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Stock assessment of hake (*Merluccius australis*) for the 2003–04 fishing year

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EXECUTIVE SUMMARY

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This report summarises the stock assessment of hake in the Quota Management Areas (QMAs) HAK 1 and HAK 4, for the sub-Antarctic and Chatham Rise stocks for the 2003–04 fishing year. The report presents an analysis of the stock assessment of hake that includes data up to the end of the 2002–03 fishing year. Catch-at-age estimates from research surveys and scientific observer data, collected from commercial tows of hake in HAK 1, 4, & 7, are revised and updated. Revised landings data for the three hake stocks (sub-Antarctic, Chatham Rise, and west coast South Island) are presented, and literature published since the previous stock assessment for hake is summarised.

The stock assessments of hake in the sub-Antarctic and on the Chatham Rise have been presented as a Bayesian assessment of two stocks of hake, the sub-Antarctic stock and the Chatham Rise stock, implemented as a two stock model using the general-purpose stock assessment program CASAL v2.01.

The model estimates of the state of the sub-Antarctic stock suggest that there has been a small decline in the stock size since the early 1990s. However, results from biomass surveys were inconclusive with respect to changes in stock status. Model fits to the most recent sub-Antarctic resource surveys were poor, and were unable to mirror the recent observed small decline in 2001 and 2002. In general, the lack of contrast in abundance indices collected since 1991 suggests that, although the status of the sub-Antarctic stock is probably similar to that in the early 1990s, the absolute level of current biomass is difficult to determine.

In contrast, information about the stock status of hake on the Chatham Rise appears reasonably strong. Biomass estimates from the Chatham Rise research series suggest strong evidence of a uniform decline in biomass, with biomass in 2003 at about 35% the level of that in the early 1990s. If the model assumptions are correct, and the recent estimated relative year class strengths are as weak as have been estimated, then current catch levels will continue to reduce the size of the Chatham Rise stock in the immediate future. Sensitivity analyses, with only minor changes in assumptions as the base case, gave similar results.

Projections for the Chatham Rise stock indicate that the rate of decline will continue, and that the risk of reducing the stock below 20% B_0 is about 47–64% in 2005–06 if catches were at levels of the current TACC, rising to 90–96% in 2006–07. At current catch levels (currently lower that that allowed by the TACC) the risk is lower — about 9–15% in 2004–05 if catches were at levels of the current TACC, rising to 31–44% in 2006–07.

1. INTRODUCTION

This report outlines the stock assessment of hake in the hake Quota Management Areas (QMAs) HAK 1 and HAK 4, for the sub-Antarctic and Chatham Rise hake stocks with the inclusion of data up to the end of the 2002–03 fishing year. Catch-at-age estimates from research surveys, and scientific observer data collected from commercial tows of hake in HAK 1, 4, and 7, were also revised and updated. Revised landings data for the three hake stocks (west coast South Island, sub-Antarctic, and Chatham Rise) (see Dunn 2003a) are presented, and literature published since the previous stock assessment for hake (Dunn 2003b) is summarised.

The current stock hypothesis for hake suggests that there are three separate hake stocks (Colman 1998); the west coast South Island stock (the area of HAK 7 on the west coast South Island), the sub-Antarctic stock (the area of HAK 1 that encompasses the Southern Plateau), and the Chatham Rise stock (HAK 4 and the area of HAK 1 on the western Chatham Rise).

The stock assessment of hake in HAK 1 and HAK 4 is presented as a Bayesian assessment of two stocks of hake, the sub-Antarctic stock and Chatham Rise stock, implemented as a two stock model using the general-purpose stock assessment program CASAL v2.01 (Bull et al. 2003). The stock assessment for the Chatham Rise and the sub-Antarctic is described, and estimates of the current stock status and projected stock status for each stock are provided.

This report fulfils Objective 7 of Project HAK2001/01 "To update the stock assessment of hake, including biomass estimates and sustainable yields".

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 other species such as hoki and southern blue whiting, although target fisheries also exist (Phillips & Livingston 2004). Present management practices divide 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. The TACC for HAK 7 is the largest, at 6855 t out of a total for the EEZ of 13 997 t. The west coast South Island 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. 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 and 1993, there has been a hake target fishery in September after the peak of the hoki fishery is over; more than 2000 t of hake were taken in this target fishery during September 1993. Bycatch levels of hake early in the fishing season in the years 1994–95, 1995–96, and 1997–89 to 2000–01 were relatively high.

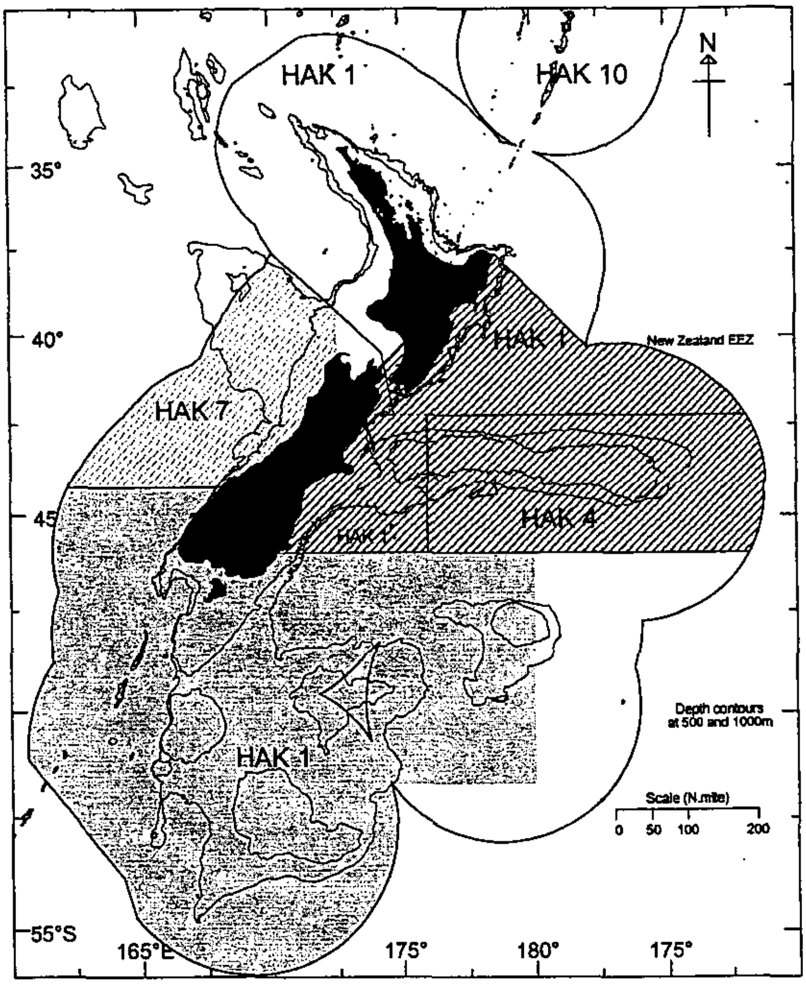

Figure 1: Quota Management Areas (QMAs) HAK 1, 4, 7, & 10; and the west coast South Island (light shading), Chatham Rise (dark shading), and sub-Antarctic (medium shading) hake stock boundaries assumed in this report.

On the Chatham Rise and in the sub-Antarctic, hake have been caught mainly as bycatch by trawlers targeting hoki (Phillips & Livingston 2004). However, in both areas significant targeting for hake occurs, particularly in Statistical Area 404 (HAK 4), and east of the Solander Trough between the Snares and Auckland Islands in the sub-Antarctic (Phillips & Livingston 2004). Increases in TACCs from 2610 t to 3632 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 their reported* landings of hake from these fish stocks. Reported catches have since risen to the levels of the new TACCs and remained close to these values up to 2001–02. In 2002–03, reported catches dropped markedly, to about two-thirds of previous values.

In 2001 and 2002, the skippers of four large trawlers pleaded guilty to charges of making false or misleading entries in their fishing returns. The charges related to the misreporting of hake from HAK 7, as catch on the Chatham Rise in the areas HAK 1 and HAK 4.

The effect of these court convictions was to raise doubts about the accuracy of the recorded landings of hake by stock in the 2000–01 fishing year (Dunn 2003a). Moreover, anecdotal reports of similar area misreporting of hake catch in earlier years prevailed within the fishing industry (G. Backhouse, Ministry of Fisheries Serious Offences Unit, pers. comm.), and raised doubts about the historical records of landings of hake by stock.

Dunn (2003a) provided revised estimates of the total landings by stocks, estimating that the level of hake over-reporting on the Chatham Rise (and hence under-reporting on the west coast South Island) had been between 16 and 23% (700–1000 t annually) of landings between 1994–95 and 2000–01, predominantly in June, July, and September. Probable levels of misreporting before 1994–95 and between the west coast South Island and sub-Antarctic were estimated as negligible (Dunn 2003a). There is no evidence of such misreporting in 2001–02 (N.L. Phillips, NIWA, unpublished results).

1.2 Literature review

Previous assessments of hake include those by Colman et al. (1991) for the 1991–92 fishing year, Colman & Vignaux (1992) for the 1992–93 fishing year, Colman (1997) for the 1997–98 fishing year, and Dunn (1998), Dunn et al. (2000) and Dunn (2001, 2003b) for the 1998–99, 1999–00, 2000–01 and 2002–03 fishing years respectively. The most recent of these assessments was a two-stock Bayesian assessment using CASAL v1.02 (Bull et al. 2002).

Since 1991, research surveys have been carried out from R.V. *Tangaroa* in the sub-Antarctic in November and December 1991, 1992, 1993, 2000, 2001, and 2002 (Chatterton & Hanchet 1994, Ingerson & Hanchet 1995, Ingerson et al. 1995, O'Driscoll et al. 2002, O'Driscoll & Bagley 2003a, 2003b), September–October 1992 (Schofield & Livingston 1994b), and April–June 1992, 1993, 1996, 1998, (Schofield & Livingston 1994a, 1994c, Colman 1996, Bagley & McMillan 1999).

On the Chatham Rise, a consistent time series of research surveys from *Tangaroa* has been in January 1992 to 2003 (Horn 1994a, 1994b, Schofield & Horn 1994, Schofield & Livingston 1995, 1996, 1997, Bagley & Hurst 1998, Bagley & Livingston 2000, Stevens et al. 2001, 2002, Stevens & Livingston 2003, Livingston et al. 2004).

Standardised CPUE indices for the sub-Antarctic and Chatham Rise stocks were updated (N.L. Phillips, NIWA, unpublished results). These update the indices estimated by Phillips & Livingston (2004), Kendrick (1998), and Dunn et al. (2000). However, the CPUE indices were not believed to be an adequate index of abundance, and were excluded from the stock modelling.

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 TACs since 1986–87 are shown in Table 2. Revised estimates of landings by QMA and by stock for 1974–75 to 2001–02 (data for 1989–90 to 2000–01 from Dunn (2003a)), are provided in Tables 3 and 4 respectively.

West coast South Island revised estimates for 1989–90 and 1990–91 are taken from Colman & Vignaux (1992) who corrected for under-reporting in 1989–90 and 1990–91 using estimates of landings from vessel trips with Ministry of Fisheries observers to correct catches from vessel trips that did not carry Ministry of Fisheries observers, and not from Dunn (2003a) who ignored such possible under-reporting.

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 2001–02 and actual TACs (t) for 1986–87 to 2002–03. Data from 1983–84 to 1985–86 from Fisheries Statistics Unit; data from 1986–87 to 2002–03 from Quota Management System (– indicates that the data are unavailable).

QMA	HAK 1		HAK 4		HAK 7		HAK 10		Total	
	Landings	TAC	Landings	TAC	Landings	TAC	Landings	TAC	Landings	TAC
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	2 635	2 610	743	1 000	6 189	3 310	0	10	9 567	6 930
1991–92	3 156	3 500	2 013	3 500	3 027	6 770	0	10	8 196	13 780
1992–93	3 525	3 501	2 545	3 500	7 154	6 835	0	10	13 224	13 846
1993–94	1 803	3 501	2 587	3 500	2 973	6 835	0	10	7 363	13 847
1994–95	2 572	3 632	3 369	3 500	8 840	6 855	0	10	14 781	13 997
1995–96	3 956	3 632	3 466	3 500	8 660	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	3 810	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	3 628	3 632	2 784	3 500	7 698	6 855	0	10	14 110	13 997
2001–02	2 876	3 632	1 427	3 500	7 520	6 855	0	10	11 826	13 997
2002–03	–	3 632	–	3 500	–	6 855	–	10	–	13 997

Table 3: Revised landings (t) by QMA 1989–90 to 2000–01 from Dunn (2003a).

Fishing		QMA		Total
Year	HAK 1	HAK 4	HAK 7	
1989–90	2 115	763	4 903	7 781
1990–91	2 592	703	6 199	9 494
1991–92	3 156	2 013	3 027	8 196
1992–93	3 525	2 504	7 196	13 224
1993–94	1 787	2 587	2 990	7 364
1994–95	2 319	2 922	9 537	14 779
1995–96	3 782	2 894	9 581	16 257
1996–97	3 229	2 752	7 030	13 011
1997–98	3 728	2 892	8 118	14 738
1998–99	3 645	2 511	9 170	15 326
1999–00	3 663	2 307	7 621	13 591
2000–01	3 402	2 318	8 383	14 103

Table 4: Previously assumed landings (Prev.) (Dunn 2001), landings assuming no misreporting (None), and revised landings 1974–75 to 2000–01 (t) (Dunn 2003a) and 2001–02 (Rev.) for the west coast South Island, sub-Antarctic and Chatham Rise stocks.

Fishing	West coast S.I.			Sub-Antarctic			Chatham Rise		
Year	Prev.	None	Rev.	Prev.	None	Rev.	Prev.	None	Rev.
1974–75	71	71	71	120	120	120	191	191	191
1975–76	5 005	5 005	5 005	281	281	281	488	488	488
1976–77	17 806	17 806	17 806	372	372	372	1 288	1 288	1 288
1977–78	498	498	498	762	762	762	34	34	34
1978–79	4 737	4 737	4 737	364	364	364	609	609	609
1979–80	3 600	3 600	3 600	350	350	350	750	750	750
1980–81	2 565	2 565	2 565	272	272	272	997	997	997
1981–82	1 625	1 625	1 625	179	179	179	596	596	596
1982–83	745	745	745	448	448	448	302	302	302
1983–84	945	945	945	722	722	722	344	344	344
1984–85	965	965	965	525	525	525	544	544	544
1985–86	1 918	1 918	1 918	818	818	818	362	362	362
1986–87	3 755	3 755	3 755	713	713	713	509	509	509
1987–88	3 009	3 009	3 009	1 095	1 095	1 095	574	574	574
1988–89	8 696	8 696	8 696	1 237	1 237	1 237	804	804	804
1989–90	8 741	4 886	8 741	1 522	1 923	1 928	977	950	950
1990–91	8 546	6 116	8 246	1 756	2 370	2 388	991	959	907
1991–92	3 027	3 001	3 027	2 464	2 743	2 752	2 454	2 415	2 417
1992–93	7 154	7 014	7 196	3 206	3 263	3 269	2 775	2 798	2 801
1993–94	2 973	2 920	2 974	1 586	1 448	1 455	2 898	2 948	2 933
1994–95	8 840	8 807	9 537	2 019	1 844	1 856	4 094	4 081	3 386
1995–96	8 660	8 606	9 574	2 479	2 820	2 918	4 760	4 501	3 755
1996–97	6 119	6 006	7 023	2 293	2 282	2 292	4 761	4 768	3 694
1997–98	–	7 310	8 112	2 566	2 626	2 638	4 673	4 650	3 942
1998–99	–	8 002	9 132	2 645	2 787	2 798	4 524	4 385	3 389
1999–00	–	6 719	7 619	2 699	3 008	3 028	4 003	3 670	2 943
2000–01	–	7 581	8 380	–	2 939	2 856	–	3 456	2 491
2001–02	–	7 520	7 520	–	2 523	2 523	–	1 782	1 782

Note: West coast South Island revised estimates for 1989–90 and 1990–91 are taken from Colman & Vignaux (1992) who corrected for under reporting in 1989–90 and 1990–91, and not from Dunn (2003a) who ignored such under reporting.

2.2 Recreational and Maori customary fisheries

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.

2.3 Other sources of fishing mortality

Colman & Vignaux (1992) suggested, in a comparison of hoki and hake catches from vessels carrying Ministry of Fisheries scientific observers with those not carrying observers, that catches of hake were not always fully reported in HAK 7 between 1988–89 and 1990–91. They estimated the actual catch of hake was significantly under-reported in HAK 7 in some years, and they 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. More recently, the level of such misreporting has not been estimated and is not known.

Dunn (2003a) investigated levels of area misreporting between the west coast South Island and the Chatham Rise fisheries between 1989–90 and 2000–01. He concluded that the level of hake over-reporting on the Chatham Rise had been between 16 and 23% (700–1000 t annually) of landings since 1994–95, predominantly in June, July, and September. Levels of misreporting before to 1994–95 and after 2000–01, and between the west coast South Island and sub-Antarctic, were estimated as negligible (Dunn 2003a). There is no evidence of similar misreporting in 2001–02 (N.L. Phillips, NIWA, unpublished results).

There is likely to be some mortality associated with escapement from trawl nets, but the level is not known and is assumed to be negligible.

3. BIOLOGY, STOCK STRUCTURE, AND RESOURCE SURVEYS

3.1 Biology

Data collected by observers on commercial trawlers and from research 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 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. Readings of otoliths from hake have been used to develop age-length keys to scale length frequency distributions for hake collected on research surveys and from commercial fisheries on the Chatham Rise, sub-Antarctic, and west coast South Island. The resulting age frequency distributions are shown in Appendix A as Figures A4–A8. Numbers of measurements are given in Appendix A in Tables A1–A3. The relative observed proportions-at-age data (for ages 3–19) from research surveys and the observer data for the sub-Antarctic and Chatham Rise stocks are also shown in Figures 2 and 3 respectively.

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. Length frequency plots from research surveys and observer data are given in Appendix A as Figures A1–A3 for the sub-Antarctic, Chatham Rise, and west coast South Island respectively.

Both sexes reach sexual maturity between 6 and 10 years of age, at total lengths of about 67–75 cm (males) and 75–85 cm (females). Estimated von Bertalanffy parameters (Horn 1998) are given in Table 5. Juvenile hake have been taken in coastal waters on both sides of the South Island and on the Campbell Plateau. They reach a total length of about 15–20 cm at 1 year old, and about 35 cm total length at 2 years (Colman 1998). Colman (1998) concluded that hake reached 50% maturity at between 6 and 8 years in HAK 1, and 7–8 years in HAK 4.

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}.

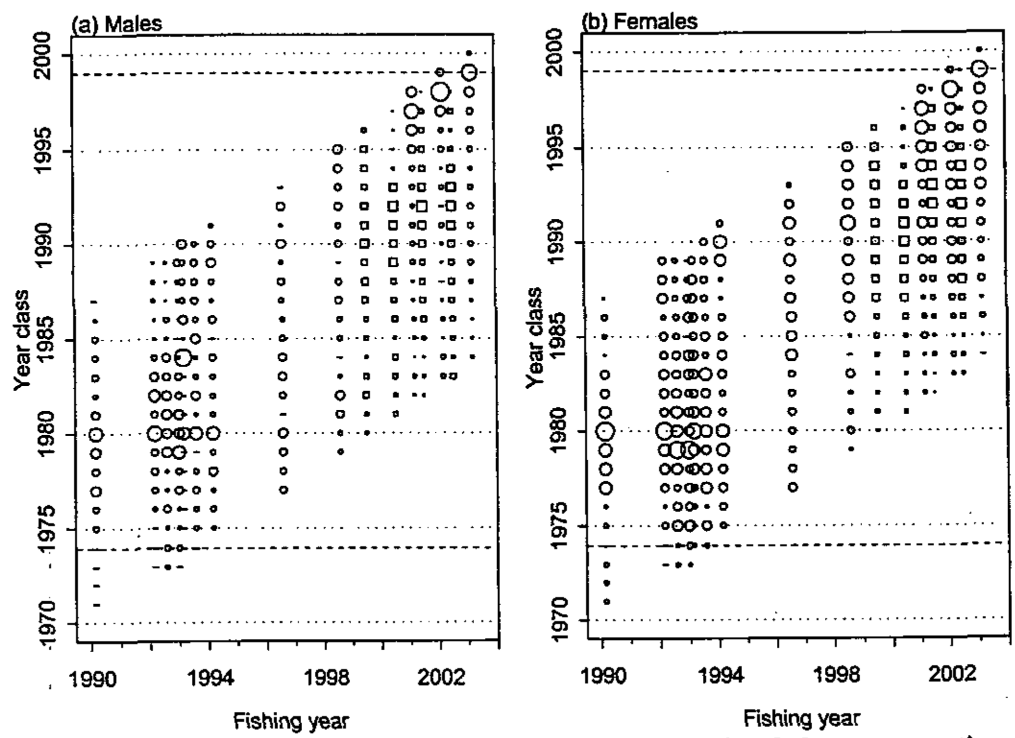

Figure 2: Age frequencies (ages 3 to 19) by year class and year (symbol area proportional to the proportions-at-age within sampling event) in the sub-Antarctic for (a) research surveys (circles) and (b) commercial catch-at-age data (squares). Zero values are represented by a dash, and horizontal lines indicate the earliest (1974) and latest (1999) year class strengths estimated within the stock assessment model.

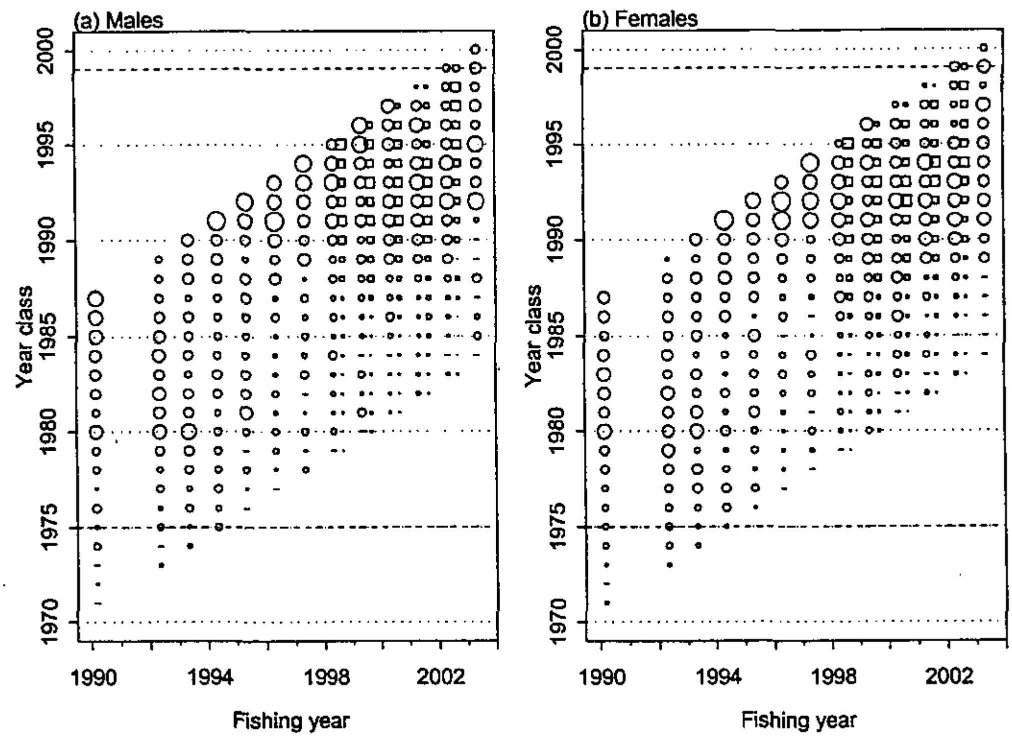

Figure 3: Age frequencies (ages 3 to 19) by year class and year (symbol area proportional to the proportions-at-age within sampling event) on the Chatham Rise for (a) research surveys (circles) and (b) commercial catch-at-age data (squares). Zero values are represented by a dash, and horizontal lines indicate the earliest (1975) and latest (1999) year class strengths estimated within the stock assessment model.

Table 5: Estimates of biological parameters for the Chatham Rise and sub-Antarctic stocks.

