



## A review of the hoki stock assessment in 2018

New Zealand Fisheries Assessment Report 2018/42.

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## EXECUTIVE SUMMARY

**Dunn, M.R.; Langley, A. (2018). A review of the hoki stock assessment for 2018.**

*New Zealand Fisheries Assessment Report 2018/42. 55 p.*

The New Zealand hoki stock assessment was independently reviewed, with a focus on evaluating the assumptions and observational data sets that were determining the estimates of stock size and status. The review was conducted in the first half of 2018.

The review described the assumed model structure, likelihood profiles, and aspects of the assumptions concerning recruitment, natural mortality rates, growth, maturity, retrospective patterns, year class strength estimation (priors), and stock-recruitment steepness, including conducting sensitivity runs in the CASAL software using the 2017 assessment base model.

The review then split the base assessment model, which assumed two inter-related stocks, into two individual stock assessments. This was done using the Stock Synthesis software, and was intended to provide further clarity in model assumptions and influence of the data by removing the complex two-stock inter-relationships.

The most informative observational data sets are known to be the catch-at-age estimates, which suggest a larger stock, and the SubAntarctic trawl survey, which suggests a smaller stock. The prior assumptions (Bayesian priors) were also important in determining stock size and status. Overall, the stock assessment model estimates of stock size and status seemed to be robust to many changes in model assumptions.

Conclusions and recommendations for further work arising from the review are presented. Briefly, these are: to conduct retrospective analyses; move the assessment from CASAL to CASAL2; remove where possible any confounding in the selectivity-migration-YCS-M assumptions; conduct further research into the assumed catchability change in the SubAntarctic; partition the age compositions into separate age blocks; conduct likelihood profiles for the various priors; further evaluate the estimation of the pE (proportion of biomass in the eastern stock) parameter; investigate sources of variation in the age composition data; further investigate CPUE trends; and report vulnerable biomass from the model; revise the biological assumptions, including deriving sensitivity runs; and further review catch history.

## 1. INTRODUCTION

Hoki (*Macruronus novaezelandiae*) is an important fisheries resource in New Zealand, and has been the focus of much scientific research and regular stock assessments. The assumptions, data, and population models used in hoki stock assessment are summarised by Ministry for Primary Industries (2017).

In 2017–18, there was a degree of concern from some sectors of the commercial fishing industry that the most recent hoki stock assessment was not providing results that were consistent with the performance of the commercial fishery, especially off the west coast South Island (WCSI). The complexity of the hoki assessment model means that it is difficult to easily evaluate the influence of key model assumptions and data sets to determine the components of the model that are most influential in the estimation of current stock status (Butterworth et al., 2014). The following review was contracted in 2018 to provide a brief summary and review of the model and data inputs. The overall objective of the project was:

- (1) To carry out a review of the hoki stock assessment model.

And the specific objectives were:

- (1) To document and review the assumptions of the 2017 hoki stock assessment model.
- (2) To compare whether the model expected values reflect the stock status indicated by the observations that describe changes in abundance.
- (3) To recommend, and conduct where possible, analyses to evaluate assumptions.

The first part of this report focuses on documenting and reviewing the assessment model currently used (Specific Objective 1), and evaluating whether the model estimates seem consistent with the observations (Specific Objective 2). This part includes some investigative model runs (Specific Objective 3).

The second part of the report attempts to simplify the assessment and provide a clearer understanding of the assessment data and assumptions, by splitting the assessment into two discrete stocks. This reduces the complexity of the model (the selectivity – migration - year class strength inter-relationships in particular) and conducts model runs to provide further insight into observations and model estimates (Specific Objectives 1-3).

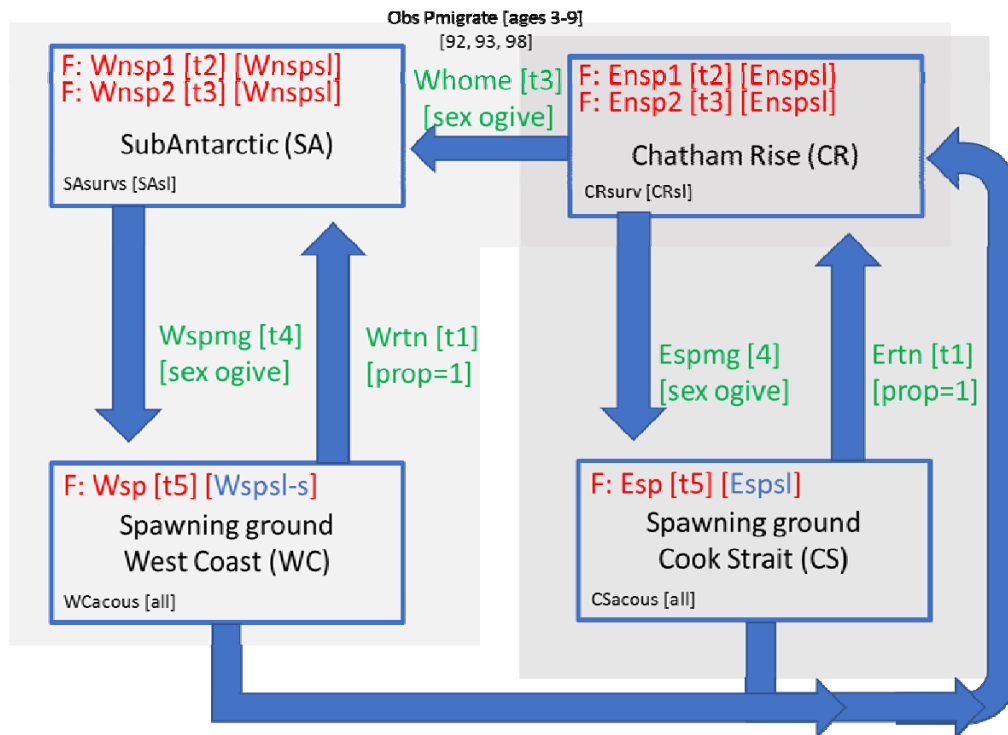
The final part of the report presents recommendations (Specific Objective 3).

The authors of this report did not have sufficient time to conduct a thorough review of all the substantial published reports associated with this stock assessment (although we thank Andy McKenzie, NIWA, for providing much of this). This means some issues may already be known to the assessment scientists and Fisheries Assessment Working Group concerned. However, this approach did also mean that the review was unbiased by previous findings.

## 2. INVESTIGATIONS WITH THE CASAL MODEL

### An overview of the model structure and assumptions

A schematic of the basic model structure and assumptions is shown in Figure 1. Full details of the model are described by McKenzie (2018), and the labels for model components and processes are as described in that report.



**Figure 1: Schematic of the hoki assessment model showing key attributes.** Areas are shown as the blue boxes (area in the partition). All selectivities are labelled E or W, and show in brackets the timestep and ogive assumed. The -s for  $W_{spsl}$  means the selectivity is shifted according to the median day of the fishery. All ogives are size based and applied to males and females (although this may result in different ogives by age for each sex). Red = double normal; blue = logistic. All migrations (other than  $prop=1$ ) are allvalues\_bounded (free ages 1-8) and are separate for males and females. All fish migrating to spawning grounds are considered mature (migration ogive = maturity; maturity isn't in the partition). All migrating fish spawn. Biomass observations shown in small font in the area boxes. Chatham Rise and SubAntarctic surveys have their own double normal selectivities. Observations of migrations shown in small font next to relevant migration. There are numerous catch-at-age observations. Acoustic surveys measure all fish (i.e., selectivity is the migration ogive). There are penalties to make the spawning migrations at age for E and W similar.

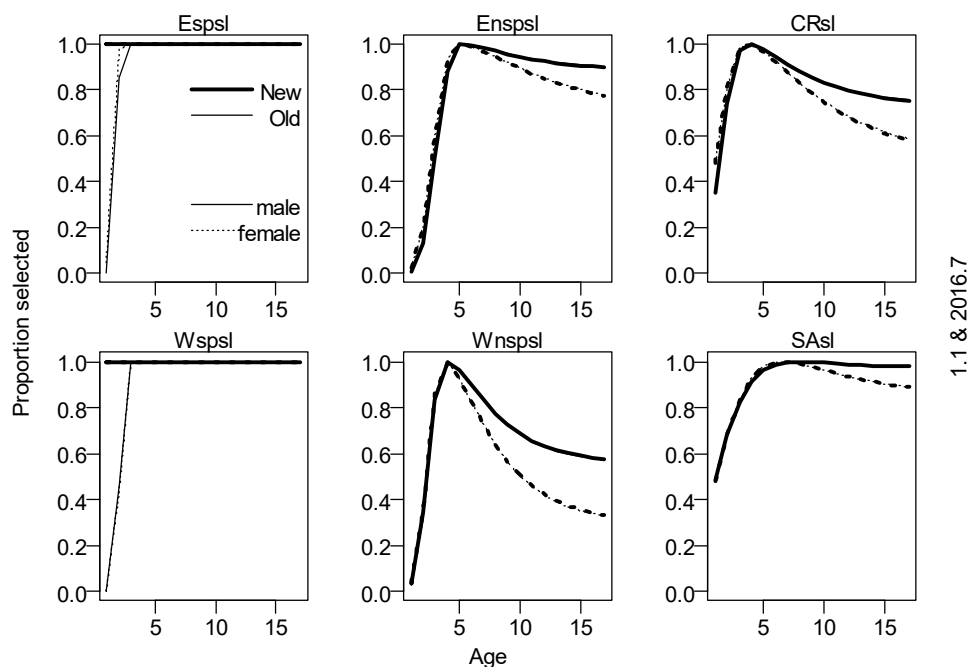
The version of CASAL currently used for the assessment (*casalMpriorv230*) is modified from the released version of CASAL (Bull et al., 2012), in that it is hard-coded to have a prior on  $M$ -at-age for ages 5-9 (lognormal with mean 0.18 and 50% CV; Cordue, 2006); the  $M$  of 0.18 is substantially lower than the *a priori*  $M$  estimates reported in MPI (2017) of 0.25 for females and 0.3 for males. The prior was based on a "best guess" for survival (0.85 for the age group 5-9 years).

The model (Figure 1) allows for an assumption that the spawning fisheries potentially do not select all the spawning fish (the  $W_{spsl}$  and  $E_{spsl}$  are fixed to be the same, and applied to the fisheries; whereas the acoustic surveys measure all migrating fish, as determined by  $W_{spmg}$  and  $E_{spmg}$ ). This assumption would seem to allow potential confounding. Prior to the 2017 assessment, the model estimated a logistic selectivity with full selectivity at about age four; the 2017 assessment estimated a flat ogive (Figure 2).

The 2018 assessment again estimated a logistic ogive (A.McKenzie, NIWA, pers.comm.). The selectivity ogive was therefore estimated to be redundant in the 2017 assessment, and was potentially confounded in other assessments.

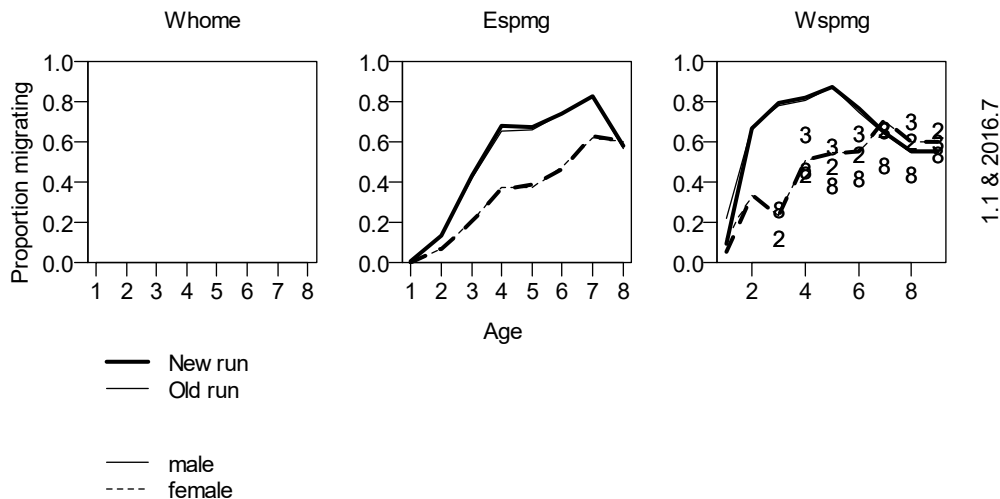
Figure 3 shows proportion migrating to spawn, which is asymptotic or domed across the free ages; it is assumed to be equal to one for ages 9 and above. The eastern non-spawning fishery, and the Chatham Rise survey, also have domed selectivities (Figure 2). The right-hand limb of these would seem to be confounded, to some extent, with the Whome migration ogive.

The model estimates that not all fish go to spawn each year (Figure 3). The combination of the spawning migration ogives, and the logistic spawning fishery ogives, would seem to yield (to eye) an overall logistic-capped or domed selectivity ogive across the free ages (ages 1-8), where the dome is more pronounced on the west coast (similar to the non-spawning fishery). The model assumes that the absence of intermediate-age fish in the spawning fishery is caused by relatively low migration rates, but could be interpreted equally as relatively low availability. Whether this is plausible is unclear.



**Figure 2: Estimated selectivities from McKenzie (2018):** Estimated selectivity curves for the new model run 1.1 from new 2017 (heavy lines) and analogous model run from the previous assessment (light lines). Males are shown by a solid line, females by a dotted line. The label 2016.7 denotes run 1.7 for the 2016 assessment.





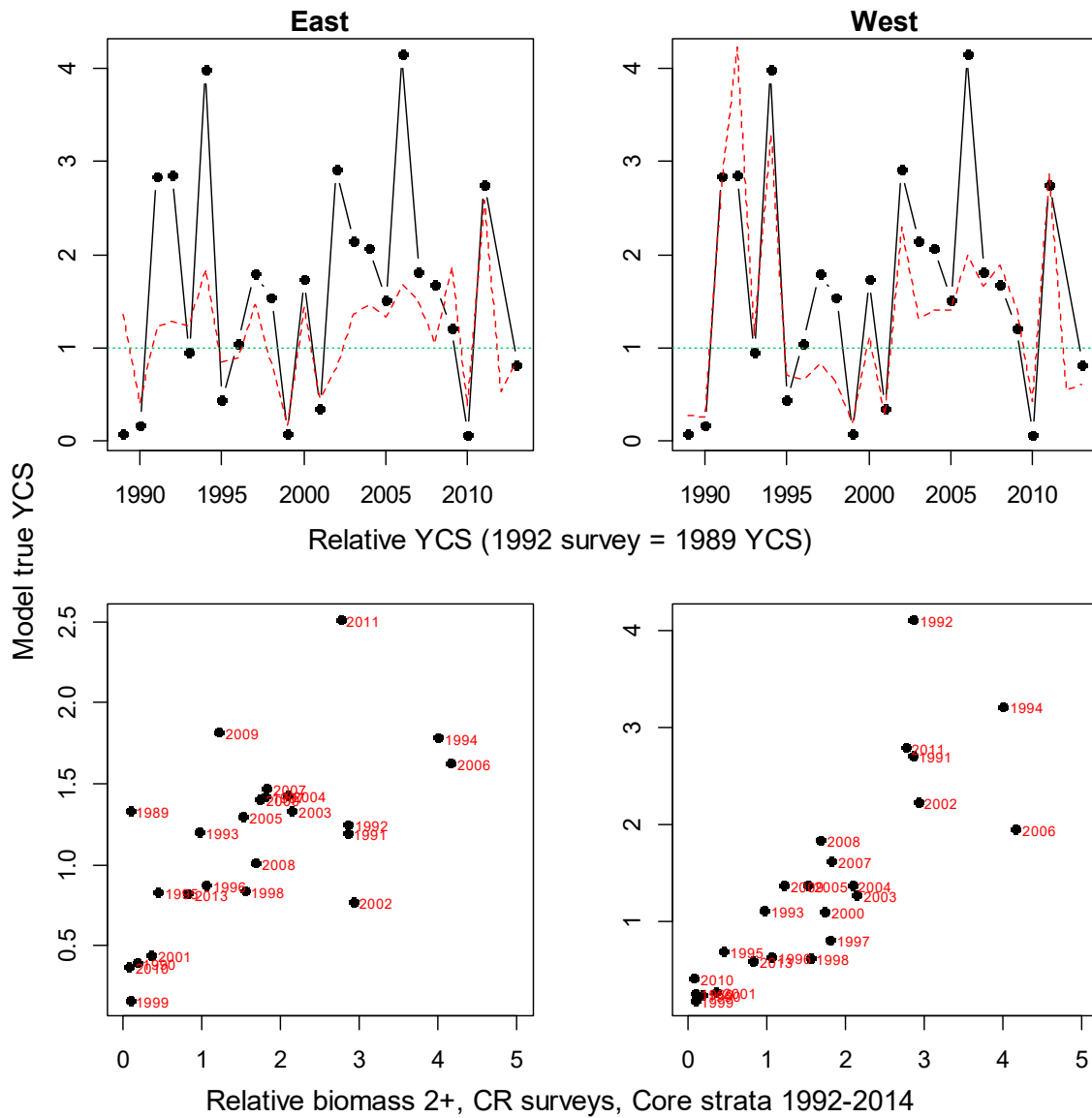
**Figure 3: Estimated migration ogives from McKenzie (2018):** Estimated migration ogives for new run 1.1 from 2017 (heavy lines) and the analogous model run from the previous assessment (light lines). Each row of plots compares ogives from the new run (heavy lines) with that from the previous assessment (light lines). Where ogives differ by sex, female ogives are plotted as broken lines. The observations pspawn are also plotted in the rightmost panel, with the plotting symbol identifying the year of sampling ('2' = 1992, '3' = 1993, '8' = 1998). The label 2016.7 denotes run 1.7 for the 2016 assessment.

### Recruitment and the Chatham Rise trawl survey

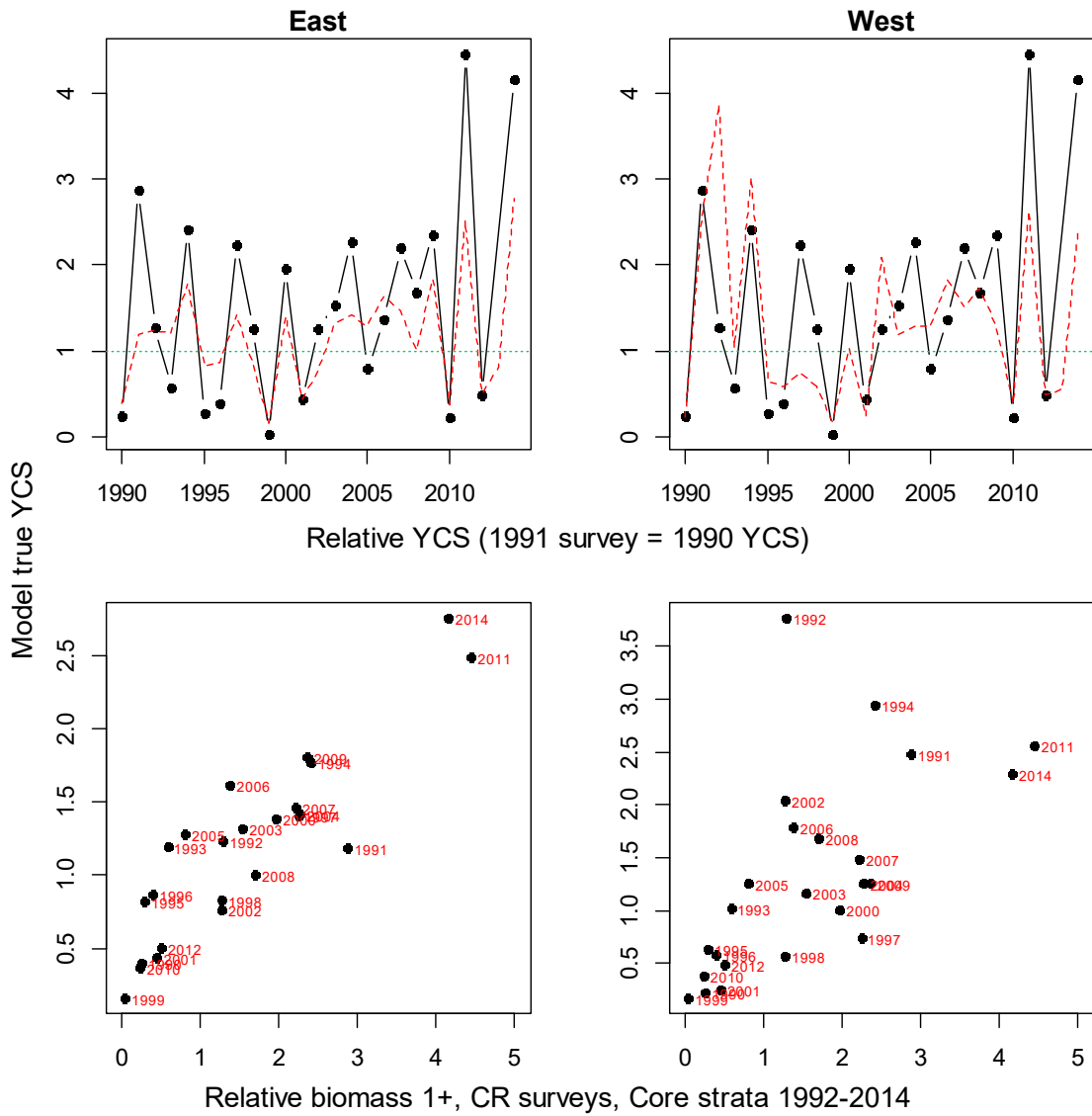
The trawl survey of Chatham Rise (and to a lesser extent the SubAntarctic) is intended to provide an index of pre-recruit and newly-recruiting fish, but it has been anecdotally suggested that the survey estimates of year class strength (YCS) and the model estimates may not be equivalent. In general, the YCS estimated by the model vary less than the survey estimated YCS (Figure 4). The period of relatively low recruitment estimated for the western stock during the late 1990s was not as strongly reflected in the survey YCS. Also, the 2006 YCS was estimated to be the largest observed in the survey, but was not particularly strong in the model.

The YCS estimated from the survey at age 2+ had a greater correlation to YCS for the western stock than the eastern stock (Figure 4). The Chatham Rise survey at age 2+ was visually better correlated with recruitment for the western stock than at survey age 1+. At age 1+ the reverse was true (Figure 5), with the survey YCS being (slightly) better correlated for the eastern than western stock. Nevertheless, the relative YCS for age 2+ observed in the survey on Chatham Rise would seem to be fairly well maintained into the western stock. The correlation between year class strengths estimated at ages 1+ and 2+ on the survey was not visually strong and, presumably because of the catch, migration and selectivity assumptions, the model estimates slightly different YCS patterns for each stock.

The correlation between 1+ and 2+ appears to be potentially non-linear and perhaps asymptotic (Figure 6), which could imply density-dependent mortality or migration rates (for 1+ YCS above about 15, the large YCS at age 1+ do not appear as large at 2+).



**Figure 4: Hoki recruitment estimates. Top panel – Comparison of the Chatham Rise research trawl survey estimates of year class strength (YCS) as age 2+ (points), and the estimates of YCS for the same cohort from the base model (red broken line); green line marks the time series geometric mean (1). Bottom panel – Correlation between YCS estimates from the survey and the model, labelled by model YCS (age 0+).**



**Figure 5: Hoki recruitment estimates. Top panel – Comparison of the Chatham Rise research trawl survey estimates of year class strength (YCS) as age 1+ (points), and the estimates of YCS for the same cohort from the base model (red broken line); green line marks the time series geometric mean (1). Bottom panel – Correlation between YCS estimates from the survey and the model, labelled by model YCS (age 0+).**

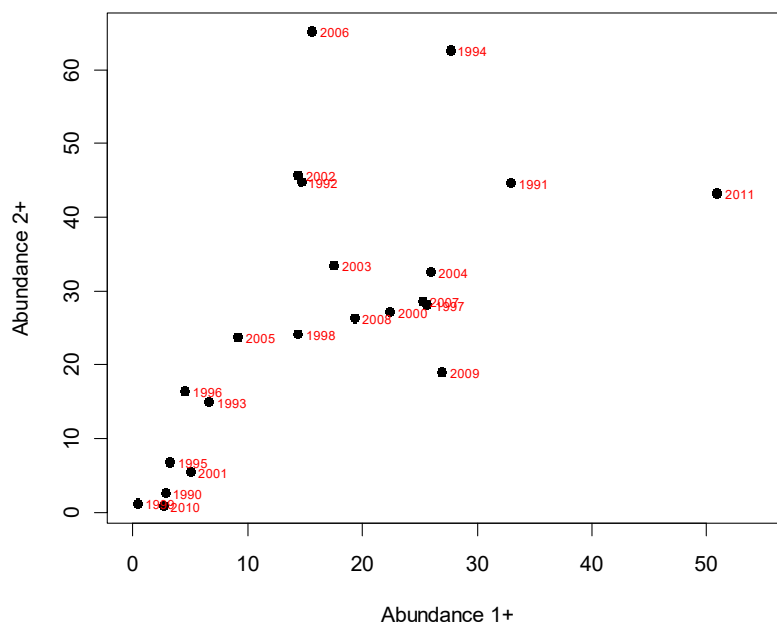


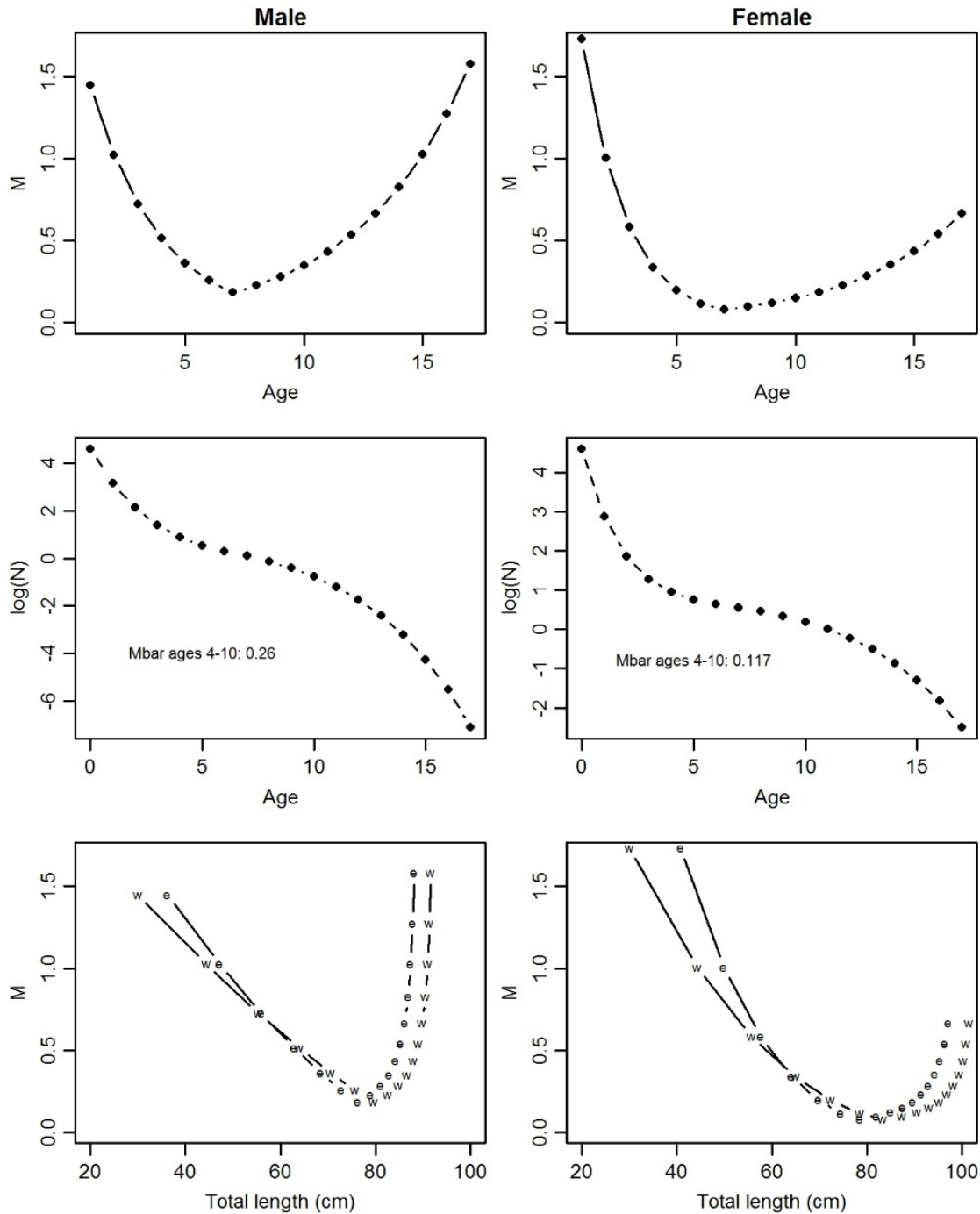
Figure 6: Chatham Rise trawl survey biomass estimates at age 1+ and 2+, labelled by year class.

