 0.24 | 71 749  | 0.17 | 74 035           | (Fu et al. 2013)         |
| 2002 | 1 969    | 0.39 | 247      | 0.76 | 66 034  | 0.68 | 68 250           | (Fu et al. 2013)         |
| 2004 | 639      | 0.67 | 5 617    | 0.16 | 42 236  | 0.35 | 48 492           | (Fu et al. 2013)         |
| 2006 | 504      | 0.38 | 3 423    | 0.24 | 43 843  | 0.32 | 47 770           | (Fu et al. 2013)         |
| 2009 | 0        | –    | 24 479   | 0.26 | 99 521  | 0.27 | 124 000          | (Fu et al. 2013)         |
| 2011 | 0        | –    | 14 454   | 0.17 | 53 299  | 0.22 | 67 753           | (Fu et al. 2013)         |
| 2013 | 0        | –    | 8 004    | 0.55 | 65 801  | 0.25 | 73 805           | (O’Driscoll et al. 2014) |
| 2016 | 775      | 0.37 | 4 456    | 0.19 | 97 117  | 0.16 | 102 348          | (O’Driscoll et al. 2018) |
| 2019 |          |      | 4 020    | 0.18 | 91 145  | 0.27 | 91 165           | (Ladroit et al. 2020)    |

## 2.2.2 Proportions-at-age in the commercial catch

Catch-at-age observations by sex were available from the commercial fishery for 1979 to 2019 from observer data, excluding 1987 (Figure 2).

Although length data were available for 1987, there were no otoliths aged for 1987, so the age length key was estimated using the length at age keys from 1986 and 1988, and adding or subtracting 1 year of growth, respectively, following Hanchet & Ingerson (1995). Commercial catch-at-age data were fitted to the model as proportions-at-age by sex, where associated CVs 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 (Bull et al. 2012).

A robustifying function was used to avoid division by zero errors (see Bull et al. 2012 for more details). Proportions-at-age data were derived from the aged otoliths collected by observers and the length frequency of the catch. Large (in press) described the catch-at-age data available for the assessment models from 1990, and data before 1990 were described by Hanchet et al. (2006). The derivation of the assumed multinomial sample sizes for the proportions-at-age data is described below.



**Figure 2: Commercial catch proportions at age for the Campbell Island stock by sex and year class, 1978–2019 for ages 2–15+. Symbol area proportional to the proportions-at-age within the sampling event. (Reproduced from Large in press)**

### 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  $\mathbf{p}$ , the vector of the free parameters,  $L$  the likelihood function, and  $O_i$  the  $i$ th observation was

$$\text{Objective}(\mathbf{p}) = -\sum_i \log[L(\mathbf{p} | O_i)] - \log[\theta(\mathbf{p})],$$

where  $\theta$  is the joint prior (and penalty) density of the parameters  $\mathbf{p}$ . The observations, likelihoods, penalties, and priors are described later.

Initial model fits were evaluated at the maximum of the posterior density (MPD) by inspecting the 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 was 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 Markov chain Monte Carlo (MCMC).

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. 2012 for more detail) and used as the starting point for the chain.

An initial MCMC chain was estimated using a burn-in length of 1 million iterations, with every 10 000<sup>th</sup> sample taken from the next 10 million iterations (i.e., a final sample of length 1000 was taken from the Bayesian posterior). To improve mixing at MCMC (following the approach of Roberts & Doonan 2016) the covariance matrix was recalculated empirically from the 1000 samples obtained from the initial MCMC chain and the chain started afresh with the new covariance matrix out to a length  $3.3 \times 10^6$  iterations (no burn in). The initial chain was discarded.

### 2.3.1 Prior distributions and penalties

With the exception of natural mortality, which was assumed to be lognormal with mean 0.2 and CV 0.2, the assumed prior distributions used in the assessment were intended to be non-informative with wide bounds (Table 4). The prior assumed for the relative year class strengths was lognormal, with mean 1.0 and CV 1.3, for all year classes. For annual adjustments to maturation, the upper bound was zero (no effect), which allows maturation for “normal” times, but an increased age of maturity when the cohort size is large (large cohort sizes are known to reduce growth and fish take longer to mature).

**Table 4: The parameters, number of degrees of freedom (N), priors (including distributions, and means and CVs for the lognormal), and bounds assumed for estimated parameters for the models.**

| Parameter                         | N  | Distribution | Priors |      |        |         |
|-----------------------------------|----|--------------|--------|------|--------|---------|
|                                   |    |              | Values |      | Bounds |         |
|                                   |    |              | Mean   | CV   | Lower  | Upper   |
| $B_0$                             | 1  | Uniform-log  | –      | –    | 30 000 | 800 000 |
| Male maturation ogive             | 5  | Uniform      | –      | –    | 0.001  | 0.999   |
| Female maturation ogive           | 5  | Uniform      | –      | –    | 0.001  | 0.999   |
| Male fishing selectivity          | 5  | Uniform      | –      | –    | 0.001  | 0.999   |
| Female fishing selectivity        | 5  | Uniform      | –      | –    | 0.001  | 0.999   |
| Year class strength               | 60 | Lognormal    | 1.0    | 1.3  | 0.001  | 100     |
| Acoustic catchability $q$         |    |              |        |      |        |         |
| Mature                            | 1  | Lognormal    | 0.54   | 0.44 | 0.1    | 1.5     |
| Immature                          | 1  | Uniform      | –      | –    | 0.1    | 1.5     |
| *Natural mortality (average)      | 1  | Lognormal    | 0.2    | 0.2  | 0.075  | 0.325   |
| *Natural mortality (difference)   | 1  | Normal       | 0.0    | 0.05 | -0.05  | 0.05    |
| *Annual adjustments to maturation | 30 | Uniform      | –      | –    | -5     | 0       |

\* estimated in sensitivity runs

After the 2016 assessment (Dunn & Hanchet 2017), and before the 2017 assessment (Roberts & Hanchet 2019), the log-normal prior for the wide area acoustic survey catchability coefficient was revised following the adoption of a new TS-length relationship for southern blue whiting (O’Driscoll et al. 2013). The revised prior had a mean of 0.54 and CV of 0.44. The old prior had a mean of 0.87 and a CV of 0.30. Details of the factors and values used are shown in Table 5. The revised prior was used in this assessment.

**Table 5: Best and lower and upper bounds for the factors for the acoustic catchability prior. A lognormal prior with mean 0.54 and CV 0.44 was used for the assessment.**

| Factor                       | Lower | Best | Upper |
|------------------------------|-------|------|-------|
| Target strength: Uncertainty | 0.80  | 1.00 | 1.20  |
| Target strength: Tilt angle  | 0.25  | 0.70 | 1.00  |
| Target identification        | 0.85  | 1.00 | 1.15  |
| Vertical availability        | 0.90  | 0.95 | 1.00  |
| Areal availability           | 0.80  | 0.90 | 1.00  |
| System calibration           | 0.90  | 1.00 | 1.10  |
| Combined                     | 0.11  | 0.60 | 1.52  |

Natural mortality was estimated to be  $0.2 \text{ y}^{-1}$  by Hanchet (1991). When estimated in the current model (sensitivity), natural mortality was parameterised by the average of male and female, with the difference estimated with an associated normal prior with a mean of zero and bounds of  $0.05 \text{ y}^{-1}$ .

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.