		Estimate			Source
Natural mortality					
Males	$M = 0.20$				(Dunn et al. 2000)
Females	$M = 0.18$				(Dunn et al. 2000)
Weight = a·(length)^b (Weight in t, length in cm)					
Sub-Antarctic					
Males	a = 3.95×10^{-9}	b = 3.130			(Horn 1998)
Females	a = 1.86×10^{-9}	b = 3.313			(Horn 1998)
Chatham Rise					
Males	a = 2.49×10^{-9}	b = 3.234			(Horn 1998)
Females	a = 1.70×10^{-9}	b = 3.328			(Horn 1998)
von Bertalanffy growth parameters					
Sub-Antarctic					
Males	$k = 0.263$	$t_0 = -0.06$	$L_\infty = 90.8$		(Horn 1998)
Females	$k = 0.188$	$t_0 = -0.13$	$L_\infty = 115.0$		(Horn 1998)
Chatham Rise					
Males	$k = 0.277$	$t_0 = -0.11$	$L_\infty = 90.3$		(Horn 1998)
Females	$k = 0.202$	$t_0 = -0.20$	$L_\infty = 113.4$		(Horn 1998)
Age at 50% maturity					
Males	$A_{50} = 6–7$				(Colman 1998)
Females	$A_{50} = 7–8$				(Colman 1998)

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 (Horn 1998) 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 research 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 on the sub-Antarctic resulted in a return to the November–December series in 2000, 2001, and 2002. 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 used in the stock assessments of the sub-Antarctic for the first time, with the assumption that its selectivity was equivalent to the November–December series.

Sub-Antarctic surveys before those of *Tangaroa*, 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 had different performance characteristics and used different gear (Livingston et al. 2002), hence (except for the October–November 1989 *Amaltal Explorer* survey — see later) cannot be used as a part of a consistent time series.

The data inputs to the stock model included biomass and age data from the region of the sub-Antarctic defined by strata with depths of 300–800 m for the April–May and September *Tangaroa* series, with the November-December *Tangaroa* series adding the 800–1000 m depth strata around Puysegur. Other *Tangaroa* surveys (April–May 1996 and 1998; and November–December 2000, 2001, and 2002) have also surveyed additional deepwater strata (i.e., 800–1000 m strata to the north and to the south of the survey region). The deepwater strata were excluded from the data used in this analysis to maintain consistency in the time series. In some model runs, biomass and age data from the 1989 *Amaltal Explorer* survey (200–800 m) were included in data inputs. How these data were included within the model structure is described in more detail below.

The biomass estimates from the sub-Antarctic *Tangaroa* and 1989 *Amaltal Explorer* surveys are shown in Figure 4. Distribution of catch in the sub-Antarctic from these are shown as Figure B1 (Appendix B).

Research 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 (see Appendix B, Table B2). However, although 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 most recent surveys in 2000, 2001, 2002, and 2003 used a revised design — with some strata being split and additional stations added. In addition, the 2000 and 2002 surveys included deepwater strata (i.e., 800–1000 m) on the northern Chatham Rise. The deepwater strata were excluded from the *Tangaroa* data used in this analysis to maintain consistency in the time series.

Chatham Rise surveys before those of *Tangaroa* 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 (except for the November–December 1989 *Amaltal Explorer* survey — see later) cannot be used as a consistent time series. In some model runs, biomass and age data from the 1989 *Amaltal Explorer* survey (200–800 m) were included in data inputs. How these data were included within the model structure is described in more detail below.

The biomass estimates from Chatham Rise research surveys are shown in Figure 5. Distribution of catch on the Chatham Rise from these are shown as Figure B2, in Appendix B.

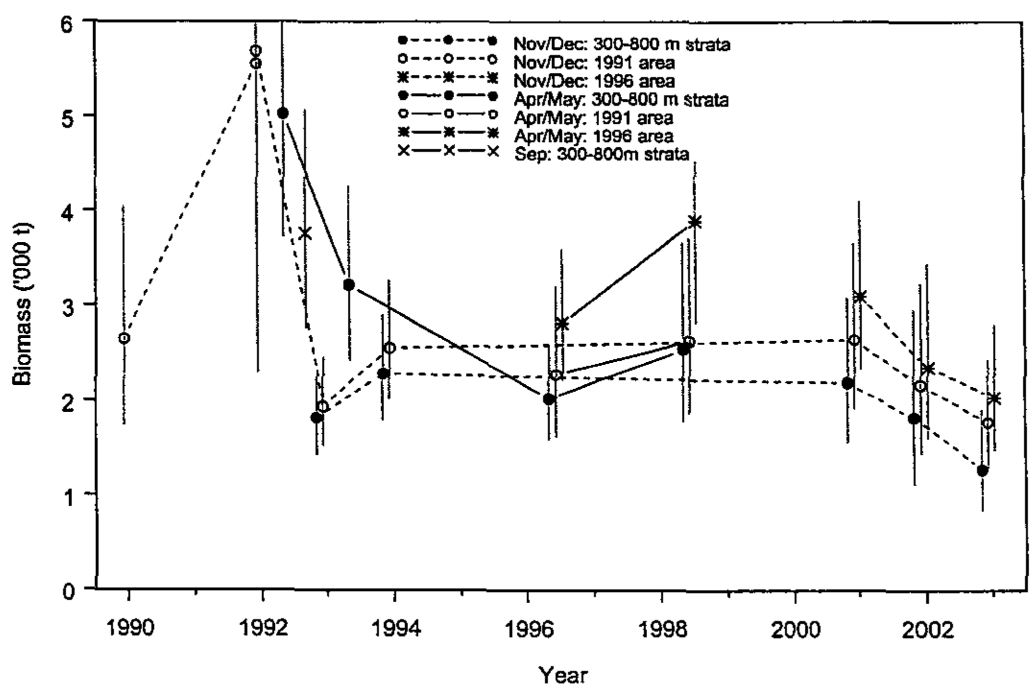

Figure 4: Hake biomass estimates from the *Amaltal Explorer* (October–November 1989) and *Tangaroa* (1992–2002 including the November–December, April–May, and September series) surveys of the sub-Antarctic, with approximate 95% confidence intervals. (See also Table B1, Appendix B.)

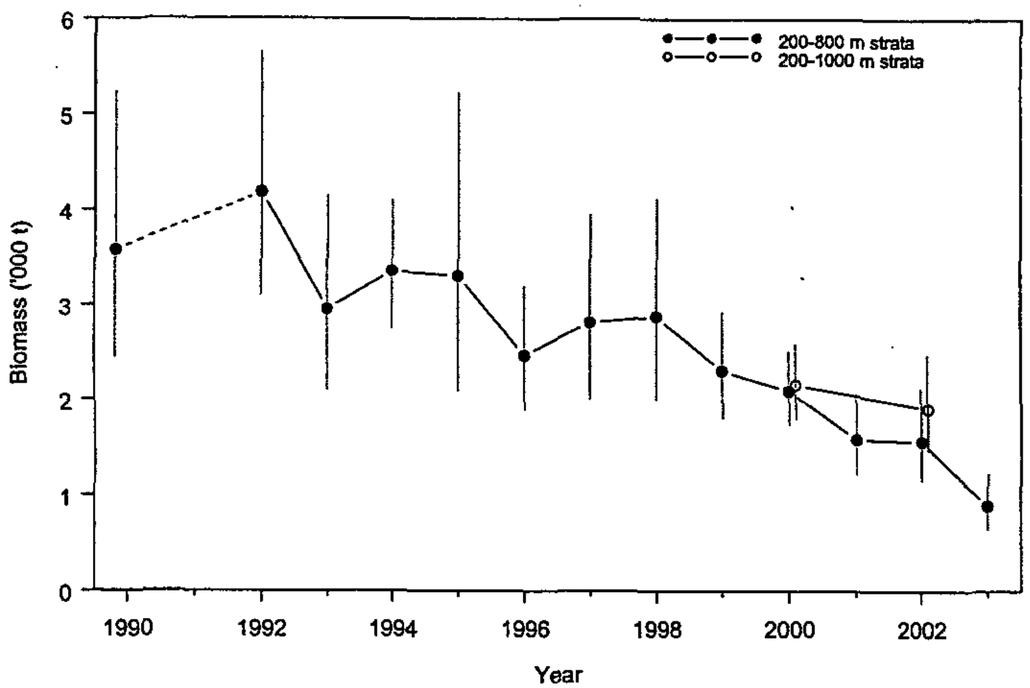

Figure 5: Hake biomass estimates from the *Amaltal Explorer* (November–December 1989) and *Tangaroa* (1992–2003 for the January series), with approximate 95% confidence intervals. (See also Table B2, Appendix B.)

4. MODEL STRUCTURE, INPUTS, AND ESTIMATION

4.1 Model structure

The stock assessment model partitions the sub-Antarctic and Chatham Rise populations into sexes and age groups 3–30, with no plus group. Each stock was considered to reside in a single area (sub-Antarctic and Chatham Rise), with no interaction between the stocks. Unlike models before 2002 (Dunn 2003b), the model includes both the sub-Antarctic and Chatham Rise stocks that are estimated simultaneously, but are considered independent. Although this offers no advantage over the use of separate stock models, the structure allows the option of sensitivity analyses, with some common parameters, to be estimated across both stocks simultaneously.

The model's annual cycle was based on the fishing year and divided the year into three steps (Table 6). Note that model references to "year" within this document refer to the fishing year, and are labelled as the most recent calendar year, i.e., the fishing year 1998–99 is referred to as "1999".

The model used 10 selectivity ogives; male and female fishing selectivities on the sub-Antarctic and Chatham Rise, male and female survey selectivities for each of the sub-Antarctic *Tangaroa* November–December and April–May research survey series (with the September 1992 survey assumed to have a selectivity equal to the November–December series), and male and female survey selectivities for the Chatham Rise *Tangaroa* research survey series. Research survey selectivities were initially assumed to be smoothed degree-3 polynomials, while fishing selectivities were assumed to be logistic. In all cases, female selectivity curves were estimated relative to male selectivity. A logistic parameterisation was used as it forces a monotonic increasing curve to selectivities by age, with a minimum number of parameters. Fishing selectivities for hake are unlikely to be exactly logistic shaped, and may even be domed, but the low sample sizes and high variability in the numbers at age data make accurate determination of the shape difficult. The logistic parameterisation of selectivity (for male observations) for each age x was,

$$f(x)=1\Big/\left[1+19^{(a_{50}-x)/a_{to95}}\right]$$

with estimable parameters a_{50} and a_{to95}. This has value 0.5 at $x = a_{50}$ and 0.95 at $x = a_{50} + a_{to95}$. Similarly, the parameterisation for female observations was,

$$f(x)=1\Big/\left[1+19^{(a_{50}-x)/a_{to95}}\right].a_{max}$$

with estimable parameters a_{50}, a_{to95}, and a_{max}. When $a_{max} = 1$, this is identical to the standard logistic parameterisation. This has value $0.5a_{max}$ at $x = a_{50}$ and $0.95a_{max}$ at $x = a_{50} + a_{to95}$. Selectivities were assumed constant over all years in each fishery, and hence there was no allowance for annual changes in selectivity.

Table 6: Annual cycle of the 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^1	Age[2]	Description	%M^3
1	Oct–Feb	Fishing, recruitment, & spawning	0.42	0.25	Nov./Dec. survey (sub-Antarctic)	50
					Jan. survey (Chatham Rise)	100
2	Mar–May	None	0.25	0.50	Apr./May survey (sub-Antarctic)	50
3	Jun–Sep	Increment age	0.33	0.00	Sep. survey (sub-Antarctic)	100

1. M is the proportion of natural mortality that was assumed to have occurred in that time step.
2. Age is the age fraction, used for determining length at age, that was assumed to occur in that time step.
3. %M is the percentage of the natural mortality in each time step that was assumed to have taken place at the time each observation was made.

In some model runs, biomass and age data from the two 1989 *Amaltal Explorer* surveys (i.e., one in the sub-Antarctic and one on the Chatham Rise) were included with data inputs. Selectivities for these surveys were assumed equal to the selectivity for the appropriate *Tangaroa* series (i.e., the January series for the Chatham Rise or the November–December series for the sub-Antarctic).

Logistic length based selectivities were employed in some model runs. The logistic length based selectivities determine the relative selectivity for male and females via a single selectivity curve, based on their respective mean length at age using the logistic parameterisation described earlier. The relative selectivity by age therefore depends on age, sex, growth rate (determined from the von Bertalanffy growth equation), and the proportion of growth that was assumed to occur in the time step when the selectivity was applied.

Maximum exploitation rates for hake are assumed to be 0.5 for both the sub-Antarctic and Chatham Rise stocks. The choice of the maximum exploitation rate has the effect of determining the minimum possible virgin biomass allowed by the model. This value was set relatively high as there was little external information from which to determine it.

The catch histories assumed in all model runs were the revised estimates of catch for the sub-Antarctic and Chatham Rise reported by Dunn (2003a) and updated for 2001–02 (N.L. Phillips, NIWA, unpublished results), with the assumption that the catch in 2002–03 was the same as that reported for 2001–02 (2523 t in the sub-Antarctic and 1782 t on the Chatham Rise). Five-year projected biomass estimates have assumed that future catches in the sub-Antarctic and Chatham Rise are at (a) the level of the current combined TACC, with exactly half occurring in the sub-Antarctic (3566 t) and Chatham Rise (3566 t) fisheries respectively, and (b) the level of the most recently recorded catch on the sub-Antarctic and Chatham Rise (2523 t and 1782 t respectively in 2001–02). Note that although the TACC for HAK 1 and HAK 4 combined is currently 7132 t, the total HAK 1 and 4 catch (Dunn 2003a) has been at most 94% of the combined TACC (1995–96), averaged about two-thirds of the combined TACC since 1989–90, and was only 60% in 2001–02.

4.2 Biological parameters and observations

Estimates of known biological parameters and fixed biological parameters used in the assessments are given in Tables 5 and 7 respectively. A stock-recruitment relationship (Beverton-Holt relationship with steepness 0.9) was assumed. This differs slightly from the assumption made by Dunn (2003b), who assumed a stock-recruitment relationship only in projections.

Variability was assumed in the von Bertalanffy age-length relationship, with variability assumed to be lognormal with a constant c.v. (coefficient of variation) of 0.1.

The proportion of males at recruitment was assumed to be 0.5 of all recruits, as there are no external data from which to estimate this value. The maturity ogive represents the proportion of fish at each age that are assumed to be mature. Maturity values at age were assumed known, and were based on model fits to the 1998 HAK 7 assessment (Dunn 1998), using the commercial catch-at-age data under an assumption that all year class strengths were 1.0. These values are broadly consistent with estimates from Colman (1998), who concluded that hake reached 50% maturity at between 6 and 8 years for sub-Antarctic hake, and 7–8 years for Chatham Rise hake.

Catch-at-age observations were available for each survey on the sub-Antarctic and Chatham Rise, and from commercial observer data for the two fisheries (see Figures 2 and 3). A plus group for all the catch-at-age data was set at 20 with the lowest age set at 3. Catch-at-age data were fitted to the model as proportions-at-age, where estimates of the proportions-at-age and associated c.v.s by age were estimated using the NIWA catch-at-age software by bootstrap (Bull & Dunn 2002). Zero values were replaced with 0.0001 with an associated c.v. of 3.0. This replacement was because zero values cannot be used with the lognormal error distribution assumed for the proportions-at-age data. The value 0.0001 was (approximately) the lowest minimum observed value in the data and such low values typically had a c.v. of about 3.0. 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 resulting age misclassification matrix is shown as Figure 6.

Biomass estimates from the research surveys were used as relative biomass indices, with associated c.v.s estimated from the survey analysis. Catchability constants (qs) were assumed to be constant and estimated independently for the Chatham Rise *Tangaroa* survey series, sub-Antarctic November–December and September *Tangaroa* series combined, and the sub-Antarctic April–May *Tangaroa* series respectively. Where model runs included the two 1989 *Amaltal Explorer* surveys, their catchability constants were assumed to differ from that of the *Tangaroa* survey series but were constrained so that the ratio of the qs from the Chatham Rise and the November–December sub-Antarctic *Tangaroa* surveys was equal to the ratio of the catchability constants from the Chatham Rise and sub-Antarctic *Amaltal Explorer* surveys. The constraint was imposed in the form of a prior on the ratio and is described in more detail later.

Table 7: Fixed biological parameters assumed for the sub-Antarctic and Chatham Rise stock assessment model.

Parameter	Value
Steepness (Beverton & Holt stock- recruitment relationship)	0.90
Proportion spawning	1.0
Proportion of recruits that are male	0.5
Spawning season length	0
Natural mortality (*M*) Male, Female	0.20 y^{-1}, 0.18 y^{-1}
Maximum exploitation rate (U_{max})	0.5
Maturity ogive (for ages 4–8 & 9+) Male	0.02, 0.07, 0.31, 0.78, 1.00, 1.00
Female	0.02, 0.04, 0.07, 0.45, 0.86, 1.00

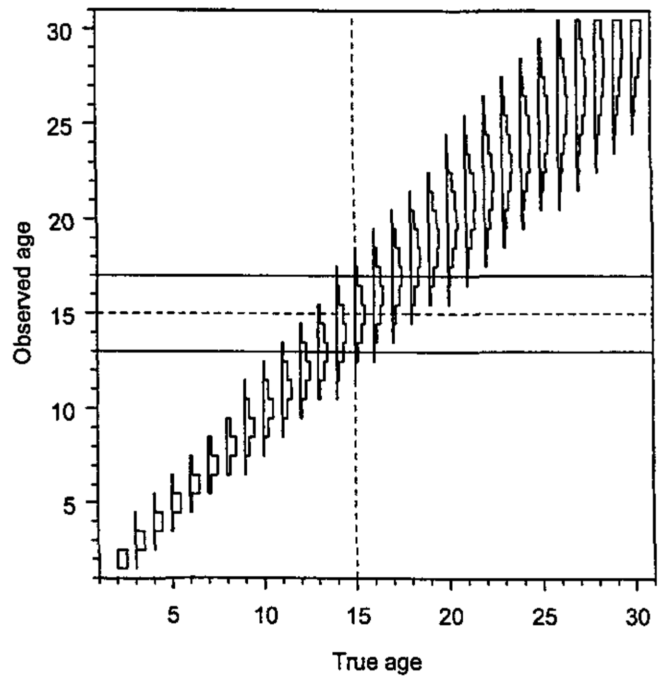

Figure 6: Plot of the ageing error misclassification matrix, showing the distribution of ages obtained with discrete normally distributed errors with constant c.v. 0.08. Grey lines show an example where the true age is 15, and the resulting observed ages lie mostly (95%) in the range 13–17.

4.3 Model estimation

Model parameters were estimated using Bayesian estimation implemented using the CASAL software. (Full details of the CASAL algorithms, software, and methods were detailed by Bull et al. 2003.) However, only the mode of the joint posterior distribution (MPD) was estimated in preliminary runs. For final runs, the full posterior distribution was sampled using Monte Carlo Markov Chain (MCMC) methods, based on the Metropolis-Hastings algorithm.

Lognormal errors, with known c.v.s, were assumed for all relative biomass and proportions-at-age observations. For the proportions-at-age observations, the lognormal assumption was slightly modified to make it robust against outliers. The negative log-likelihood was,

$$-\log(L) = \sum_{i=1}^{n}\left(\log(\sigma_i) - \log\left(\exp\left(-0.5\left(\frac{\log(O_i/qE_i)}{\sigma_i} + 0.5\sigma_i\right)^2\right) + 0.01\right)\right)$$

where O and E are the observed and expected values, and σ is the standard deviation of the log of the error. The lognormal distribution was made robust by the addition of the term 0.01, and is a similar modification to that employed by Fournier et al. (1990) for the normal distribution, with the aim of minimising the influence of large absolute residuals (i.e., against type II deviations where observed values are either much higher or much lower than predicted values).

The c.v.s available for the relative abundance and catch-at-age observations allow for sampling error only. However, additional variance, assumed to arise from differences between model simplifications and real world variation, was added to the sampling variance. The additional variance, termed process error, was estimated in early runs of the model, using all available data from MPD fits. Hence, the overall c.v. assumed in the initial model runs for each observation was calculated by adding process error and observation error. Process errors were estimated from the MPD fits to the base case model, and were assumed to be the same for all other model runs. The process error added was a c.v. of 0.53 and 0.19 for the sub-Antarctic and Chatham Rise observer proportions-at-age data. The process error estimated for the research survey relative abundance estimates and proportions-at-age data was zero.

Year class strengths were assumed known (and equal to one) for years before to 1974 (sub-Antarctic stock) and 1975 (Chatham Rise stock), and after 1999, 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. However, in the projections, the assumption that the relative year class strengths were equal to one was relaxed. Here, relative year class strengths from 2000 were assumed to be unknown, with a lognormal distribution with mean 1.0 and standard deviation set equal to the standard deviation of the previously estimated year class strengths.

MCMCs were estimated using a burn-in length of 5×10^5 iterations, with every 1000^{th} sample taken from the next 10^6 iterations (i.e., a final sample of length 1000 was taken from the Bayesian posterior). Autocorrelations and single chain convergence tests of Geweke (1992) and Heidelberger & Welch (1983) were applied to resulting chains to determine evidence of non-convergence. The tests used a significance level of 0.05 and the diagnostics were calculated using the Bayesian Output Analysis software (Smith 2003).

4.4 Prior distributions and penalty functions

The assumed prior distributions used in the assessment are given in Table 8. Most priors were intended to be relatively uninformed, and were estimated with wide bounds. The exceptions were the choice of informative priors for the survey qs, the ratio of catchability constants for the *Amaltal Explorer* surveys (when used), and natural mortality M (when estimated).

The priors for survey qs were estimated by assuming that the catchability constant was the product of areal availability, vertical availability, and vulnerability. A simple simulation was conducted that estimated a distribution of possible values for the catchability constant by assuming that each of these factors was 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 (0.01–0.40). The assumed distribution for the survey catchability constants are shown in Figure 7. Selectivity priors, for all parameters, were uniform with bounds for the degree-3 polynomial set at (0.01, 5.00). Note that the values of survey catchability constants are dependant 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.

As described earlier, the catchability constants for the *Amaltal Explorer* surveys were constrained so that the ratio of the qs from the Chatham Rise and the November–December sub-Antarctic *Tangaroa* surveys was equal to the ratio of the catchability constants from the Chatham Rise and sub-Antarctic *Amaltal Explorer* surveys. The constraint was imposed in the form of a lognormal prior on the relative ratio, r, with mean 1.0 and c.v. 0.05 (Figure 8), where the r was defined as;

$$r = \frac{q_{\text{Chatham Rise}(Tangaroa)}}{q_{\text{Sub-Antarctic}(Tangaroa)}} \bigg/ \frac{q_{\text{Chatham Rise}(Amaltal\ Explorer)}}{q_{\text{Sub-Antarctic}(Amaltal\ Explorer)}}$$

The prior on natural mortality, M, (when estimated) was determined by assuming that the current estimate of natural mortality was a reasonable approximation to the true value with the assumption that the true value could differ from the current point estimate by about 0.05, and not more than 0.1 (see Figure 7). Note that natural mortality was parameterised by the average of male and female, with the difference estimated with an associated normal prior with mean 0.0, standard deviation of 0.1, and bounds (-0.2,0.2).

Penalty functions were used to constrain the model so that any combination of parameters that did not allow the historical catch to be taken was strongly penalised. A small penalty was applied to the estimates of year class strengths to encourage estimates that average to 1.0. In addition, in scenarios where selectivity ogives were not parameterised by logistic curves, selectivity estimates were penalised to encourage the shape of the age-based selectivity ogive to approximate a degree-3 polynomial.

