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Stock assessment of hake (*Merluccius australis*) in the Sub-Antarctic (part of HAK 1) for the 2011–12 fishing year

New Zealand Fisheries Assessment Report 2013/5.

P.L. Horn

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EXECUTIVE SUMMARY

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***New Zealand Fisheries Assessment Report 2013/5.* 52 p.**

This report summarises the stock assessment of hake in Quota Management Area HAK 1 south of latitude 46° S (the Sub-Antarctic) for the 2011–10 fishing year. An updated Bayesian assessment was conducted using the general-purpose stock assessment program CASAL v2.22. The assessment incorporated all relevant biological parameters, the commercial catch histories, updated CPUE series, and series of proportion-at-age data from the commercial trawl fishery and two research survey series. The analysis includes fishery data up to the end of the 2009–10 fishing year. New model input data and revised catch histories for all three hake stocks (Sub-Antarctic, Chatham Rise, and west coast South Island) are also reported here.

Initial investigations of the available data and preliminary model runs indicated that the sex ratios in the at-age data were inconsistent; the CPUE series was inconsistent with survey biomass estimates; and widely fluctuating estimates of year class strengths throughout the late 1970s were driven by the error structure applied to the age data acting on sparse data sets. Consequently, a base case model was developed in which sex was excluded, the 1974 to 1979 year class strengths were smoothed, and the CPUE series was omitted.

Three additional models were run as sensitivity analyses. The ‘two sex’ model included sex in the partition and ‘at-age’ data were provided by sex. The ‘CPUE’ model was the same as the single sex model, but it incorporated a trawl fishery CPUE series. The ‘estimate *M*’ model estimated instantaneous natural mortality as a function of age.

The stock status of hake in the Sub-Antarctic is not well known in absolute terms. It appears likely that the stock has declined throughout the 1990s, with the decline driven by poor recruitment rather than fishing pressure. The single sex model indicated that the spawning stock is currently at about 52% B_0, and that B_0 was about 95 000 t. The estimate *M* model produced slightly lower estimates (52% B_0, and 84 000 t), but fitted the available data better than the single sex model. The two sex model was considered undesirable because it was not believed that the inclusion of sex in the partition could logically account for a more than doubling of biomass. The CPUE model produced the most optimistic assessment (current spawning stock of 68% B_0), but the CPUE series was not well fitted and did not capture the decline in biomass during the 1990s. However, none of the model runs were indicative of current biomass being lower than the target of 40% B_0, and all projected an increase in biomass over the next five years with future catches equal to those from recent years (2300 t).

The stock is probably being well monitored by the November-December trawl survey series. While the stock status appears to be reasonably well defined, estimates of past and current absolute stock size are very uncertain owing to poor contrast in the relative abundance series. Because of the high uncertainty in estimates of absolute biomass, yield estimates are also very uncertain. However, there are probably no current sustainability issues for this stock.

1. INTRODUCTION

This report outlines the stock assessment of hake (*Merluccius australis*) in the Sub-Antarctic section of Quota Management Area (QMA) HAK 1 (i.e., HAK 1 south of latitude 46° S), with the inclusion of data up to the end of the 2009–10 fishing year. The current stock hypothesis for New Zealand hake suggests that there are three separate hake stocks (Colman 1998); the west coast South Island stock (WCSI, the area of HAK 7 off the west coast of South Island), the Sub-Antarctic stock (the area of HAK 1 that encompasses the Southern Plateau, the Stewart-Snares shelf, and Puysegur Bank), and the Chatham Rise stock (HAK 4 and the area of HAK 1 on the western Chatham Rise).

The stock assessment of hake in the Sub-Antarctic is presented as a Bayesian assessment implemented as a single stock model using the general-purpose stock assessment program CASAL (Bull et al. 2008). Estimates of the current stock status and projected stock status are provided.

This report fulfils Objective 3 of Project DEE201002HAKA “To update the stock assessment of hake, including biomass estimates and sustainable yields”, funded by the Ministry of Fisheries. Revised catch histories are reported here, as are new model input data and research results for all three hake stocks. Although some of these data are not relevant to the assessment reported here, they are included to provide in one place an up-to-date summary of the available knowledge and literature on *Merluccius australis* in New Zealand waters.

1.1 Description of the fishery

Hake are widely distributed through the middle depths of the New Zealand Exclusive Economic Zone (EEZ) mostly south of latitude 40° S (Anderson et al. 1998). Adults are mainly distributed in depths from 250 to 800 m although some have been found as deep as 1200 m, while juveniles (0+) are found in shallower inshore regions under 250 m (Hurst et al. 2000). Hake are taken by large trawlers — often as bycatch in fisheries targeting hoki, although target fisheries also exist (Devine 2009). Present management divides the fishery into three main fish stocks: (a) the Challenger QMA (HAK 7), (b) the Southeast (Chatham Rise) QMA (HAK 4), and (c) the remainder of the EEZ comprising the Auckland, Central, Southeast (Coast), Southland, and Sub-Antarctic QMAs (HAK 1). An administrative fish stock exists in the Kermadec QMA (HAK 10) although there are no recorded landings from this area. The hake QMAs are shown in Figure 1.

The largest fishery has been off the west coast of the South Island (HAK 7) with the highest catch (17 000 t) recorded in 1977, immediately before the establishment of the EEZ. Currently, the TACC for HAK 7 is the largest, at 7700 t out of a total for the EEZ of 13 211 t. The WCSI hake fishery has generally consisted of bycatch in the much larger hoki fishery, but it has undergone a number of changes during the last decade (Devine 2009). These include changes to the TACCs of both hake and hoki, and also changes in fishing practices such as gear used, tow duration, and strategies to limit hake bycatch. In some years, notably in 1992, 1993, 2006, and 2009 there has been a hake target fishery in September after the peak of the hoki fishery is over (Ballara 2012).

On the Chatham Rise and in the Sub-Antarctic, hake have been caught mainly as bycatch by trawlers targeting hoki, although significant targeting occurs in both areas (Devine 2009). Increases in TACCs from 2610 t to 3500 t in HAK 1 and from 1000 t to 3500 t in HAK 4 from the 1991–92 fishing year allowed the fleet to increase the landings of hake from these fish stocks. Reported catches rose over a number of years to the levels of the new TACCs in both HAK 1 and HAK 4, with catches in HAK 1 remaining relatively steady since. The TACC for HAK 1 has increased since then to its current level of 3701 t. Landings from HAK 4 steadily declined from 1998–99 to a low of 811 t in 2002–03, but increased to 2275 t in 2003–04. However, from 2004–05, the TACC for HAK 4 was reduced from 3500 t to 1800 t with an overall TAC of 1818 t. Annual landings have been markedly lower than the new TACC since then. From 1 October 2005 the TACC for HAK 7 was increased to 7700 t with an overall TAC of 7777 t. This new catch limit was set equal to average annual catches over the previous 12 years, a catch level that is believed to be sustainable in the short term.

Dunn (2003a) found that area misreporting between the WCSI and the Chatham Rise fisheries occurred from 1994–95 to 2000–01. He estimated that between 16 and 23% (700–1000 t annually) of WCSI landings were misreported as deriving from Chatham Rise, predominantly in June, July, and September. Levels of misreporting before 1994–95 and after 2000–01, and between WCSI and Sub-Antarctic, were estimated as negligible, and there is no evidence of significant misreporting since 2001–02 (Devine 2009).

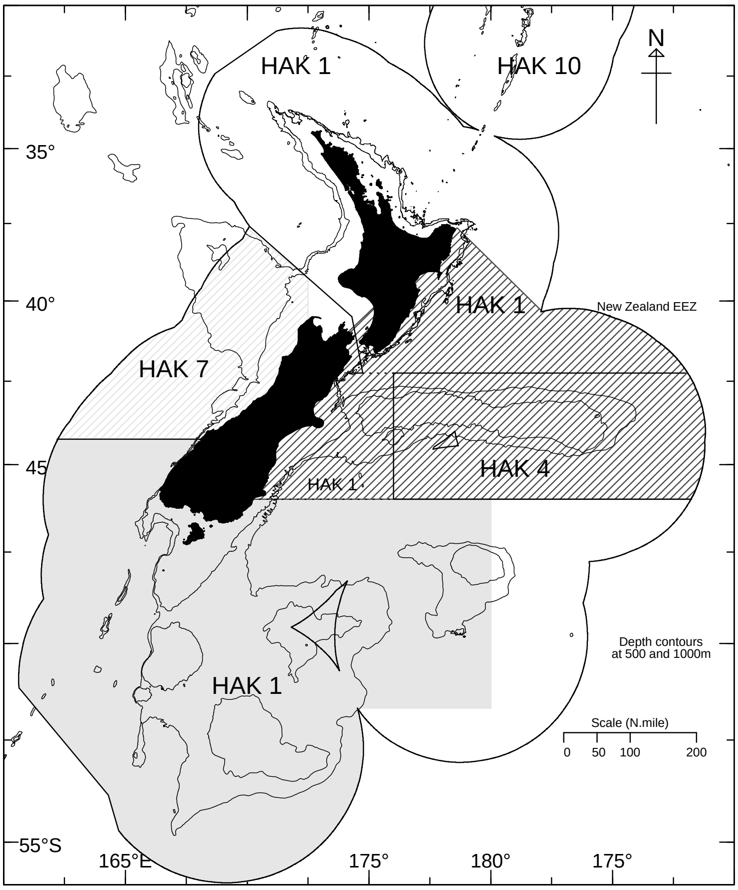


Figure 1: Quota Management Areas (QMAs) HAK 1, 4, 7, and 10; and the west coast South Island (light shading), Chatham Rise (dark shading), and Sub-Antarctic (medium shading) hake stock boundaries assumed in this report.

1.2 Literature review

Previous assessments of hake, by fishing year, are as follows: 1991–92 (Colman et al. 1991), 1992–93 (Colman & Vignaux 1992), 1997–98 (Colman 1997), 1998–99 (Dunn 1998), 1999–2000 (Dunn et al. 2000), 2000–01 (Dunn 2001), 2002–03 (Dunn 2003b), 2003–04 (Dunn 2004a, 2004b), 2004–05 (Dunn et al. 2006), 2005–06 (Dunn 2006), and 2006–07 (Horn & Dunn 2007). The Bayesian stock assessment software CASAL (Bull et al. 2008) has been used for all assessments since 2002–03. The most recent assessments by stock are: Chatham Rise (Horn & Francis 2010), Sub-Antarctic (Horn 2008), and WCSI (Horn 2011).

Since 1991, resource surveys have been carried out from R.V. *Tangaroa* in the Sub-Antarctic in November–December 1991–1993 and 2000–2009, September–October 1992, and April–June 1992, 1993, 1996, and 1998. On Chatham Rise, a consistent time series of resource surveys from *Tangaroa* has been carried out in January 1992–2011. Appendix A gives more details on these surveys.

Standardised CPUE indices for the Sub-Antarctic, Chatham Rise, and WCSI stocks were updated for the period up to the 2008–09 fishing year (Ballara & Horn 2011). These update the indices estimated by Phillips & Livingston (2004), Kendrick (1998), Dunn et al. (2000), Dunn & Phillips (2006), Devine & Dunn (2008), and Devine (2010). Indices for the Sub-Antarctic stock only were updated to the 2009–10 fishing year by Ballara (2012). A descriptive analysis of all New Zealand's hake fisheries up to the 2005–06 fishing year was prepared by Devine (2009).

2. REVIEW OF THE FISHERY

2.1 TACCs, catch, landings, and effort data

Reported catches from 1975 to 1987–88 are shown in Table 1, and reported landings for each QMA since 1983–84 and TACCs since 1986–87 are shown in Table 2. Revised estimates of landings by QMA for 1989–90 to 2009–10 (Table 3) were derived by examining the reported tow-by-tow catches of hake and correcting for possible misreporting, using the method of Dunn (2003a).

Revised landings by stock are given in Table 4. The derivation of the catch from 1974–75 to 1988–89 was described for the Chatham Rise and Sub-Antarctic stocks by Dunn et al. (2000) and for WCSI by Dunn (2004b). Landings since 1989–90 from Chatham Rise and Sub-Antarctic and since 1991–92 for WCSI were obtained from the corrected data used to produce Table 3, but this time summing the landings reported in each of the three shaded areas shown on Figure 1. WCSI revised estimates for 1988–89 to 1990–91 are from Colman & Vignaux (1992), who estimated the actual hake catch in HAK 7 by multiplying the total hoki catch (which was assumed to be correctly reported by vessels both with and without observers) by the ratio of hake to hoki in the catch of vessels carrying observers. Reported and estimated catches for 1988–89 were respectively 6835 t and 8696 t; for 1989–90, 4903 t reported and 8741 t estimated; and for 1990–91, 6189 t reported and 8246 t estimated. The catch for 2010–11 from the Sub-Antarctic was assumed based on landings from recent years (Table 4).

Table 1: Reported hake catches (t) from 1975 to 1987–88. Data from 1975 to 1983 from Ministry of Agriculture & Fisheries (Fisheries); data from 1983–84 to 1985–86 from Fisheries Statistics Unit; data from 1986–87 to 1987–88 from Quota Management System.

	New Zealand vessels			Foreign licensed vessels				
Fishing year	Domestic	Chartered	Total	Japan	Korea	USSR	Total	Total
1975 [1]	0	0	0	382	0	0	382	382
1976 [1]	0	0	0	5 474	0	300	5 774	5 774
1977 [1]	0	0	0	12 482	5 784	1 200	19 466	19 466
1978–79 [2]	0	3	3	398	308	585	1 291	1 294
1979–80 [2]	0	5 283	5 283	293	0	134	427	5 710
1980–81 [2]				No data available				
1981–82 [2]	0	3 513	3 513	268	9	44	321	3 834
1982–83 [2]	38	2 107	2 145	203	53	0	255	2 400
1983 [3]	2	1 006	1 008	382	67	2	451	1 459
1983–84 [4]	196	1 212	1 408	522	76	5	603	2 011
1984–85 [4]	265	1 318	1 583	400	35	16	451	2 034
1985–86 [4]	241	2 104	2 345	465	52	13	530	2 875
1986–87 [4]	229	3 666	3 895	234	1	1	236	4 131
1987–88 [4]	122	4 334	4 456	231	1	1	233	4 689

1. Calendar year
2. 1 April to 31 March
3. 1 April to 30 September
4. 1 October to 30 September

Table 2: Reported landings (t) of hake by QMA from 1983–84 to 2009–10 and actual TACCs (t) for 1986–87 to 2009–10. Data from 1983–84 to 1985–86 from Fisheries Statistics Unit; data from 1986–87 to 2009–10 from Quota Management System (– indicates that the data are unavailable).

QMA	HAK 1		HAK 4		HAK 7		HAK 10		Total	
	Landings	TACC	Landings	TACC	Landings	TACC	Landings	TACC	Landings	TACC
1983–84	886	–	180	–	945	–	0	–	2 011	–
1984–85	670	–	399	–	965	–	0	–	2 034	–
1985–86	1 047	–	133	–	1 695	–	0	–	2 875	–
1986–87	1 022	2 500	200	1 000	2 909	3 000	0	10	4 131	6 510
1987–88	1 381	2 500	288	1 000	3 019	3 000	0	10	4 689	6 510
1988–89	1 487	2 513	554	1 000	6 835	3 004	0	10	8 876	6 527
1989–90	2 115	2 610	763	1 000	4 903	3 310	0	10	7 783	6 930
1990–91	2 603	2 610	743	1 000	6 148	3 310	0	10	9 567	6 930
1991–92	3 156	3 500	2 013	3 500	3 026	6 770	0	10	8 196	13 780
1992–93	3 525	3 501	2 546	3 500	7 154	6 835	0	10	13 224	13 846
1993–94	1 803	3 501	2 587	3 500	2 974	6 835	0	10	7 363	13 847
1994–95	2 572	3 632	3 369	3 500	8 841	6 855	0	10	14 781	13 997
1995–96	3 956	3 632	3 465	3 500	8 678	6 855	0	10	16 082	13 997
1996–97	3 534	3 632	3 524	3 500	6 118	6 855	0	10	13 176	13 997
1997–98	3 809	3 632	3 523	3 500	7 416	6 855	0	10	14 749	13 997
1998–99	3 845	3 632	3 324	3 500	8 165	6 855	0	10	15 333	13 997
1999–00	3 899	3 632	2 803	3 500	6 898	6 855	0	10	13 600	13 997
2000–01	3 504	3 632	2 472	3 500	8 134	6 855	0	10	14 110	13 997
2001–02	2 870	3 701	1 424	3 500	7 519	6 855	0	10	11 813	14 066
2002–03	3 336	3 701	811	3 500	7 433	6 855	0	10	11 581	14 066
2003–04	3 461	3 701	2 272	3 500	7 943	6 855	0	10	13 686	14 066
2004–05	4 797	3 701	1 266	1 800	7 316	6 855	0	10	13 377	12 366
2005–06	2 743	3 701	305	1 800	6 906	7 700	0	10	9 955	13 211
2006–07	2 025	3 701	900	1 800	7 668	7 700	0	10	10 592	13 211
2007–08	2 445	3 701	865	1 800	2 620	7 700	0	10	5 930	13 211
2008–09	3 415	3 701	856	1 800	5 954	7 700	0	10	10 226	13 211
2009–10	2 156	3 701	208	1 800	2 351	7 700	0	10	4 715	13 211

Table 3: Revised landings (t) by QMA 1989–90 to 2009–10 from Ballara (2012).

Fishing	QMA			Total
Year	HAK 1	HAK 4	HAK 7	
1989–90	2 115	763	4 903	7 781
1990–91	2 593	726	6 175	9 494
1991–92	3 156	2 013	3 027	8 196
1992–93	3 522	2 546	7 157	13 225
1993–94	1 787	2 587	2 990	7 364
1994–95	2 346	2 896	9 538	14 780
1995–96	3 828	3 070	9 089	15 987
1996–97	3 300	3 190	6 846	13 336
1997–98	3 659	3 239	7 683	14 581
1998–99	3 703	2 740	8 786	15 229
1999–00	3 781	2 756	7 042	13 579
2000–01	3 429	2 321	8 351	14 101
2001–02	2 865	1 420	7 499	11 784
2002–03	3 334	805	7 406	11 545
2003–04	3 455	2 254	7 943	13 652
2004–05	4 795	1 260	7 302	13 357
2005–06	2 742	305	6 897	9 944
2006–07	2 006	900	7 660	10 566
2007–08	2 442	865	2 615	5 922
2008–09	3 409	854	5 945	10 208
2009–10	2 156	208	2 340	4 704

Table 4: Revised landings (t) from 1974–75 to 2009–10 for the Sub-Antarctic (Sub-A), Chatham Rise (Chat), and west coast South Island (WCSI) stocks. The Sub-Antarctic catch for the most recent year is assumed based on recent catch levels in the fishery.

Fishing year	Sub-A	Chat	WCSI
1974–75	120	191	71
1975–76	281	488	5 005
1976–77	372	1 288	17 806
1977–78	762	34	498
1978–79	364	609	4 737
1979–80	350	750	3 600
1980–81	272	997	2 565
1981–82	179	596	1 625
1982–83	448	302	745
1983–84	722	344	945
1984–85	525	544	965
1985–86	818	362	1 918
1986–87	713	509	3 755
1987–88	1 095	574	3 009
1988–89	1 237	804	8 696
1989–90	1 927	950	8 741
1990–91	2 370	931	8 246
1991–92	2 750	2 418	3 010
1992–93	3 269	2 798	7 059
1993–94	1 453	2 934	2 971
1994–95	1 852	3 387	9 535
1995–96	2 873	4 028	9 082
1996–97	2 262	4 234	6 838
1997–98	2 606	4 252	7 674
1998–99	2 796	3 669	8 742
1999–00	3 020	3 517	7 031
2000–01	2 790	2 962	8 346
2001–02	2 510	1 770	7 498
2002–03	2 738	1 401	7 404
2003–04	3 245	2 465	7 939
2004–05	2 531	3 526	7 298
2005–06	2 557	489	6 892
2006–07	1 818	1 081	7 660
2007–08	2 202	1 096	2 583
2008–09	2 427	1 825	5 912
2009–10	1 958	391	2 282
2010–11	2 000	–	–

2.2 Other sources of fishing mortality

The recreational fishery for hake is believed to be negligible. The amount of hake caught by Maori is not known, but is believed to be negligible. There is likely to be some mortality associated with escapement from trawl nets, but the level is not known.

3. BIOLOGY, STOCK STRUCTURE, AND RESOURCE SURVEYS

3.1 Biology

Data collected by observers on commercial trawlers and from resource surveys suggest that there are at least three main spawning areas for hake (Colman 1998). The best known area is off the west coast of the South Island, where the season can extend from June to October, possibly with a peak in September. Spawning also occurs to the west of the Chatham Islands during a prolonged period from at least September to January. Spawning fish have also been recorded occasionally near the Mernoo Bank. Spawning on the Campbell Plateau, primarily to the northeast of the Auckland Islands, may occur from September to February with a peak in September–October. Spawning fish have also been recorded occasionally on the Puysegur Bank, with a seasonality that appears similar to that on the Campbell Plateau (Colman 1998).

Horn (1997) validated the use of otoliths to age hake. New Zealand hake reach a maximum age of at least 25 years. Males, which rarely exceed 100 cm total length, do not grow as large as females, which can grow to 120 cm total length or more. Readings of otoliths from hake have been used as age-length keys to scale up length frequency distributions for hake collected on resource surveys and from commercial fisheries in all three stocks. The resulting age frequency distributions were reported by Horn & Sutton (2012). The observed proportions-at-age data available from resource surveys of the Sub-Antarctic and Chatham Rise stocks are also shown in Figure 2, and estimated proportions-at-age data from the commercial trawl fisheries are shown for the Sub-Antarctic and west coast South Island in Figure 3a and the Chatham Rise in Figure 3b.

Colman (1998) found that hake reach sexual maturity between 6 and 10 years of age, at total lengths of about 67–75 cm (males) and 75–85 cm (females); he concluded that hake reached 50% maturity at between 6 and 8 years in HAK 1, and 7–8 years in HAK 4. In assessments before 2005, the maturity ogive for the Chatham Rise and Sub-Antarctic was assumed from a combination of the estimates of Colman (1998) and model fits to the west coast South Island stock presented by Dunn (1998). From 2005 to 2007, maturity ogives for the Chatham Rise and Sub-Antarctic stocks were fitted within the assessment model to data derived from resource survey samples with information on the gonosomatic index, gonad stage, and age (Horn & Dunn 2007, Horn 2008). Individual hake were classified as either immature or mature at sex and age, where maturity was determined from the gonad stage and gonosomatic index (GSI, the ratio of the gonad weight to body weight). Fish identified as stage 1 were classified as immature. Stage 2 fish were classified as immature or mature depending on the GSI index, using the definitions of Colman (1998) — i.e., classified as immature if GSI was less than 0.005 (males) or GSI less than 0.015 (females), or mature if GSI at least 0.005 (males) or GSI at least 0.015 (females). Fish identified as stages 3–7 were classified as mature. Model fits indicated that Chatham Rise hake reach 50% maturity at about 6 years for males and 7 years for females, and Sub-Antarctic hake reach 50% maturity at 6 years for males and 7.5 years for females (Figure 4). From 2009, fixed ogives (derived from the fitted curves in Figure 4) were used in the assessment models, with values listed in Table 5. The values for Chatham Rise combined sexes maturity were taken as the mean of the male and female values. In the absence of sufficient data to estimate an ogive for WCSI hake, maturity for this stock was assumed to be the same as for Chatham Rise hake.