### 2.3.2 Process error and data weighting

In addition to sampling error, 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 proportions-at-age data, and for the acoustic estimates from the wide area surveys.

The proportions-at-age had a multinomial distribution where the sampling error for a year is indexed by the sampling size,  $N_j$ . Estimates of the effective sample size,  $N_j'$ , which incorporated process error, were obtained by adding additional process error,  $NPE$ , to  $N_j$  using Method TA1.8 of Francis (2011) — i.e., from an initial MPD model fit, an estimate of the additional process error was made such that the standardised residuals from the mean observed age and mean expected age in each year had mean equal to one.

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

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

### 2.3.3 Model runs

Five model runs were considered: a base case and four sensitivity tests (Table 6). As recommended by the DWWG, the base case run had an equilibrium age distribution in the year 1960, YCSs were estimated from 1958 to 2016, the 1971 to 2019 catch history was used, and natural mortality was assumed equal to 0.2. The first three sensitivity tests considered the influence of uncertainty in natural mortality in the model: the first two assumed natural mortality equal to 0.15 or 0.25; and the third allowed for the estimation of the natural mortality rate for males and females. The last sensitivity run investigated the influence of time varying maturity.

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

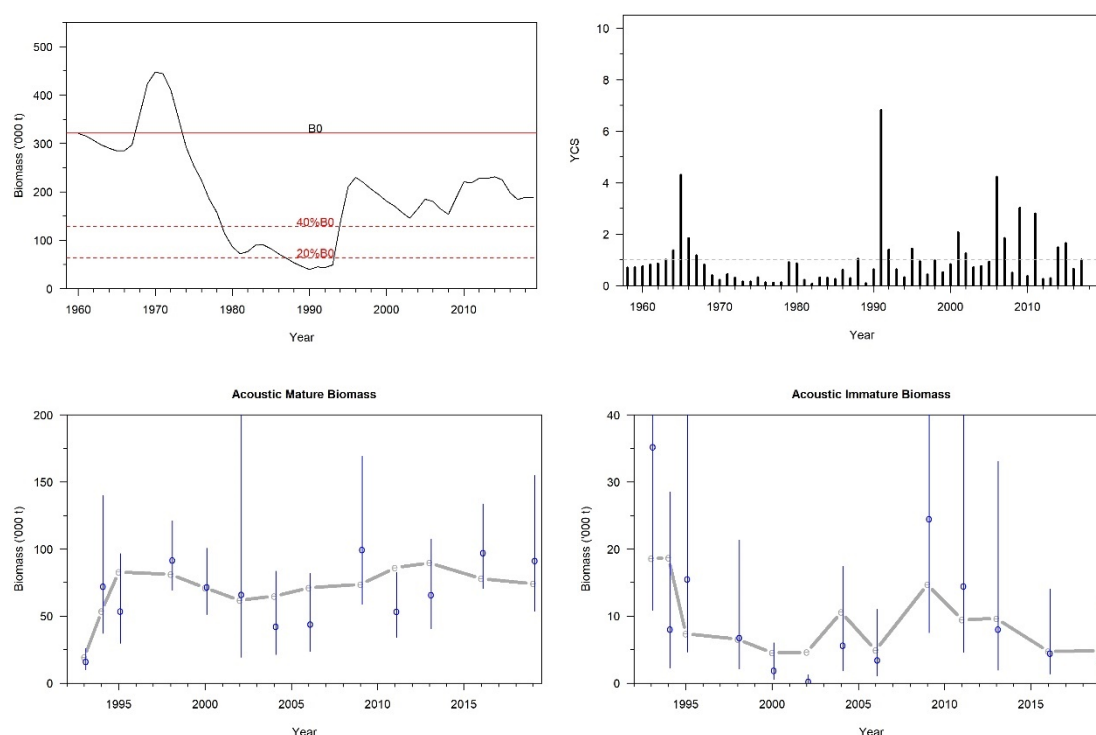
| Model type  | Model label | MCMC | Description  |
|-------------|-------------|------|--|
| Base case   | Base        | Yes  | Model with equilibrium age distribution for the year 1960, YCSs estimated for years 1958–2013, catch history for years 1971–2019, natural mortality equal to 0.20. |
| Sensitivity | M0.15       | No   | Model Base, but with natural mortality set to 0.15   |
| Sensitivity | M0.25       | No   | Model Base, but with natural mortality set to 0.25   |
| Sensitivity | Mfree       | Yes  | Model Base, but with natural mortality estimated.  |
| Sensitivity | Tvary       | Yes  | Model Base, but with time varying adjustment to maturity from 1990 to 2019.  |

### 3. RESULTS

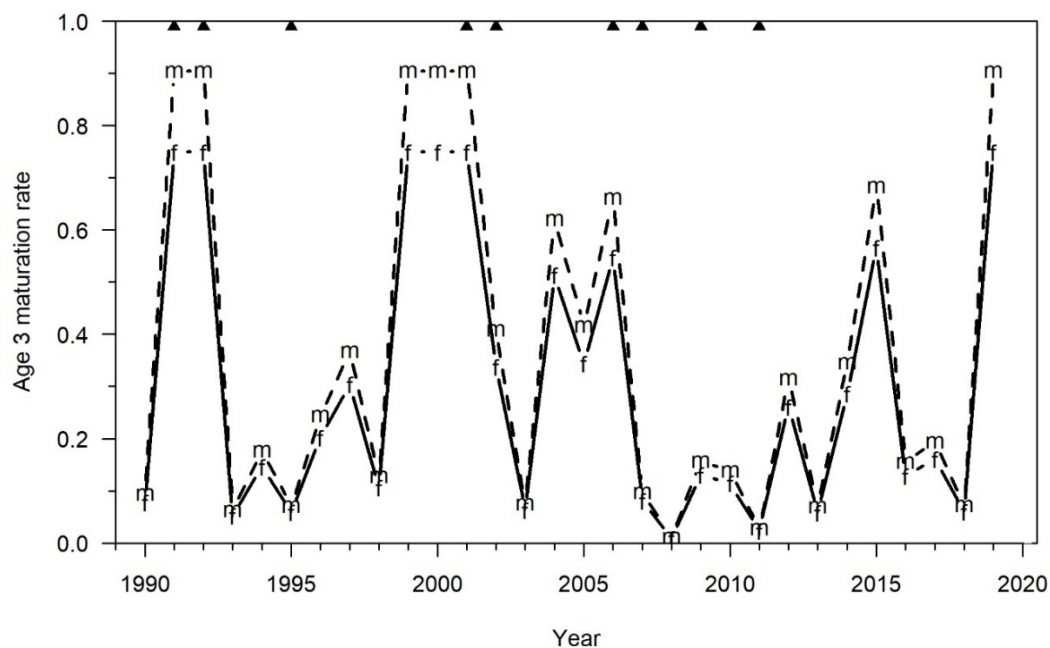
#### 3.1 MPD results

The spawning stock biomass (SSB) trajectories for the MPD fits are shown for the Base model in Figure 3. The relative year class strengths and fits to the acoustic indices are also shown in Figure 3. Fits to the acoustic indices were generally good. For the acoustic biomasses, the estimated processes error CV was zero for the mature biomass, but 66% for the immature acoustic biomass so the latter did not really have a good fit in the model.