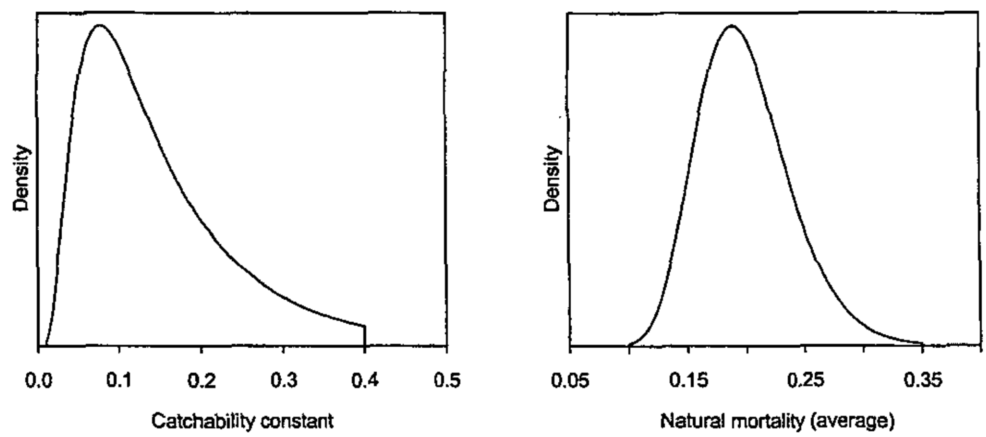

Figure 7: The assumed prior distribution for (left figure) survey catchability constants (qs), lognormal where μ=0.16, c.v.=0.79, and bounds (0.01,0.40), and (right figure) natural mortality (average), lognormal where μ=0.20, c.v.=0.20, and bounds (0.10,0.35).

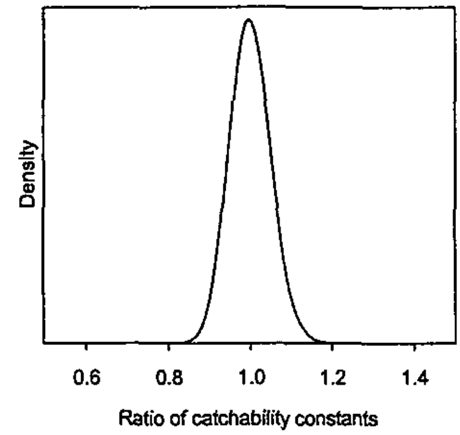

Figure 8: The prior distribution for the ratio of the *Tangaroa* survey catchability constants (qs) to the *Amaltal Explorer* survey catchability constants, lognormal where μ=1.0, c.v.=0.05.

Table 8: The priors assumed for key distributions (when estimated). The parameters are mean (in natural space) and c.v. for lognormal; and mean and s.d. for normal.

Stock	Parameter	Distribution	Parameters		Bounds	
Chatham Rise	B_0	Uniform-log	–	–	2 500	250 000
	Survey q	Lognormal	0.16	0.79	0.01	0.40
	YCS	Uniform	–	–	0.01	100
	M (mean)	Lognormal	0.19	0.20	0.10	0.30
	M (difference)	Normal	0.0	0.05	-0.20	0.20
Sub-Antarctic	B_0	Uniform-log	–	–	2 500	250 000
	Survey q	Lognormal	0.16	0.79	0.01	0.40
	YCS	Uniform	–	–	0.01	100
	M (mean)	Lognormal	0.19	0.20	0.10	0.30
	M (difference)	Normal	0.0	0.05	-0.20	0.20

5. MODEL ESTIMATES

Base case estimates of biomass were estimated using the biological parameters (see Table 5) and model input parameters described earlier, but excluding *Amaltal Explorer* data. Sensitivity runs included parameterising the research survey selectivities as logistic curves, rather than by using a penalty to encourage smoothed degree-3 polynomials ("logistic"); estimating natural mortality M over both stocks simultaneously ("estimate M"); use of length based logistic ogives for the research survey and fishing selectivities ("length"); including the *Amaltal Explorer* data with all ogives parameterised as logistic functions ("AEX-logistic"); and including the *Amaltal Explorer* data using length based logistic ogives ("AEX-length"). Table 9 lists the names and descriptions of the various model runs.

In addition, as model estimates of research survey catchability coefficients for the sub-Antarctic stock model appeared unrealistically low, additional sensitivities for the base case were run using a range of fixed catchability coefficients. These additional sensitivity estimates are described later (see Section 5.3).

Selectivity runs were chosen to investigate aspects of the model where strong model assumptions may have influenced the model output, and where there was little evidence that the particular series of input data were well estimated.

For each model run, MPD fits were obtained and qualitatively evaluated. Objective function values (negative log-likelihood) for each model run are shown in Table 10. MCMC estimates of the posterior distribution were obtained for all model runs, and are presented below. In addition, MCMC estimates of the median posterior and 95% percentile credible intervals are reported for the key output parameters. Summary plots of the base case MPD model fits are given as Appendix C.

Table 9: Model run labels and descriptions for the base case and sensitivity model runs.

Model run	Description
Base case	Base case model using all data, with logistic fishing selectivities and degree-3 polynomial research selectivities, excluding *Amaltal Explorer* data
Logistic	Logistic parameterisation of research survey selectivities
Estimate *M*	Estimated natural mortality over both stocks simultaneously
Length	Length based selectivity ogives with logistic parameterisation
AEX-logistic	Similar to the logistic case mode, but including *Amaltal Explorer* data
AEX-length	Similar to the length case mode, but including *Amaltal Explorer* data

Table 10: Objective function values (negative log-likelihood) for MPD fits to observations (data), priors, penalties resulting from penalties to catch (catch), year class strengths averaging to one (YCS), and smoothed degree-3 polynomial fits to selectivities (3D poly.), and the total objective function (negative log-likelihood) value.

Model run	Data	Priors	Penalties			Total
			Catch	YCS	3D poly.	
Base case	69.71	14.33	0.00	0.00	4.40	88.43
Logistic	120.98	15.50	0.00	0.00	–	136.47
Estimate *M*	45.53	16.58	0.00	0.00	4.20	66.30
Length	218.44	13.66	0.00	0.00	–	232.10
AEX-logistic	147.47	11.41	0.00	0.00	–	158.88
AEX-length	234.25	9.31	0.00	0.00	–	243.56

Convergence diagnostics for the sub-Antarctic and Chatham Rise stock models are given in Table 11. Diagnostics were run on chains of final length 5×10^6 iterations, after a burn-in of 1×10^6 iterations, after systematically subsampling ("thinning") to 1000 samples.

The Geweke (1992) convergence diagnostic is based on a test that compares the means of the first 10% and last 50% of a Markov chain. Under the assumption that the samples were drawn from the stationary distribution of the chain, the two means are equal and Geweke's statistic has an asymptotically standard normal distribution. The resulting test statistic is a standard Z-statistic, with the standard error estimated from the spectral density at zero. Values of the Z-statistic that have a p-value less than 0.05 indicate that, at the 5% significance level, there is evidence that the samples were not drawn from a stationary distribution.

Heidelberger & Welch (1983) proposed two linked tests. The first is a stationarity test that uses the Cramer-von Mises statistic to test the null hypothesis that the sampled values come from a stationary distribution. The test is successively applied, first to the whole Markov chain, then after discarding the first 10, 20, etc, percent of the chain until, either the null hypothesis is accepted, or 50% of the chain has been discarded. If more than 50% of the chain is discarded, then the test returns a failure of the stationarity test. Otherwise, the number of iterations to keep is reported. The second test is the half-width test that calculates a 95% confidence interval for the chain mean, using the portion of the chain that passed the Heidelberger & Welch stationarity test. Half the width of this interval is compared with the estimate of the mean. If the ratio between the half-width and the mean is lower than 2% of the mean, the half width test is passed.

No evidence of lack of convergence was found in the estimates of B_0, although some estimates of selectivity parameters and YCS showed strong evidence of lack of convergence (Table 11). The constraint of degree-3 polynomials on selectivity functions and YCS having average 1 contributed to large correlations between some parameters, resulting in a lack of possible convergence. Trace diagnostics of key parameters for the sub-Antarctic and Chatham Rise stock models are shown in Figures 9 and 10.

Table 11: Percentage of parameters that passed the Geweke and Heidelberger & Welch convergence diagnostics for selected parameters from the base case MCMC chain for the sub-Antarctic and Chatham Rise stock models (% refers to the percentage of parameters that passed each test).

Model	Stock	Parameter	n	Geweke	Heidelberger & Welch	
					Stationarity	Half width test
Base case	Sub-Antarctic	B_0	1	100.0 %	Passed	Passed
		Selectivity	146	99.3 %	100.0 %	100.0 %
		YCS	26	71.4 %	78.6 %	82.1 %
	Chatham Rise	B_0	1	100.0 %	Passed	Passed
		Selectivity	102	65.7 %	93.1 %	100.0 %
		YCS	25	81.5 %	92.6 %	92.6 %

5.1 Sub-Antarctic base case results

The estimated MCMC marginal posterior distributions for selected parameters for the sub-Antarctic stock are shown in Figures 11–18. Research survey selectivities for males and females were divergent, with the selectivities for males generally lower than for females in the research surveys in both the November–December and the April–May survey series. Selectivities were significantly dome shaped, with the selectivity at age 12–14 about twice than at ages 15+. Both the male and female selectivities suggested that males and females were not fully selected by the trawl gear until aged at least 13+. However, in both cases, the posterior density estimates of selectivities indicated considerable uncertainty in the estimates of selectivity by age and sex (see Figures 11 and 12).

Fishing selectivities were again poorly estimated, with strong evidence that the selectivity of male fish was considerably higher at age than for females (Figure 13). There is no information outside the model that allows the shape of the estimated selectivity ogives to be verified. Year class strength estimates were poorly estimated for years when only older fish were available to determine age class strength (i.e., before the mid 1980s), and the most recent year class strength (1999) was also poorly determined (Figure 14).

The estimates suggested that the sub-Antarctic stock is characterised by a group of moderate or strong year classes in the late 1970s, followed by a period of slightly less than average recruitment. Consequently, biomass estimates for the stock have declined, in particular since the early 1990s (Figure 15). However, biomass estimates for the stock appear relatively healthy, with estimated current biomass at about 70% of B_0 (95% credible intervals 59–83%) (see Figure 16 and Table 12.) Exploitation rates (Figure 17) for the sub-Antarctic also appear low, and are a consequence of the high estimated stock size in relationship to the level of relative catches.

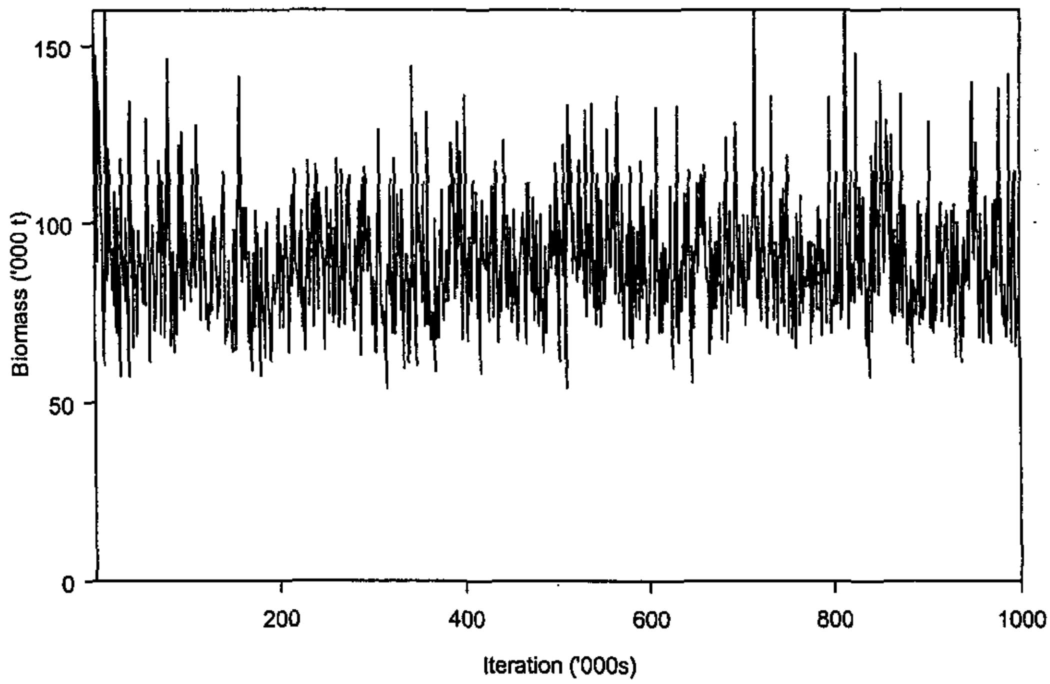

Figure 9: Trace diagnostic plot for base case MCMC chain for estimates of B_0 for the sub-Antarctic stock model.

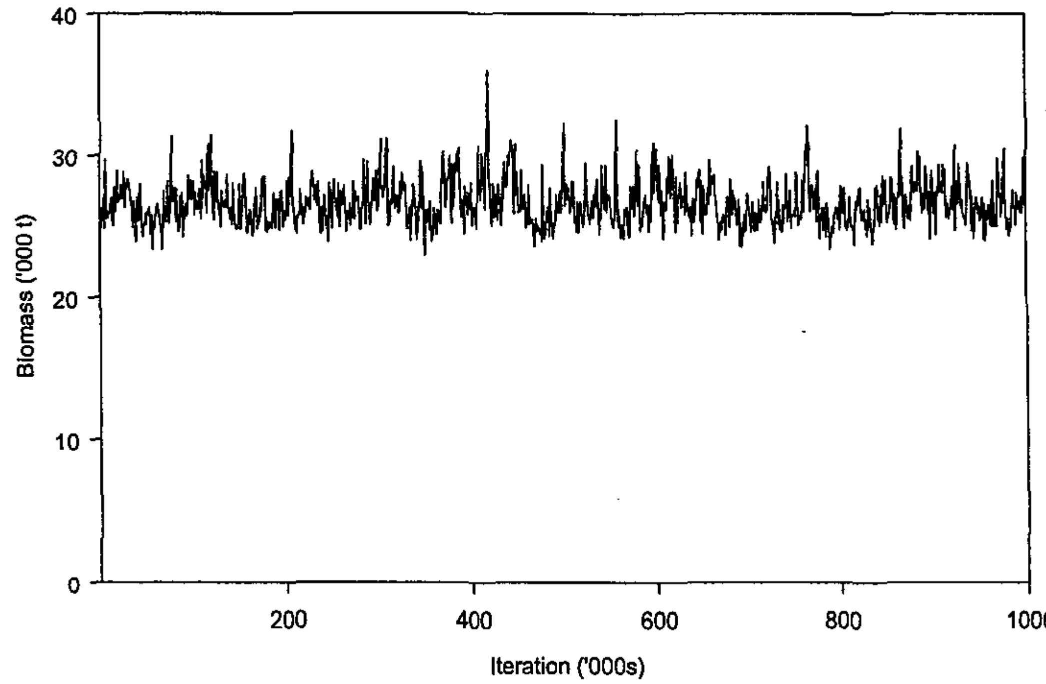

Figure 10: Trace diagnostic plot for base case MCMC chain for estimates of B_0 for the Chatham Rise stock model.

Sensitivity runs did not suggest any great departure from the base case estimates of current biomass (approximate ranges over all sensitivities was 60–75% B_0), (see Table 12). The estimated research survey catchability constants (Figure 18) are estimated as very low (about 1–6%, and are constrained by the lower bound on the prior for q), suggesting that the absolute catchability of the sub-Antarctic research survey series is extremely low. However, it is not known if the catchability of the sub-Antarctic research survey series is as low as estimated by the stock model, and we note that higher estimates of the catchability constant q (although confounded with selectivity) would result in lower current and virgin biomass estimates. A plausible explanation for the estimated values is that there appears little contrast in the biomass indices from the sub-Antarctic research survey series, and that the model has little information on which to determine an appropriate "scale" of biomass estimates. An exception to this result was when the *Amaltal Explorer* biomass indices were included within the model. Here, estimated catchability coefficients were higher, and, in the case of the AEX-length case, much higher (see Figure 19). As an alternative, sensitivity runs (to MPD stage only) were carried out where the research survey catchability coefficients for the November–December series were fixed at a range of values from $q = 0.1$ to $q = 0.3$. The results for these runs are described later (Section 5.3).

Projections assumed catches at a level equal to half of the combined HAK 1 and 4 TACC, with future recruitment assumed to be lognormally distributed with standard deviation equal to the log of estimated recruitment. Estimated standard deviations had mean 0.73 (95% range 0.47–1.15) for the base case. Projections with catches at the level of the current catch or at the TACC appear to have little effect on the 2008 projected stock size (see Table 13).

Table 12: Bayesian median and 95% credible intervals of B_0, B_{2003}, and B_{2003} as a percentage of B_0 for the sub-Antarctic base and sensitivity cases.

Model run	B_0	B_{2003}	B_{2003} (%B_0)
Base case	88 100 (63 600–131 500)	62 900 (39 900–105 400)	71.6 (59.9–83.8)
Logistic	79 100 (56 400–122 800)	59 700 (36 900–104 200)	76.0 (63.3–87.5)
Estimate *M*	82 400 (57 700–129 200)	59 400 (35 700–102 400)	71.9 (58.2–85.2)
Length	81 000 (54 200–145 700)	52 100 (29 200–110 900)	64.0 (52.2–77.1)
AEX-logistic	65 100 (48 900–90 500)	45 500 (29 000–70 400)	70.2 (58.3–80.9)
AEX-length	63 700 (48 000–98 900)	38 100 (23 900–68 200)	59.9 (48.9–70.6)

Table 13: Bayesian median and 95% credible intervals of projected B_{2008}, B_{2008} as a percentage of B_0, and B_{2008}/B_{2003} (%) for the sub-Antarctic base and sensitivity cases where future catches are assumed equal to the TACC or current levels.

Future catch	Model run	B_{2008}	B_{2008} (%B_0)	B_{2008}/B_{2003} (%)
TACC	Base case	68 600 (38 200–127 000)	77.0 (55.7–107.7)	112.2 (90.3–146.5)
(=3 566 t)	Logistic	63 300 (33 500–120 900)	79.1 (55.8–111.9)	112.7 (89.5–142.5)
	Estimate *M*	64 800 (33 400–130 200)	77.9 (54.4–116)	114.8 (89.6–153.1)
	Length	60 700 (28 800–132 700)	73.5 (50.1–109.9)	115.5 (92.9–153.9)
	AEX-logistic	45 600 (25 300–83 900)	70.4 (48.7–101.2)	106.7 (83.9–137.4)
	AEX-length	41 800 (22 500–82 800)	65.7 (44.3–95.1)	110.5 (86.3–142.1)
Current	Base case	71 500 (42 200–130 100)	81.3 (61.7–111.6)	117.3 (96.3–148.3)
(=2 523 t)	Logistic	67 500 (36 900–124 400)	83.5 (60.0–113.7)	117.5 (95.0–149.6)
	Estimate *M*	69 100 (38 000–140 400)	82.0 (60.3–126.4)	119.5 (97.4–159.1)
	Length	64 200 (31 300–142 800)	78.5 (55.8–120.5)	121.6 (99.8–166.3)
	AEX-logistic	49 000 (27 200–85 400)	75.4 (53.6–108.2)	112.8 (90.4–145.6)
	AEX-length	45 400 (26 200–84 200)	70.4 (50.9–98.9)	118.0 (95.1–149.7)

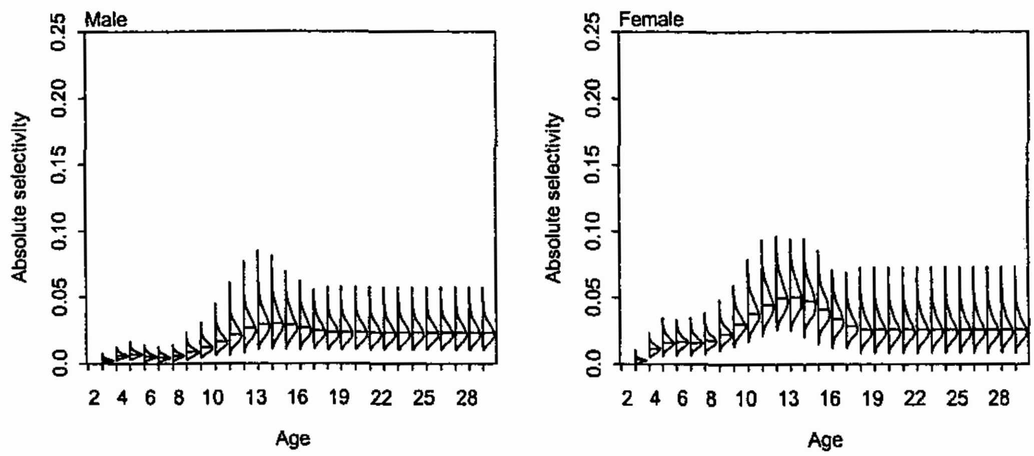

Figure 11: Estimated posterior distributions of absolute selectivity by age and sex for the base case for the sub-Antarctic November–December research survey proportions-at-age. Individual distributions show the marginal posterior distribution, with horizontal lines indicating the median.

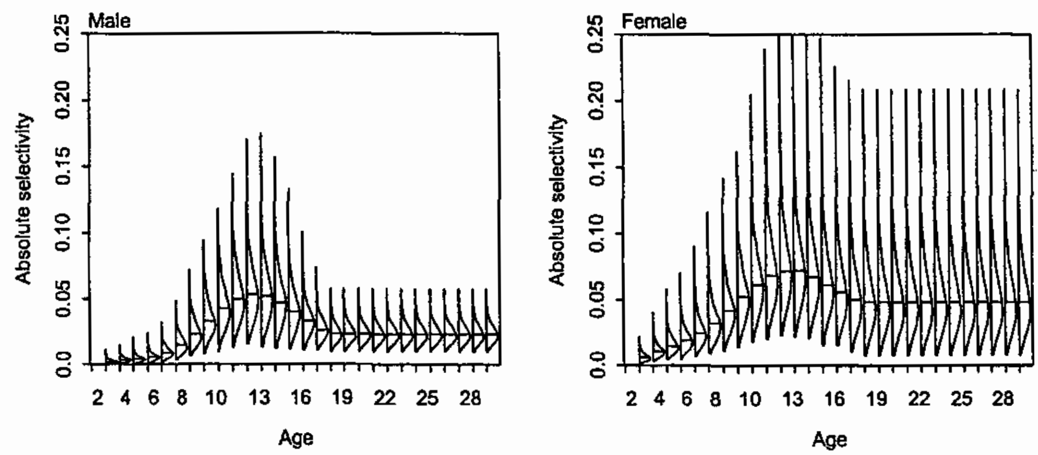

Figure 12: Estimated posterior distributions of absolute selectivity by age and sex for the base case for the sub-Antarctic April–May research survey proportions-at-age. Individual distributions show the marginal posterior distribution, with horizontal lines indicating the median.

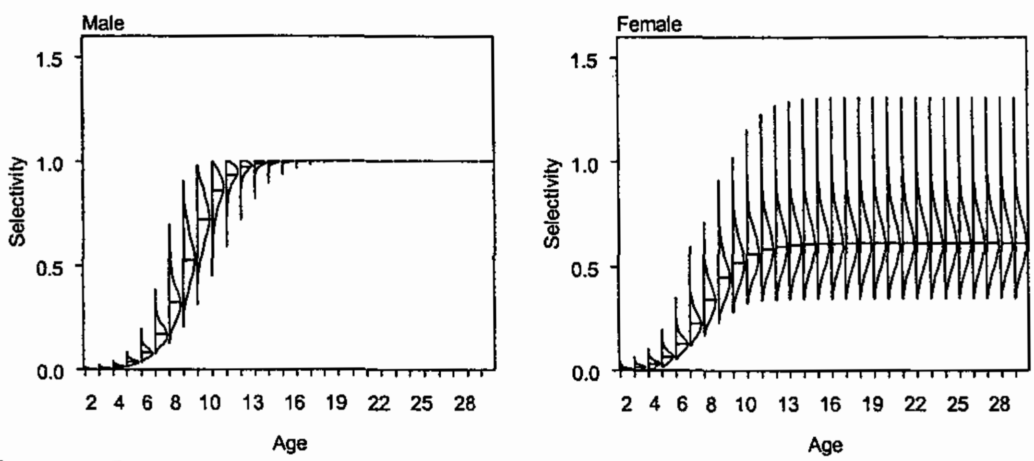

Figure 13: Estimated posterior distributions of relative selectivity by age and sex for the base case for the sub-Antarctic fishery proportions-at-age. Individual distributions show the marginal posterior distribution, with horizontal lines indicating the median.