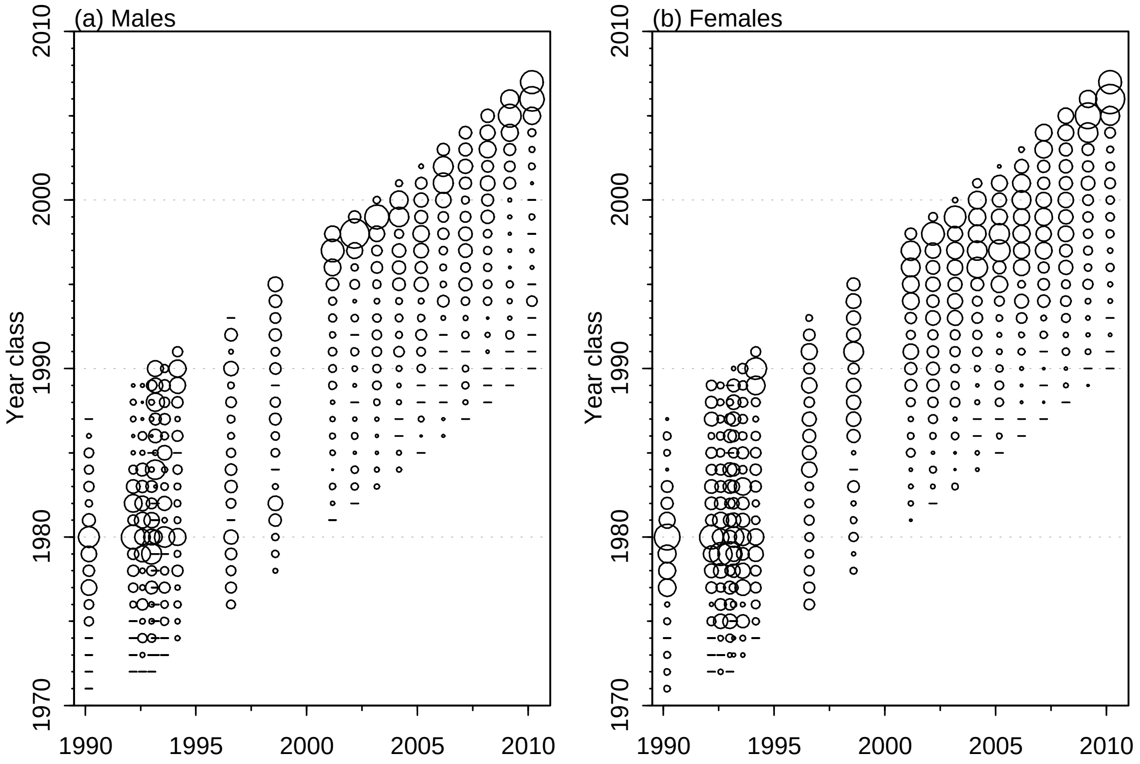
Von Bertalanffy parameters were previously estimated using data up to 1997 (Horn 1998). The parameters for all three stocks were updated using all data available at February 2007 (Horn 2008). Plots of the fitted curves on the raw data indicated that the von Bertalanffy model tended to underestimate the age of large fish (Figure 5). Consequently, the growth model of Schnute (1981) was fitted to the data sets (Table 5). This model appeared to better describe the growth of larger hake (Figure 5), and the resulting parameters can be used in the CASAL stock assessment software. Most aged hake have been 3 years or older. However, juvenile hake have been taken in coastal waters on both sides of the South Island and on the Campbell Plateau. It is known that they reach a total length of about 15–20 cm at 1 year old, and about 35 cm total length at 2 years (Horn 1997).

Estimates of natural mortality (M) and the associated methodology were given by Dunn et al. (2000); M was estimated as 0.18 y^{-1} for females and 0.20 y^{-1} for males. Colman et al. (1991) estimated M as 0.20 y^{-1} for females and 0.22 y^{-1} for males using the maximum age method of Hoenig (1983) (where they defined the maximum ages at which 1% of the population survives in an unexploited stock as 23 years for females and 21 years for males). These are similar to the values proposed by Horn (1997), who determined the age of hake by counting zones in sectioned otoliths and concluded from that study that it was likely that M was in the range 0.20–0.25 y^{-1}.

Dunn et al. (2010) found that the diet of hake on the Chatham Rise was dominated by teleost fishes, in particular Macrouridae. Macrouridae accounted for 44% of the prey weight and consisted of at least six species, of which javelinfish, *Lepidorhynchus denticulatus*, was most frequently identified. Hoki were less frequent prey, but being relatively large accounted for 37% of prey weight. Squids were found in 7% of the stomachs, and accounted for 5% of the prey weight. Crustacean prey were predominantly natant decapods, with pasiphaeid prawns occurring in 19% of the stomachs.

Length-weight relationships for hake from the Sub-Antarctic and Chatham Rise stocks were revised here using all available length-weight data collected during trawl surveys since 1989. Parameters were calculated for males, females, and both sexes combined (Table 5). Sample sizes were large (Sub-Antarctic: 3182 males, 6010 females; Chatham Rise, 3527 males, 3511 females) and all r^2 values were greater than 0.96.

Sub-Antarctic



Chatham Rise

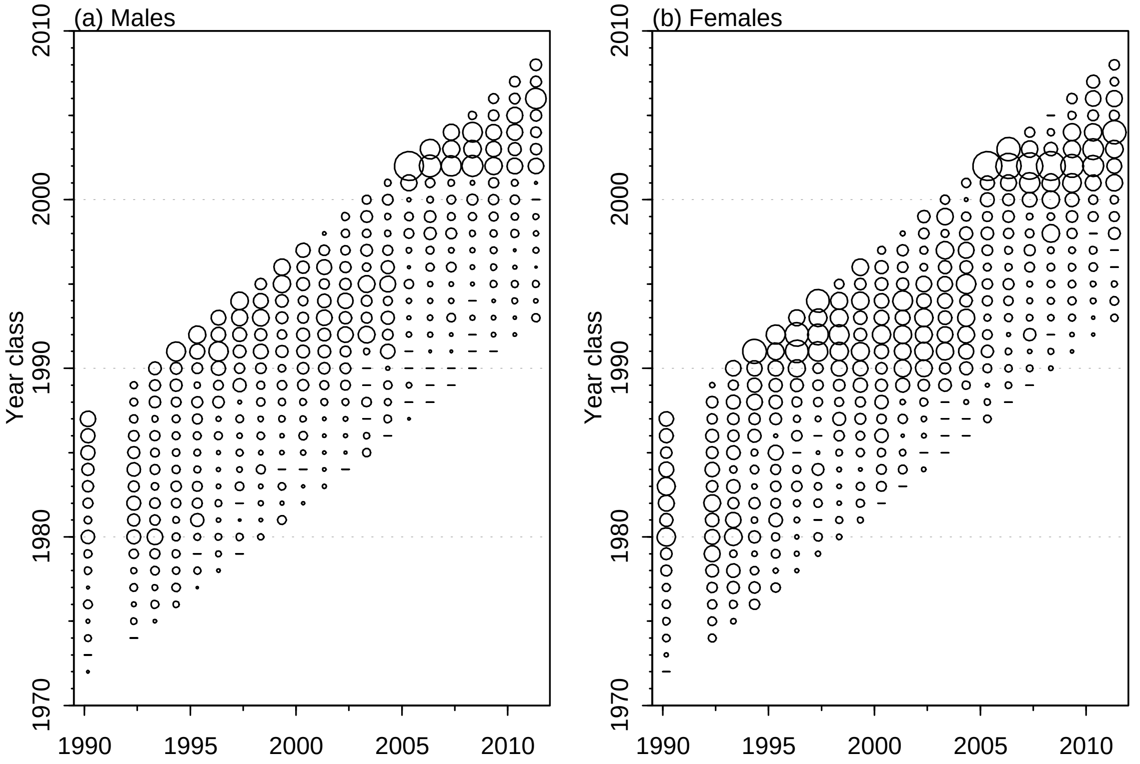
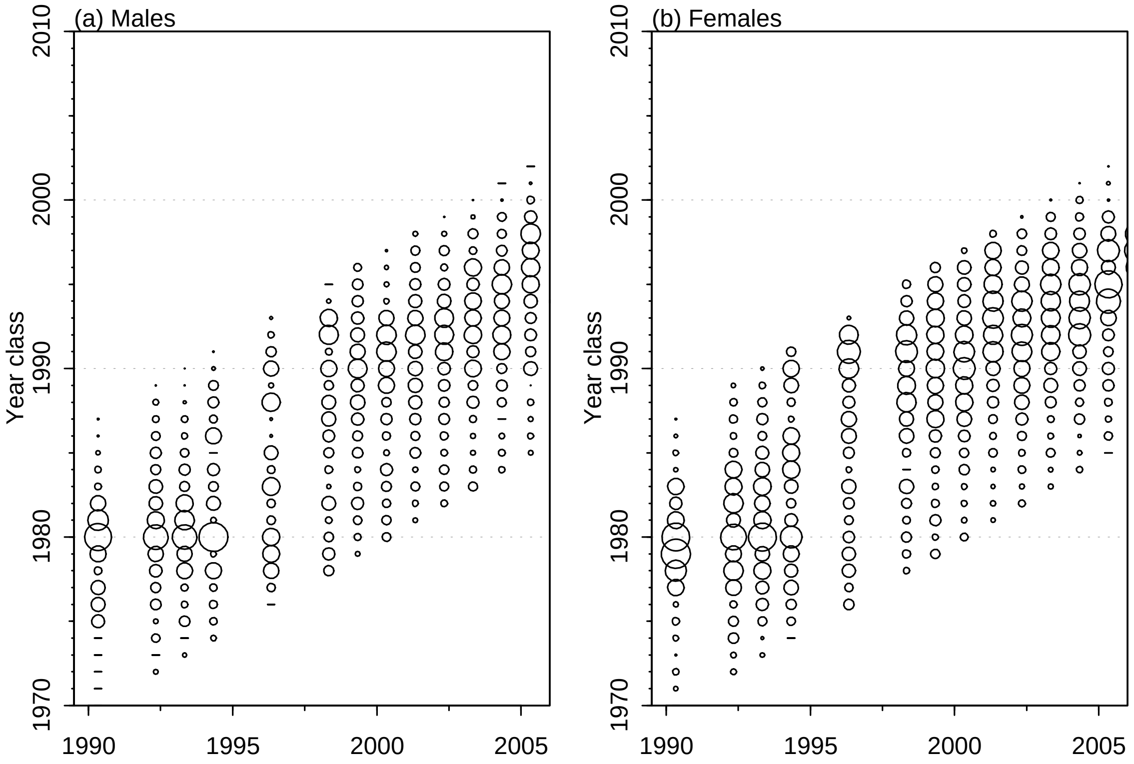


Figure 2: Age frequencies by year class and year (symbol area proportional to the proportions-at-age within sampling event) from the Sub-Antarctic (ages 3–20) and Chatham Rise (ages 3–18) resource surveys. Zero values are represented by a dash.

Sub-Antarctic



West coast South Island

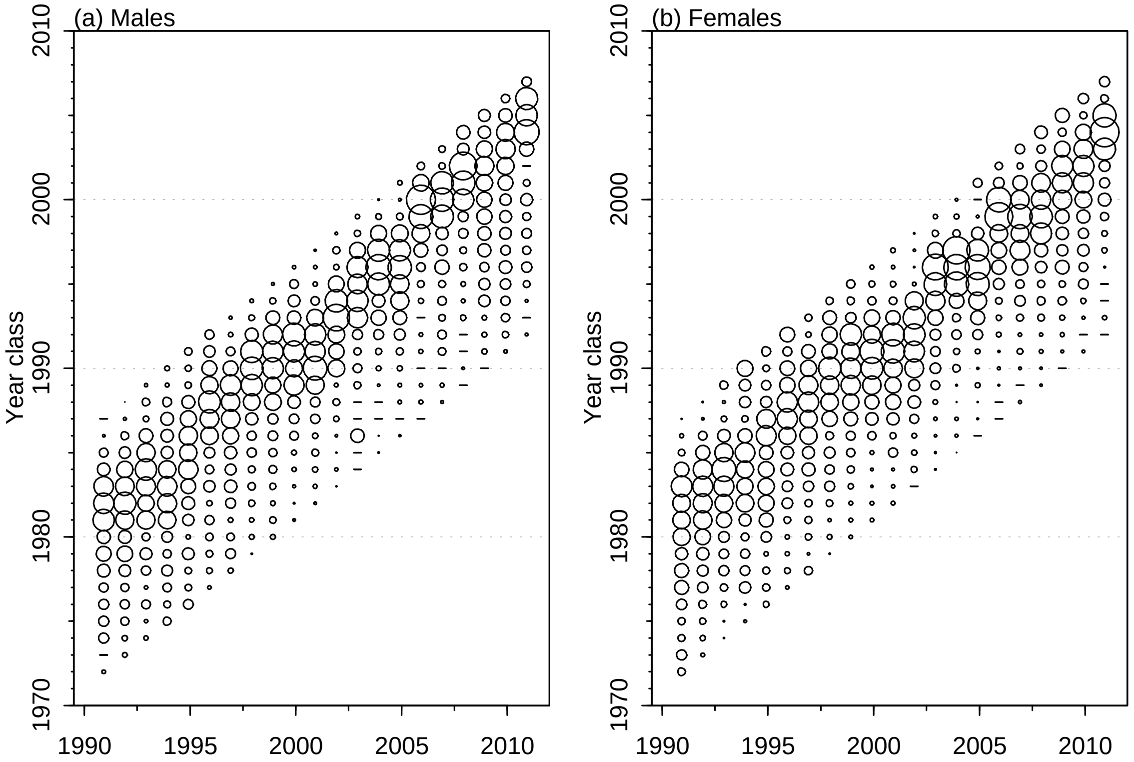
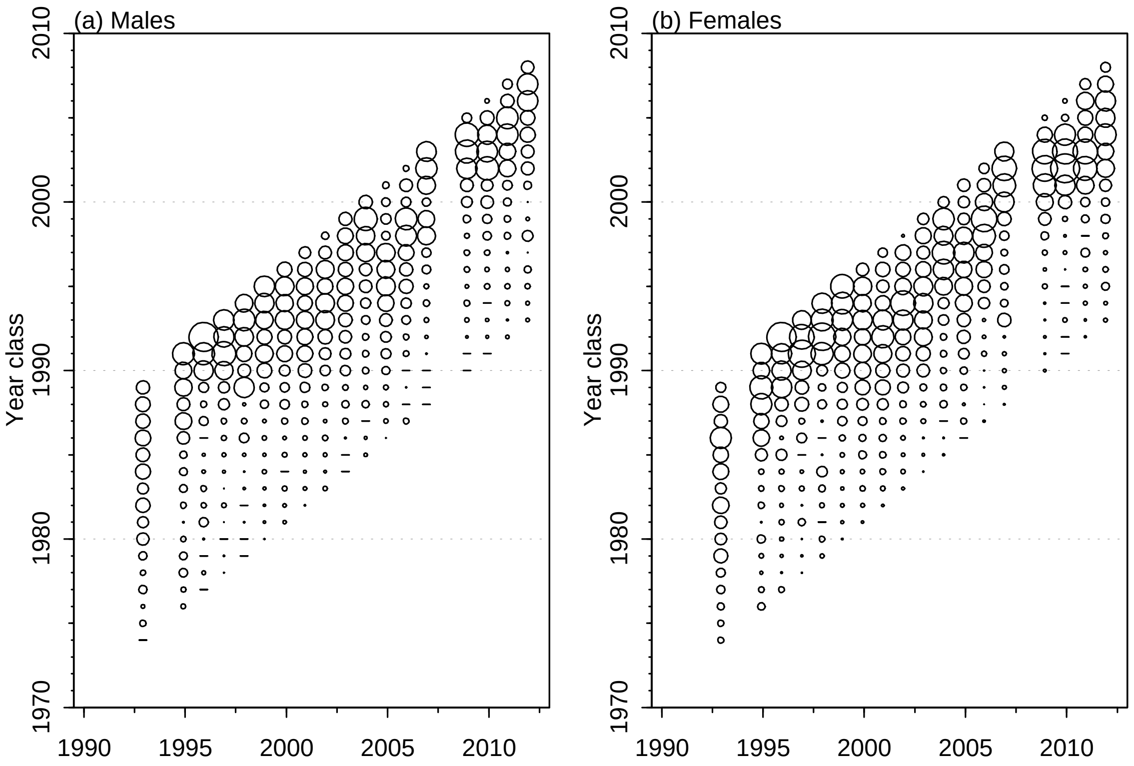


Figure 3a: Age frequencies by year class and year (symbol area proportional to the proportions-at-age within sampling event) from commercial trawl fisheries in the Sub-Antarctic (ages 3–20) and west coast South Island (ages 3–18) resource surveys. Zero values are represented by a dash.

Chatham Rise west



Chatham Rise east

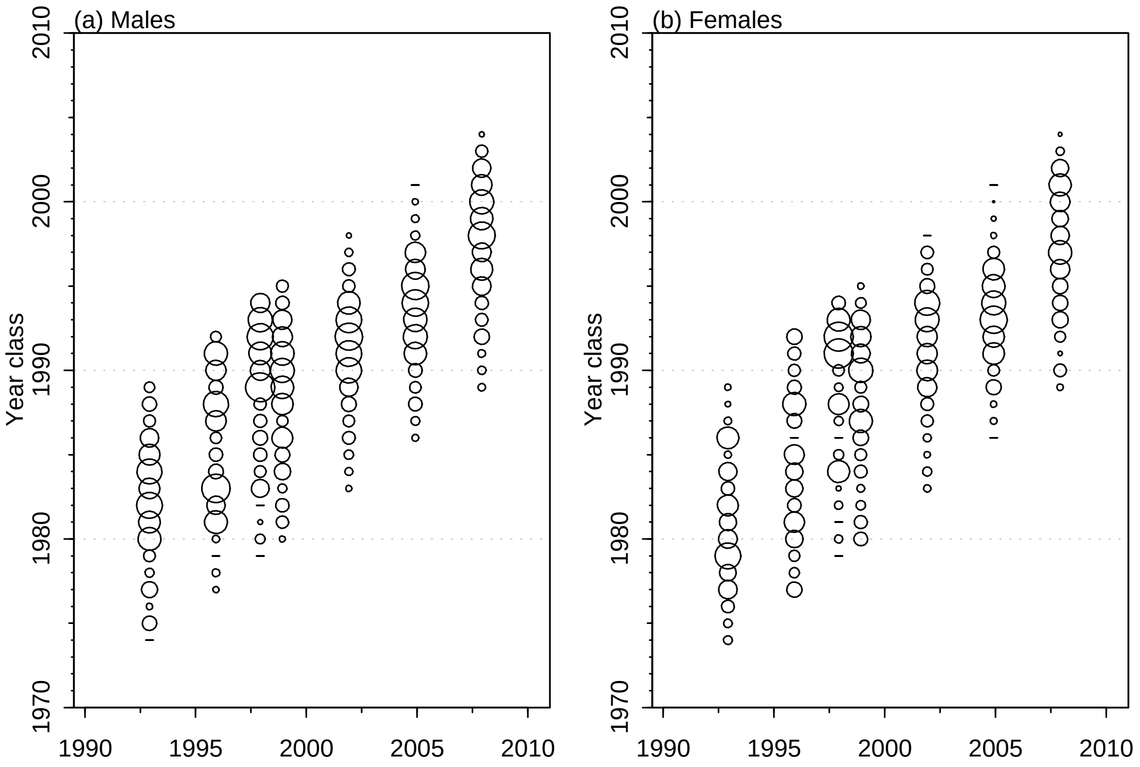


Figure 3b: Age frequencies by year class and year (symbol area proportional to the proportions-at-age within sampling event) from commercial trawl fisheries on the western and eastern sections of Chatham Rise (ages 3–18). Zero values are represented by a dash.

Table 5: Estimates of biological parameters for the three hake stocks.

		Estimate				Source
Natural mortality						
	Males	$M = 0.20$				(Dunn et al. 2000)
	Females	$M = 0.18$				(Dunn et al. 2000)
Weight = $a \cdot (\text{length})^b$ (Weight in t, length in cm)						
Sub-Antarctic						
	Males	$a = 2.13 \text{ x}10^{-9}$	$b = 3.281$			(Current study)
	Females	$a = 1.83 \text{ x}10^{-9}$	$b = 3.314$			(Current study)
	Both sexes	$a = 1.95 \text{ x}10^{-9}$	$b = 3.301$			(Current study)
Chatham Rise						
	Males	$a = 2.56 \text{ x}10^{-9}$	$b = 3.228$			(Current study)
	Females	$a = 1.88 \text{ x}10^{-9}$	$b = 3.305$			(Current study)
	Both sexes	$a = 2.00 \text{ x}10^{-9}$	$b = 3.288$			(Current study)
von Bertalanffy growth parameters						
Sub-Antarctic						
	Males	$k = 0.295$	$t_0 = 0.06$	$L_\infty = 88.8$		(Horn 2008)
	Females	$k = 0.220$	$t_0 = 0.01$	$L_\infty = 107.3$		(Horn 2008)
Chatham Rise						
	Males	$k = 0.330$	$t_0 = 0.09$	$L_\infty = 85.3$		(Horn 2008)
	Females	$k = 0.229$	$t_0 = 0.01$	$L_\infty = 106.5$		(Horn 2008)
WCSI						
	Males	$k = 0.357$	$t_0 = 0.11$	$L_\infty = 82.3$		(Horn 2008)
	Females	$k = 0.280$	$t_0 = 0.08$	$L_\infty = 99.6$		(Horn 2008)
Schnute growth parameters ($\tau_1 = 1$ and $\tau_2 = 20$ for all stocks)						
Sub-Antarctic						
	Males	$y_1 = 22.3$	$y_2 = 89.8$	$a = 0.249$	$b = 1.243$	(Horn 2008)
	Females	$y_1 = 22.9$	$y_2 = 109.9$	$a = 0.147$	$b = 1.457$	(Horn 2008)
	Both sexes	$y_1 = 22.8$	$y_2 = 101.8$	$a = 0.179$	$b = 1.350$	(Current study)
Chatham Rise						
	Males	$y_1 = 24.6$	$y_2 = 90.1$	$a = 0.184$	$b = 1.742$	(Horn 2008)
	Females	$y_1 = 24.4$	$y_2 = 114.5$	$a = 0.098$	$b = 1.764$	(Horn 2008)
	Both sexes	$y_1 = 24.5$	$y_2 = 104.8$	$a = 0.131$	$b = 1.700$	(Horn & Francis 2010)
WCSI						
	Males	$y_1 = 23.7$	$y_2 = 83.9$	$a = 0.278$	$b = 1.380$	(Horn 2008)
	Females	$y_1 = 24.5$	$y_2 = 103.6$	$a = 0.182$	$b = 1.510$	(Horn 2008)
	Both sexes	$y_1 = 24.5$	$y_2 = 98.5$	$a = 0.214$	$b = 1.570$	(Horn 2011)

Maturity ogives (proportion mature at age)

Age	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Sub-Antarctic														
Males	0.01	0.03	0.09	0.22	0.46	0.71	0.88	0.96	0.98	0.99	1.00	1.00	1.00	1.00
Females	0.01	0.02	0.05	0.11	0.23	0.43	0.64	0.81	0.91	0.96	0.98	0.99	1.00	1.00
Both	0.01	0.02	0.07	0.16	0.29	0.57	0.76	0.88	0.94	0.97	0.99	0.99	1.00	1.00
Chatham Rise (and assumed for WCSI)														
Males	0.02	0.06	0.15	0.32	0.55	0.77	0.90	0.96	0.98	0.99	1.00	1.00	1.00	1.00
Females	0.04	0.07	0.13	0.22	0.34	0.49	0.64	0.77	0.86	0.92	0.95	0.98	0.99	1.00
Both	0.03	0.06	0.14	0.27	0.45	0.63	0.77	0.86	0.92	0.96	0.98	0.99	1.00	1.00

Miscellaneous parameters

Steepness (Beverton & Holt stock-recruitment relationship)	0.90
Proportion spawning	1.0
Proportion of recruits that are male	0.5
Ageing error c.v.	0.08
Maximum exploitation rate (U_{max})	0.7

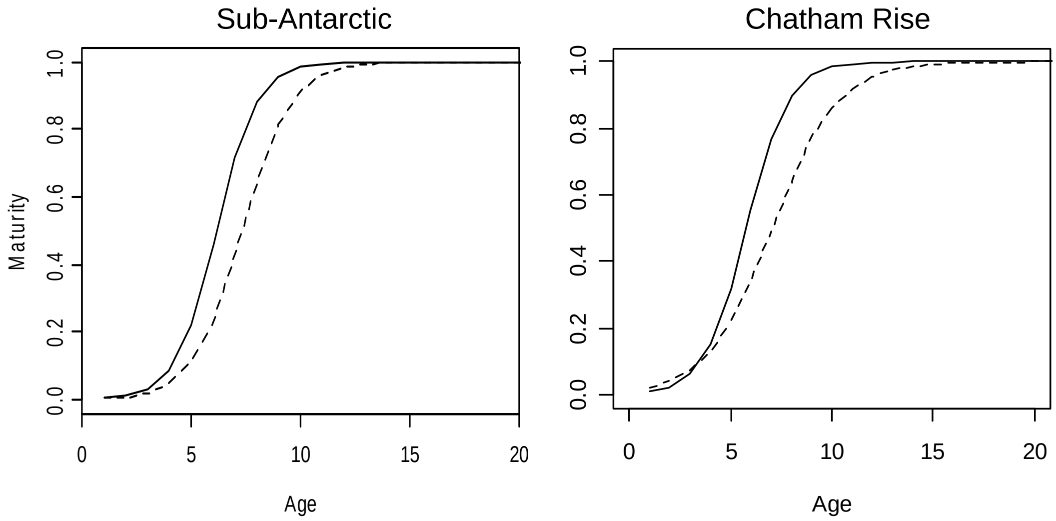


Figure 4: Estimated ogives of proportions mature by age for Sub-Antarctic and Chatham Rise hake males (solid lines) and females (broken lines).