The fits to the mature biomass acoustic indices and the age data looked very similar for the sensitivity runs (not shown).  $M$  was estimated to be 0.14 for males and 0.15 for females in model run Mfree. The annual adjustment to maturation from model Tvary showed shifts in the age of maturity that were not “normal” in most years where the effect was estimated (Figure 4), i.e., usual was ~80% mature for females age 3, and ~90% for males at age 3, and 14 (out of 30 years) estimates with the proportion of age 3 fish maturing being 20% or lower. For cohorts with a YCS over 2, the percentage of year 3 fish maturing was always below 10% (Figure 3 and Figure 4). The main improvement to the model Tvary fits was for the age compositions (43 log-likelihood units). However, model Tvary also estimated the process error CV on the immature (mostly age 2 fish) acoustic estimate to be zero (all others had a CV of 60 to 80%) which meant that the immature biomass estimate could be fitted using just its sampling error.



**Figure 3: Results of MPD fits for model base showing (top left panel) estimated SSB trajectory (with  $B_0$  shown as a solid line and 20%  $B_0$  and 40%  $B_0$  shown as a dashed lines) 1960–2019; (top right panel) estimated relative year class strength (with the average of one shown as a dashed line); (bottom left panel) observed (o) and expected (e) mature acoustic biomass index ( $\pm 2$  s.d.); and (bottom right panel) immature acoustic observed (o) and expected (e) biomass indices ( $\pm 2$  s.d. including process error).**



**Figure 4: Proportion of age 3 fish that matured by year by sex ('m' male, 'f' female) from model Tvary. The solid triangles show the years with better than average recruitments (age 1), e.g., the very large cohort in 1991 had fish aged three in 1993 in which only 8% matured. Years with YCS over 2 were 1991, 2001, 2006, 2009, and 2010.**

For the Base model and the sensitivities, the MPD estimated virgin biomass and current spawning biomass in 2019 are shown in Table 7.

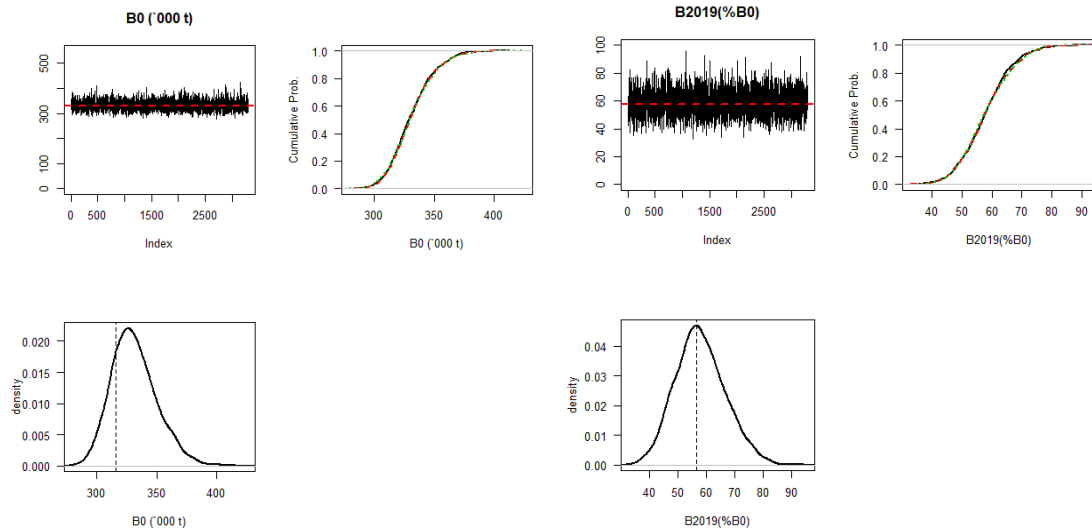
**Table 7: For the Base model and sensitivities, MPD estimates of  $B_0$  and  $B_{2019}$ .**

| Model | $B_0$ (000 t) | $B_{2019}$ (% $B_0$ ) |
|-------|---------------|-----------------------|
| Base  | 324           | 66                    |
| M0.15 | 321           | 53                    |
| M0.25 | 389           | 73                    |
| Mfree | 319           | 52                    |
| Tvary | 310           | 65                    |

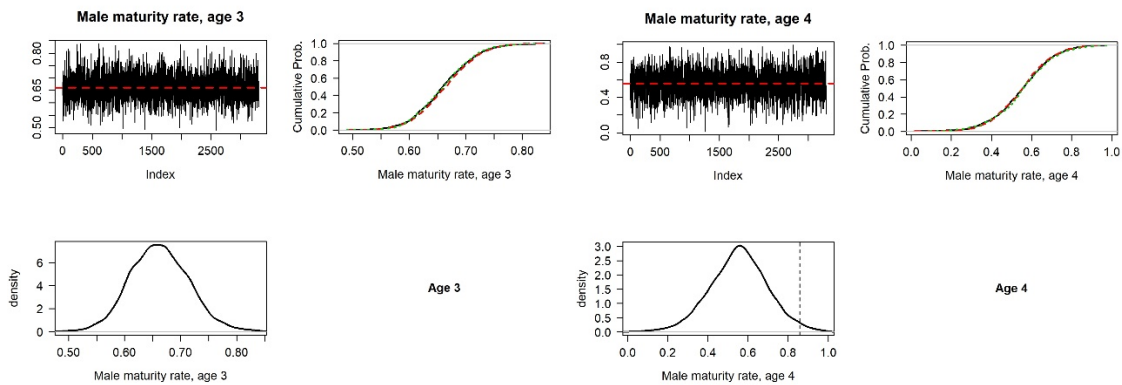
## 3.2 MCMC results

### 3.2.1 MCMC diagnostics

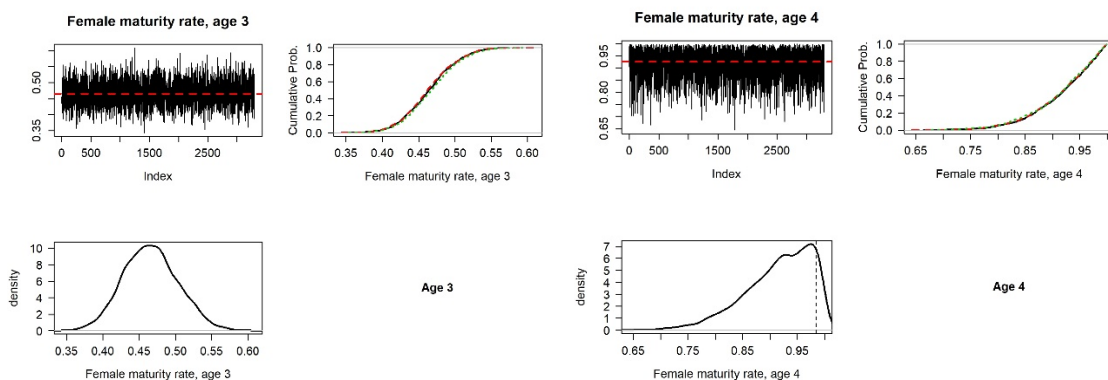
MCMC diagnostics were reasonably good for  $B_0$  and for  $B_{2019}$  (% $B_0$ ) for model Base (Figure 5), and also for the maturation rates at ages 3 and 4, the main ages when fish mature (Figures 6 and 7). The sensitivity model runs had similar results (not shown).