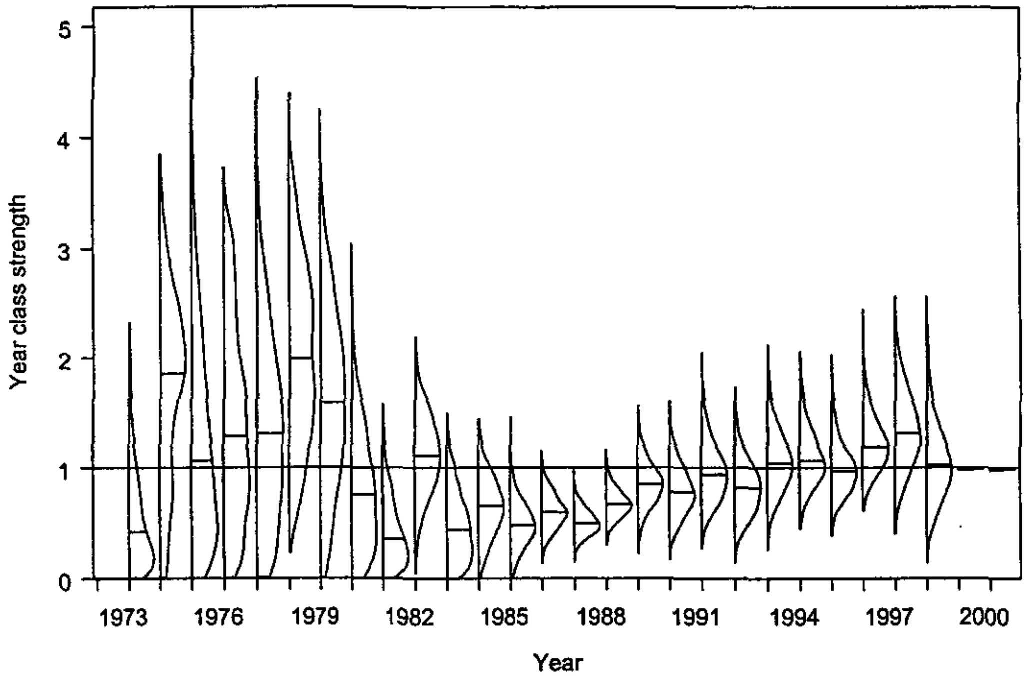

Figure 14: Estimated posterior distributions of year class strengths for the base case for the sub-Antarctic stock. The horizontal line indicates the year class strength of one. Individual distributions show the marginal posterior distribution, with horizontal lines indicating the median.

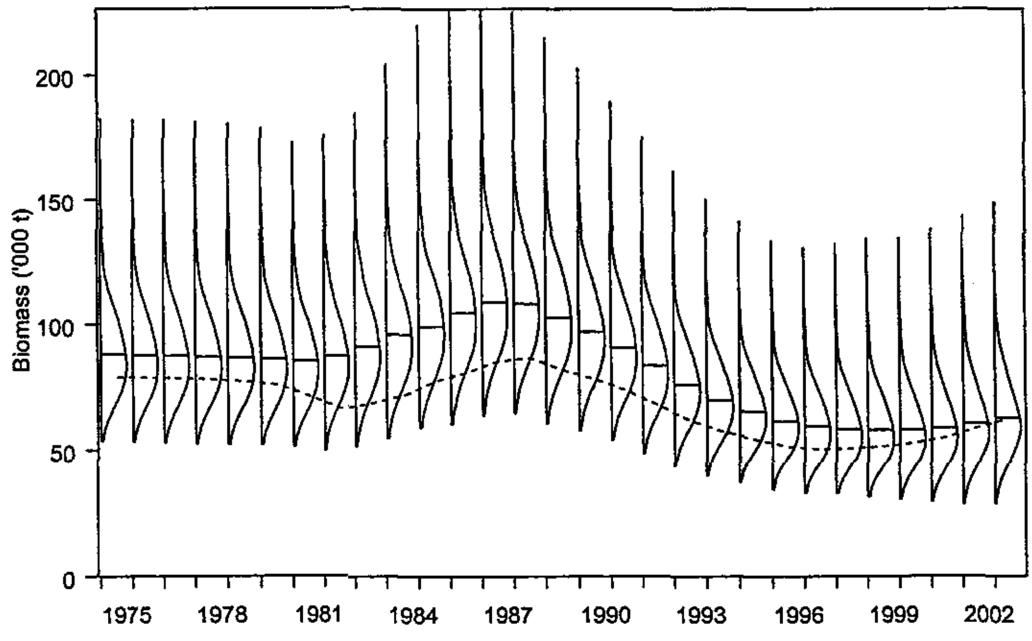

Figure 15: Estimated posterior distributions of biomass trajectories for the base case for the sub-Antarctic stock. Individual distributions show the marginal posterior distribution, with horizontal lines indicating the median. The MPD trajectory is shown as a dashed line.

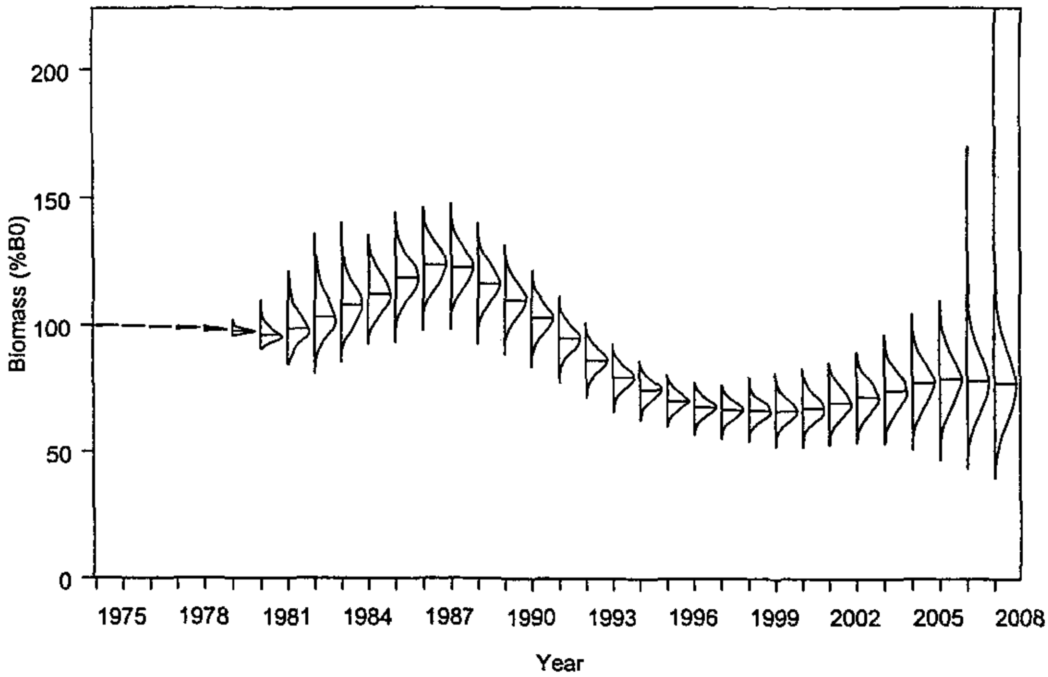

Figure 16: Estimated posterior distributions of biomass trajectories (%B_0) for the base case for the sub-Antarctic stock, projected to 2008. Individual distributions show the marginal posterior distribution, with horizontal lines indicating the median.

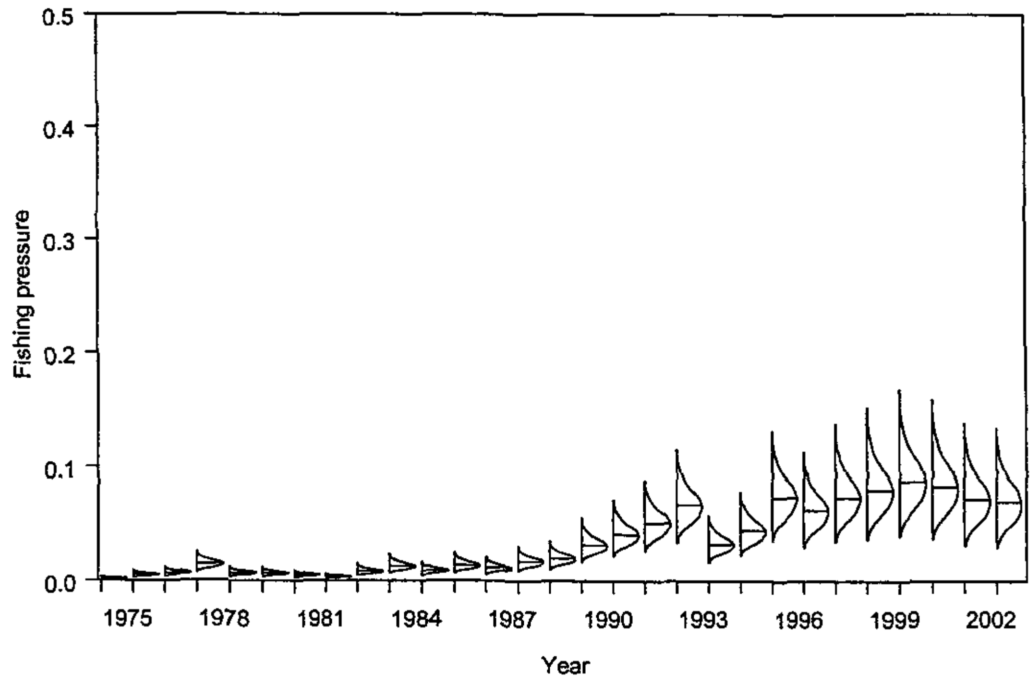

Figure 17: Estimated posterior distributions of exploitation rates for the base case for the sub-Antarctic stock. Individual distributions show the marginal posterior distribution, with horizontal lines indicating the median.

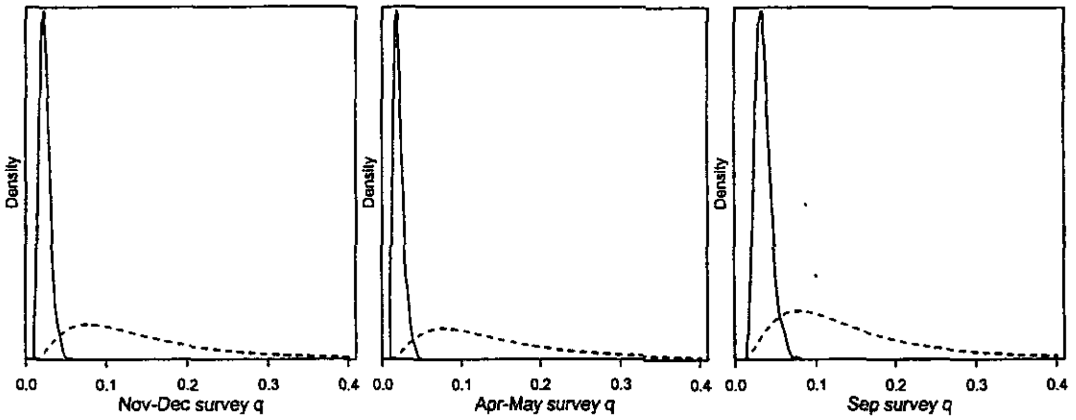

Figure 18: Estimated posterior distributions (solid lines) and priors (dashed line) of survey catchability constants for the base case for the sub-Antarctic November–December, April–May, and September research survey series.

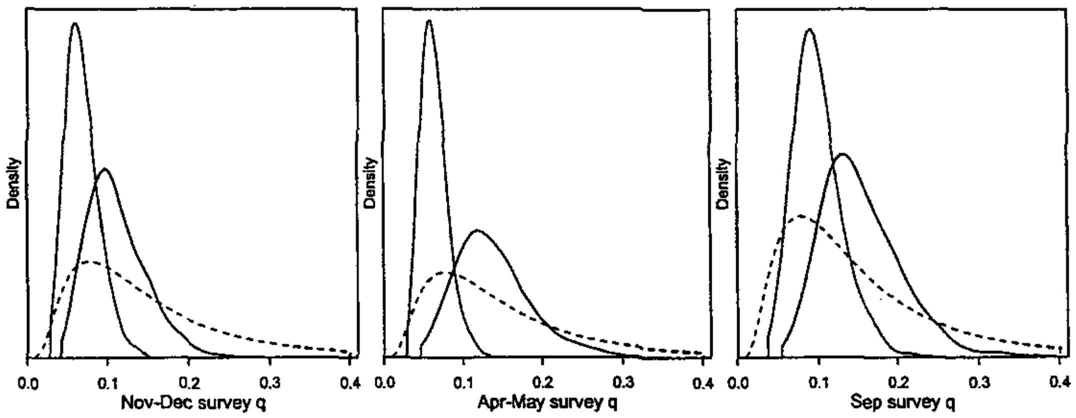

Figure 19: Estimated posterior distributions for the AEX (dark solid lines) and AEX-length (light solid lines) sensitivity cases, and priors (dashed line) of survey catchability constants for the sub-Antarctic November–December, April–May, and September research survey series.

5.2 Chatham Rise base case results

The estimated MCMC marginal posterior distributions for selected parameters for the Chatham Rise stock are shown in Figures 20–26. As with the sub-Antarctic research survey selectivity estimates, selectivities for males and females were divergent with the selectivities for males lower than those for females in the research surveys at older ages (15+). Survey selectivities on the sub-Antarctic and Chatham Rise both showed a very similar pattern, with dome shaped selectivities, and, in particular, male selectivity at age 12–14 about twice that at ages 15+. Both the male and female selectivities suggested that males and females were not fully selected by the research gear until aged at least 14+. However, the posterior density estimates of selectivities indicated considerable uncertainty in the estimates of selectivity by age and sex (Figure 20). Fishing selectivities were again poorly estimated, with roughly equivalent male and female fishing selectivity (Figure 21). There is no information outside the model that allows the shape of the estimated selectivity ogives to be verified.

Year class strength estimates were poorly estimated for years where only older fish were available to determine age class strength (i.e., before the mid 1980s). More recent year class strengths appear well estimated, although the signal in the very recent year class strengths is unlikely to be as strong as indicated by the model estimates (Figure 23). The year class strength estimates suggested that the Chatham Rise stock is characterised by a group of strong year classes in the late 1970s and 1980s, with strong recruitment in the early 1990s, followed by a period of rapidly declining recruitment. Consequently, biomass estimates for the stock have declined (Figure 24). Biomass estimates for the stock appear to be low, at about 36% of B_0 (95% credible intervals 28–46%) (see Figure 25 and Table 14.)

Exploitation rates (Figure 26) for the Chatham Rise appear to be increasing, with upper estimates approaching about 0.4. These are defined as the maximum exploitation rate (catch to vulnerable biomass ratio) in the fishery from fishing. This is indicative of a sustained high level of fishing pressure.

Sensitivity runs did not suggest any great departure from the base case estimate of biomass (approximate range of B_{2003} over all sensitivities was about 34–43% B_0, see Table 14). The estimated research survey catchability constants (Figure 22) are estimated as similar to the prior (about 8–21%, while the prior had a mean of about 16%), suggesting that the estimated catchability of the Chatham Rise research survey series is similar, but slightly lower, than the prior.

Projections assumed catches at a level equal to half of the combined HAK 1 and 4 TACC (see earlier), with future recruitment assumed to be lognormally distributed with standard deviation equal to the log of estimated recruitment. Estimated standard deviations had mean 0.74 (95% range 0.52–1.11) for the base case. Projections with catches at the level of the TACC, or with catches at the level of the 2001–02 catch, show that current catch levels will result in a steep decline in stock status towards 2008. The model suggests that estimated biomass in 2008, assuming that future catches are equal to the TACC, will be about 17–60% of current biomass, and between 5 and 28% B_0 (Table 15). These projections incorporate a range of recruitment strengths from very low to high, suggesting that unless future recruitment in the Chatham Rise stock is at high levels, the stock size will continue to rapidly decline in the immediate future.

Less pessimistic are projections at the level of the current catch (Table 15). Although these projections still indicate a decline in biomass to about half current levels by 2008, the rate of decline is less steep.

Risks that the stock will fall below 20% B_0 are estimated with catches assumed equal to the TACC and with catches assumed equal to the current catch (Table 16). Under either catch scenario, the risks to the stock increase with time — reaching about 50% at TACC catch levels in 2005 and at current catch levels in 2007. Sensitivity analyses suggest that the model parameterisations considered here have little impact on the assessment of risk.

Table 14: Bayesian median and 95% credible intervals of B_0, B_{2003}, and B_{2003} as a percentage of B_0 for the Chatham Rise base and sensitivity cases.

Model run	B_0	B_{2003}	B_{2003} (%B_0)
Base case	26 300 (24 100–30 300)	9 500 (7 000–13 400)	35.9 (28.4–45.6)
Logistic	25 600 (23 800–27 800)	9 100 (6 900–12 200)	35.5 (28.5–43.5)
Estimate *M*	27 300 (24 200–33 500)	11 300 (7 900–17 700)	41.5 (31.9–54.1)
Length	29 400 (26 700–33 900)	10 000 (7 400–14 600)	33.9 (27.1–43.1)
AEX-logistic	25 900 (23 800–28 600)	9 000 (6 800–11 900)	34.9 (27.9–42.6)
AEX-length	30 100 (27 100–35 300)	10 500 (7 600–15 400)	35.2 (27.9–44.5)

Table 15: Bayesian median and 95% credible intervals of projected B_{2008}, B_{2008} as a percentage of B_0, and B_{2008}/B_{2003} (%) for the Chatham Rise base and sensitivity cases where future catches are assumed equal to the TACC or current levels.

Future catch	Model run	B_{2008}	B_{2008} (%B_0)	B_{2008}/B_{2003} (%)
TACC	Base case	2 600 (1 300–7 300)	9.9 (4.8–26.4)	26.7 (16.1–55.6)
(= 3 566 t)	Logistic	3 300 (1 500–7 900)	12.9 (6.0–30.2)	33.1 (19.3–62.5)
	Estimate *M*	4 100 (1 500–12 300)	14.8 (5.8–42.6)	31.7 (17.5–69.7)
	Length	2 200 (800–9 000)	7.5 (2.9–29)	23.2 (11.4–62.4)
	AEX-logistic	2 700 (1 400–7 000)	10.6 (5.3–26.4)	28.1 (16.9–54.8)
	AEX-length	2 500 (800–10 400)	8.3 (2.8–33.3)	24.5 (10.8–68.3)
Current	Base case	6 000 (2 700–12 800)	22.8 (10.3–47.6)	52.8 (32.5–91.5)
(=1 782 t)	Logistic	5 600 (2 300–12 600)	21.7 (9.4–48.4)	51.6 (30.2–91.7)
	Estimate *M*	7 900 (3 200–19 100)	28.5 (12.6–66.1)	55.2 (34.3–101.1)
	Length	6 500 (2 600–15 400)	21.8 (9.4–49.9)	51.1 (31.3–90.2)
	AEX-logistic	5 300 (2 200–13 100)	20.2 (8.7–49.1)	48.9 (28.8–91.7)
	AEX-length	6 800 (2 800–15 600)	22.4 (10.0–48.8)	50.9 (31.3–89.6)

Table 16: Estimates of stock risk, i.e., the probability that the stock will fall below 20% B_0, for the Chatham Rise base and sensitivity cases where future catches are assumed equal to the TACC or current levels.

						Year
Future catch	Model run	2004	2005	2006	2007	2008
TACC	Base case	0.01	0.57	0.92	0.94	0.94
(= 3 566 t)	Logistic	0.00	0.47	0.88	0.90	0.87
	Estimate *M*	0.00	0.24	0.66	0.73	0.72
	Length	0.04	0.68	0.93	0.93	0.91
	AEX-logistic	0.01	0.64	0.95	0.96	0.92
	AEX-length	0.03	0.59	0.90	0.90	0.88
Current	Base case	0.00	0.09	0.31	0.40	0.36
(=1 782 t)	Logistic	0.00	0.10	0.34	0.44	0.41
	Estimate *M*	0.00	0.02	0.12	0.18	0.17
	Length	0.01	0.17	0.44	0.47	0.39
	AEX-logistic	0.00	0.15	0.44	0.53	0.49
	AEX-length	0.00	0.13	0.40	0.44	0.37

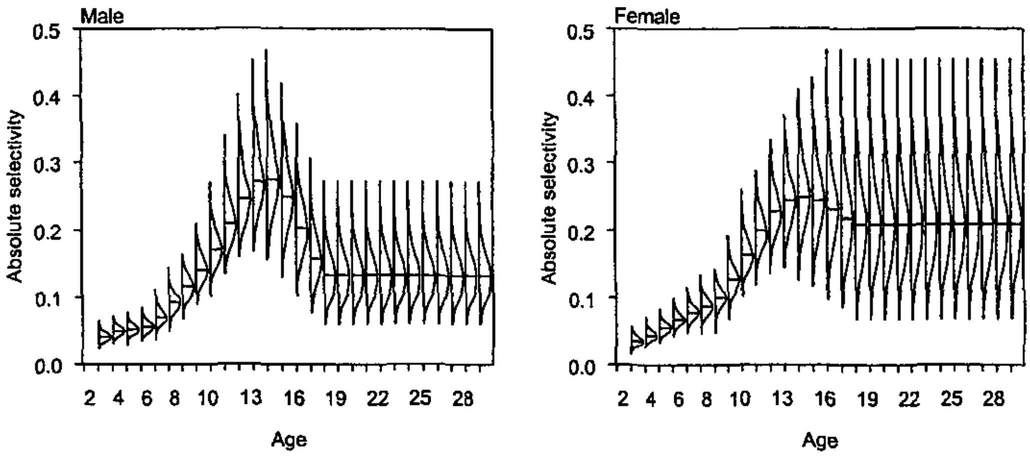

Figure 20: Estimated posterior distributions of absolute selectivity by age and sex for the base case for the Chatham Rise January research survey proportions-at-age. Individual distributions show the marginal posterior distribution, with horizontal lines indicating the median.

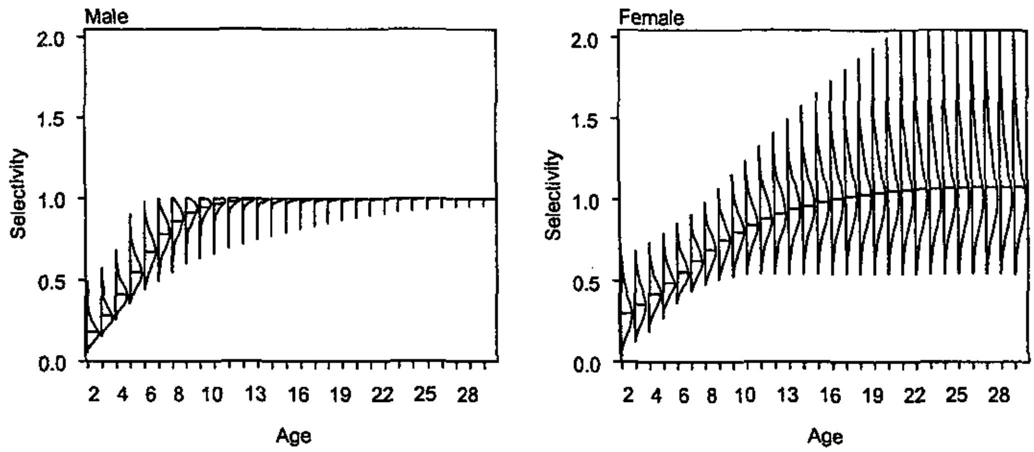

Figure 21: Estimated posterior distributions of relative selectivity by age and sex for the base case for the Chatham Rise fishery proportions-at-age. Individual distributions show the marginal posterior distribution, with horizontal lines indicating the median.

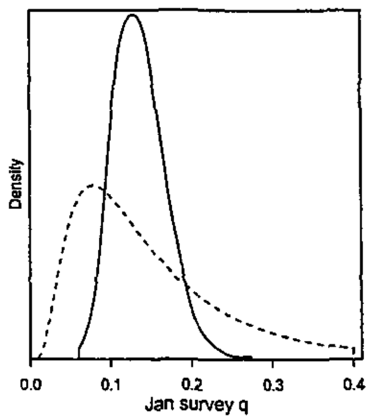

Figure 22: Estimated posterior distribution (solid line) and prior (dashed line) of survey catchability constant for the base case for the Chatham Rise January research survey series.

