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Descriptive analysis and stock assessment model inputs of hake (*Merluccius australis*) in the Sub-Antarctic (HAK 1) up to 2023–24

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PLAIN LANGUAGE SUMMARY

This report summarises the Sub-Antarctic hake (HAK 1) fishery with spatial structure of the stock, biological parameters, and standardised catch per unit effort (CPUE). The CPUE indices showed a similar trend to the Sub-Antarctic trawl surveys. In general, the CPUE indices had declined over the period of fishing but had levelled off in recent years as the total catch declined.

EXECUTIVE SUMMARY

Dunn, A.[1]; Mormede, S.[2]; Webber, D.N.[3] (2026). Descriptive analysis and stock assessment model inputs of hake (*Merluccius australis*) in the Sub-Antarctic (HAK 1) up to 2023–24.

***New Zealand Fisheries Assessment Report 2026/01.* 67 p.**

Hake (*Merluccius australis*) is an important commercially caught species found throughout the middle depths of the New Zealand Exclusive Economic Zone (EEZ) south of 40° S and caught mainly by deepwater demersal trawls. Hake are managed in three Fishstocks: (i) the Challenger Fisheries Management Area (FMA) (HAK 7), (ii) the Chatham Rise FMA (HAK 4), and (iii) the remainder of the EEZ comprising the Auckland, Central, Southeast (Coast), Southland, and Sub-Antarctic FMAs (HAK 1). Hake are assessed as three main biological stocks: the west coast South Island, Chatham Rise, and Sub-Antarctic.

This report provides a characterisation of the hake stock and fishery in the Sub-Antarctic, including a description of the fishery and updated catch-per-unit-effort (CPUE) indices up to the end of the 2023–24 fishing year.

The Sub-Antarctic fishery is concentrated off the south and east of the Stewart-Snares shelf. The Sub-Antarctic hake fishery has undergone significant changes since the early 2000s, with annual catches declining from approximately 3000 tonnes in 2003–04 to less than 1000 tonnes in recent years. The fishery has shifted from primarily hoki-targeted trawls to concentrated hake-targeted fishing on the Stewart-Snares shelf.

Updated biological parameters include revised length-weight relationships, von Bertalanffy growth models, and maturity ogives estimated from survey data. Spatial-temporal analyses identified distinct age-structured spatial patterns, with smaller, younger fish spatially separated from the main fishing grounds that catch larger, older fish.

Standardised catch-per-unit-effort (CPUE) indices were developed using generalised additive models applied to tow-by-tow data from core vessels. The combined delta-lognormal CPUE index showed general stability through 2010–11 followed by a declining trend in recent years, consistent with Sub-Antarctic trawl survey biomass indices. However, influence plots revealed significant changes in fishery dynamics around 2005–06, coinciding with changes in target species, vessel participation, and spatial concentration of effort.

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1. INTRODUCTION

Hake (*Merluccius australis*) is an important commercially caught species found throughout the middle depths of the New Zealand Exclusive Economic Zone (EEZ) south of 40° S, typically in depths of 250–800 m (Hurst et al. 2000). Around New Zealand, hake are caught mainly by deepwater demersal trawls, usually as bycatch in hoki (*Macruronus novaezelandiae*) target fisheries, and with some caught by direct targeting (Dunn et al. 2021a).

The current management of hake divides the fishery into three Fishstocks: (i) the Challenger Fisheries Management Area (FMA) (HAK 7), (ii) the Chatham Rise FMA (HAK 4), and (iii) the remainder of the EEZ comprising the Auckland, Central, Southeast (Coast), Southland, and Sub-Antarctic FMAs (HAK 1). An administrative Fishstock (with no recorded landings) is also defined for the Kermadec FMA (HAK 10) (Fisheries New Zealand 2024). There are likely to be three main biological stocks of hake. These are the west coast of the South Island (HAK 7), the Chatham Rise (HAK 4 and the northern regions in HAK 1), and the Sub-Antarctic (HAK 1) (Fisheries New Zealand 2024). The Quota Management Areas (QMA) for hake and stock boundaries are shown in Figure 1.

Previous analyses showed that the length frequencies of west coast hake were different to both the Chatham Rise and the Sub-Antarctic. The growth parameters were also different among the three areas (Horn 1997) and juvenile hake were found in all three areas (Hurst et al. 2000). Analysis of morphometric data from the 1990s (Colman, NIWA, unpublished data) showed little difference between hake on the Chatham Rise and those off the east coast of the North Island, but significant differences between Chatham Rise hake and those from the Sub-Antarctic, Puysegur, and off the west coast of the South Island. Hake in Puysegur were morphometrically similar to west coast South Island hake and may be different from the Sub-Antarctic hake. Hence, the stock affinity of hake from Puysegur was considered to be uncertain (Kienzle et al. 2019).

In HAK 1, reported landings peaked at almost 5000 t in 2004–05 and have since declined to about 1000 t in the most recent two years (Table 1, Figure 2); the Total Allowable Commercial Catch (TACC) for hake has remained at just over 3700 t since 2000–01. In the late 1990s and early 2000s, hake fishers misreported catches between QMAs, typically misreporting catches of hake from HAK 7 as catch from either HAK 1 or HAK 4. The reported catches of hake in each area were reviewed in 2002 and several suspect records identified. Dunn (2003a) provided revised estimates of the total landings by stock. Almost all the area misreporting was from HAK 7 (west coast South Island) to the Chatham Rise (HAK 4 and the part of HAK 1 on the Chatham Rise), with a small amount in the Sub-Antarctic area of HAK 1 (Dunn 2003a). Dunn (2003a) estimated that the level of hake over-reporting on the Chatham Rise (and hence under-reporting off the west coast South Island) was between 16 and 23% (700–1000 t annually) of landings between 1994–95 and 2000–01, mainly in June, July, and September. Levels of area misreporting prior to 1994–95 and between the west coast South Island and Sub-Antarctic were estimated as low (Dunn 2003a). There has been no evidence of similar area misreporting since 2001–02 (Ballara 2018). A revised catch history for hake, accounting for this misreporting, for each stock is given as Table 2.

Hake stocks have previously been assessed with stock assessments for at least one of the three stocks each year since 1991. Previous assessments of hake were in the 1991–92 (Colman et al. 1991), 1992–93 (Colman & Vignaux 1992), 1997–98 (Colman 1997), 1998–99 (Dunn 1998), 1999–2000 (Dunn et al. 2000), 2000–01 (Dunn 2001), 2002–03 (Dunn 2003b), 2003–04 (Dunn 2004), 2004–05 (Dunn et al. 2006), 2005–06 (Dunn 2006), 2006–07 (Horn & Dunn 2007), 2007–08 (Horn 2008), 2009–10 (Horn & Francis 2010), 2010–11 (Horn 2011), 2011–12 (Horn 2013a), 2012–13 (Horn 2013b), 2014–15 (Horn 2015), 2016–17 (Horn 2017), 2017–18 (Dunn 2019), 2018–19 (Kienzle et al. 2019), 2019–20 (Holmes 2021), 2020–21 fishing years (Dunn et al. 2021b), 2022–23 (Dunn et al. 2023a), and 2023–24 (Dunn 2025a). The most recent stock assessment for Sub-Antarctic hake was for the 2020–21 fishing year (Dunn et al. 2021b).

Commercial catch and effort data were first analysed to produce standardised catch-per-unit-effort (CPUE) indices for HAK 1 in 1998 (Kendrick 1998) and were updated, using the methodology of Gavaris (1980), by Vignaux (1994). Since then, CPUE abundance indices have been updated for hake using a similar methodology but have not often been used as a main abundance index in stock assessments. In 2012 and 2013, Ballara (2012, 2013) showed that the estimated tow-by-tow and daily summary CPUE indices had similar trends. More recently for the Sub-Antarctic, Dunn et al. (2021a) updated the descriptive analyses of hake and estimates CPUE abundance indices, including data up to the end of 2020–21.

Estimates of age frequencies from the commercial catch and from resource surveys were derived under annual Fisheries New Zealand ageing projects that are reported elsewhere (e.g., Horn & Sutton 2019, Saunders et al. 2021, Ballara et al. 2022, 2024, Ballara & Barnes 2024).

This report fulfils Specific Objective 1 of Project HAK2024-01. The overall Objective was “To carry out stock assessments of hake (*Merluccius australis*) in the Sub-Antarctic (HAK 1) including estimating stock biomass and stock status” and Specific Objective 1 was “To carry out a descriptive analysis of the commercial catch and effort data for hake in the Sub-Antarctic and update the standardised catch and effort analyses”. This report provides a descriptive summary of catch data since 1974–75, and catch and effort data since 1989–90, a summary of resource surveys, an update of biological parameters, and an update and revision of the analysis of the CPUE data for hake from the Sub-Antarctic stock for the fishing years 1990–91 (1991) to 2023–24 (2024).

Table 1: Reported landings (t) of hake by Fishstock from 1983–84 to 2023–24 and actual total allowable commercial catches (TACCs) (t) for 1986–87 to 2021–22. Fisheries Statistics Unit (FSU) data from 1984–1986; QMS data from 1986 to the present (Fisheries New Zealand 2024).

Fishstock	HAK 1		HAK 4		HAK 7		HAK 10			
FMA(s)	1, 2, 3, 5, 6, 8, 9		4		7		10		Total	
	Landings	TACC	Landings	TACC	Landings	TACC	Landings	TACC	Landings	TACC
1983–84 [1]	886	–	180	–	945	–	0	–	2 011	–
1984–85 [1]	670	–	399	–	965	–	0	–	2 034	–
1985–86 [1]	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	7 781	6 930
1990–91	2 603	2 610	743	1 000	6 148	3 310	0	10	9 494	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	2 546	3 500	7 154	6 835	0	10	13 225	13 846
1993–94	1 803	3 501	2 587	3 500	2 974	6 835	0	10	7 364	13 847
1994–95	2 572	3 632	3 369	3 500	8 841	6 855	0	10	14 782	13 997
1995–96	3 956	3 632	3 466	3 500	8 678	6 855	0	10	16 100	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	14 748	13 997
1998–99	3 845	3 632	3 324	3 500	8 165	6 855	0	10	15 334	13 997
1999–00	3 899	3 632	2 803	3 500	6 898	6 855	0	10	13 600	13 997
2000–01	3 429	3 632	2 321	3 500	8 360	6 855	0	10	14 110	13 997
2001–02	2 870	3 701	1 424	3 500	7 519	6 855	0	10	11 813	14 066
2002–03	3 336	3 701	811	3 500	7 433	6 855	0	10	11 580	14 066
2003–04	3 466	3 701	2 275	3 500	7 945	6 855	0	10	13 686	14 066
2004–05	4 795	3 701	1 264	1 800	7 317	6 855	0	10	13 376	12 366
2005–06	2 743	3 701	305	1 800	6 906	7 700	0	10	9 954	13 211
2006–07	2 025	3 701	900	1 800	7 668	7 700	0	10	10 593	13 211
2007–08	2 445	3 701	865	1 800	2 620	7 700	0	10	5 930	13 211
2008–09	3 415	3 701	856	1 800	5 954	7 700	0	10	10 225	13 211
2009–10	2 156	3 701	208	1 800	2 352	7 700	0	10	4 716	13 211
2010–11	1 904	3 701	179	1 800	3 754	7 700	0	10	5 837	13 211
2011–12	1 948	3 701	161	1 800	4 459	7 700	0	10	6 568	13 211
2012–13	2 079	3 701	177	1 800	5 434	7 700	0	10	7 690	13 211
2013–14	1 883	3 701	168	1 800	3 642	7 700	0	10	5 693	13 211
2014–15	1 725	3 701	304	1 800	6 219	7 700	0	10	8 248	13 211
2015–16	1 584	3 701	274	1 800	2 864	7 700	0	10	4 722	13 211
2016–17	1 175	3 701	268	1 800	4 701	7 700	0	10	6 144	13 211
2017–18	1 350	3 701	267	1 800	3 086	5 064	0	10	4 703	10 575
2018–19	896	3 701	183	1 800	1 563	5 064	0	10	2 642	10 575
2019–20	1 062	3 701	137	1 800	2 063	2 272	0	10	3 263	7 783
2020–21	1 503	3 701	207	1 800	1 368	2 272	0	10	3 077	7 783
2021–22	1 692	3 701	137	1 800	1 325	2 272	0	10	3 154	7 783
2022–23	1 083	3 701	124	1 800	1 696	2 272	0	10	2 902	7 783
2023–24	945	3 701	198	1 800	966	2 272	0	10	2 109	7 783
2024-25	–	3 701	–	1 800	–	2 272	–	10	–	7 783

[1] FSU data.

Table 2: Total (scaled) catches (t) by stock for hake from 1990–2024 for the October–September definition of a fishing year (where 1990 is 1 October 1989–30 September 1990), accounting for misreporting (Fisheries New Zealand 2024).

Fishing year	WCSI	Sub-Antarctic	Chatham Rise
1974–75	71	120	191
1975–76	5 005	281	488
1976–77	17 806	372	1 288
1977–78	498	762	34
1978–79	4 737	364	609
1979–80	3 600	350	750
1980–81	2 565	272	997
1981–82	1 625	179	596
1982–83	745	448	302
1983–84	945	722	344
1984–85	965	525	544
1985–86	1 918	818	362
1986–87	3 755	713	509
1987–88	3 009	1 095	574
1988–89	8 696	1 827	804
1989–90[1]	8 741	2 366	950
1990–91[1]	8 246	2 749	931
1991–92	3 010	3 265	2 418
1992–93	7 059	1 452	2 798
1993–94	2 971	1 844	2 934
1994–95	9 535	2 888	3 271
1995–96	9 082	2 273	3 959
1996–97	6 838	2 599	3 890
1997–98	7 674	2 789	4 074
1998–99	8 742	2 789	3 589
1999–00	6 895	2 961	3 163
2000–01	8 346	2 787	2 962
2001–02	7 498	2 510	1 770
2002–03	7 404	2 741	1 401
2003–04	7 939	3 251	2 465
2004–05	7 298	2 530	3 518
2005–06	6 892	2 555	489
2006–07	7 660	1 812	1 081
2007–08	2 583	2 204	1 096
2008–09	5 912	2 427	1 825
2009–10	2 282	1 958	391
2010–11	3 462	1 288	951
2011–12	4 299	1 893	194
2012–13	5 171	1 883	344
2013–14	3 387	1 832	187
2014–15	5 966	1 639	348
2015–16	2 733	1 504	355
2016–17	4 701	1 037	406
2017–18	3 085	1 205	412
2018–19	1 562	636	443
2019–20	2 063	930	318
2020–21	1 367	1 353	357
2021–22	1 324	1 497	332
2022–23	1 695	922	286
2023–24	965	751	393
2024–25	–	–	–

[1] West Coast South Island revised estimates for 1989–90 and 1990–91 were from Colman & Vignaux (1992) who corrected for under-reporting in 1989–90 and 1990–91, and not Dunn (2003) who ignored such under-reporting.

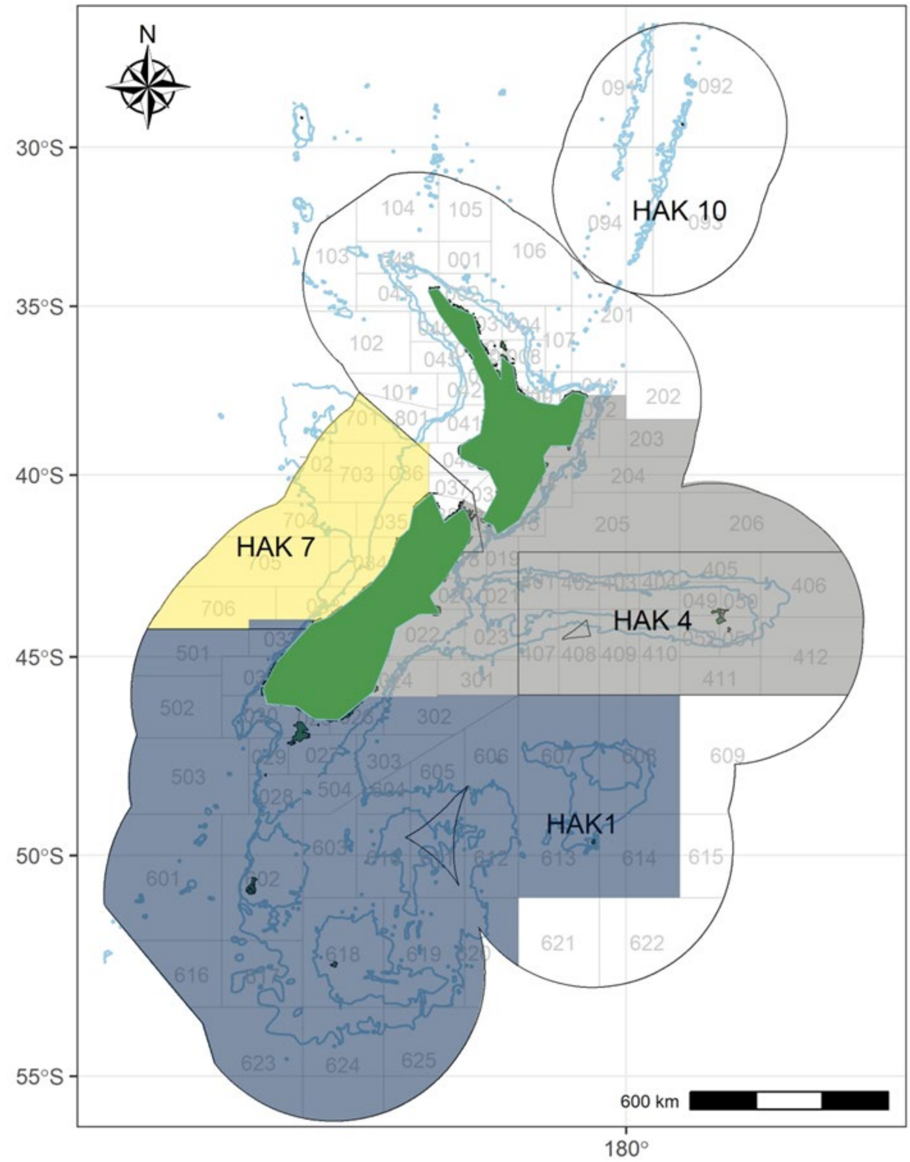

Figure 1: Quota Management Areas (QMAs) HAK 1, 4, 7, and 10 (black lines), statistical areas (grey), and hake biological stock boundaries: west coast South Island (yellow), Chatham Rise (light grey), and Sub-Antarctic (dark grey).