**Figure 5: MCMC diagnostic plots for the model Base: left panel set,  $B_0$ ; right panel set, current status,  $B_{2019} \%B_0$ . Each panel set shows posterior trace plots (top left), the three cumulative distributions from splitting the chain into three consecutive parts (black, red, and green) (top right), and the posterior distribution (vertical dotted line is the MPD estimate) (lower left).**



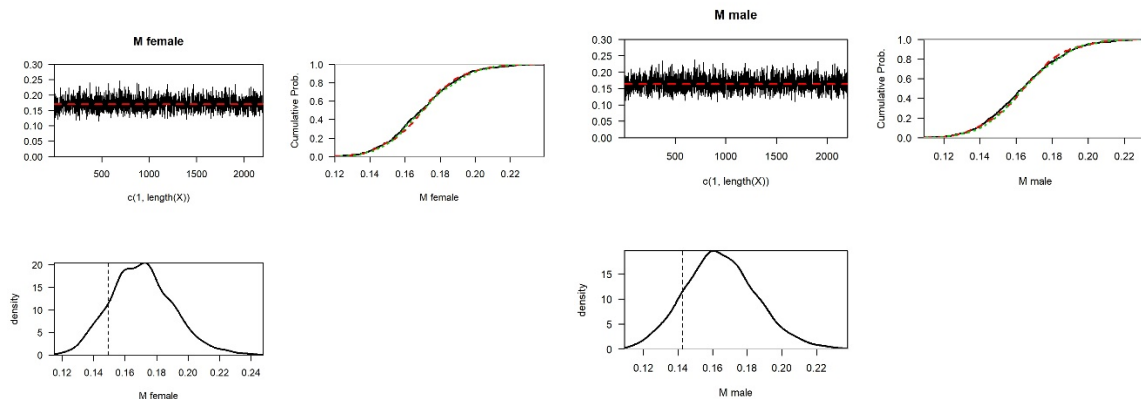
**Figure 6: MCMC diagnostic plots for the model Base: left panel set, maturity rate for age 3 male; right panel set, maturity rate for age 4 male. Each panel set shows posterior trace plots (top left), the three cumulative distributions from splitting the chain into three consecutive parts (black, red, and green) (top right), and the posterior distribution (vertical dotted line is the MPD estimate) (lower left).**



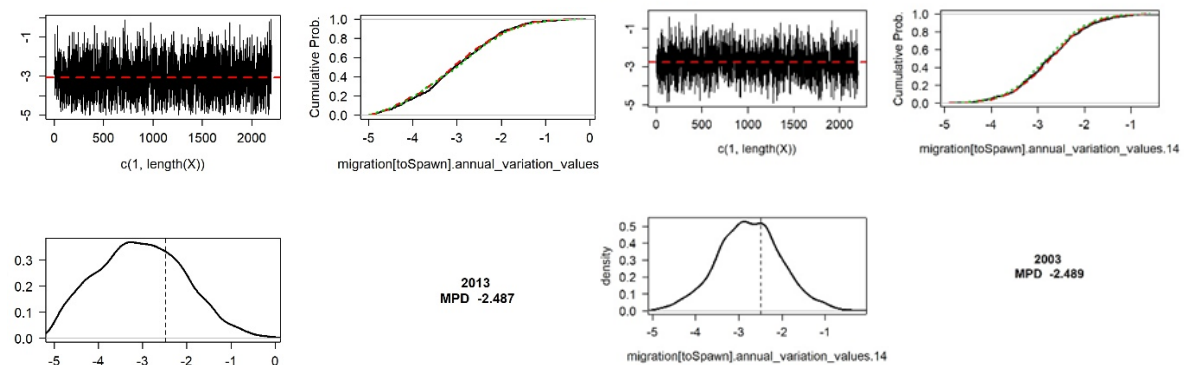
**Figure 7: MCMC diagnostic plots for the model Base: left panel set, maturity rate for age 3 female; right panel set, maturity rate for age 4 female. Each panel set shows posterior trace plots (top left), the three cumulative distributions from splitting the chain into three consecutive parts (black, red, and green) (top right), and the posterior distribution (vertical dotted line is the MPD estimate) (lower left).**



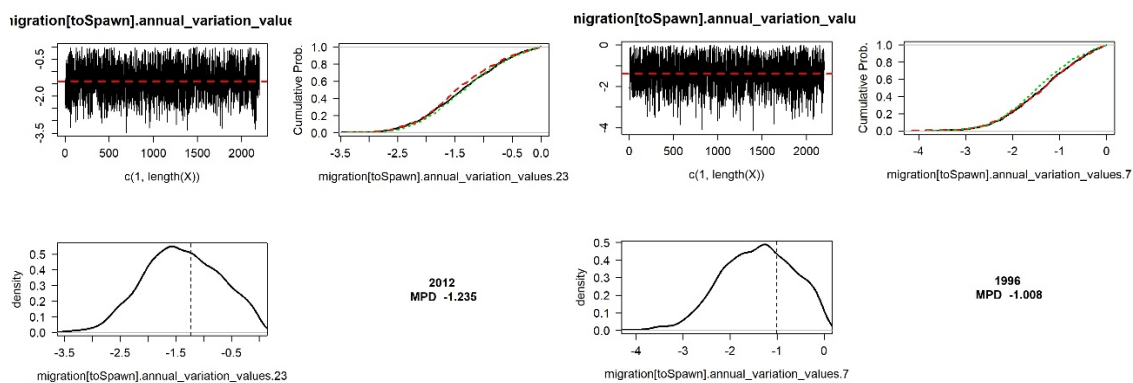
Model Mfree estimated  $M$  and its diagnostics are good (Figure 8). For the annual adjustments in maturity (model Tvary), there are 30 estimates of which 25 had good diagnostics (Figure 9) with only five estimates being not so good, but they are adequate (Figure 10).



**Figure 8: MCMC diagnostic plots for the model Mfree: left panel set,  $M$  for females; right panel set,  $M$  for males. Each panel set shows posterior trace plots (top left), the three cumulative distributions from splitting the chain into three consecutive parts (black, red, and green) (top right), and the posterior distribution (vertical dotted line is the MPD estimate) (lower left).**



**Figure 9: MCMC diagnostic plots for the model Tvary: example plots for annual maturation rates with good diagnostics: left panel set, 2013; right panel set, 2003. Each panel set shows posterior trace plots (top left), the three cumulative distributions from splitting the chain into three consecutive parts (black, red, and green) (top right), and the posterior distribution (vertical dotted line is the MPD estimate) (lower left).**



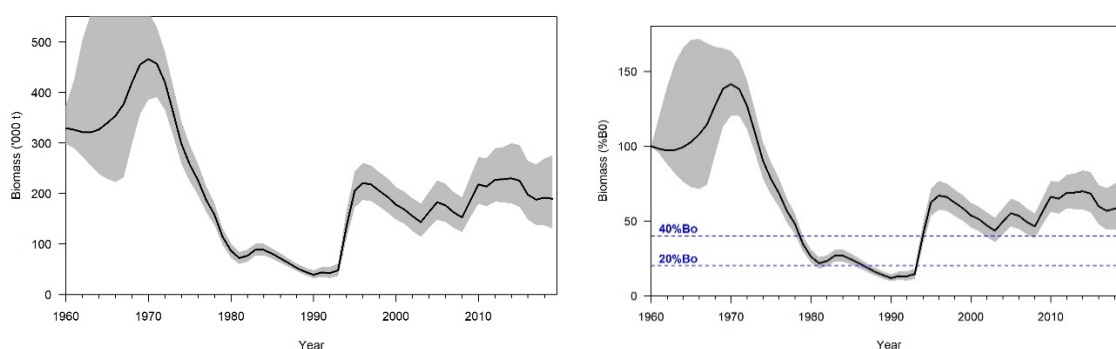
**Figure 10: MCMC diagnostic plots for the model Tvary: example plots for annual maturation rates with adequate diagnostics: left panel set, 2012; right panel set, 1996. There were three others like these. Each panel set shows posterior trace plots (top left), the three cumulative distributions from splitting the chain into three consecutive parts (black, red, and green) (top right), and the posterior distribution (vertical dotted line is the MPD estimate) (lower left).**