### The natural mortality assumption

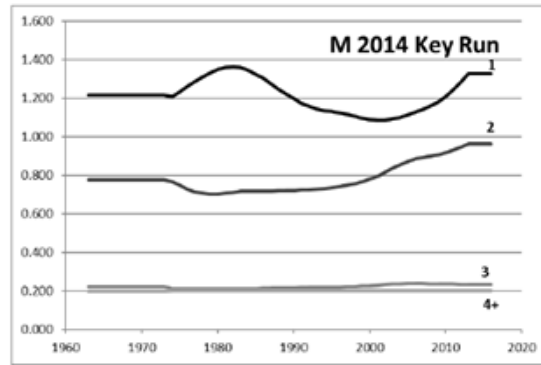
The assessment base model estimates  $M$ -at-age for males and females. A sensitivity run for this has been conducted, where  $M$  is estimated but is constant at age. In this sensitivity run, the spawning fishery selectivities are allowed to be domed (therefore all selectivities are domed), the sexes are combined, and the selectivities are age rather than length-based; presumably the latter changes were made because otherwise the model run is problematic (see Table 3).

The assessment base model assumes a double exponential natural mortality rate, which is estimated separately for each sex (Figure 7), but not stock, although growth is different for each stock (see next section). The double exponential assumption has also been used in ling and hake assessments, but the U-shape is more pronounced in hoki, varying from about 1.5, to 0.1, to 1.5. The effect of this ogive is more dramatic when presented at-length.

The assumption of U-shaped mortality is unusual in stock assessment models, although age- and year-specific  $M$  is used in other models, e.g., North Sea cod. For North Sea cod,  $M$  has been estimated to be relatively high and more variable over time for young ages, and then lower and more stable for older ages (Figure 8); there is no indication of an increase in  $M$  at older ages (but  $F$  has been high and the fish do not live very long). Such results suggest that the left-hand limb of the hoki  $M$ -at-age may be plausible, but do not allow much comment on the right-hand limb. A likelihood profile for  $M$  would be useful, and for the specific parameters ( $y_2$  in particular).



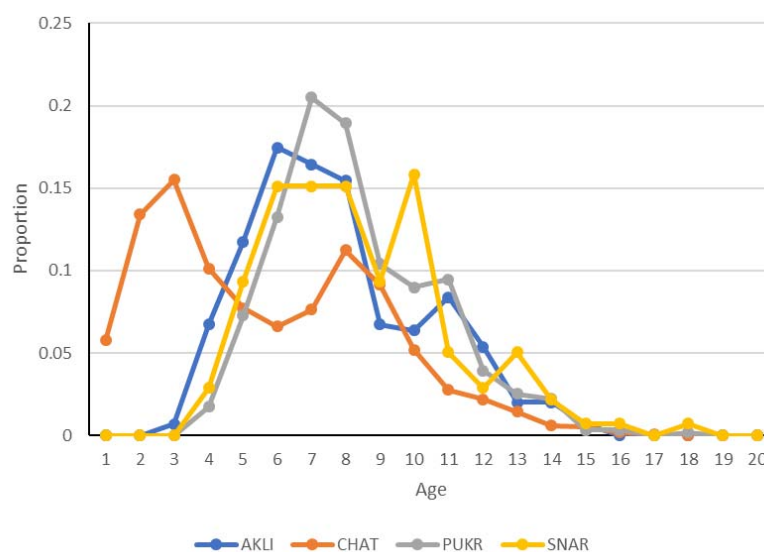
**Figure 7: Hoki base model 2017: top panel, natural mortality rate at age estimated by the model (double exponential parameterisation); middle panel, the log of the percentage surviving at age following the  $M$  model, with the mean  $M$  over the ages 4-10; bottom panel, the natural mortality rate at length. Shown for males (left panels), and females (right panels). In the bottom panels, the  $M$  model is the same but the growth model differs for each stock; e, eastern stock; w, western stock.**



**Figure 8:** *M*-at-age and by year for North Sea cod. *M* is estimated from diet data via a multispecies model. Taken from ICES (2017); Cod in subarea 4; Divisions 7.d and Subdivision 20: Smoother, annually varying natural mortality from the 2014 key run (ICES WGSAM 2014). Values for 1963–72 are set equal to the 1973 value, while 2014–2016 are set equal to 2013.

The mean productivity across the ages forming the bulk of the spawning stock biomass (SSB) is twice as high for males as females, and females is lower than would be anticipated (Figure 7). The mean *M* across ages 4 to 10 for males was 0.26, and females 0.12, compared with *M* estimates *a priori* of 0.3 and 0.25 respectively (MPI 2017). At an *M* of 0.12, about 5% of the population would live to age 25; in the age samples, ages beyond 15 have been rare (e.g., Tables 1 and 2; catch-at-age for other fisheries was examined but is not reproduced here). The concern is not the longevity, however, rather the influence this assumption is having on the interpretation of total mortality from the catch-at-age observations.

Samples from 1983–6 (these are not in the model) are consistent with maximum longevity of around 15 years (Figure 9). The data do not suggest a dramatically different mortality rate in recent years compared to the early 1980s; fish up to age 12 are still clearly present in 2016 (Tables 1 and 2). Ages 1–3 are virtually absent from the SubAntarctic in the 1983–86 samples. The current model migration and selectivity estimates would assume them to be present, and they have been caught in the fishery, and were in fact predominant in some years in the late 2000s (Tables 1 and 2). This could suggest a shift in either availability, or migration rates (potentially maturation rates), of the younger cohorts between the 1980s and early 1990s, to the period after the mid-1990s.



**Figure 9:** Catch-weight age composition for hoki by region from samples on the SHI8301, SHI8302, SHI8303, and SHI8602 surveys.

**Table 1: Proportion of hoki at age for the eastern spawning fishery by sex (from CASAL input files). Shading proportional to proportion.**

EspAge M	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1988	0.00058	0.012458	0.049858	0.05121	0.028342	0.039184	0.028248	0.04186	0.037599	0.027803	0.016132	0.004854	0.004208	1.00E-04
1989	0.001804	0.050402	0.092955	0.074027	0.077042	0.030504	0.016056	0.017981	0.021964	0.033262	0.016183	0.017602	0.005045	1.00E-04
1990	0.001393	0.049083	0.096735	0.074735	0.085562	0.049249	0.021972	0.041834	0.01273	0.041236	0.038973	0.018174	0.001671	0.001289
1991	0.000113	0.050722	0.189332	0.107508	0.040049	0.043903	0.037377	0.014403	0.010514	0.008116	0.010468	0.013116	1.00E-04	0.004916
1992	0.00076	0.015987	0.094824	0.151854	0.023598	0.039854	0.048703	0.020388	0.012955	0.010803	0.004861	0.006724	0.002687	0.005152
1993	0.000528	0.023871	0.094584	0.206157	0.102843	0.014964	0.021136	0.026308	0.010101	0.005862	0.003284	0.002921	0.001699	0.0034
1994	0.000833	0.014024	0.037223	0.12786	0.130735	0.147158	0.011504	0.024432	0.009298	0.006726	0.00107	0.008652	1.00E-04	0.002109
1995	0.001183	0.026091	0.06063	0.046945	0.065035	0.136931	0.093043	0.009649	0.013003	0.010369	0.007801	0.001832	0.001427	0.001375
1996	0.004271	0.062924	0.107733	0.068569	0.01561	0.070531	0.081682	0.045823	0.003201	0.00605	0.001342	0.000359	0.001845	0.00042
1997	0.000375	0.047552	0.105519	0.111988	0.105	0.014367	0.04458	0.0481	0.028872	0.00437	0.005305	0.001727	0.00179	0.000318
1998	0.00234	0.125526	0.102843	0.101736	0.030964	0.026826	0.009024	0.028042	0.019162	0.012931	0.001423	0.003933	0.000697	0.000582
1999	0.008026	0.067967	0.163868	0.090711	0.065421	0.03257	0.019448	0.008052	0.012477	0.016274	0.006456	0.005037	0.001022	0.001114
2000	0.005601	0.100513	0.078224	0.048882	0.122492	0.069522	0.046208	0.016578	0.014292	0.011468	0.003884	0.002124	0.000441	0.00064
2001	0.000611	0.060511	0.123968	0.075423	0.041149	0.049995	0.036348	0.020751	0.007403	0.001369	0.003263	0.000882	1.00E-04	0.00052
2002	0.011744	0.013705	0.06026	0.089888	0.114274	0.046541	0.04752	0.02852	0.014238	0.010831	0.000445	0.001039	0.001866	0.00157
2003	0.007558	0.12682	0.019238	0.067798	0.062578	0.056047	0.0188	0.036885	0.010429	0.003556	0.001583	0.001195	0.000878	1.00E-04
2004	0.008891	0.05935	0.188539	0.036313	0.048938	0.031662	0.016493	0.006512	0.007459	0.003323	0.002776	0.001283	0.000352	0.000207
2005	0.007817	0.04325	0.100924	0.144372	0.015103	0.031867	0.033764	0.019777	0.005289	0.007214	0.002532	0.001455	1.00E-04	0.000374
2006	0.043106	0.23512	0.143325	0.052771	0.032816	0.010795	0.009719	0.011101	0.005948	0.001391	0.004183	0.000205	0.000937	1.00E-04
2007	0.015646	0.189952	0.159305	0.09568	0.052611	0.040552	0.006054	0.014392	0.014275	0.005046	1.00E-04	0.002319	0.001079	0.000329
2008	0.008492	0.156908	0.178288	0.149996	0.042889	0.023771	0.019467	0.005001	0.004148	0.003734	0.003024	0.000255	0.002778	0.001249
2009	0.018063	0.148582	0.171679	0.101159	0.063101	0.017477	0.011731	0.008623	0.00083	0.002422	0.00068	0.000856	1.00E-04	0.00023
2010	0.004613	0.135453	0.146395	0.091919	0.044876	0.032086	0.023243	0.003282	0.001825	0.000879	0.000795	0.000812	1.00E-04	0.000279
2011	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2012	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2013	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2014	0.002279	0.098186	0.056666	0.172585	0.076035	0.0794	0.074104	0.03165	0.020639	0.008978	0.002509	0.001644	0.002818	0.000426
2015	0.00355	0.039187	0.251217	0.052767	0.065556	0.039974	0.034867	0.029703	0.024076	0.007607	0.003716	1.00E-04	0.001397	0.002411
2016	0.018229	0.058268	0.074981	0.209534	0.042204	0.057808	0.035677	0.03461	0.026364	0.011324	0.005296	6.00E-04	1.00E-04	0.000778
2017	-	-	-	-	-	-	-	-	-	-	-	-	-	-
EspAge F														
1988	0.001095	0.010803	0.054666	0.066632	0.03636	0.069579	0.050721	0.106285	0.106829	0.082452	0.042592	0.023255	0.005915	0.00038
1989	0.000819	0.021754	0.045046	0.080879	0.051946	0.02505	0.040653	0.039928	0.08806	0.081058	0.037839	0.018111	0.005276	0.008655
1990	1.00E-04	0.011923	0.033216	0.047972	0.054553	0.044659	0.026882	0.040717	0.028523	0.068665	0.054742	0.021188	0.018113	0.014112
1991	1.00E-04	0.031047	0.07945	0.034329	0.036029	0.053428	0.059389	0.023868	0.036542	0.016857	0.041138	0.037935	0.004151	0.015099
1992	0.000172	0.000806	0.072346	0.173124	0.02559	0.041234	0.066329	0.03881	0.032035	0.023755	0.02389	0.026538	0.026597	0.009624
1993	1.00E-04	0.005326	0.050088	0.152876	0.085654	0.014818	0.046598	0.037925	0.017316	0.012753	0.014133	0.012011	0.010422	0.024322
1994	0.000638	0.012168	0.022286	0.089368	0.101763	0.120992	0.015779	0.037325	0.026211	0.020506	0.010574	0.002056	0.004407	0.014204
1995	0.000722	0.012406	0.033685	0.029969	0.051139	0.097501	0.121582	0.022751	0.056298	0.030274	0.016762	0.019241	0.009892	0.022465
1996	0.001603	0.023591	0.051751	0.040331	0.01665	0.059343	0.111846	0.117577	0.014072	0.038051	0.021103	0.018255	0.00318	0.012288
1997	0.00051	0.028959	0.086386	0.059054	0.065336	0.015436	0.044441	0.058238	0.060451	0.014529	0.020708	0.010465	0.008589	0.007035
1998	0.000417	0.040294	0.065874	0.069109	0.036989	0.051644	0.020546	0.07215	0.084022	0.043374	0.00976	0.025737	0.003776	0.01028
1999	0.002763	0.04002	0.07661	0.076158	0.053438	0.043021	0.034795	0.022098	0.040384	0.043204	0.038647	0.007107	0.004627	0.018687
2000	0.000909	0.073188	0.045646	0.033154	0.098225	0.056995	0.033147	0.026615	0.014939	0.041901	0.019855	0.018071	0.001572	0.014914
2001	0.001904	0.045205	0.084059	0.054629	0.05326	0.089781	0.089536	0.047469	0.032861	0.025071	0.025006	0.015095	0.008973	0.004857
2002	0.003627	0.004061	0.037127	0.066454	0.095704	0.09051	0.079004	0.057538	0.041704	0.024326	0.018768	0.01821	0.01333	0.007197
2003	0.00388	0.098047	0.018355	0.042309	0.106877	0.080179	0.060566	0.061741	0.044935	0.028866	0.010221	0.005412	0.01054	0.014608
2004	0.003254	0.021554	0.132225	0.056608	0.066768	0.059574	0.072914	0.033996	0.045311	0.026434	0.031711	0.018799	0.003035	0.015717
2005	0.002832	0.018424	0.053851	0.139639	0.024251	0.065604	0.098893	0.041527	0.010534	0.058868	0.015549	0.020747	0.020249	0.016876
2006	0.004641	0.105041	0.078236	0.039315	0.045757	0.025859	0.041906	0.030696	0.022015	0.014619	0.016946	0.0087	0.005649	0.009104
2007	0.004109	0.040123	0.05193	0.053921	0.029716	0.048804	0.012613	0.037689	0.032799	0.032545	0.009404	0.02062	0.005606	0.022784
2008	0.001827	0.059054	0.076093	0.081357	0.034684	0.027511	0.040212	0.009427	0.016417	0.017367	0.010609	0.002289	0.011274	0.011881
2009	0.001162	0.035389	0.061161	0.089778	0.077254	0.041257	0.040626	0.044228	0.014805	0.01811	0.014194	0.006849	0.003335	0.00632
2010	0.003212	0.078806	0.069873	0.078712	0.064651	0.081934	0.050217	0.027132	0.023948	0.007124	0.009856	0.001624	0.007027	0.00933
2011	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2012	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2013	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2014	0.000403	0.042965	0.013236	0.08048	0.023176	0.052863	0.035062	0.044846	0.027618	0.027453	0.009524	0.00372	0.007313	0.003422
2015	0.003076	0.020775	0.106659	0.028693	0.047316	0.030905	0.04976	0.063214	0.040469	0.021244	0.022558	0.003582	0.001195	0.004428
2016	0.006921	0.022558	0.019433	0.074223	0.034353	0.048733	0.048954	0.053749	0.048582	0.027216	0.021435	0.010041	0.005859	0.002171
2017	-	-	-	-	-	-	-	-	-	-	-	-	-	-



**Table 2: Proportion of hoki at age by sex for the western spawning fishery (from CASAL input files). Shading proportional to proportion.**

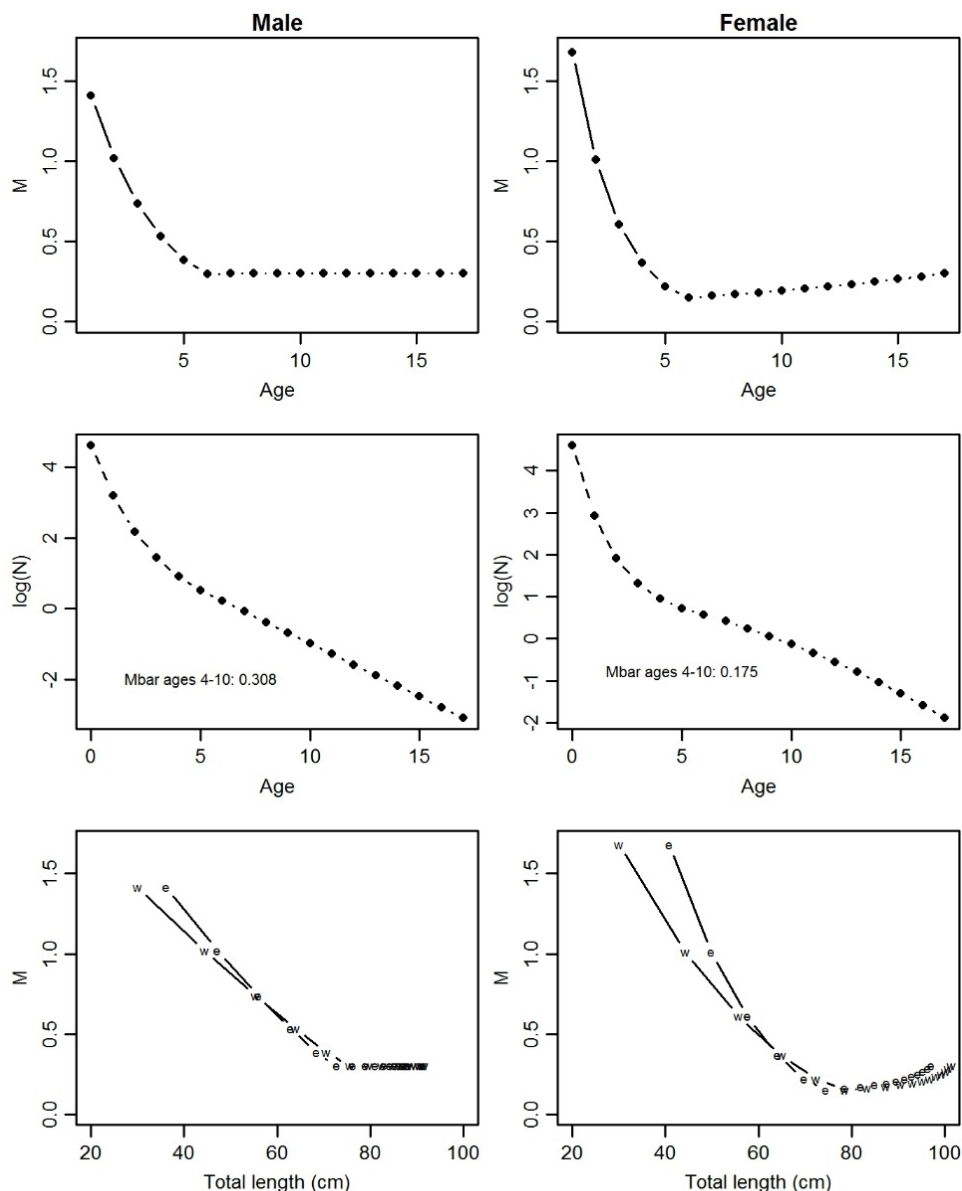
WspAge M	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1988	0.001678	0.000486	0.041035	0.059667	0.083078	0.078727	0.050162	0.031998	0.033543	0.037817	0.043432	0.007387	0.004809	0.002862
1989	0.004261	0.002274	0.007714	0.075326	0.161215	0.068788	0.058877	0.038084	0.013478	0.023282	0.020031	0.014631	0.003039	0.001197
1990	0.000602	0.023864	0.010238	0.031759	0.080917	0.135357	0.045159	0.040147	0.01158	0.023903	0.02016	0.004754	0.007706	1.00E-04
1991	0.000133	0.023372	0.12695	0.02363	0.037645	0.06989	0.067336	0.027146	0.012433	0.00888	0.003143	0.004564	0.003694	1.00E-04
1992	0.001524	0.002761	0.05281	0.18574	0.01313	0.033746	0.056364	0.033559	0.011527	0.013975	0.002086	0.002359	0.000835	0.001368
1993	0.023612	0.001135	0.01495	0.129905	0.224032	0.027425	0.014456	0.018543	0.027046	0.006968	0.00553	0.000926	0.000418	1.00E-04
1994	0.047487	0.084928	0.004795	0.032728	0.079989	0.143038	0.02568	0.015205	0.010765	0.012977	0.002824	0.000655	0.000104	0.000889
1995	0.040673	0.108374	0.150441	0.016012	0.019287	0.062947	0.058005	0.008375	0.005693	0.011928	0.010456	0.000685	0.001002	0.000982
1996	0.020741	0.064102	0.245458	0.105144	0.015061	0.018398	0.023362	0.027987	0.009792	0.007347	0.002576	0.00389	0.000642	0.00172
1997	0.014527	0.097765	0.135609	0.156738	0.061953	0.013549	0.015037	0.016748	0.009364	0.002937	0.000827	0.000623	0.000482	1.00E-04
1998	0.007448	0.057872	0.126688	0.090672	0.110297	0.057899	0.007051	0.014169	0.019951	0.009207	0.00049	1.00E-04	0.001009	0.001562
1999	0.012212	0.061273	0.081571	0.109703	0.075858	0.085778	0.040474	0.00999	0.004724	0.002905	0.005267	0.001895	0.000251	0.002172
2000	0.000874	0.026126	0.069916	0.048788	0.094755	0.052042	0.063962	0.027456	0.004252	0.004915	0.002371	0.002236	1.00E-04	0.000199
2001	0.001527	0.011934	0.0467	0.036348	0.094745	0.013549	0.015037	0.016748	0.009364	0.001701	0.003077	0.000498	0.0004192	1.00E-04
2002	0.016902	0.006352	0.053475	0.03681	0.044735	0.025393	0.03691	0.025071	0.014448	0.004159	0.002842	1.00E-04	0.000621	0.000324
2003	0.000944	0.068366	0.008453	0.030298	0.021597	0.043773	0.015985	0.045115	0.017376	0.012668	0.009498	1.00E-04	1.00E-04	0.001
2004	0.050281	0.003213	0.078684	0.009742	0.018345	0.018237	0.020861	0.007698	0.034953	0.011583	0.014698	0.009154	0.000905	0.001984
2005	0.10882	0.290719	0.027119	0.057059	0.007948	0.01358	0.01165	0.010521	0.001556	0.011655	0.003408	0.005145	0.000223	0.000115
2006	0.06955	0.164527	0.228388	0.037254	0.036496	0.004595	0.008904	0.006075	0.003399	0.001592	0.003015	0.000961	0.001312	0.000207
2007	0.045	0.094356	0.139292	0.180225	0.069884	0.043729	0.006567	0.001606	0.002164	0.000982	1.00E-04	1.00E-04	0.000809	0.000465
2008	0.069175	0.138222	0.13697	0.137075	0.081697	0.02083	0.007331	0.000373	0.000319	6.00E-04	0.001246	0.001208	0.002251	1.00E-04
2009	0.012519	0.1782	0.154336	0.114473	0.084781	0.038194	0.006383	0.008992	0.00233	0.000557	1.00E-04	1.00E-04	0.000284	0.000284
2010	0.035178	0.161623	0.119185	0.098521	0.063101	0.055574	0.063061	0.015619	0.005209	0.00074	0.000264	1.00E-04	1.00E-04	1.00E-04
2011	0.023726	0.124483	0.138573	0.108594	0.05343	0.070168	0.033544	0.012112	0.001781	0.001961	0.000787	0.001101	1.00E-04	1.00E-04
2012	0.006011	0.089095	0.117043	0.11257	0.067494	0.048617	0.022714	0.032686	0.01521	0.002394	0.003035	1.00E-04	1.00E-04	0.00169
2013	0.012519	0.026586	0.079978	0.101057	0.087759	0.066567	0.044341	0.026107	0.006033	0.001733	0.000286	0.00124	1.00E-04	1.00E-04
2014	0.024815	0.09218	0.028887	0.094047	0.07174	0.063046	0.03812	0.018866	0.011963	0.016476	0.004218	0.003292	0.000874	0.000284
2015	0.007244	0.0158	0.229252	0.028273	0.062241	0.032522	0.034916	0.024991	0.013773	0.013314	0.010914	0.001788	0.000603	0.000684
2016	0.031604	0.011661	0.017204	0.118076	0.058524	0.066894	0.048319	0.036184	0.020753	0.01311	0.003798	0.004554	0.001875	0.001217
2017	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1988	0.000446	0.000479	0.018652	0.031969	0.052135	0.057365	0.065556	0.044748	0.070261	0.056272	0.060513	0.031297	0.014664	0.018963
1989	0.002903	0.001368	0.018341	0.035819	0.102087	0.079226	0.058867	0.050676	0.048334	0.034108	0.032555	0.026065	0.004867	0.007186
1990	0.001095	0.009517	0.007681	0.030569	0.102577	0.146884	0.055449	0.07595	0.039951	0.022809	0.022557	0.016283	0.018254	0.014176
1991	0.000303	0.019952	0.045085	0.019679	0.082125	0.125858	0.111615	0.062368	0.044856	0.031761	0.023657	0.012481	0.003778	0.007569
1992	0.000775	0.006303	0.038786	0.190126	0.014989	0.06149	0.105297	0.072371	0.028978	0.025787	0.018102	0.009802	0.008651	0.006758
1993	0.008299	0.002157	0.000568	0.074019	0.197067	0.041398	0.039808	0.046699	0.047742	0.018654	0.011041	0.005093	0.005015	0.007394
1994	0.017606	0.025997	0.005129	0.042483	0.114876	0.183583	0.030086	0.038825	0.029149	0.017658	0.011032	0.013116	0.001251	0.007145
1995	0.014378	0.033547	0.049374	0.014658	0.029807	0.127884	0.11859	0.032144	0.018611	0.029982	0.021572	0.00586	0.002608	0.006125
1996	0.005145	0.026146	0.077758	0.059333	0.022313	0.028567	0.101127	0.067027	0.02467	0.015091	0.007213	0.010894	0.002945	0.005551
1997	0.011827	0.044852	0.085548	0.115761	0.060172	0.017354	0.054597	0.035137	0.029385	0.004877	0.006148	0.005367	0.001708	0.000978
1998	0.009558	0.019655	0.049619	0.072671	0.094918	0.086242	0.02877	0.024833	0.061605	0.025281	0.006183	0.004691	0.004875	0.006686
1999	0.0061	0.024471	0.0385	0.089542	0.067279	0.10943	0.070417	0.033098	0.029925	0.0201	0.005606	0.00142	0.003798	0.006242
2000	0.001002	0.016738	0.057458	0.056473	0.141797	0.087227	0.116566	0.063631	0.01071	0.020446	0.015027	0.011169	0.000546	0.003219
2001	0.003034	0.006986	0.054705	0.085184	0.069238	0.182777	0.083151	0.101447	0.018922	0.006211	0.018586	0.005954	0.004561	0.005069
2002	0.014725	0.00756	0.030578	0.040844	0.105074	0.108396	0.17405	0.1122	0.07604	0.026183	0.014169	0.010209	0.003321	0.008511
2003	0.001044	0.051627	0.011	0.040937	0.075015	0.107193	0.064905	0.1858	0.035424	0.090419	0.038305	0.00577	0.005525	0.011762
2004	0.029873	0.00194	0.067191	0.013711	0.035027	0.05291	0.107796	0.048398	0.135573	0.046129	0.094518	0.05724	0.001984	0.027373
2005	0.032036	0.090249	0.008246	0.042103	0.004783	0.026451	0.055818	0.048393	0.015704	0.056463	0.022053	0.030281	0.0137	0.004204
2006	0.02569	0.085095	0.118058	0.027064	0.035722	0.012962	0.021745	0.020295	0.033302	0.012132	0.018553	0.010825	0.005381	0.0069
2007	0.021727	0.027056	0.048653	0.128891	0.063592	0.058757	0.015311	0.012443	0.008628	0.008245	0.004674	0.00753	0.003938	0.005278
2008	0.021657	0.037122	0.038338	0.098382	0.091264	0.05141	0.037571	0.005323	0.006694	0.008153	0.004771	0.002447	0.002405	0.002467
2009	0.008236	0.039535	0.057828	0.05586	0.05084	0.063553	0.027425	0.041832	0.008992	0.009761	0.002116	0.005359	0.001433	0.00313
2010	0.006899	0.053411	0.046466	0.032822	0.044658	0.070835	0.066859	0.029999	0.016022	0.003643	0.003608	0.002101	0.002125	0.002177
2011	0.014691	0.061088	0.046857	0.060788	0.045577	0.05888	0.067325	0.037177	0.010404	0.012141	0.00338	0.005397	0.002142	0.003692
2012	0.004214	0.041305	0.040548	0.060982	0.072389	0.055105	0.038968	0.088403	0.042913	0.005504	0.018716	0.003421	0.00576	0.003013
2013	0.016316	0.016801	0.032488	0.077244	0.051694	0.104118	0.105762	0.061341	0.043071	0.012959	0.007451	0.007601	0.003937	0.004811
2014	0.02656	0.042136	0.021533	0.057543	0.065874	0.09532	0.0724	0.045153	0.039817	0.033416	0.014028	0.010656	0.003258	0.0035
2015	0.006566	0.010513	0.097111	0.021924	0.085608	0.064797	0.066296	0.047245	0.045794	0.026493	0.025801	0.009284	0.010408	0.005846
2016	0.020001	0.008571	0.014545	0.059893	0.033377	0.085293	0.069791	0.09448	0.04969	0.051221	0.026423	0.024741	0.014941	0.01326
2017	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Sex ratio differences at age are clear in the age compositions (e.g., Tables 1 and 2). Differences in selectivity and maturation ogives by sex in the model presumably reflect biased sex ratios observed in the age compositions.