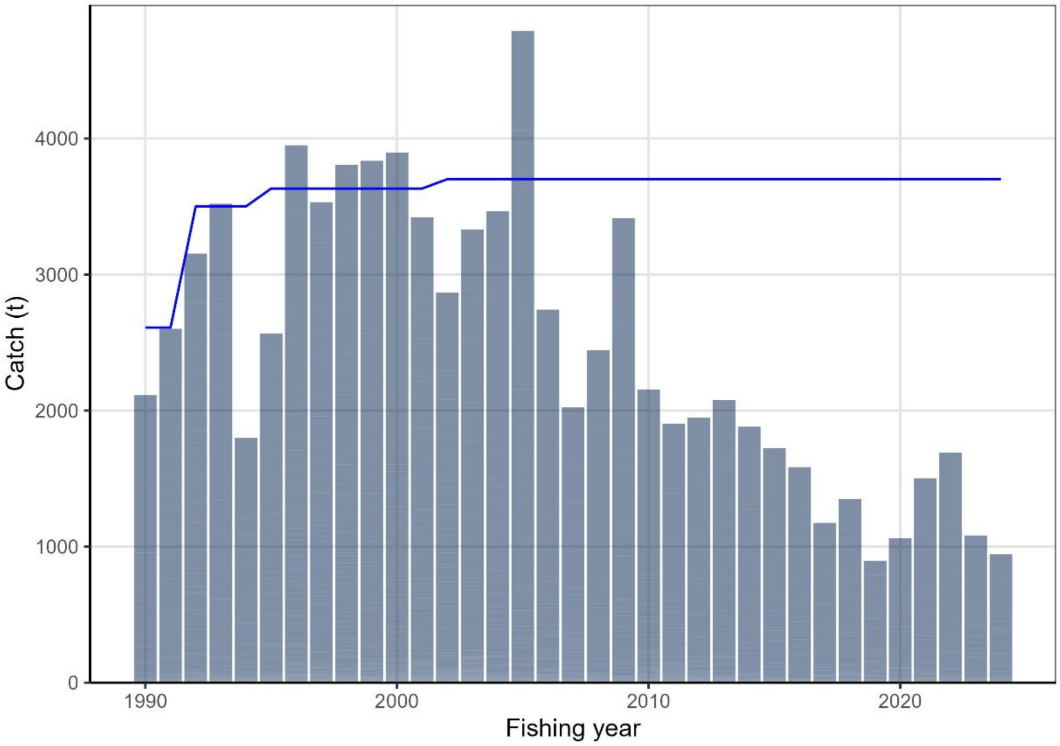

Figure 2: Annual reported catch of hake in HAK 1 (bars) and the TACC for hake (blue line) for the fishing years 1989–90 (labelled 1990) to 2023–24 (labelled 2024).

2. SUMMARY OF THE HAKE FISHERY IN THE SUB-ANTARCTIC

2.1 Available data

Data available for Sub-Antarctic hake include catch and effort data, observer data from observed trips, and resource surveys.

Commercial catch and effort data were analysed to summarise and characterise the hake fishery and revise the CPUE indices for the stock. Catch and effort, and landings of hake have been misreported by area, with hake caught on the west coast of New Zealand in HAK 7 misreported as catch either in HAK 1 or HAK 4, with the majority misreported to the Chatham Rise (HAK 4 and the part of HAK 1 on the western Chatham Rise) (Dunn 2003a). While misreporting between the Chatham Rise and the Sub-Antarctic was low, significant misreporting occurred between the west coast South Island and the Chatham Rise in the late 1990s (Dunn 2003a).

Catch and effort data were extracted by Fisheries New Zealand for the period from October 1989 to September 2024 (REPLOG 14055) including all available data at the date of the extract (20th November 2024). The data extract included all data from trips where hoki, hake, or ling were reported as caught, processed, or landed, and all fishing recorded on trawl catch, effort and processing returns (TCEPRs); trawl catch and effort returns (TCERs); catch, effort and landing returns (CELRs); lining catch and effort returns (LCERs); lining trip catch and effort returns (LTCERs); netting catch, effort and landing returns (NCELRs); electronic reporting system returns for all methods (ERS); and any high seas reports.

Observer data for hake from the Fisheries New Zealand observer sampling programme were also extracted, and included all observer trips that reported hoki, hake, or ling as of 20th

November 2024 (REPLOG 14055). Biological and length frequency data from these trips were also extracted, along with any associated otolith age readings. Additional age data for the 2024 survey, and the 2022 and 2023 commercial fisheries were included in this analysis but were not available on the Fisheries New Zealand age database at the time of this report and were supplied by NIWA.

Resource survey data (including data from the Tangaroa Sub-Antarctic standardised trawl survey and any other research voyage that reported hake) were also extracted by Fisheries New Zealand from its research database, along with any biological and length frequency information and associated otolith age readings from these trips. A summary of the biomass estimates from the resource surveys for hake on the Chatham Rise, Sub-Antarctic, and west coast of New Zealand are given in Appendix A.

2.2 Methods

Catch and effort data were checked for errors, using simple checking and imputation algorithms for missing and unlikely data, similar to those reported by Dunn et al. 2021a and Dunn et al. 2023b, and implemented in the software package R (R Core Team 2019). Individual tows were investigated, and errors were corrected using median imputation for start/finish latitude or longitude, fishing method, target species, tow speed, net depth, bottom depth, wingspread, duration, and headline height for each fishing day for each vessel. Range checks were defined for the remaining attributes to identify potential outliers in the data. The outliers were checked and corrected with median or mean imputation on larger ranges of data such as vessel, target species, and fishing method for a year or month. Transposition of some data was carried out (e.g., bottom depth and depth of net) to correct potential recording errors. The tow-by-tow commercial and observed catches of hake were corrected for possible misreporting between 1990 and 2007 following to the methods of Dunn (2003a).

Fish biological stocks (and statistical areas) were assigned based on the corrected positions or the reported statistical area where no location was available. Vessels were assigned as having a meal plant or not based on vessel name (provided by Fisheries New Zealand), noting that no date range was available for this information. Tows carried out with midwater gear (MW), but with fishing depth within five metres of the bottom were recoded as midwater bottom gear (MB). Bottom tows (BT) were not recoded.

2.3 Results

The TACC for hake has been stable in the HAK 1 and HAK 4 QMAs since 2004–05. In HAK 7, the TACC was reduced from 7700 t to 5064 t in 2016–17, and then again to 2272 t in 2019–20. Most hake are caught in HAK 7, off the west coast South Island, with a decreasing proportion caught in HAK 4. Over all areas, catches of hake have significantly declined since the mid-2000s as the commercial value of hake has declined. Catches of hake peaked in 1995–96 at about 16 000 t from a total TACC of 13 997 t. But, by 2023–24, the catch of hake across all areas has significantly reduced and was 2109 t, less than a third of the available TACC of 7783 t.

In the Sub-Antarctic, hake catches have also declined, from about 3000 t in 2003–04 to less than 1000 t in recent years. Almost all catches were reported using TCEPR forms up to 2016–17, with data then switching to the ERS-trawl forms since (Figure 3).

Hake have been caught predominantly by bottom trawls or midwater gear fished at or near the sea floor (Figure 4) from trawls targeting hoki, hake, or ling. Hake caught from hoki target tows made up a significant proportion of the catch up to 2003–04, but hake target tows became the predominate source of catch following the reduction in hoki availability and the hoki TACC reduction in 2005–06 (McGregor et al. 2022) (Figure 5).

Hake are caught mostly during the summer months in the Sub-Antarctic (Figure 6) from a trawl fleet dominated by vessels 60 to 70 m in length. The trawl fleet was mostly New Zealand or formerly flagged vessels to Japan, with a few vessels that were previously flagged to Korea. Vessels recorded as 'other' in the years 1990–1995 were previously identified by Ballara (2018) as likely to be flagged to Japan and Norway. Hake have typically been caught at depths of 500 to 750 m depth, with the depth of fish caught remaining stable over time. Although the trawl fleet targeting hoki and other species has also fished in Statistical Areas 033, 034, 036, and 703, most of the hake catch was taken from Statistical Area 034 (Figure 7) at depths of 500 to 750 m.

To evaluate the expansion or retraction of the area fished, the area covered by the fleet was investigated using a 0.1° cell grid by summarising the number of cells fished in any one year as well as the cumulative number of new cells fished over time. The bottom trawl fleet showed an increase in the new areas explored to about 2004–05, followed by a subsequent plateau (very few new areas investigated) with an annual expansion or contraction of the area fished in any one year (Figure 8). The change in the pattern of cells fished occurred at the time of the change in target species and the reduction in the number of statistical areas fished. There has been an increase from 2014–15 in the number of 0.1° cells fished, due to a small amount of apparent range expansion as a consequence of the change in reporting systems from TCEPR forms to the higher resolution position data reported on ERS-trawl data forms.

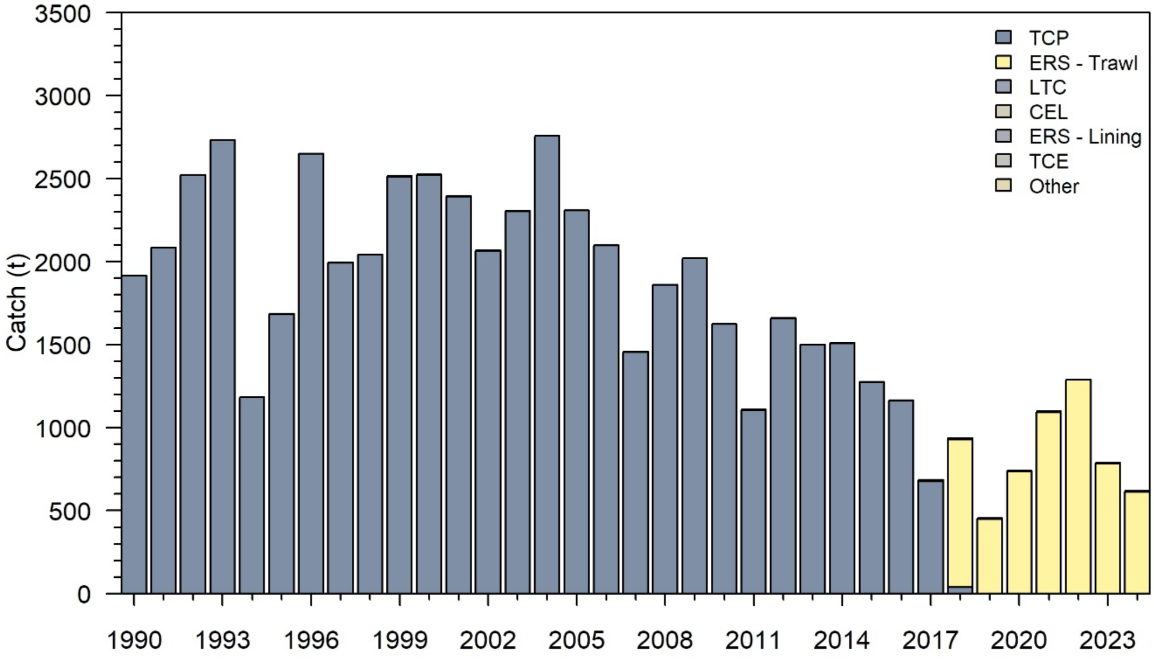

Figure 3: Total catch of hake (t) in the Sub-Antarctic by data reporting form type and fishing year from 1989–90 to 2023–24.

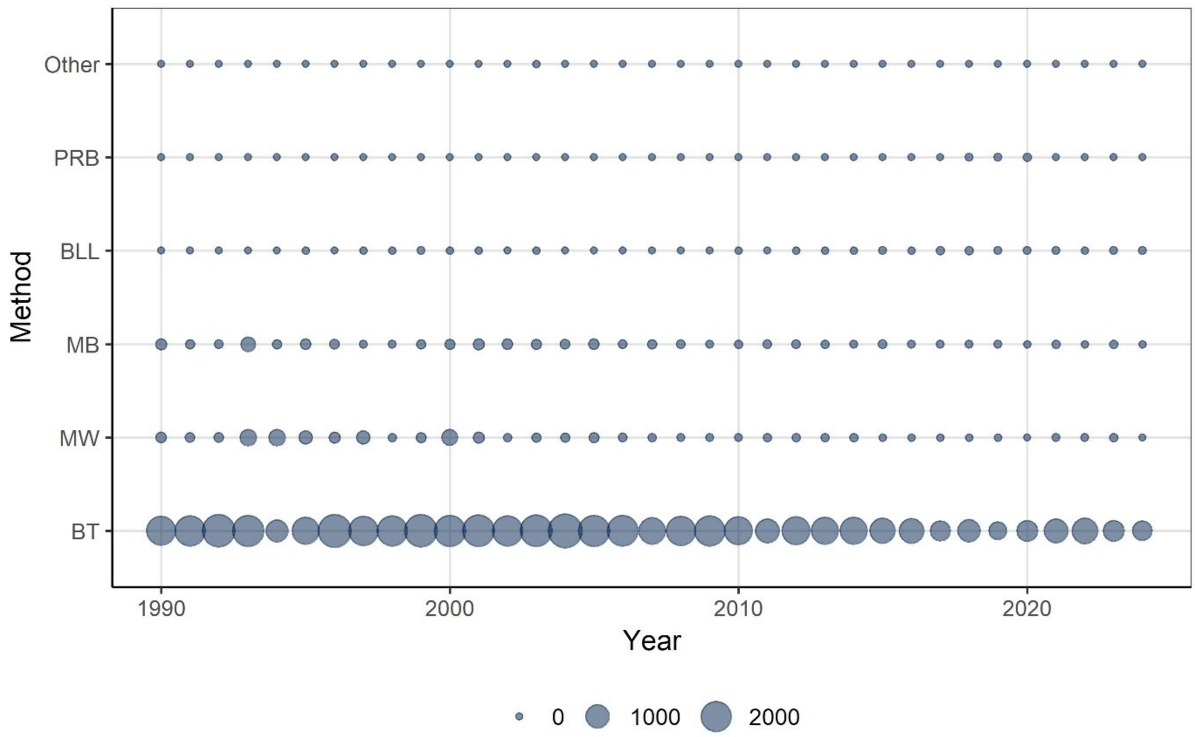

Figure 4: **Relative proportion of hake catch (t) in the Sub-Antarctic by gear type (BT = bottom trawl gear, MW = midwater trawl gear, MB = midwater trawl gear fished near the sea floor, BLL = bottom longline, PRB = modular harvesting system bottom trawl gear, and Other = all other gears combined) and fishing year, from 1989–90 to 2023–24.**

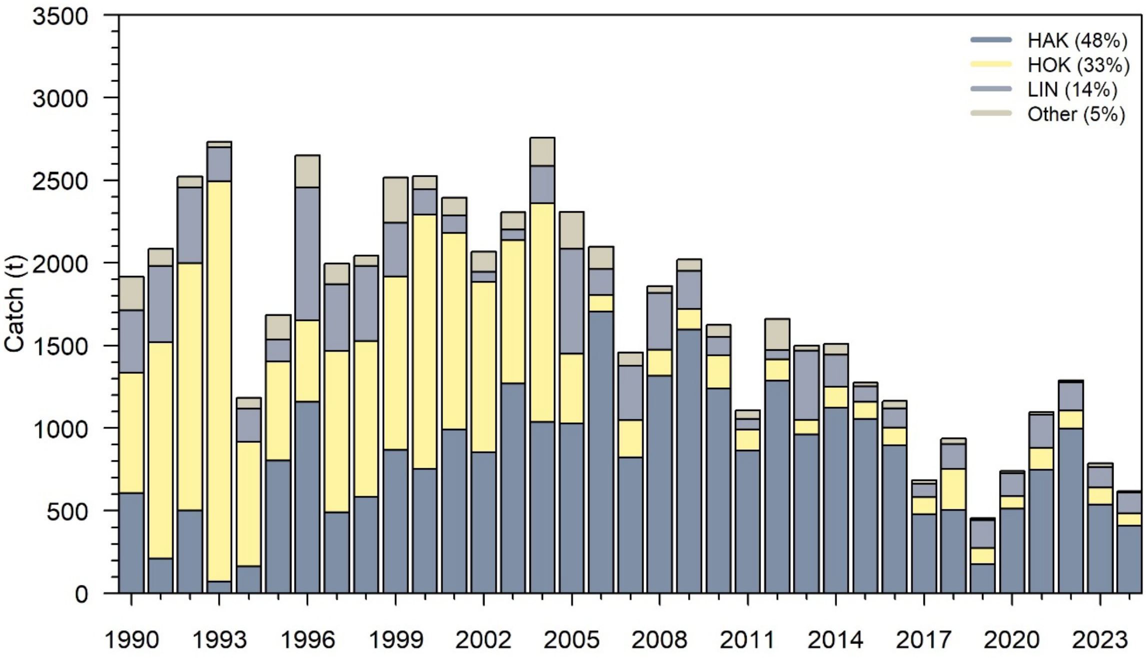

Figure 5: **Total catch (t) of hake in the Sub-Antarctic by target species (hake, hoki, ling, and other species combined) by fishing year, from 1989–90 to 2023–24, and proportion of the catch for all years combined.**

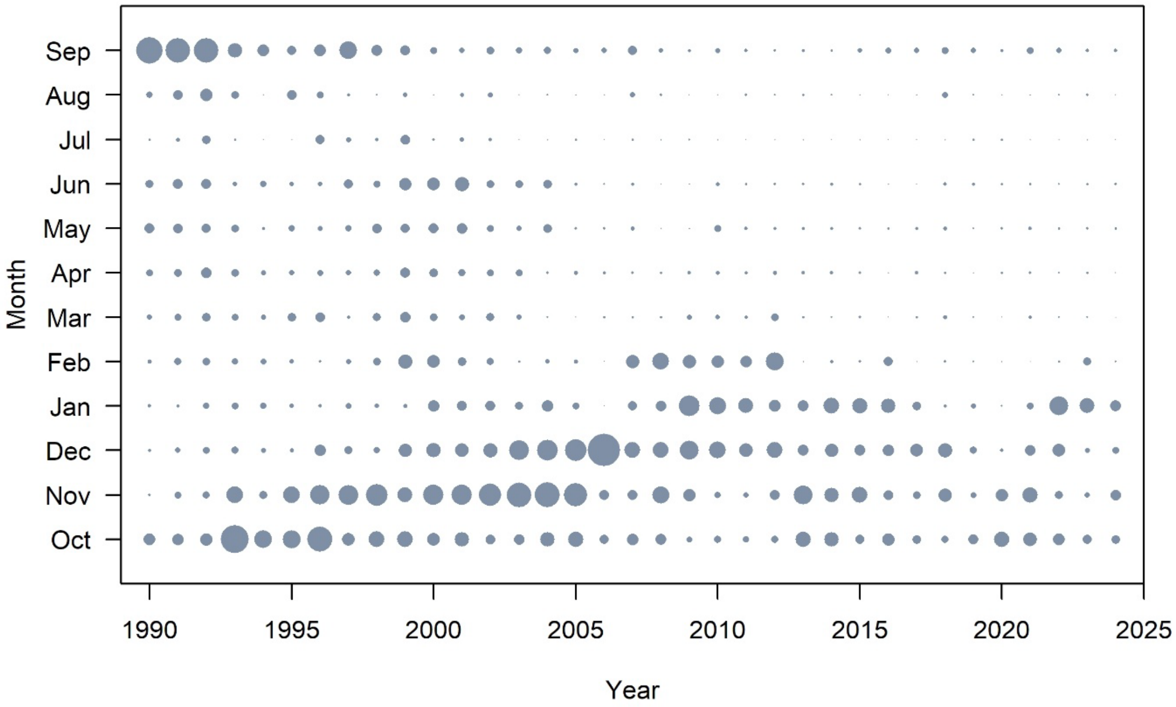

Figure 6: Relative catch of hake in the Sub-Antarctic by month and fishing year from 1989–90 to 2023–24.