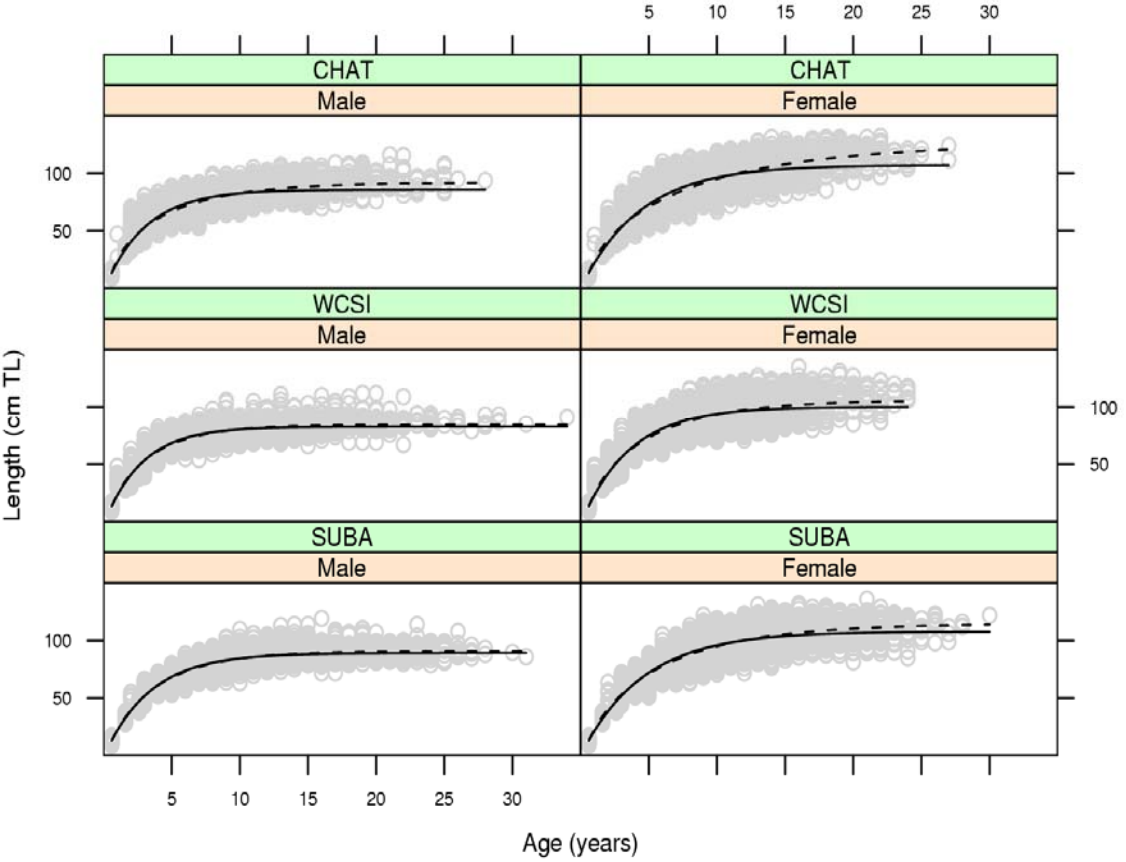


Figure 5: Raw age-length data, by sex, for hake from Chatham Rise (CHAT), west coast South Island (WCSI), and Sub-Antarctic (SUBA), with fitted von Bertalanffy curves (solid lines) and Schnute curves (broken lines).

3.2 Stock structure

There are at least three hake spawning areas: off the west coast of the South Island, on the Chatham Rise, and on the Campbell Plateau (Colman 1998). Juvenile hake are found in all three areas, there are differences in size frequency of hake between the west coast and other areas, and differences in growth parameters between all three areas (Horn 1997). There is reason, therefore, to believe that at least three separate stocks may exist in the EEZ.

Analysis of morphometric data (J.A. Colman, NIWA, unpublished data) showed little difference between hake from the Chatham Rise and from the east coast of the North Island, but highly significant differences between these fish and those from the Sub-Antarctic, Puysegur, and on the west coast. The Puysegur fish are most similar to those from the west coast South Island, although, depending on which variables are used, they cannot always be distinguished from the Sub-Antarctic hake. However, the data are not unequivocal, so the stock affinity is uncertain.

For stock assessment models, the Chatham Rise stock was considered to include the whole of the Chatham Rise (HAK 4 and the western end of the Chatham Rise that forms part of the HAK 1 management area). The Sub-Antarctic stock was considered to contain hake in the remaining Puysegur, Southland, and Sub-Antarctic regions of the HAK 1 management area. The stock areas assumed for this report are shown earlier, in Figure 1.

3.3 Resource surveys

In the Sub-Antarctic, three resource surveys were carried out by *Tangaroa* with the same gear and similar survey designs in November–December 1991, 1992, and 1993, but the series was then terminated as there was evidence that hake, in particular, might be aggregated for spawning at that time of the year and that spawning aggregations had a high probability of being missed during a survey. However, research interest in hoki in the Sub-Antarctic resulted in a return to the November–December survey annually from 2000 to 2009. Surveys by *Tangaroa* in April 1992, May 1993, April 1996, and April 1998 formed the basis for a second series, with hake appearing to be more evenly distributed through the survey area at that time of year. A single survey in September 1992 by *Tangaroa* was also completed. The biomass estimates from the Sub-Antarctic *Tangaroa* surveys are shown in Figure 6 with further details given in Appendix A. There was some variation in the area surveyed within the November–December and April–May series. Consequently, multiple biomass estimates have been presented in Figure 6 for some of these surveys to show biomass estimates across consistent sets of strata. However, only the longest consistent time series (i.e., November–December 1991 area, April–May 300–800 m strata) are included as assessment model inputs.

Sub-Antarctic surveys were conducted by *Shinkai Maru* (March–May 1982 and October–November 1983) and *Amaltal Explorer* (October–November 1989, July–August 1990, and November–December 1990). However, these vessels used different gear and had different performance characteristics (Livingston et al. 2002), so biomass estimates from these surveys cannot be used as part of a consistent time series.

Resource surveys have been carried out at depths of 200–800 m on the Chatham Rise since 1992 by *Tangaroa* with the same gear and similar survey designs (Figure 7, Appendix A). While the survey designs since 1992 have been similar, there was a reduction in the number of stations surveyed between 1996 and 1999, and some strata in the survey design used between 1996 and 1999 were merged (see Bull & Bagley 1999). The surveys since 2000 used a revised design, with some strata being split and additional stations added. Since 2000 some of the *Tangaroa* surveys included deepwater strata (i.e., 800–1300 m) on the Chatham Rise. Although only the longest consistent time series (i.e., 200–800 m strata) is included in the assessment model, additional estimates from surveys fishing the deepwater strata are shown in Figure 7.

Chatham Rise surveys were conducted by *Shinkai Maru* (March 1983 and June–July 1986) and *Amaltal Explorer* (November–December 1989). However, these surveys used a range of gear, survey methodologies, and survey designs (Livingston et al. 2002), and cannot be used as part of a consistent time series.

Research surveys of hoki and hake have been conducted periodically off WCSI, but these have been 'one-off' surveys by different vessels (i.e., *Shinkai Maru* in 1976, *James Cook* in 1978–79, *Wesermünde* in 1979, *Giljanes* in 1990, and *Tangaroa* in 2000) so any biomass estimates from them are not useful model inputs. It is possible that the 2000 *Tangaroa* survey (O'Driscoll et al. 2004) may be able to be linked to a trawl and acoustic survey series due to commence off WCSI in winter 2012 to produce a future series. A long-running trawl survey series of inshore waters off WCSI by *Kaharoa* has not provided a useful index of hake biomass as it surveys no deeper than 400 m (Stevenson & Hanchet 2000). Age data, and consequent estimates of proportion-at-age, are available for only the 1979 *Wesermünde* survey; these are incorporated in the WCSI assessment model.

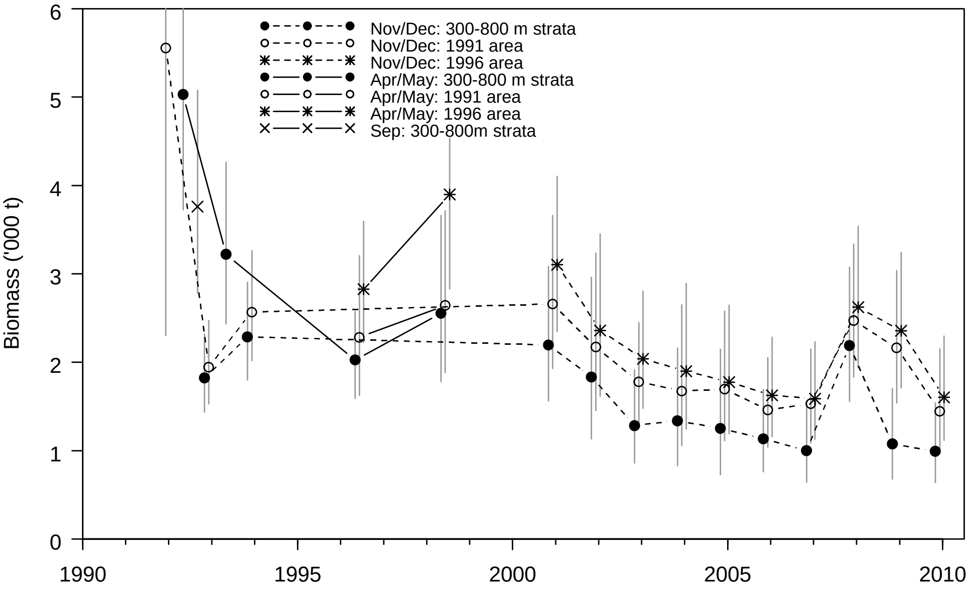


Figure 6: Hake biomass estimates from the *Tangaroa* surveys of the Sub-Antarctic (1991–2009 including the November–December, April–May, and September series), with approximate 95% confidence intervals. (See also Appendix A.)

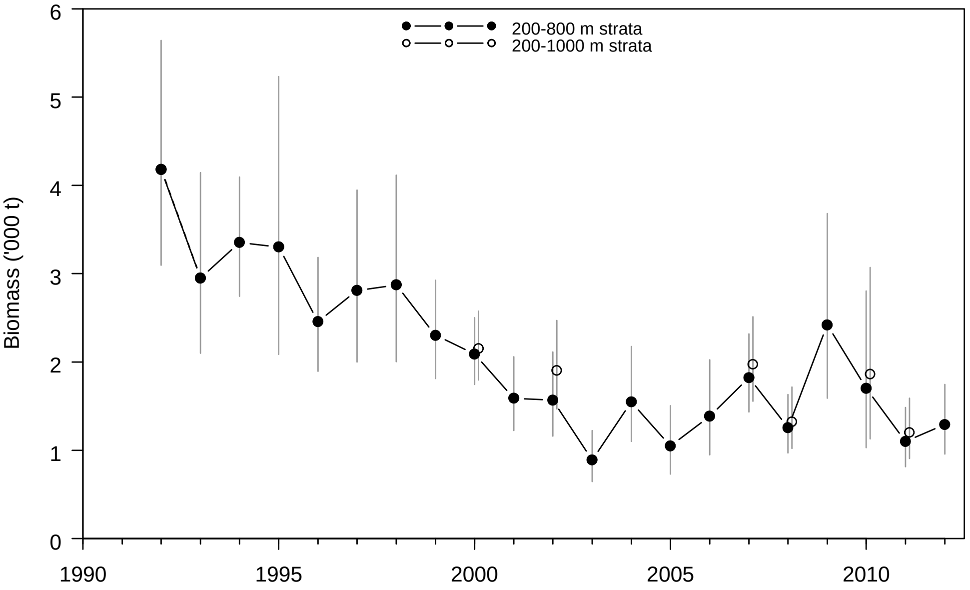


Figure 7: Hake biomass estimates from the *Tangaroa* (1992–2011 for the January series) of the Chatham Rise, with approximate 95% confidence intervals. (See also Appendix A.)

3.4 Observer age data

3.4.1 Chatham Rise

The fishery on the Chatham Rise was stratified using a tree-based regression on mean lengths of hake in tows where observers had measured five or more hake (Horn & Dunn 2007). The defined strata are shown in Figure 8. Mean fish length tends to increase from west to east, and with increasing depth. Area 404 contains a known spawning ground. Where sufficient data were available, catch-at-age series were developed and selectivity ogives estimated separately for each fishery in the stock assessment model by Horn & Dunn (2007).

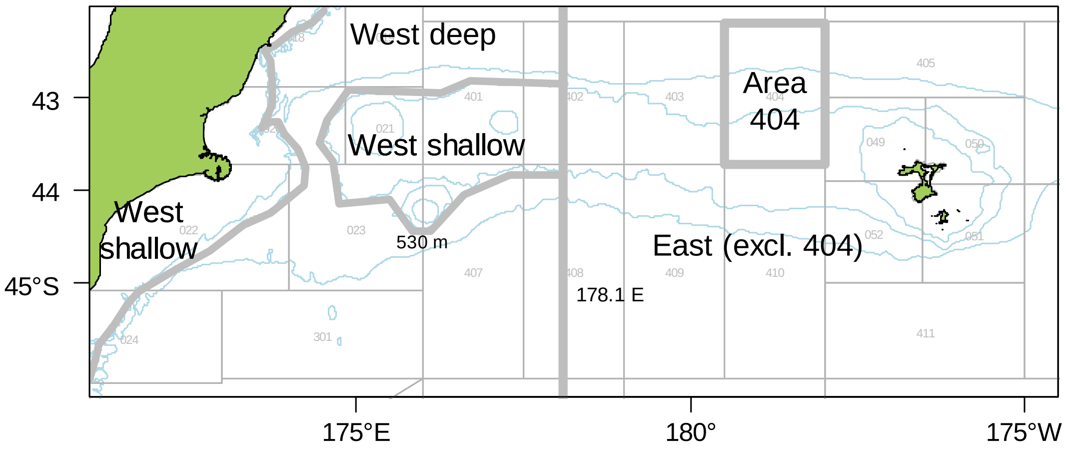


Figure 8: Fishery strata defined for the Chatham Rise hake fishery. Large numbers show longitudes or depths of fishery boundaries; small numbers denote statistical areas. The stratum boundary defined by depth (530 m) is shown only approximately. Isobaths at 1000, 500, and 250 m are also shown.

However, Horn & Francis (2010) showed that the two western fisheries had similar age-frequency distributions, and the two eastern fisheries were data poor. Consequently, they used two strata, eastern and western, divided at 178.1° E. Observer data from each fishery stratum were converted into catch-at-age distributions if there were at least 400 length measurements (from western strata) or 320 length measurements (from eastern strata), and the mean weighted c.v. over all age classes was less than 30%. The available data (described by Horn & Sutton (2012)) are from 1991–92 and 1993–94 to 2009–10. Although the observer length data from each year were partitioned into fisheries (i.e., two strata in each of the two fisheries, as shown in Figure 8), the age data from each year were not (i.e., a single age-length key was constructed for each year and applied to all available sets of length data from that year). Horn & Dunn (2007) showed that mean age at length did not differ between fisheries, so the use of a single age-length key per year would not bias the age distributions.

3.4.2 Sub-Antarctic

The Sub-Antarctic hake observer data were found to be best stratified into the four areas shown in Figure 9 (Horn 2008). Most of the hake target fishing, and most of the catch (average 94% per year), is associated with the Snares-Pukaki area. Puysegur is the next most important area with about 3% of the catch. Available observer data are also concentrated in the Snares-Pukaki region, but it is clear that the smaller fisheries (particularly the Campbell Island area) can be over-sampled in most years. Consequently, the Sub-Antarctic observer data are analysed as one major and three very minor fisheries, with a single fishery ogive. However, because of clear differences in mean fish length between the fisheries (Horn 2008), it is important to use the four fishery strata when calculating catch-at-age distributions. Without stratification, the frequent over-sampling in the minor fisheries could strongly bias the catch-at-age distributions. A single age-length key was applied to the scaled length-frequency distributions for each fishery to produce the catch-at-age data. Catch-at-age distributions from the Sub-Antarctic trawl fishery are available from all but three years from 1989–90 to 2009–10 (Horn & Sutton 2012).

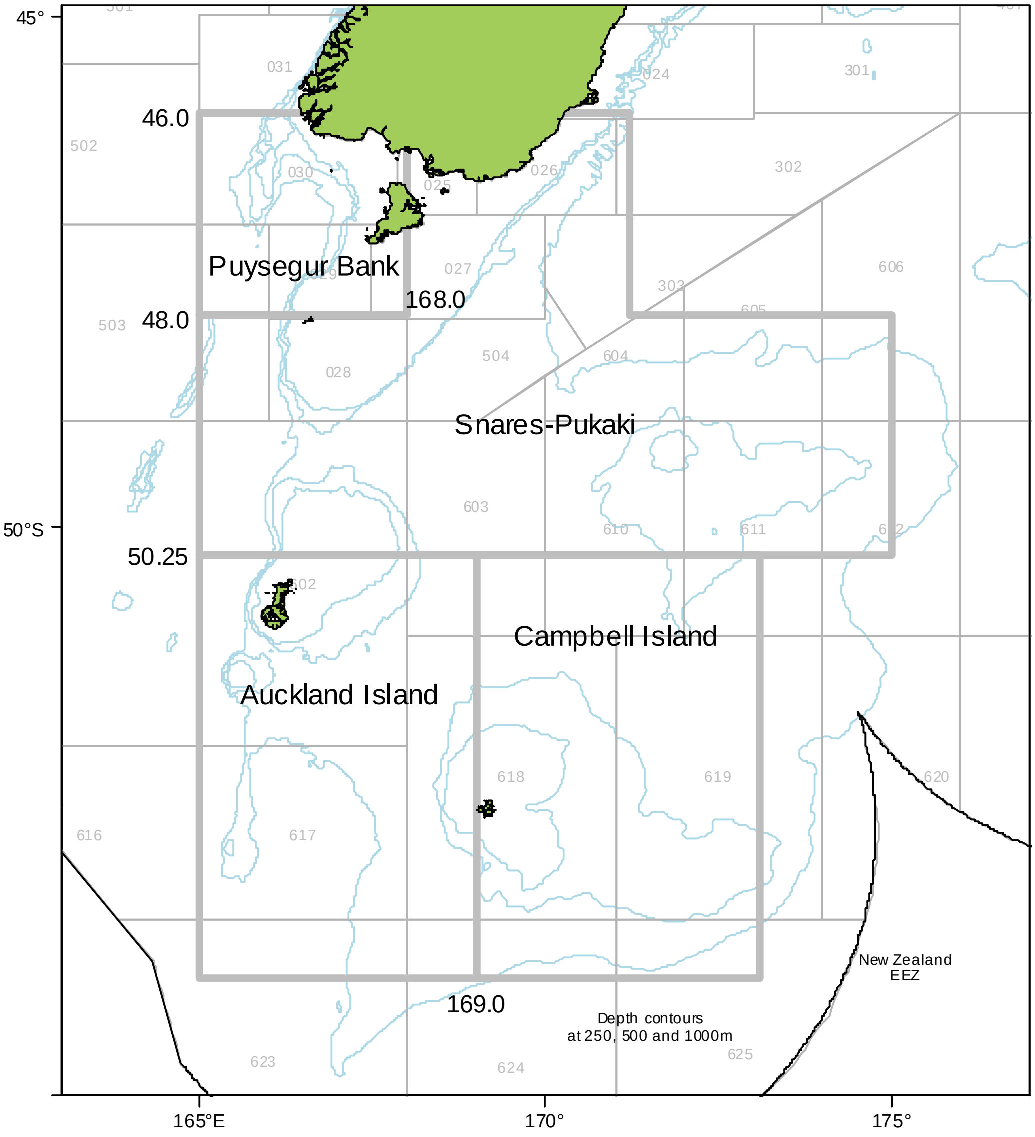


Figure 9: Fishery strata defined for the Sub-Antarctic hake fishery. Large numbers show latitudes or longitudes of fishery boundaries; small numbers denote statistical areas. Isobaths at 1000, 500, and 250 m are also shown.

3.4.3 WCSI

The fishery off WCSI was stratified using a tree-based regression on mean lengths of hake in tows where observers had measured five or more hake (Horn & Dunn 2007). A single catch-at-age distribution was estimated for each year, stratified as shown in Figure 10. Catch-at-age distributions from the WCSI trawl fishery are available from all years from 1989–90 to 2009–10 (Horn & Sutton 2012).

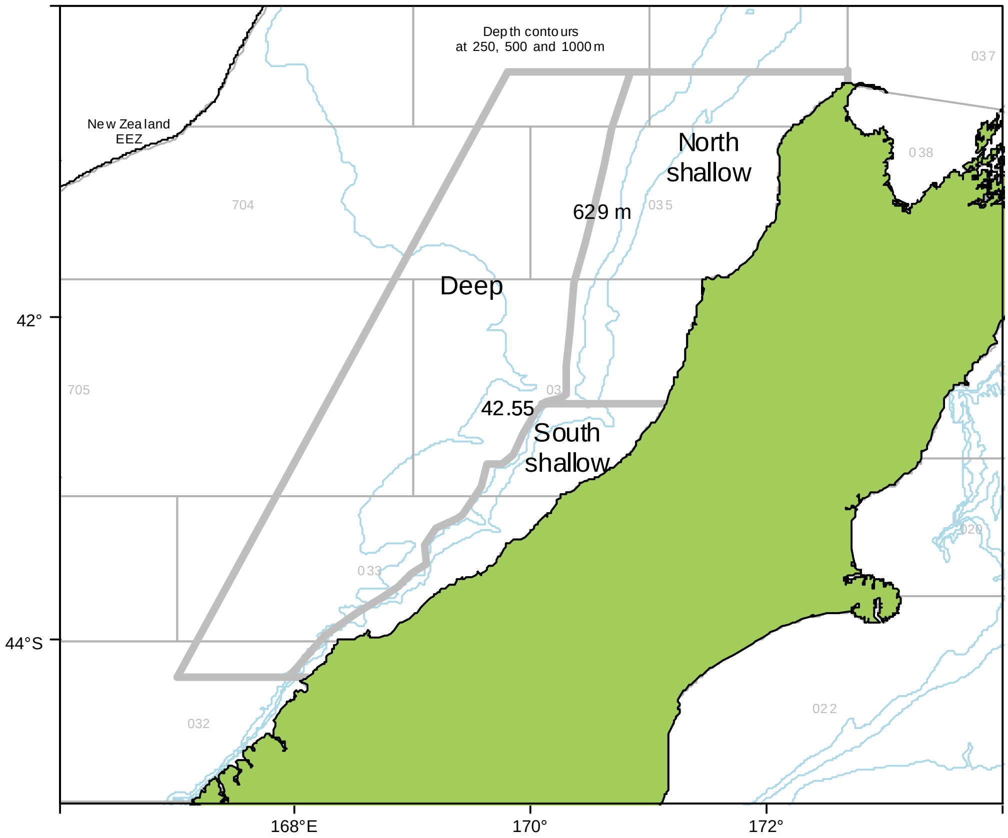


Figure 10: Fishery strata defined for the WCSI hake fishery. Large numbers show latitudes or depths of fishery boundaries; small numbers denote statistical areas. The stratum boundary defined by depth (629 m) is shown only approximately. Isobaths at 1000, 500, and 250 m are also shown.

3.5 CPUE indices

Standardised CPUE indices were calculated by Ballara & Horn (2011) from daily processed summary data up the end of the 2008–09 fishing season. Series were produced for the separate eastern and western fisheries on the Chatham Rise, and for all areas combined in each of the Chatham Rise, Sub-Antarctic, and WCSI stocks.