### 3.2.2 MCMC estimates

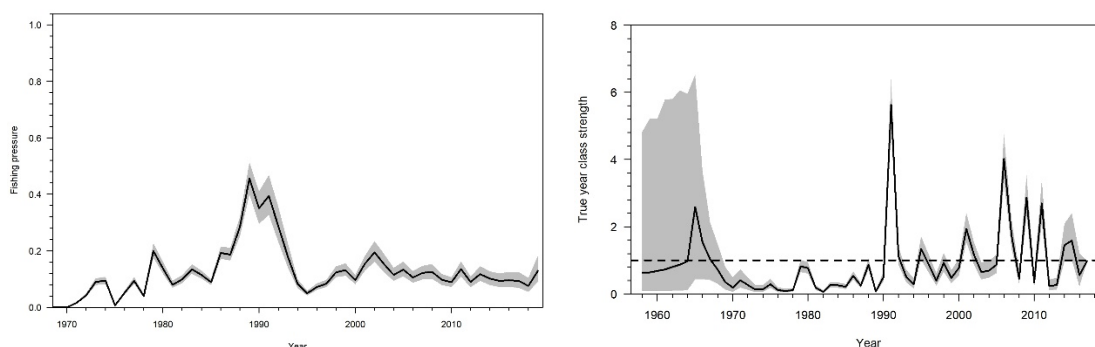
#### Base case model run

The estimated MCMC marginal posterior distributions for parameters of interest are shown for the Base model in Figures 11 and 12, and the results are summarised in Table 8 and Table 9. This run suggested that the spawning stock biomass increased from 1960 to 1970 as a result of a strong year class and no fishery exploitation. There followed a period of low recruitment and some fishing, in which the SSB steadily declined until 1993, when it rose sharply as the very strong 1991 recruitment matured. Subsequently, the SSB declined steadily from 1997 until 2008, and then showed a moderate increase by 2010, remaining flat to 2015 as the 2006 and 2009 and then 2011 year classes recruited to the fishery. In the recent years, the SSB was flat at a new lower level. At the start of fishing in 1971, the spawning stock biomass was estimated to be at about 140%  $B_0$ . During the late 1980s and early 1990s the biomass was estimated to have dropped to below 20%  $B_0$  for several years, but since 1994 it has remained well above the target level of 40%  $B_0$ .

The estimate of the median mature biomass acoustic  $q$  was 0.40, which is less than the prior value of 0.54 so that the prior is strongly updated by the current data. Note that the previous assessment in 2017 (Roberts & Hanchet 2019) estimated  $q$  to be 0.36 so this parameter is not stable yet although 0.36 is within the current assessment's 95% CI. The estimate of the median immature biomass acoustic  $q$  was 0.26 (same estimate as in the 2017 assessment).



**Figure 11: MCMC median and 95% credible intervals of the trajectory of (left) spawning stock biomass and (right) stock status (% $B_0$ ) for the Base model.**



**Figure 12: MCMC median and 95% credible intervals for (left) exploitation rates and (right) relative year class strength for the Base model.**

**Table 8: Bayesian median and 95% credible intervals of equilibrium ( $B_0$ ) and current status ( $\%B_0$ ) for Base model and the sensitivity cases.**

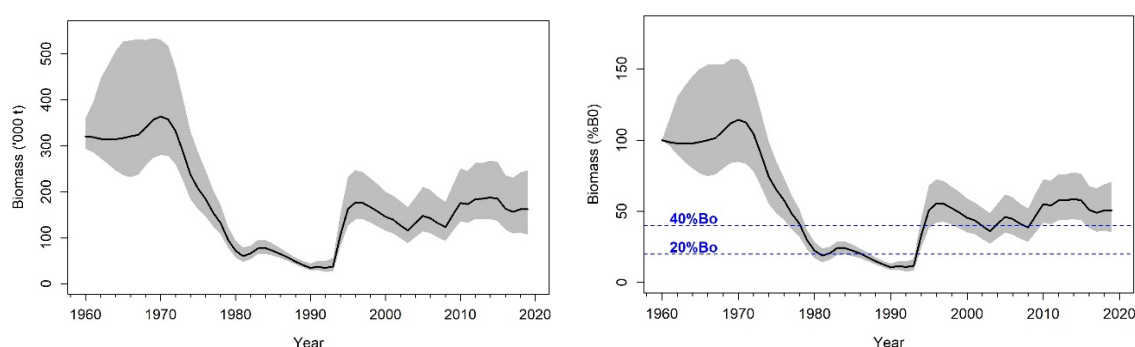
| Model | $B_0$ ('000 t) | $B_{2019}$ ( $\%B_0$ ) |
|-------|----------------|------------------------|
| Base  | 329 (299–372)  | 58 (42–76)             |
| Mfree | 321 (294–360)  | 51 (35–71)             |
| Tvary | 331 (300–373)  | 54 (40–72)             |

**Table 9: Bayesian median and 95% credible intervals of the catchability coefficients ( $q$ ) for the wide area acoustic biomass indices and estimates of natural mortality for Base model and the sensitivity cases Mfree and Tvary.**

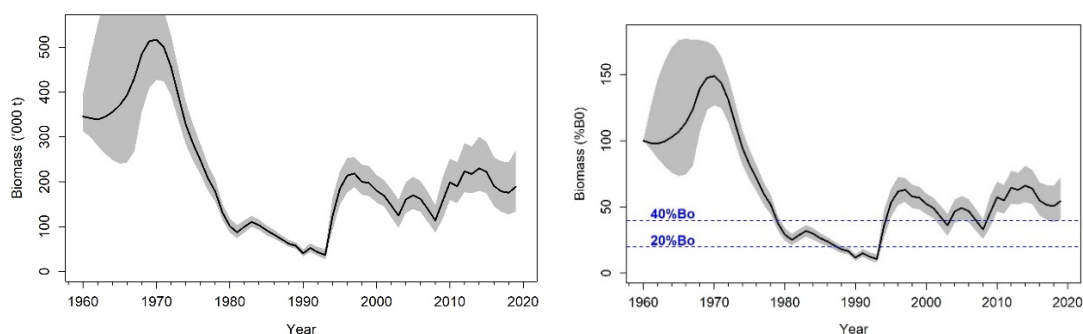
| Model | Catchability     |                  | Natural mortality   |                     |
|-------|------------------|------------------|---------------------|---------------------|
|       | Immature         | Mature           | Male                | Female              |
| Base  | 0.26 (0.22–0.32) | 0.40 (0.33–0.48) | –                   | –                   |
| Mfree | 0.35 (0.24–0.49) | 0.49 (0.35–0.62) | 0.164 (0.126–0.208) | 0.170 (0.135–0.213) |
| Tvary | 0.26 (0.21–0.31) | 0.42 (0.35–0.50) | –                   | –                   |