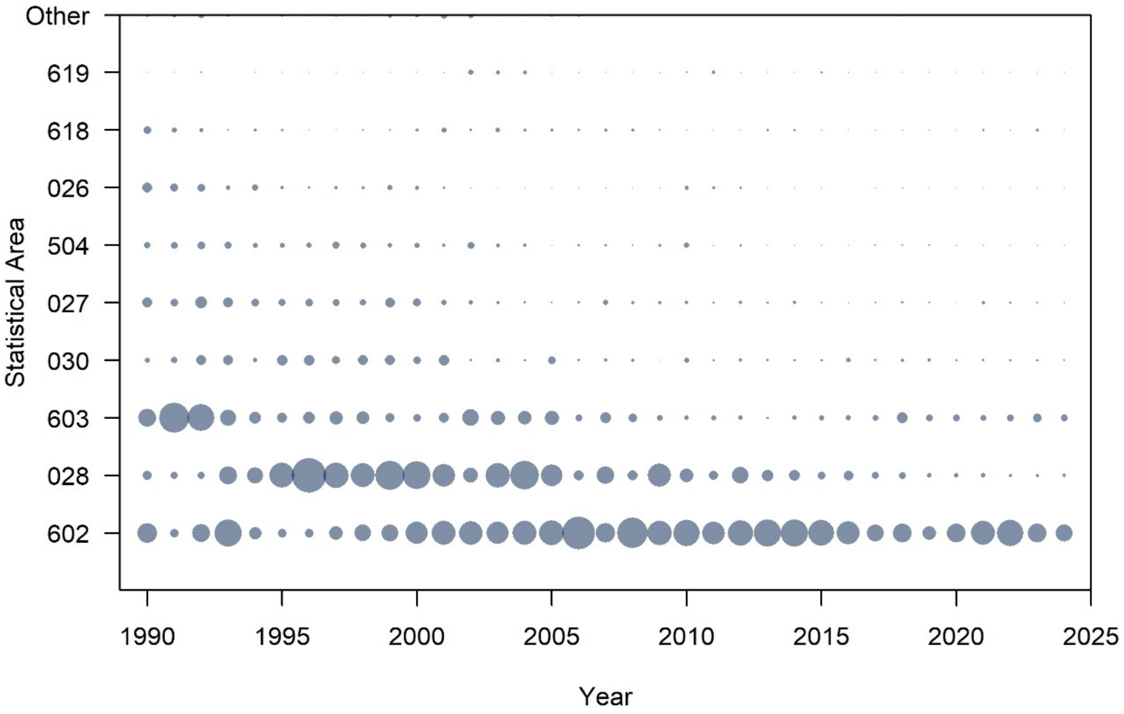

Figure 7: Relative catch of hake in the Sub-Antarctic, by statistical area and fishing year from 1989–90 to 2023–24.

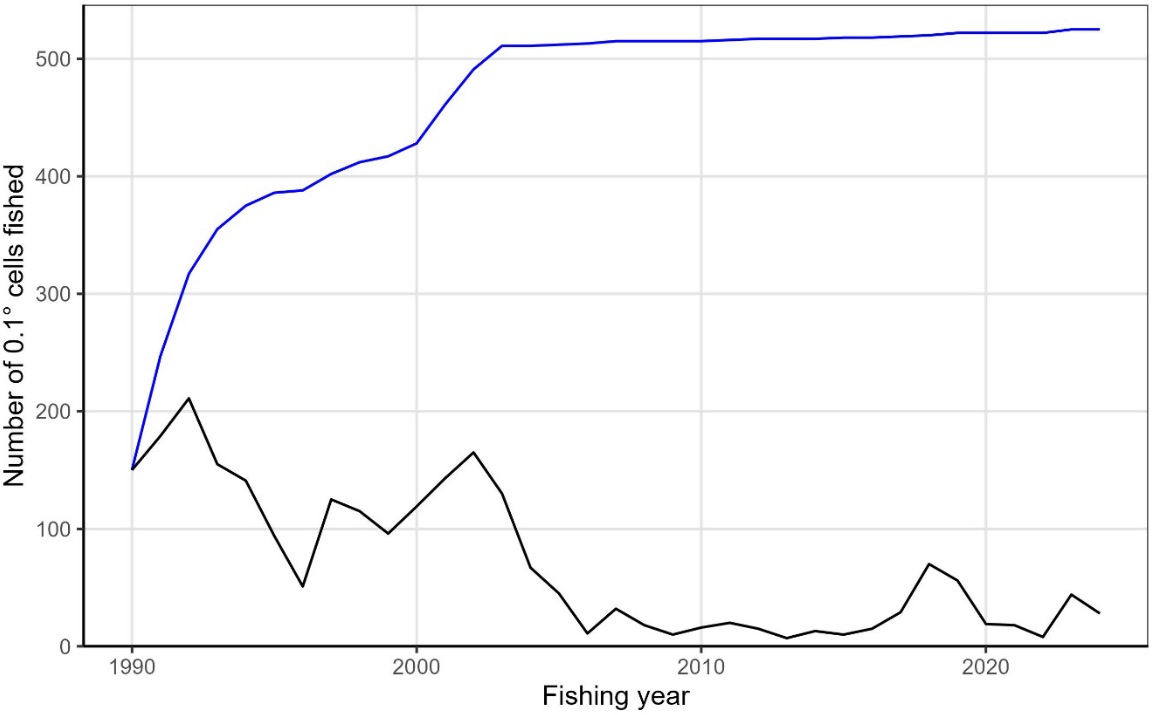

Figure 8: Annual number of 0.1° cells (black line) and cumulative new 0.1° cells (blue line) in the Sub-Antarctic that had reported hake catch, by fishing year, from 1989–90 to 2023–24.

3. SPATIO-TEMPORAL ANALYSES

Spatio-temporal analyses of the hake catch data in the Sub-Antarctic was undertaken to investigate whether there were suitable spatial splits of the underlying population that would allow development of spatial areas within which consistent fishing selectivity patterns and consistent areas could be assumed for CPUE analyses. For example, as hake were distributed differently by age and sex over spatial areas (for example, older fish around the Stewart-Snares shelf and younger fish west of Campbell Islands) the changing pattern of the fishery would introduce changes in selectivity and CPUE indices over time. Assessment models would then be likely to interpret changes in the population age composition as a population dynamic, rather than a spatial-temporal dynamic of the fishery.

The spatial strata used in previous analyses for Sub-Antarctic hake were derived from an analysis by Horn (2008) who determined that there was one major and three minor spatially defined hake fisheries in the Sub-Antarctic area (Campbell Island, Puysegur Bank, Stewart-Snares, and Auckland Islands – see Figures 10 and 11 later). These regions have been used to scale the commercial fishery length compositions that were applied to an area-wide age-length key and summed to provide a single area-wide commercial fishery age composition since then (e.g., see Dunn 2019). They were also used as a potential factor in previous CPUE analyses for hake (see Ballara 2018).

Describing and modelling the spatial distribution using length or age and correcting for variables such as month and year (i.e., analogous to that used for CPUE standardisations), can help better understand the spatial and temporal patterns in fish size and age. In this analysis, we investigate alternative spatial analyses to define regions that are then used to estimate each region’s age and sex structure, as well as to develop region-specific CPUE indices.

3.1 Methods

3.1.1. Bayesian spatial-temporal analysis

Integrated Nested Laplace Approximation (INLA) (Rue et al. 2009) was used to develop spatial-temporal models of fish age. A spatial mesh (i.e., made up of nodes connected by edges to delineate spatial regions) was developed using constrained Delaunay triangulation (Figure 9). The mesh was limited to 1500 nodes (i.e., the number of nodes was constrained to be at least about 10 percent of the number of observations, while still maintaining an appropriate spatial resolution). The analysis used the available age measurements from the surveys (as these were more likely to be random samples of the population as most survey caught fish were aged, as distinct from observer age samples which were more likely to have been selected to fill out an age-length key, *n*=9831) at the time of this report and included data up to the end of 2024. Each node was an estimated model parameter, constrained by the stochastic partial differential equation (SPDE) underpinning INLAs spatial smoothers.

Only the survey caught fish that were aged were used in this analysis. The information for determining spatial structure for use in an age-structured model was likely to be best informed by age. While length information would be useful, without spatially explicit age-length information, any inference may not be as reliable as the age data. However, we compare the resulting age-based spatial regions with that from a length-based analysis using the observer data to ensure that these were not inconsistent. For the analysis, records with unknown sex were dropped from the age data and ages were rounded to the nearest integer.

The age data were fitted assuming a Poisson distribution. The variables year, month, sex, and node (i.e. spatial structure) were offered to the model. Spatial structure was assumed to be either constant, sex-specific, or year and sex specific, depending on the model run. Although there may be correlations within tows in the age data, any such correlations were ignored in these analyses, and it was assumed that each sample was an independent sample from the population at that time in that location for each sex. Models were compared using the deviance information criterion (DIC) and Watanabe-Akaike information criterion (WAIC).

The R package *ClustGeo* (Chavent et al. 2018) was used to derive spatial fishery strata using hierarchical clustering with geographic constraints. The *ClustGeo* package implements a clustering algorithm that includes soft contiguity constraints. The algorithm requires two dissimilarity matrices (D0 and D1) and a mixing parameter alpha. D0 is a matrix containing the Euclidean distance between all data points, and D1 is a matrix containing the distance in space (in metres) between all data points. The alpha parameter (a real value between 0 and 1) stipulates the relative importance of the data (D0) relative to space (D1).

The value of alpha can be somewhat subjective and can sometimes radically change the clusters. However, a somewhat objective method for finding an acceptable value for alpha was to:

1. Define the number of clusters (e.g., k=2, 3, or 4 clusters);
2. Run the clustering algorithm for evenly spaced values of alpha between 0 and 1 (e.g., alpha={0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0}); and
3. Visually examine a plot of the proportion of explained inertia of the partitions in K clusters for each alpha value and using this to decide on an alpha value. In these analyses, an alpha=0.2 provided an acceptable trade-off between D0 and D1, and was used as the value for the definition of spatial clustering algorithm, to define the spatial regions.

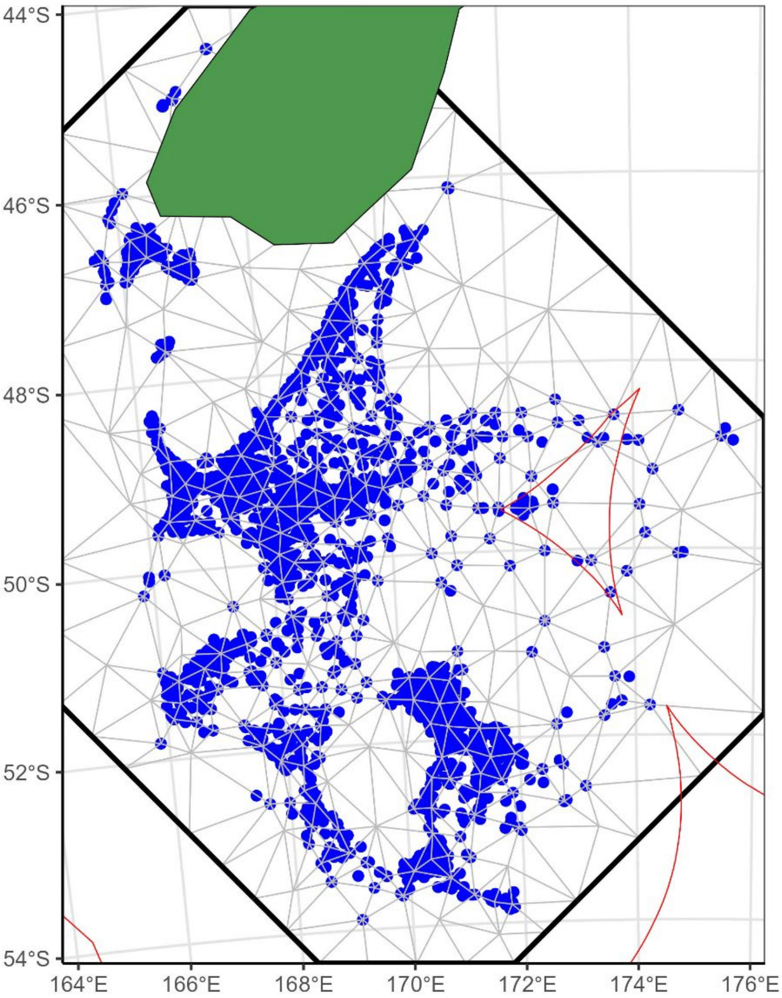

Figure 9: Spatial mesh for the Sub-Antarctic hake spatial-temporal models showing the locations of data (blue points), the spatial mesh (grey lines), the extent of the spatial model (thick black lines), and the New Zealand EEZ (red line).

3.2 Results

An initial investigation of the age structure across the biological stocks was carried out. Unscaled length and age observations were plotted for all hake measured in HAK 1, HAK 4, and HAK 7. Although the largest and oldest fish were found in the Sub-Antarctic, most of the range of observed ages or lengths were seen in each of the three stock areas (west coast South Island, Chatham Rise, and the Sub-Antarctic) and there was no evidence from the age or length frequencies that contradicted the current stock structure assumptions (Figure 10).

Exploratory analyses for the Sub-Antarctic suggested that the observed ages and lengths could be clustered into at least three main spatial regions, but with no strong evidence of temporal splits (Figure 11). These three spatial strata suggested that slightly smaller fish were located to the south of the Stewart-Snares shelf and to the west of Campbell Plateau, with larger fish located on the Stewart-Snares shelf in the Sub-Antarctic, and with the majority of the catch coming from the region on the Stewart-Snares shelf.

The spatio-temporal analysis allowed the consideration of spatially non-contiguous areas, i.e., locations where the age structure was similar but was not located in a neighbouring location. Clustering was investigated for k=2, 3, and 4, clusters and the relative catch and (scaled) sex ratio between each cluster compared over the time series of ages. Alpha levels of about 0.2

were considered the most appropriate based on the trade-off between the D0 and D1 statistics (Figure 12).

Both the DIC and WAIC suggested that the models that included terms of year, sex, and space were the most parsimonious. The spatial effect for the model of mean length with sex and space is shown in Figure 13, Figure 14, and Figure 15. The estimated mean age model with annually varying effects is shown in Figure 16.

Alpha levels of between 0.15 and 0.25 were considered optimal (Figure 12). Clustering was investigated for k=2, 3, and 4 clusters and the relative catch between each cluster compared over the time series of hake lengths and ages. The application of three or four clusters grouped almost all of the relative catch into an area on the Stewart-Snares Shelf, similar to that from the tree regression and the analysis of Horn (2011). The relative catches were dominated by this cluster (Figure 17), and additional clusters mostly had the effect of dividing the lower catch areas into more groups (Figure 18). The four cluster stratum (comprising of strata labelled ‘youngest’, ‘young’, ‘medium’, and ‘old’ as descriptive names that approximately identified the age groups within each) was the most complex (see Figure 15), and was used to identify an alternative catch split, age compositions, and CPUE indices (see Section 5 later) for stock assessment modelling (see Dunn et al. 2025).

These clusters can be used to identify spatial regions that compartmentalise the commercial catch for use in an assessment model, and we developed (see below) the associated age compositions for each of these clusters to allow these to be included and hence evaluated in the assessment model. However, due to the spatial nature of the fishery, the clustering grouped almost all of the catch into a single area (centred around the southern Stewart-Snares shelf), similar to patterns identified in the analysis of Horn (2008).

While these clusters can be used to determine spatial structure in the commercial catch for use in an assessment model, the pattern of age frequencies resulting was broadly similar to the age frequencies resulting from the strata defined by Horn (2011). Evaluation of the available age data and initial model runs suggested that ignoring the Bayesian stratification in determining spatially explicit strata for the age frequencies did not result in any significant modification to the Sub-Antarctic stock assessment (Dunn et al. 2025).

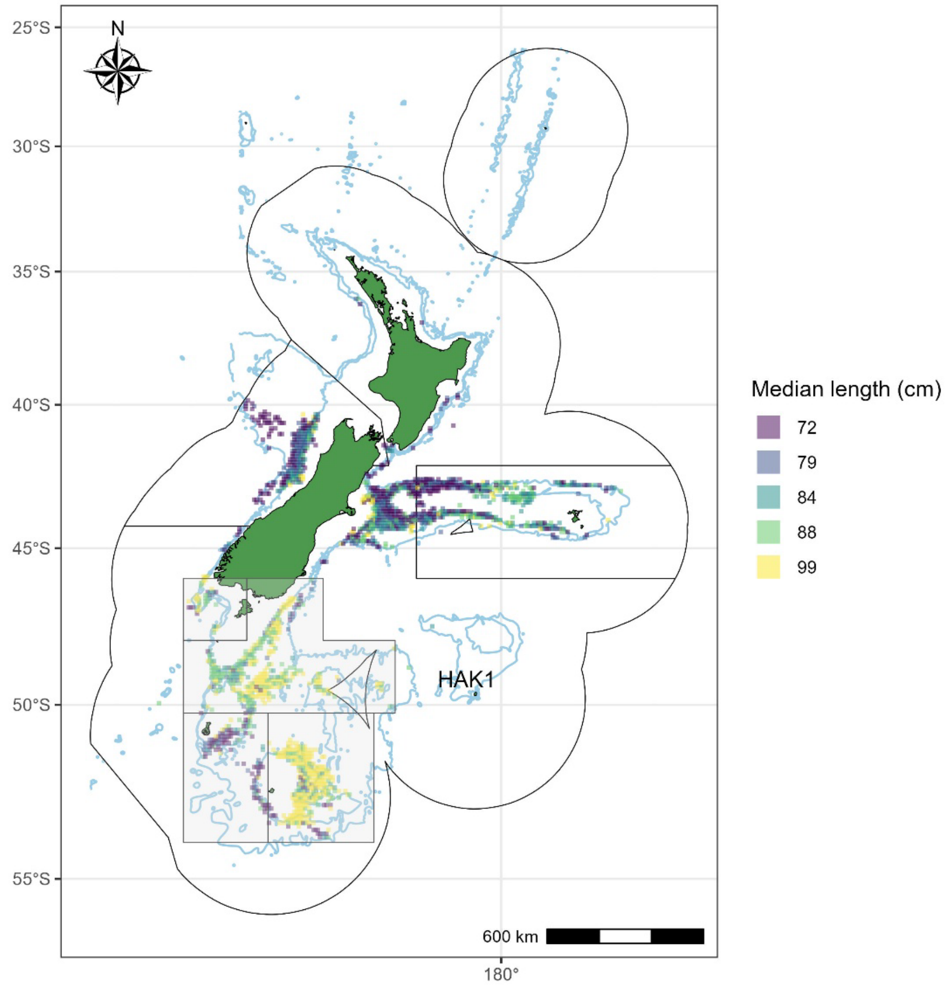

Figure 10: Observed median length of hake within the New Zealand EEZ by 0.1° cell overlaid with the Sub-Antarctic strata defined by Horn (2008), for males and females combined for years 1989–90 to 2023–24. Also plotted are the hake QMAs and 500 m and 1000 m depth contours. The boxed regions show Puysegur Bank (top left), Stewart-Snares (middle), Auckland Islands (bottom left), and Campbell Island (bottom right).