A model run was completed constraining the right-hand side of the double exponential model to a value of 0.3, for both males and females. The other parameters, determining the left-hand side and the inflexion point, remained free. The  $M$  of 0.3 was chosen because it approximated the *a priori*  $M$ , even



though it was outside of the 95% credible intervals from the posterior of the base model (McKenzie, 2018). A theoretical catch curve estimated using this assumption was more conventional, being close to linear for fully recruited fish (Figure 10). This run was expected to reduce biomass, because the mortality previously attributed to  $M$  would have to come from  $F$  (with fixed catches, the biomass would therefore have to be smaller). This was indeed the case (Table 3). At the best fit (MPD), the only observational data set for which the fit (as likelihood) was substantially degraded with this assumption was the eastern stock spawning fishery catch-at-age; the fits to the western stock data were not materially degraded at all, despite the stock size estimates decreasing substantially. However, although the likelihood change suggests a degrading of fit, this likelihood difference is split across 52 catch-at-age distributions (it will also depend on the data weighting). For males, the difference in fits was negligible (Figure 11). For females, after the first three years of observations (1988 to 1990), the visual difference in fit between the two model runs was negligible except for the female plus group (Figures 11 and 12).



**Figure 10: Hoki base model 2017 after assuming the maximum  $M$ -at-age to be 0.3: top panel, natural mortality rate at age estimated by the model (double exponential parameterisation); middle panel, the log of the percentage surviving at age following the  $M$  model, with the mean  $M$  over the ages 4-10; bottom panel, the natural mortality rate at length. Shown for males (left panels), and females (right panels). In the bottom panels, the  $M$  model is the same but the growth model differs for each stock; e, eastern stock; w, western stock.**

The fit and outcome was much the same when the right-hand-side of all selectivity ogives was fixed to their upper bound, forcing less-domed ogives (Table 3). Extending the proportion migrating to spawn in the eastern stock from estimating over ages 1–8, to 1–15, then improved the fit; this assumes that the observed age structure was caused by incomplete spawning migrations, rather than selectivity or  $M$ . Reducing the terminal  $M$ -at-age from 0.3 down to 0.15 did degrade the fit more substantially. When a constant  $M$  at age was assumed, the fits to the Espage was little different to the base case, but the fits to the SAsumage and Wspage were degraded, and the western stock was estimated to be at 81%  $B_0$  (in this MPD run, more migration parameter estimates were estimated at bounds).

**Table 3: The likelihoods for the observations in the base model run, and the change in likelihood for the alternative natural mortality model runs. For comparability, all runs were done with the same process error and effective sample sizes (fixed to the estimates from the base model). When the process error was estimated in the Mrhs = 0.3 sensitivity runs, it was lower for the SubAntarctic biomass index.**

Component	Base	Mrhs=0.3	Mrhs=0.3 & all 'logistic'	Mrhs=0.3 & all logistic & extend Espmg	Mrhs=0.15 & all logistic & extend Espmg	Constant $M$
CRsumbio	-29.386	-0.04	-0.04	-0.01	-0.17	-0.37
CSacous	-10.382	0.39	0.39	0.49	0.37	-0.96
SAautbio	-4.2008	-0.03	-0.02	-0.01	-0.04	-0.41
SAsumbio	-7.8638	1.53	1.53	1.54	2.30	-2.61
WCacous	-5.7278	-0.18	-0.18	-0.17	-0.43	0.51
CRsumage	534.999	-0.50	-0.49	-0.92	-4.10	-2.08
SAautage	43.2602	-0.04	-0.04	-0.02	-0.43	-1.09
SAsumage	306.841	-4.65	-4.64	-4.42	-8.14	-27.33
EnspOLF	38.7191	0.22	0.22	0.16	0.35	-0.58
Enspage	412.723	-1.18	-1.20	-1.63	-6.15	-3.40
Espage	925.19	-21.75	-21.76	-13.28	-36.76	-6.56
WnspOLF	105.329	-0.81	-0.82	-0.83	-1.12	-1.96
Wnspage	216.331	0.75	0.76	0.77	-0.59	-3.26
Wspage	514.395	-1.45	-1.43	-1.44	-8.14	-14.44
pspawn	-13.12	0.62	0.61	0.55	0.65	0.85
pspawn_1993	-7.212	-0.41	-0.41	-0.38	-0.59	-0.90
$B_0$ E	450 500	381 100	385 000	389 000	375 600	485 500
W	870 100	741 400	744 000	745 000	779 300	1 598 100
% $B_0$ E	63%	59%	58%	62%	57%	52%
W	48%	31%	32%	32%	24%	81%
Mbar male	0.26	0.31	0.31	0.31	0.34	0.30
Mbar female	0.12	0.17	0.16	0.18	0.24	0.25
Total likelihood	2994	3026	3026	3018	3067	3069

The summer SubAntarctic catch-at-age, eastern spawning catch-at-age, and western spawning catch-at-age would seem to provide the greatest information about  $M$ . The eastern spawning catch-at-age would seem to stand out as having a different signal about increasing natural mortality rate at age (fewer females in the plus group than expected); this suggests a stock difference as the same selectivity is shared by both fisheries. It may be useful to further consider the representativeness of these samples.

The base model assumes that older fish both die from natural mortality at a faster rate, and also become unavailable to the fisheries. It would be useful to check whether this results in cryptic (unavailable) spawning biomass.

These investigations do not yet identify a plausible sensitivity run, and they require some further thought. They do, however, indicate that an alternative (and potentially simpler) set of hypotheses for natural mortality, movement, and availability, could yield equally acceptable model fits, yet produce a quite different stock status for the western stock.

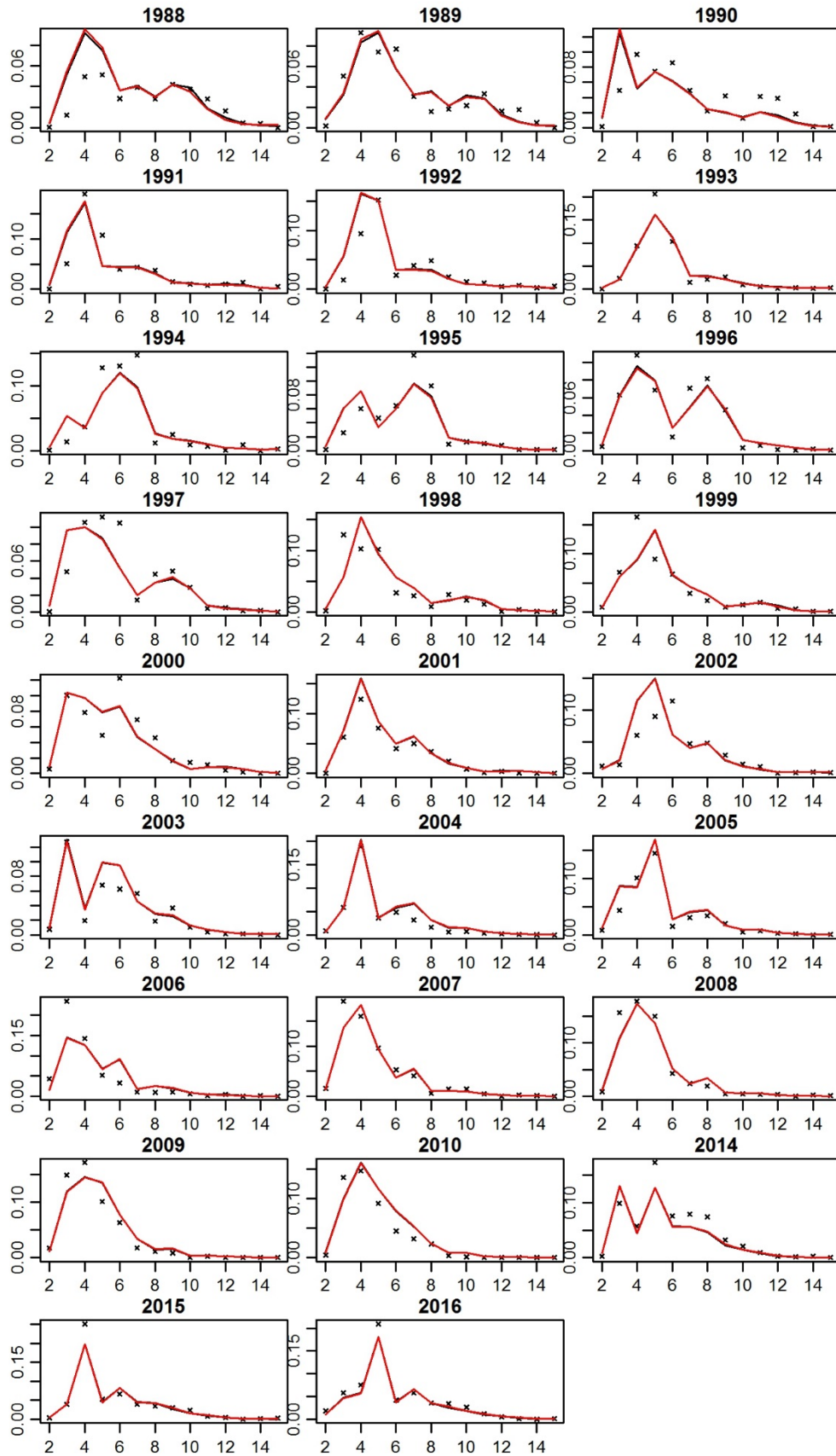


Figure 11: Fits to the male hoki catch-at-age for the Eastern spawning fishery (Espage), for the base run (black line), and the run fixing  $M$ -at-age at the maximum age to 0.3 (red lines).

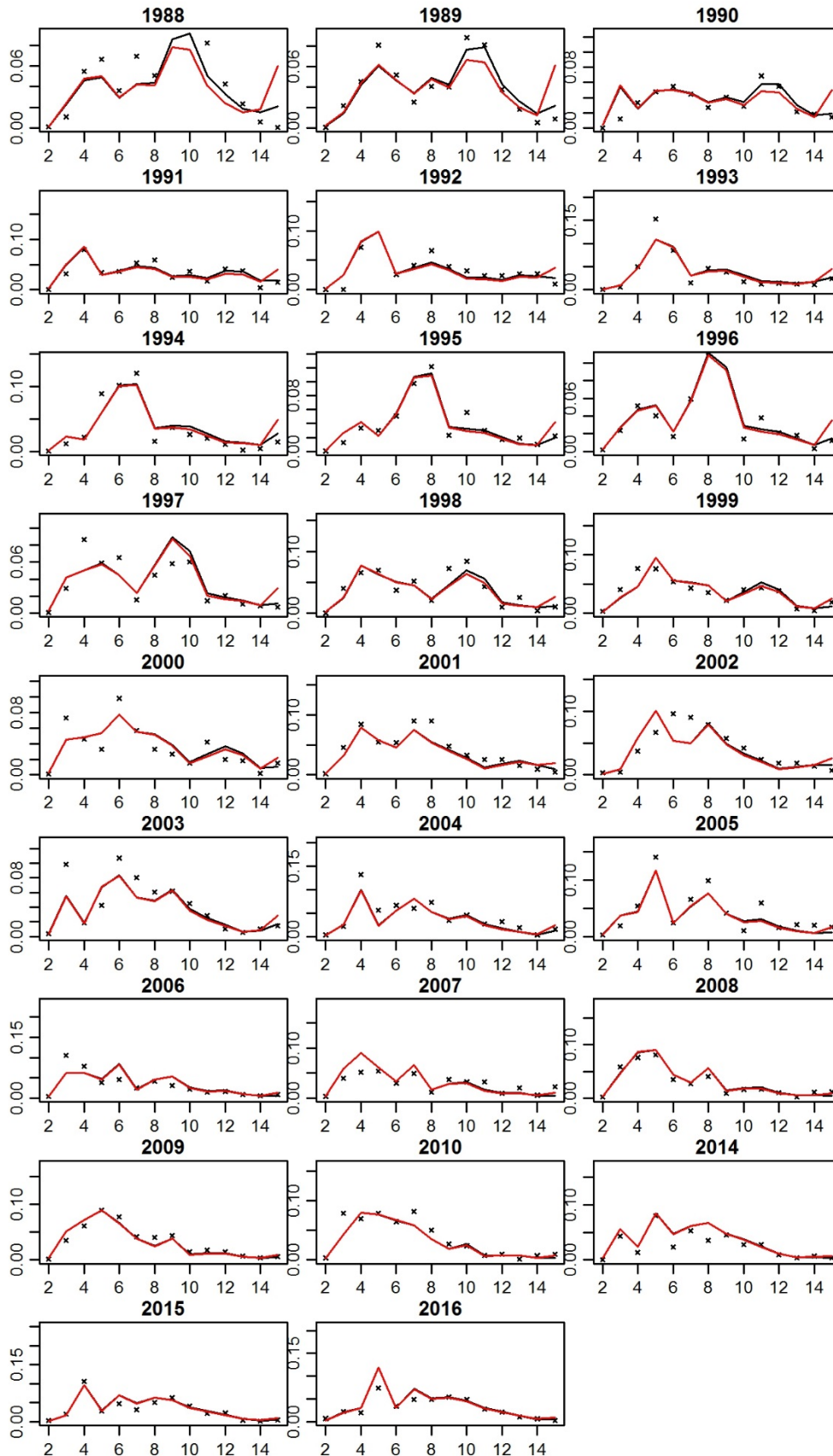
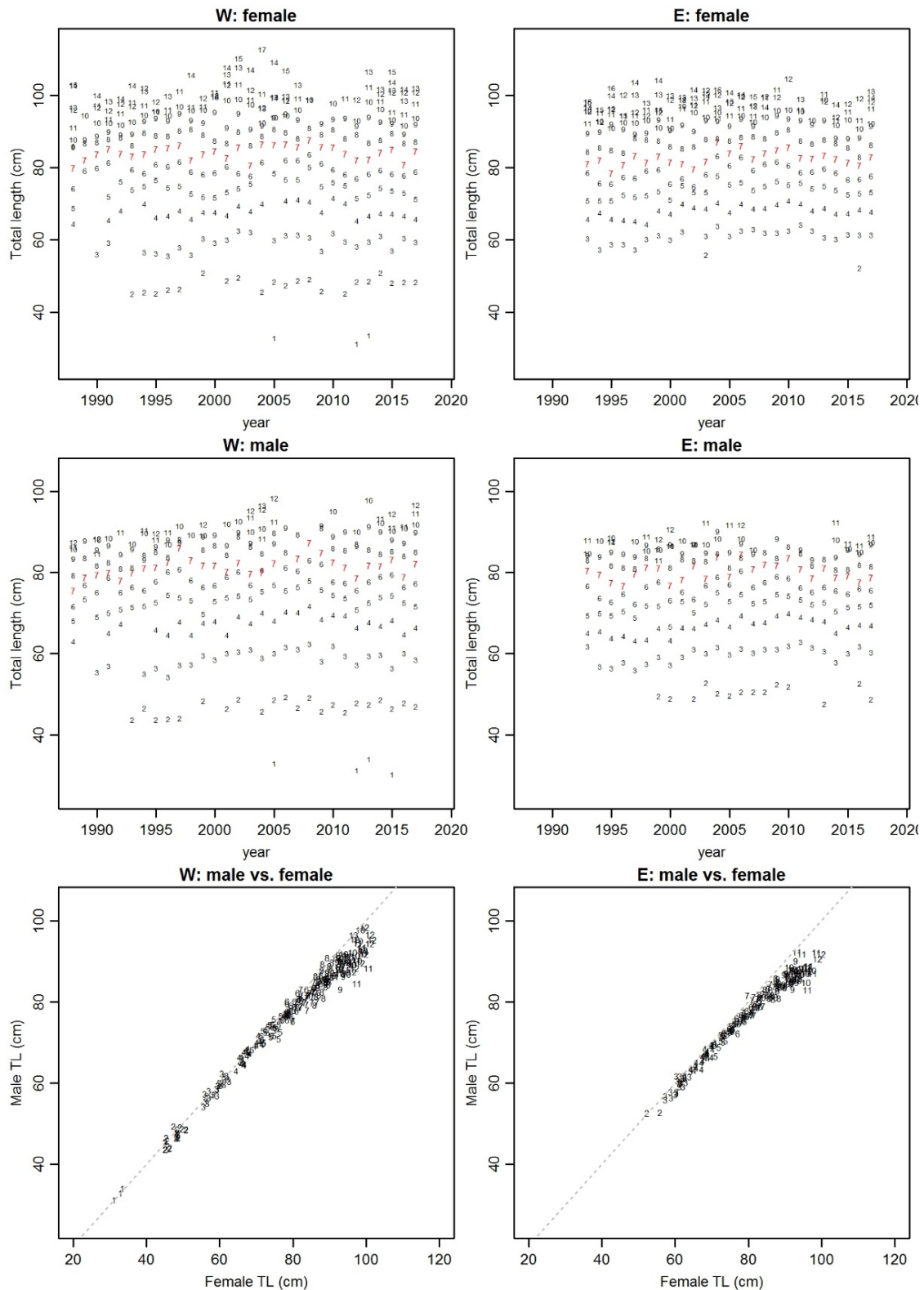


Figure 12: Fits to the female hoki catch-at-age for the Eastern spawning fishery (Espage), for the base run (black line), and the run fixing  $M$ -at-age at the maximum age to 0.3 (red lines).

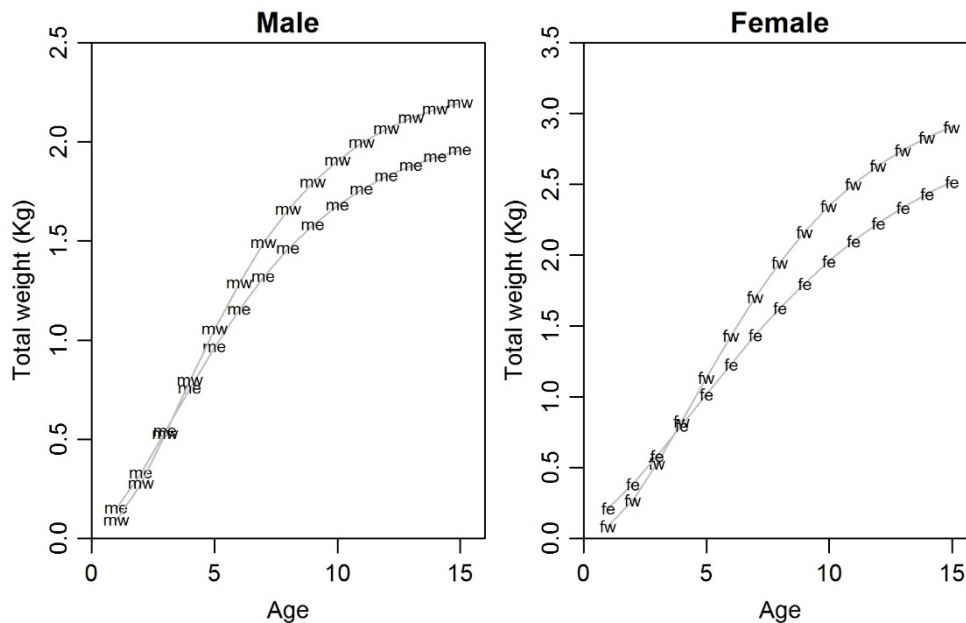
## The growth model

It has been noted that the length at age of hoki has changed over time (Figure 13), and become inconsistent with the assumed von Bertalanffy growth curves (S. Ballara, NIWA, pers.comm.).

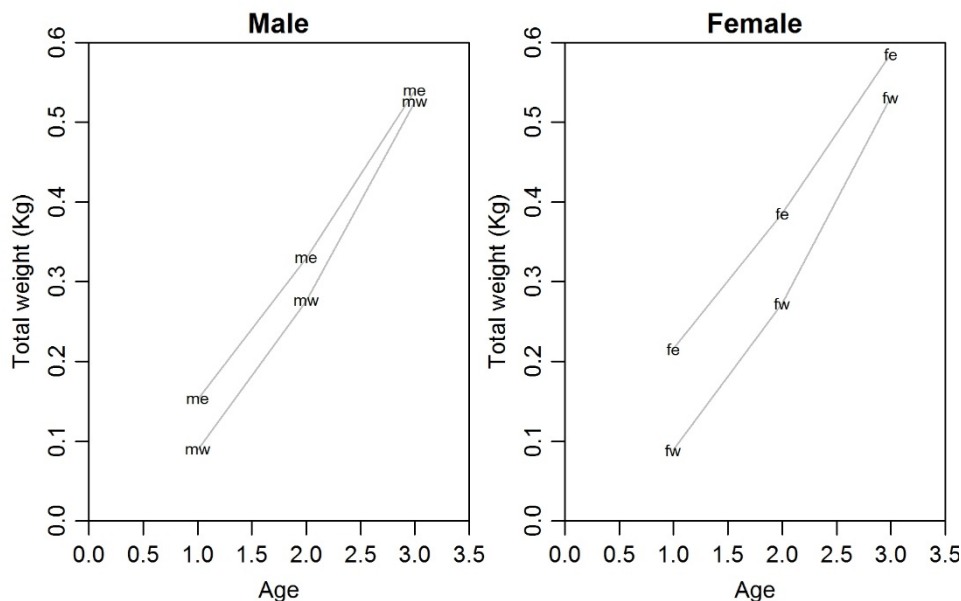


**Figure 13: Empirical estimates of length at age (labelled as points) by year for the east and west coast stocks, male and female (S. Ballara, pers.comm.). Bottom panels show the correlation between male and female size at age for age (labelled as points).**

There is a conventional difference in growth rate and asymptotic length between males and females (Figure 14). Growth in weight is almost linear for females. Whilst the length at age for the two stocks is estimated to be almost the same at age four, at ages less than this it diverges quite substantially (Figure 15). This divergence would seem to make little sense, as the juveniles of both stocks start their lives in the same place, on Chatham Rise. The length to weight conversion is assumed to be constant and the same for males and females, but differs between stocks; whether weight-at-age varies substantially and with trend over time seems to be unknown.