### Model sensitivity run

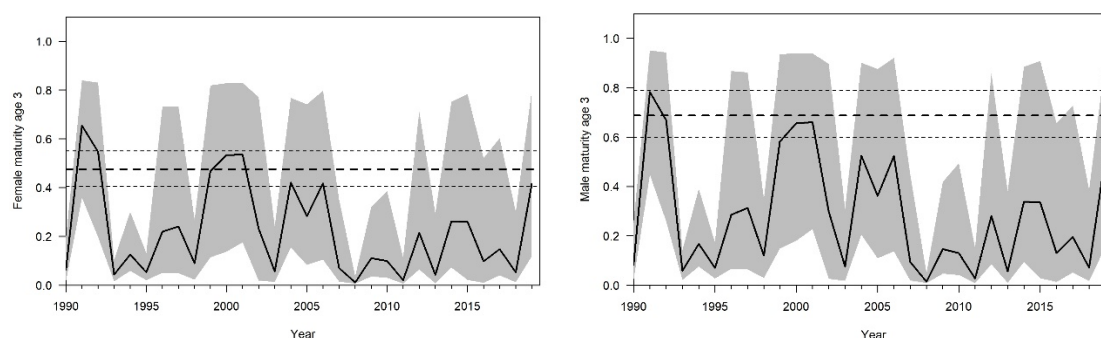
The biomass trajectories for both sensitivity runs (Figure 13 and Figure 14) showed very similar patterns to the base case. The key difference was in the stock status, but the differences were modest. Model Mfree estimated lower values of  $M$  than used in the model Base (0.20) at 0.16–0.17, and these were similar to those estimated in the 2017 assessment (0.17–0.18). Taking the annual adjustments and calculating the maturity rates for age 3 fish (Figure 15) shows wide CIs for half the estimates, generally for the high rates and the rates in the last eight years. Years with low maturity rates for age 3 fish (e.g., 1993 when the large 1991 cohort turned 3) generally had well determined rates. Figure 15 also shows the median and 95% CI for the model Base age 3 maturity rates (fixed at one level) and these do not appear to match the versions using annual adjustments, e.g., about 14 model Tvary estimates (out of 30) have 95% CIs that do not overlap with those for model Base. The formulation of annual adjustments will lower all maturation rates for ages 2 to 5, and, because at age 6 the rate is fixed to one, years with a large adjustment (i.e., reduction in rates) will have a step change in the rate from age 5 to 6, which seems implausible biologically. It might be better to re-parametrise annual adjustments by shifting the maturity “shape” to older ages. In CASAL, this currently can only be done by switching the maturity to a logistic curve.



**Figure 13: Mfree model: MCMC median and 95% credible intervals of the trajectory of (left) spawning stock biomass and (right) stock status ( $\%B_0$ ).**



**Figure 14: Tvary model: MCMC median and 95% credible intervals of the trajectory of (left) spawning stock biomass and (right) stock status ( $\%B_0$ ).**

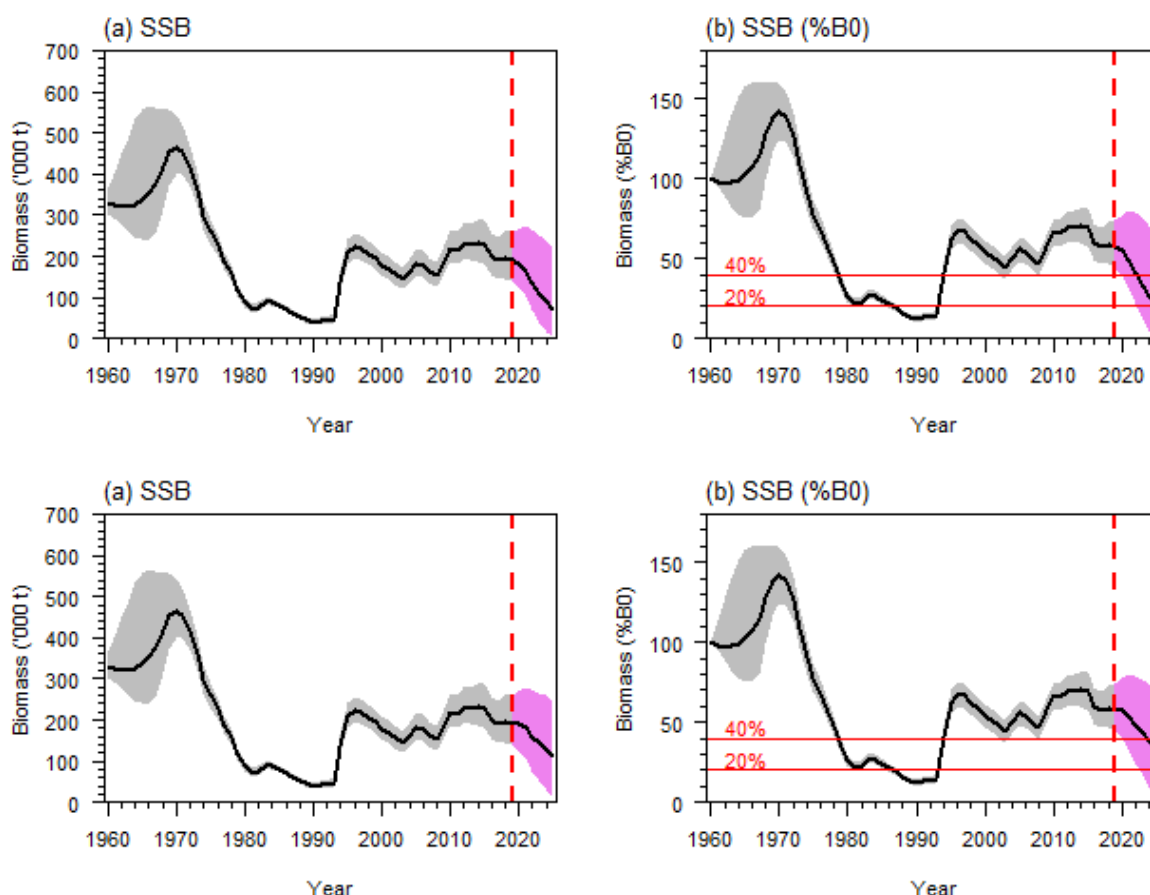


**Figure 15: Tvary model: MCMC median and 95% credible intervals of the maturity rate for age 3 fish, (left) female and (right) male. The thick dotted horizontal line is the model Base's median estimate and the thin dotted lines are the 95% credible intervals.**

### 3.3 Projections

Projections were made for model Base and the sensitivity models assuming fixed catch levels of 39 200 t (2019 TACC) for the years 2020 to 2025. Projections were made using the MCMC samples, with recruitments drawn randomly from the distribution of year class strengths as estimated for the period 1958–2016 and applied from 2017 onwards (in model runs, recruitments for 2017 and 2018 were ill-determined and that for 2019 was set to one). Because of the link between mean size at age of fish in the population and the population density, projections assumed that the mean size at age was the average over the 2014–2019 estimates, rather than return to the average size at age that might be expected at lower abundances. An alternative projection was run using the estimated year class strengths for the period 2007–2016 (i.e., the last 10 estimated YCS).