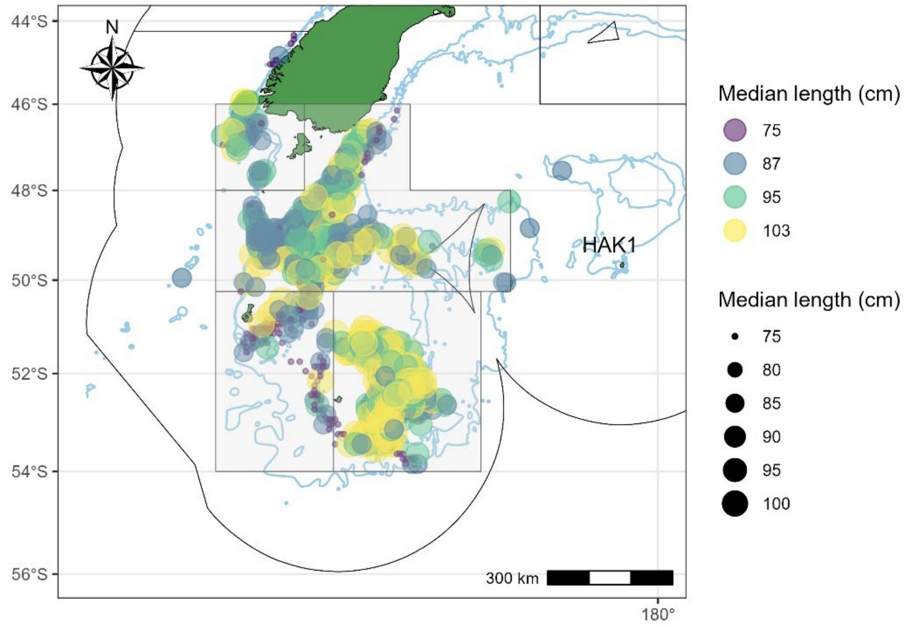

Figure 11: **Observed median length of hake in the Sub-Antarctic, overlaid with the spatial strata defined by Horn (2008), for males and females combined for years 1989–90 to 2023–24. Also plotted are the 500 m and 1000 m depth contours. The boxed regions show Puysegur Bank (top left), Stewart-Snares (middle), Auckland Islands (bottom left), and Campbell Island (bottom right).**

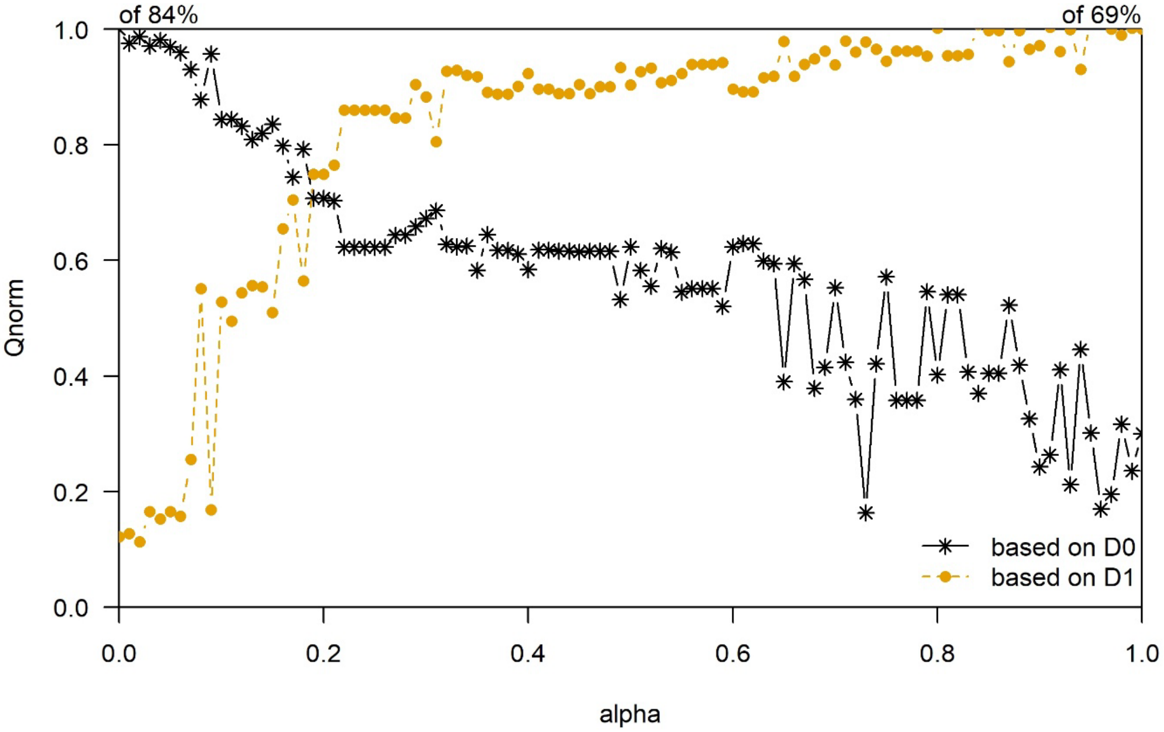

Figure 12: **The proportion of explained inertia of the data (D0) and distance (D1) partitions (in k=4 clusters) for different values of the mixing parameter alpha.**

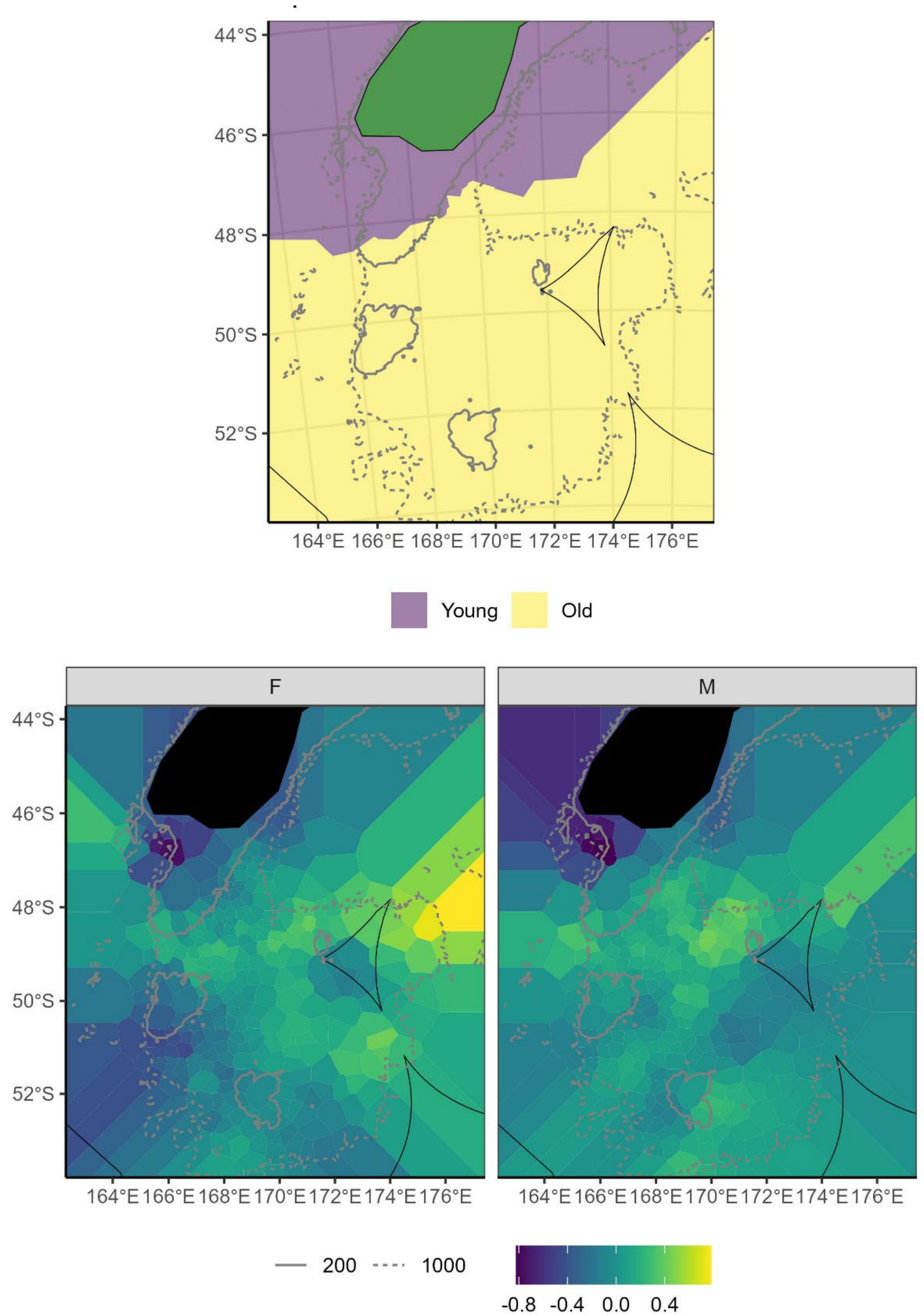

Figure 13: The sex and spatial effect for the model of mean age of sub-adult and adult fish (length ~ intercept + sex × space) and the resulting k=2 cluster spatial definition. Also plotted are the 500 m (white line) and 1000 m (broken white line) depth contours.

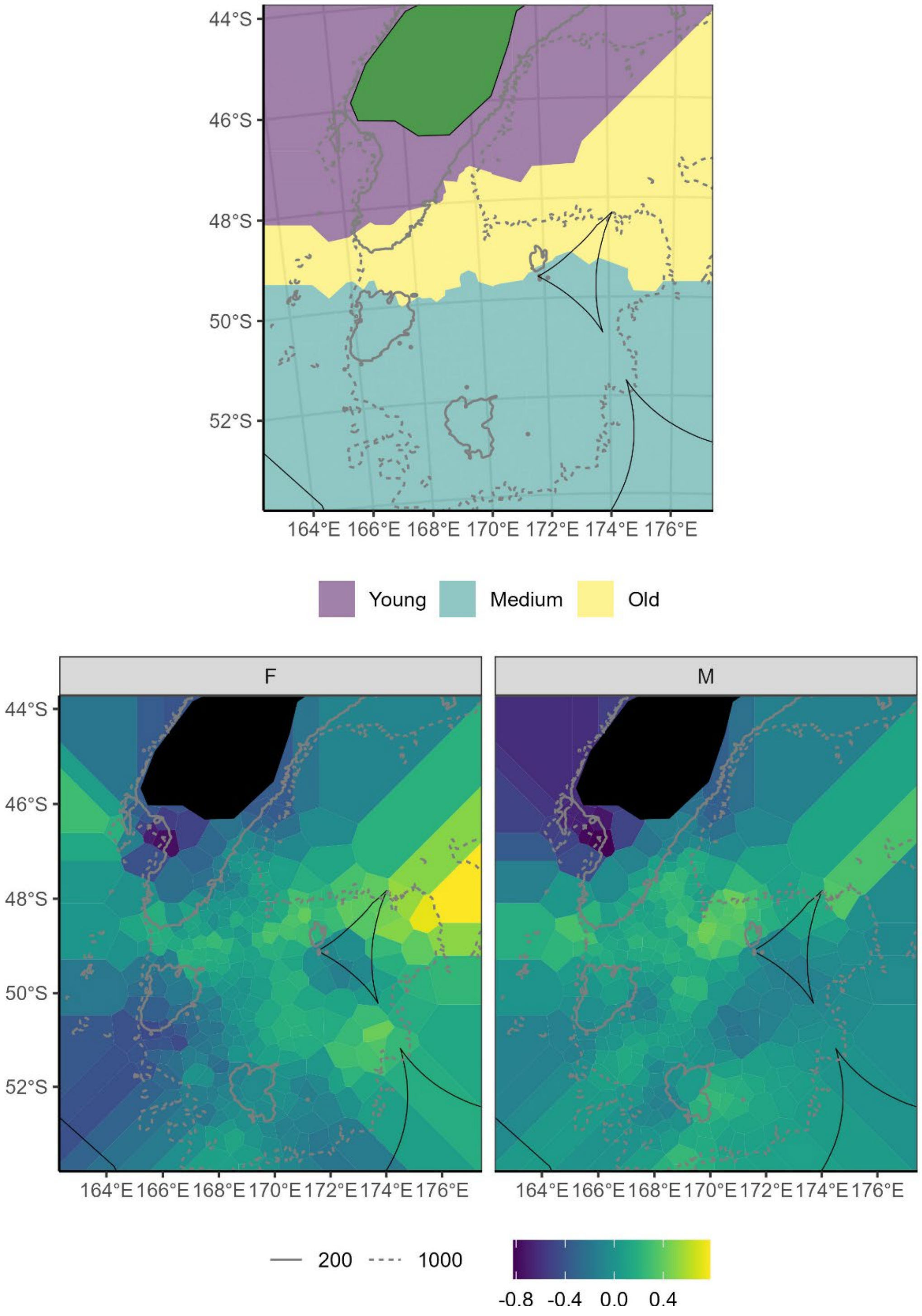

Figure 14: **The spatial effect for the model of mean age of sub-adult and adult fish (length ~ intercept + sex × space) and the resulting k=3 cluster spatial definition. Also plotted are the 500 m (white line) and 1000 m (broken white line) depth contours.**

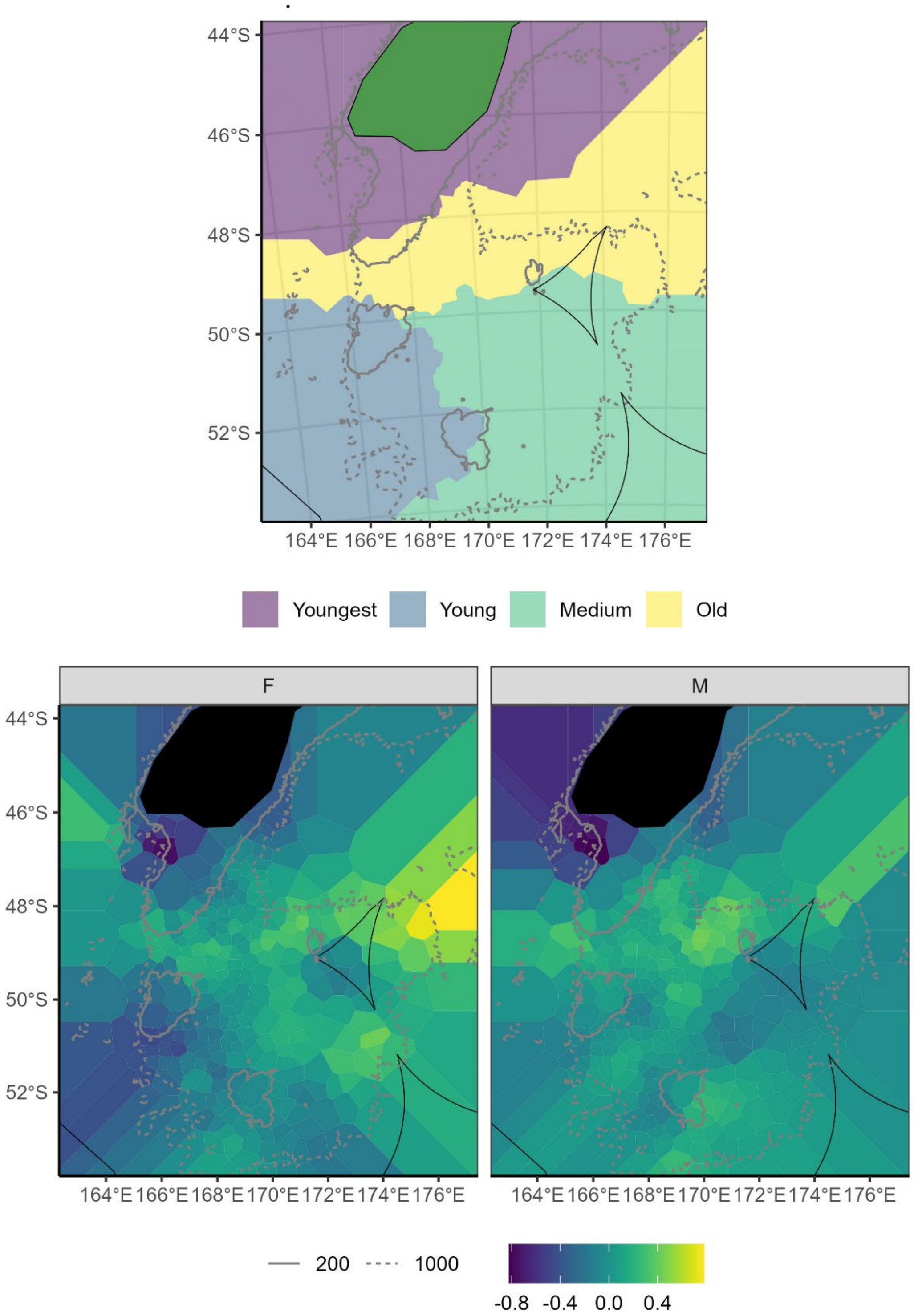

Figure 15: The spatial effect for the model of mean age of sub-adult and adult fish (length ~ intercept + sex × space) and the resulting k=4 cluster spatial definition. Also plotted are the 500 m (white line) and 1000 m (broken white line) depth contours.

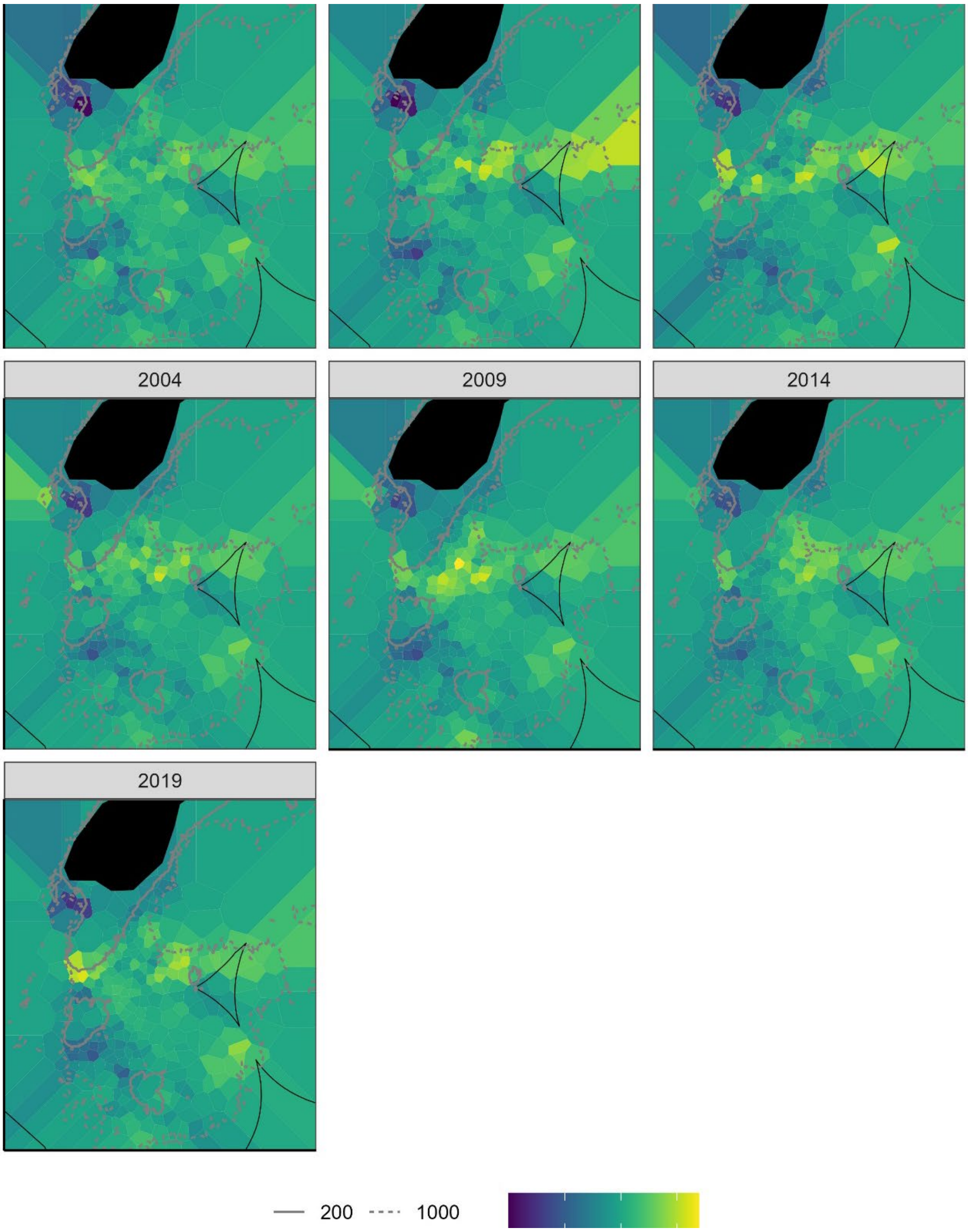

Figure 16: The spatial effect for the annually varying model of mean age (age ~ intercept + sex × (space × year)) for sub-adult and adult fish, estimated in 5-year blocks. Also plotted are the 500 m (white line) and 1000 m (broken white line) depth contours.