**Figure 14: Assumed von Bertalanffy growth curves (as weight at age) for male and female hoki in the eastern and western stocks. Labels: me, male east; mw, male west, fe, female east; fw, female west.**



**Figure 15: Assumed von Bertalanffy growth curves for male and female hoki in the eastern and western stocks over ages 1 to 3. Labels: me, male east; mw, male west, fe, female east; fw, female west.**

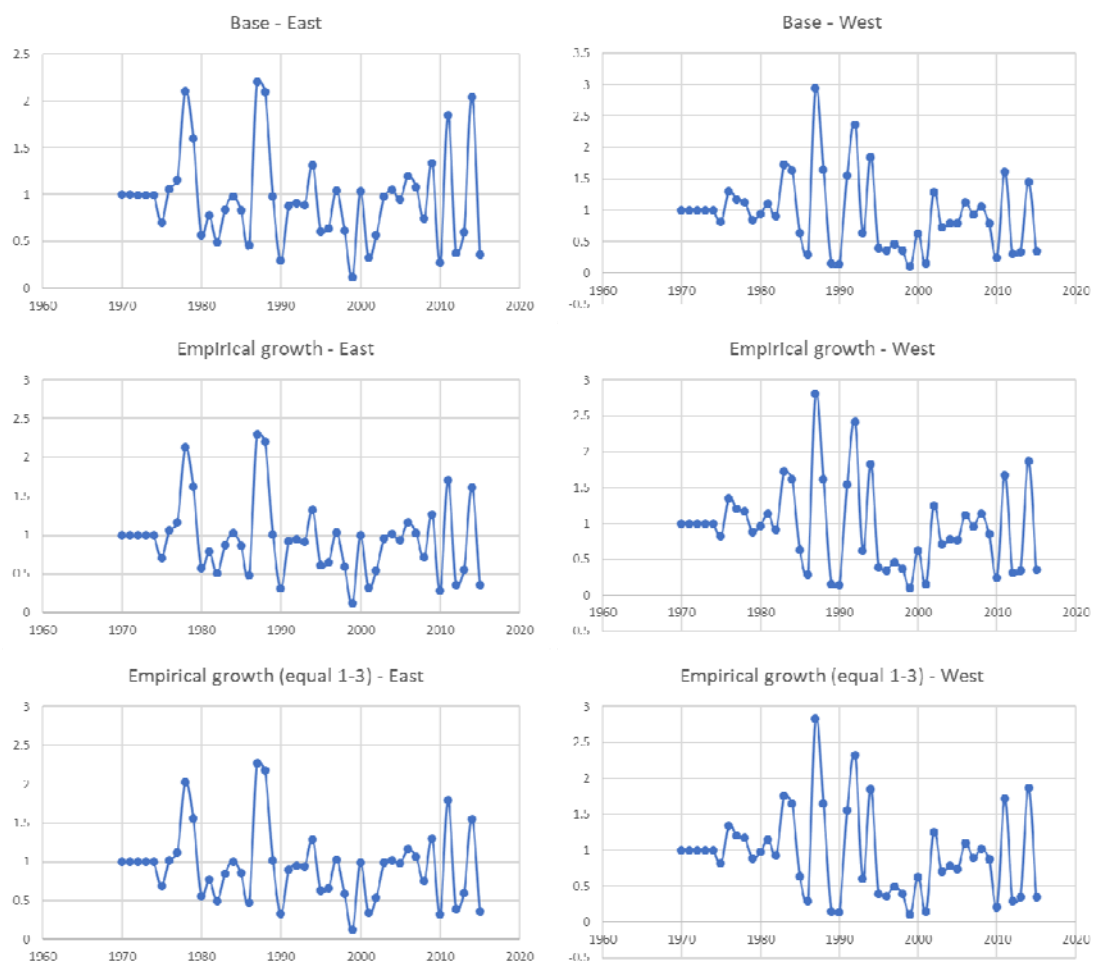
A modification of the base model run was completed replacing the von Bertalanffy length at age with the empirical estimates. Where there were gaps in the empirical estimates, values were linearly



interpolated, or assumed to be the average of the adjacent three estimates; where no empirical data were available, either the previous age length-at-age was used (for the highest ages), or the von Bertalanffy growth estimates were used (for the lowest ages). The change to empirical growth estimates didn't make any material difference to the model estimates of SSB (Table 4), and negligible difference to the estimated YCS for most of the time series; there is some difference in the recent years, where western recruitment is increased by about a third, and eastern recruitment decreased by about a quarter (Figure 16).

**Table 4: MPD estimates of  $B_0$  in the base model, and models using empirical growth matrices, with the length at age varying between stocks (empirical growth model), or equalised to the eastern stock length-at-age (equalised ages 1-3).**

	$B_0$ (E)	$B_0$ (W)	Total
Base model	450 503	870 119	1 320 622
Empirical growth model	454 590	911 785	1 366 375
Empirical growth model (equalised ages 1-3)	454 240	881 691	1 335 931



**Figure 16: True YCS estimates for the model runs described in Table 3.**

In the empirical model MPD runs, several parameters ran to a bound in the base run (Figures 17 and 18). Compared to the base model, where this behaviour also happened, the additional parameters running to bounds in the empirical growth model runs were:

- Spawning migration rates for males at ages 1 and 2 in the western stock (upper bound)
- Spawning migration rate for females at age 8 in the eastern stock (lower bound)
- Selectivity for the Chatham Rise at age 3 (upper bound)

It isn't entirely clear how the model is compensating for the changes to size at age, but this presents evidence of the interactions between growth, migration rates, and selectivity.

Minimiser failed to achieve convergence after 2501 quasi-Newton iterations

The following parameters were estimated at or near a bound:

Parameter	Estimate	lower_bound	upper_bound
recruitment[E].YCS[25]	0.06	0.06	8.6
recruitment[W].YCS[25]	0.06	0.06	8.6
migration[Wspmg].rates_male[1]	1	0	1
migration[Wspmg].rates_male[2]	0.999952	0	1
migration[Espmg].rates_female[8]	0.600008	0.6	1
migration[Wspmg].rates_female[8]	0.6	0.6	1
selectivity[Wnspsl].all[1]	64.0023	64	84
selectivity[CRsl].all[1]	64	64	84
selectivity[CRsl].all[3]	44	4	44
selectivity[SAsl].all[1]	84	64	84
selectivity[SAsl].all[2]	43.9998	4	44
selectivity[SAsl].all[3]	43.9973	4	44

**Figure 17: Parameters running to bounds in the MPD run with empirical length at age.**

Minimiser failed to achieve convergence after 2501 quasi-Newton iterations

The following parameters were estimated at or near a bound:

Parameter	Estimate	lower_bound	upper_bound
recruitment[E].YCS[25]	0.0600029	0.06	8.6
recruitment[W].YCS[25]	0.06	0.06	8.6
migration[Wspmg].rates_male[1]	0.999994	0	1
migration[Wspmg].rates_male[2]	1	0	1
migration[Espmg].rates_female[8]	0.6	0.6	1
migration[Wspmg].rates_female[8]	0.600001	0.6	1
selectivity[CRsl].all[1]	64.0001	64	84
selectivity[SAsl].all[1]	83.9974	64	84
selectivity[SAsl].all[2]	43.999	4	44
selectivity[SAsl].all[3]	44	4	44

**Figure 18: Parameters running to bounds in the MPD run with empirical length at age, and length-at-age for ages 1–3 set to the eastern estimates for both stocks.**

## The datasets determining $B_0$

Likelihood profiles for  $B_0$  are presented by McKenzie (2018). These show that the lower bound to the biomass estimate was determined largely by the catch-at-age data, and by priors (Figure 19). The upper bound was determined by the SubAntarctic biomass survey, and priors.

The profiles are not shown for individual priors; this would be useful. The prior determining the lower bound seems most likely to be the prior on the western spawning acoustic biomass surveys (Figures 20 and 21). The priors determining the upper bound appear most likely to be the trawl survey  $q$ 's. The CVs around the means of the biomass survey priors are high, and vary between 60 and 90%.

The signal in the likelihood from the catch-at-age will be modified by some assumptions around  $M$ -at-age, selectivity, migration, and YCS; (the earlier investigations on  $M$  are an example). Because of this complexity, it may not be appropriate for these data to have such a dominant influence on the stock size and status (at least not without pertinent sensitivity runs).



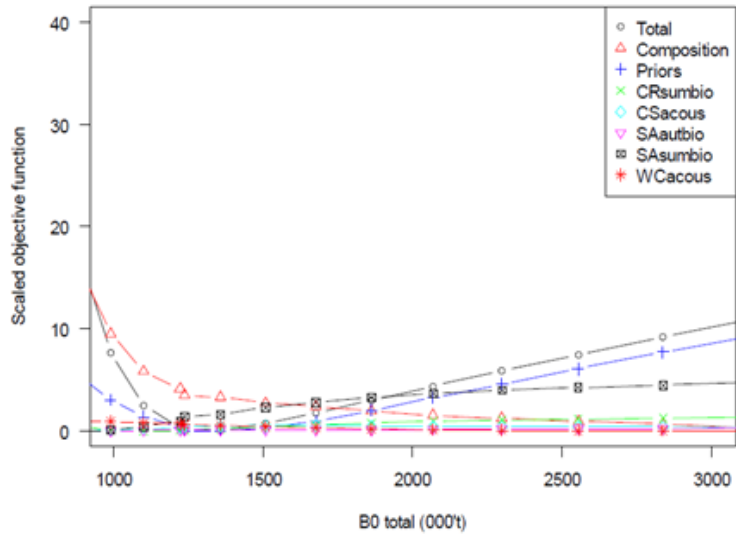


Figure 19: Likelihood profiles for  $B_0$  from the base model (McKenzie 2017). A similar profile over the  $B_0$  range 700–1000 kt is presented for the western stock only in McKenzie (2018).

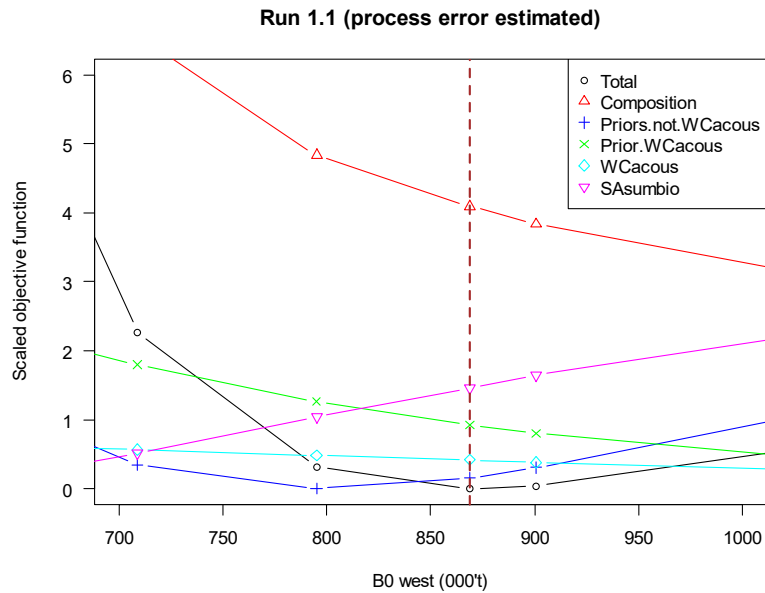
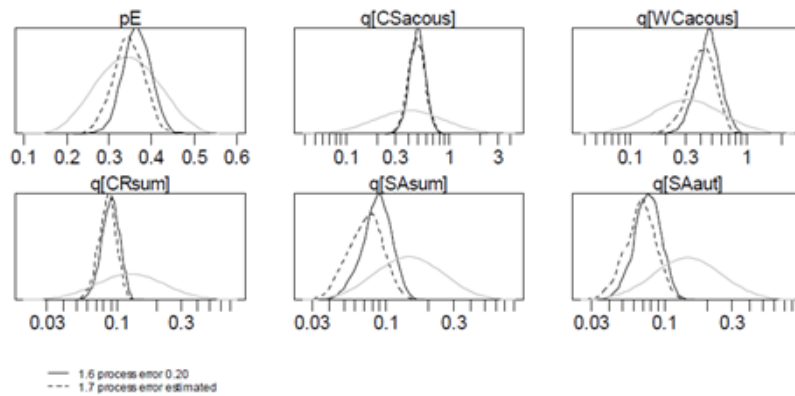


Figure 20: Likelihood profile for run 1.1, but with the process error fixed at their estimated values for the run (0.15 for CRsumbio and 0.38 for SAsumbio). Likelihood components are scaled so that they are zero at their minimum value. Only selected components are shown, and separating out the prior for WCacous from the rest of the priors. Reproduced from McKenzie (2018).

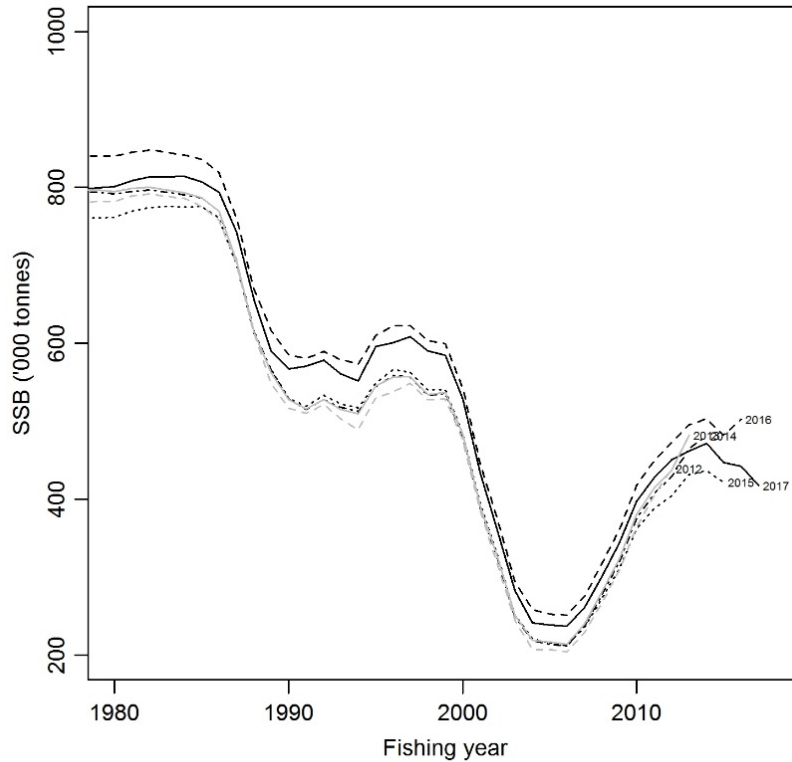


**Figure 21: Priors and posteriors from the base run (McKenzie 2017). 2016 assessment prior (grey lines) and estimated posterior (black lines, solid for run 1.6, broken for run 1.7) distributions for the following parameters:  $pE$  (proportion of  $B_0$  in E stock), and survey catchabilities (acoustic and trawl). Note that the priors for CSacous and WCacous were changed for the 2016 assessment.**

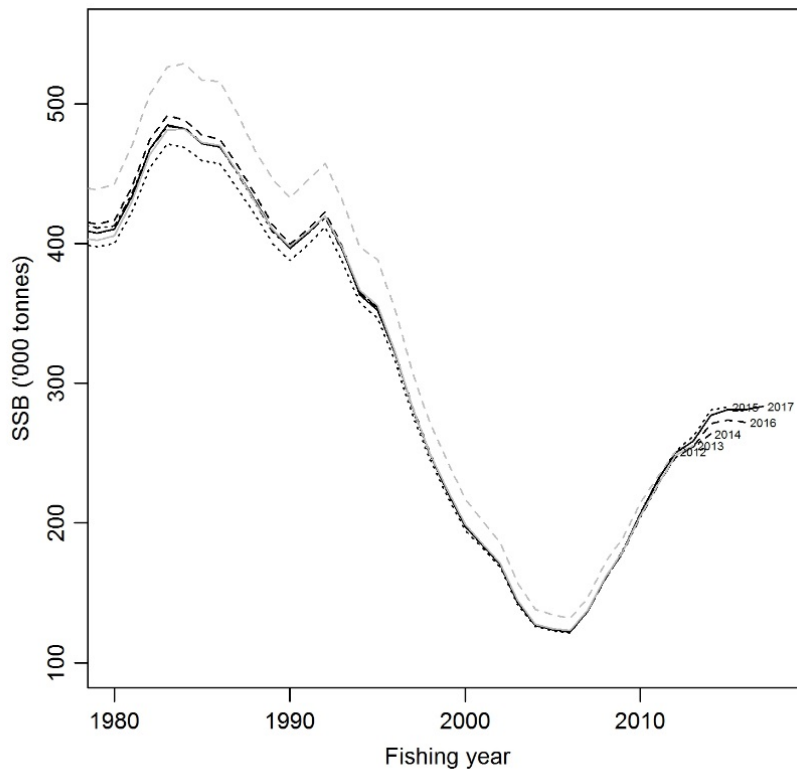
## Other investigations

### Retrospective patterns in biomass estimates

A retrospective analysis was completed for the base assessment model using MPD runs. This indicated substantial variability but no persistent bias in the western stock (Figure 22). However, there appeared to be a small but persistent negative bias in biomass estimates for the eastern stock (Figure 23).



**Figure 22: Retrospective analysis for the Western stock (2017 includes all data to 2017, etc.).**



**Figure 23: Retrospective analysis for the Eastern stock (2017 includes all data to 2017, etc.).**

### The year class strength prior

The CV on the recruitment priors for year class strengths is assumed to be 0.95, and this model estimated  $B_0$  to be 1 320 600 t. Modifying this assumption made little difference to the outcome ( $\sigma_R = 0.6$ ,  $B_0 = 1\ 320\ 100$  t;  $\sigma_R = 1.3$ ,  $B_0 = 1\ 308\ 200$  t).

### Steepness

The assumed Beverton-Holt steepness of 0.75 could seem a little low for a species that has relatively high productivity characteristics (growth, longevity etc). Changing steepness to 0.9 made little difference to model outcome ( $B_0 = 1\ 271\ 900$  t). There seems to be no evidence for assuming a Ricker curve (e.g., cannibalism), other than that shown in Figure 6 (which could be catches of age 1+ fish, or migration, rather than natural mortality).

### Other sources of mortality

The authors of this report were made aware of anecdotal reports or concerns about unmeasured (illegal) discarding, and incidental mortality, where the latter could mean damaged fish escaping from the nets either die from wounds/shock, or suffer higher natural mortality following behavioural impairment. These issues are noted in the Working Group report (Section 1.5). The potential influence of these issues were not investigated during this review.

The presence of hoki in the diets of sharks, skates, and ling seems more likely to include scavenging of hoki escapees or discards rather than direct mortality. Skates and ling are known to scavenge (Forman & Dunn 2012; Dunn et al., 2010), and sharks often take only chunks of hoki prey, suggesting feeding during capture in the net (taking advantage of the herding effect of the trawl) (Dunn et al., 2013). The presence of hoki in the diets of stargazers, ling, and hake may also include some hoki eaten in the net.

### 3. THE SEPARATE STOCK SIMULATIONS

The CASAL hoki stock assessment integrates the assessment of the eastern and western stocks of hoki. The main purpose for conducting the assessment in an integrated framework is to account for the proportion of the catch taken from the Chatham Rise that is comprised of the western stock, and to utilise estimates of the abundance of juvenile (1+ and 2+ year) hoki to predict recruitment to the SubAntarctic and west coast South Island (WCSI) fisheries. The assessment framework also enables model parameters (selectivity and natural mortality) to be shared between the two stock units.

The combined assessment model links the two stock components by the apportioning of juvenile abundance between eastern and western stocks and the migration of (western) fish from the Chatham Rise to the SubAntarctic area. Some key elements of the structure of the combined assessment model are as follows (see also Figure 1):

- Estimation of relative strength of individual year classes to the eastern and western stocks (estimates of E and W year class strength and the estimation of overall average recruitment levels for E and W)
- Migration coefficients (by age class) from Chatham Rise to the SubAntarctic area
- Spawning migration coefficients (SubAntarctic to WCSI; Chatham Rise to Cook Strait)
- Fishery and Survey selectivity functions
- Natural mortality parameterisation

The complexity of the assessment model makes it difficult to investigate and evaluate the influence of these key model assumptions as many of the model parameters are likely to be strongly correlated (especially migration, selectivity, and natural mortality). Further, the model framework makes it difficult to evaluate the influence of individual data sets on the estimation of the key model parameters, and the estimation of stock status for the two stocks (and the associated uncertainty).

This part of the review focussed on investigating the influence of the key data sets (and associated model assumptions) on the estimates of current stock status for the two stocks. This was conducted by configuring simple assessment models for the individual stocks (i.e., separate western and eastern models). The models were implemented in Stock Synthesis (SS3; Methot & Wetzel 2013) and incorporated data from the 2017 hoki stock assessment model. The western stock model included data from the SubAntarctic and WCSI areas only, while the eastern stock model included data from the Chatham Rise and Cook Strait areas only.

These exploratory models simplified the key assumptions from the hoki assessment. Each model was comprised of a single region, and differences in age structure between spawning and non-spawning components of the population were accommodated in the estimation of the respective selectivity functions (i.e., no migration). The natural mortality and selectivity functions were also simplified. Natural mortality was assumed to be constant and trawl survey selectivities were parameterised using a logistic function where appropriate; priors on the catchability coefficients for trawl surveys and acoustic surveys were not included (Tables 5 and 6).

Clearly, the separation of the western and eastern stock models does not adequately account for the catch of hoki from the Chatham Rise fishery, which is assumed to be comprised of both stocks. The single region models attributed all the catch from the Chatham Rise fishery to the eastern stock. This assumption will influence the estimation of recruitment estimates for both stocks (average recruitment and YCS estimates). An additional level of natural mortality for the younger age classes was also estimated for the eastern stock to account for the emigration of the younger age classes from the Chatham Rise (Table 6).

The flexibility in the estimation of annual recruitments means that estimates of recruited biomass from the western and eastern stock models are likely to be less sensitive to the impacts of differential levels

of catch from the Chatham Rise fishery. Nonetheless, it is important to emphasise that the individual stock models are not considered to represent an alternative stock assessment. Rather, the models provide an exploratory framework to investigate the influence of the key data sets and to investigate potential sources of conflict amongst the data sets, as was evident from the diagnostics of the 2017 hoki stock assessment model.

The results from western and eastern SS3 stock models were compared with the results from the MPD of Run 1.1 (base-case) from the 2017 hoki stock assessment.

**Table 5: Configuration of the Western stock model in SS3 in comparison to the 2017 CASAL stock assessment model.**

Parameter, assumption	2017 CASAL assessment	SS3 Model parameterisation	Rationale/Comment
Natural mortality	Estimate U-shape functions, male and female	Sex specific. Age invariant.	Constant M values Males = 0.3, females = 0.25.
Growth	Western stock growth parameters	Western stock growth parameters	Equivalent to assessment model
Maturity	Mature biomass is determined from biomass on spawning ground (defined by migration parameters).	Full maturity at age 4 yr.	Maturity ogive used to determine spawning biomass (female only).
SRR steepness SigmaR	0.75 CV=0.95	0.75 CV=0.80	Equivalent to assessment model Likelihood profile of the parameter indicated that a value of 0.8 was sufficient to fully account for variation in YCS strength.
Recruit deviations Regional structure	1975–2015 Two stock model, eastern region, partitioned spawning/non spawning.	1975–2015 Single region	No partition for spawning/non spawning.
Migration	Migration from Chatham Rise to SubAntarctic. Spawning migrations.	NA	Spawning migration is approximated via parameterisation of selectivity of the spawning fishery (sex specific). Similarly, migration from CR is mediated by the estimated selectivity of younger fish (< 5 years).
Trawl survey process error	Estimated (value, CV=0.379).	Additional error of 0.38 added to survey CV.	The magnitude of the process error estimated is consistent with the between survey variation in the abundance of individual year classes (cohorts) from successive surveys (approx 4 fold variation).

**Table 5 (cont.)**

Acoustic survey $q$	Prior	No prior, free parameter	Acoustic survey biomass indices represent relative index of spawning (=mature female) biomass.
Trawl survey $q$ Selectivity $W_{nsp}$ (SubAntarctic commercial)	Prior Double normal	No prior, free parameter Age specific, sex invariant. Double normal.	Preliminary model options indicated double normal selectivity was appropriate. However, in final model the estimated selectivity function approaches full selectivity for recruited age classes. Results would be very similar with a logistic selectivity.
Selectivity $W_{sp}$ (WCSI commercial)	Logistic, length based.	Age specific, sex variant. Double normal.	Model estimates lower selectivity for female fish in 4-6 year age classes to account for older age at maturity of female fish. Full selectivity of male fish at age 5 years. Full selectivity of female fish at age 8 years.
Selectivity $C_{sl}$ (SubAntarctic trawl survey)	Double normal	Age specific, sex invariant. Logistic.	Approximated full selectivity of older age classes when double normal used. Switched to logistic for final options.
Age composition weighting	Moderate weighting for age composition data (WCSI, SubAntarctic fishery, SubAntarctic trawl survey)	Approximate assessment base case	Weighting of age composition data may have resulted in relatively poor convergence of the model options in the likelihood profiling of $\ln R_0$ parameter.
Ageing Error	Yes, matrix specified	Not included	

**Table 6: Configuration of the Eastern stock model in SS3 in comparison to the 2017 CASAL stock assessment model.**

Parameter, assumption	2017 CASAL assessment	SS3 Model parameterisation	Rationale/Comment
Natural mortality	Estimate U-shape functions male and female	Sex specific. Constant M age class 6+ years. Estimate age specific M for age classes 1-5.	Constant M values Males = 0.3, females = 0.25. Estimate natural mortality for younger age classes to account for migration of fish from Chatham Rise. The model estimates substantially higher values of M for age classes 2–5 for both male and female fish.
Growth	Eastern stock growth parameters	Eastern stock growth parameters	Equivalent to assessment model
Maturity	Mature biomass is determined from biomass on spawning ground (defined by migration parameters).	Full maturity at age 4 yr.	Maturity ogive used to determine spawning biomass (female only).