For model Base, another projection was made using a fixed catch of 21 100 t, the average catch over 2013–2019 (Figure 16). For model Tvary, the projected annual adjustments to maturity-by-age were drawn randomly from the estimated values for 2014–2019.



**Figure 16: MCMC posterior plots for the median (solid line) and 95% credible intervals for (a) spawning stock biomass and (b) stock status ( $\%B_0$ ) using a catch of 39 200 t for the base case assuming (top panels) average recruitment and (bottom panels) the last 10 estimated recruitments. Horizontal lines indicate 40% and 20%  $B_0$ , and the vertical dotted line represents the beginning of the projection period (2020–2025).**

For each scenario, the probability that the mid-season biomass for the specified year will be greater than or equal to 40%  $B_0$ , less than 10%  $B_0$ , and less than 20%  $B_0$  are given in Table 10, Table 11, and Table 12. For the Base model, the probability of being below 20%  $B_0$  at catch levels of 21 058 t was less than 7% for both recruitment distribution over all the years. The probability of dropping below the 20%  $B_0$  threshold biomass at catch levels of 39 200 t exceeded 10% by 2023–24 for all models, with the sensitivities exceeding 10% by 2020–21. Under both recruitment conditions, the biomass was expected to steadily decline under both catch scenarios in all model runs.

**Table 10: Base model: probability (%) that the projected mid-season spawning stock biomass for 2020–2025 will be greater than or equal to 40%  $B_0$ , less than 10%  $B_0$ , and less than 20%  $B_0$ , at a projected catch of 21 059 t and 39 200 t.**

|                                       | Fishing year |         |         |         |         |         |
|---------------------------------------|--------------|---------|---------|---------|---------|---------|
|                                       | 2019–20      | 2020–21 | 2021–22 | 2022–23 | 2023–24 | 2024–25 |
| <b>Catch 39 200 t + YCS 1958–2016</b> |              |         |         |         |         |         |
| Median SSB (% $B_0$ )                 | 55           | 49      | 40      | 33      | 26      | 20      |
| %[SSB $\geq$ 40 % $B_0$ ]             | 95           | 78      | 51      | 35      | 26      | 22      |
| %[SSB < 20 % $B_0$ ]                  | 0            | 0       | 3       | 18      | 37      | 49      |
| %[SSB < 10 % $B_0$ ]                  | 0            | 0       | 0       | 3       | 13      | 29      |
| <b>Catch 39 200 t + YCS 2007–2016</b> |              |         |         |         |         |         |
| Median SSB (% $B_0$ )                 | 57           | 54      | 48      | 43      | 38      | 35      |
| %[SSB $\geq$ 40 % $B_0$ ]             | 96           | 85      | 70      | 57      | 47      | 40      |
| %[SSB < 20 % $B_0$ ]                  | 0            | 0       | 2       | 8       | 16      | 24      |
| %[SSB < 10 % $B_0$ ]                  | 0            | 0       | 0       | 2       | 5       | 10      |
| <b>Catch 21 059 t + YCS 1958–2016</b> |              |         |         |         |         |         |
| Median SSB (% $B_0$ )                 | 55           | 51      | 48      | 45      | 43      | 41      |
| %[SSB $\geq$ 40 % $B_0$ ]             | 95           | 85      | 73      | 62      | 56      | 52      |
| %[SSB < 20 % $B_0$ ]                  | 0            | 0       | 0       | 1       | 4       | 7       |
| %[SSB < 10 % $B_0$ ]                  | 0            | 0       | 0       | 0       | 0       | 1       |
| <b>Catch 21 059 t + YCS 2007–2016</b> |              |         |         |         |         |         |
| Median SSB (% $B_0$ )                 | 57           | 57      | 56      | 55      | 55      | 55      |
| %[SSB $\geq$ 40 % $B_0$ ]             | 96           | 90      | 85      | 82      | 80      | 78      |
| %[SSB < 20 % $B_0$ ]                  | 0            | 0       | 0       | 1       | 2       | 2       |
| %[SSB < 10 % $B_0$ ]                  | 0            | 0       | 0       | 0       | 0       | 0       |

**Table 11: Mfree model: probability that the projected mid-season spawning stock biomass for 2020–2025 will be greater than or equal to 40%  $B_0$ , less than 10%  $B_0$ , and less than 20%  $B_0$ , at a projected catch of 39 200 t.**

|                                       | Fishing year |         |         |         |         |         |
|---------------------------------------|--------------|---------|---------|---------|---------|---------|
|                                       | 2019–20      | 2020–21 | 2021–22 | 2022–23 | 2023–24 | 2024–25 |
| <b>Catch 39 200 t + YCS 1958–2016</b> |              |         |         |         |         |         |
| Median SSB (% $B_0$ )                 | 38           | 33      | 26      | 19      | 12      | 6       |
| %[SSB $\geq$ 40 % $B_0$ ]             | 46           | 34      | 23      | 16      | 12      | 9       |
| %[SSB < 20 % $B_0$ ]                  | 2            | 13      | 35      | 53      | 65      | 73      |
| %[SSB < 10 % $B_0$ ]                  | 0            | 1       | 11      | 30      | 45      | 58      |
| <b>Catch 39 200 t + YCS 2007–2016</b> |              |         |         |         |         |         |
| Median SSB (% $B_0$ )                 | 39           | 34      | 26      | 19      | 12      | 6       |
| %[SSB $\geq$ 40 % $B_0$ ]             | 47           | 35      | 25      | 17      | 13      | 10      |
| %[SSB < 20 % $B_0$ ]                  | 2            | 12      | 34      | 52      | 65      | 74      |
| %[SSB < 10 % $B_0$ ]                  | 0            | 1       | 10      | 29      | 47      | 59      |

**Table 12: Tvary model: probability that the projected mid-season spawning stock biomass for 2020–2025 will be greater than or equal to 40%  $B_0$ , less than 10%  $B_0$ , and less than 20%  $B_0$ , at a projected catch of 39 200 t.**

|                                       | Fishing year |         |         |         |         |         |
|---------------------------------------|--------------|---------|---------|---------|---------|---------|
|                                       | 2019–20      | 2020–21 | 2021–22 | 2022–23 | 2023–24 | 2024–25 |
| <b>Catch 39 200 t + YCS 1958–2016</b> |              |         |         |         |         |         |
| Median SSB (% $B_0$ )                 | 42           | 38      | 32      | 26      | 20      | 14      |
| %[SSB $\geq$ 40 % $B_0$ ]             | 58           | 45      | 32      | 23      | 19      | 15      |
| %[SSB < 20 % $B_0$ ]                  | 1            | 5       | 22      | 38      | 51      | 61      |
| %[SSB < 10 % $B_0$ ]                  | 0            | 0       | 4       | 15      | 28      | 41      |
| <b>Catch 39 200 t + YCS 2007–2016</b> |              |         |         |         |         |         |
| Median SSB (% $B_0$ )                 | 42           | 38      | 31      | 25      | 20      | 15      |
| %[SSB $\geq$ 40 % $B_0$ ]             | 57           | 46      | 32      | 25      | 20      | 16      |
| %[SSB < 20 % $B_0$ ]                  | 0            | 5       | 21      | 39      | 50      | 60      |
| %[SSB < 10 % $B_0$ ]                  | 0            | 0       | 3       | 15      | 29      | 41      |

#### 4. DISCUSSION

The results of the base case assessment suggested that the spawning stock biomass of the Campbell Island Rise in 2019 was 190 000 t (95% CI 130 000–276 000 t), and it was at 58%  $B_0$  (95% CI 42–76%). Projections with an annual catch of 39 200 t (the current TACC) suggested that the spawning stock biomass is expected to decline steadily to 20% or 35%  $B_0$  by 2025 depending on whether future recruitment is drawn from the historical series or from just the last 10 estimates (2007 to 2016). Both model sensitivities give a more pessimistic prediction for SSB in 2025, down to 6%  $B_0$  for Mfree and down to 14 to 15%  $B_0$  for Tvary. However, if the future catch is maintained at about the average for the last six years, 21 000 t, then the Base model estimates that the SSB is at 41 % $B_0$  if recruitment follows the historical distribution, and at 55%  $B_0$  if recruitment is similar to the later period, 2007–2016.