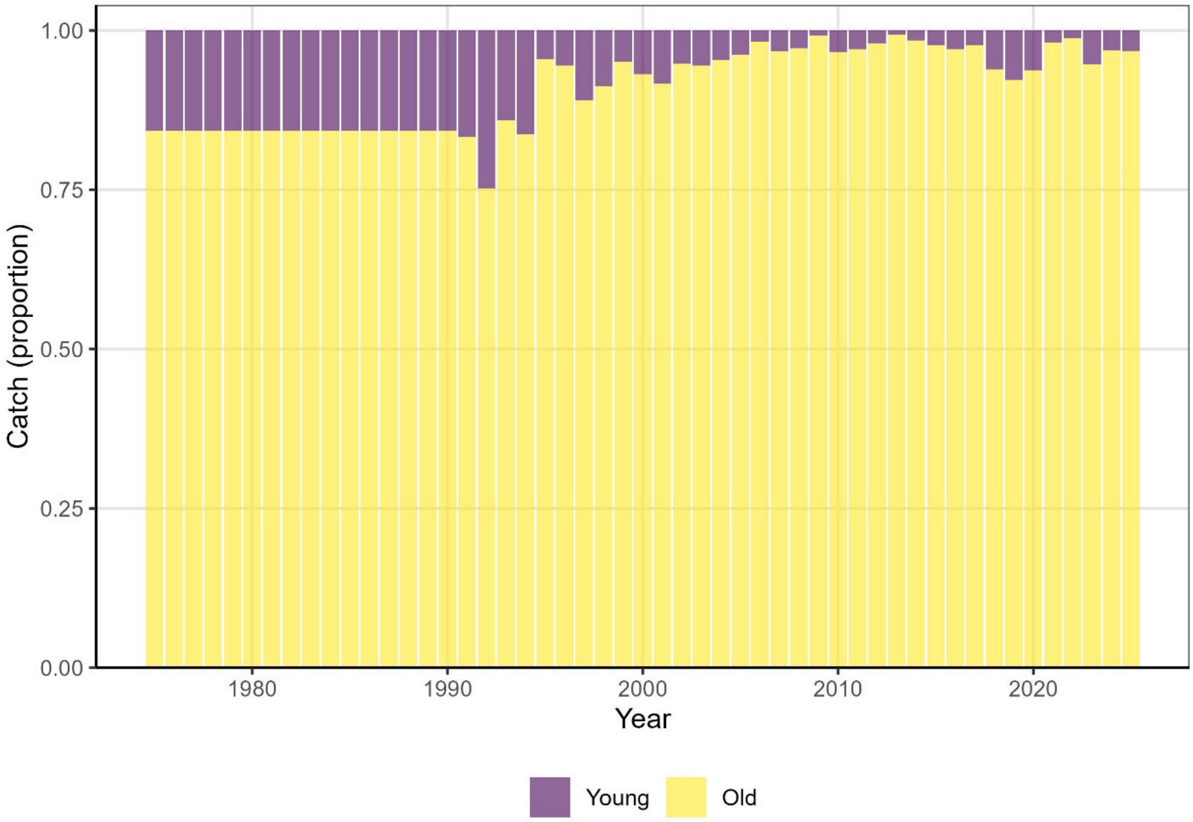

Figure 17: Relative catch of hake in the Sub-Antarctic from allocation to the k=2 clustering algorithm with alpha=0.2 for the Bayesian spatio-temporal analysis of age by fishing year, and assuming a catch ratio equal to 1990–1995 for years before 1990, and a catch ratio equal to 2019–2024 for years after 2024.

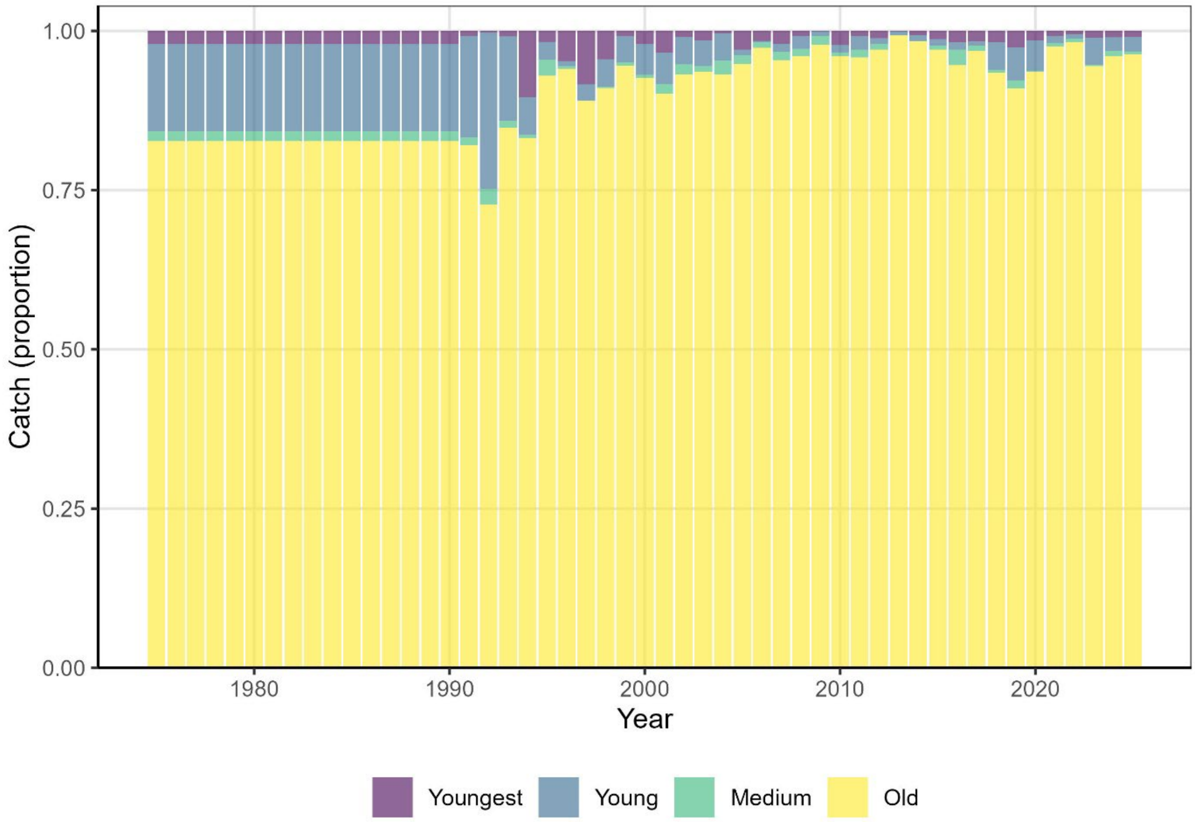

Figure 18: Relative catch of hake in the Sub-Antarctic from allocation to the k=4 clustering algorithm with alpha=0.2 for the Bayesian spatio-temporal analysis of age by fishing year, and assuming a catch ratio equal to 1990–1995 for years before 1990, and a catch ratio equal to 2019–2024 for years after 2024.

4. BIOLOGICAL PARAMETERS

4.1 Length-weight parameters

Length-weight parameters for hake were updated by Dunn et al. (2021a) based on data collected from resource surveys. Data from all available data from resource surveys in the Sub-Antarctic were analysed to update the length-weight relationship (n=12 252). The numbers of length-weight observations by year for males and females is shown in Figure 19.

A log-linear regression was applied to the available length and weight parameters, where weight=$a \cdot (\text{length})^b$, to estimate the a and b parameters for each sex separately (see Table 3 and Figure 20). Plots of residuals indicated a reasonable fit to the data with the length-weight relationship, with no apparent pattern or trend over time (Figure 21). The resulting parameter estimates were only slightly different from those reported by Horn (2013a) and Dunn et al. (2021b), and there was only a slight change in the shape of the resulting length-weight curves.

Table 3: Estimated length-weight parameters from Horn (2013a), Dunn at al. (2021b), and the updated estimates from this analysis for Sub-Antarctic hake.

Sex	N	Parameter	Horn (2013a)	Dunn at al. (2021b)	This analysis
Male	3 078	*a*	2.13e-06	2.34e-06	2.347e-06
		b	3.281	3.258	3.257
Female	5 923	*a*	1.83e-06	1.86e-06	2.458e-06
		b	3.314	3.310	3.246

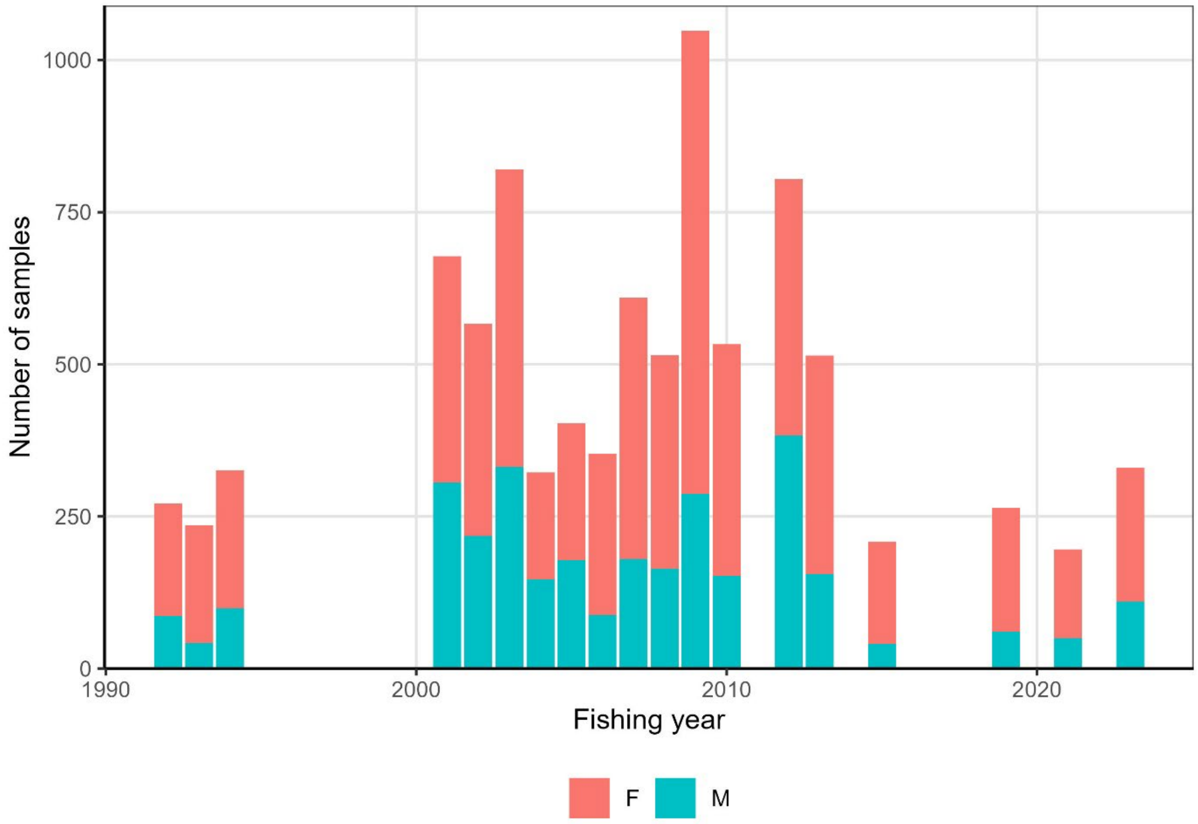

Figure 19: Number of length and weight observations for Sub-Antarctic hake by sex and fishing year from 1988–89 to 2022–23.

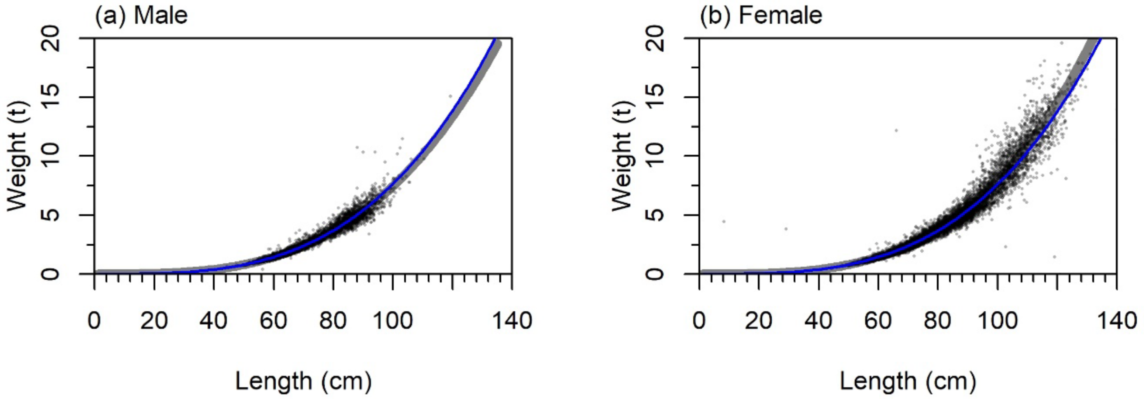

Figure 20: Observed and fitted (blue line) length-weight relationship for (left) male and (right) female hake for Sub-Antarctic hake. The relationship estimated by Horn (2013a) is given as a thick grey line.

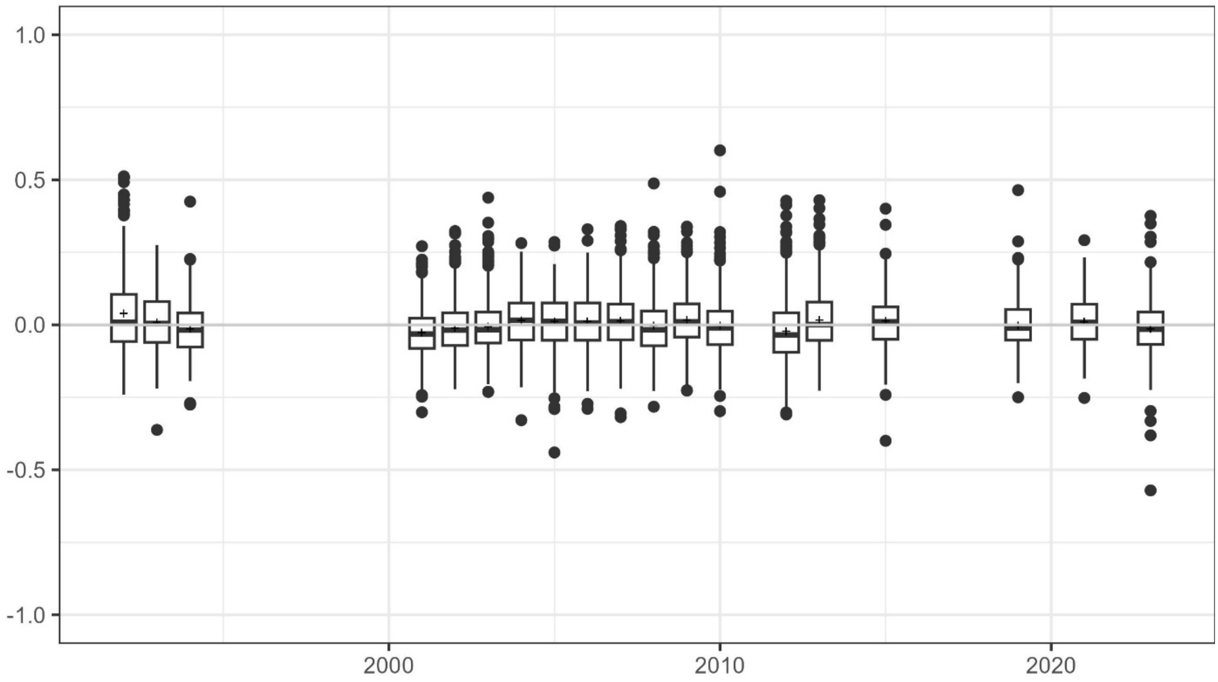

Figure 21: Boxplots of the length weight relationship residuals (dark line = median; grey box = interquartile range; and values more than 1.5 times the interquartile range plotted as black circles) by fishing year (1991–92 to 2022–23), of the fitted length-weight relationship for Sub-Antarctic hake, with the residuals for both sexes combined.

4.2 Length and age composition data

Commercial fishery age frequencies for hake assessment are typically calculated as part of the Fisheries New Zealand middle-depths aging project (see Saunders et al. 2021, Ballara et al. 2022), but were recalculated for this project using consistent criteria and stratum area definitions.

Length compositions were analysed using the revised length weight parameters, for years from 1990–2024 using length samples from hauls with at least five fish measured during the months from September to April as they represented a period of likely constant length at age and represented more than 99% of all age-length observations for the Sub-Antarctic. The observations were groomed for outliers by removing hake of implausible length given their age. This removed less than 0.1% of the age-length data, and the resulting data were used to calculate the age-length keys for estimating the scaled age frequencies.

Scaled length frequencies were calculated by scaling observed sex and length frequencies in each tow to the catch from that tow, then aggregating over all tows and scaling to a stratum catch. Total aggregated length frequencies were calculated by summing over strata. The scaled length compositions are given in Figure 22.

Age frequencies were then estimated by applying an annual sex specific age-length key, and uncertainty estimates were approximated using bootstrapping. Age observations for the years 1994–1998 were not well recorded on Fisheries New Zealand age databases, and hence age compositions for these years are not available. The resulting age compositions for hake males and females are given, by year, in Figure 23 and as year class strength bubble plots in Figure 24.