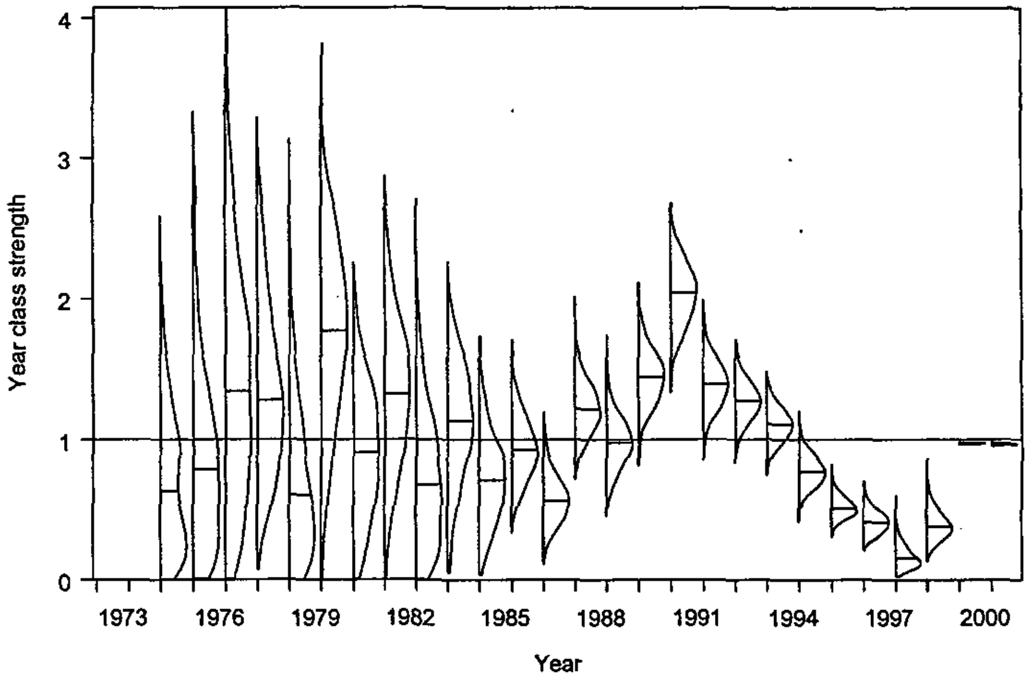

Figure 23: Estimated posterior distributions of year class strengths for the base case for the Chatham Rise stock. The horizontal line indicates the year class strength of one. Individual distributions show the marginal posterior distribution, with horizontal lines indicating the median.

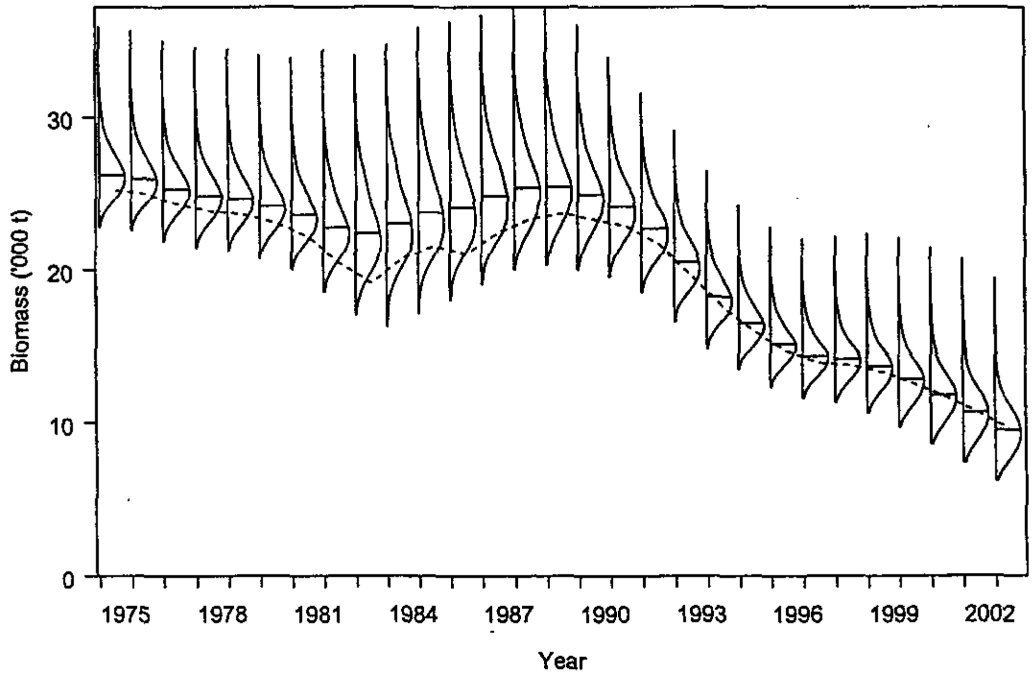

Figure 24: Estimated posterior distributions of biomass trajectories for the base case for the Chatham Rise stock. Individual distributions show the marginal posterior distribution, with horizontal lines indicating the median. The MPD trajectory is shown as a dashed line.

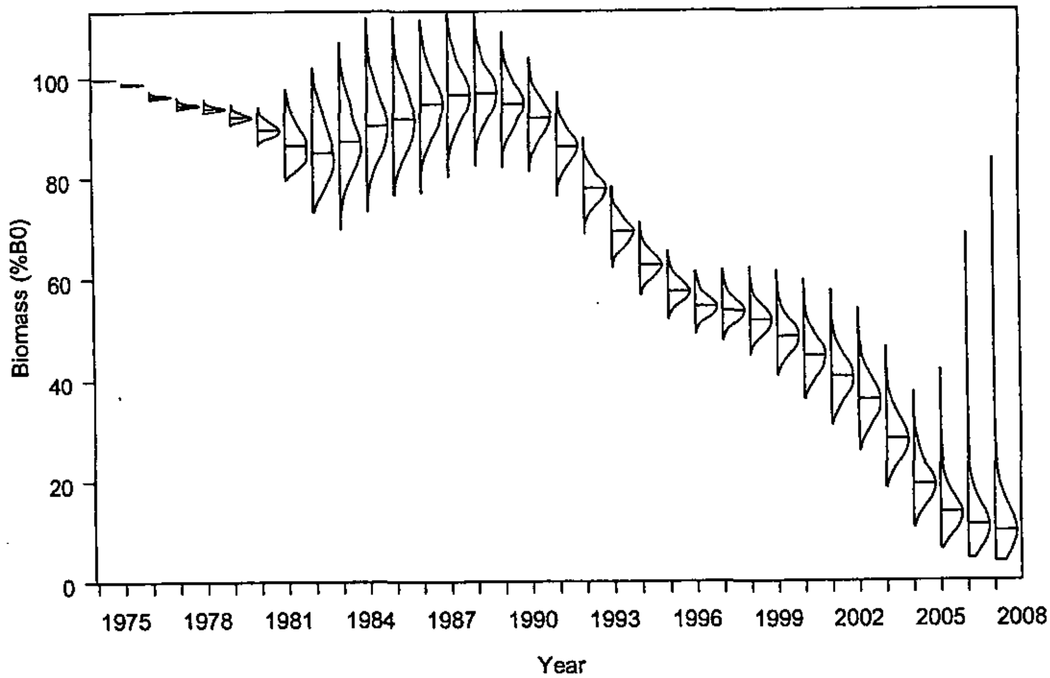

Figure 25: Estimated posterior distributions of biomass trajectories (%B_0) for the base case for the Chatham Rise stock, projected to 2008 with future catches assumed equal to the TACC. Individual distributions show the marginal posterior distribution, with horizontal lines indicating the median.

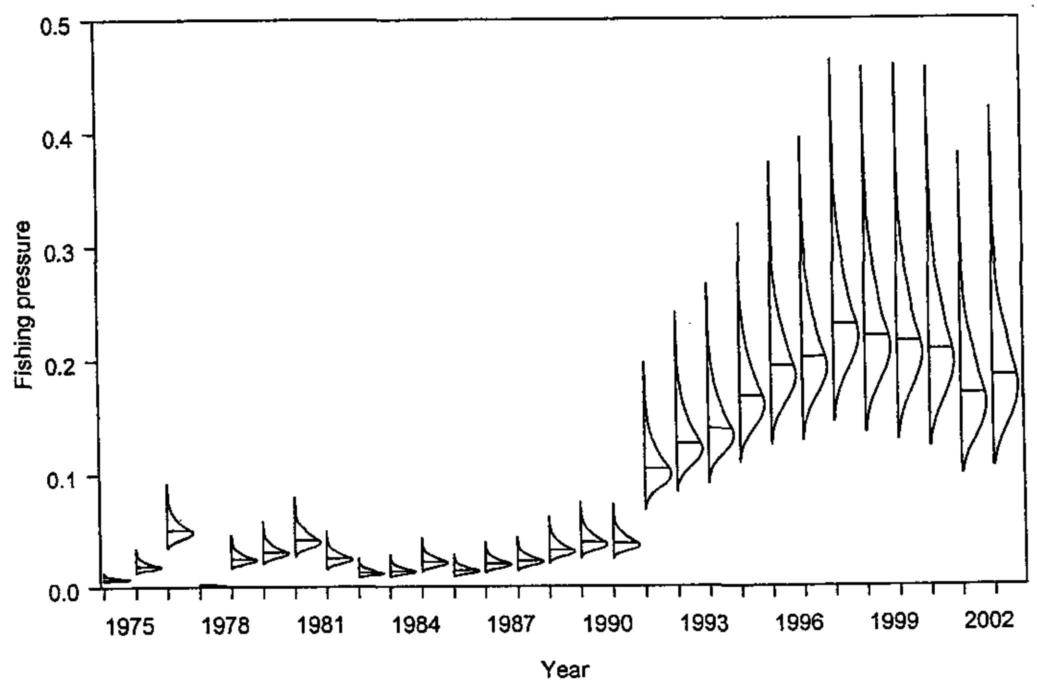

Figure 26: Estimated posterior distributions of exploitation rates for the base case for the Chatham Rise stock. Individual distributions show the marginal posterior distribution, with horizontal lines indicating the median.

5.3 Sensitivity results

Sensitivity runs included parameterising the research survey selectivities as logistic curves ("logistic"), estimating natural mortality *M* over both stocks simultaneously ("estimate *M*") use of length based logistic ogives ("length"), and including the *Amaltal Explorer* data with logistic ogives ("AEX-logistic") and length based ogives ("AEX-length").

In addition, MPD sensitivity runs were made of alternative values for the research survey catchability coefficients for the sub-Antarctic stock model. Base case estimates of these were very low, and these sensitivities investigate the impact of alternative assumptions of the value of the catchability coefficient.

Estimates of the sub-Antarctic current stock size had a range of values, and were not well determined, with estimates of B_0 ranging from 49 000 to 139 000 t (Figure 27). However, estimates of current stock size as a percentage of B_0 were less variable, and ranged from 50 to 90% B_0, and MPD sensitivity estimates with fixed research survey catchability coefficients were about 73–80% B_0 (Table 17) The different assumptions for the research selectivity ogives (i.e., either length based, logistic, or degree-3 polynomial curves) had little impact on the estimates of B_0, current stock size (B_{2003}), and projected stock size in 2008. However, there is no information available that would allow determination of which parameterisation better describes the selectivity functions.

Table 17: MPD estimates of April–May catchability coefficients, B_0 and B_{2003}, with the November–December sub-Antarctic resource survey catchability constants fixed at values 0.05–0.30. Values where *q* (Nov–Dec) = 0.05 are the MPD estimates from the base case.

q (Nov–Dec)	*q* (Apr–May)	B_0	B_{2003}	B_{2003} (%B_0)
0.05	0.05	79 096	62 948	79.6
0.10	0.08	65 207	49 874	76.5
0.15	0.10	61 614	45 385	73.7
0.20	0.12	56 556	42 219	74.6
0.25	0.14	54 752	40 717	74.4
0.30	0.15	54 752	39 887	72.9

Inclusion of the *Amaltal Explorer* biomass and age data resulted in lower estimates of current stock status, with estimates of B_{2003} ranging from 50 to 80% B_0. The value of including such data requires more work to determine if that approach is worth continuing, but we note that the use of the *Amaltal Explorer* data combined with length based selectivities gave more appealing fits to the research survey data in the more recent years (data not shown).

Estimates of Chatham Rise current stock size were all similar, with estimates of B_{2003} ranging from 27 to 57 % B_0 (Figure 28). All sensitivity runs showed a similar pattern of reducing recruitment in recent years, and rapidly declining stock status. The most optimistic run was when natural mortality was estimated within the model — although this resulted in high estimates of natural mortality. As for the sub-Antarctic stock, different assumptions on selectivity ogives had little impact on estimates of B_0, current stock size (B_{2003}) and projected stock size in 2008. No information is available that would allow determination of which parameterisation better describes the selectivity functions.

Inclusion of the *Amaltal Explorer* biomass and age data resulted in similar estimates of current stock status, and appeared to have a greater impact on the sub-Antarctic stock than the Chatham Rise stock estimates.

Two sensitivity runs used joint parameter estimation over both stocks. These were when natural mortality, *M*, was estimated, and when a fishing selectivity ogive for males and females was fitted to both stocks simultaneously.

The estimated (median) natural mortality rates for male and female hake were 0.21 y^{-1} (95% credible intervals 0.18–0.24) and 0.23 y^{-1} (95% credible intervals 0.19–0.26) respectively (see Figure 29). These values are higher than those estimated by Dunn et al. (2000) of 0.20 y^{-1} and 0.18 y^{-1} respectively. Posterior distributions of the difference between the male and female rates (i.e., male less female) had median -0.02 (95% credible intervals -0.03–0.00), suggesting, under the model structural assumptions, that female natural mortality rates were higher than those for males. This is contrary to expectations, and it is unlikely that the model has sufficient information to be able to distinguish between research and fishing selectivity estimates, and estimates of *M*.

Estimates of stock size (B_0) and stock status (B_{2003}) when *M* was estimated did not show significant differences from the base case model, although model estimates of *M* were higher than had been assumed for the base case, and, consequently, a higher estimate of B_0 and B_{2003} was obtained.

Estimates when data from *Amaltal Explorer* research surveys were included had little impact on results for the Chatham Rise stock, but did, however, result in substantial reductions in the estimates of B_0 and current biomass for the sub-Antarctic stock. The validity of including *Amaltal Explorer* data is unknown, and these sensitivity runs require additional investigative work. Estimated posterior distributions on the ratio of the catchability coefficients were either equal to the prior (for 3-degree polynomial selectivities), or had a much greater variance than the prior (for length based selectivities) (see Figure 30).

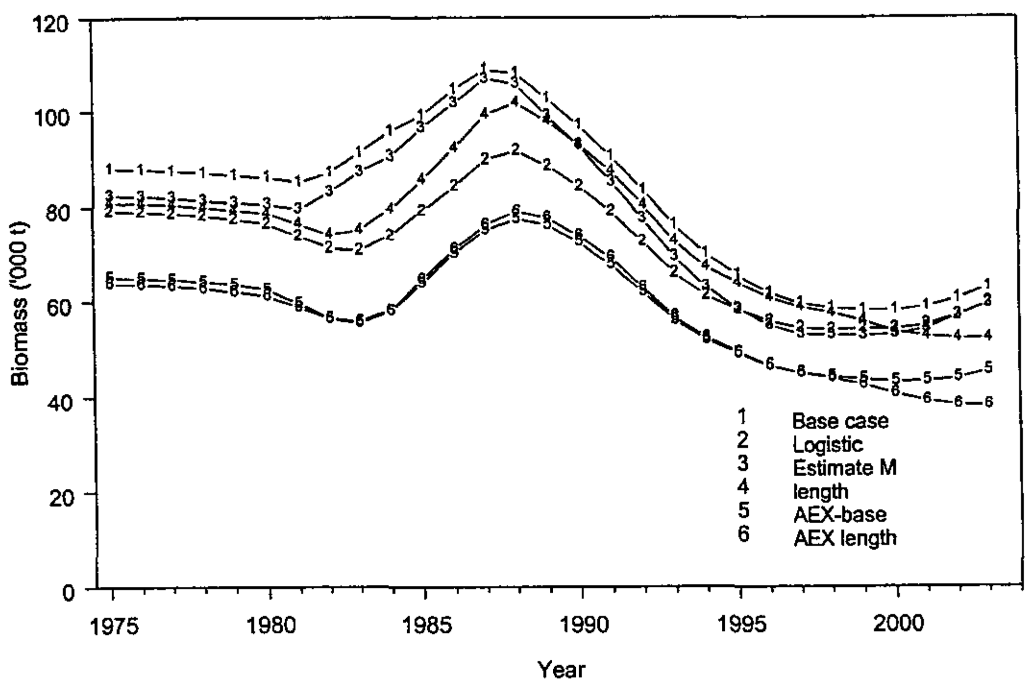

Figure 27: Estimated spawning stock biomass median of the posterior distribution for the base and sensitivity cases for the sub-Antarctic stock.

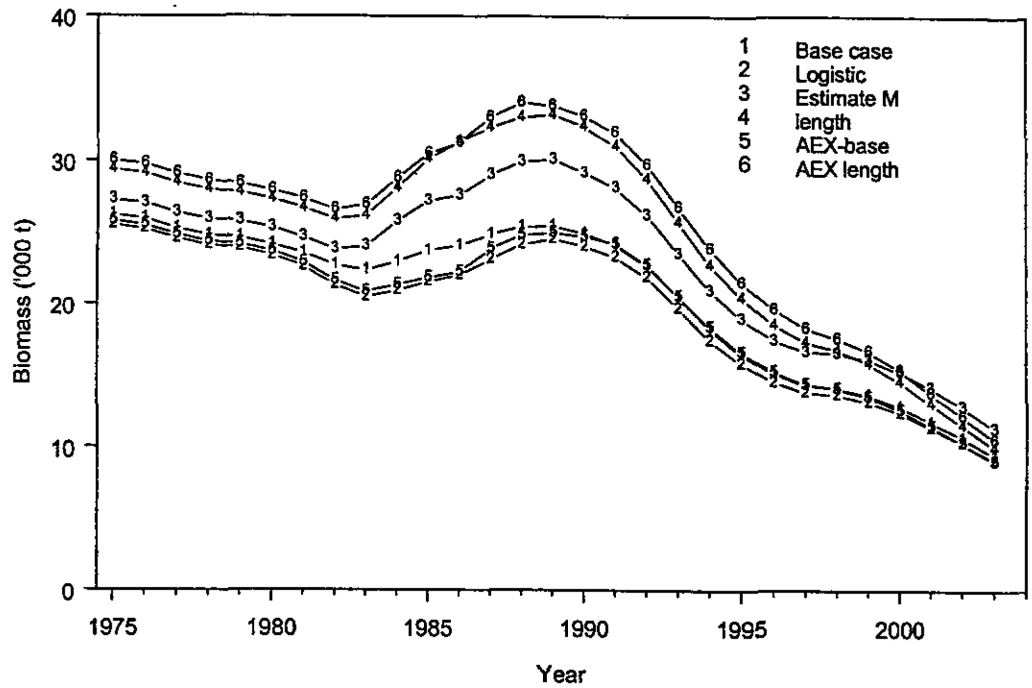

Figure 28: Estimated spawning stock biomass median of the posterior distribution for the base and sensitivity cases for the Chatham Rise stock.

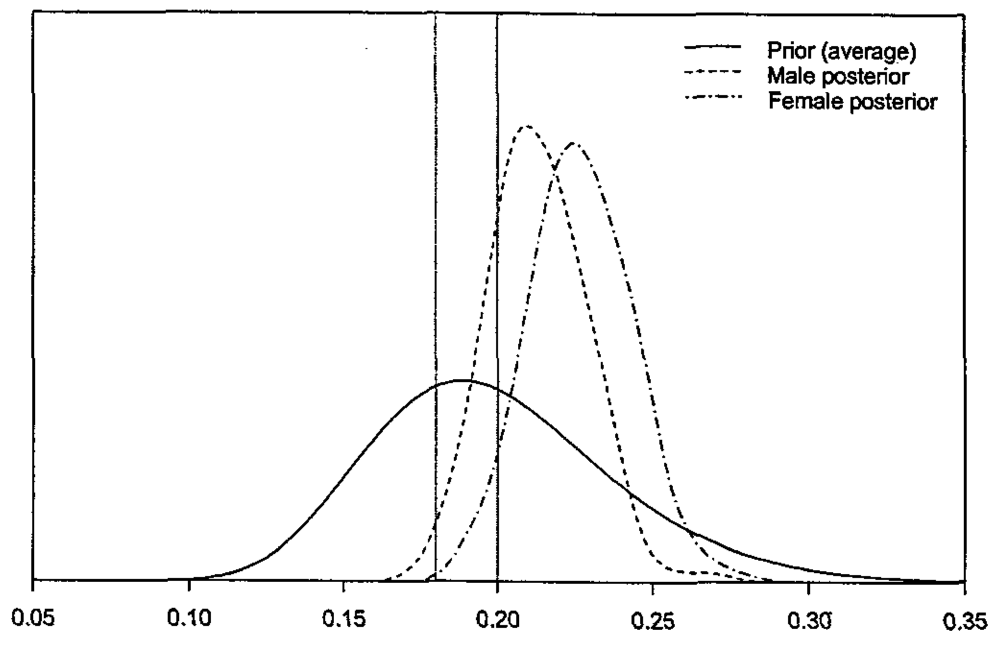

Figure 29: Estimated posterior distributions for the "estimate *M*" case for male and female natural mortality rates and the natural mortality prior (average of male and female *M*) for the sub-Antarctic and Chatham Rise stocks combined.

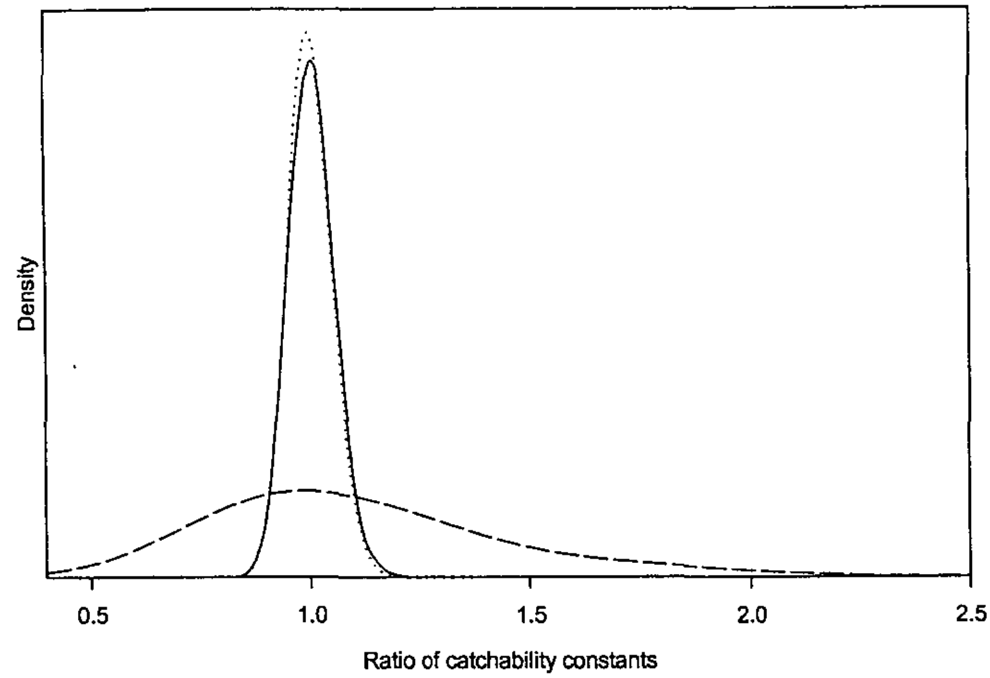

Figure 30: Estimated posterior distributions for the ratio of catchability constants for the AEX-logistic case (solid line) and the AEX-length case (dashed line), and the prior (dotted line).