As only the HAK 1 assessment is being completed under the current project, the Sub-Antarctic CPUE was updated using data to the end of the 2009–10 fishing year by Ballara (2012) (Table 6).

Table 6: Hake CPUE indices (and associated 95% confidence intervals and c.v.s) for the Sub-Antarctic trawl fishery (from Ballara 2012).

Year	Index	95% CI	c.v.	Year	Index	95% CI	c.v.
1991	1.25	1.15–1.35	0.04	2001	1.05	0.99–1.11	0.03
1992	1.21	1.13–1.29	0.03	2002	0.95	0.90–1.01	0.03
1993	1.18	1.11–1.26	0.03	2003	0.93	0.88–0.98	0.03
1994	1.07	0.99–1.15	0.04	2004	1.05	0.99–1.11	0.03
1995	0.93	0.87–1.00	0.04	2005	0.81	0.75–0.87	0.04
1996	1.17	1.08–1.27	0.04	2006	1.14	1.04–1.25	0.05
1997	0.96	0.90–1.02	0.03	2007	1.04	0.95–1.13	0.05
1998	0.91	0.86–0.96	0.03	2008	0.90	0.83–0.97	0.04
1999	0.86	0.81–0.91	0.03	2009	0.88	0.81–0.95	0.04
2000	0.88	0.83–0.93	0.03	2010	1.00	0.93–1.09	0.04

4. MODEL STRUCTURE, INPUTS, AND ESTIMATION

4.1 Introduction

An updated assessment of the Sub-Antarctic stock is presented here. The previous assessment of this stock (Horn 2008) partitioned the population into two sexes and age groups 1–30, with the last age class considered a plus group. The partition included maturity, with ogives estimated within the model. The model's annual cycle began on 1 September and was divided into three steps. The current assessment model used the same annual cycle (Table 7), but maturity ogives were always fixed and maturity was never included in the partition. Note that model references to "year" within this document are labelled as the most recent calendar year, i.e., the year 1 September 1998 to 31 August 1999 is referred to as "1999". Some previous assessments of Sub-Antarctic hake have been based on fishing year, i.e., years starting on 1 October. However, landings peaks tend to occur from September to January (Ballara 2012), so it is logical to include the September catch with landings from the five months following it, rather than with catch taken about seven months previously.

Table 7: Annual cycle of the Sub-Antarctic stock model, showing the processes taking place at each time step, their sequence within each time step, and the available observations. Fishing and natural mortality that occur within a time step occur after all other processes, with half of the natural mortality for that time step occurring before and half after the fishing mortality.

					Observations	
Step	Period	Processes	M fraction[1]	Age fraction[2]	Description	%Z[3]
1	Sep–Feb	Fishing, recruitment, and spawning	0.42	0.25	Summer survey	40
					Trawl CPUE	40
2	Mar–May	–	0.25	0.50	Autumn survey	50
3	Jun–Aug	Increment age	0.33	0.00	Spring survey	100

[1] The proportion of natural mortality that was assumed to have occurred in that time step.
[2] The age fraction (used for determining length at age) that was assumed to occur in that time step.
[3] %Z is the % of total mortality in the step that was assumed to have taken place at the time each observation was made.

For all subsequent models, estimates of fixed biological parameters used in the assessments are given in Table 5. A Beverton-Holt stock-recruitment relationship, with steepness 0.9, was assumed. Variability in the Schnute age-length relationship was assumed to be lognormal with a constant c.v. of 0.1. The maximum exploitation rate was assumed to be 0.7 for the stock. The choice of the maximum exploitation rate has the effect of determining the minimum possible virgin biomass allowed by the model, given the observed catch history. This value was set relatively high as there was little external information from which to determine it. The model's annual cycle was as described in Table 7.

Biomass estimates from the resource surveys were used as relative biomass indices, with associated c.v.s estimated from the survey analysis. The survey catchability constant (q) for each survey series was assumed to be constant over all years in that series. Three q values were estimated; one for each of the summer, autumn, and spring survey series. Although the summer and autumn series were believed to have different q values, no information was available to indicate whether the spring survey might have a q similar to either of the other series, so a separate q was estimated for it. Catch-at-age observations were available for each *Tangaroa* research survey (see Figure 2), from a single *Amaltal Explorer* survey in November 1989, and from commercial observer data for the fishery. Two selectivity ogives were used for the survey catch-at-age data; one for the summer series (i.e., the *Tangaroa* and *Amaltal Explorer* data), and another for the autumn and spring *Tangaroa* data. There was no information to indicate that the *Amaltal Explorer* and the *Tangaroa* in summer had similar selectivities, or that the autumn and spring *Tangaroa* selectivities were the same. However, it was considered undesirable to estimate selectivity ogives for single surveys (i.e., the *Amaltal Explorer* and the *Tangaroa* in spring), so they were analysed as described above. Lognormal errors, with known c.v.s, were assumed for all relative biomass and proportions-at-age observations. Ageing error was assumed to occur for the observed proportions-at-age data, by assuming a discrete normally distributed error with c.v. 0.08.

The c.v.s (for observations fitted with lognormal likelihoods) are assumed to have allowed for sampling error only. Additional variance, assumed to arise from differences between model simplifications and real world variation, was added to the sampling variance for all observations in all model runs. For catch-at-age data the additional variance, termed process error, was estimated in MPD runs of each model. Process error of 0.2 was added to all survey biomass indices following the recommendation of Francis et al. (2003). For CPUE indices, process error was fixed at 0.18 so that the final point c.v.s were approximately 0.2, as recommended by Francis et al. (2001).

Year class strengths were assumed known (and equal to one) for years before 1974 and after 2007, when inadequate or no catch-at-age data were available. Otherwise, year class strengths were estimated under the assumption that the estimates from the model must average one. The Haist parameterisation for year class multipliers is used here (see Bull et al. (2008) for details).

The catch history assumed in all model runs was derived as follows. Using the grooming algorithms of Dunn (2003a), landings of hake reported on TCEPR and CELR forms from 1989–90 to 2009–10 were allocated to month and fishery (based on reported date and location). Annual totals were obtained by summing the monthly totals using a September to August year (for reasons described above). Thus, catch histories for model years 1990 to 2010 were produced for the Sub-Antarctic section of HAK 1 (Table 8). Annual catches before 1990 are as presented in Table 4.

Table 8: Estimated catch (t) from the Sub-Antarctic stock, by fishing year, and model year. Note that from 1989–90 totals by fishing year and model year differ because the September catch has been shifted from the fishing year into the following model year. Model year landings from 2011 are estimated assuming catch patterns similar to the previous year.

Fishing year	Catch (t)	Model year	Catch (t)	Fishing year	Catch (t)	Model year	Catch (t)
1974–75	120	1975	120	1993–94	1 450	1994	1 596
1975–76	281	1976	281	1994–95	1 852	1995	1 995
1976–77	372	1977	372	1995–96	2 870	1996	2 779
1977–78	762	1978	762	1996–97	2 271	1997	1 915
1978–79	364	1979	364	1997–98	2 628	1998	2 958
1979–80	350	1980	350	1998–99	2 802	1999	2 854
1980–81	272	1981	272	1999–00	3 030	2000	3 108
1981–82	179	1982	179	2000–01	2 849	2001	2 820
1982–83	448	1983	448	2001–02	2 512	2002	2 444
1983–84	722	1984	722	2002–03	2 729	2003	2 777
1984–85	525	1985	525	2003–04	3 252	2004	3 223
1985–86	818	1986	818	2004–05	2 528	2005	2 592
1986–87	713	1987	713	2005–06	2 554	2006	2 541
1987–88	1 095	1988	1 095	2006–07	1 815	2007	1 711
1988–89	1 237	1989	1 237	2007–08	2 204	2008	2 329
1989–90	1 917	1990	1 897	2008–09	2 432	2009	2 446
1990–91	2 370	1991	2 381	2009–10	1 958	2010	1 927
1991–92	2 743	1992	2 810	2010–11	–	2011	2 000
1992–93	3 254	1993	3 941				

4.2 Prior distributions and penalty functions

The assumed prior distributions used in the assessment are given in Table 9. The priors for B_0 and year class strengths were intended to be relatively uninformed, and had wide bounds. The prior for the survey *q* was informative and was estimated by assuming that the catchability constant was the product of areal availability, vertical availability, and vulnerability. This same *q* prior was used in the previous Sub-Antarctic hake assessment (Horn 2008). A simulation was conducted that estimated a distribution of possible values for the catchability constant by assuming that each of these factors was independent and uniformly distributed. A prior was then determined by assuming that the resulting, sampled, distribution was lognormally distributed. Values assumed for the parameters were areal availability (0.50–1.00), vertical availability (0.50–1.00), and vulnerability (0.01–0.50). The resulting (approximate lognormal) distribution had mean 0.16 and c.v. 0.79, with bounds assumed to be 0.01 and 0.40 (Figure 11). Priors for all selectivity parameters were assumed to be uniform. The values of survey catchability constants are dependent on the selectivity parameters, and the absolute catchability can be determined by the product of the selectivity by age and sex, and the catchability constant q.

Penalty functions were used a) to constrain the model so that any combination of parameters that resulted in a stock size that was so low that the historical catch could not have been taken was strongly penalised, b) to ensure that all estimated year class strengths averaged 1, and c) to smooth the year class strengths estimated over the period 1974 to 1979.

Table 9: The priors assumed for estimated parameters. The given parameters for the priors are mean (in natural space) and c.v.

Parameter description	Distribution	Parameters		Bounds	
B_0	uniform-log	–	–	5 000	350 000
Year class strengths	Lognormal	1.0	1.1	0.01	100
Trawl survey q[1]	Lognormal	0.16	0.79	0.01	0.4
CPUE q	uniform-log	–	–	1e-8	1e-3
Selectivities	Uniform	–	–	0	20–200[2]
M (x_0, y_0, y_1, y_2)[3]	Uniform	–	–	3, 0.01, 0.01, 0.01	15, 0.6, 1.0, 1.0

[1] Three trawl survey q values were estimated, but all had the same priors.

[2] A range of maximum values was used for the upper bound.

[3] x_0, age at minimum M; y_0, M at x_0; y_1, M at the minimum age in the partition; y_2, M at the maximum age in the partition.

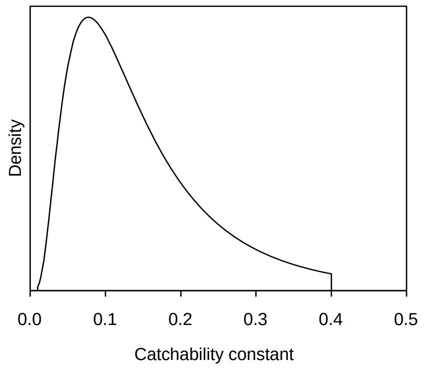


Figure 11: The prior distribution for all three of the survey catchability constants (q), lognormal where μ=0.16, c.v.=0.79, and bounds (0.01,0.40).

4.3 Developing a 'base' model

Some initial investigations were completed to develop a 'base' model. Model parameters were estimated for final model runs using Bayesian estimation implemented using the CASAL software. However, only the mode of the joint posterior distribution (MPD) was estimated in these initial runs. All runs included survey biomass indices and proportion-at-age data, and the fishery catch-at-age data. Full details of the CASAL algorithms, software, and methods were detailed by Bull et al. (2008).

In developing a base model a series of seven models was considered, with each new model typically differing from previous models in only one key assumption (Table 10).

Table 10: Brief description of the assumptions that differed amongst the eight models that were considered in developing a base case model (see text for more detail). For each model, the underlined assumption is the main one that distinguished it from preceding models.

	Model number						
Assumption	1	2	3[1]	4	5[2]	6	7
Ageing error assumed	Y	N	Y	Y	Y	Y	Y
Smooth 1974–79 year-class strengths	N	N	Y	Y	Y	Y	Y
All selectivities domed[3]	Y	Y	Y	N	Y	Y	N
Sex in partition and data	Y	Y	Y	Y	N	N	N
CPUE data used	N	N	N	N	N	Y	N
M estimated in model as an ogive	N	N	N	N	N	N	Y

[1] Referred to as the 'two sex' model.
[2] Base case model for the assessment.
[3] Logistic selectivities were used for the surveys in model 4 and the fishery in model 7.

All models estimated an absolute biomass trajectory, year class strengths from 1974 to 2007, fits to any included relative abundance series, selectivity ogives for the trawl surveys and trawl fishery, and trawl survey catchability coefficients. One model also estimated instantaneous natural mortality.

An initial model (model 1) was set up, partitioning the population into two sexes and age groups 1–30, with the last age class considered a plus group. The partition did not include maturity. The model used six selectivity ogives: male and female survey selectivities for the summer resource survey series, male and female survey selectivities for the autumn and spring resource survey series, and male and female selectivities for the commercial trawl fishery. Male selectivity was estimated relative to female selectivity. Selectivities were assumed constant over all years in the fisheries and the research surveys. All selectivity ogives were estimated using the double-normal parameterisation. Process error for all the catch-at-age series was estimated in this initial MPD model, and these values were used in all subsequent models. The initial model produced the following estimates of process error for the catch-at-age series: summer research survey, 0.3; autumn research survey, 0.2; spring research survey, 0.1; fishery, 0.6. No CPUE data were incorporated.

B_0 was 184 500 t, and stock status in 2011 was estimated to be 57% of B_0. The two survey biomass series with multiple points appeared to be reasonably well fitted, with no obvious trends in the residuals (Figure 12). However, a striking feature of model 1 is that the spawning biomass was estimated to have increased by 56% in the 1980s, before the survey series started, and this increase was driven primarily by extremely strong year classes in 1977 and 1980 (Figure 13).

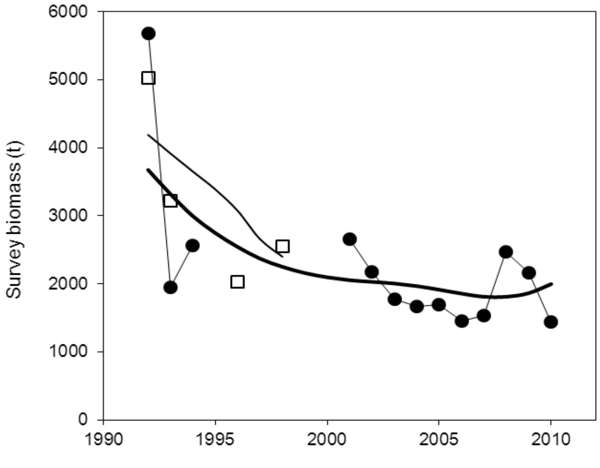


Figure 12: Fits to the summer (thick line, with observed values as solid circles) and autumn (thin line, with observed values as open squares) research survey series.

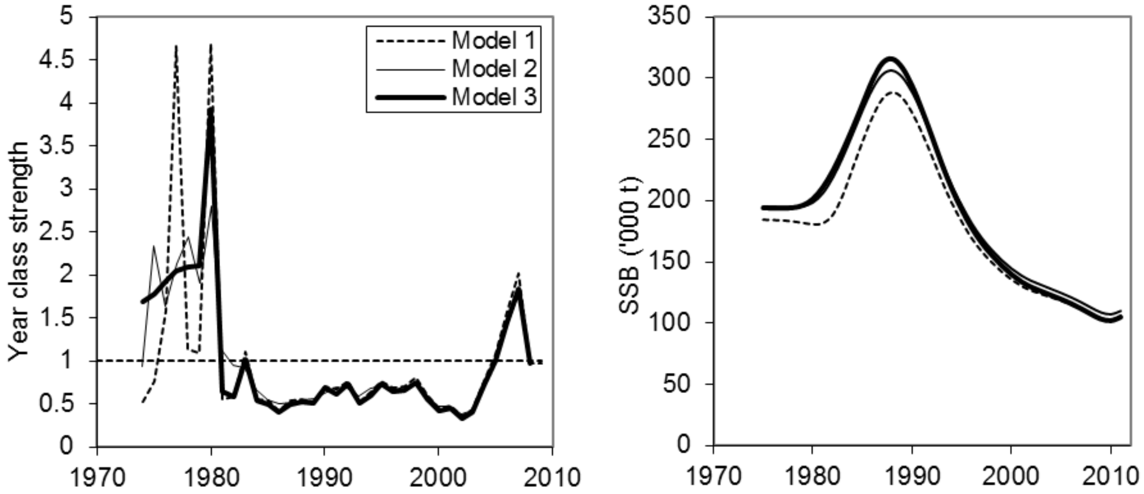


Figure 13: Estimated year class strengths and spawning stock biomass, from models 1–3.

The age data were examined to see what information existed to indicate that the 1980 and 1977 year classes were particularly strong (Figure 14). There was clear indication from the early parts of the proportion-at-age series (i.e., 1990 and 1992–1994) that the 1980 year class is strong. However, the 1977 year class seldom appears to be strong in any data set; only the 1990 summer and 1993 autumn survey distributions suggest that this year class might be stronger than average. It was suspected that the estimated 1977 strong year class was an artefact, the consequence of a tendency for models which assume ageing error to estimate high variability in year-class strength in periods with few data.

Consequently, two additional models were run to investigate year class strength estimation: in model 2, the assumption of ageing error was dropped; model 3 retained this assumption but smoothed the year class strengths from 1974 to 1979.

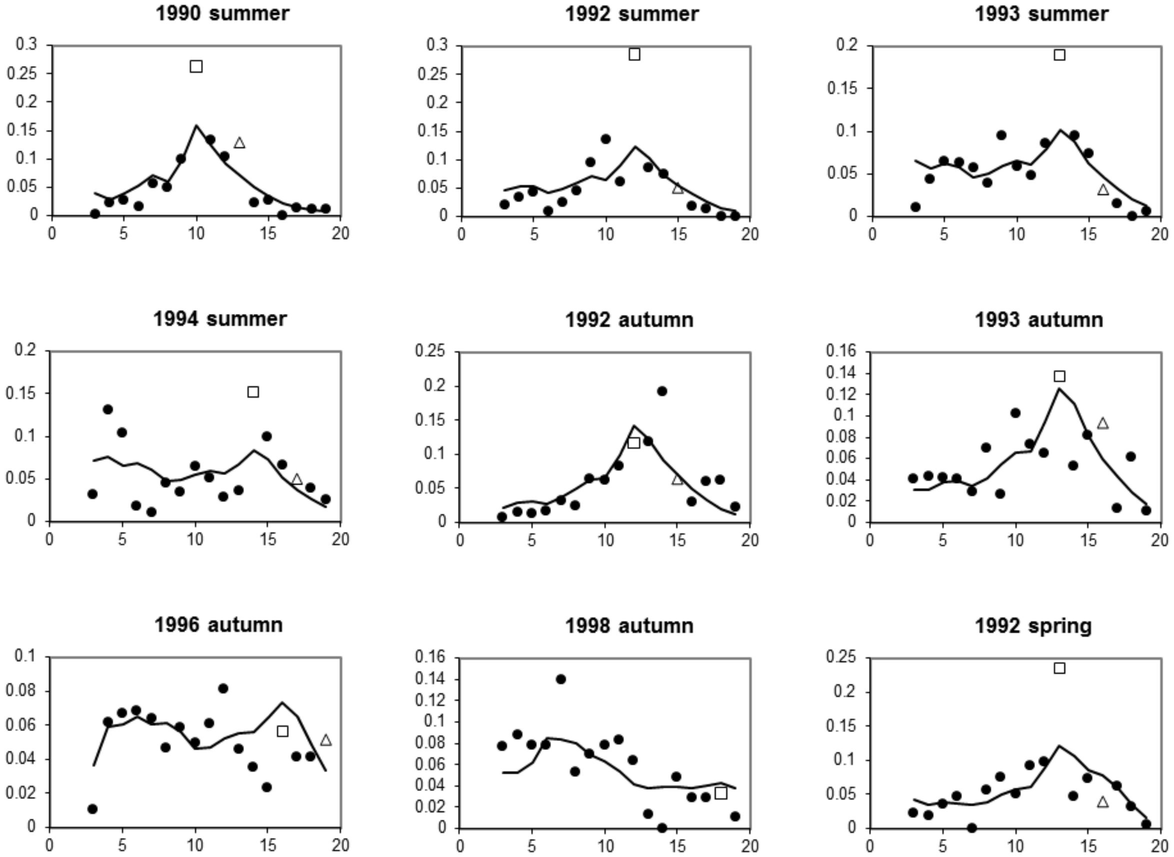
The new models both produced early year class strength estimates that were markedly different from those of model 1, but there was little change in estimated spawning stock biomass or stock status (Figure 13). It appeared very likely that the extreme estimates of year class strength before 1980 (both high and low) are artefacts of the application of ageing error to age classes with few data. All three models produced similar patterns of year class strengths from 1981 to 2008, where the data were more abundant. The two new models were similar over their entire range, and they still provided a clear indication of some stronger than average year classes in the late 1970s.

It was considered desirable to include some ageing error in the assessment model, so the smoothing of early year class strengths was retained for all subsequent models. The effect of including this smoothing was to only slightly degrade the overall fit (Table 11).

Table 11: Negative log likelihood of all data series for models 1 and 3, showing how the smoothing of early year class strengths in the latter model slightly degraded the fits compared to those in the former.

Data series	Model 1	Model 3	Gain
Survey biomass (summer)	-10.7	-10.4	-0.3
Survey biomass (autumn)	-3.7	-4.3	0.6
Survey biomass (spring)	-1.3	-1.3	0.0
Survey age (summer)	183.1	185.9	-2.8
Survey age (autumn)	55.0	50.1	4.9
Survey age (spring)	22.7	24.7	-2.0
Fishery age	162.0	161.6	0.4
Priors & penalties	84.1	85.8	-1.7
Total log likelihood	491.2	492.3	-1.1

Trawl surveys



Commercial fishery

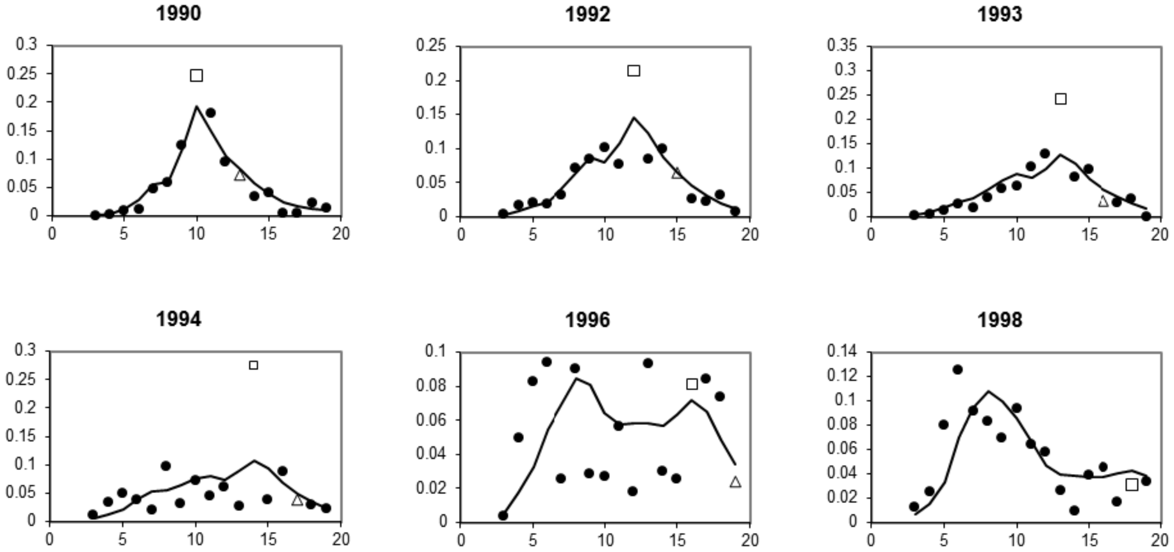


Figure 14: Observed (symbols) and estimated (lines, calculated for model 1) proportions-at-age, by year, from the research trawl surveys and commercial fishery. Observed data for the 1980 year class are represented as open squares, and 1977 year class data as open triangles.

The models investigated so far had selectivity ogives that had been fitted using the double-normal parameterisation. The effects of forcing logistic selectivity ogives for the research biomass surveys were examined in model 4, with the underlying assumptions being that the surveys comprehensively sample all the adult population. However, the overall fit for this model was much worse than for model 3, particularly for the three series of at-age data where logistic selectivity ogives were applied (Table 12). Consequently, it was concluded that given the currently used constant values for natural mortality rate, catch-at-age data from all sources are much better fitted by double-normal, rather than logistic, ogives. However, the double-normal selectivity ogives were markedly different between sexes (Figure 15), particularly for the summer survey, and this was believed to be unsatisfactory and unrealistic.