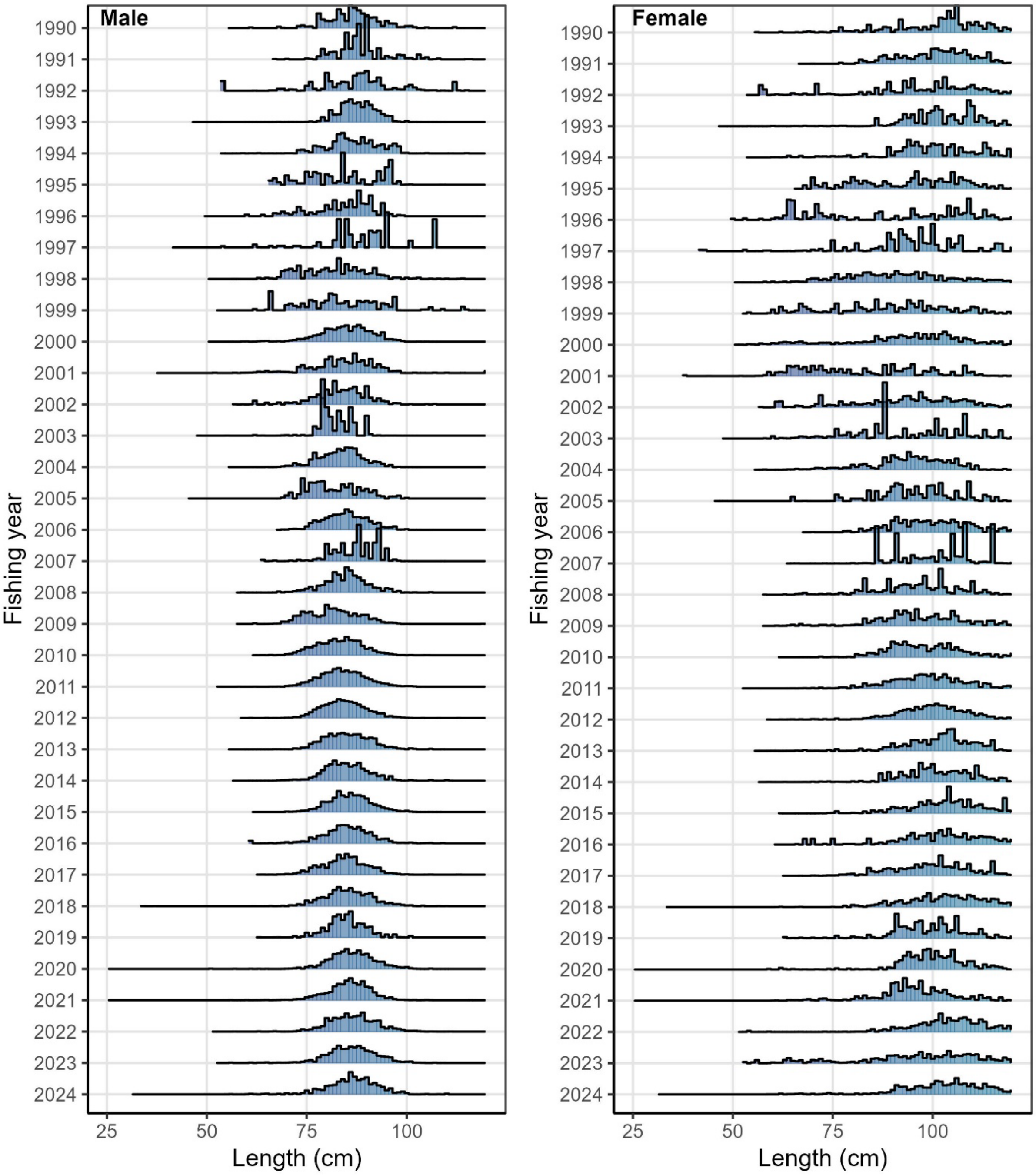

Figure 22: Scaled length frequencies for hake in the Sub-Antarctic for 1989–90 to 2023–24.

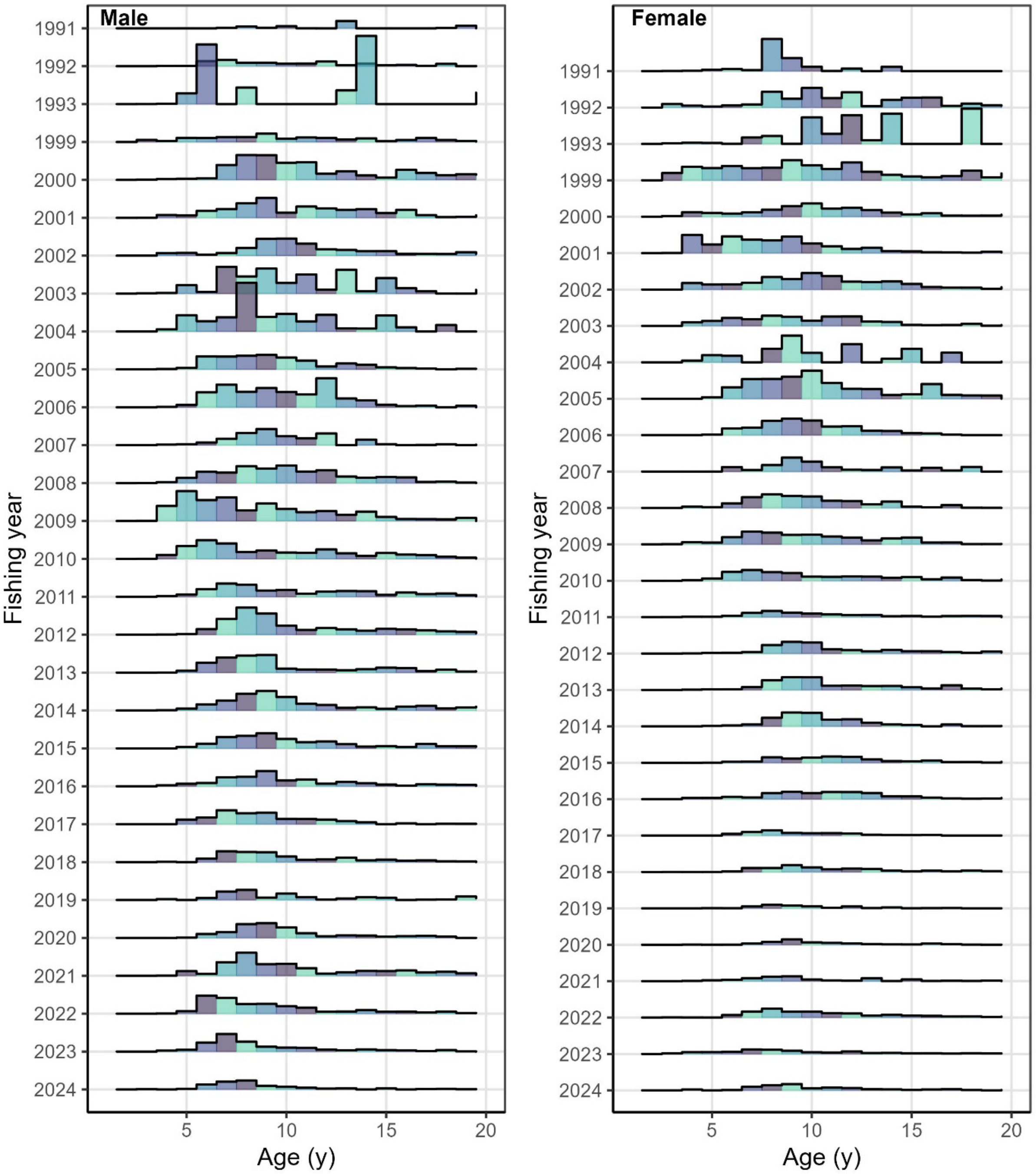

Figure 23: Estimated proportions at age in the Sub-Antarctic for 1989–90 to 2023–24, with YCS progression shown as shaded colours.

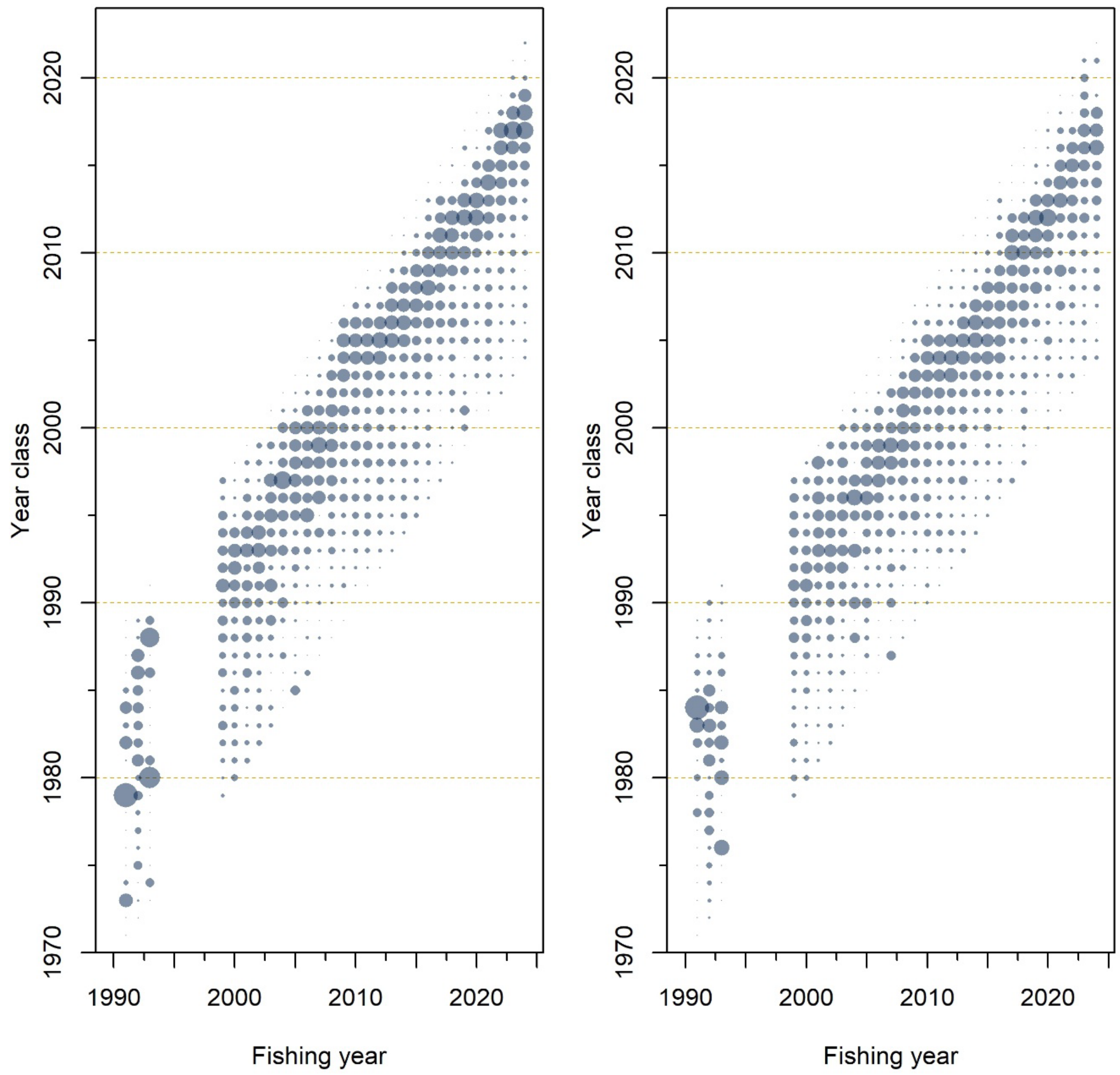

Figure 24: Estimated proportions at age by year class and sex for in the Sub-Antarctic for 1989–90 to 2023–24.

4.3 Growth models

Growth models were last updated by Horn (2008) (with a minor revision by Horn (2013a) who used the same data to estimate a combined-sex growth curve), who estimated Schnute (Schnute 1981) as well as von Bertalanffy curves (von Bertalanffy 1938). In this study, we investigated both the von Bertalanffy curve and Schnute curve using maximum likelihood estimation (MLE) methods (e.g., Dunn & Parker 2019). The von Bertalanffy and a non-parametric monotonically increasing mean length-at-age model were also explored using Bayesian inference. A total of 20 196 age at length observations were available (*n*=7872 female and *n*=12 234 male) for Sub-Antarctic hake, over the years 1990–2024 (Figure 25), with most of the data collected from the fishery and the remainder from surveys

Inspection of the relationship between length and age suggested approximately linear or slightly slowing growth until about age seven for males and age nine for females, with the growth then slowing quickly towards a horizontal asymptote. The changes in growth up to age seven or nine for males and females, respectively, approximately corresponded to the age

of 50% maturity for males and females and hence was consistent with the change from allometric growth to gonadosomatic growth as fish age and mature.
Initially, the available data were used to estimate the growth curve parameters using maximum likelihood estimation (MLE) and Bayesian inference. The von Bertalanffy growth curve was fitted assuming normally distributed errors with a constant coefficient of variation (CV) (*c*) parameterised as a function of mean length. The length-at-age data were assumed to consist of length (*L)* and age (*t)* observations for *n* fish of sex *i*:

$$\bar{L}_i = L_i^{\infty}(1 - \exp(-k_i(t - t_i^0)) + \varepsilon \text{ where } \varepsilon \sim N(0, c\bar{L}_i).$$

where L_∞ is asymptotic length, k is the Brody growth coefficient, t_0 is the age at which the length is zero, L_i the expected length-at-age, and c is a constant CV at length L_i.

The MLE and Bayesian von Bertalanffy growth parameters are given in Table 4, and the MLE von Bertalanffy curves and raw data are plotted in Figure 26. Diagnostic plots of the fits to all ages suggested significant departure from the normal distributional assumptions for fish aged under four, which is likely to be due to length-based selectivity effects at younger ages in which juvenile sized fish were less likely to be caught or sampled. Hence the von Bertalanffy growth models were also refitted using only age data for ages four and over (4+ model). The resulting growth curve was similar to that of the von Bertalanffy estimate of Horn (2008) but with a slightly higher estimate of L_∞.

Although quantile-quantile diagnostic plots for the von Bertalanffy curves suggested that there was no evidence of departure from normally distributed errors with a constant CV, the normalised residual plots by age suggested some evidence of departure of the observed mean lengths from the estimated von Bertalanffy equation (Figure 27). Plots of residuals indicated reasonable fit to the data with the age-length relationship, with small annual fluctuations in the residuals, but no apparent trend over time (Figure 28).

Model estimates of growth from both equations produced very similar relationships between length and age, and neither of these models adequately fit the length data for younger ages (i.e., under four years of age). Hence, we developed a monotonically increasing mean length-at-age model using Bayesian inference, extending the maximum likelihood mean length-at-age approach of Dunn & Parker (2019). In this model, the mean length for each age was estimated, but constrained to be monotonically increasing, with a constant CV (as a function of the mean length-at-age) and normally distributed errors.

Growth models were developed using the R package *brms* which uses Stan (Stan Development Team 2020) to sample from the posterior distribution of the von Bertalanffy model. The Bayesian von Bertalanffy model was defined as:

$$
\begin{aligned}
&L_\infty \sim N(100, 100^2)\\
&k \sim N(0, 100^2)\\
&t_0 \sim N(0, 100^2)\\
&\tau \sim N(0, 100^2)\\
&L_t \sim N(\mu_t, \sigma^2)\\
&\mu_t = L_\infty\left(1 - e^{-k(t - t_0)}\right)\\
&\sigma = \tau\mu_t
\end{aligned}
$$

where L_∞ is asymptotic length, k is the Brody growth coefficient, t_0 is the age at which the length is zero, μ^t is the expected length-at-age, and L_t is the predicted length-at-age.

Model selection was done using the leave-one-out information criterion (LOO IC, see Vehtari et al. 2017) which suggested that the mean length-at-age model provided a more parsimonious fit to the data than that of the von Bertalanffy model (Table 5). Posterior predictive distributions for the mean length-at-age model showed some improvement over the Bayesian von Bertalanffy model (see Figure 29 and Figure 30). Further, the standardised residuals suggest that the mean length-at-age model fit the data better across the full range of observed ages.

However, without any constraint for older fish, the mean length-at-age model estimates of mean length (Figure 31) drifted implausibly high for the older fish when compared with the von Bertalanffy model. This suggests that the monotonic model could be improved by constraining the lengths of older fish where there were few data.

In conclusion, however, there was little difference between the resulting growth curves; the estimates of mean size-at-age and variation about these estimates that resulted from the MLE von Bertalanffy, Bayesian von Bertalanffy, and the mean length-at-age models were very similar and would be very unlikely to result in different outcomes from the choice of curve in a stock assessment.

Table 4: Revised growth parameters (MLE von Bertalanffy, and Bayesian von Bertalanffy) for Sub-Antarctic hake.

Growth curve	Sex	Parameter (units)			MLE	Bayesian
			Horn (2008)	All ages	Ages 4+	Ages 4+
von Bertalanffy	Male	L_∞ (cm)	82.3	90.0	89.0	88.8
		k (y^{-1})	0.357	0.290	0.342	0.354
		t_0 (y)	0.11	-0.39	0.37	0.51
		CV	–	0.07	0.07	0.07
	Female	L_∞ (cm)	99.6	114.9	112.2	111.1
		k (y^{-1})	0.280	0.166	0.194	0.197
		t_0 (y)	0.08	-1.15	-0.39	-0.290
		CV	–	0.09	0.09	0.09

Table 5: The leave-one-out information criterion (LOO IC) for the Bayesian von Bertalanffy and mean length-at-age models (lower LOO IC suggests a more parsimonious model).

Model	LOO IC	
	Female	Male
Bayes von Bertalanffy	80 173.2	53 498.9
Mean length-at-age	79 532.6	45 769.9

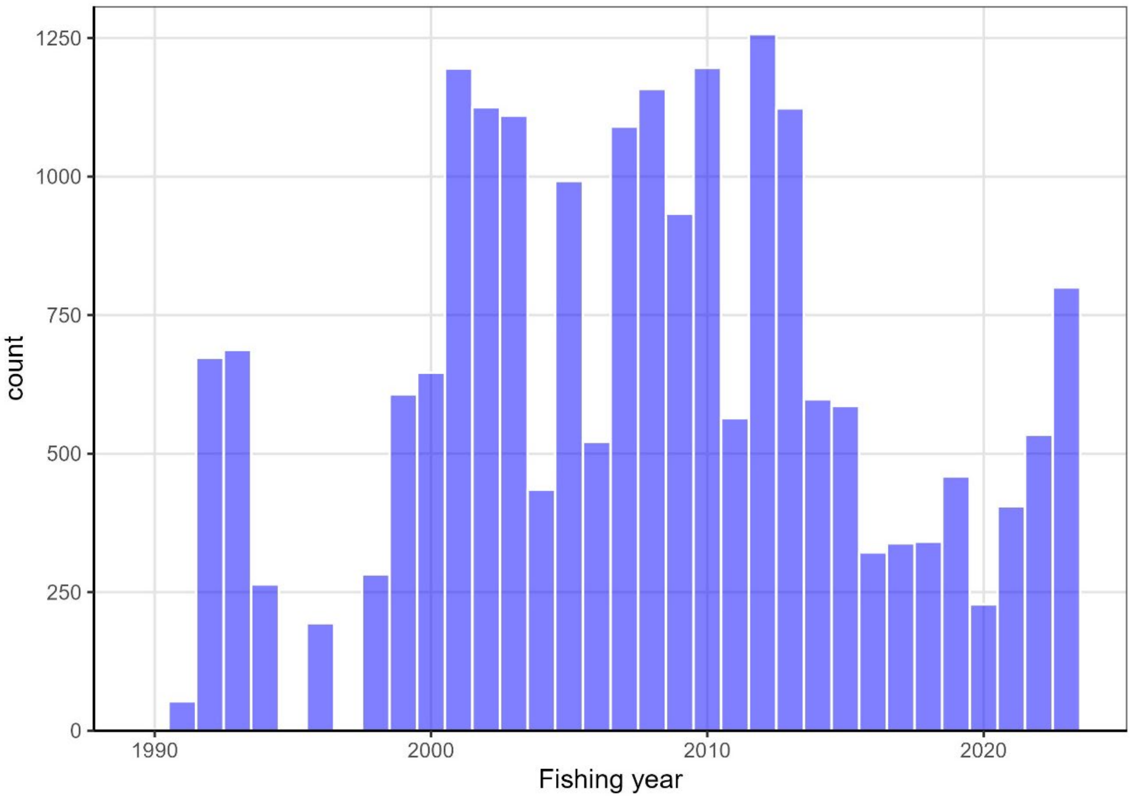

Figure 25: Number of length and age observations in the Sub-Antarctic by fishing year from 1989–90 to 2023–24.