5.4 Estimates of sustainable yields

Estimates of sustainable yields were carried out on the base and sensitivity cases for the Chatham Rise stock only. (Yields were not estimated for the sub-Antarctic stock as that model may not be an adequate representation of the current status.) Yield estimates were based on the 1000 samples from the Bayesian posterior for each stock, with yield estimates based on stochastic simulations run over 100 years. The method used to estimate MCY was MCY = ρB_0, where ρ is determined for each stock using the simulation method described by Francis (1992), and is such that the projected biomass is below 20% B_0 exactly 10% of the time. The simulation method of Francis (1992) was also used to estimate determine MAY and CAY with the same definition of risk. The estimates of B_{MCY}, MCY, B_{MAY}, MAY, and CAY are given in Table 18.

Table 18: Yield estimates (MCY, MAY, and CAY) and associated parameters for the Chatham Rise stock.

Model run	B_{MCY} (t)	MCY (t)	B_{MAY} (t)	MAY (t)	CAY (t)
Base case	12 157	1 693	7 475	2 096	1 817
Logistic	12 033	1 610	7 446	1 993	1 697
Estimate *M*	14 232	1 957	8 226	2 696	2 440
Length	14 848	1 693	8 651	2 287	1 857
AEX-logistic	12 268	1 603	7 479	2 009	1 686
AEX-length	14 941	1 751	8 765	2 342	1 935

6. DISCUSSION

The model estimates of the state of the sub-Antarctic stock suggest that there has been a small decline in the stock status since the early 1990s. However, biomass surveys were inconclusive with respect to changes in stock status. Model fits to the most recent sub-Antarctic research surveys were poor and, except when the *Amaltal Explorer* data were included, were unable to mirror the recent observed decline in 2001 and 2002. In general, the lack of contrast in abundance indices collected since 1991 suggests that, although the status of the sub-Antarctic stock is probably similar to that in the early 1990s, the absolute level of current biomass is difficult to determine. The most pessimistic sensitivity run (AEX-length) suggested that current biomass was about 60% B_0 (95% credible intervals 49–71%), and that continued catches at either the TACC or current levels were unlikely to result in a decline in stock size.

In contrast, information about the stock status of hake on the Chatham Rise appears reasonably strong. Biomass estimates from the Chatham Rise research series suggests strong evidence of a uniform decline in biomass, with biomass in 2003 at about 40% the level of that in the early 1990s. Model estimates suggest that recent relative year class strengths are weak, and that current catch levels will continue to reduce the size of the Chatham Rise stock in the immediate future. Sensitivity analyses gave similar results.

Projections indicated that the rate of decline will continue, and that the risk of reducing the stock below 20% B_0 is about 47–64% in 2005–06 if catches were at levels of the current TACC, rising to 90–96% in 2006–07. At current catch levels the risk is lower — about 9–15% in 2004–05 if catches were at levels of the current TACC, rising to 31–44% in 2006–07.

Biomass estimates from the previous assessment are reasonably consistent with, although more optimistic than, the results from this assessment. That assessment suggested that B_0 on the Chatham Rise was about 37 000 t (ranging from 28 000 to 64 000 t) (Dunn 2003b) with declining recruitment, and suggested that stock status would continue to decline to about 30% B_0 (17–52%) by 2007.

The estimates of stock size and projected stock status, for both stocks, rely on the estimated shape of the selectivity ogives. Both stock models suggest that maximum selectivity (for both research and fishing selectivities) appears to occur at ages about 12–15. These ages are higher than expected given the age at maturity, growth rates, and the maximum age of hake. Length-based ogives suggest a pattern that is more consistent with that expected by the age at maturity, growth rates, and the maximum age of hake. However, sensitivity analyses with alternative selectivity patterns suggest that the conclusions of current and future stock status for both stocks are reasonably robust to alternative selectivity parameterisations.

Estimates of research survey catchability constants (*q*s) appear low for the sub-Antarctic stock — although no information is available that would allow these estimates to be verified. The low estimated catchability constants are of some concern, as higher values for these constants result in lower biomass estimates. However, MPD estimates with alternative assumptions of the research surveys catchability coefficients suggest that estimates of current biomass are unlikely to be low. MPD estimates of current biomass remained similar as a percentage of B_0 between the sensitivity runs for the catchability coefficients (e.g., B_{2003} was about 63 000 t or 75% B_0 when $q = 0.1$; and 40 000 t or 73% B_0 when $q = 0.3$). Additional biomass and age data collected during the 2003 sub-Antarctic research survey may be of assistance in future model runs. In particular, the recent decline in abundance observed by the 2001 and 2002 November–December sub-Antarctic survey may be better determined with additional data.

Estimates of the relative catchability constant (q) for the Chatham Rise research survey were closer to the range of values assumed in the prior and appeared more reasonable.

In both the Chatham Rise and sub-Antarctic models, poor fits to the observer proportions-at-age suggest that better estimates of commercial catch-at-age may be beneficial. Neither model was able to adequately explain the commercial proportions-at-age data without assuming relatively high variability. In addition, while there is evidence that strong and weak year classes track between research survey observations of proportions-at-age, there is little evidence that such patterns can be observed in the commercial proportions-at-age data. Annual changes in selectivity are possible in the hake fishery, especially as hake are taken predominantly as a bycatch species. It is possible that the lack of observed pattern in the observer proportions-at-age may reflect this. Annual changes in selectivity have not been modelled here, as the data are probably not adequate to allow sensible estimation of additional selectivity parameters.

Estimates of recruitment on the Chatham Rise suggest strong evidence of collapse in recruitment in recent years. There is some suggestion in the research survey proportions-at-age data that the relative numbers of younger fish have declined, but there is stronger evidence from the commercial catch proportions-at-age data. This continues the trend noted in previous assessments (Dunn 2003b).

For both models, the model structural assumptions are likely to lead to the Bayesian posteriors of current stock status under-estimating the true level of uncertainty. The projected stock status relies on adequate estimation of recent recruitment. With small sample size age data from research surveys on the sub-Antarctic and inconclusive commercial catch proportions-at-age data, the projections of future stock status are likely to underestimate the true level of uncertainty.

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Appendix A: Summaries of the proportions-at-age data from research surveys and trawl fishery observer sampling in the sub-Antarctic, Chatham Rise, and west coast South Island fisheries

Table A1: Numbers of measured and aged fish by data source for male and female hake, and the number of sampled tows and estimated mean weighted c.v. (%) by age for the sub-Antarctic.

	Males		Females			Mean c.v.
Source	Measured	Aged	Measured	Aged	Tows	
AEX8902	45	43	76	66	34	52.7
TAN9105	337	117	332	217	61	65.1
TAN9204	60	58	113	107	48	46.8
TAN9209	76	68	141	113	44	43.8
TAN9211	14	46	133	168	48	48.6
TAN9304	36	36	124	122	54	49.5
TAN9310	57	93	181	182	59	47.2
TAN9605	32	86	93	137	45	61.9
TAN9805	49	94	146	189	31	52.0
TAN0012	348	239	392	352	56	37.3
TAN0118	219	212	351	349	44	35.6
TAN0219	336	191	497	377	41	36.1
Commercial catch 1998–99	408	190	969	406	189	24.4
Commercial catch 1999–00	3 112	250	2 868	389	415	23.0
Commercial catch 2000–01	568	183	2 227	392	353	29.7
Commercial catch 2001–02	834	140	1221	427	189	29.1

Table A2: Numbers of measured and aged fish by data source for male and female hake, and the number of sampled tows and estimated mean weighted c.v. (%) by age for the Chatham Rise.

	Males		Females			Mean c.v.
Source	Measured	Aged	Measured	Aged	Tows	
AEX8903	220	154	212	179	63	39.5
TAN9106	322	233	305	230	122	30.0
TAN9212	243	200	275	225	121	32.7
TAN9401	293	181	355	217	123	33.1
TAN9501	201	170	229	191	87	38.7
TAN9601	149	113	200	165	56	36.4
TAN9701	149	145	159	149	77	36.1
TAN9801	137	135	142	139	55	39.0
TAN9901	94	103	142	157	62	44.1
TAN0001	177	177	178	177	72	35.9
TAN0101	104	112	148	150	66	37.3
TAN0201	104	177	121	172	61	36.4
TAN0301	33	34	69	71	46	61.4
Commercial catch 1997–98	3 512	264	3 442	258	543	17.9
Commercial catch 1998–99	1 013	190	1 698	285	297	23.1
Commercial catch 1999–00	1 157	269	1 124	323	314	19.2
Commercial catch 2000–01	1 893	205	1 576	276	363	22.0
Commercial catch 2001–02	522	278	481	247	119	21.6

Table A3: Numbers of measured and aged fish by data source for male and female hake, and the number of sampled tows and estimated mean weighted c.v. (%) by age for the west coast South Island.

	Males		Females			
Source	Measured	Aged	Measured	Aged	Tows	Mean c.v.
WES7904	2 331	289	1 865	206	30	23.2
Commercial catch 1989–90	609	210	605	261	69	28.2
Commercial catch 1990–91	2 339	286	1 705	358	168	18.3
Commercial catch 1991–92	2 627	196	1 237	261	147	24.4
Commercial catch 1992–93	2 640	188	1 299	163	125	28.8
Commercial catch 1993–94	1 632	151	1 728	272	229	28.7
Commercial catch 1994–95	2 549	271	2 814	342	171	26.6
Commercial catch 1995–96	2 876	287	1 776	326	209	24.8
Commercial catch 1996–97	3 362	262	1 787	198	284	20.8
Commercial catch 1997–98	2 375	257	1 539	253	268	34.9
Commercial catch 1998–99	4 230	270	3 800	240	345	19.4
Commercial catch 1999–00	2 964	258	2 573	269	397	26.8
Commercial catch 2000–01	1 612	176	1 931	280	314	36.3
Commercial catch 2001–02	2 355	93	2 651	385	493	36.5

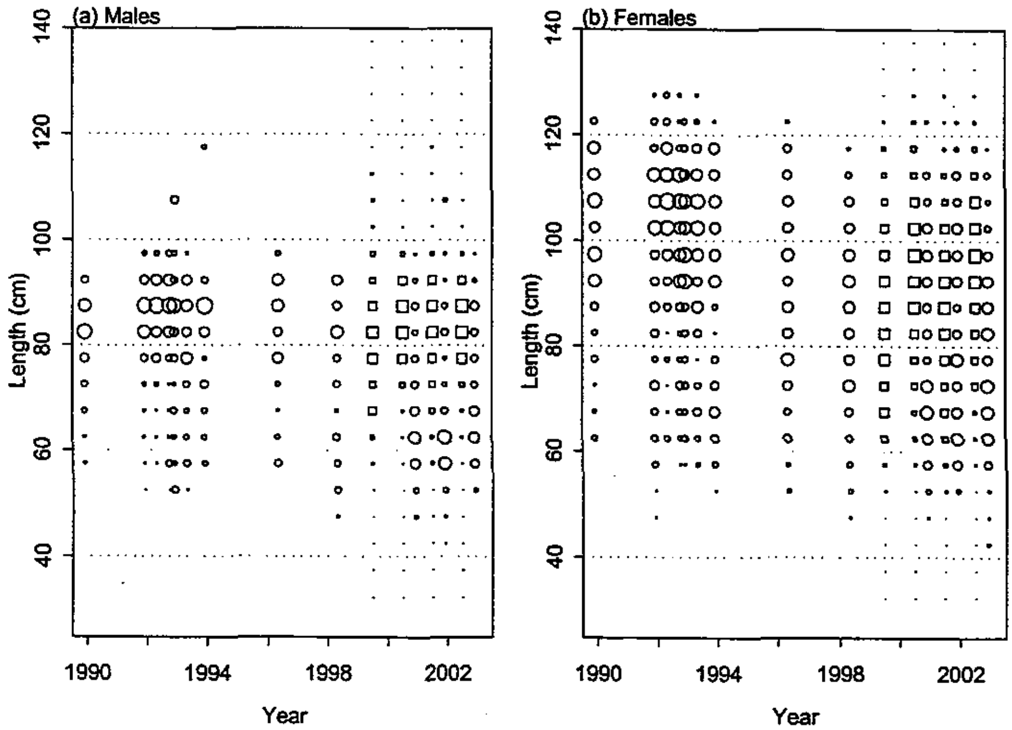

Figure A1: Length frequencies by year (symbol area proportional to the proportions-at-length within sampling event) in the sub-Antarctic for (a) research surveys (circles) and (b) commercial catch-at-age data (squares). Zero values are represented by a dash.

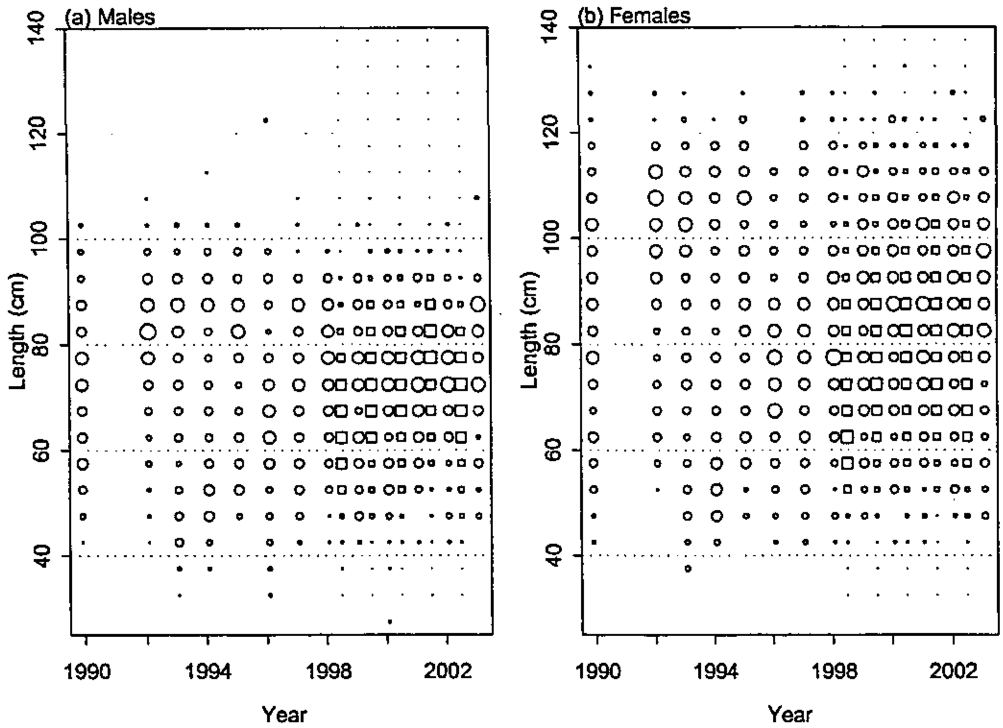

Figure A2: Length frequencies by year (symbol area proportional to the proportions-at-length within sampling event) on the Chatham Rise for (a) research surveys (circles) and (b) commercial catch-at-age data (squares). Zero values are represented by a dash.

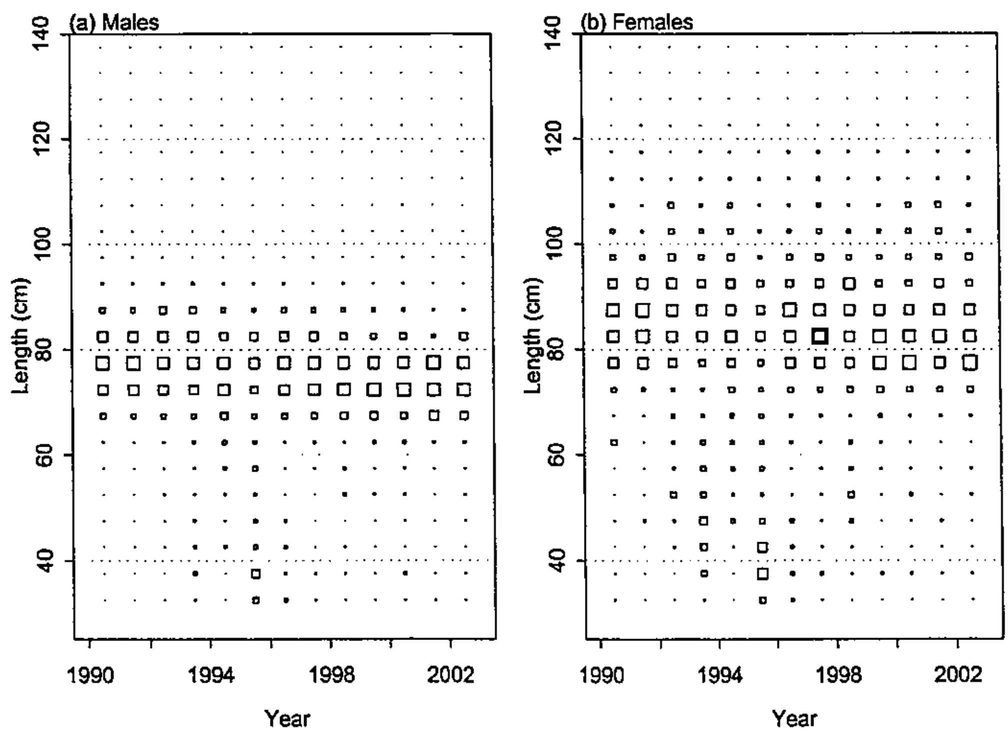

Figure A3: Length frequencies by year (symbol area proportional to the proportions-at-length within sampling event) in the west coast South Island for commercial catch-at-age data (squares). Zero values are represented by a dash.

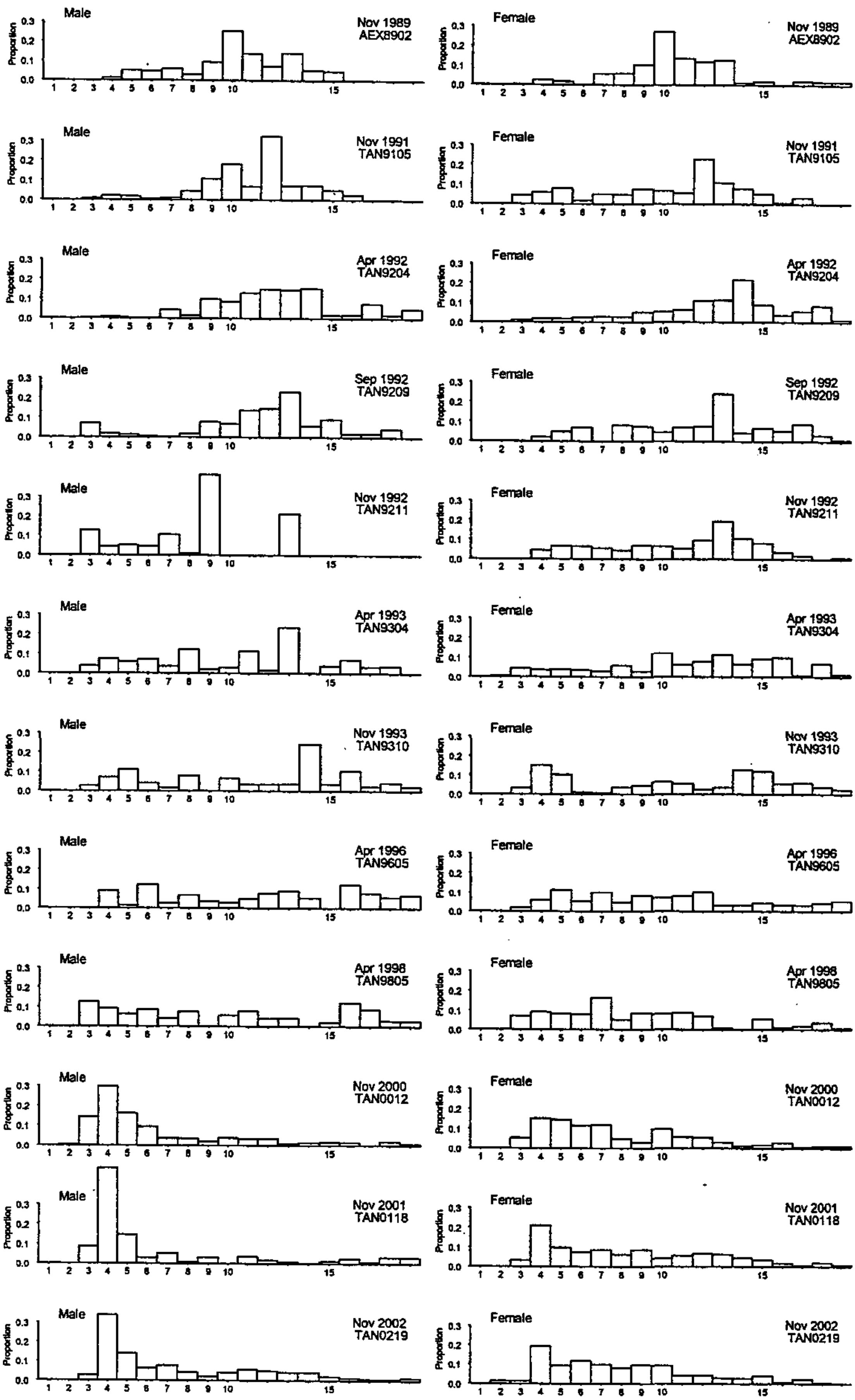

Figure A4: Age frequencies of hake (ages 1 to 19) from research surveys in the sub-Antarctic, 1988–89 to 2001–02.

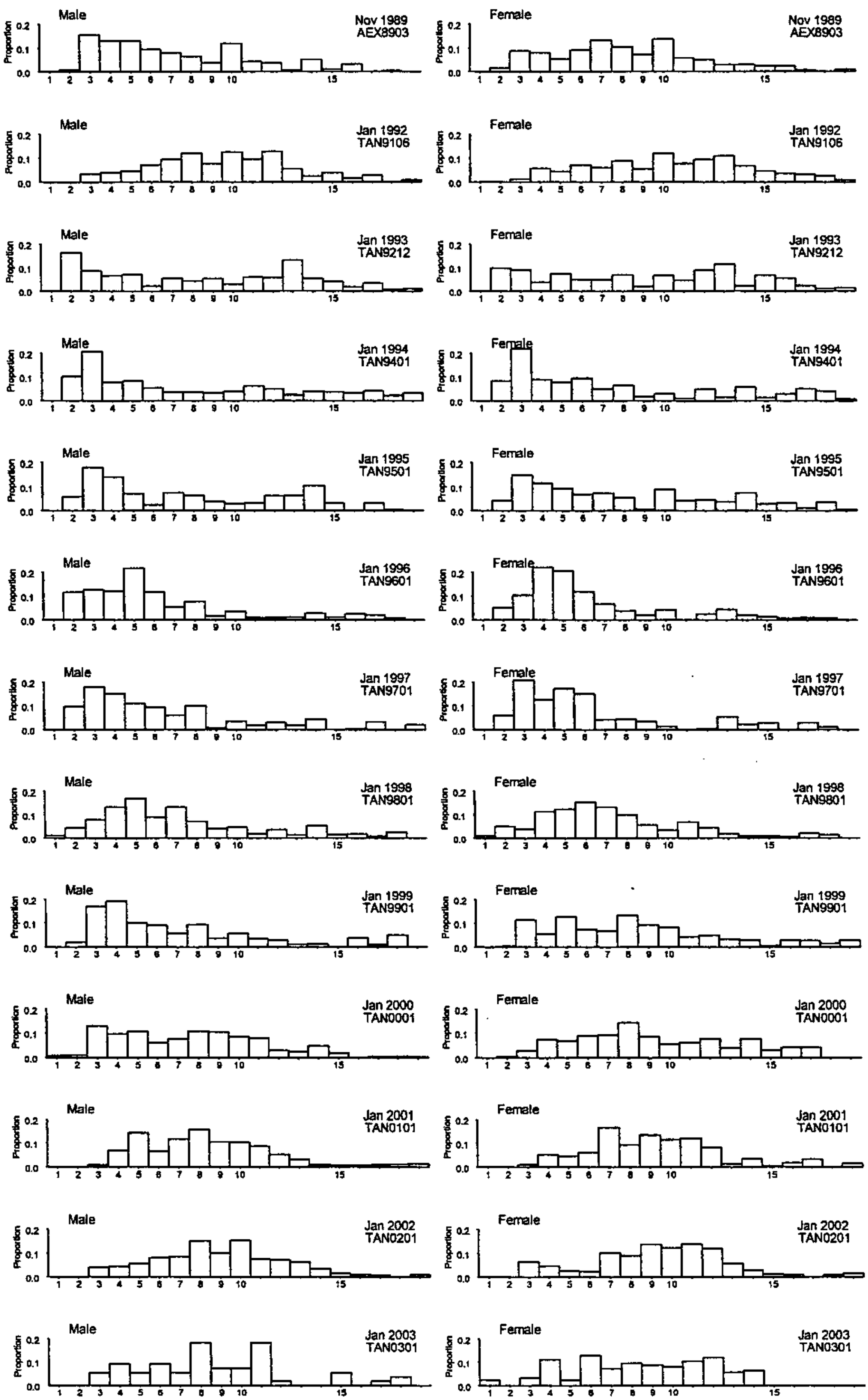

Figure A5: Age frequencies of hake (ages 1 to 19) from research surveys in the Chatham Rise, 1989–90 to 2002–03.