**Table 6 (cont.)**

SRR steepness SigmaR	0.75 CV=0.95	0.75 CV=0.80	Equivalent to assessment model Likelihood profile of the parameter indicated that a value of 0.8 was sufficient to full account for variation in YCS strength.
Recruit deviations Regional structure	1975–2015 Two stock model, eastern region, partitioned spawning/non spawning.	1975–2015 Single region	No partition for spawning/non spawning.
Migration	Migration from Chatham Rise to SubAntarctic. Spawning migration.	NA	Migration processes are approximated via parameterisation of selectivity and natural mortality of younger age classes. Approximate base model
Trawl survey process error Acoustic survey q	Estimated (value, CV=0.146). Prior	Additional error of 0.15 added to survey CV. No prior, free parameter	Acoustic survey biomass indices represent relative index of spawning (=mature female) biomass.
Trawl survey $q$ Selectivity Ensp (Chatham Rise commercial)	Prior Double normal, length based.	No prior, free parameter Age specific, sex invariant. Logistic.	Preliminary model options included double normal selectivity approaching full selectivity of older age classes. Switched to logistic for final options.
Selectivity Esp (Cook Strait commercial)	Logistic, length based.	Age specific, sex specific. Double normal.	Model estimates lower selectivity for female fish in 4–6 year age classes to account for older age at maturity of female fish. Full selectivity for female fish estimated for age classes 7+ years. Full selectivity of male fish at age 5 years. Selectivity of male fish declines considerably over 10 years old.
Selectivity Csl (Chatham Rise trawl survey)	Double normal, length based	Age specific, sex invariant. Logistic.	Approximated full selectivity of older age classes when double normal used. Switched to logistic for final options.
Age composition weighting	High weighting for age composition data especially for Cook Strait and Chathan Rise surveys	Approximate assessment base case	Weighting reduced for likelihood profiles as model struggled to converge with high base weightings. Set ESS = 10 for all observations for likelihood profiles.
Ageing Error	Yes, matrix specified	Not included	

## Single stock models: Results

### Western stock SS3 model (base model)

The western SS3 model approximates the biomass trajectory of western stock from the CASAL assessment, although the SS3 model estimates a lower biomass level during the mid-2000s. Current biomass is estimated to be very similar for the two models (Figure 24).

The SS3 model estimated a slightly lower level of recruitment in the late 1990s contributing to the lower biomass in the mid-2000s. Overall, the recruitment trends are comparable between the SS3 and CASAL models, although the latter exhibits a higher degree of inter-annual variability (Figure 2).

There is little contrast in the WCSI acoustic survey indices, and these indices are relatively uninformative in the SS3 model. The catchability coefficient ( $q$ ) estimated for the acoustic survey series was similar to the CASAL model (SS3  $q = 0.39$ , CASAL  $q = 0.49$ ).

The SS3 model fits the general trend in the SubAntarctic trawl survey biomass indices. The catchability coefficient ( $q$ ) estimated for the trawl survey series was higher than the CASAL model (SS3  $q = 0.119$ , CASAL  $q = 0.075$ ). The recent level of biomass estimated by the model is sensitive to the precision of the trawl survey biomass estimates; for example, a model option with process error of 0.20 yielded a slightly lower estimate of current biomass (43% SB<sub>0</sub>) than the base model with process error of 0.38 (48% SB<sub>0</sub>).

The level of process error included in the base model appears to be consistent with the changes in the catchability of individual year classes (cohorts) between successive trawl surveys. A limited number of cohorts (3 or 4) can be followed through the series of trawl surveys from 2001 to 2013, and these cohorts exhibit a 3–6 fold change in relative abundance (number of fish) over the period with higher availability, in 2001–2003 and 2008–2010, and lower availability in 2004–2007. The CASAL assessment model uses this information to derive the estimate of process error for the entire trawl survey series.

The model fits also indicate that the catchability of the 2015 and 2017 SubAntarctic trawl surveys was relatively low. Tracking individual cohorts (2004–2007 year classes) over recent surveys reveals a marked decline (60–80%) in the trawl survey abundance estimates of these cohorts between 2012–2013 and 2015.

The fits to the SubAntarctic commercial age composition data are quite poor (Appendix, Figures A1 and A2). There is a shift in the pattern of the residuals; during 2002–2004 the proportion of older fish (8–12 years) in the age composition was under-estimated by the model, whilst during 2009–2014 the proportion of older female fish in the age compositions was over-estimated. The pattern in the residuals may be partly related to a large reduction in the proportion of the SubAntarctic catch taken from the Auckland Islands (Stat Area 602) and Norwegian Hole (Stat Area 603); the peak in catch from the area was in late 1990s to early 2000s. In recent years, more of the catch has been taken along the southeast shelf edge (Statistical Areas 027 and 028).

There are some marked patterns in the residuals from the fits to the SubAntarctic trawl survey age composition data (Appendix, Figures A3 and A4). These primarily represent an under-estimation of the proportion of young (2–3 years) male fish in the age composition and a corresponding over-estimation of young female fish. This may be attributable to the earlier arrival of male fish in the SubAntarctic area (from the Chatham Rise) which is not adequately accounted for in the single region western stock model (which assumes a 50% sex ratio). One way to address this would be to estimate sex specific selectivity functions for the SubAntarctic trawl survey (attempts to apply this approach were not very successful).

The model fits to the WCSI age composition data are also quite variable (Appendix, Figures A5 and A6). There is a marked pattern in the residuals with catches of younger (3–5 year old) fish over-



estimated in the earlier years (1988–1995) and catches of younger fish, particularly males, under-estimated during 2005–2015. Correspondingly, catches of older fish (7–12 years) were under-estimated in the earlier period.

There were also some years when the proportion of young female fish in the SubAntarctic trawl survey age composition were high and were under-estimated by the assessment model (Appendix, Figures A3 and A4). It may be that the survey estimates of age 2 and 3 year old abundance are poorly determined. This should be evaluated by deriving age specific estimates of abundance (and associated precision) for the trawl survey time series.

A likelihood profile was conducted for the overall average level of recruitment ( $\ln R_0$  parameter) for the western SS3 model (Figure 26 and 27). The total likelihood is dominated by the catch-at-age, especially from the WCSI. These catch-at-age strongly influence the lower bound for  $R_0$ . The SubAntarctic trawl survey age composition data seems to influence the upper bound of the  $R_0$  estimate. SubAntarctic commercial age composition does not seem informative about the upper bound of  $R_0$ . The SubAntarctic trawl survey biomass indices contribute a small amount to the total likelihood; although it is minimised around the same value of  $R_0$  as the WCSI and SubAntarctic survey age compositions. The acoustic survey is also uninformative about the upper bound but is more consistent with a higher value of  $R_0$ .

The likelihood profiles revealed considerable variability in the model fits across the parameter range. This indicates poor model convergence (presence of local minima) and appears to be related to the relatively high weighting of the age composition data sets in the base model.

A likelihood profile was also conducted for the SigmaR parameter. The model total likelihood was minimised with a SigmaR of 0.65 which is lower than the value of SigmaR included in the base model. The lower value of SigmaR resulted in a somewhat lower value of initial biomass ( $SB_0$ ) for the western SS3 stock model and a more optimistic estimate of current stock status (from both MPD and MCMCs).

For the SS3 western stock model, the trends in spawning biomass and recruitment were similar from the model MPD and the median of the MCMCs (Figures 28 and 29). The MCMCs reveal considerable uncertainty in the biomass estimates for the last 5 years related to uncertainty in the estimation of year class strengths, especially for the last three years of the model (Figure 29).

A retrospective analysis was conducted for the western SS3 stock model for the last seven years of the model (2011 to 2017). The analysis indicated that the model was systematically over-estimating the “current” biomass ( $SB_y$ ) in 2012–2014, although biomass has been estimated more consistently for the more recent years (2015–2017) (Figure 30). This is equated to an over-estimate of the 2008–2009 year classes in the initial years in the model (age classes 3–5 years) (Figure 31). These year classes may be poorly estimated from the SubAntarctic trawl survey and/or commercial age compositions. It may be that the strength of these year classes is more reliably determined with the inclusion of data from the Chatham Rise trawl survey (in the two-stock CASAL model).

The initial modelling results highlighted a number of issues for further examination, specifically: time varying selectivity of the WCSI trawl fishery, formulating the prior for the SubAntarctic trawl survey catchability coefficient, and the partitioning of the SubAntarctic trawl survey biomass by age class groups (Figures 32–35). These were investigated as single changes from the base model option. The specific model scenarios are presented in Table 7.

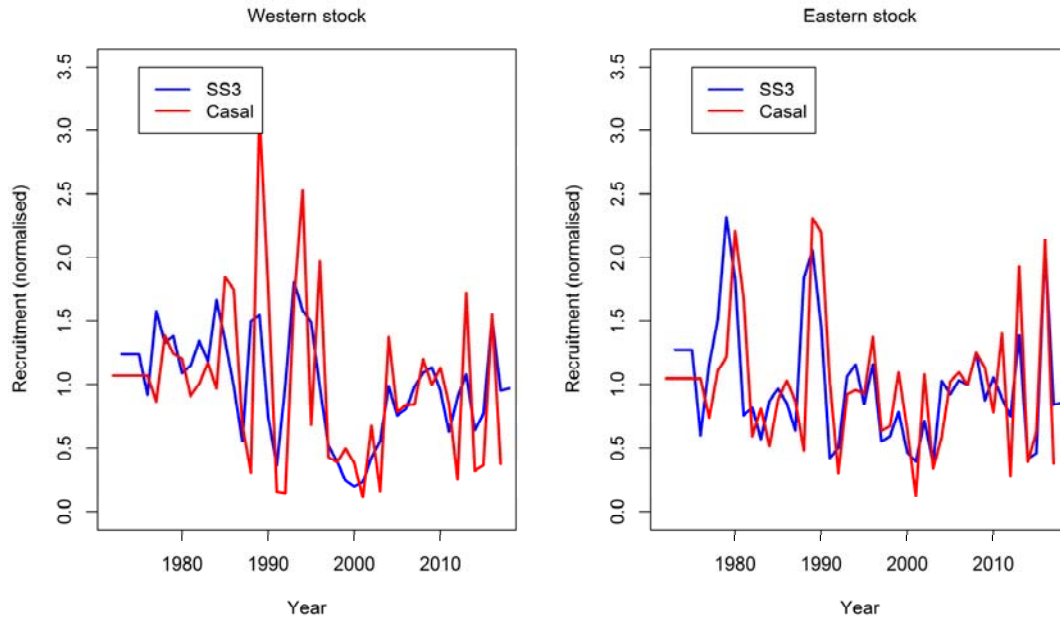
Excluding the data from the 2 year and 3 year age classes from the SubAntarctic trawl survey data (catch-at-age and biomass) resulted in a slight reduction in the estimate of current spawning biomass. The root-mean-square error (RMSE) of the trawl survey biomass estimates was slightly lower than the base model option. The RMSE was highest when the trawl survey series was derived for the 4–7 year age classes and lowest for the trawl survey series derived from 8+ year classes. This result indicates that the biomass in the 4–7 year age classes is more variable amongst trawl surveys and less consistent with the other age composition data included in the model.

The trawl survey biomass derived for the 8+ year classes has remained relatively stable from 2008 onwards, although the fit to the indices is relatively poor especially in 2009 and 2010 (Figure 35). There is a modest improvement in the fit to these trawl survey biomass estimates when temporal variation is incorporated in the selectivity of the WCSI commercial fishery, although the poor fit to the 2009 and 2010 indices persists.

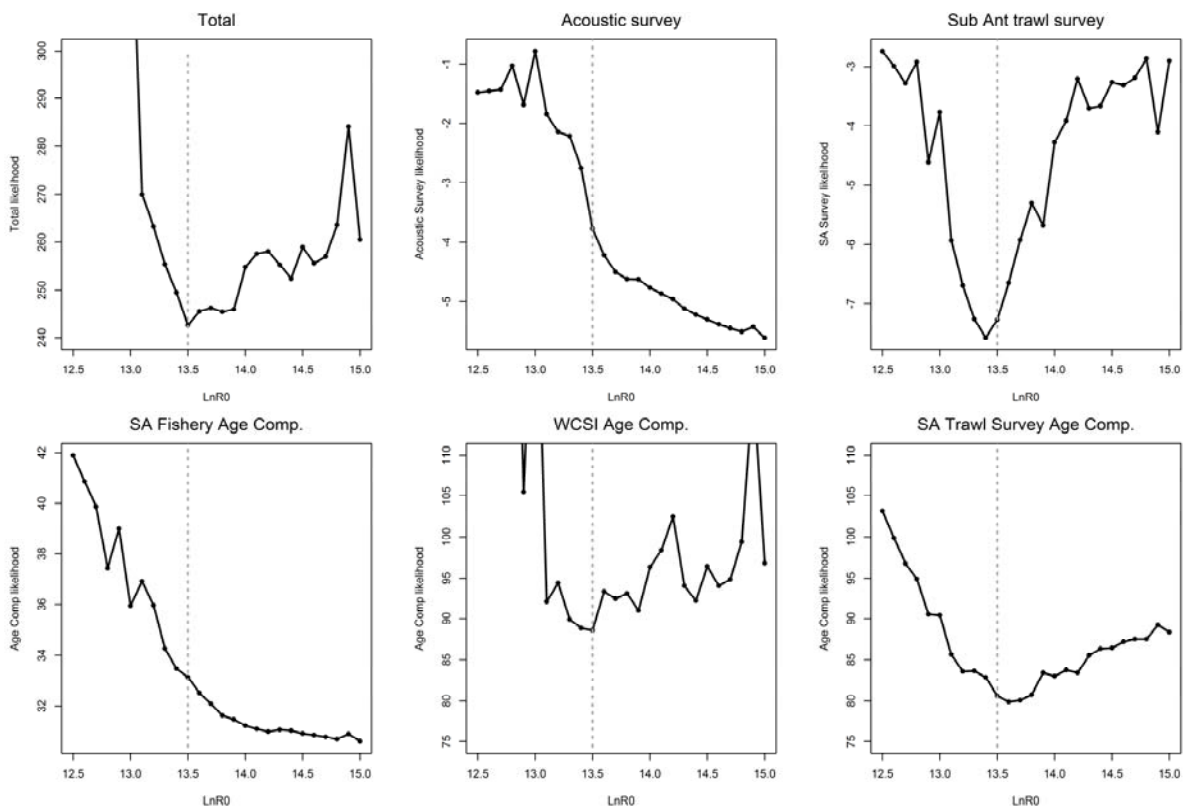
The two model options that incorporated temporal variation in the selectivity of the WCSI commercial fishery did not estimate trends in spawning biomass that were substantially different from the base model option. However, the recent trends in WCSI vulnerable biomass estimated from the two alternative model options differed markedly from the base model, especially from 2005 onwards (Figure 36). The vulnerable biomass increased several years earlier than for the base model (with constant selectivity) and peaked in 2012–2013. Vulnerable biomass was then predicted to decline considerably in 2016 and 2017. The trends in vulnerable biomass from the models with time varying selectivity are generally consistent with the trends in CPUE from the WCSI fishery over the last 10–12 years (Figure 36).



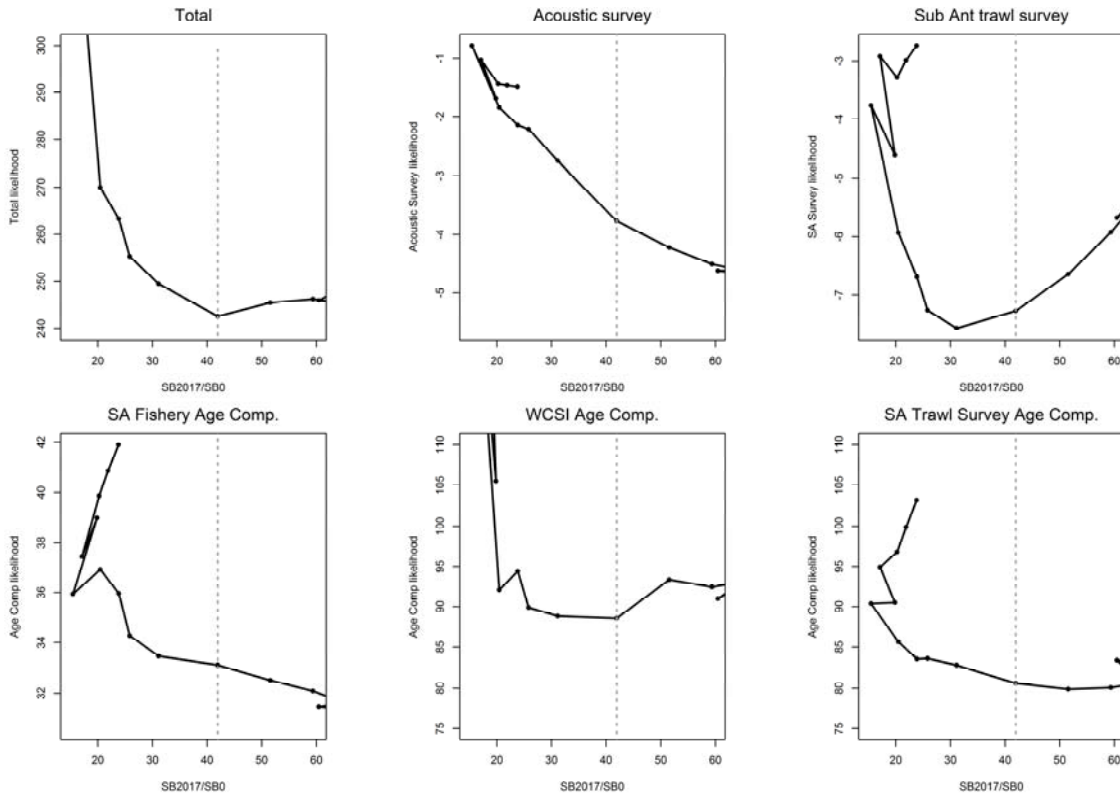
**Figure 24. A comparison of the biomass trajectories (relative to SB0) from the SS3 and CASAL models for the western stock (left panel) and eastern stock (right panel).**



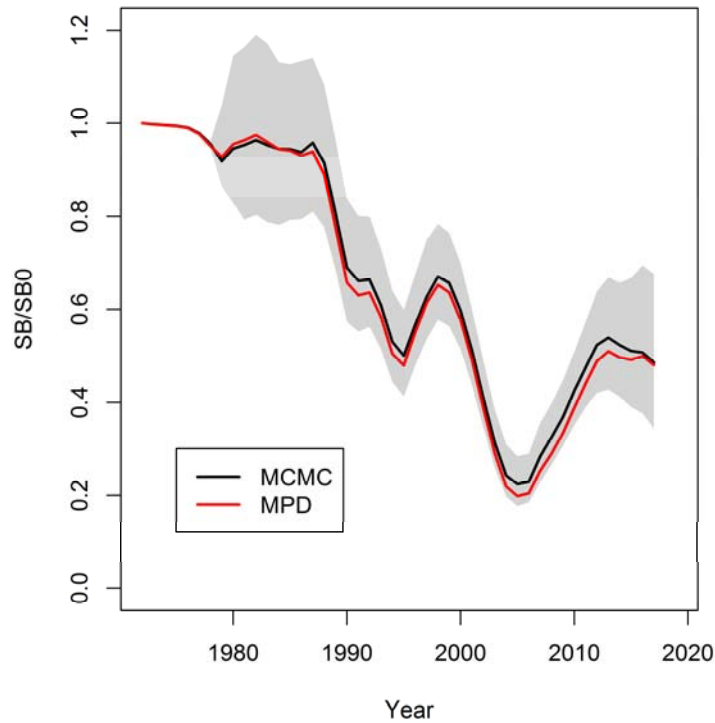
**Figure 25: A comparison of the relative annual recruitments (normalised) from the SS3 and CASAL models for the western stock (left panel) and eastern stock (right panel).**



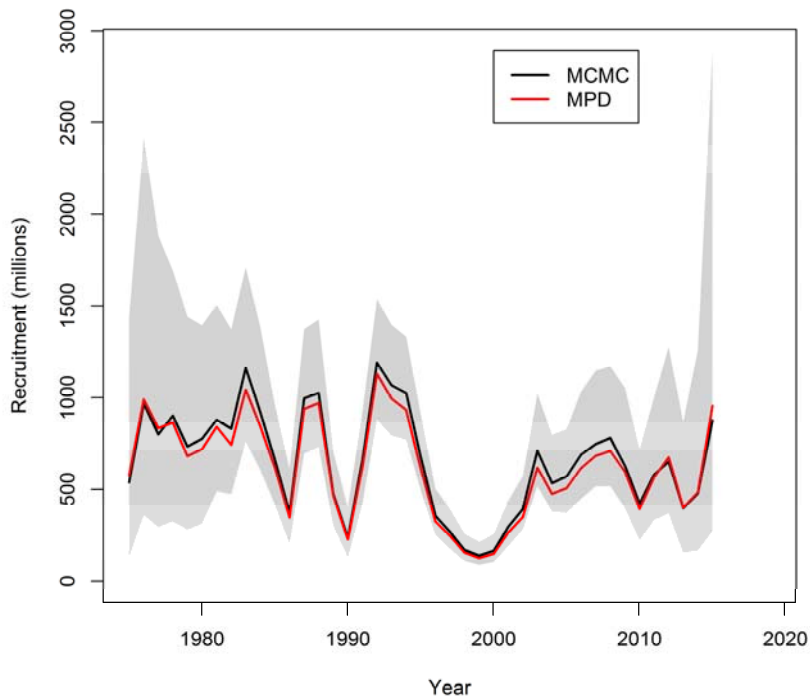
**Figure 26: Likelihood profile of  $\ln R_0$  parameter for the main data components included in the western SS3 model. The dashed vertical line represents the  $\ln R_0$  parameter estimate in the model.**



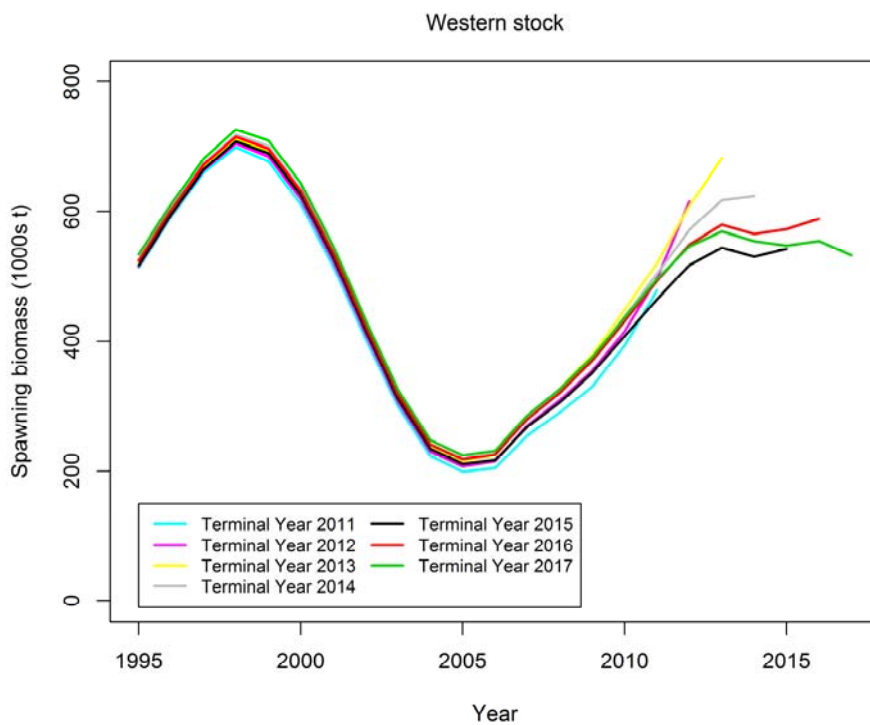
**Figure 27: Likelihood profile of current stock status ( $SB_{2017}/SB_0$ ), obtained from profiling  $LnR_0$  parameter, for the main data components included in the western SS3 model. The dashed vertical line represents the estimate of stock status from the model.**



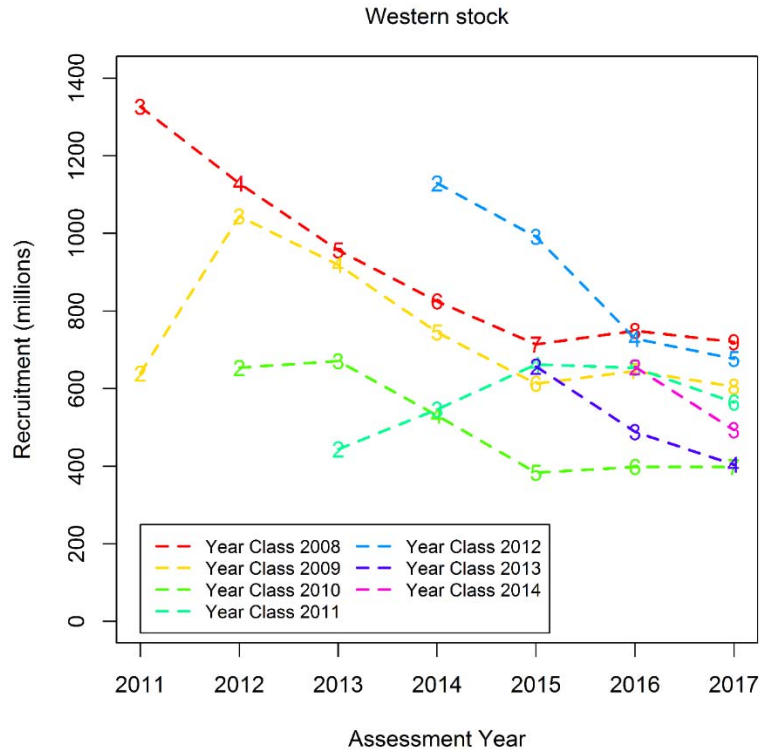
**Figure 28: A comparison of the biomass trajectory from the MPD (red line) and median of the MCMCs from the western SS3 model. The confidence interval represents the 95% CI from the MCMCs.**



**Figure 29:** A comparison of the annual recruitments from the MPD (red line) and median of the MCMCs (black line) from the western SS3 model. The confidence interval represents the 95% CI from the MCMCs.