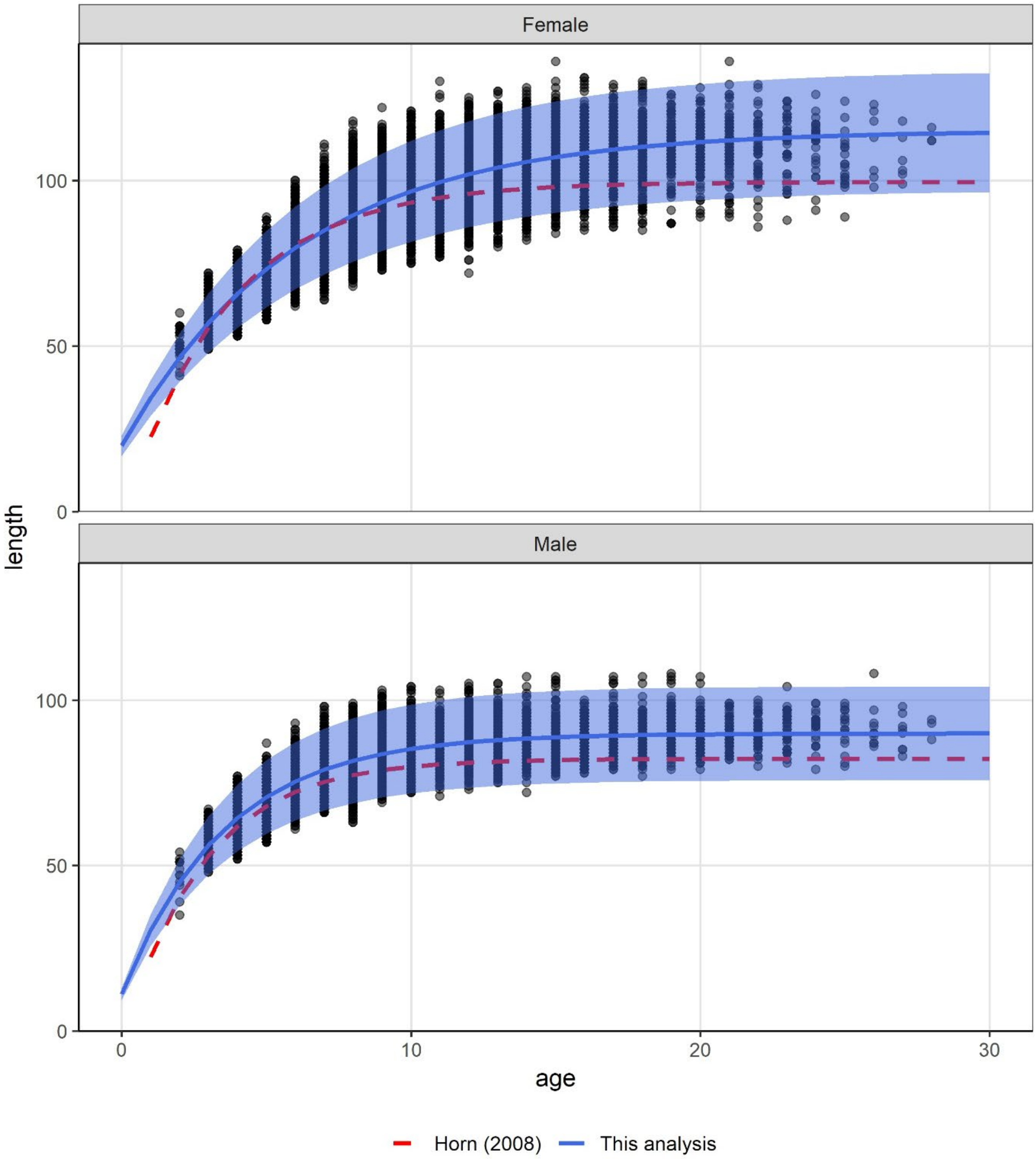

Figure 26: MLE von Bertalanffy growth curves for males (fitted to ages 4+) and females (fitted to ages 4+) for Sub-Antarctic hake, with points showing the observations of age-at-length for males and females (points). Shaded regions show 95% confidence intervals.

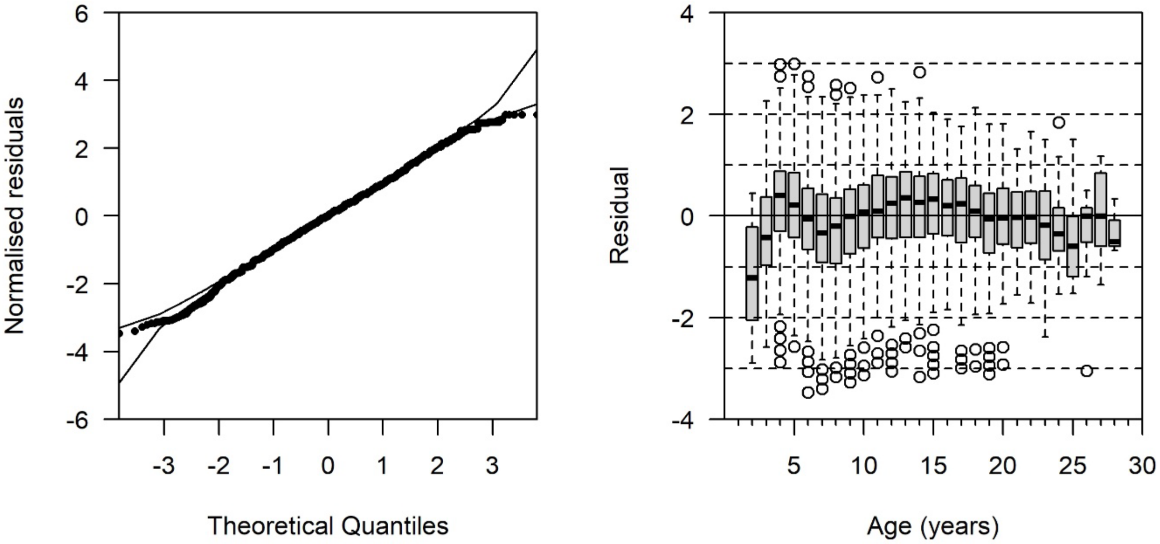

Figure 27: Diagnostic plots for the MLE von Bertalanffy growth curves for male and female hake: (left) quantile-quantile plot of normalised residuals with 95% confidence envelopes; and (right) boxplot of the normalised residuals by age.

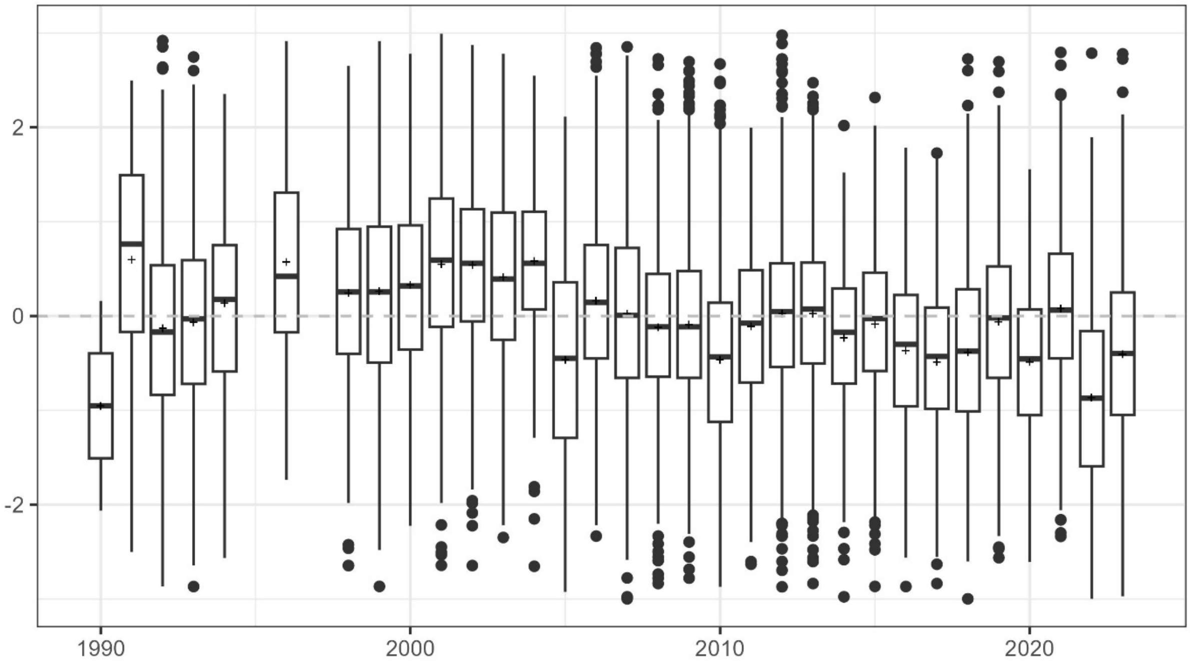

Figure 28: Boxplots of residuals (dark line = median; grey box = interquartile range; and values more than 1.5 times the interquartile range plotted as black circles) by fishing year (1989–90 to 2023–24), of the fitted von Bertalanffy growth relationship for Sub-Antarctic hake, with the residuals for both sexes combined.

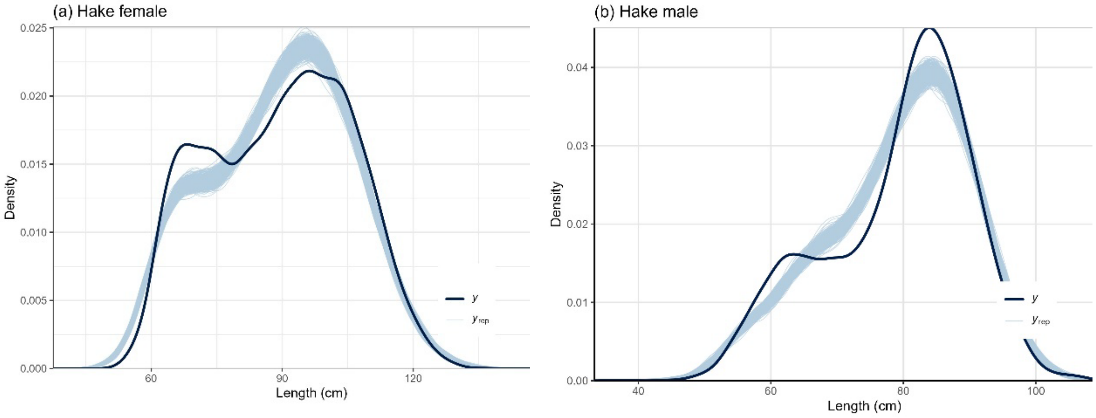

Figure 29: Comparison of the empirical distribution of the data (y) to the posterior predictive distributions of simulated data (y_{rep}) from the Bayesian von Bertalanffy growth model for Sub-Antarctic hake for (a) females and (b) males.

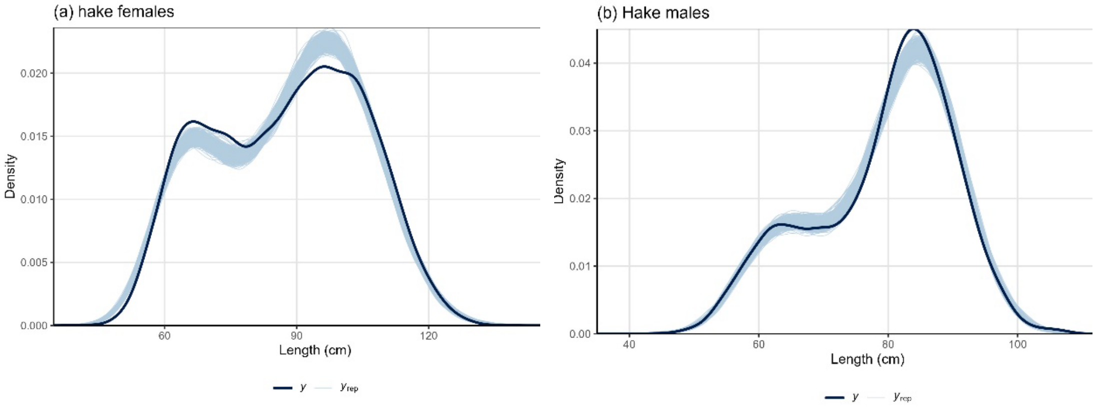

Figure 30: Comparison of the empirical distribution of the data (y) to the posterior predictive distributions of simulated data (y_{rep}) from the mean length-at-age growth model for Sub-Antarctic hake for (a) females and (b) males.

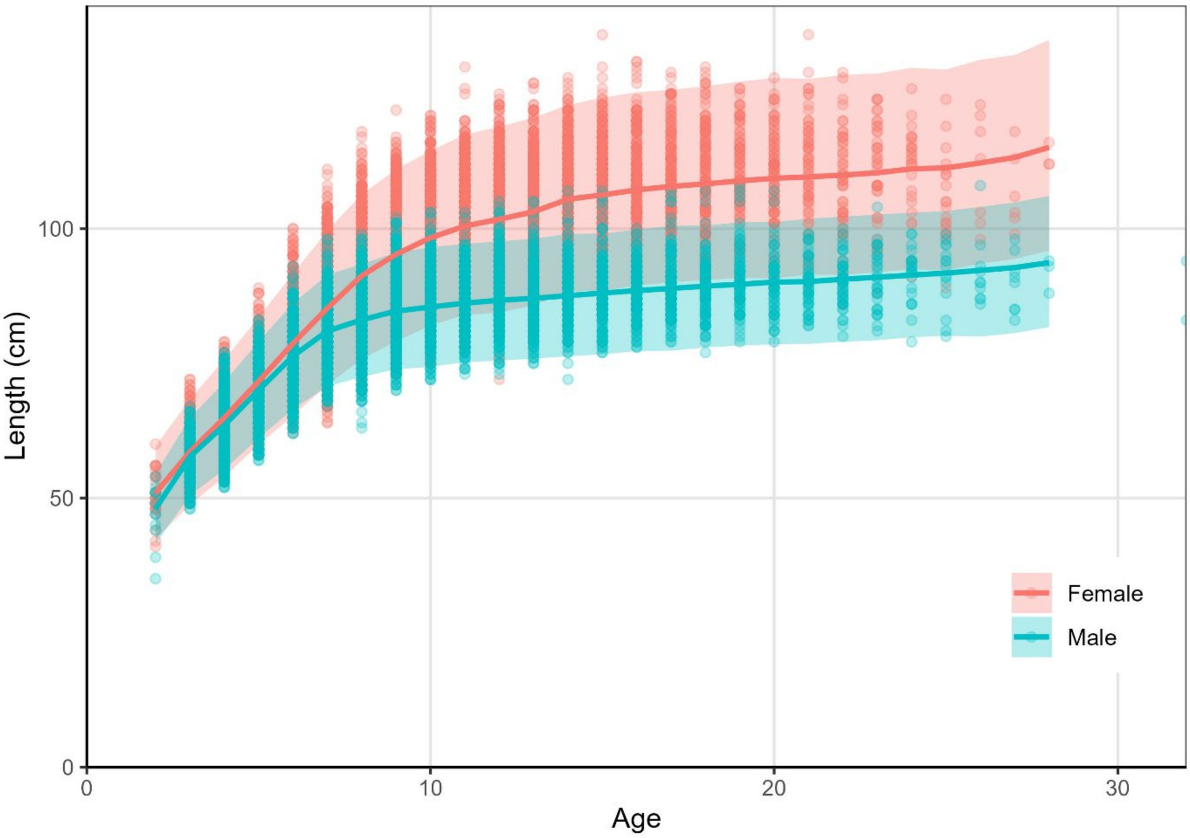

Figure 31: Estimated relationship between length and age from the Bayesian mean-length-at-age monotonic growth model for males (blue) and females (red) for Sub-Antarctic hake, with points showing the observations of age-at-length for males (blue points) and females (red points). Shaded regions show 95% credible intervals.

4.4 Maturity

Horn & Dunn (2007) estimated the maturation ogive (i.e., proportions of immature fish that become mature by age) using resource survey data from the Sub-Antarctic and within an assessment model with maturity in the partition. Hake were classified as either immature or mature at sex and age, where maturity was determined from the gonad stage and gonosomatic index (GSI, the ratio of the gonad weight to body weight). Fish of stage 1 were classified as immature; stage 2 fish were either immature or mature depending on the GSI index, using the definitions of Colman (1998) (i.e., immature if GSI < 0.005 (males) or GSI < 0.015 (females), and mature otherwise); and fish of stages 3–7 were classified as mature. The estimates of maturation were, however, misinterpreted in more recent assessments (Horn 2015, Dunn 2019) that did not have maturity in the partition as a maturity ogive (i.e., an ogive of the proportions of all fish that are mature at age). This resulted in the recent assessment models using a maturity ogive that was incorrectly right shifted by approximately one year. However, spawning in the Subantarctic is assumed to be in January, not September as assumed for the west coast South Island stock, and adjustment for this timing change moved the estimates closer together. Model estimates for maturity were estimated using a binomial GAM using *mgcv* (Wood 2003, 2004, 2011, 2017, Wood et al. 2016) with terms for month, year, and proportions mature. Proportions mature were derived from survey age data where gonad weight and total weight were recorded to be able to calculate GSI.

The available data were from resource surveys between September and March in the Sub-Antarctic (Figure 32). Model fits were good and the resulting maturity curves are given in Figure 33.