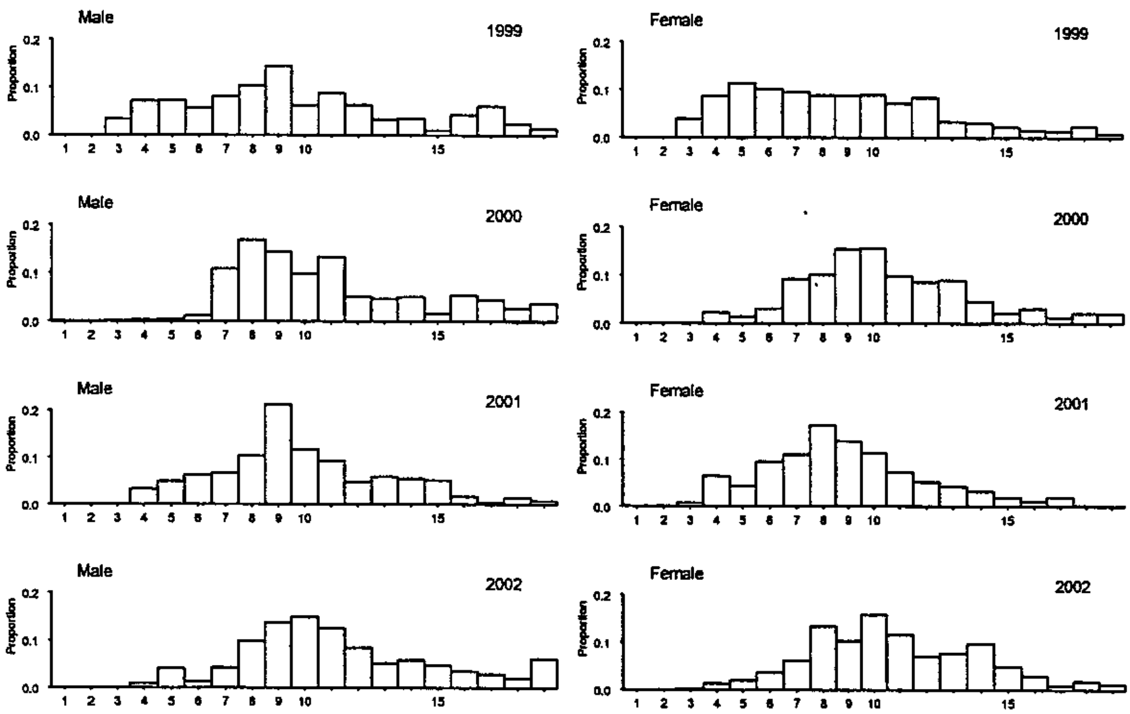

Figure A6: Age frequencies of hake (ages 1 to 19) from commercial catch-at-age data in the sub-Antarctic trawl fishery, 1998–99 to 2001–02.

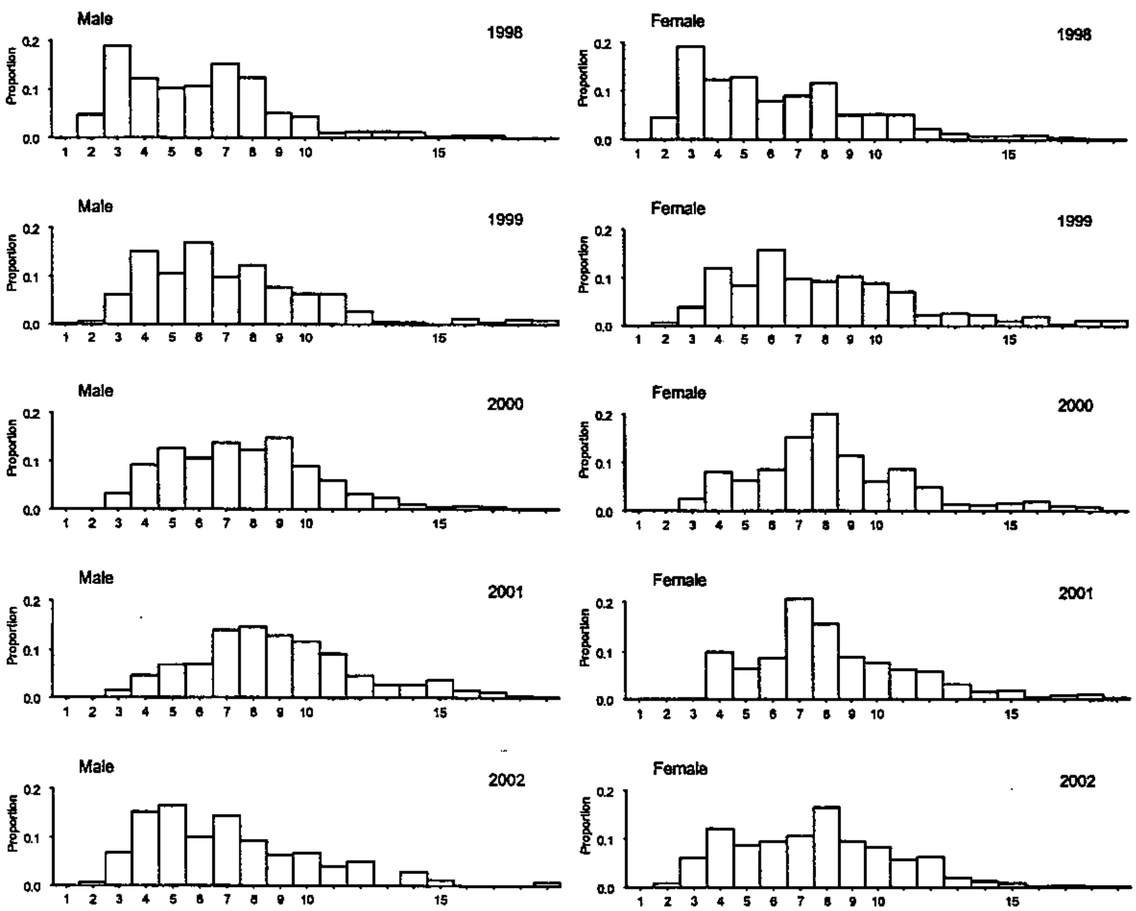

Figure A7: Age frequencies of hake (ages 1 to 19) from commercial catch-at-age data in the Chatham Rise trawl fishery, 1997–98 to 2001–02.

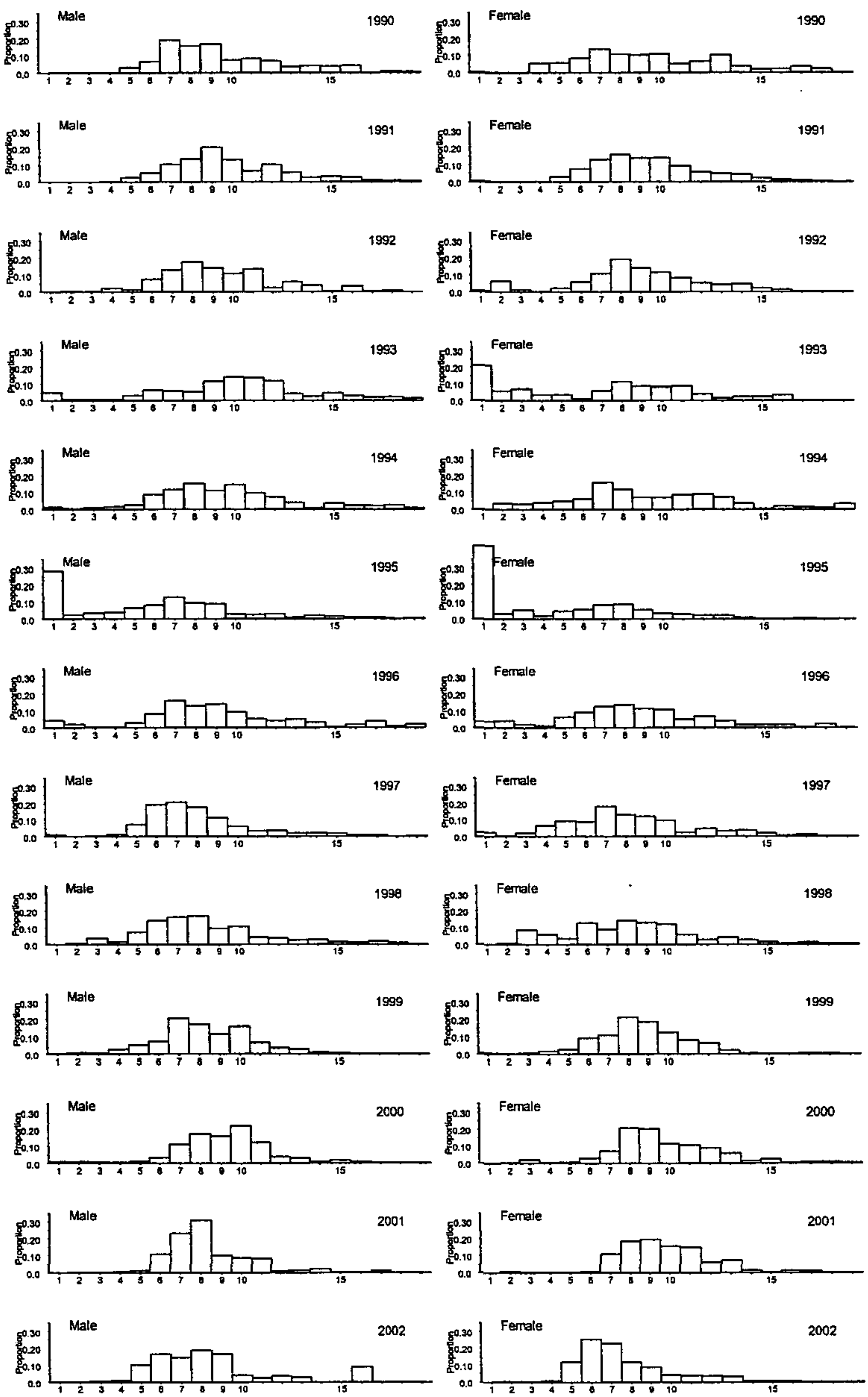

Figure A8: Age frequencies of hake (ages 1 to 19) from commercial catch-at-age data in the west coast South Island trawl fishery, 1989–90 to 2001–02.

Appendix B: Research survey biomass indices for hake in HAK 1, 4, & 7

Table B1: Biomass indices (t) and coefficients of variation (c.v.) for hake from research 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 1991	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]	–	–	

Table B1: (Continued...)

Vessel	Date	Trip code	Depth		Biomass	c.v.	Reference
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	–	–	
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)

1. Surveys by the *Wesermünde* were carried out on the Sub-Antarctic in 1979, but biomass estimates for hake were not calculated.
2. The depth range, biomass and c.v. reported by 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.

Table B2: Biomass indices (t) and coefficients of variation (c.v.) for hake from research 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	890	0.16	(Livingston et al. 2004)

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

Table B3: Biomass indices (t) and coefficients of variation (c.v.) for hake from research surveys of the west coast South Island. (These estimates assume that the areal availability, vertical availability, and vulnerability are equal to one.)

Vessel	Date	Trip code	Depth	Biomass	c.v.	Reference
Shinkai Maru	1976	–	–	–	–	(Details from Patchell 1981)
Wesermünde	1979	–	– [1]	–	–	(Kerstan & Sahrhage 1980)
Giljanes	1990	GIL9001	300–900	1 350	0.17	(Francis & Fisher 1979)

1. A survey by the *Wesermünde* was carried out on the west coast South Island in 1979, but biomass estimates for hake were not calculated.

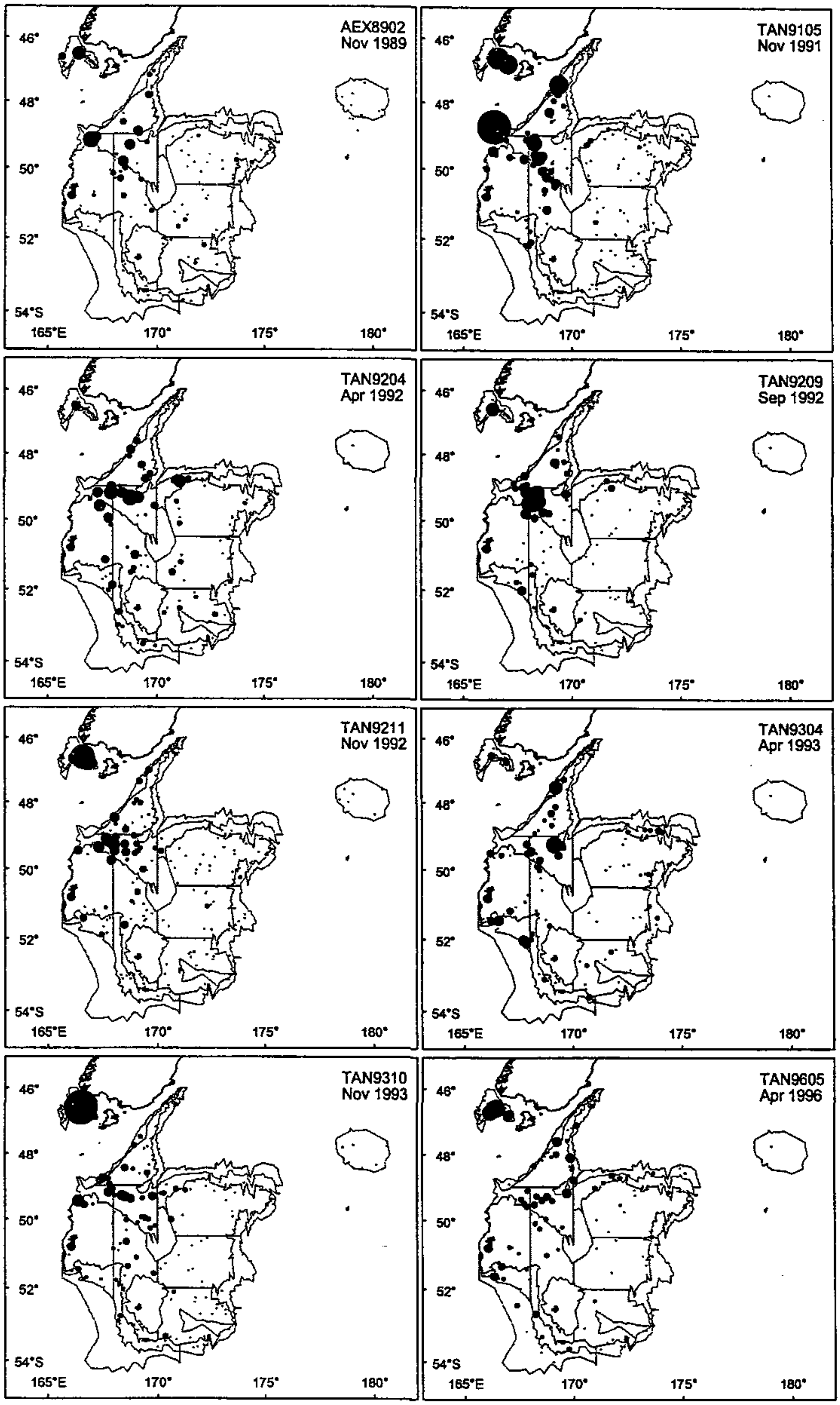

Figure B1: Density of hake by location from the 1989–2002 sub-Antarctic research surveys. Tow density (kg/km^2) proportional to symbol area, zero values indicated in grey.

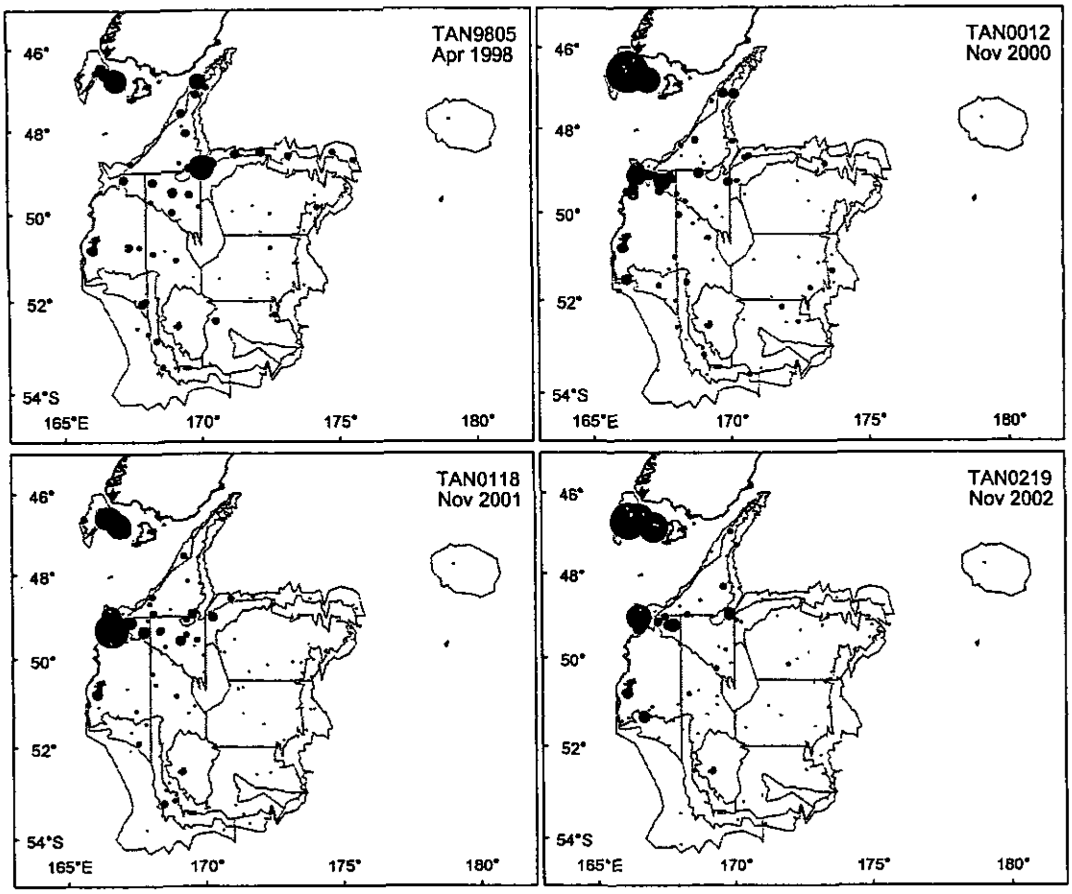

Figure B1: (Continued...) Density of hake by location from the 1989–2002 sub-Antarctic research surveys. Tow density (kg/km²) proportional to symbol area, zero values indicated in grey.

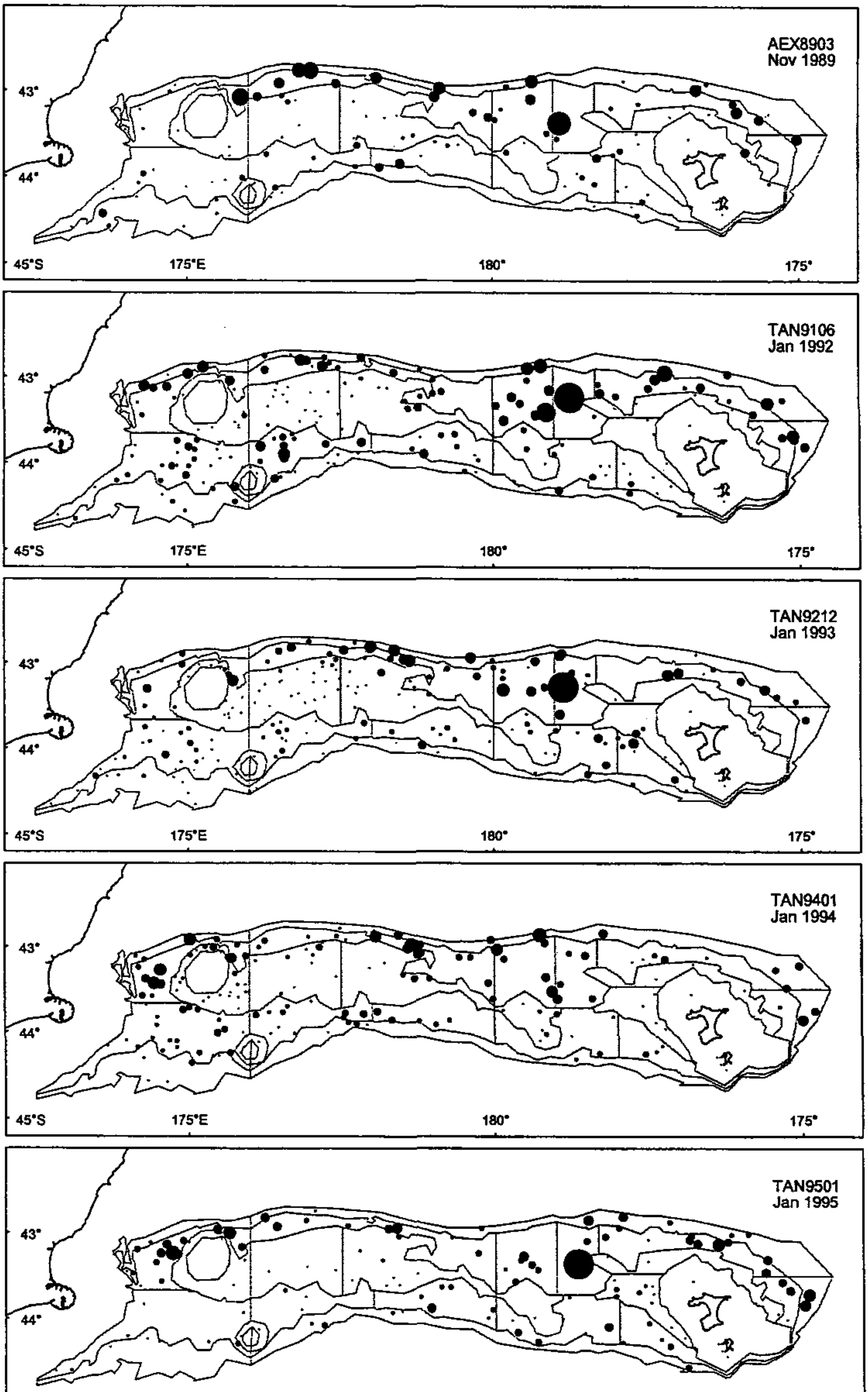

Figure B2: Density of hake by location from the 1989 to 2003 Chatham Rise research surveys. Tow density (kg/km²) proportional to symbol area, zero values indicated in grey.