Table 12: Negative log likelihood of all data series from models 3 and 4, showing how forcing ogives for the survey and east fishery to be logistic substantially degraded the fit to the corresponding at-age data.

Data series	Model 3	Model 4	Gain
Survey biomass (summer)	-10.4	-11.2	0.8
Survey biomass (autumn)	-4.3	-3.9	-0.4
Survey biomass (spring)	-1.3	-1.3	0.0
Survey age (summer)	185.9	214.1	-28.2
Survey age (autumn)	50.1	59.2	-9.1
Survey age (spring)	24.7	29.4	-4.7
Fishery age	161.6	161.8	-0.2
Priors & penalties	85.8	86.1	-0.3
Total log likelihood	492.3	534.2	-41.9

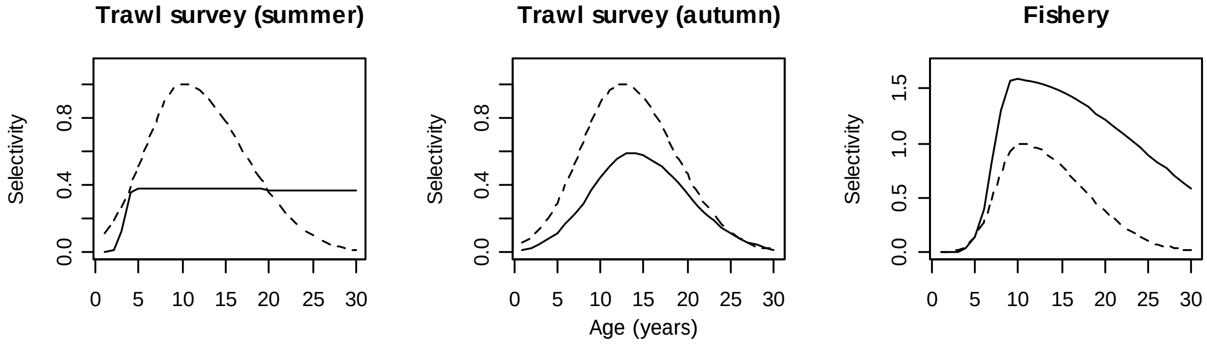


Figure 15: MPD estimates of trawl selectivity from model 3, for male (solid line) and female (dashed line) hake.

A likelihood profile for model 3 showed that there were two groups of inputs producing conflicting signals (Figure 16). High values of B_0 (greater than 270 000 t) were strongly supported by the three largest sets of at-age data (i.e., the summer survey, the autumn survey, and the trawl fishery) and the summer survey biomass indices. Low values of B_0 (90 000 t or less) were weakly supported by the autumn survey biomass indices and the at-age data from the spring survey. However, biomass levels at the high end of this range would require exceptionally low trawl survey *q* values (i.e., less than 0.02), and would be inconsistent with B_0 estimates for other New Zealand hake stocks, i.e., 41 000 t and 82 000 t for the Chatham Rise and west coast South Island stocks, respectively (Horn & Francis 2010, Horn 2011).

It was also apparent that the sex ratio information for the trawl surveys and commercial fishery were inconsistent. Sex ratios in the surveys have been relatively consistent over time, with perhaps a weak trend of increasing proportions of males over time (Figure 17). However, the samples from the commercial catch are indicative of an increasing proportion of males being removed from the population over time (Figure 17). If proportionally more males have been removed in recent years then the surveys would be expected to show a reduction in the proportion of males over time. It was also found that male proportion-at-age data from the fishery were consistently poorly fitted relative to female data; the residuals for male data points were, on average, 1.5 times greater than for female data. Similar characteristics were observed in the Chatham Rise and west coast South Island hake fisheries, and the Chatham Rise fishery also exhibited similar conflicts in sex ratio trends. However, for both those stocks, the subsequent modelling problems were alleviated by removing sex from the partition (Horn & Francis 2010, Horn 2011).

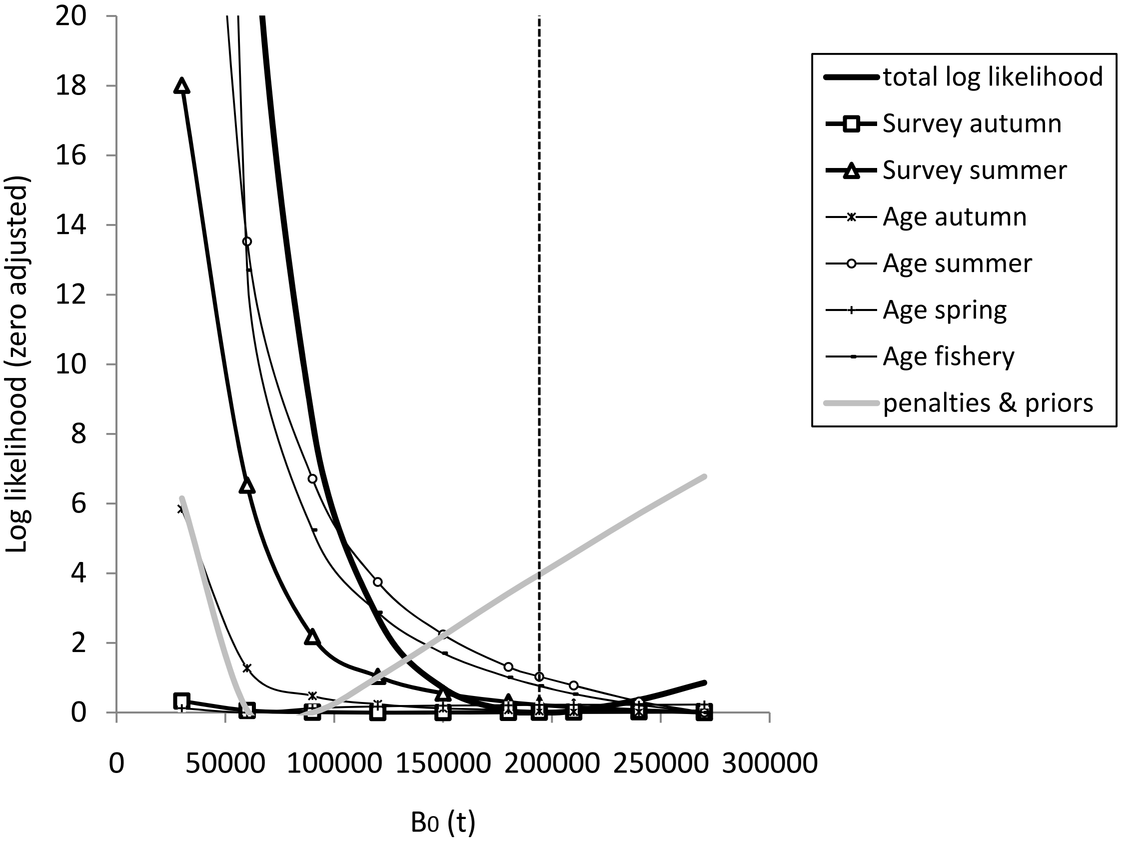


Figure 16: Likelihood profile on B_0 for model 3, showing both the total likelihood (heavy line) and those for individual data series. Vertical dashed line shows the model estimate of B_0.

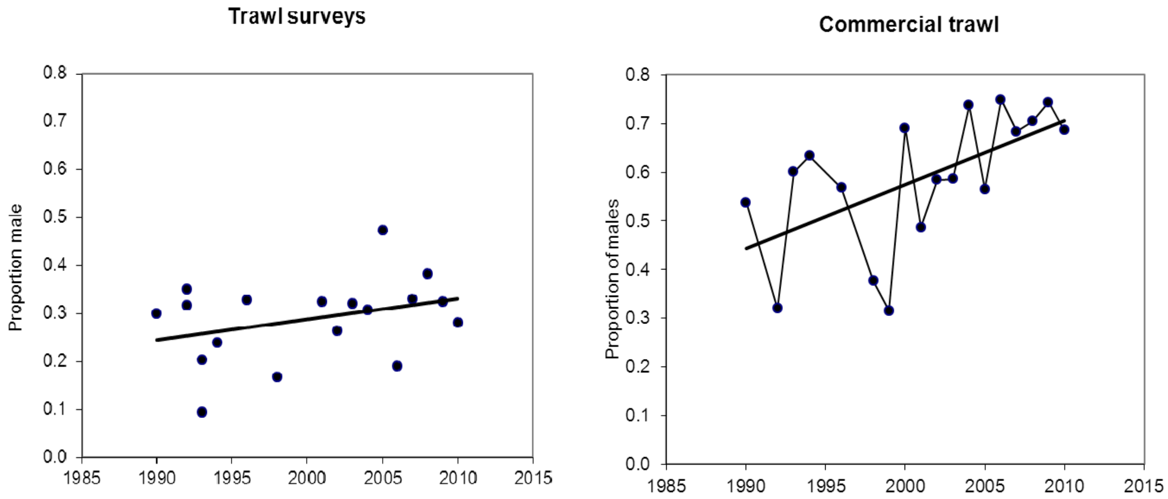


Figure 17: Proportion of male fish recorded in trawl surveys (scaled to survey area) and in the observer length data for the commercial trawl fishery (scaled to total catch by year). Solid lines are linear regressions.

Consequently, a single-sex model was tested. In that model, sex was removed from the partition, length-weight and Schnute growth parameters were calculated for both sexes combined (see Table 5), *M* was set at 0.19 (the average of the male and female values), all catch-at-age data were unsexed, and the 1974–79 year class strengths were smoothed as before.

Removing sex from the model substantially reduced the estimate of B_0 (from 194 000 t to 95 000 t) (Figure 18). It had comparatively little effect on the estimated year class strengths, slightly flattening the estimates (Figure 18). Despite the lower B_0, stock status in 2011 of 51% of B_0 was little different to the 54%B_0 estimated from the two sex model. A period of relatively strong recruitment in the late 1970s was still indicated, resulting in a moderate increase in stock biomass during the 1980s before the start of the survey series. The selectivity ogives are logical, i.e., the two survey ogives are similar and exhibit greater selectivity on young (small) fish than the commercial fishery, as would be expected given the smaller codend mesh in the survey trawl (Figure 19).

A major effect of removing sex from the model was to reduce the degree of conflict between the input data series. All series strongly reject a B_0 lower than 60 000 t. However, there was little clear support for a distinct value greater than about 90 000 t (Figure 20).

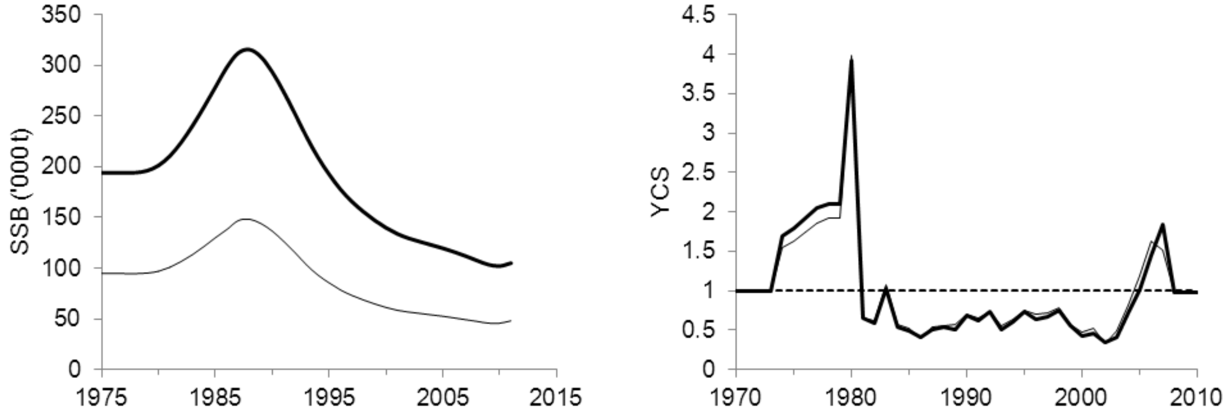


Figure 18: Biomass trajectories and estimates of year class strengths from the initial two-sex model (model 3, thick lines) and the subsequent single-sex model (model 5, thin lines).

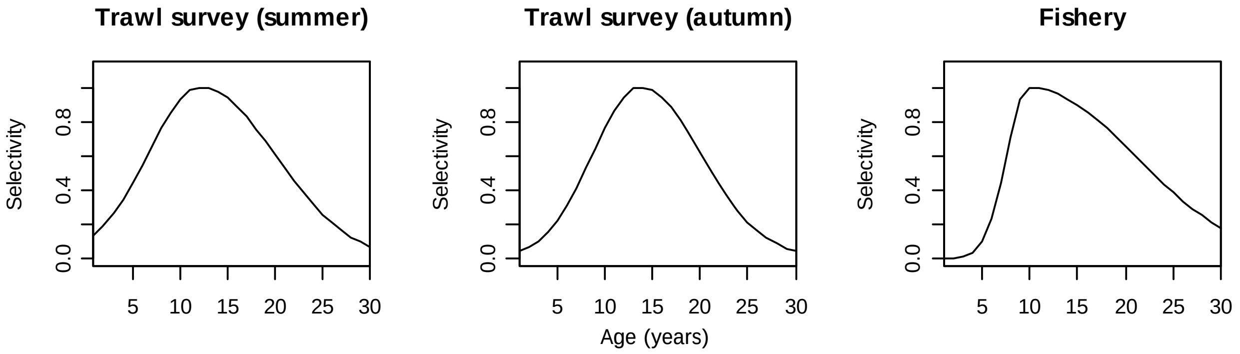


Figure 19: Estimated selectivity ogives for the research surveys and the commercial fishery from model 5.

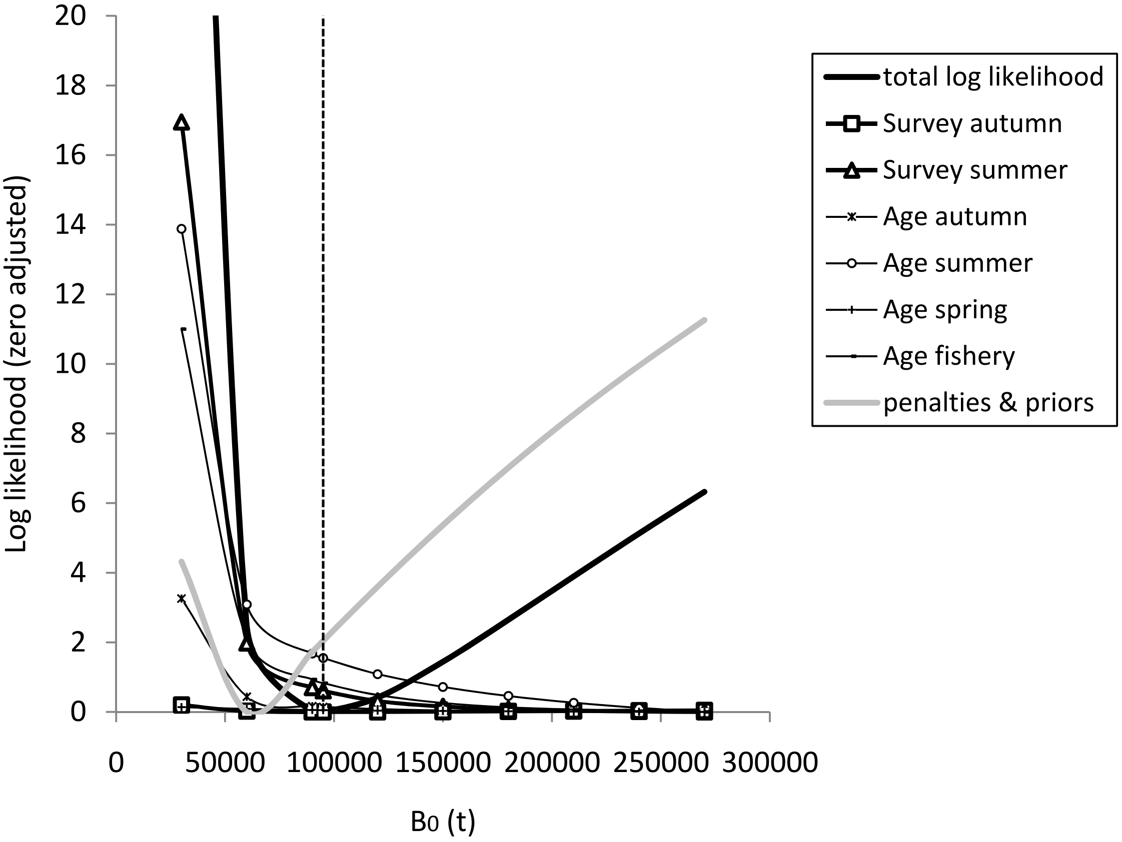


Figure 20: Likelihood profile on B_0 for model 5, showing both the total likelihood (heavy line) and those for individual data series. Vertical dashed line shows the model estimate of B_0.

The impact of adding a trawl fishery CPUE series to the single-sex model was investigated and found to markedly increase the estimate of B_0 (from 95 000 t to 131 000 t) (Figure 21). It had comparatively little effect on the estimated year class strengths, generally reducing earlier estimates and increasing later ones (Figure 21). It encouraged a flatter biomass trajectory, and consequently a better stock status in 2011 of 67% of B_0 (compared to 51%B_0 for the single-sex model). However, the initial part of the CPUE series is poorly fitted; it does not show the marked decline in biomass throughout the early 1990s indicated by other model inputs (Figure 22). Consequently, the CPUE also encourages flatter (but not clearly worse) fits to the trawl survey series (Figure 22).

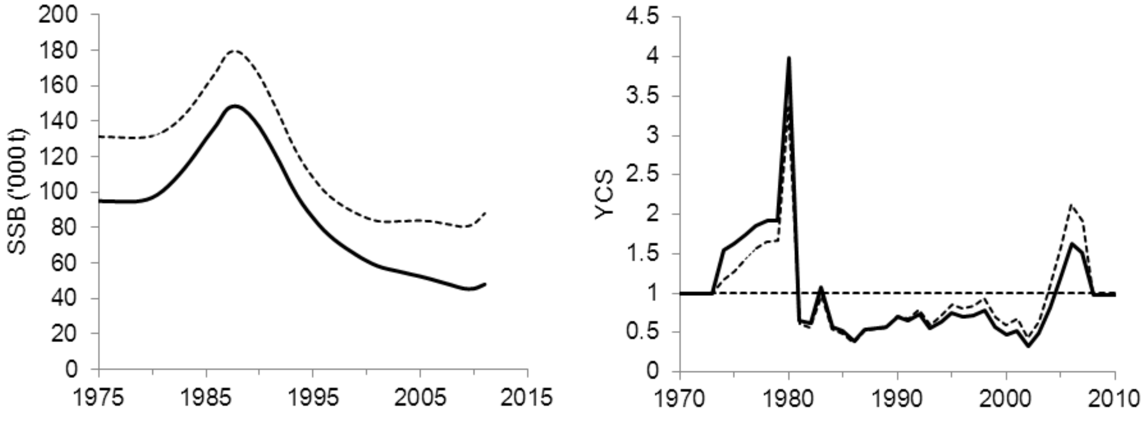


Figure 21: Biomass trajectories and estimates of year class strengths from the single-sex model without CPUE (model 5, solid lines) and with CPUE (model 6, dashed lines).

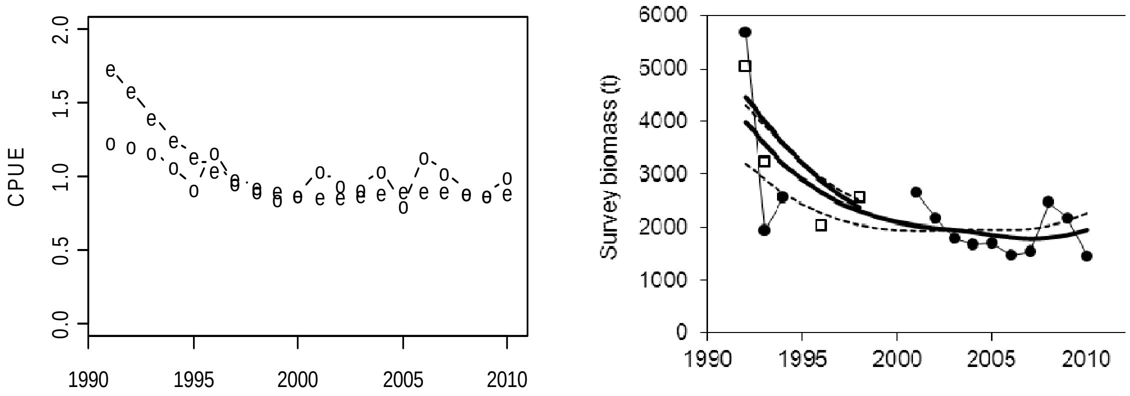


Figure 22: MPD fits to the CPUE series ('o', observed; 'e', expected), and fits to the trawl survey series from the single-sex model without CPUE (model 5, solid lines) and with CPUE (model 6, dashed lines).

The data for this stock comprise a large amount of catch-at-age information so it was considered desirable to investigate the estimation of *M* in the model. Because *M* is confounded with selectivity, the model run where *M* was estimated (model 7) had the selectivity ogive for the trawl fishery estimated using the logistic (rather than double-normal) parameterisation, with the underlying assumption being that the fishery comprehensively samples all the adult population. The effects of forcing logistic selectivity ogives for the surveys were examined above in model 4, but *M* was fixed as a constant in that case. In model 7, *M* was estimated using the double exponential parameterisation. It was clear that by allowing the model to estimate an age-dependent *M*, the fits to the summer survey age data could be markedly improved with no significant degradation to the fits to any other input series (Table 13).

Table 13: Negative log likelihood of all data series from models 5 and 7, showing how estimating *M* as age-dependent and forcing the fishery ogive to be logistic substantially improved the fit to the corresponding at-age data.

Data series	Model 5	Model 7	Gain
Survey biomass (summer)	-10.1	-9.6	-0.5
Survey biomass (autumn)	-4.3	-4.3	0.0
Survey biomass (spring)	-1.4	-1.4	0.0
Survey age (summer)	7.9	-11.6	19.5
Survey age (autumn)	-9.3	-8.4	-0.9
Survey age (spring)	2.6	2.8	-0.2
Fishery age	-5.5	-6.1	0.6
Priors & penalties	81.0	66.8	14.2
Total log likelihood	60.1	28.1	32.0

The estimated ogive for *M* was logical with a minimum at age 7 (slightly lower than the estimated age at 100% maturity of 11 years), and a range from 0.08 to 0.74 (Figure 23). The impact of estimating *M* was a marked decrease in the estimate of B_0 (69 100 t, down from 95 000 t in model 5) (Figure 24). It had comparatively little effect on the estimated year class strengths, and also resulted in only slight changes in the fits to the trawl survey series (Figure 24). The biomass trajectory still exhibits a steep decline throughout the 1990s, resulting in a stock status in 2011 of 43% of B_0 (compared to 51%B_0 for the single-sex model). This was the most pessimistic of all the models tested.

Figure 23: Estimated *M* ogive from model 7. The horizontal dashed line indicates the constant *M* of 0.19 used in all other model runs.