**Figure 30:** Trends in recent spawning biomass from a retrospective analysis of the western stock SS3 model.



**Figure 31: Estimates of recruitment strength (numbers) for individual cohorts (year classes) from the retrospective models of the western stock SS3 model. The number represents the age of individual year classes in the terminal year of each model.**

**Table 7: Alternative model scenarios investigated for the Western stock SS3 model.**

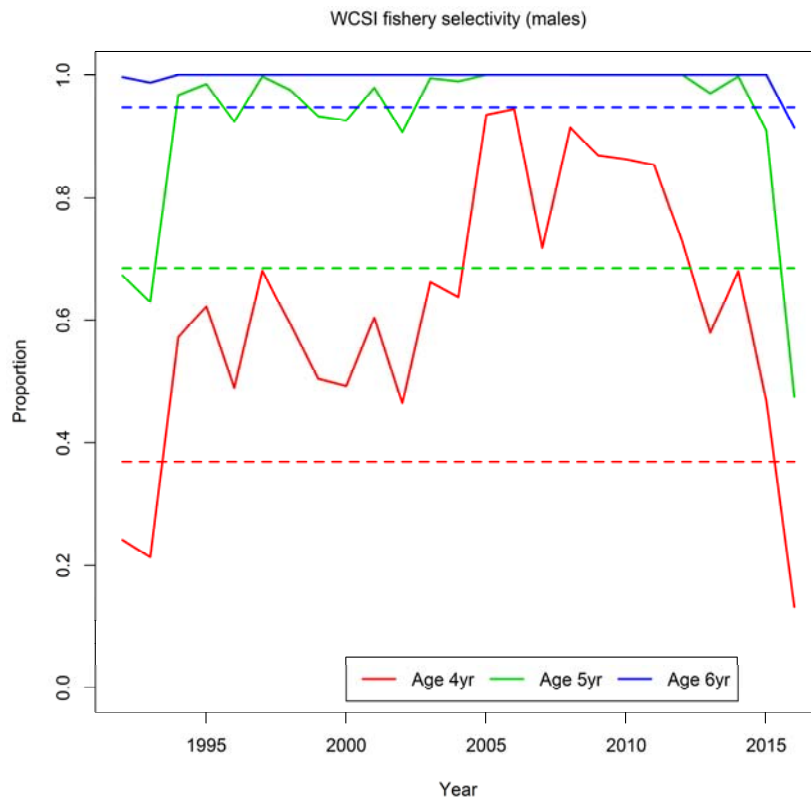
Model	Parameter, structural change(s)	Comment
Base2017 SigmaR60	- SigmaR 0.60 (compared to 0.80 in base model).	Lower initial (virgin) biomass compared to base model and, consequently, higher current stock status (relative to SB0). Estimates of equilibrium yield are 12% lower than base model. MCMC are consistent with MPDs.
WCselectDev	Incorporate time varying selectivity for WCSI fishery, primarily the parameter controlling the age of the peak in selectivity of the double normal function	The model estimates a considerable increase in the selectivity of 4 year old fish during 2005–2012. The selectivity of these younger fish is estimated to have declined in subsequent years. There is a large improvement in the fit to the WCSI age composition data. Trivial influence on spawning biomass trajectory; trivial difference in annual recruitments. Slightly higher estimates of yield (6% higher) due to difference in current F-at-age matrix.

**Table 7 (cont.)**

SubAntSurveyPrior	Remove process error from SubAnt survey biomass estimates. Instead, assume a prior distribution for survey q and estimate q deviates for each survey.	Prior was informed based on observed variation in the abundance of individual year classes (at ages 4–12 years) from successive trawl surveys. Limited observations to inform prior. There was (approximately) a four-fold increase in biomass of fully recruited age classes between 2007 and 2008. The same year classes declined by at least 50% between 2010 and 2012 and declined further in 2015.
SubAntSurveyPrior10	Constrain catchability deviation prior	Prior Normal(0,0.4) which corresponded to a 95% probability distribution for q to vary by a factor of five. Catchability was estimated to vary by a factor of about three. The resultant model biomass trajectory was virtually identical to the base model. Prior Normal(0,0.1) which corresponded to a 95% probability distribution for q to vary by about 50%. Biomass trajectory more consistent with the trend in trawl survey biomass estimates. There is a relatively small deterioration in the total Age Comp likelihood (from 203.2 to 210.1). Most of the deterioration in fit occurs in the SubAntarctic Trawl Survey age compositions from 2006–2010 and, secondarily, from the SubAntarctic age compositions from 2007–2012. These periods correspond to the period of increased abundance of the individual year classes monitored by the trawl survey.
SubAntSurvey_AgeDwt	Reduce survey process error (CV) to 0.10 (from 0.38) and reduce ESS on age composition data.	Biomass trajectory more consistent with the trend in trawl survey biomass estimates.
SubAntSurveyexclude2and3yr	Excluded 2 and 3 year old fish from Sub Ant survey age composition and biomass estimate.	No appreciable change to the fit to the Age Comp data from WCSI or SubAnt commercial fisheries. Reduction in estimates of recent recruitment especially 2015 year class (=2016 in CASAL) (from exclusion of high proportion of 2 year old fish in 2017 trawl survey age composition). This has a modest effect on the recent spawning biomass in the model but is probably more influential in the projection period. The preceding strong recruitment in 2012 is also moderated by the exclusion of the 2 and 3 year age classes from the trawl survey age comps.

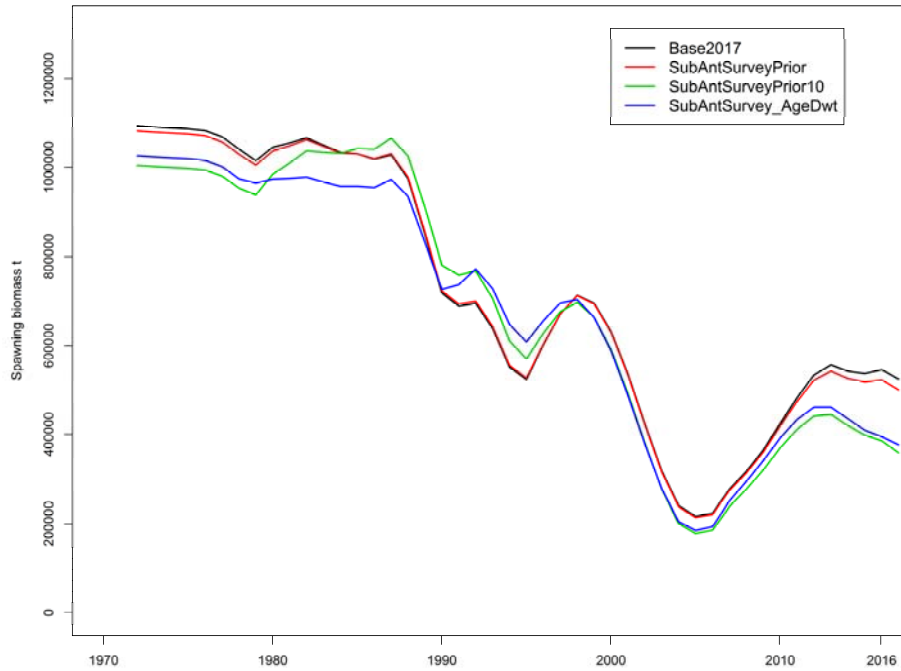
**Table 7 (cont.)**

SubAntSurveyBiomass4to7year	Trawl survey biomass and age compositions restricted to age classes 4-7 year. ProcessError, CV=0.38	Modest reduction in estimate of recent spawning biomass, akin to the SubAntSurveyexclude2and3yr model option. Small improvement to WCSI age composition.
SubAntSurveyBiomass7OLDyear	Trawl survey biomass and age compositions restricted to age classes 8 years and older. ProcessError, CV=0.28	The process error of the trawl survey biomass was reduced to 28% and the age composition data were reweighted following Francis (2011) TA1.8. Modest reduction in estimate of recent spawning biomass, akin to the SubAntSurveyexclude2and3yr model option. Small improvement to WCSI age composition; considerable improvement in the fit to the SubAnt commercial fishery age comp.

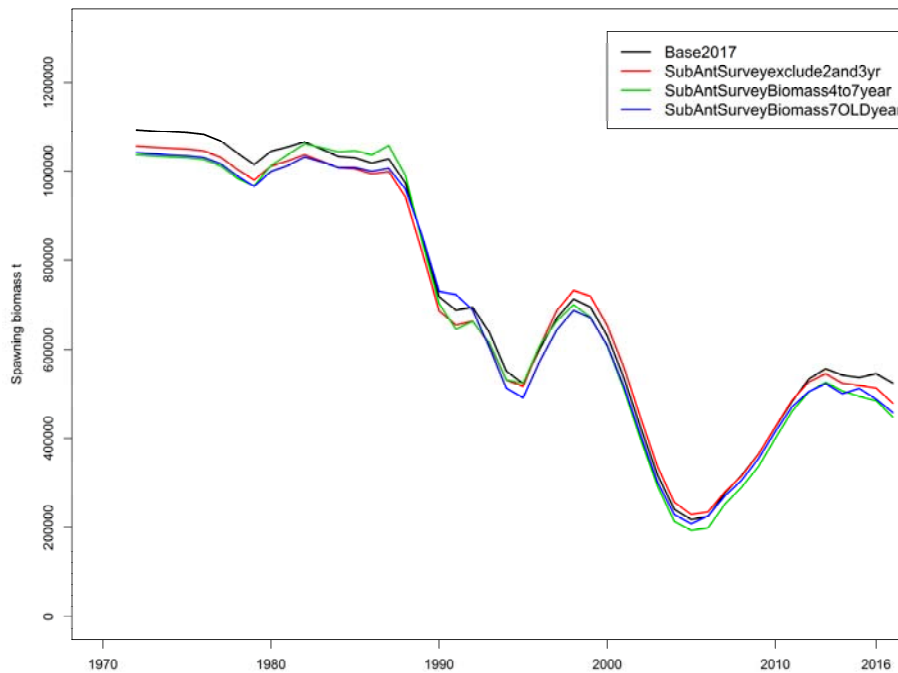


**Figure 32: A comparison of the annual selectivity of 4 year, 5 year and 6 year age classes for male fish by the WCSI commercial fishery estimated from the WCselectDev model (solid lines) compared to the temporally invariant selectivity from the Base2017 model (dashed lines).**

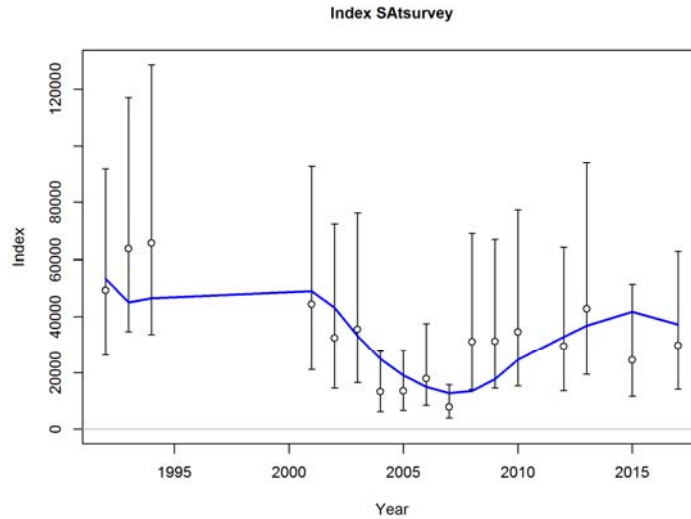




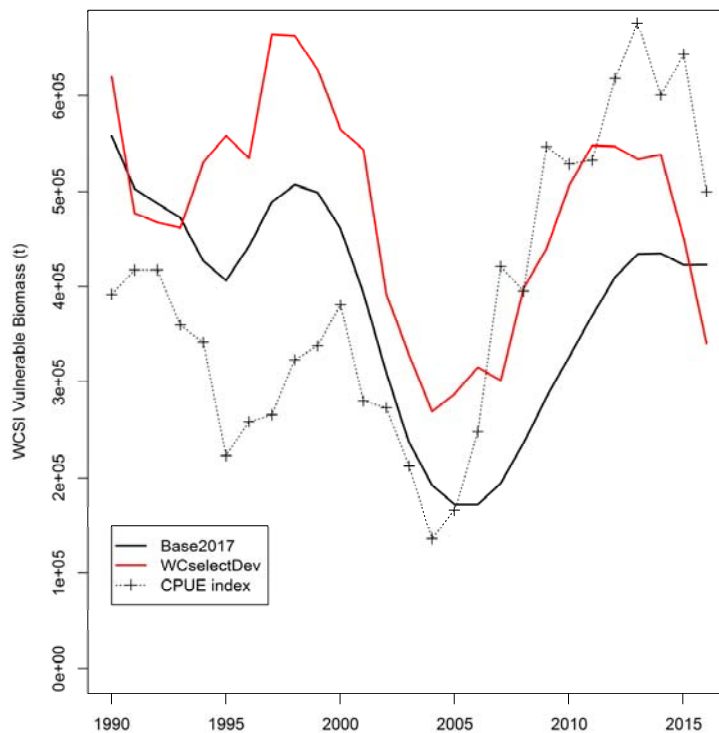
**Figure 33:** A comparison of the western biomass trajectory derived from model options with different weightings of the SubAntarctic trawl survey biomass estimates relative to the age composition data.



**Figure 34:** A comparison of the biomass trajectories from the base Western stock SS3 model and model options excluding components of the SubAntarctic trawl survey (age compositions and biomass).



**Figure 35: Fit to the 8+ year trawl survey biomass estimates in the SubAntSurveyBiomass7OLDyear model.**



**Figure 36: A comparison of the recent trends in vulnerable biomass for the WCSI fishery from two model options and the trend in CPUE indices from the WCSI commercial fishery.**

### Eastern SS3 stock model

The eastern SS3 model approximates the biomass trajectory of eastern stock from the CASAL assessment, although biomass trajectories deviate from about 2009 and the SS3 model is less optimistic in the latter period (Figure 24). The difference in biomass in the latter period corresponds to deviations in the recruitment estimates in the latter period (Figure 2 25). These differences may relate to differences in the weighting assigned to individual age observations and/or the interaction with the western stock dynamics in the CASAL model (i.e. the apportionment of recent Chatham Rise catches to the western stock in the CASAL model).

The CASAL model assigns very high weights to the individual age composition observations from the Cook Strait fishery from 2004 onwards. However, increasing the weighting of the recent age compositions did not result in a convergence of the biomass trajectories from the two model platforms. This suggests that the incorporation of the western stock dynamics within the CASAL model is likely to be influential in the determination of stock status, especially in the more recent period.

The SS3 model provided a reasonable fit to the Cook Strait acoustic biomass indices, although the most recent index (2015) is underestimated by the model. The SS3 model does not include a prior for the acoustic survey  $q$ . The SS3 model also provided a good fit to the Chatham Rise trawl survey biomass indices.

There is a reasonable fit to the time series of Chatham Rise commercial age composition observations (Ensp1) (Appendix Figures A7 and A8).

The model fits the overall age compositions from the Cook Strait commercial fishery; however, there is a high degree of variability amongst the individual age compositions and some strong patterns in the residuals. The proportion of younger (3–4 year) male fish is underestimated by the model in the last decade (corresponding to an increase in the proportion of male fish in the age compositions in recent years).

Overall, the model provides a good fit to the time-series of age compositions from the Chatham Rise trawl survey, with the exception of the 1-year age class (Appendix Figures A9 and A10). Fits to the 1-year age class are variable (under- or over-estimated). This suggests that the abundance of 1-year old fish is probably not well determined by the trawl survey. It may be worth excluding 1-year old fish from the survey age composition (and biomass estimates). The estimate of abundance of 1-year old fish could be fitted in the assessment model separately, allowing for a different (higher) level of uncertainty to be assigned to these indices.

A likelihood profile was conducted for the  $\ln R_0$  parameter to investigate the influence of the various input data sets on the overall scale of the population (and current stock status). It was not possible to conduct the likelihood profiling with the very high weights assigned to the age composition data in the base model and the ESS was reduced to 10 for all age comp observations (for likelihood profiling).

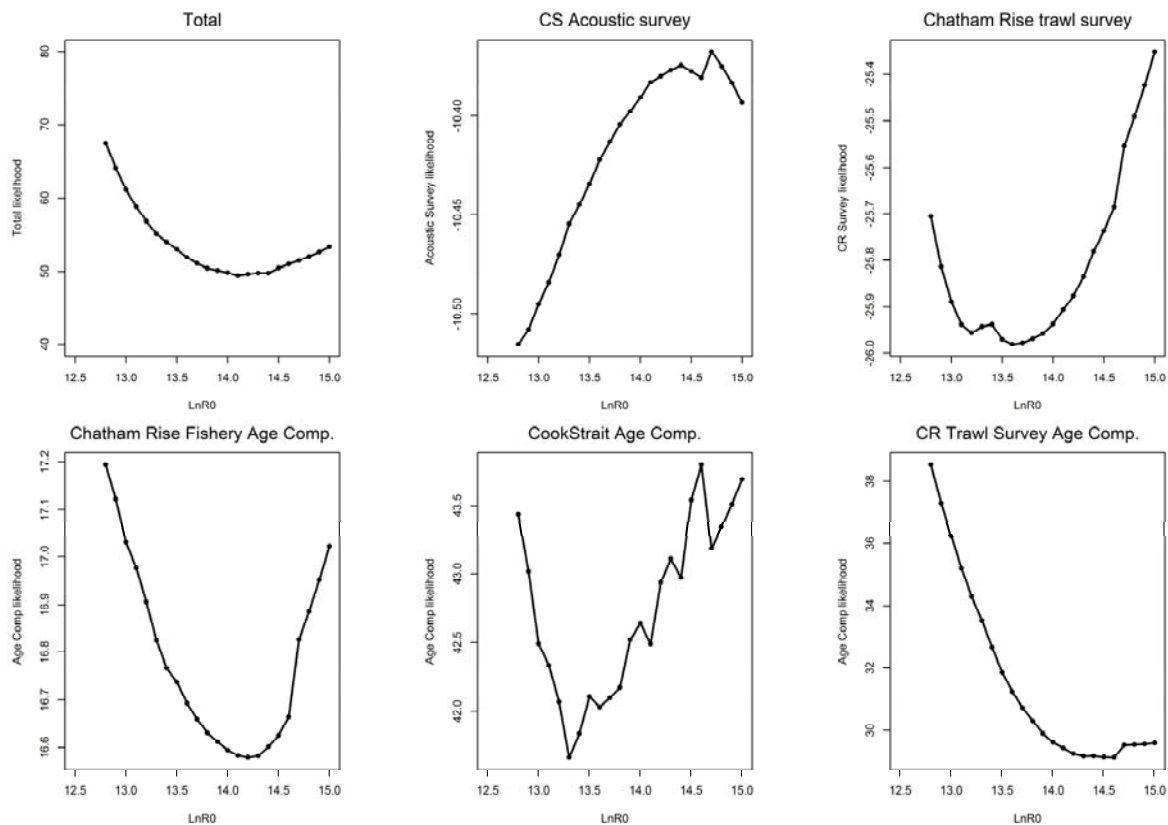
The total likelihood profile indicates that the data are not very informative regarding overall stock size. The Chatham Rise trawl survey age composition data is most influential in determining the lower bound of the  $\ln R_0$  parameter and these data are generally consistent with the age composition data from the Chatham Rise commercial fishery (Figures 37 and 38). There is limited information in the various data sets to determine the upper bound of the  $\ln R_0$  parameter, although the Cook Strait age composition and Chatham Rise trawl survey biomass indices are the most informative data sets and these two data sets are relatively coherent in the information regarding  $\ln R_0$ . The former data set is given a high weighting in the CASAL assessment model. The catchability coefficient estimated for the Chatham Rise trawl survey biomass indices was very similar to the MPD value from the CASAL assessment model (SS3  $q = 0.072$ , CASAL  $q = 0.078$ ).

The Cook Strait acoustic survey does not contribute significantly to the overall likelihood and does not provide information regarding overall stock size (Figure 37). The SS3 model estimated a considerably lower catchability coefficient for the acoustic survey compared to the CASAL assessment model (SS3  $q = 0.300$ , CASAL  $q = 0.595$ ).

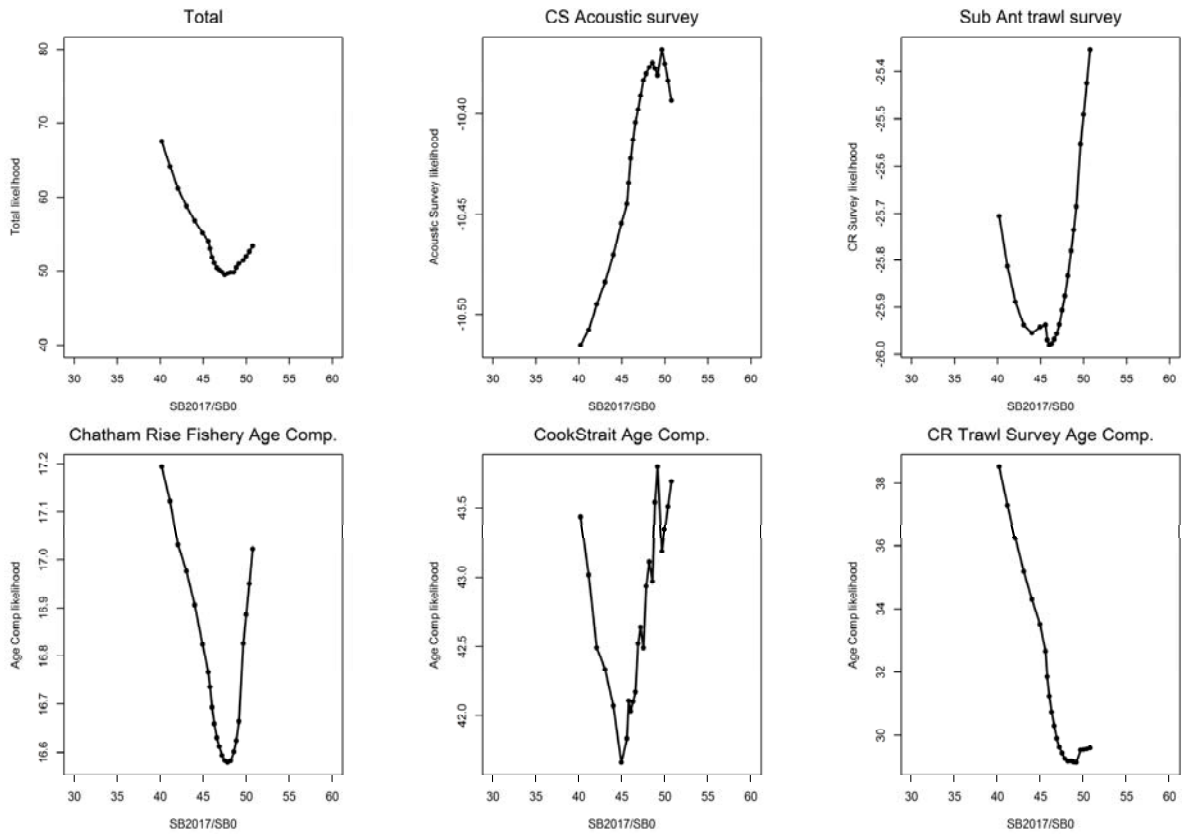
A small number of sensitivity runs were conducted for the eastern SS3 model (Table 8). Most notable was the estimation of temporal variation in the selectivity of the Chatham Rise commercial trawl fishery. The model estimated a strong shift towards the 2–3 year old fish during the late 1990s. The selectivity of these age classes was lower from the early 2000s onwards (Figure 9). The incorporation of the variation in selectivity resulted in a large improvement in fit to corresponding age composition data. However, this change resulted in a relatively small reduction in the level of spawning biomass

(10–15%) and the relative level of depletion. Estimates of annual recruitments were very similar between the two models. However, differences in the current  $F$ -at-age matrix and the overall level of recruitment ( $R_0$ ) resulted in slightly lower overall yields (15% lower) from the model option including variation in selectivity.

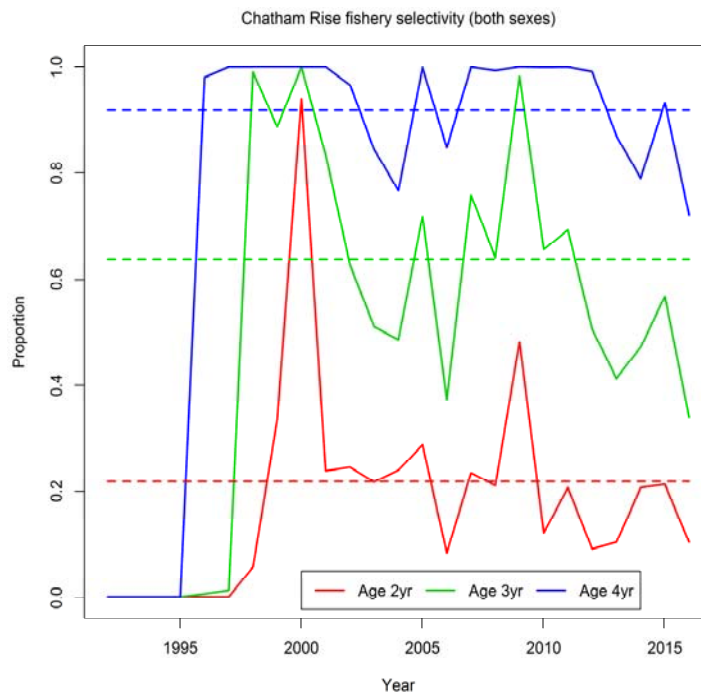
The incorporation of temporal variation in selectivity resulted in a considerably different trend in the vulnerable biomass for the Chatham Rise trawl fishery (Figure 40). The resulting trend in vulnerable biomass was more consistent with the trend in the fishery CPUE indices, especially from 2000 onwards, compared to the base model with constant (temporally invariant) selectivity (Figure 40).