The last strong year classes are for 2006, 2009, and 2011 and these are well determined. After 2011, there are two weak year classes (well determined), but after that they are poorly determined with 2014 and 2015 potentially being above average. The current assessment has revised down the 2006 and 2009 YCS from about 3.5 (2017 assessment) to 2.8 and this has affected the estimated SSB for 2016 (the 2017 assessment's final year) making it 60%  $B_0$  (CI 48–74%) for this assessment, down from 70%  $B_0$  (CI 54–86%) in the 2017 assessment. Overall, this assessment is more pessimistic than the 2017 assessment, but it still does not present any management concerns at the current catch levels.

#### 5. ACKNOWLEDGMENTS

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#### 6. REFERENCES

- Bull, B.; Dunn, A. (2002). Catch-at-age: User manual v1.06.2002/09/12. NIWA Internal Report 114. 23 p. National Institute of Water and Atmospheric Research. (Unpublished report held by NIWA library, Wellington.)
- Bull, B.; Francis, R.I.C.C.; Dunn, A.; McKenzie, A.; Gilbert, D.J.; Smith, M.H.; Bian, R.; Fu, D. (2012). CASAL (C++ algorithmic stock assessment laboratory): CASAL user manual v2.30-2012/03/21. *NIWA Technical Report 135*. 280 p.

- Dunn, A.; Hanchet, S.M. (2011). Southern blue whiting (*Micromesistius australis*) stock assessment for the Campbell Island Rise, 2009–10. *New Zealand Fisheries Assessment Report 2011/40*. 37 p.
- Dunn, A.; Hanchet, S.M. (2017). Southern blue whiting (*Micromesistius australis*) stock assessment for the Campbell Island Rise for 2016. *New Zealand Fisheries Assessment Report 2017/38*. 20 p.
- Francis, R.I.C.C. (2011). Data weighting in statistical fisheries stock assessment models. *Canadian Journal of Fisheries and Aquatic Sciences* 68: 1124–1138.
- Fu, D.; Hanchet, S.M.; O'Driscoll, R.L. (2013). Estimates of biomass and c.v.s of southern blue whiting from previous acoustic surveys from 1993 to 2012 using a new target strength – fish length relationship. Final Research Report to the Ministry of Fisheries. Project DEE201002SBWB. 52 p. (Unpublished report held by Fisheries New Zealand.)
- Gelman, A.B.; Carlin, J.S.; Stern, H.S.; Rubin, D.B. (1995). Bayesian data analysis. Chapman and Hall, London. 526 p.
- Gilks, W.R.; Richardson, S.; Spiegelhalter, D.J. (eds.) (1998). Markov chain Monte Carlo in practice. *Interdisciplinary statistics*. 399 p. Chapman and Hall/CRC Press, Boca Raton, Florida.
- Hanchet, S.M. (1991). Southern blue whiting (*Micromesistius australis*) fishery assessment for the 1991–92 fishing year. New Zealand Fisheries Assessment Research Document 91/7. 32 p. (Unpublished report held by NIWA library, Wellington.)
- Hanchet, S.M. (1998). Documentation of the separable Sequential Population Analysis used in the assessments of southern blue whiting, and a comparison with other models. New Zealand Fisheries Assessment Research Document 98/33. 22 p. (Unpublished report held by NIWA Library, Wellington.)
- Hanchet, S.M.; Blackwell, R.G.; Stevenson, M.L. (2006). Southern blue whiting (*Micromesistius australis*) stock assessment for the Campbell Island Rise for 2006. *New Zealand Fisheries Assessment Report 2006/41*. 45 p.
- Hanchet, S.M.; Haist, V.; Fournier, D. (1998). An integrated assessment of southern blue whiting (*Micromesistius australis*) from New Zealand waters using separable Sequential Population Analysis. In: *Fishery Stock Assessment Models*. Funk, F.; Quinn II, T.J.; Heifetz, J.; Ianelli, J.N.; Powers, J.E.; Schweigert, J.F.; Sullivan, P.J.; Zhang, C.-I. (eds.). University of Alaska Sea Grant AK-SG-98-01, Fairbanks, Alaska.
- Hanchet, S.M.; Ingerson, J.K.V. (1995). Southern blue whiting (*Micromesistius australis*) fishery assessment for the 1995–96 fishing year. *New Zealand Fisheries Assessment Research Document 95/20*. 37 p.
- Ladroit, Y.; O'Driscoll, R.L.; Large, K. (2020). Acoustic estimates of southern blue whiting from the Campbell Island Rise, August-September 2019 (TAN1905). *New Zealand Fisheries Assessment Report 2020/26*. 56 p.
- Large, K. (in press). Review and summary of the time series of input data available for the assessment of southern blue whiting (*Micromesistius australis*) stocks up to and including the 2019 season. Draft New Zealand Fisheries Assessment Report held by Fisheries New Zealand. 80 p.
- O'Driscoll, R.L.; Dunford, A.J.; Ladroit, Y. (2014). Acoustic estimates of southern blue whiting from the Campbell Island Rise, August-September 2013. *New Zealand Fisheries Assessment Report 2014/22*. 46 p.
- O'Driscoll, R.L.; Large, K.; Marriott, P. (2018). Acoustic estimates of southern blue whiting from the Campbell Island Rise, August-September 2016. *New Zealand Fisheries Assessment Report 2018/56*. 62 p.
- O'Driscoll, R.L.; Oeffner, J.; Dunford, A.J. (2013). In situ target strength estimates of optically verified southern blue whiting (*Micromesistius australis*). *ICES Journal of Marine Science* 70: 431–439.
- Roberts, J.; Doonan, I. (2016). Quantitative risk assessment of threats to New Zealand sea lions. *New Zealand Aquatic Environment and Biodiversity Report No. 166*. 111 p.
- Roberts, J.; Dunn, A. (2017). Investigation of alternative model structures for the estimation of natural mortality in the Campbell Island Rise southern blue whiting (*Micromesistius australis*) stock assessment (SBW 6I). *New Zealand Fisheries Assessment Report 2017/26*. 14 p.
- Roberts, J.; Hanchet, S.M. (2019). Southern blue whiting (*Micromesistius australis*) stock assessment for the Campbell Island Rise for 2017. *New Zealand Fisheries Assessment Report 2019/44*. 21 p.