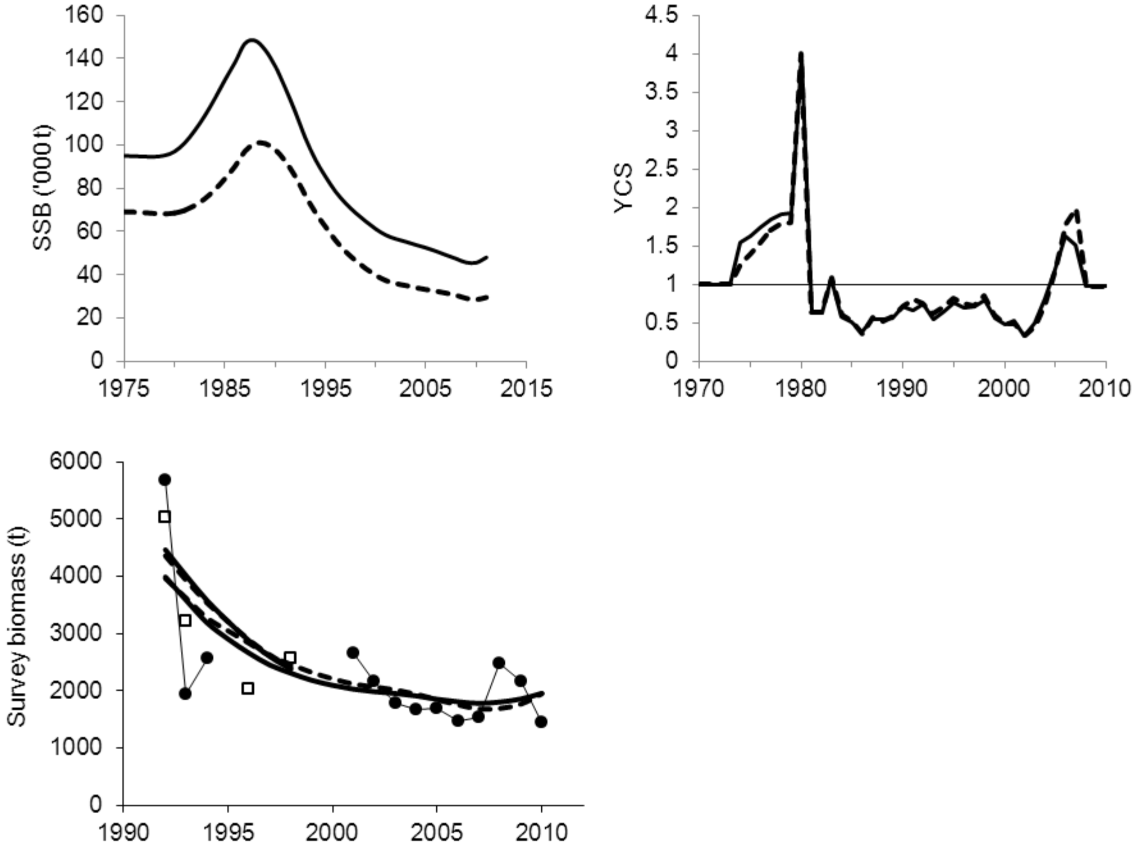


Figure 24: Biomass trajectories, estimates of year class strengths, and fits to the trawl survey series from model 5 (single-sex model, solid lines) and model 7 (estimate *M* model, dashed lines).

Following the investigations above with MPD model fits it was concluded that the best base case model for MCMC estimation was model 5 (the single sex model). Sensitivity model runs using MCMC estimation were also completed to investigate sex in the partition (model 3, the two sex model), the influence of CPUE (model 6, the CPUE model), and the estimation of *M* (model 7, the estimate *M* model).

4.4 Model estimation using MCMC

Model parameters were derived using Bayesian estimation implemented using the CASAL software. For final runs, the full posterior distribution was sampled using Monte Carlo Markov Chain (MCMC) methods, based on the Metropolis-Hastings algorithm. MCMCs were estimated using $3\text{x}10^6$ iterations, a burn-in length of $5\text{x}10^5$ iterations, and with every 2500th sample kept from the final $2.5\text{x}10^6$ iterations (i.e., a final sample of length 1000 was taken from the Bayesian posterior). Year class strengths were estimated as in the MPD runs except that values for 2008–10 were no longer fixed at 1.

5. MODEL ESTIMATES

Estimates of biomass were made using the biological parameters (see Table 5) and model input parameters described earlier. MCMC estimates of the posterior distribution were obtained for all four model runs (i.e., single sex, two sex, CPUE, and *M* estimation), and are presented below. In addition, MCMC estimates of the median posterior and 95% percentile credible intervals are reported for the key output parameters. The MCMC chains for estimates of B_0 and B_{2011} from the base (single sex) model are not well converged (Figure 25). However, the distributions of estimates of B_0 and B_{2011} (as $\%B_0$) from the single sex model are reasonably consistent between the first, middle, and last thirds of the chain (Figure 25), so convergence is probably adequate for stock-assessment purposes.

The estimated MCMC marginal posterior distributions for selected parameters from the single sex model are shown in Figures 26–30. The selectivity ogives for the trawl survey series and the trawl fishery were all strongly domed (Figure 26). The ogives suggest that hake were fully selected by the fishery by age 10, and that younger fish were more selected by the trawl surveys (as would be expected given the smaller codend mesh). There is no information outside the model that allows the shape of the estimated selectivity ogives to be verified.

Year class strength estimates were well estimated for all years from 1985 to 2005, and moderately well estimated in all other years (Figure 27). Recall, however, that the estimates from 1974 to 1979 were smoothed. The 1980 year class stands out as being exceptionally strong, but variation in year class strength since then does not appear to be great with virtually all median estimates being between 0.5 and 2.

Estimated biomass for the Sub-Antarctic stock increased throughout the 1980s owing to relatively low catch levels, and the recruitment of stronger than average 1974 to 1980 year classes (Figure 28). Biomass then steadily declined from 1988 to about 2000 owing to higher levels of exploitation (Figure 29) and the recruitment of year classes that were generally of below-average strength. A slower decline continued to about 2009, with a slight increase since then being a consequence of the recruitment of three year classes since 2005 that are estimated to be of above-average strength. Bounds around the biomass estimates are wide, with current stock size being about 52% of B_0 (95% credible interval 39–64%) (see Figure 28 and Table 14). Exploitation rates (catch over vulnerable biomass) were negligible (less than 0.02) up to 1990, and have probably not exceeded 0.1 yr^{-1} in any year since then (Figure 29).

The research survey catchability constants are estimated to be about 3%, 4% and 4% for the summer, autumn and spring survey series, respectively, suggesting that the absolute catchability of all the surveys is very low, and not very consistent with the prior (Figure 30).

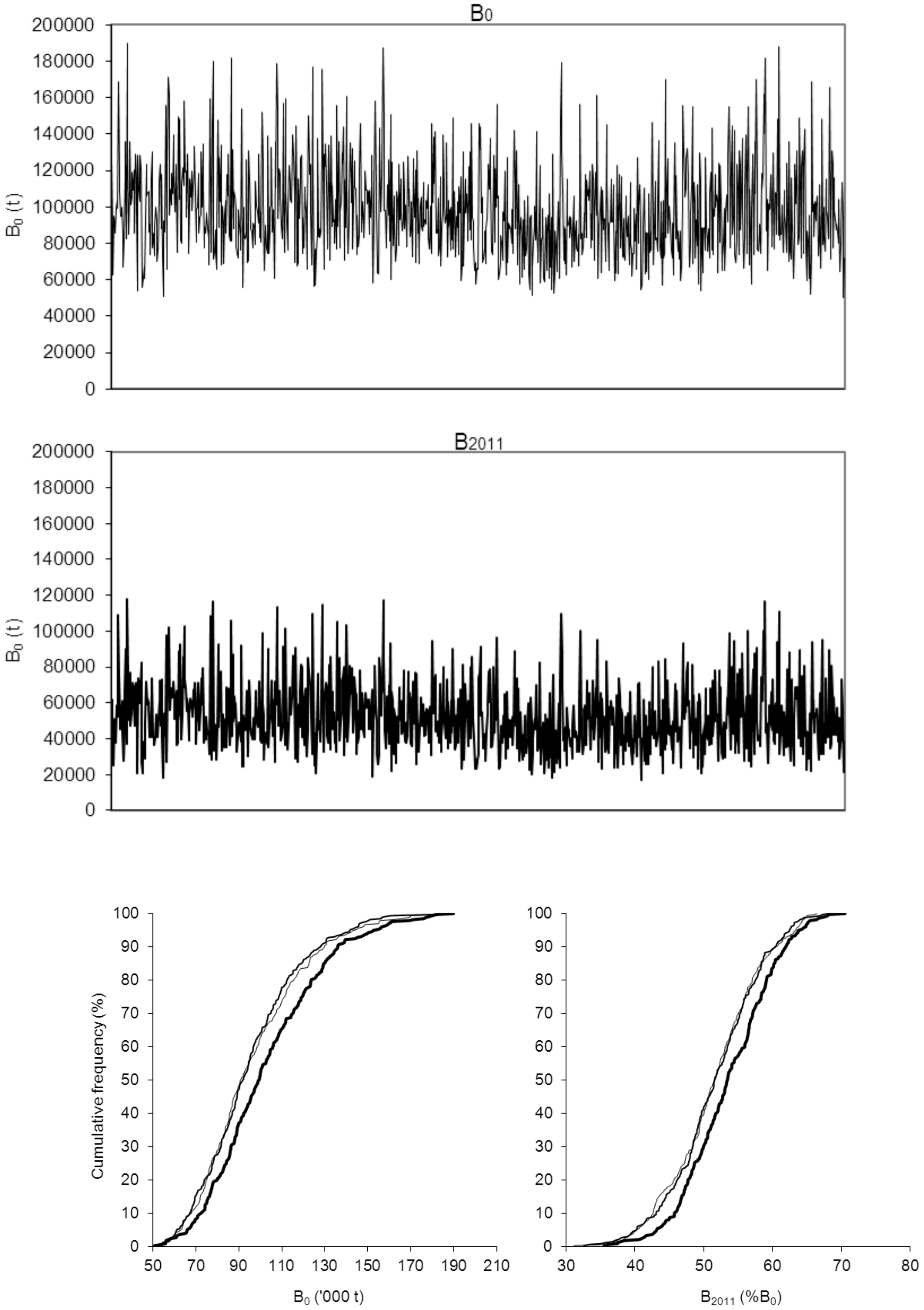


Figure 25: Trace diagnostic plot of the MCMC chains for estimates of B_0 and B_{2011} for the single sex model run (top and middle panel). MCMC diagnostic plots showing the cumulative frequencies of B_0 and B_{2011} (%B_0) for the first (thick line), middle (medium line), and last (thin line) third of the MCMC chain for the single sex model (bottom panel).

Table 14: Bayesian median and 95% credible intervals of B_0, B_{2011}, and B_{2011} as a percentage of B_0 for all model runs.

Model run	B_0		B_{2011}		B_{2011} (%B_0)	
Single sex	94 150	(59 220–156 350)	49 590	(23 860–95 220)	52.3	(39.0–64.5)
Two sex	192 190	(121 120–295 650)	106 740	(59 400–178 110)	54.7	(45.9–63.9)
CPUE	135 700	(84 040–227 040)	91 930	(51 870–166 760)	67.8	(58.3–77.3)
Estimate *M*	78 240	(51 810–135 590)	36 170	(17 820–77 080)	46.2	(32.3–58.6)

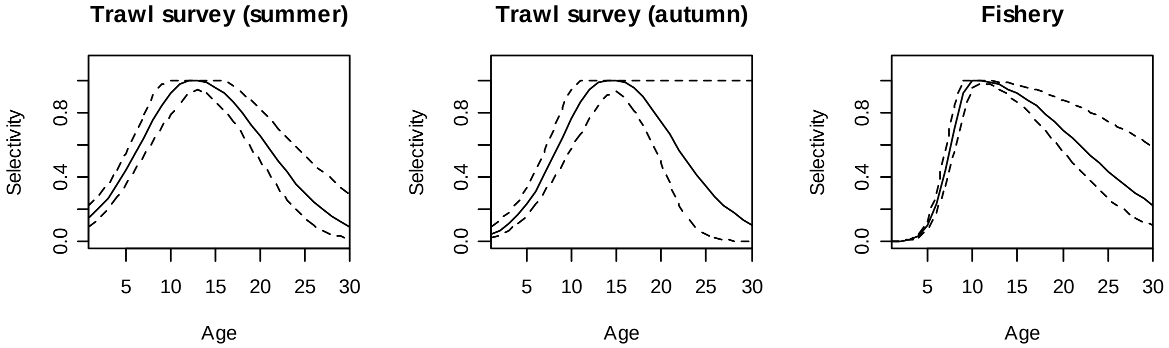


Figure 26: Single sex model — Estimated median selectivity ogive (with 95% credible intervals shown as dashed lines) for the trawl surveys and the trawl fishery.

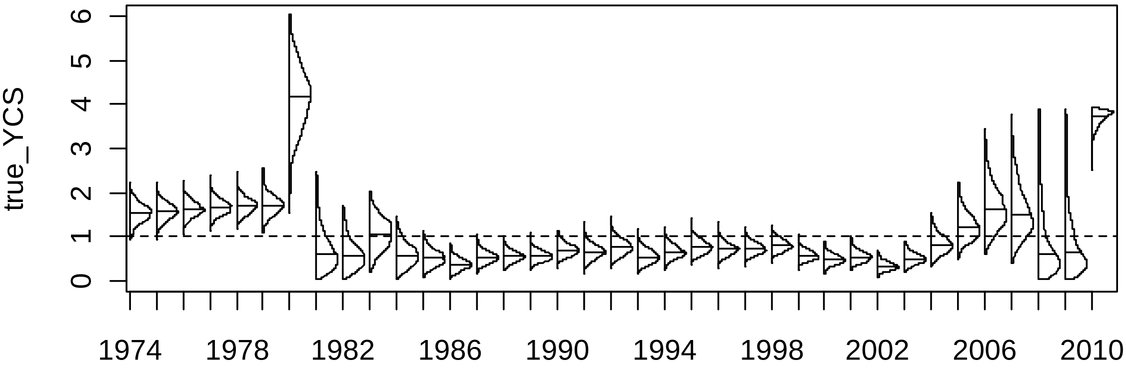


Figure 27: Single sex model — Estimated posterior distributions of year class strengths. The dashed horizontal line indicates the year class strength of one. Individual distributions are the marginal posteriors, with horizontal lines indicating the median.

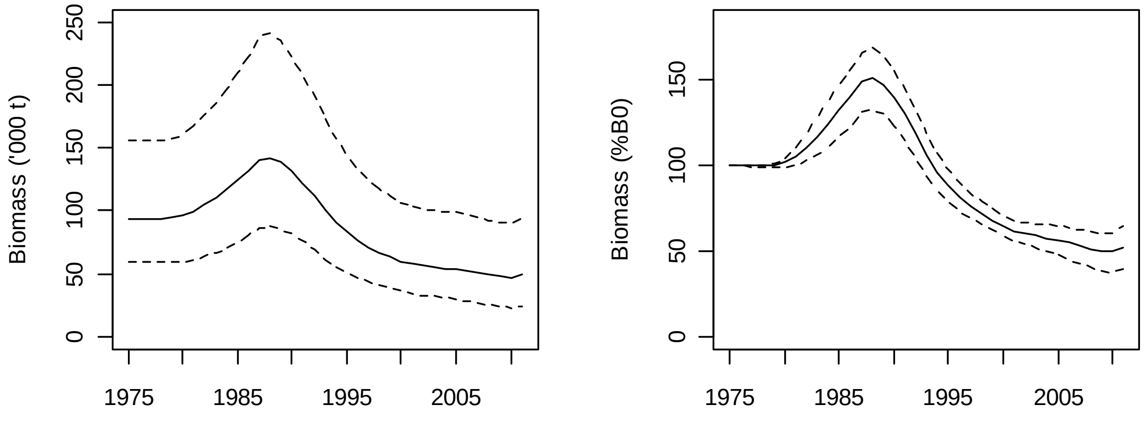


Figure 28: Single sex model — Estimated median trajectories (with 95% credible intervals shown as dashed lines) for absolute biomass and biomass as a percentage of B_0.

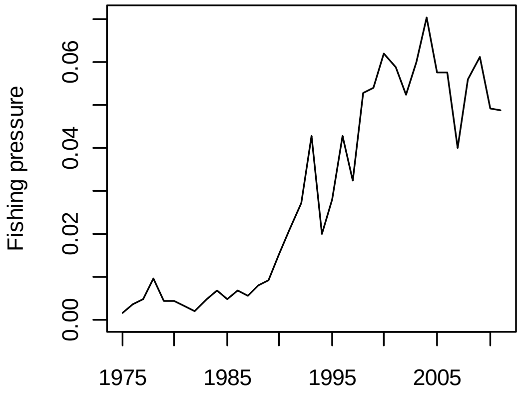


Figure 29: Single sex model — Estimated median trajectory of exploitation rate.

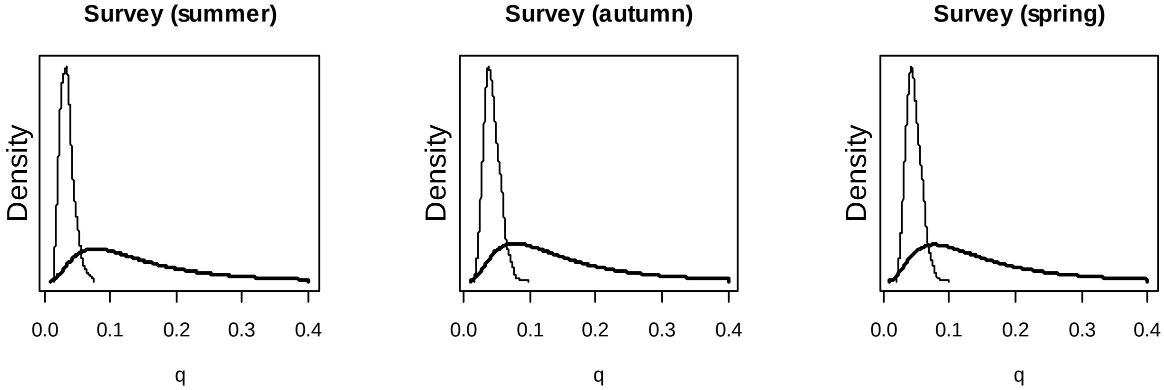


Figure 30: Single sex model — Estimated posterior distribution (thin line) and prior (thick line) of survey catchability constants (*q*) for the three resource survey series.

The first sensitivity run investigated the effect of including sex in the partition. As in the MPD run for this model, the selectivity ogives varied markedly between sexes; old females were always much less selected than old males in the surveys and the fishery (Figure 31). Estimated year class strengths were little different to those from the single sex model. Estimates of absolute biomass, both virgin and current, were more than double those of the single sex model, but stock status was virtually identical between the two models (Table 14, Figure 32). The increased biomass results in even smaller estimates of survey catchability constants than in the single sex model, i.e., 2%, 2% and 3% for the summer, autumn and spring survey series, respectively. These values appear unrealistic and are certainly not consistent with the prior. Exploitation rates (catch over vulnerable biomass) were estimated to have never been greater than 0.05 yr^{-1}.

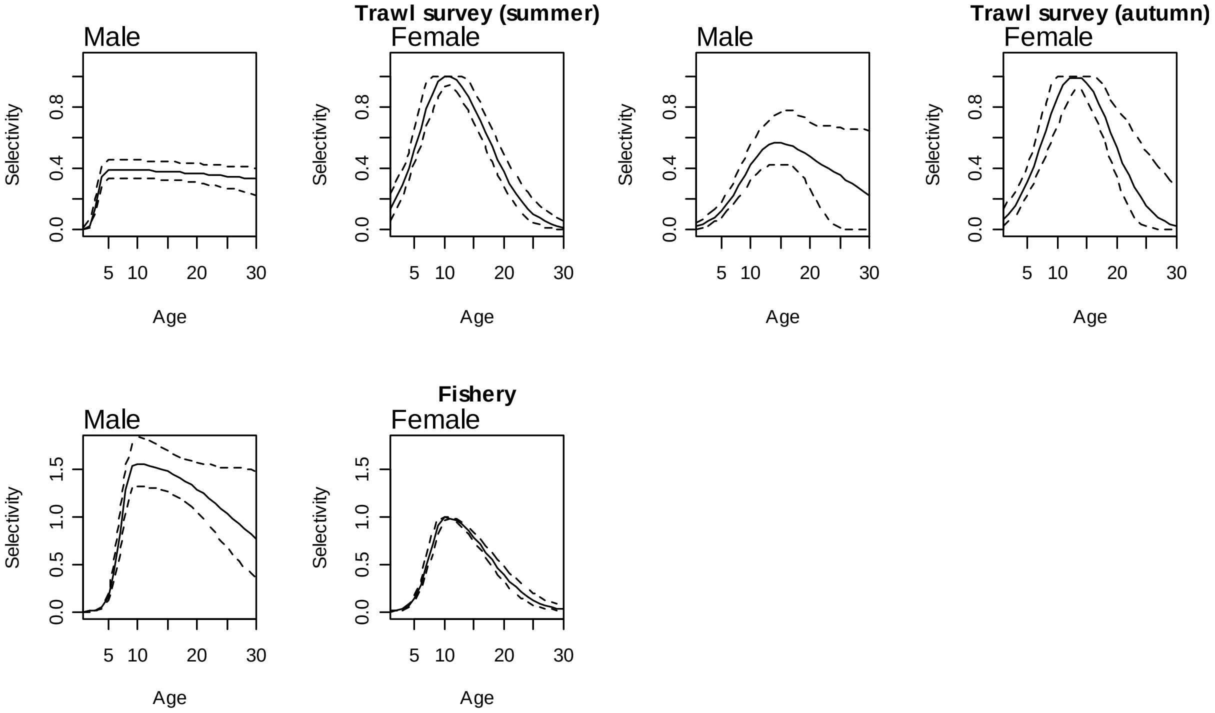


Figure 31: Two sex model — Estimated median selectivity ogive (with 95% credible intervals shown as dashed lines) for the trawl surveys and the trawl fishery.

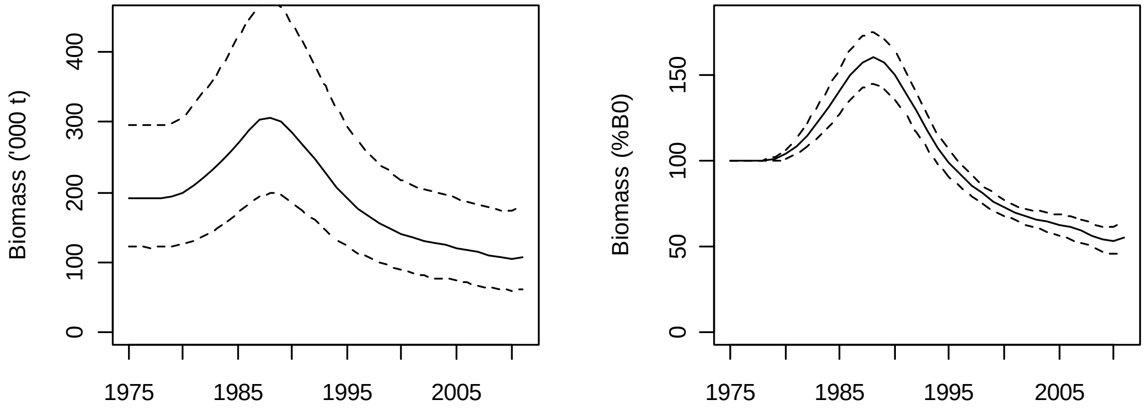


Figure 32: Two sex model — Estimated median trajectories (with 95% credible intervals shown as dashed lines) for absolute biomass and biomass as a percentage of B_0.

A sensitivity run investigating the influence of adding the CPUE series to the single sex model also resulted in higher estimates of absolute biomass (both virgin and current) and also in stock status, i.e., 68% of B_0, compared to 52% for the single sex model (Table 14). The CPUE series is relatively flat (see Figure 21), so it has the effect of flattening the biomass trajectory (particularly the latter part), and hence, improving current stock status (Figure 33). A consequence of the overall flattening of the biomass trajectory is that the earlier year classes are estimated to be weaker and the later ones are stronger (Figure 34). The selectivity ogives are little different to those estimated in the single sex model. Exploitation rates (catch over vulnerable biomass) were estimated to have never been greater than 0.05 yr^{-1}. The estimates of trawl survey catchability constants (i.e., 3%, 2% and 4% for the summer, autumn and spring survey series, respectively) are very low, and probably unrealistic.

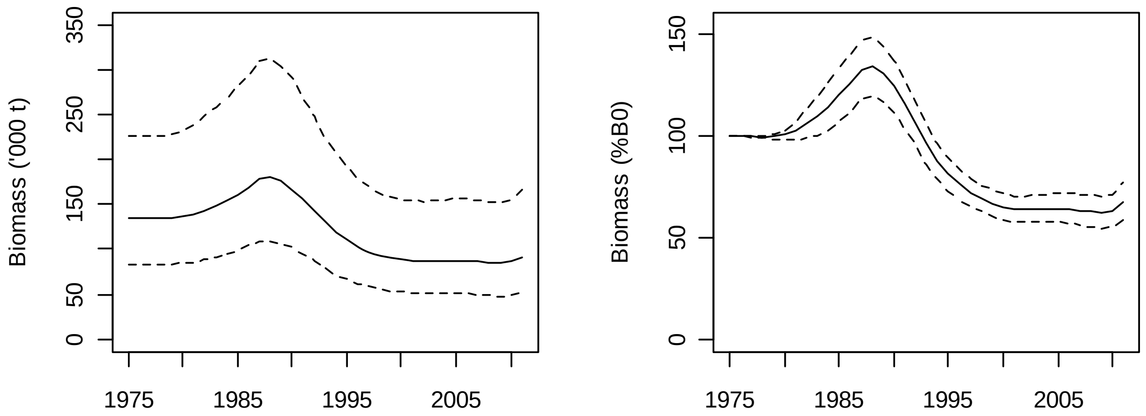


Figure 33: CPUE model — Estimated median trajectories (with 95% credible intervals shown as dashed lines) for absolute biomass and biomass as a percentage of B_0.