**Figure 37: Likelihood profile  $LnR_0$  parameter for the main data components included in the Eastern SS3 model. The dashed vertical line represents the estimate of stock status from the model.**



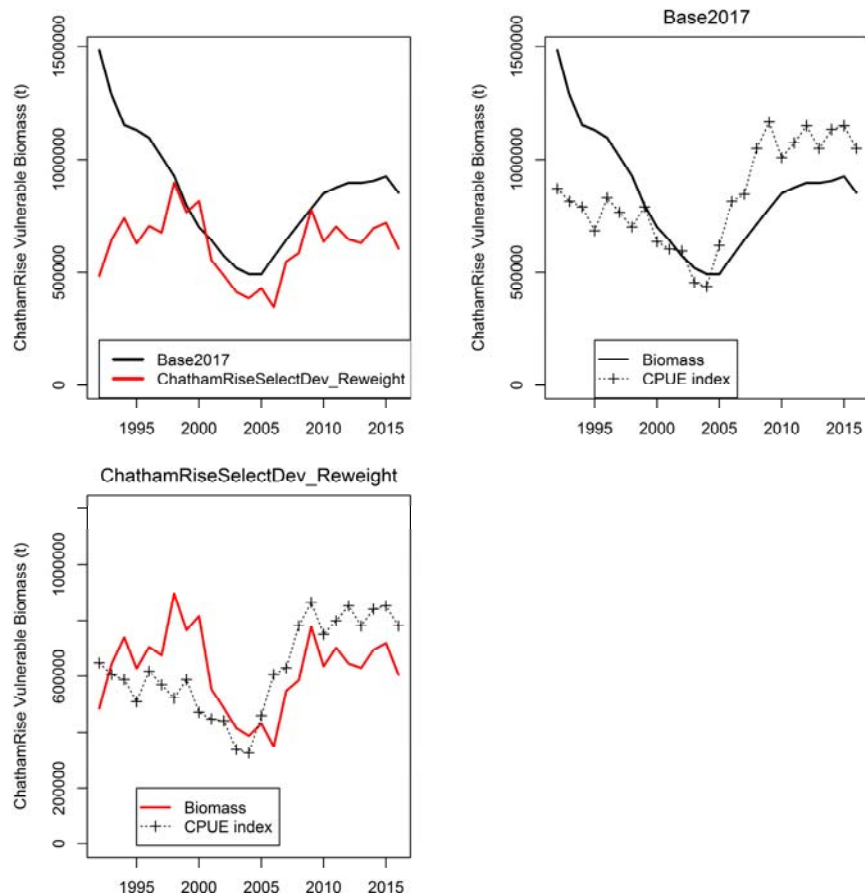
**Figure 38: Likelihood profile of current stock status ( $SB_{2017}/SB_0$ ), obtained from profiling  $LnR_0$  parameter, for the main data components included in the Eastern SS3 model. The dashed vertical line represents the estimate of stock status from the model.**



**Figure 39: A comparison of the annual selectivity of 2 year, 3 year and 4 year age classes for the Chatham Rise commercial fishery estimated from the ChathamRiseSelectDev model (solid lines) compared to the temporally invariant selectivity from the Base2017 model (dashed lines).**

**Table 8: Alternative model scenarios investigated for the Eastern stock SS3 model.**

Model	Parameter, structural change(s)	Comment
Base2017 SigmaR60	- SigmaR 0.60 (compared to 0.80 in base model).	- Lower initial (virgin) biomass compared to base model and, consequently, higher current stock status (relative to $SB_0$ ). Estimates of equilibrium yield are 14% lower than base model.
Mestimate	Estimate male and female M for age classes 6+ years.	Estimated Female M = 0.30, Male M = 0.37. Significant improvement to likelihood component for Cook Strait Age Comp. Increase in overall level of biomass but no appreciable change in current stock status (relative to $SB_0$ ).
ChathamRiseSelectDev	Incorporate time varying selectivity for Chatham Rise fishery, primarily the parameter controlling the age of the peak in selectivity of the double normal selectivity function and the width of the ascending limb of the selectivity ogive.	Estimates a strong trend in selectivity of the Chatham Rise trawl fishery and a large improvement in fit to corresponding age composition data, although patterns in the model residuals for the Age composition data persist. Smaller improvements in fit to the two other sets of age composition data. Trivial influence on spawning biomass trajectory; small increase in $R_0$ ; trivial difference in annual recruitments. Lower estimates of yield (15% lower) due to difference in current F-at-age matrix.
DownWtAgeComp	Base model has very high weighting for Age Comp data sets. Reduce ESS to 5 for all age comp observations (from three data sets)	Base model has very high weighting for Age Comp data sets. Trivial influence on spawning biomass trajectory; small increase in $R_0$ ; trivial difference in annual recruitments. Lower estimates of yield (15% lower) due to difference in current F-at-age matrix.



**Figure 40: A comparison of the recent trends in vulnerable biomass for the Chatham Rise trawl fishery from the model options with and without temporal variation in fishery selectivity. The trend in CPUE indices from the Chatham Rise commercial trawl fishery is also presented.**

### The two-model approach: Summary

The two separate SS3 models (eastern and western) were configured to enable an investigation of the influence of the key input data sets using a simpler modelling framework. The models yielded results that were similar to the corresponding stock components of the CASAL combined stock assessment model, despite being considerably less complex in structure (regarding stock structure, migration, natural mortality and selectivity). However, the SS3 single stock models do not adequately account for the complexity of the interaction between the two stocks on the Chatham Rise. This factor appears to be of significance in the estimation of recent levels of biomass for the Eastern stock, probably related to the estimation of recent recruitments (partitioned by E and W stock) and the attribution of Chatham Rise catches of the E or W stocks within the CASAL model.

The similarity of the overall results from the CASAL and SS3 models indicate that the SS3 models provide a useful framework for evaluating model performance, especially related to the weighting of individual data sets and changes in structural assumptions. The results of the SS3 model testing are likely to be indicative of the behaviour of the CASAL assessment model.

The similarity of the overall results between the CASAL and SS3 models also indicates that the additional complexity of the CASAL modelling framework (including movement dynamics, age-specific natural mortality and complex selectivity functions) does not significantly influence the assessment results, probably due to the high correlation between some of these parameters. However, the additional complexity of the CASAL modelling framework appears to result in higher uncertainty

in the estimates of current stock status, especially for the Western stock (based on the MCMC results from the SS3 model).

The parameterisation of natural mortality and selectivity in the CASAL model appears to have been adopted to address the relatively poor fits to the time-series of age composition data, especially from the commercial fishery. The SS3 modelling indicated that some of the discrepancies in the model fits are likely to be related to temporal changes in the selectivity of the commercial fisheries, presumably related to changes in the operation of the respective fisheries. However, marked patterns in the residuals do persist in those model options.

The likelihood profiles conducted using the SS3 models highlighted that the current assessment models are very strongly influenced by the age composition data sets. These data sets have attracted a high weighting relative to the abundance indices (primarily from trawl surveys) and hence dominate the overall model likelihoods.

For the SS3 eastern model, the lower bound of the estimate of current biomass is informed primarily by the Chatham Rise trawl survey age composition data. The data are generally less informative regarding the upper bound of overall biomass ( $R_0$ ) and current biomass ( $SB_{2017}/SB_0$ ), although the data from the Chatham Rise trawl survey biomass, Chatham Rise commercial age composition and Cook Strait age composition provide a relatively coherent signal regarding the overall magnitude of biomass.

For the SS3 western model, the likelihood profiles were rather poorly determined (suggesting local minima). Nonetheless, the results indicate that the estimation of the overall size of the stock ( $R_0$ ,  $SB_0$ ) is strongly influenced by the WCSI age composition data. The SubAntarctic trawl survey biomass indices are consistent with a somewhat lower overall biomass level, while the SubAntarctic trawl survey age composition data set is consistent with a somewhat higher overall biomass level. The estimate of current stock size is also primarily informed by the SubAntarctic trawl survey age composition data and the WCSI commercial age composition data. The SubAntarctic trawl survey biomass indices are consistent with lower estimates of current stock size (31%  $SB_0$  compared to 42%  $SB_0$ ).

The relatively low influence of the SubAntarctic trawl survey biomass indices in the overall likelihood is attributable to the relatively high process error ( $CV=38\%$ ) estimated for these indices in the CASAL assessment model. The level of process error is informed by the conflict between the age composition data and the survey biomass indices, primarily during the 2004–2007 when the catchability of the trawl survey appears to have been low. This observation is supported by the time-series of abundance estimates for individual year classes (determined as numbers of fish at age) from successive surveys. The respective year classes were also observed in the WCSI and SubAntarctic commercial age composition data sets for successive years and, consequently, the relative strength of these year classes is likely to be reasonably well determined.

While the age composition data are influential in the overall likelihoods from the Western and Eastern SS3 models, the down-weighting of these data sets (ESS 5) did not significantly influence the estimates of current stock status for either stock, although lower equilibrium yields were estimated for the Eastern stock (due to a change in the recent  $F$ -at-age matrix).

A range of other model trials were conducted for the Western and Eastern SS3 models. For the credible model options, there was no substantive change in the estimates of current stock status. This indicates that the CASAL assessment model results are relatively robust to the range of scenarios considered in the current analysis.

The recent trends in CPUE from the WCSI commercial fishery (and the SubAntarctic fishery) revealed a considerable decline in the catch rates from the fishery in 2016 and 2017. This decline was not evident in the CASAL stock trajectory (spawning biomass or WCSI vulnerable biomass). However, the estimation of temporal variation in the selectivity of the WCSI trawl fishery yielded trends in vulnerable biomass that were more similar to the WCSI CPUE indices, including a sharp decline in vulnerable



biomass in the last few years. This result reinforces the need to adequately account for changes in fishery selectivity in the CASAL model. The estimation of reliable trends in vulnerable biomass could improve the utility and application of the results from the assessment model (i.e., provide more reliable predictions for the performance of the commercial fishery).

#### 4. OVERALL CONCLUSIONS AND RECOMMENDATIONS

We recommend that the conclusions and recommendations in this report are considered alongside those of Butterworth et al. (2014).

Briefly, our recommendations are (not in order of importance):

- (1) Conduct retrospective analyses.
- (2) Move the assessment from CASAL to CASAL2.
- (3) Remove where possible any confounding in the selectivity-migration-YCS- $M$  assumptions.
- (4) Conduct further research into the assumed catchability change in the SubAntarctic.
- (5) Partition the age compositions into separate age blocks.
- (6) Conduct likelihood profiles for the various priors.
- (7) Further evaluate the estimation of the  $pE$  parameter.
- (8) Investigate sources of variation in the age composition data.
- (9) Further investigate CPUE trends, and report vulnerable biomass from the model.
- (10) Tidy up the biological assumptions, including deriving sensitivity runs.
- (11) Further review catch history.

The rationale for these is given below:

Retrospective analyses should be routinely conducted to investigate potential sources of bias in estimates of current stock status. Recent estimates of recruitment may be relatively poorly determined, and current status in the western stock model could vary more than the eastern stock.

Move the assessment from CASAL to CASAL2. The rationale for this is that CASAL2 will allow commercial selectivities to be modelled as a random walk. In conjunction with this, it would be useful to examine and develop covariates for selectivity.

The lower bound of the Western  $B_0$  estimates is influenced largely by the catch-at-age data, and priors (probably west coast acoustics); the upper bound to  $B_0$  is influenced largely by the SubAntarctic survey, and priors. The information from the catch-at-age data is interpreted via a complex selectivity-migration-YCS-natural mortality model, therefore we might be cautious about letting the catch-at-age data dominate estimates of stock size unless the assumptions around these data are clearly justified (e.g., having both selectivity and migration ogives determine availability to spawning fisheries, having domed selectivity, some poorly informed migration parameters, relatively low natural mortality rate on adult females, followed by severe mortality on older/larger fish). Any unnecessary or confounded parameters should be removed from the model.

Regarding the upper bound, evidence for any SubAntarctic regime shift that might be influencing catchability should be documented (if not already), and the survey periods with different  $q$ 's might be more carefully considered and justified, and might more appropriately be fitted assuming a  $q$ -ratio prior (rather than independent priors).

Further analysis of the variation in the abundance of individual year classes sampled at age by successive SubAntarctic trawl surveys may improve the understanding of the apparent variability in trawl survey catchability. More immediately, such an analysis could form the basis for developing a prior for defining the variation in catchability. Trawl survey biomass estimates could then be fitted in

the model incorporating catchability deviates constrained by the prior. This would remove the estimation of process error implemented in the CASAL assessment. The proposed approach may be less sensitive to the influence of other data sources and data weighting procedures (especially age composition reweighting), although it introduces a considerable number of additional parameters.

Partitioning the age compositions into separate age blocks, having different effective sample sizes, should be considered. In particular, further consideration should be given to the SubAntarctic trawl survey, specifically the reliability of the estimates of abundance of 2 (and 3?) year old fish. The CASAL assessment assumes that the process error is equivalent for all age classes, while the current study indicates that different components of the population (2–3 yr, 4–7 yr and 8+ yr) may be more or less consistent with other sets of data included in the model. Additional analyses could be conducted that simultaneously fit individual abundance indices (and age compositions) from these three age components of the survey (with their associated CVs). This approach may enable further evaluation of the extent of the factors contributing to the process error estimated for the SubAntarctic trawl survey biomass indices.

It would be useful to conduct  $B_0$  profiles for each of the priors, so that the veracity of highly influential priors might be reconsidered in detail.

Further consideration of the factors influencing the Eastern  $B_0$  would be worthwhile. In particular, it seems like the pE prior may be quite influential.

Age composition data from the commercial fisheries are quite variable over time and there are strong patterns in the associated model residuals. The precision of the age composition proportions at-age estimates appears to vary with age, but the model does not account for this.

Sources of variation in the length and age composition data should be investigated; for example, applying a GLM approach to investigate the main sources of variation (e.g. year, fishing depth, area, time of day, season, gear, size of vessel, processing type of vessel, inside/outside 25-mile line, etc). The identification of significant factors may highlight the need to account for temporal changes in the selectivity of specific fisheries (and formulate appropriate covariates). Preliminary modelling has already identified a number of fisheries where selectivity may have varied considerably (WCSI and Chatham Rise). Changes in fishery selectivity have the potential to influence recruitment estimates, age specific mortality estimates and, correspondingly, estimates of current and future yields.

In addition, it would be useful to determine the appropriateness of current approaches of determining the scaled age compositions from the commercial fisheries (especially stratification of length samples).

The estimation of process error for the Chatham Rise trawl survey biomass indices assumes that the error structure is equivalent for all age classes sampled by the survey. However, estimates of the abundance of the 1+ year class generally have a lower precision than abundance estimates for older age classes 2+ year and 3++ years (see table 4a of [DWWG\\_2017\\_24\\_Section\\_4\\_Hoki\\_Data\\_Collate\\_Trawl\\_Surveys.pdf](#)). On that basis it may be appropriate to incorporate the indices of 1+ abundance from the Chatham Rise trawl survey separately from the older age classes.

This review was stimulated by a difference in stock status perception between the assessment model and anecdotal reports from parts of the fishing industry. Whilst we have considered the assessment model, it would be useful to examine the performance of the west coast fishery, and to further develop a CPUE index. Vulnerable biomass should be reported, as it is possible that this might explain part of the mis-match.

Investigate the potential to incorporate recent CPUE indices as indices of abundance in the assessment models. Recent CPUE indices from Chatham Rise, SubAntarctic and WCSI fisheries were relatively

consistent with trends in vulnerable biomass for the corresponding fisheries (once temporal variation in selectivity was incorporated into the model). Incorporation of recent CPUE indices (from 2005 onwards) may improve the precision of estimates of recent stock status, especially for the Western stock (the WCSI acoustic survey indices are relatively uninformative and there is a high process error estimated for the SubAntarctic trawl survey indices).

Although they may not substantively influence stock status, it would be useful to revise some of the biological assumptions, for example, the different growth functions for the Western and Eastern stocks, and the assumptions of constant growth over time.

Revision of the biological assumptions (in particular M-at-age), and some simplification of the model (especially selectivities and migration ogives), could lead to a range of plausible sensitivity runs.

The CASAL assessment model applies the Francis (2011) weighting approach (TA1.8) to determine the appropriate weighting of the age composition observations. This approach has assigned some relatively large weights (ESS) to the age composition data, especially Cook Strait commercial (ESS 37-115) and Chatham Rise age compositions (trawl survey ESS 43-91, fishery ESS 22-57). There was concern that the high weightings applied to these Eastern age compositions could potentially be influencing the fit to the other data sets and corresponding parameters, including data from the Western components of the CASAL model. However, the age compositions included in the separate SS3 models received similar weightings when the TA1.8 approach was applied. This suggests that the relative weightings of the age composition data were generally consistent with the corresponding error assumptions associated with the relevant (stock specific) abundance indices (and other age compositions and structural assumptions). Nonetheless, the influence of the individual age composition data set on current stock status should be routinely evaluated in the assessment modelling process.

A further review of catch history would be useful. In particular, to investigate the extent of mis-specification of conversion factors, mis-reporting of catches of juvenile hoki, and incidental mortality. There is potential to evaluate this in the modelling framework. The reviewers noted a decline in recruitment (E and W) in the mid-1990s corresponding to the development of the CR fishery. Research has already shown that a range of alternative catch histories make negligible difference to estimates of stock status (Horn et al., 2018).

## 5. ACKNOWLEDGMENTS

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## APPENDIX A: Residual diagnostic plots for the two-model approach

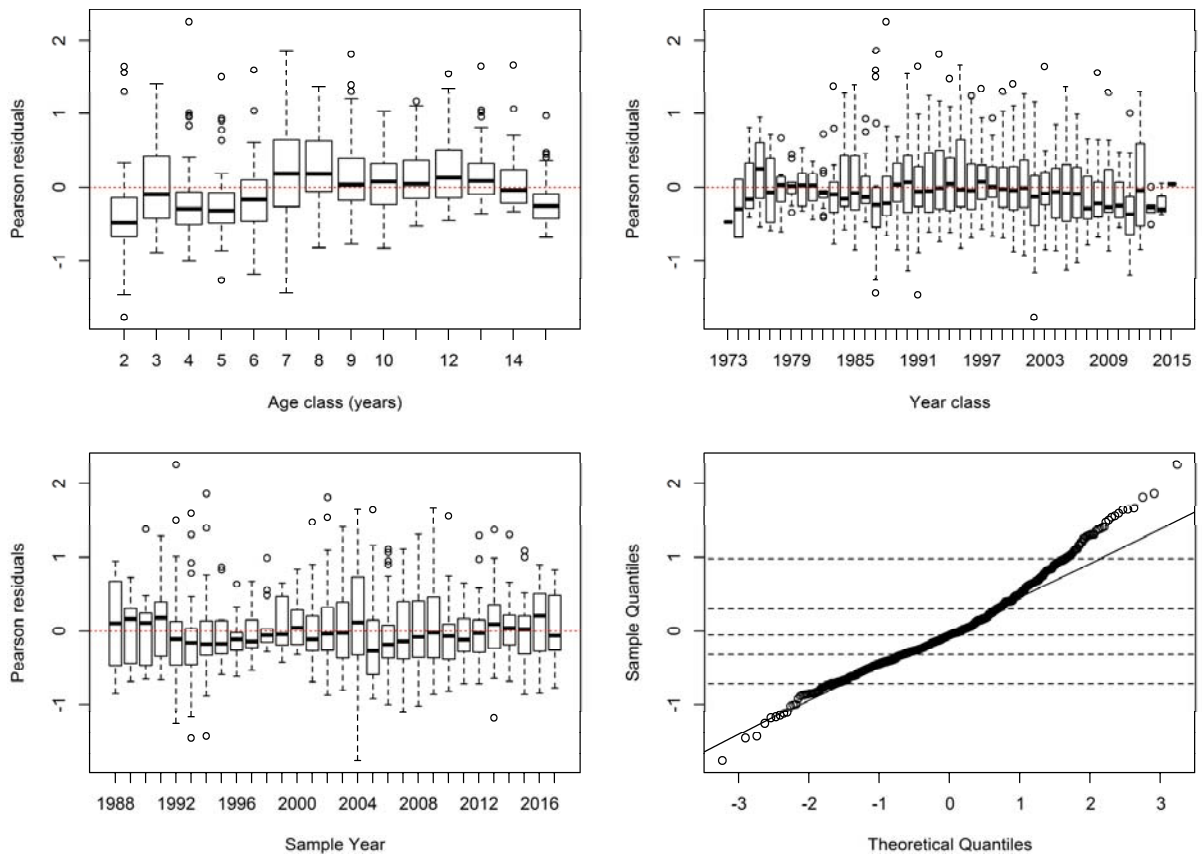
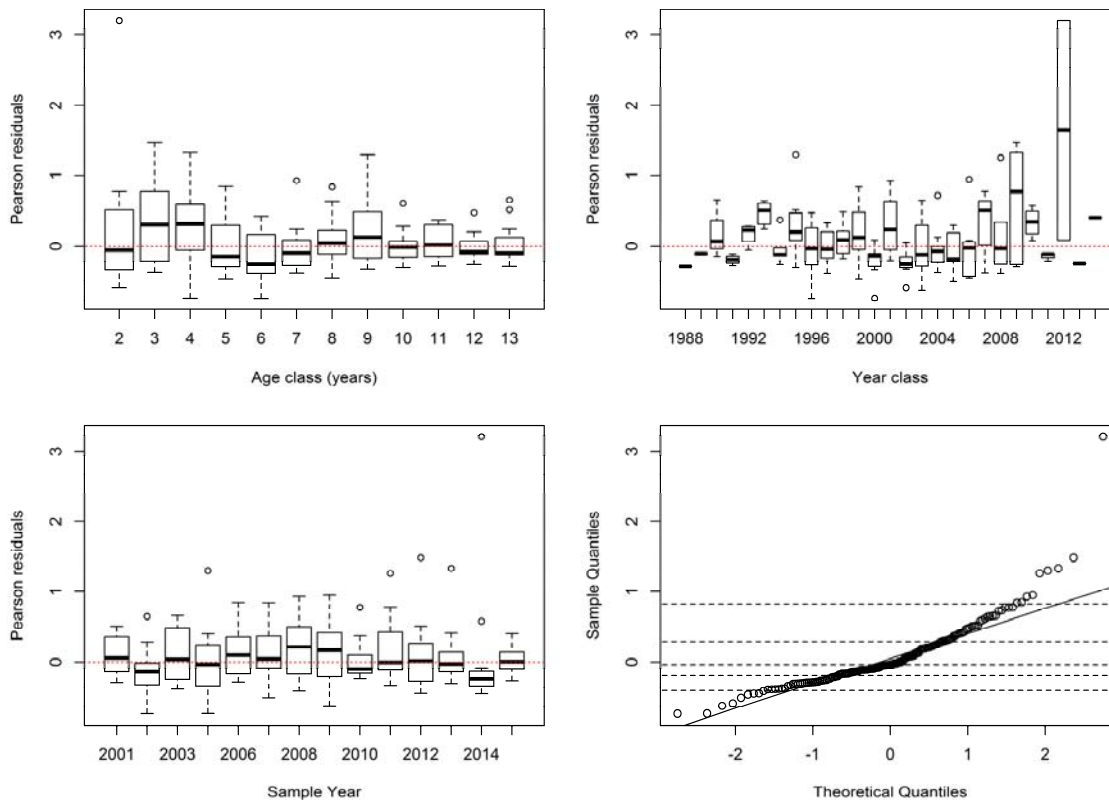
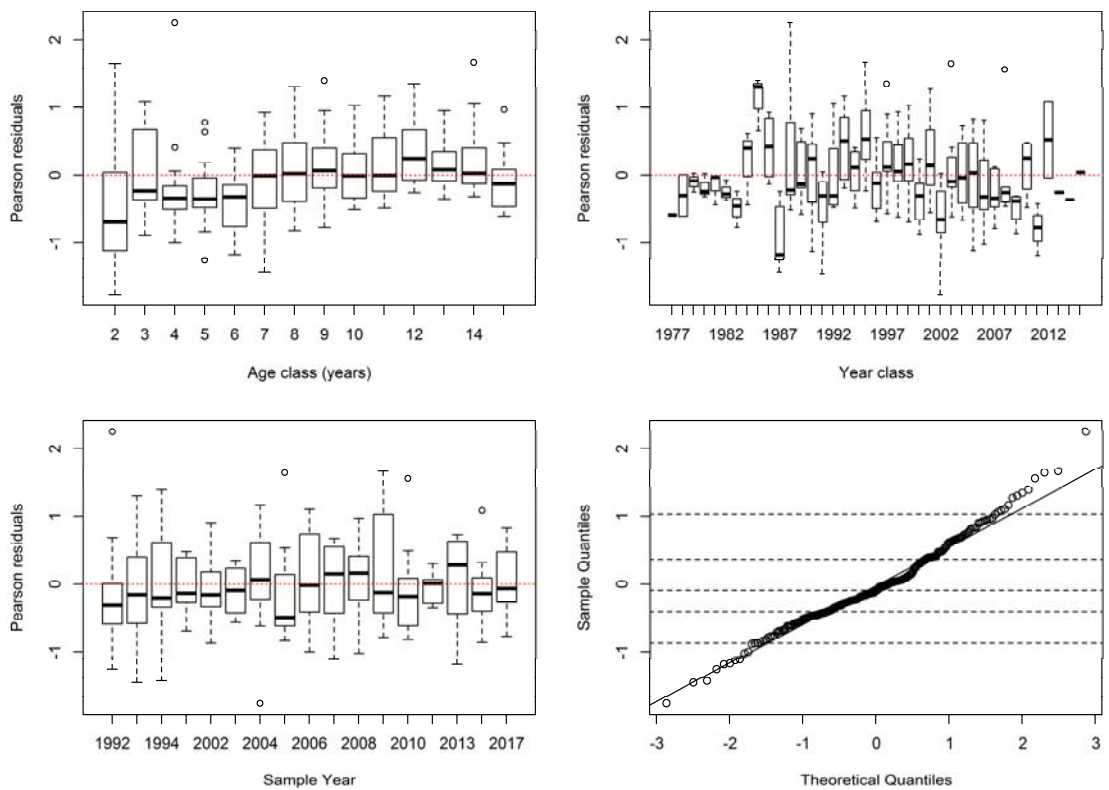


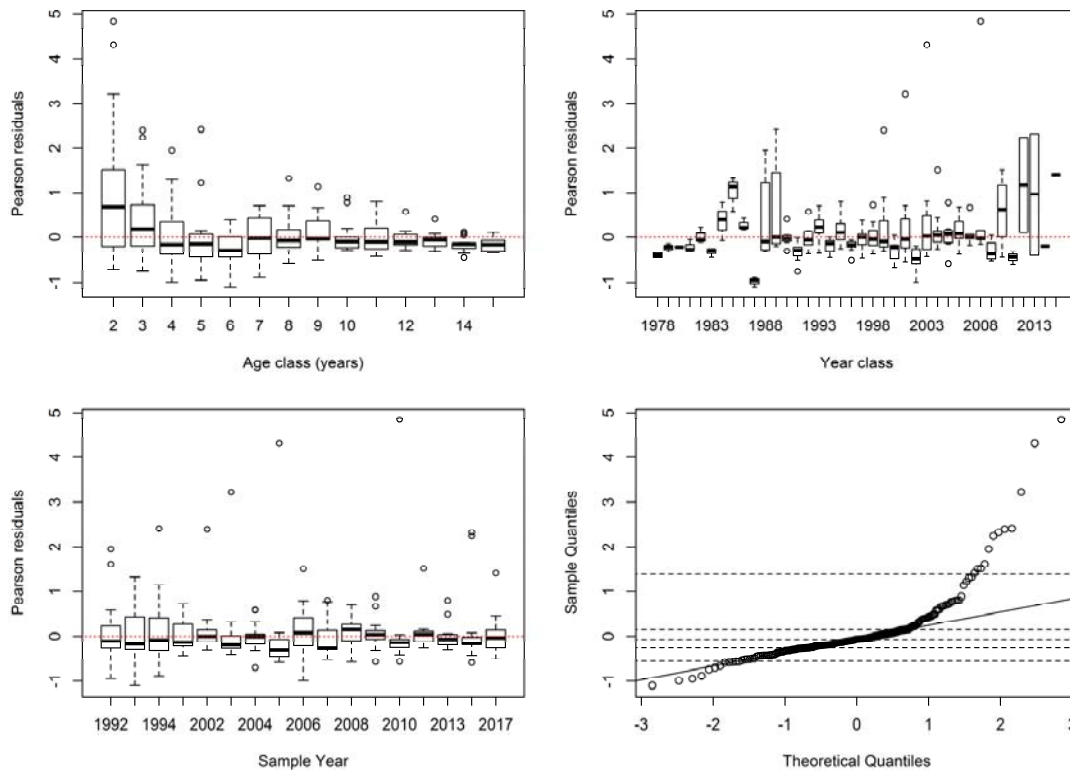
Figure A1. Residuals from the fit to the female age compositions from the SubAntarctic commercial fishery for the SS3 western model.