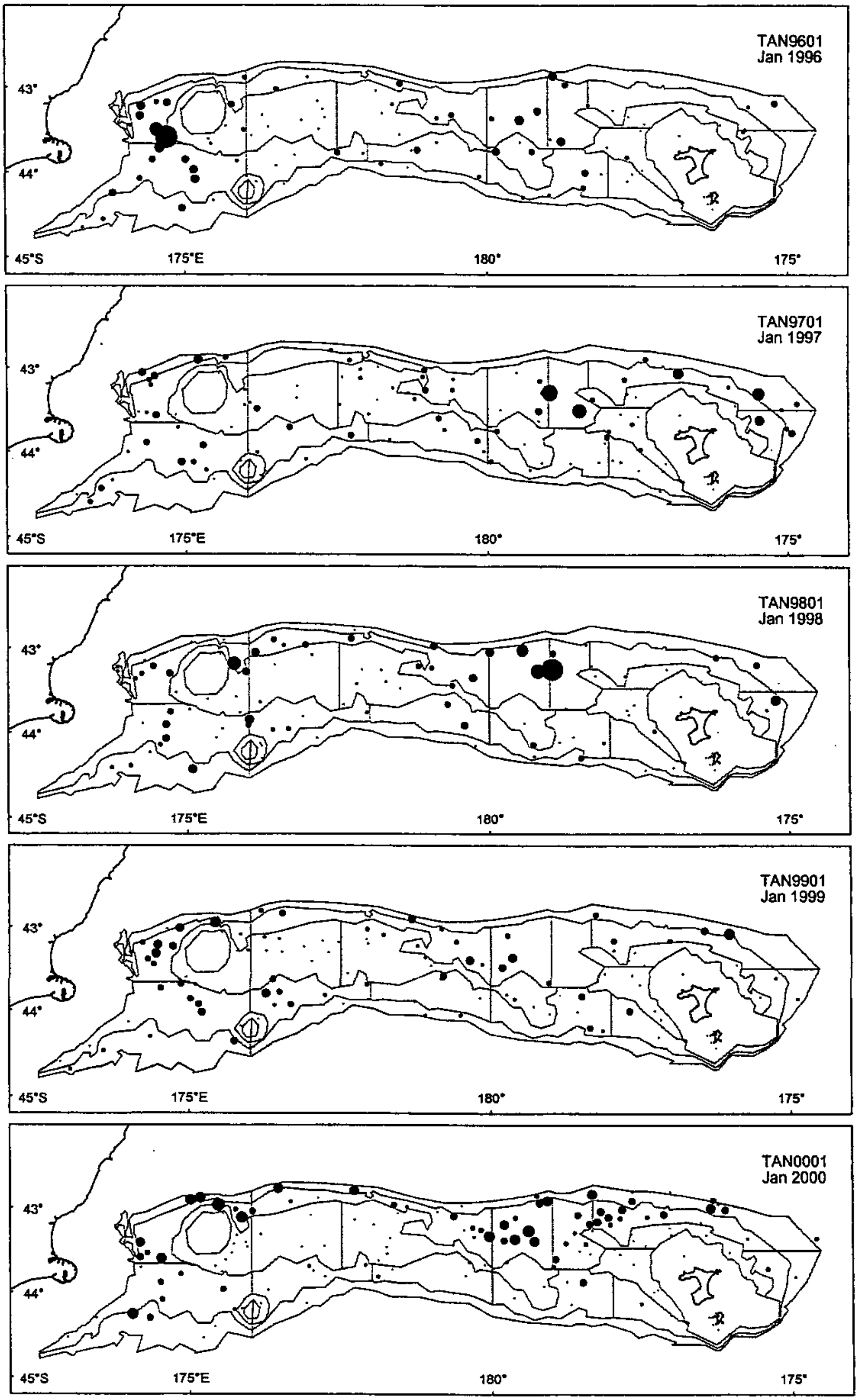

Figure B2: (Continued...) Density of hake by location from the 1989 to 2003 Chatham Rise research surveys. Tow density (kg/km^2) proportional to symbol area, zero values indicated in grey.

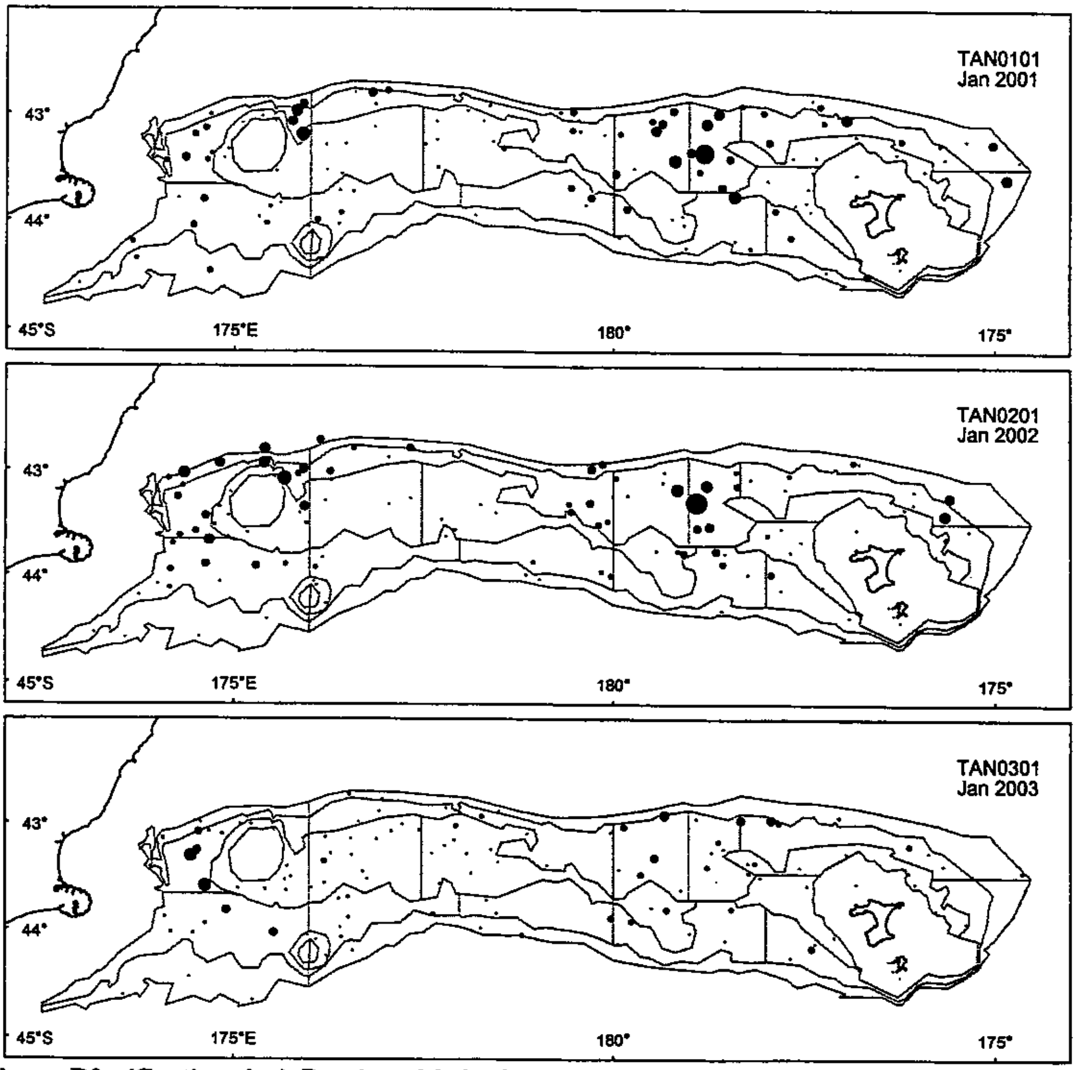

Figure B2: (Continued...) Density of hake by location from the 1989 to 2003 Chatham Rise research surveys. Tow density (kg/km^2) proportional to symbol area, zero values indicated in grey.

Appendix C: Summary MPD (base case) model fits

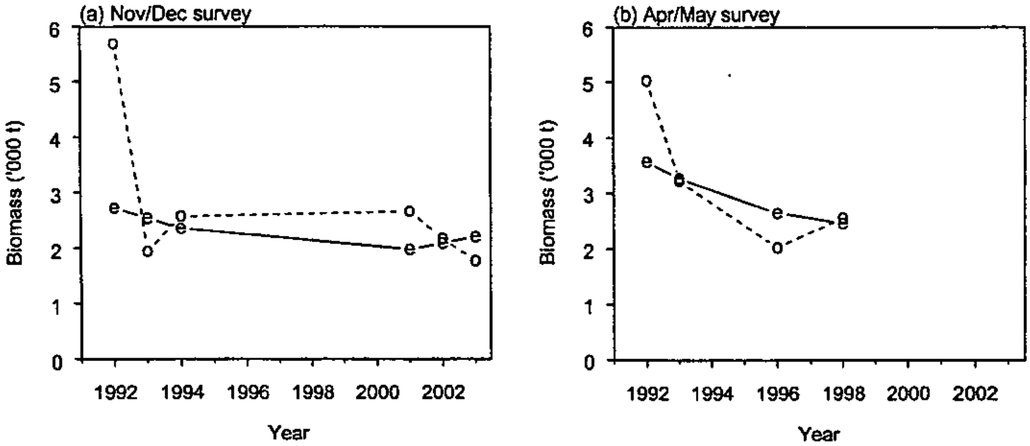

Figure C1: MPD (base case) fits to the (a) Nov–Dec research survey biomass index, and (b) Apr–May research survey biomass index, where 'o' indicated the observed value and 'e' indicated the fitted (expected) value.

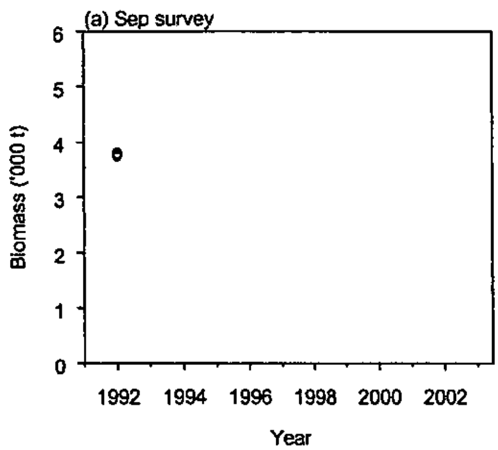

Figure C2: MPD (base case) fits to the (a) Sep research survey biomass index, where 'o' indicated the observed value and 'e' indicated the fitted (expected) value.

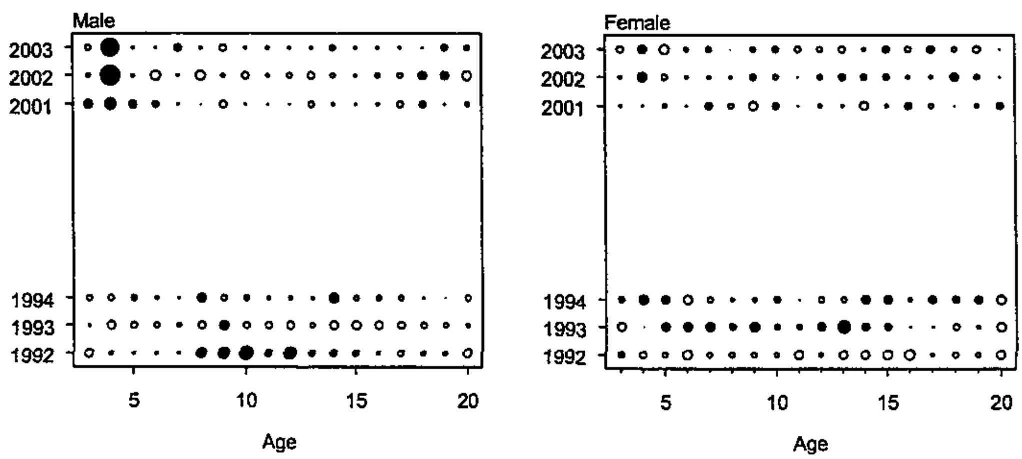

Figure C3: MPD (base case) residual values for the proportions-at-age data for the sub-Antarctic Nov–Dec research survey series. Symbol area is proportional to the absolute value of the residual, with white circles indicating positive residuals and black circles indicating negative residuals.

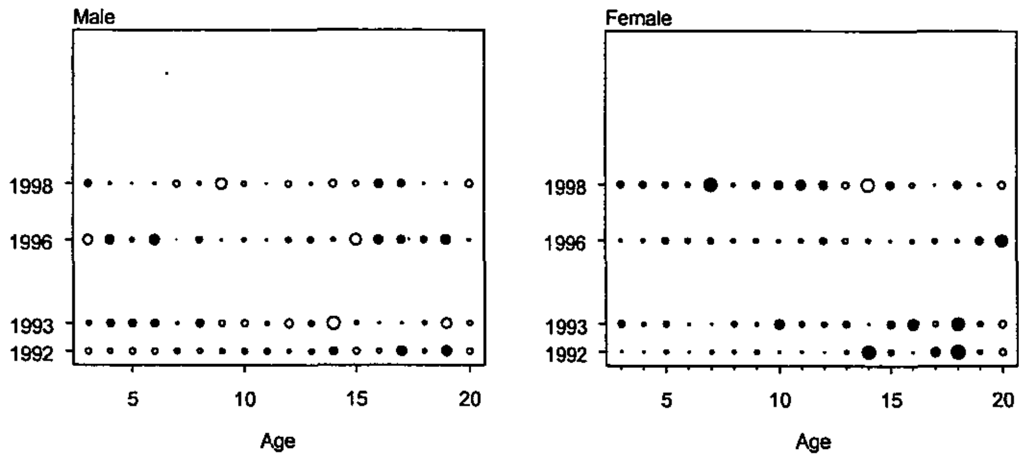

Figure C4: MPD (base case) residual values for the proportions-at-age data for the sub-Antarctic Apr–May research survey series. Symbol area is proportional to the absolute value of the residual, with white circles indicating positive residuals and black circles indicating negative residuals.

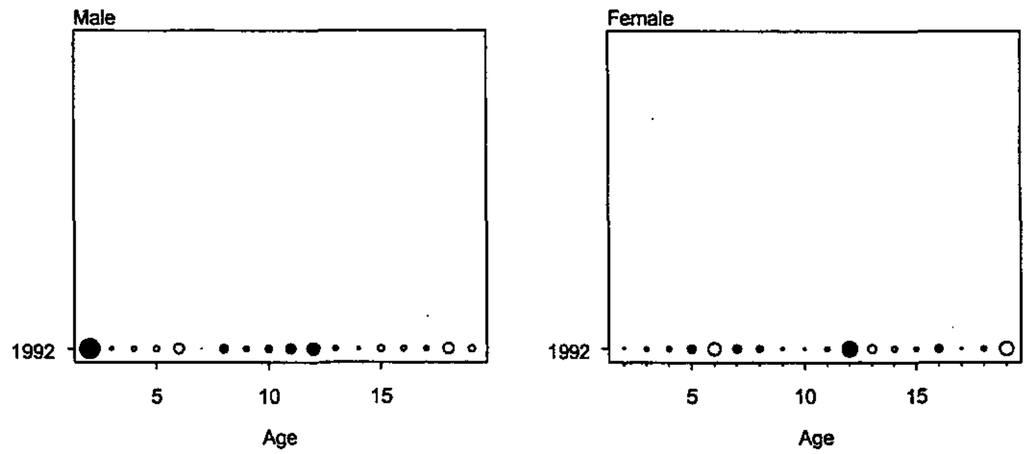

Figure C5: MPD (base case) residual values for the proportions-at-age data for the sub-Antarctic Sep research survey series. Symbol area is proportional to the absolute value of the residual, with white circles indicating positive residuals and black circles indicating negative residuals.

Figure C6: MPD (base case) residual values for the proportions-at-age data for the sub-Antarctic trawl fishery observer sampling series. Symbol area is proportional to the absolute value of the residual, with white circles indicating positive residuals and black circles indicating negative residuals.

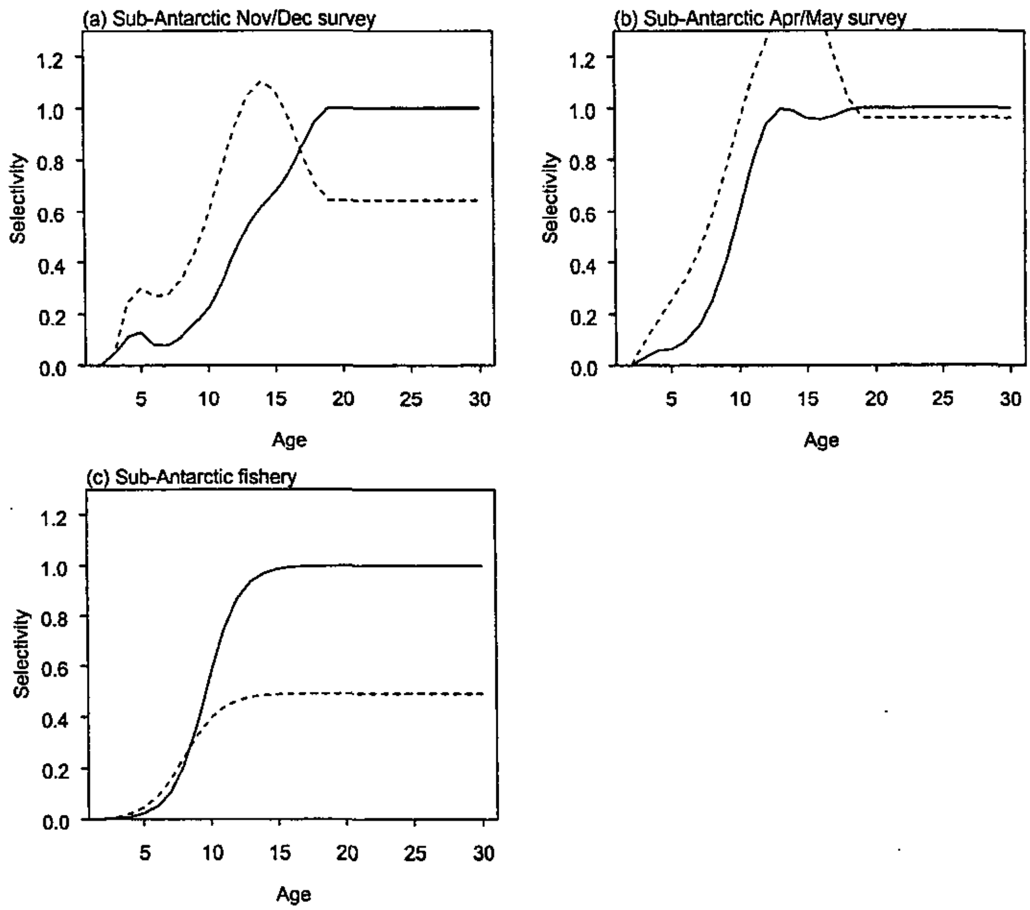

Figure C7: MPD (base case) estimated selectivities for the sub-Antarctic (a) Nov–Dec research survey proportions at age, (b) Apr–May research survey proportions at age, and (c) fishery proportions at age (solid lines for males and dashed lines for females).

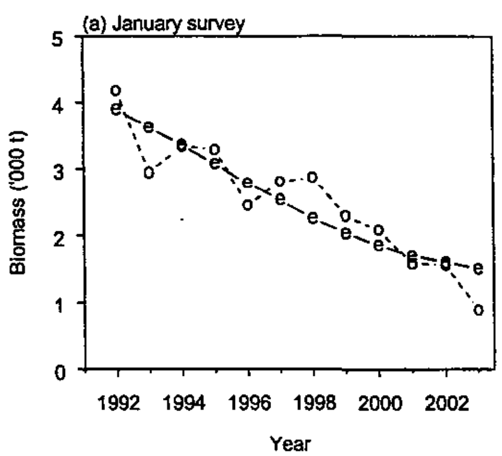

Figure C8: MPD (base case) fits to the January research survey biomass index where 'o' indicated the observed value and 'e' indicated the fitted (expected) value.

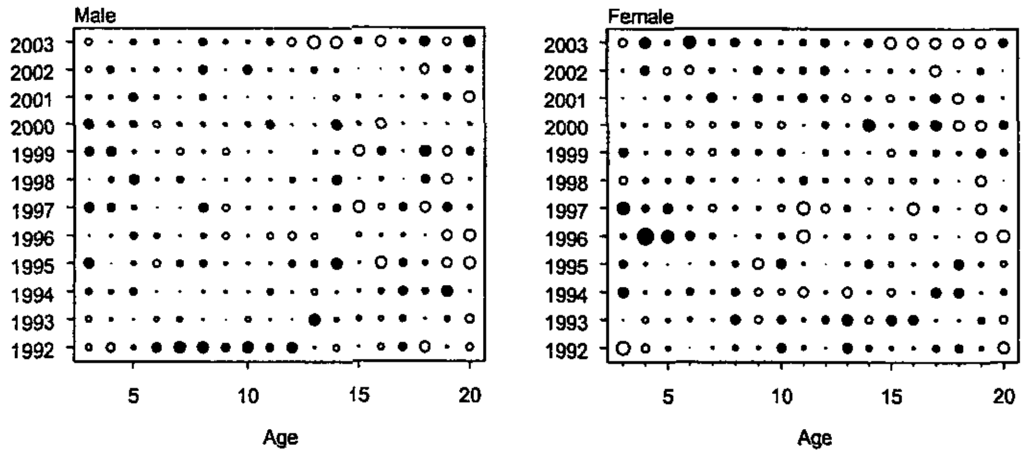

Figure C9: MPD (base case) residual values for the proportions-at-age data for the Chatham Rise January research survey series. Symbol area is proportional to the absolute value of the residual, with white circles indicating positive residuals and black circles indicating negative residuals.

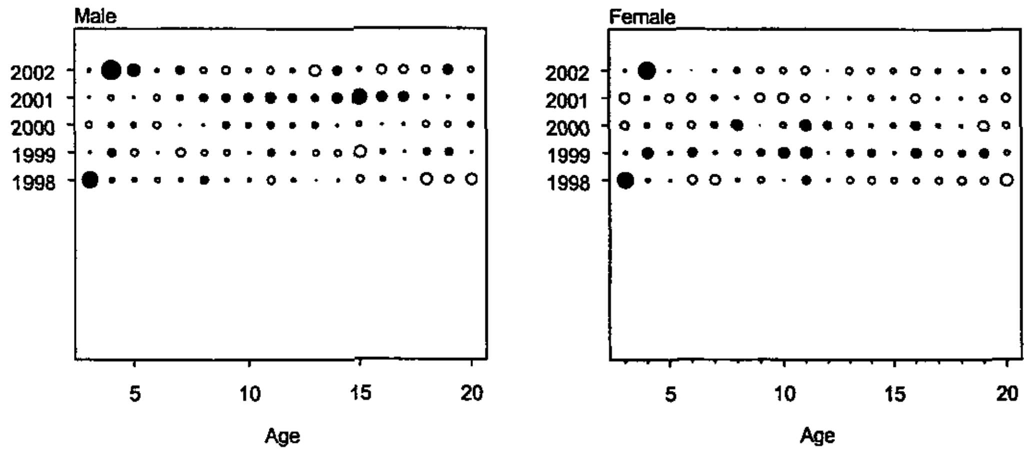

Figure C10: MPD (base case) residual values for the proportions-at-age data for the Chatham Rise trawl fishery observer sampling series. Symbol area is proportional to the absolute value of the residual, with white circles indicating positive residuals and black circles indicating negative residuals.

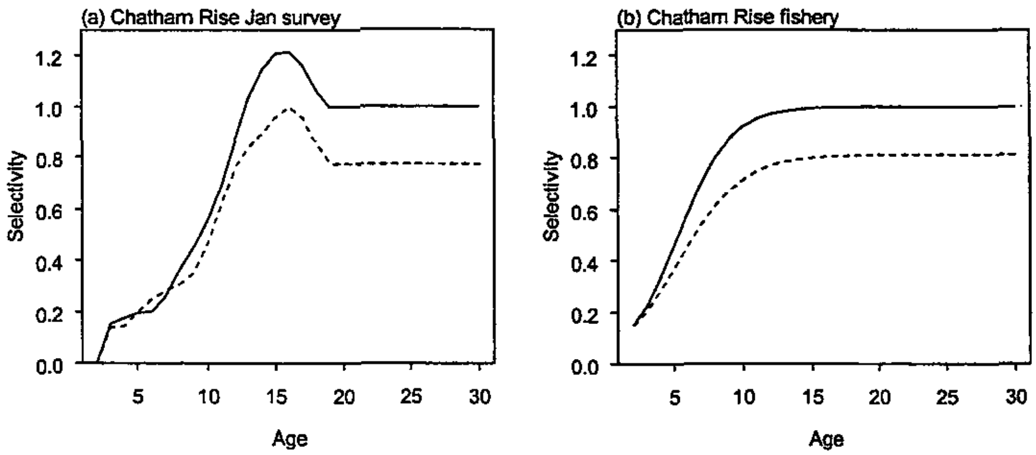

Figure C7: MPD (base case) estimated selectivities for the Chatham Rise (a) January research survey proportions at age, and (b) fishery proportions at age (solid lines for males and dashed lines for females).