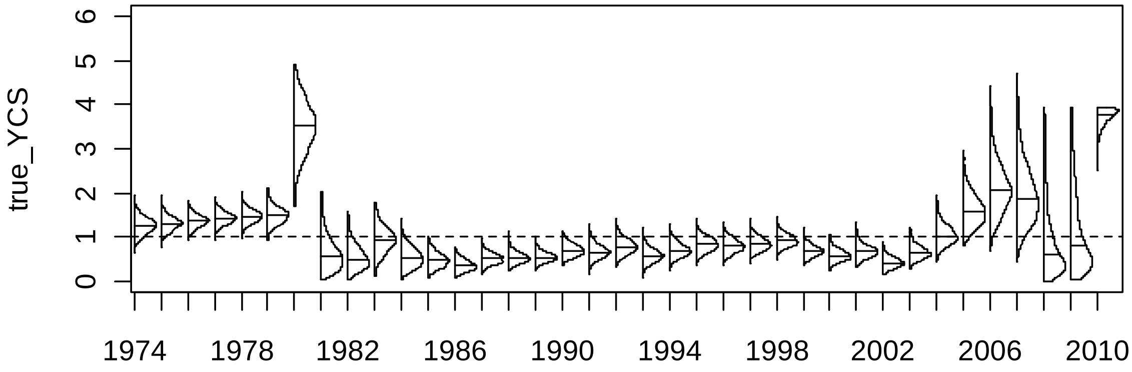


Figure 34: CPUE model — Estimated posterior distributions of year class strengths. The dashed horizontal line indicates the year class strength of one. Individual distributions are the marginal posteriors, with horizontal lines indicating the median.

The sensitivity run where an *M*-at-age relationship was estimated was the most pessimistic of the four models investigated. Estimates of absolute biomass were lower than in the single sex model, and current stock status was estimated to be 46% B_0 (see Table 14). Recall that in this model the selectivity ogive for the trawl fishery was estimated using the logistic (rather than double-normal) parameterisation, with the underlying assumption being that the fishery comprehensively samples all the adult population. The fishery selectivity ogive was tightly defined, while the survey ogives had quite wide bounds (Figure 35). The survey ogives, although estimated using double normal parameterisation, was essentially logistic shaped. Age at full selectivity for the summer survey series was markedly lower than it was in the single sex model, but was essentially unchanged for the autumn survey series and the fishery (see Figure 26).

The estimated year class strengths were little different to those from the single sex model, and the estimated maximum exploitation rate (about 0.08 yr^{-1}) was only slightly higher. The estimates of trawl survey catchability constants (i.e., medians of 3%, 5% and 5% for the summer, autumn and spring survey series, respectively) are higher than in any other model run, but still not very consistent with the prior (Figure 36).

The age-based instantaneous natural mortality (*M*) relationship estimated independent of sex had a minimum of about 0.1 at 6 years, rising to about 0.7 at 30 years, and a relatively narrow 95% credible interval across ages 6 to 23, i.e., the age classes most abundant in the surveys and the commercial catch (Figure 37). However, the estimation of *M* will be confounded with the estimation of survey and fishery selectivities, so we cannot be confident that the true relationship has been determined here.

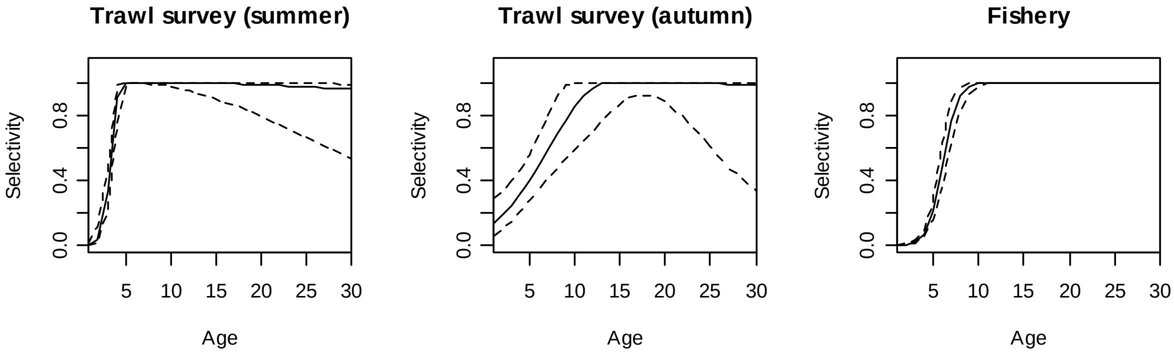


Figure 35: Estimate *M* model — Estimated median selectivity ogive (with 95% credible intervals shown as dashed lines) for the trawl surveys and the trawl fishery.

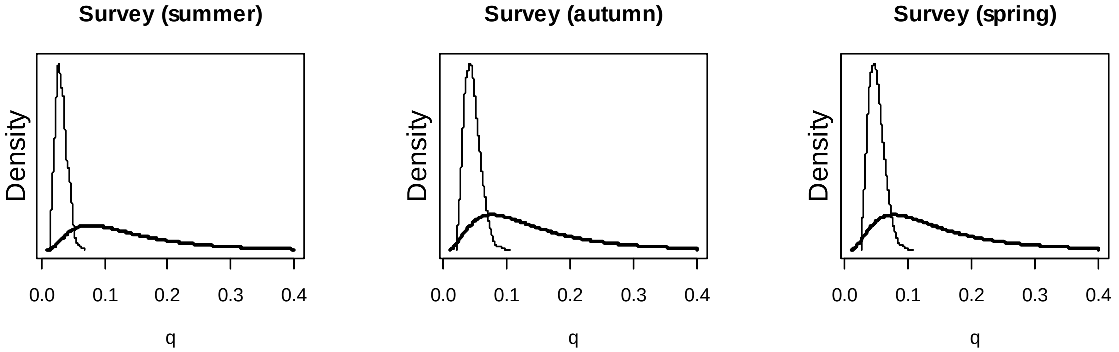


Figure 36: Estimate *M* model — Estimated posterior distribution (thin line) and prior (thick line) of survey catchability constants (*q*) for the three resource survey series.

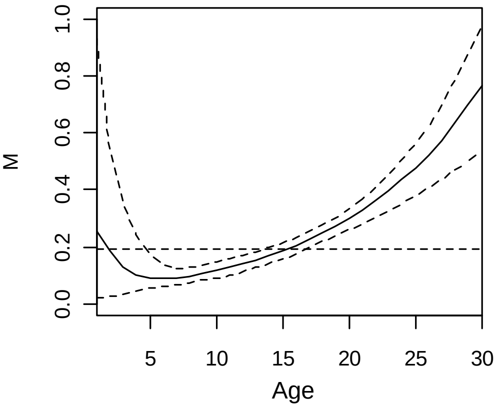


Figure 37: Estimate M model — Estimated median age-based natural mortality (M) relationship (with 95% credible intervals shown as dashed lines) for both sexes combined. The horizontal dashed line is at 0.19, the value that has been used as a fixed value for *M* in previous single sex assessments.

5.1 Biomass projections

Biomass projections from the four models investigated using MCMC estimation were made assuming future annual catches of 2300 t from 2012 to 2016. This catch is the average from 2005 to 2010, and is only slightly lower than the average annual catch since 1990 (2500 t). There is no specific TACC for the Sub-Antarctic stock. The HAK 1 administrative stock (with a TACC of 3701 t) includes all of the Sub-Antarctic, the western end of the Chatham Rise, and all around the North Island.

Year class strengths from 2008 onwards were selected randomly from the previously estimated year class strengths from 1974 to 2007.

Projections from all the models suggested that biomass will increase markedly to be between 80% and 100% of B_0 by 2016 (Table 15, Figure 38). The most pessimistic of these models suggests that there is little chance that biomass in 2016 will be lower than 51% of B_0. However, these projections are quite uncertain as indicated by the rapidly spreading confidence intervals after 2011 (Figure 38).

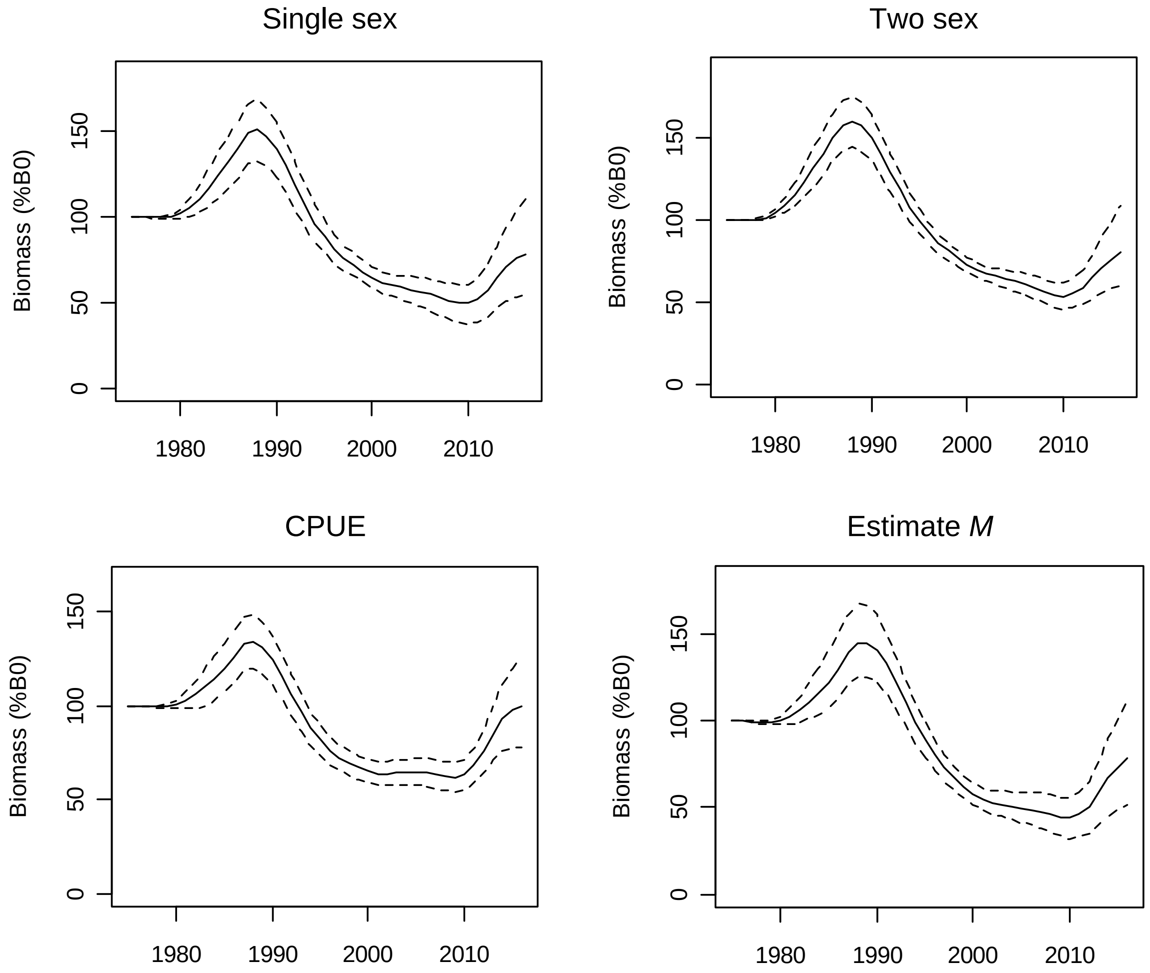


Figure 38: Estimated median trajectories (with 95% credible intervals shown as dashed lines) for biomass as a percentage of B_0, projected to 2016 with future catches assumed to be 2300 t annually, for all models.

Table 15: Bayesian median and 95% credible intervals of projected B_{2016}, B_{2016} as a percentage of B_0, and B_{2016}/B_{2011} (%) for all model runs, with future annual catch equal to the mean from 2005 to 2010.

Model run	Future catch (t)	B_{2016}	B_{2016} (%B_0)	B_{2016}/B_{2011} (%)
Single sex	2 300	74 630 (35 390–147 810)	78.4 (53.5–110.9)	150 (119–200)
Two sex	2 300	156 470 (81 790–279 230)	80.2 (59.5–108.3)	146 (118–192)
CPUE	2 300	136 200 (73 690–250 450)	99.8 (78.0–126.3)	147 (121–187)
Estimate *M*	2 300	62 080 (27 760–136 220)	78.8 (51.2–111.6)	169 (132–229)

5.2 Management biomass targets

Probabilities that current and projected biomass will drop below default management reference points from the Harvest Strategy Standard (i.e., target, 40%B_0; soft limit, 20%B_0; hard limit, 10%B_0) are shown for all four models in Table 16. It appears extremely unlikely (i.e., less than 1%) that B_{2016} will be lower than the soft limit of 20%B_0, or even the target of 40%B_0.

Table 16: Probabilities that current (B_{2011}) and projected (B_{2016}) biomass will be less than 40%, 20% or 10% of B_0. Projected biomass probabilities are presented assuming a future annual catch of 2300 t.

Model run	Biomass	Management reference points		
		40% B_0	20% B_0	10% B_0
Single sex	B_{2011}	0.036	0.000	0.000
	B_{2016}, 2300 t catch	0.003	0.000	0.000
Two sex	B_{2011}	0.000	0.000	0.000
	B_{2016}, 2300 t catch	0.000	0.000	0.000
CPUE	B_{2011}	0.000	0.000	0.000
	B_{2016}, 2300 t catch	0.000	0.000	0.000
Estimate *M*	B_{2011}	0.150	0.000	0.000
	B_{2016}, 2300 t catch	0.000	0.000	0.000

6. DISCUSSION

This document updates the assessment of the Sub-Antarctic hake last reported by Horn (2008). Past assessments of this stock have produced relatively uncertain results owing to the lack of strong contrast in the available series of relative abundance, i.e., two trawl survey series, and trawl CPUE (Dunn 2006, Horn 2008). This problem still persists in the current assessment, but at least it is indicative of a stock that has not been markedly depleted by exploitation.

An exploratory analysis of the length and sex data collected by observers from the commercial trawl fishery showed that the sex ratios in catches varied markedly between tows, trips, and years. It had also been shown previously that sex ratios varied by location across the Stewart-Snares shelf and Campbell Plateau region (Horn 2008). Similar variations by sex were found in assessments of the Chatham Rise (Horn & Francis 2010) and west coast South Island (Horn 2011) hake stocks. For those stocks, a single sex model fitted the research biomass series and the commercial fishery proportion-at-age data better as it did not have to try and deal with conflicting information about changes in sex ratios over time and area. A similar solution was adopted here for the Sub-Antarctic assessment. As for the Chatham Rise and WCSI assessments, an initial two sex model was markedly more optimistic than the single sex model. However, it is unlikely that sex alone provides sufficient ‘logical’ information to increase the Sub-Antarctic B_0 by about 204%, so the two sex model is considered less desirable than the single sex model at this stage.

The single sex model estimated that the Sub-Antarctic spawning stock is currently at about 52% B_0, and that continued fishing at recent catch levels is likely to allow stock size to increase by about a half in the next five years. Sensitivity model runs including sex in the partition or allowing the estimation in the model of an age-based relationship for instantaneous natural mortality (*M*) did not markedly alter the estimate of stock status. A sensitivity including a trawl CPUE series did indicate a much more optimistic current stock status. However, none of the model runs were indicative of current biomass being lower than 34% of B_0 (i.e., the most pessimistic 95% credible interval lower bound).

Estimated year class strengths often have quite wide 95% bounds, particularly at the start and the end of the estimated series. However, the median estimates suggest that variation in year class strength is not great for this stock; only three of the estimates from 1974 to 2007 are outside the range 0.5–2 (i.e., 1980 is much higher, and 1986 and 2002 are lower). A similar relatively low level of year class strength variation was estimated for the hake stocks on the Chatham Rise and WCSI (Horn & Francis 2010, Horn 2011). However, it is not possible to tell whether the low variability in year class strengths is correct (i.e., the actual variability is low) or is a consequence of uninformative data (e.g., the year-class signal in the at-age data could be poor either because these data are not representative of the catch, or because it is masked by year-to-year variation in selectivity).

The residuals of the MPD fits to the at-age data (Appendix B) show that in the summer trawl survey series observed numbers of 3 and 4 year old fish are, respectively, lower and higher than the estimated values. There are no apparent trends in the residuals for other age classes. The residuals for the fishery at-age data show some clear trends, particularly when sex is included in the partition (Appendix B, Figure B2). But even when sex is removed, residual trends are still apparent (Figure B1). The poor fits are generally associated with fish 6 years or younger, but with a change in the residual trend (from positive to negative) occurring about 2001. This may be indicative of some change in fishing selectivity. However, the assessment model described above used a single selectivity ogive for all years.

The structural assumptions of the model reported here are likely to lead to the Bayesian posteriors of stock status underestimating the true level of uncertainty. The projected stock status relies on adequate estimation of recent recruitment driven by year class strength estimates. The research survey proportions-at-age distributions are collected systematically over time or space, but the fishery proportions-at-age are not. Although the stratification used in the analyses of these data coupled with the removal of sex from the partition is believed to produce reasonable estimates of catch-at-age for the fishery, the projections of future stock status based on these data are likely to underestimate the true level of uncertainty.

Information about absolute stock status of hake in the Sub-Antarctic is probably quite weak owing to the low level of contrast in all of the relative abundance series. Estimates of stock size and projected stock status are strongly influenced by the shape of the selectivity ogives and the way in which M is included in the model. When a constant M is used, the model concluded that very young and very old fish comprise a cryptic biomass that is not selected by the fishing gear (both in the surveys and the fishery). Such a situation where large, old fish are essentially hidden from the fishing gear could occur in trawl surveys if these larger fish spend more time in midwater or on rough ground not able to be bottom trawled. However, the commercial fishery uses midwater trawls and so should have access to biomass ‘hidden’ from the resource surveys. When an M-at-age relationship is estimated (and the resource survey ogives are forced to be logistic), the model concluded that the old fish are not in the catch because they have died, producing a relatively high value of M for old fish, and lower levels of absolute biomass (because the old fish are dead, rather than hidden). The marked improvement in fits to the age data when M is estimated provides support for this model being better than the single sex model with a constant M.

Estimates of resource survey catchability (qs) are very low in all model runs (i.e., 2–5%), particularly for the summer series, suggesting that the absolute catchability of the Sub-Antarctic trawl surveys is extremely low. It is not known if the catchability of the Sub-Antarctic trawl survey series is as low as estimated by the model, but hake are believed to be relatively more abundant over rough ground (that is likely to be avoided during a trawl survey), and it is known that hake tend to school off the bottom, particularly during their spring–summer spawning season, hence reducing their availability to the bottom trawl. Another plausible explanation for the low values is that there is little contrast in the biomass indices from the Sub-Antarctic trawl survey series, and that the model has little information on which to determine an appropriate “scale” of biomass estimates. Higher estimates of the relativity constant q (although confounded with selectivity) would result in lower current and virgin biomass estimates. A survey q of 10% was estimated using the same fishing gear to catch hake in a summer Chatham Rise survey (Horn & Francis 2010). The assessment of that stock, fitting to a trawl biomass series with strong contrast, produced a very believable B_0 estimate of 41 000 t (Horn & Francis 2010).

That value, and the B_0 of 82 000 t estimated for the west coast South Island stock (Horn 2011), by analogy may suggest that the Sub-Antarctic virgin biomass is more likely at the lower end of the range estimated from the four model describe above (i.e., 80 000–90 000 t).

The Working Group noted that there was a marked jump in estimated biomass between the 2007 and 2008 summer surveys (i.e., the December 2006 and 2007 summer surveys, see Figure 11), and requested that the possibility of a change in survey selectivity be investigated. An analysis similar to that completed for hoki from the same survey series (Francis 2009) indicated that there appeared to be marked changes in hake catchability between three adjacent survey pairs (i.e., 1991 and 1992, 2006 and 2007, 2008 and 2009) (Figure 39). However, the vertical scale in Figure 39 (0.1–4) is much narrower than that for hoki (0.05–10, see figure 26 in Francis (2009)), so the case for any maintained step change in survey selectivity is weak. It is possible that hake behaviour differs between years, perhaps related to environmental parameters, resulting in catchability variation.

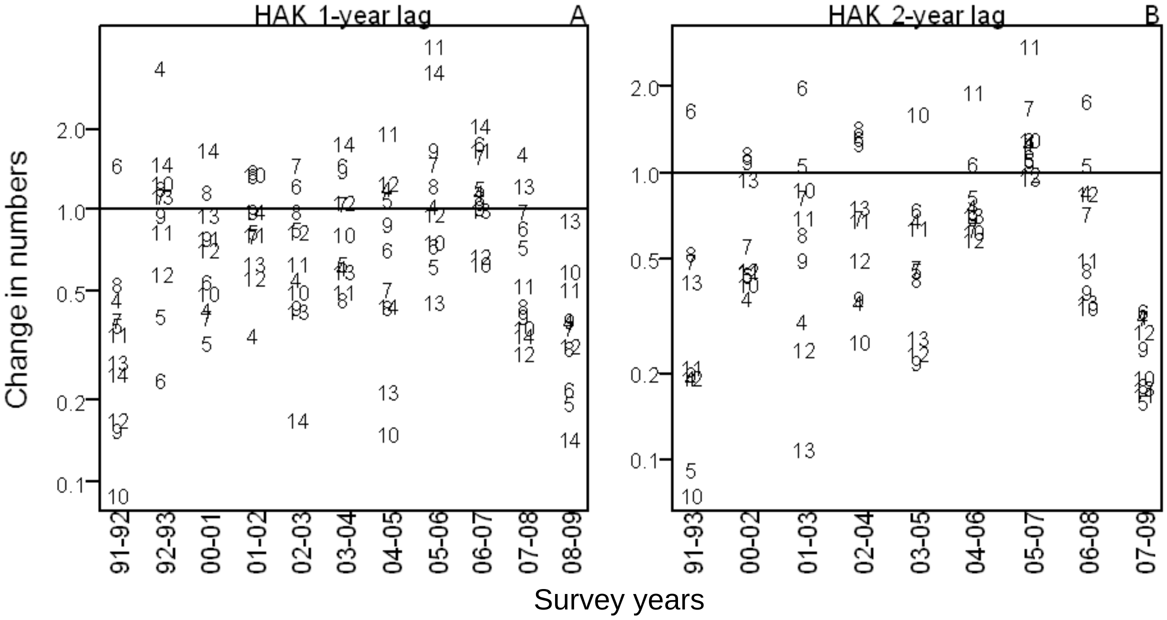


Figure 39: Testing for step changes in hake catchability. Changes, between pairs of surveys in the sub-Antarctic summer series, in estimated numbers of hake in selected cohorts: A, surveys in consecutive years and B, surveys two years apart. Each plotted point indicates how the estimated number in a cohort changed between two surveys; the plotting symbol is the age of the cohort in the earlier survey. For example, the bottom right point in panel A shows that the estimated number in the cohort that was aged 14 in the December 2008 survey decreased by about 85% between the 2008 and 2009 surveys.

The assessment for Sub-Antarctic hake has been updated, and is indicative of a stock that has declined throughout the 1990s, but is still very likely to be above 50% of B_0. The decline is most likely a result of poor recruitment rather than fishing pressure. An annual catch in the range of 2000–3000 t appears very likely to be sustainable in the medium term at least. The stock is probably being reasonably well monitored by the November-December trawl survey series. While the stock status appears to be reasonably well defined, estimates of past and current absolute stock size are very uncertain owing to a lack of contrast in the relative abundance series. Because of the high uncertainty in estimates of absolute biomass, any yield estimates would also be very uncertain.