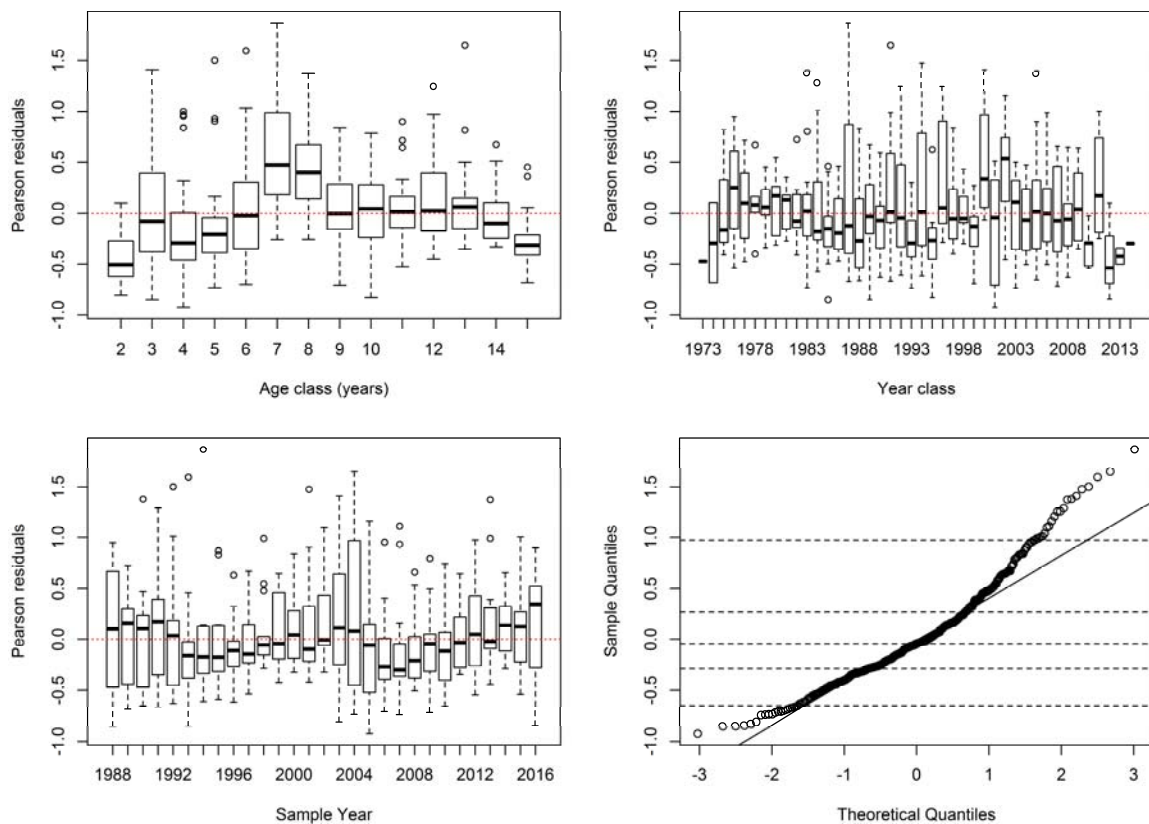
**Figure A2. Residuals from the fit to the male age compositions from the SubAntarctic commercial fishery for the SS3 western model.**



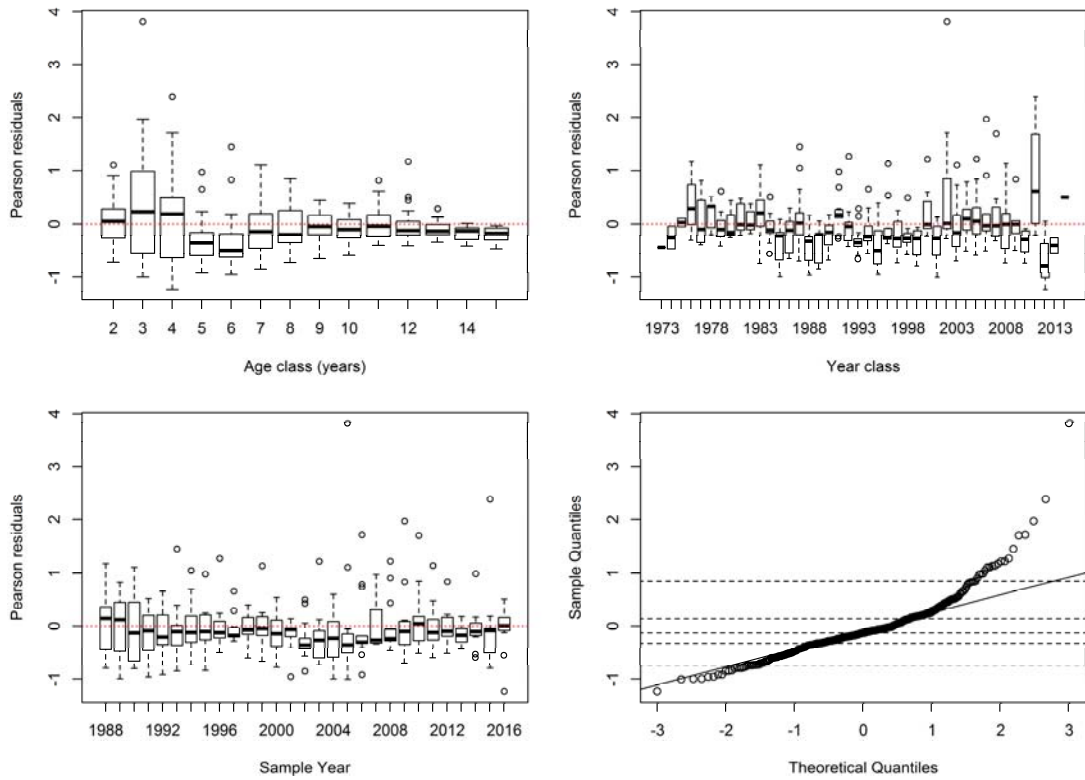
**Figure A3. Residuals from the fit to the female age compositions from the SubAntarctic trawl survey for the SS3 western model.**



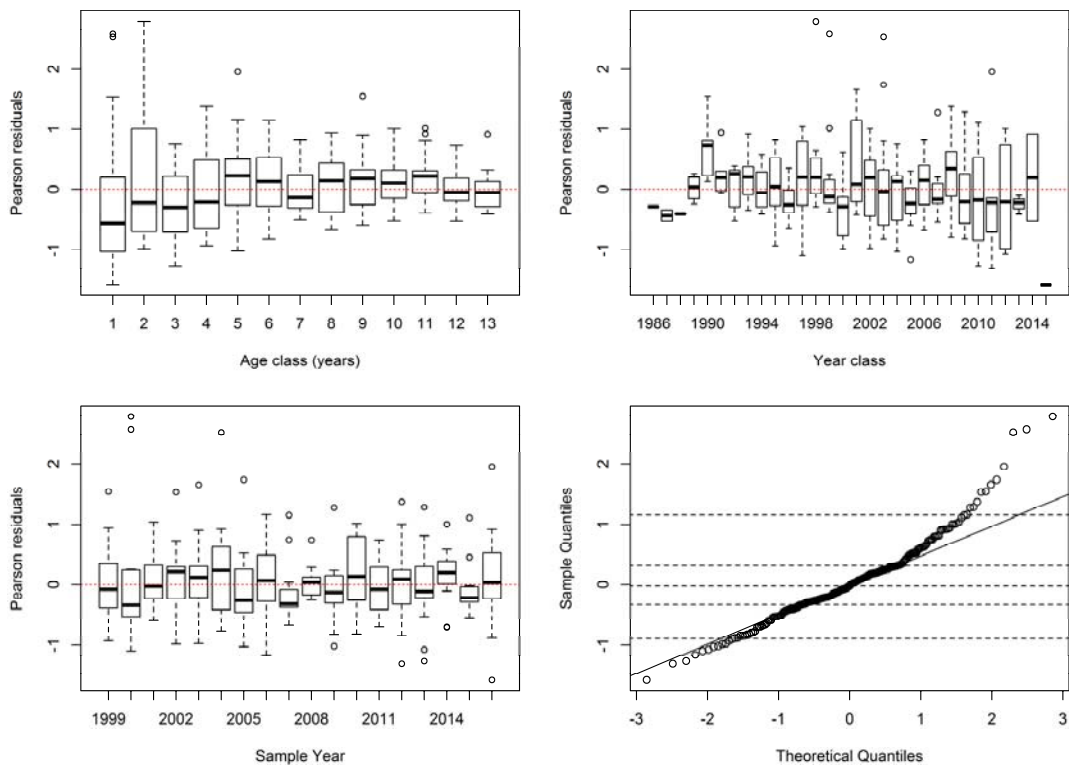
**Figure A4. Residuals from the fit to the male age compositions from the SubAntarctic trawl survey for the SS3 western model.**



**Figure A5. Residuals from the fit to the female age compositions from the WCSI commercial fishery for the SS3 western model.**

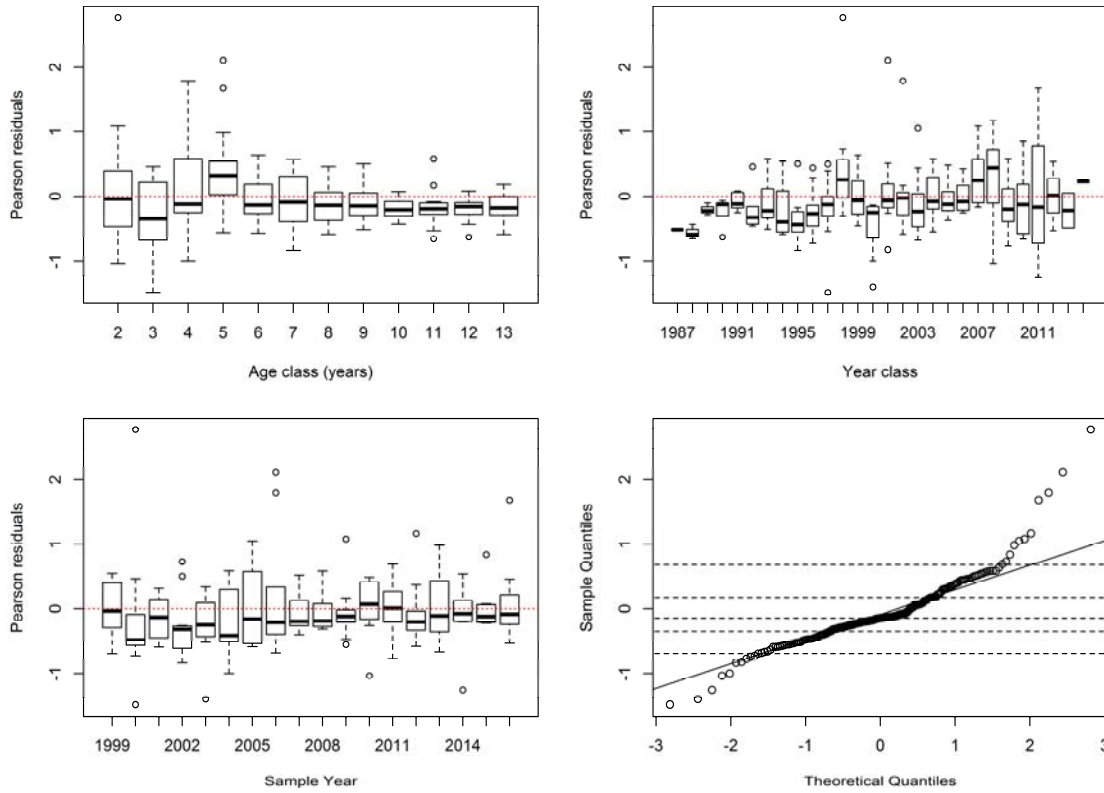


**Figure A6. Residuals from the fit to the male age compositions from the WCSI commercial fishery for the SS3 western model.**

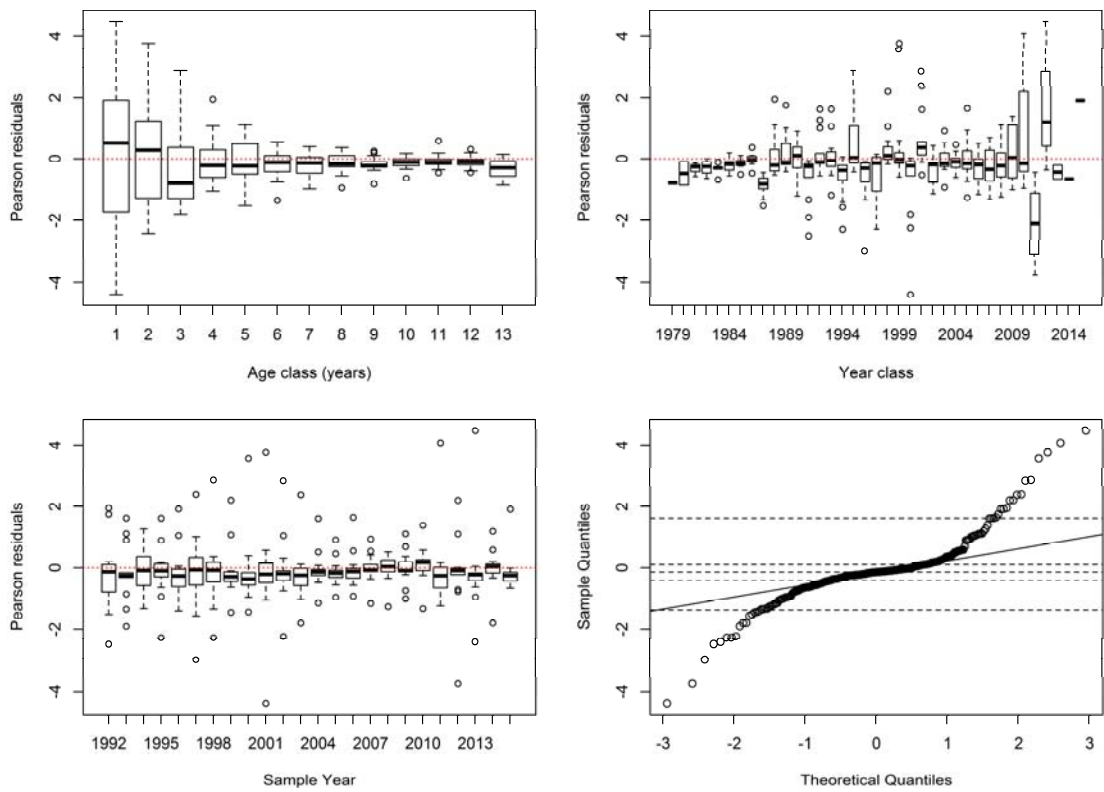


**Figure A7. Residuals from the fit to the female age compositions from the Chatham Rise commercial fishery for the SS3 Eastern model.**

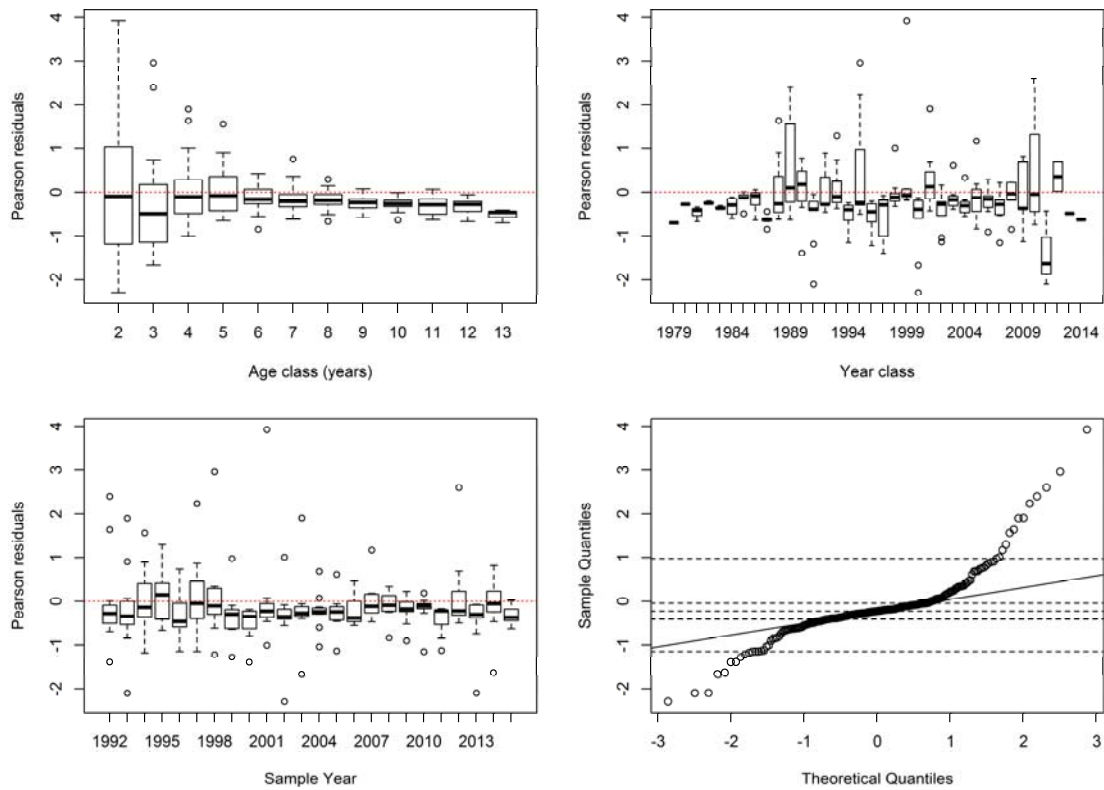




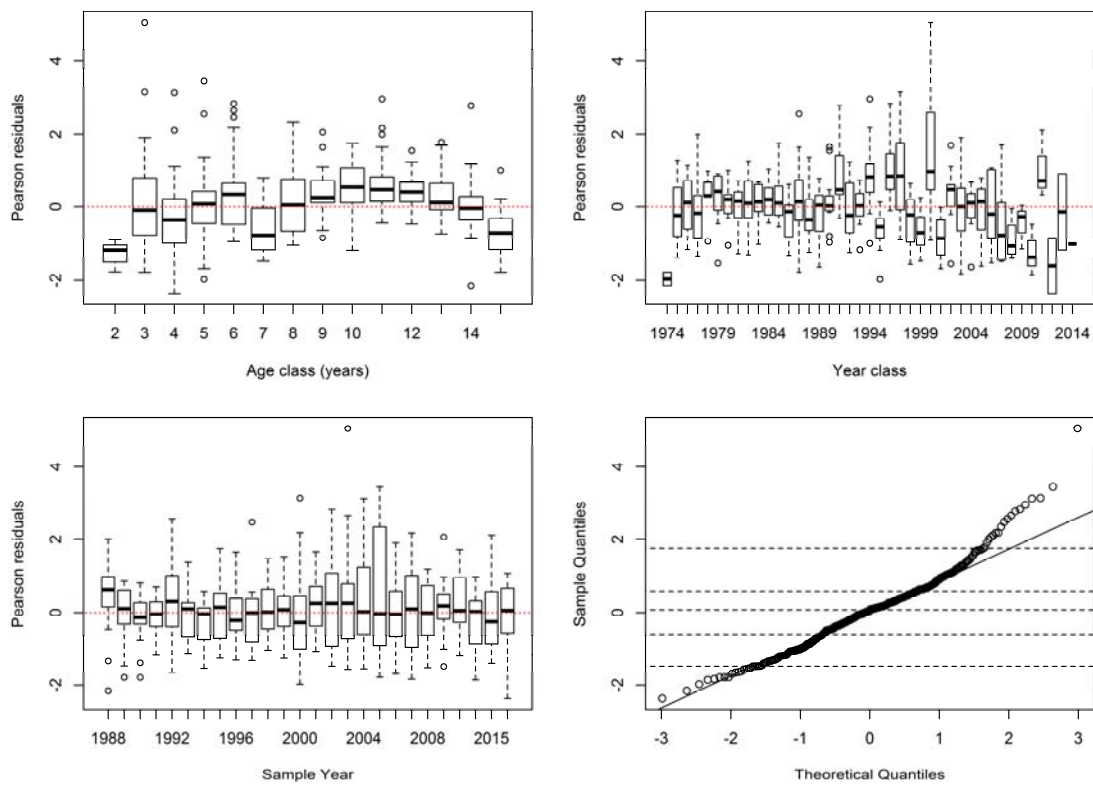
**Figure A8. Residuals from the fit to the male age compositions from the Chatham Rise commercial fishery for the SS3 Eastern model.**



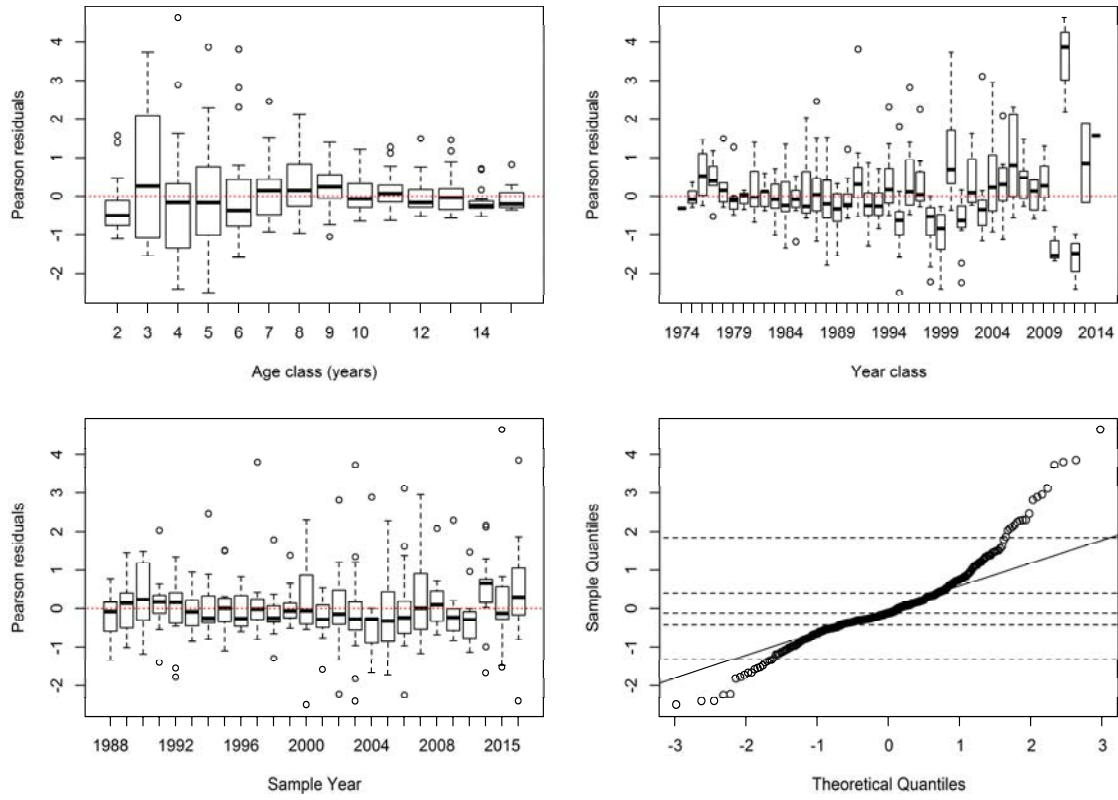
**Figure A9. Residuals from the fit to the female age compositions from the Chatham Rise trawl survey for the SS3 Eastern model.**



**Figure A10. Residuals from the fit to the male age compositions from the Chatham Rise trawl survey for the SS3 Eastern model.**



**Figure A11. Residuals from the fit to the female age compositions from the Cook Strait commercial fishery for the SS3 Eastern model.**



**Figure A12.** Residuals from the fit to the male age compositions from the Cook Strait commercial fishery for the SS3 Eastern model.