Future assessments of this and other hake stocks, consideration should be given to adopting the recommendations of Francis (2011) relating to data weighting. For the Sub-Antarctic assessment the following changes should be considered:

- use multinomial, rather than lognormal, errors for at-age and at-length data;

- use method TA1.8 from Francis (2011) for stage-2 weighting of at-age data;
- use a lowess smoother (or similar) to set a (total) c.v. for CPUE data; and
- avoid the use of conflicting biomass indices in the same model (so the trawl survey biomass indices would be removed from the final 'CPUE' model).

7. ACKNOWLEDGMENTS

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APPENDIX A: RESOURCE SURVEY BIOMASS INDICES FOR HAKE IN HAK 1 AND HAK 4

Table A1: Biomass indices (t) and coefficients of variation (c.v.) for hake from resource surveys of the Sub-Antarctic. (These estimates assume that the areal availability, vertical availability, and vulnerability are equal to one.)

Vessel	Date	Trip code	Depth	Biomass	c.v.	Reference
Wesermünde	Mar–May 1979		–[1]	–	–	Kerstan & Sahrhage 1980
Wesermünde	Oct–Dec 1979		–[1]	–	–	Kerstan & Sahrhage 1980
Shinkai Maru	Mar–Apr 1982	SHI8201	200–800	6 045	0.15	N.W. Bagley, NIWA, pers. comm.
Shinkai Maru	Oct–Nov 1983	SHI8303	200–800	11 282	0.22	N.W. Bagley, NIWA, pers. comm.
Amaltal Explorer	Oct–Nov 1989	AEX8902	200–800	2 660	0.21	Livingston & Schofield 1993
Amaltal Explorer	Jul–Aug 1990	AEX9001	300–800	4 343	0.19	Hurst & Schofield 1995
Amaltal Explorer	Nov–Dec 1990	AEX9002	300–800	2 460	0.16	N.W. Bagley, NIWA, pers. comm.
Tangaroa	Nov–Dec 1991	TAN9105	Reported[2]	5 686	0.43	Chatterton & Hanchet 1994
			300–800[3]	5 553	0.44	O'Driscoll & Bagley 2001
			1991 area[4]	5 686	0.43	O'Driscoll & Bagley 2001
			1996 area[5]	–	–	
Tangaroa	Apr–May 1992	TAN9204	Reported[2]	5 028	0.15	Schofield & Livingston 1994a
			300–800[3]	5 028	0.15	O'Driscoll & Bagley 2001
			1991 area[4]	–	–	
			1996 area[5]	–	–	
Tangaroa	Sep–Oct 1992	TAN9209	Reported[2]	3 762	0.15	Schofield & Livingston 1994b
			300–800[3, 7]	3 760	0.15	O'Driscoll & Bagley 2001
			1991 area[4]	–	–	
			1996 area[5]	–	–	
Tangaroa	Nov–Dec 1992	TAN9211	Reported[2]	1 944	0.12	Ingerson et al. 1995
			300–800[3]	1 822	0.12	O'Driscoll & Bagley 2001
			1991 area[4]	1 944	0.12	O'Driscoll & Bagley 2001
			1996 area[5]	–	–	
Tangaroa	May–Jun 1993	TAN9304[6]	Reported[2]	3 602	0.14	Schofield & Livingston 1994c
			300–800[3]	3 221	0.14	O'Driscoll & Bagley 2001
			1991 area[4]	–	–	
			1996 area[5]	–	–	
Tangaroa	Nov–Dec 1993	TAN9310	Reported[2]	2 572	0.12	Ingerson & Hanchet 1995
			300–800[3]	2 286	0.12	O'Driscoll & Bagley 2001
			1991 area[4]	2 567	0.12	O'Driscoll & Bagley 2001
			1996 area[5]	–	–	

Table A1 ctd.

Vessel	Date	Trip code	Depth	Biomass	c.v.	Reference
Tangaroa	Mar–Apr 1996	TAN9605	Reported [2]	3 946	0.16	Colman 1996
			300–800 [3]	2 026	0.12	O'Driscoll & Bagley 2001
			1991 area [4]	2 281	0.17	O'Driscoll & Bagley 2001
			1996 area [5]	2 825	0.12	O'Driscoll & Bagley 2001
Tangaroa	Apr–May 1998	TAN9805	Reported [2]	2 554	0.18	Bagley & McMillan 1999
			300–800 [3]	2 554	0.18	O'Driscoll & Bagley 2001
			1991 area [4]	2 643	0.17	O'Driscoll & Bagley 2001
			1996 area [5]	3 898	0.16	O'Driscoll & Bagley 2001
Tangaroa	Nov–Dec 2000	TAN0012	300–800 [3]	2 194	0.17	O'Driscoll et al. 2002
			1991 area [4]	2 657	0.16	O'Driscoll et al. 2002
			1996 area [5]	3 103	0.14	O'Driscoll et al. 2002
Tangaroa	Nov–Dec 2001	TAN0118	300–800 [3]	1 831	0.24	O'Driscoll & Bagley 2003a
			1991 area [4]	2 170	0.20	O'Driscoll & Bagley 2003a
			1996 area [5]	2 360	0.19	O'Driscoll & Bagley 2003a
Tangaroa	Nov–Dec 2002	TAN0219	300–800 [3]	1 283	0.20	O'Driscoll & Bagley 2003b
			1991 area [4]	1 777	0.16	O'Driscoll & Bagley 2003b
			1996 area [5]	2 037	0.16	O'Driscoll & Bagley 2003b
Tangaroa	Nov–Dec 2003	TAN0317	300–800 [3]	1 335	0.24	O'Driscoll & Bagley 2004
			1991 area [4]	1 672	0.23	O'Driscoll & Bagley 2004
			1996 area [7]	1 898	0.21	O'Driscoll & Bagley 2004
Tangaroa	Nov–Dec 2004	TAN0414	300–800 [3]	1 250	0.27	O'Driscoll & Bagley 2006a
			1991 area [4]	1 694	0.21	O'Driscoll & Bagley 2006a
			1996 area [7]	1 774	0.20	O'Driscoll & Bagley 2006a
Tangaroa	Nov–Dec 2005	TAN0515	300–800 [3]	1 133	0.20	O'Driscoll & Bagley 2006b
			1991 area [4]	1 459	0.17	O'Driscoll & Bagley 2006b
			1996 area [7]	1 624	0.17	O'Driscoll & Bagley 2006b
Tangaroa	Nov–Dec 2006	TAN0617	300–800 [3]	998	0.22	O'Driscoll & Bagley 2008
			1991 area [4]	1 530	0.17	O'Driscoll & Bagley 2008
			1996 area [7]	1 588	0.16	O'Driscoll & Bagley 2008
Tangaroa	Nov–Dec 2007	TAN0714	300–800 [3]	2 188	0.17	Bagley et al. 2009
			1991 area [4]	2 470	0.15	Bagley et al. 2009
			1996 area [7]	2 622	0.15	Bagley et al. 2009
Tangaroa	Nov–Dec 2008	TAN0813	300–800 [3]	1 074	0.23	O'Driscoll & Bagley 2009
			1991 area [4]	2 162	0.17	O'Driscoll & Bagley 2009
			1996 area [7]	2 355	0.16	O'Driscoll & Bagley 2009

Table A1 ctd.

Vessel	Date	Trip code	Depth	Biomass	c.v.	Reference
Tangaroa	Nov–Dec 2009	TAN0911	300–800 [3]	992	0.22	Bagley & O'Driscoll 2012
			1991 area [4]	1 442	0.20	Bagley & O'Driscoll 2012
			1996 area [7]	1 602	0.18	Bagley & O'Driscoll 2012

1. Although surveys by *Wesermünde* were carried out in the Sub-Antarctic in 1979, biomass estimates for hake were not calculated.
2. The depth range, biomass and c.v. in the original report.
3. The biomass and c.v. calculated from source records using the equivalent 1991 region, but excluding both the 800–1000 m strata in Puysegur region and the Bounty Platform strata.
4. The biomass and c.v. calculated from source records using the equivalent 1991 region, which includes the 800–1000 m strata in Puysegur region but excludes the Bounty Platform strata.
5. The biomass and c.v. calculated from source records using the equivalent 1996 region, which includes the 800–1000 m strata in Puysegur region but excludes the Bounty Platform strata. (The 1996 region added additional 800–1000 m strata to the north and to the south of the Sub-Antarctic to the 1991 region).
6. Doorspread data not recorded for this survey. Analysis of source data with average of all other survey doorspread estimates resulted in a new estimate of biomass.
7. The biomass and c.v. calculated from source records using the equivalent 1996 region, which includes the 800–1000 m strata in Puysegur region but excludes the Bounty Platform strata. (The 1996 region added additional 800–1000 m strata to the north and to the south of the Sub-Antarctic to the 1991 region). However, in 2003, stratum 26 (the most southern 800–1000 m strata) was not surveyed. In previous years this stratum yielded either a very low or zero hake biomass. The yield in 2003 from stratum 26 was assumed to be zero.

Table A2: Biomass indices (t) and coefficients of variation (c.v.) for hake from resource surveys of the Chatham Rise. (These estimates assume that the areal availability, vertical availability, and vulnerability are equal to one.)

Vessel	Date	Trip code	Depth	Biomass	c.v.	Reference
Wesermünde	Mar–May 1979		–[1]	–	–	Kerstan & Sahrhage 1980
Wesermünde	Oct Dec 1979		–[1]	–	–	Kerstan & Sahrhage 1980
Shinkai Maru	Mar 1983	SHI8301	200–800	11 327	0.12	N.W. Bagley, NIWA, pers. comm.
Shinkai Maru	Nov–Dec 1983	SHI8304	200–800[2]	8 160	0.12	N.W. Bagley, NIWA, pers. comm.
Shinkai Maru	Jul 1986	SHI8602	200–800	7 630	0.13	N.W. Bagley, NIWA, pers. comm.
Amaltal Explorer	Nov–Dec 1989	AEX8903	200–800	3 576	0.19	N.W. Bagley, NIWA, pers. comm.
Tangaroa	Jan 1992	TAN9106	200–800	4 180	0.15	Horn 1994a
Tangaroa	Jan 1993	TAN9212	200–800	2 950	0.17	Horn 1994b
Tangaroa	Jan 1994	TAN9401	200–800	3 353	0.10	Schofield & Horn 1994
Tangaroa	Jan 1995	TAN9501	200–800	3 303	0.23	Schofield & Livingston 1995
Tangaroa	Jan 1996	TAN9601	200–800	2 457	0.13	Schofield & Livingston 1996
Tangaroa	Jan 1997	TAN9701	200–800	2 811	0.17	Schofield & Livingston 1997
Tangaroa	Jan 1998	TAN9801	200–800	2 873	0.18	Bagley & Hurst 1998
Tangaroa	Jan 1999	TAN9901	200–800	2 302	0.12	Bagley & Livingston 2000
Tangaroa	Jan 2000	TAN0001	200–800	2 090	0.09	Stevens et al. 2001
			200–1000	2 152	0.09	Stevens et al. 2001
Tangaroa	Jan 2001	TAN0101	200–800	1 589	0.13	Stevens et al. 2002
Tangaroa	Jan 2002	TAN0201	200–800	1 567	0.15	Stevens & Livingston 2003
			200–1000	1 905	0.13	Stevens & Livingston 2003
Tangaroa	Jan 2003	TAN0301	200–800	888	0.16	Livingston et al. 2004
Tangaroa	Jan 2004	TAN0401	200–800	1 547	0.17	Livingston & Stevens 2005
Tangaroa	Jan 2005	TAN0501	200–800	1 048	0.18	Stevens & O'Driscoll 2006
Tangaroa	Jan 2006	TAN0601	200–800	1 384	0.19	Stevens & O'Driscoll 2007
Tangaroa	Jan 2007	TAN0701	200–800	1 824	0.12	Stevens et al. 2008
			200–1000	1 976	0.12	Stevens et al. 2008
Tangaroa	Jan 2008	TAN0801	200–800	1 257	0.13	Stevens et al. 2009a
			200–1000	1 323	0.13	Stevens et al. 2009a
Tangaroa	Jan 2009	TAN0901	200–800	2 419	0.21	Stevens et al. 2009b
Tangaroa	Jan 2010	TAN1001	200–800	1 701	0.25	Stevens et al. 2011
			200–1300	1 862	0.25	Stevens et al. 2011
Tangaroa	Jan 2011	TAN1101	200–800	1 099	0.15	Stevens et al. 2012
			200–1300	1 201	0.14	Stevens et al. 2012

1. Although surveys by *Wesermünde* were carried out on the Chatham Rise in 1979, biomass estimates for hake were not calculated.
2. East of 176º E only.

APPENDIX B: RESIDUALS OF MPD MODEL FITS TO THE CATCH-AT-AGE DATA

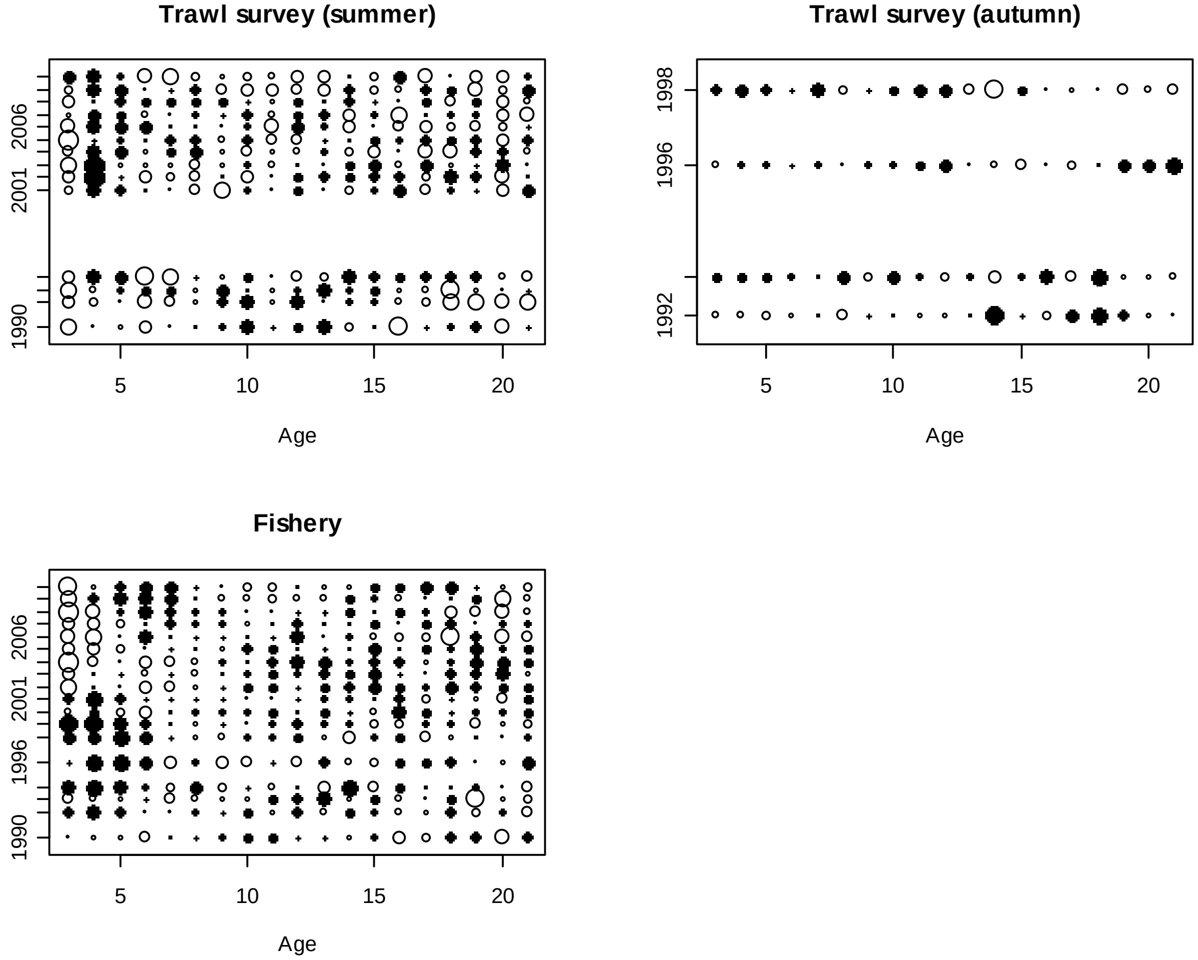

Figure B1: Single sex model — MPD residual values for the proportions-at-age data for the Sub-Antarctic resource survey series and fishery. Symbol area is proportional to the absolute value of the residual, with filled circles indicating positive residuals and open circles indicating negative residuals.

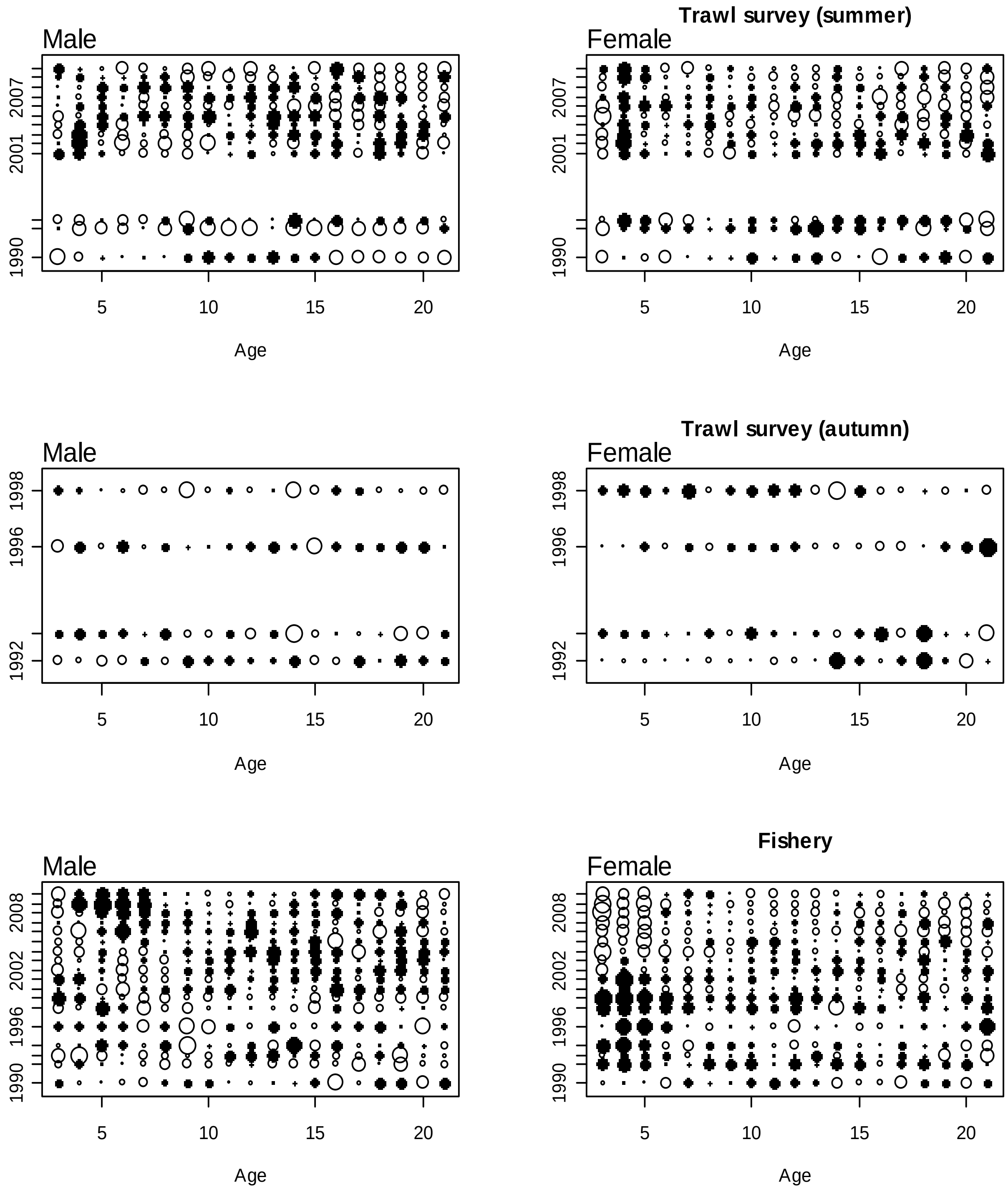

Figure B2: Two sex model — MPD residual values for the proportions-at-age data for the Sub-Antarctic resource survey series and fishery. Symbol area is proportional to the absolute value of the residual, with filled circles indicating positive residuals and open circles indicating negative residuals.

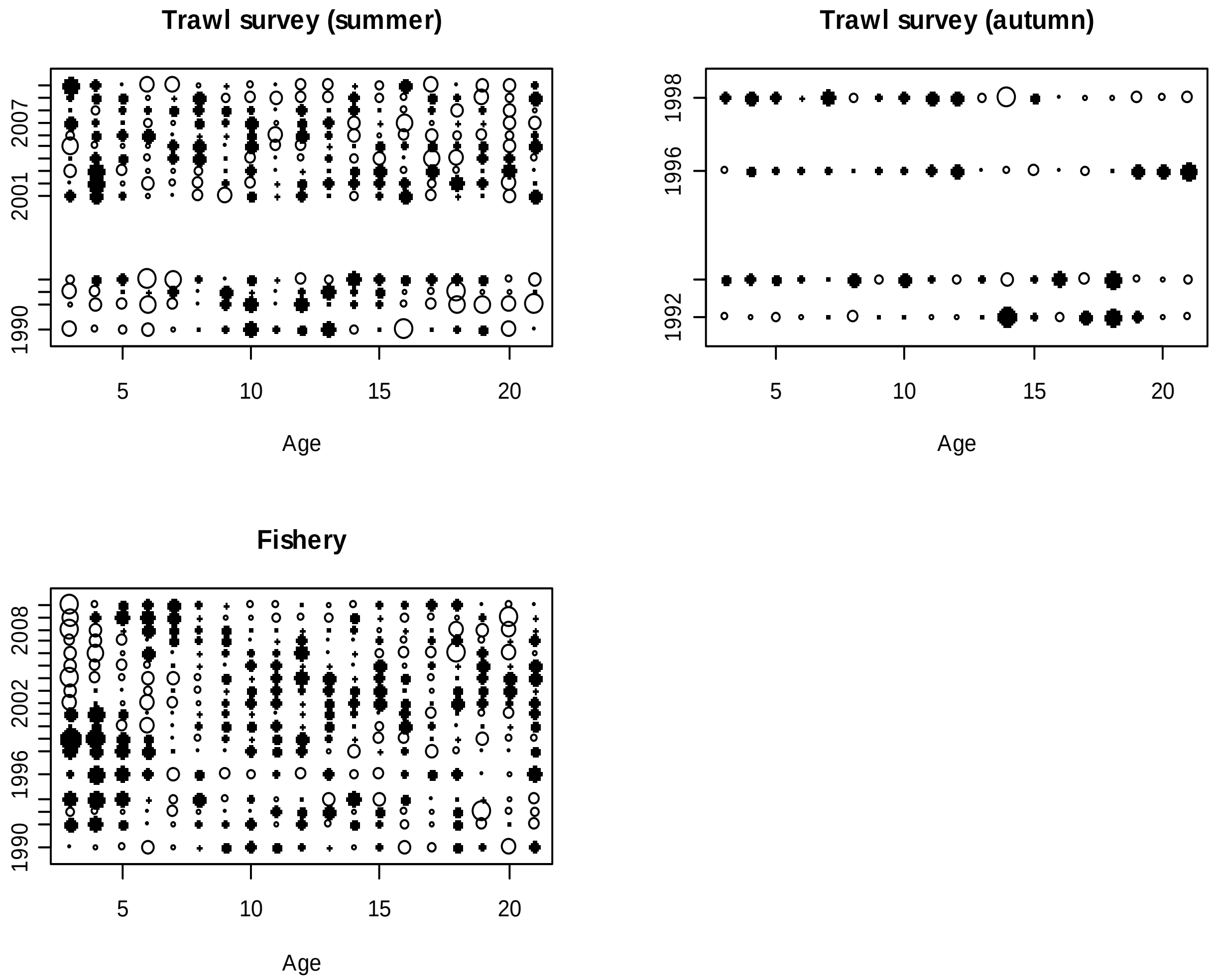

Figure B3: Estimate *M* model — MPD residual values for the proportions-at-age data for the Sub-Antarctic resource survey series and fishery. Symbol area is proportional to the absolute value of the residual, with filled circles indicating positive residuals and open circles indicating negative residuals.