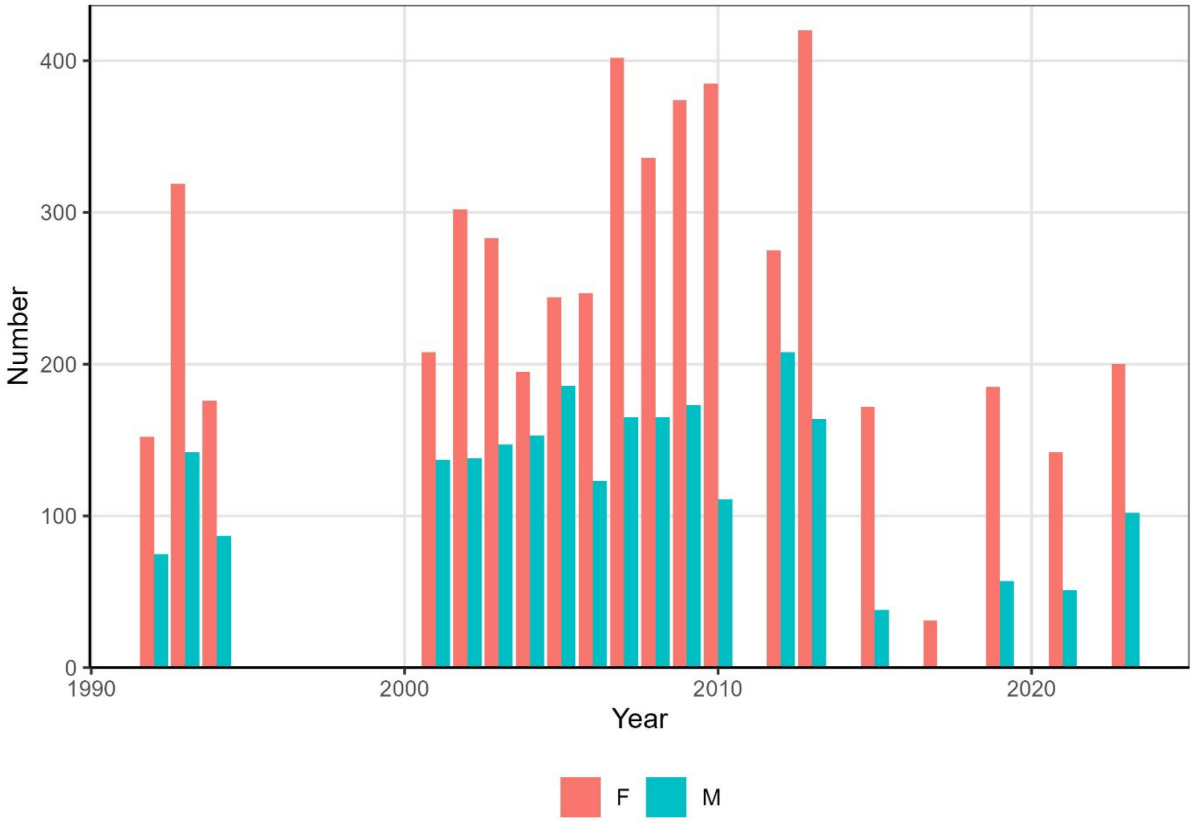

Figure 32: Number of maturity at age observations by sex, in the Sub-Antarctic by fishing year from 1989–90 to 2023–24.

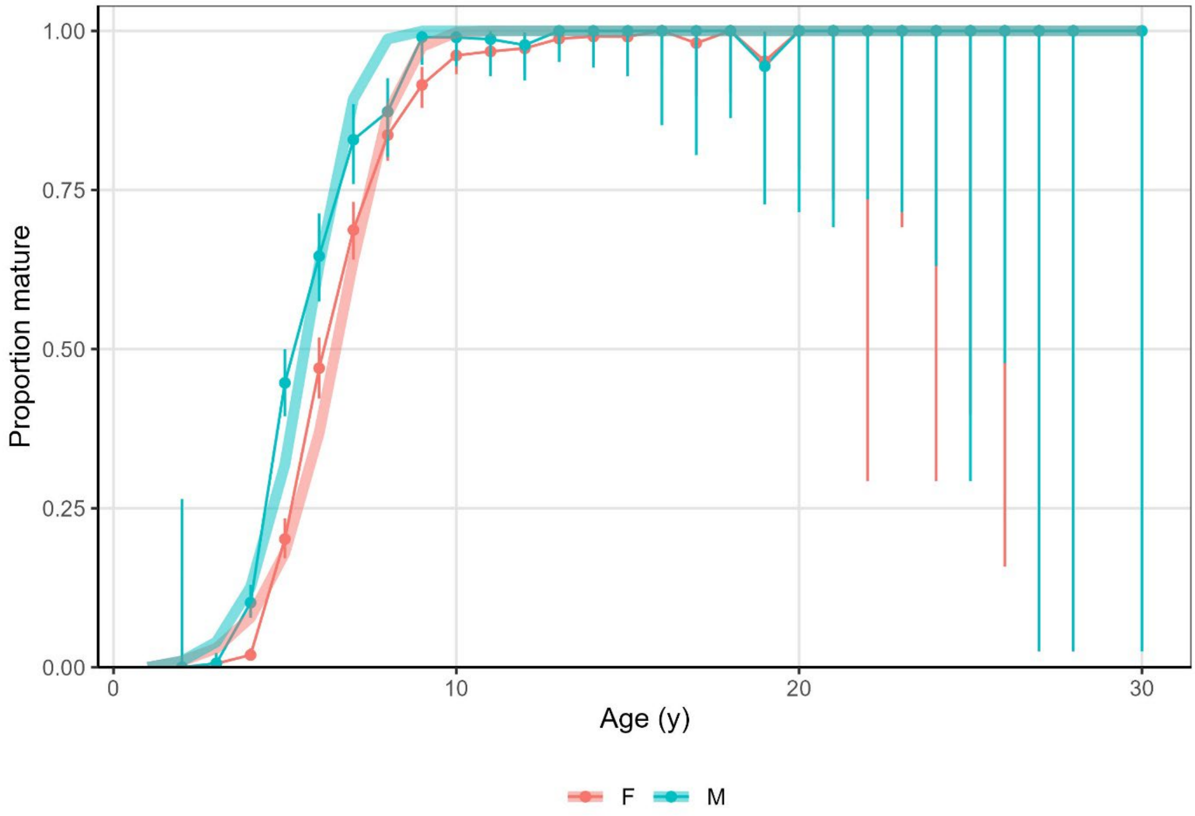

Figure 33: Estimated proportions mature for females (red) and males (blue) using the GAM (bold lines), compared with the estimates of Horn & Dunn (2007) (thin lines and points).

5. CPUE ANALYSES

5.1 Methods

Standardised CPUE indices were generated following the method described by Ballara (2018) and updated using generalised additive models (GAMs) rather than Generalised Linear Models (GLMs).

CPUE indices were calculated for the tow-by-tow data (HOK/HAK/LIN target TCEPR and ERS-trawl tows) using *mgcv* (Wood 2003, 2004, 2011, 2017, Wood et al. 2016). Effort data from catch-effort data other than TCEPR and ERS-trawl data were ignored as these made up only a very small proportion of the total recorded catch of hake in the Sub-Antarctic.

Unstandardised CPUE indices were calculated as the mean of catch (t) per tow for the tow-by-tow data. Standardised indices were calculated using a lognormal and a binomial model, where positive (i.e., non-zero) observations were modelled using a lognormal model and the proportion of zero to non-zero observations modelled as a binomial. The lognormal and binomial models were then combined using the delta-lognormal method to calculate the CPUE index using the approach of Vignaux (1994) and calculated using *gamInflu* (Dunn 2025b).

Initial models were run using similar explanatory variables as used by Dunn et al. (2021a) in the previous analyses. The GAM considered all these terms in the model, but used automatic smoothing parameter selection and variable selection, allowing the model to shrink smooth terms towards zero and effectively remove non-informative predictors from the final model by penalising the smoothing parameters towards infinity (Marra & Wood 2011). The data were filtered to include only bottom trawl (BT) gear using TCEPR and ERS data, vessels ≥28m targeting HAK, HOK, or LIN (to maintain consistency in the vessel selection between TCEPR and ERS data), fished in Statistical Areas 033, 034, 035, or 703, and with core vessels defined as those present ≥5 years with ≥20 tows per year, and using tows with bottom depths from 150–1000 m and a fishing duration of 0.2–15 hours. Extreme (and implausible) catches > 50 t and vessels that had been identified as a vessel that misreported catch were also excluded.

The core vessel subset was defined to ensure that the catch data represented vessels with a consistent presence in the fishery, using a consistent method, over a consistent area.; and had reported a minimum of 20 tows in each year. The core vessel data set was then created from all those vessels with a presence of at least five years in the fishery (comprising 90% of the total reported catch). This resulted in a data set comprising 77 unique vessels (Figure 34), and the relative contribution of effort in each year of each vessel is shown in Figure 35.

For positive catch records, a lognormal model was used where log(catch) was modelled as:

log(CPUE) ~ year + stratum + s(month, by=stratum, bs="cc", k=6) + s(vessel, bs="re") +
target + s(BottomDepth, bs="ts", k=6) + s(FishingDuration, bs="ts", k=6) +
te(long, lat, k=c(6,6))

With the terms:

- year: Fixed effect of fishing year
- stratum: Fixed effect of spatial stratum
- s(month, by=stratum, bs="cc"): Cyclic cubic spline of month varying by stratum
- s(vessel, bs="re"): Random effect of vessel
- target: Fixed effect of target species
- s(BottomDepth, bs="ts"): Thin plate spline of bottom depth
- s(FishingDuration. Bs = "ts"): Thin plate spline of fishing duration
- te(long, lat): Tensor product smooth of longitude and latitude

For the probability of positive tows, the binomial model was;

P(!zero) ~ year + stratum + s(month, by=stratum, bs="cc", k=6) + s(vessel, bs="re") +
target + s(BottomDepth, bs="ts", k=6) + s(FishingDuration, bs="ts", k=6) +
te(long, lat, k=c(6,6))

With the same definition of terms as for the positive catch model.

The final CPUE index combined predictions from both models, multiplying the lognormal model predictions (positive catch rates) by the binomial model predictions (probability of positive catch).

Model fits were investigated using standard residual diagnostics and plots. For each model, a plot of residuals against fitted values and quantile-quantile plots were evaluated to check for departures from model assumptions. Influence plots (Bentley et al. 2012, Dunn 2025b) were made for each variable in the CPUE standardisation, which show the effect of each variable on the standardisations and the annual influence of each variable. Post model residual analysis was carried out (see residual pattern analysis in Dunn 2025b) to identify whether any additional parameters should be considered in the model.

In addition to the model across all strata, CPUE indices were estimated for the four strata areas definition identified in the spatial analysis (see Section 3 above), i.e., ‘youngest’, ‘young’, ‘medium’, and ‘old’ strata separately.

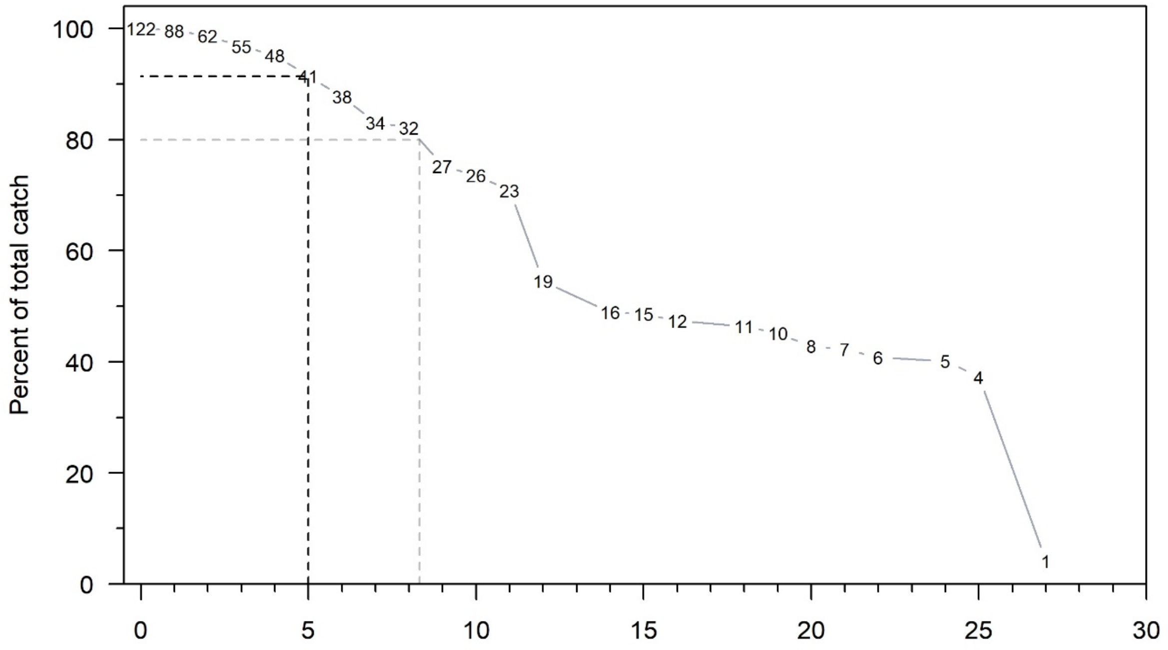

Figure 34: Percentage of catch for different numbers of years in the fishery used to determine core vessels in the tow-by-tow CPUE standardisation in the Sub-Antarctic. Dashed lines indicate the effect of selecting the years in the fishery for core vessels that give 90% of total catch (77 vessels) or 80% of total catch (52 vessels).

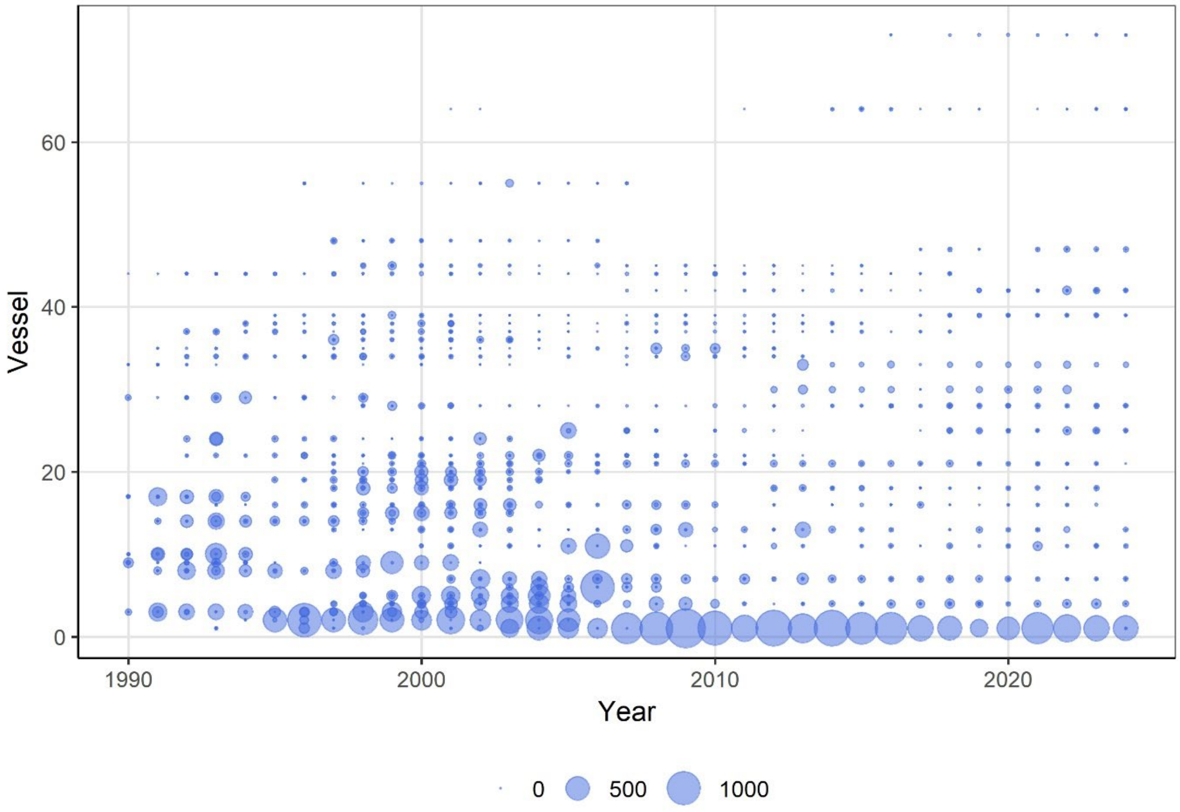

Figure 35: Relative effort by vessel and fishing year for the core data used in the tow-by-tow CPUE standardisation, in the Sub-Antarctic for 1989–90 to 2023–24.

5.2 Results

The positive catch model had an r^2 of 44.5% (Table 6). The standardised lognormal CPUE indices suggested generally flat indices up to about 2010 and a small increase after (Figure 36). The model for the binomial CPUE model showed a small decline up to 2005 and was then flat until 2018 (Figure 36). The model had an r^2 of 29% (Table 8) and the effect of the binomial on the overall index was to moderate the changes observed in the lognormal indices.

The combined index is given in Table 7 and Figure 37. Trends in the combined indices were similar to that reported by Finucci (2019) for the period where these indices overlapped, but both were different in pattern to the observed trend in the trawl survey biomass index over the same period.

For both the lognormal and the binomial models, the residual plots were adequate. Influence plots for the lognormal model indicated that changes in *target species* (Figure 38), *vessel* (Figure 39), *fishing depth* (Figure 40), *fishing duration* (Figure 41), *month* (Figure 42) and *longitude/latitude* (Figure 43) correspond to a significant change in the influence on the index in the mid-2000s.

The combined CPUE indices fluctuated higher in the late 1990s, then declined to a low in 2008, before fluctuating up again in 2012 and then declining thereafter. However, the tow-by-tow is less optimistic in the most recent years, decreasing over recent years. However, the pattern of change in the mid-2000s more likely mirrored the changes in the annual catch of hoki, the dominant target species on the west coast South Island, and the spatial concentration of the fishery on the Stewart-Snares shelf rather than the relative abundance of hake.

Diagnostic plots of the indices were similar for each of the models and did not suggest strong evidence of departure from model assumptions, albeit the residuals for the lognormal did suggest some overdispersion. Interpretation of the changes that may have occurred in reporting with the introduction of the ERS-trawl forms introduces a potential confounding factor into the interpretation of the indices. In particular, vessels that only reported on the TCEPR forms are now included with all trawl vessels. Sub-setting the data to those with a recorded length of > 28 m reduces the influence of additional vessels on the analysis, as does the choice of a long period of presence in the data required for the inclusion as a core vessel.

Applying the combined model to each of the 4-strata separately resulted in indices that suggested that different age classes had different patterns (Figure 44). The 'youngest' and 'young' categories had a flatter index over time, with a reduction only in recent years. However, the 'old' more closely reflected the trawl survey indices, showing a general decline since about 2005. There was insufficient data for the 'medium' index to show a clear trend.

Table 6: The parameters for the lognormal tow-by-tow CPUE model, degrees of freedom (df) for each variable, the effective degrees of freedom (smooth terms, edf), log-likelihood (-logLik), AIC, and r^2 value for each term.

	Term	df	edf	-logLik	AIC	r^2
1	*Intercept*	0	0	-78 912.76	157 829.5	–
2	*Year*	34	0	-77 377.33	154 826.7	0.063
3	*Stratum*	3	0	-77 022.53	154 123.1	0.077
4	*Month*	7.6	7.6	-75 576.14	151 245.5	0.132
5	*Vessel*	40.1	40.1	-69 667.84	139 509.1	0.324
6	*Target*	2.0	0.04	-67 019.28	134 216.0	0.396
7	*Bottom depth*	4.6	4.6	-66 685.22	133 557.2	0.404
8	*Fishing duration*	2.6	2.6	-66 500.90	133 193.8	0.409
9	*Long/lat*	32.6	32.6	-65 017.50	130 292.2	0.445

Table 7: Lognormal, binomial, and combined indices (with 95% confidence intervals and CV) for the tow-by-tow GLM CPUE index 1990–2021.

Year	Lognormal		Binomial		Combined	
	Index (95% CIs)	CV	Index (95% CIs)	CV	Index (95% CIs)	CV
1990	0.92 (0.71–1.19)	0.13	0.50 (0.39–0.61)	0.11	1.30 (0.86–1.75)	0.17
1991	1.28 (1.05–1.57)	0.10	0.52 (0.43–0.62)	0.09	1.91 (1.39–2.43)	0.14
1992	1.00 (0.82–1.21)	0.10	0.65 (0.56–0.72)	0.06	1.83 (1.41–2.25)	0.12
1993	1.39 (1.14–1.69)	0.10	0.55 (0.47–0.64)	0.08	2.18 (1.64–2.73)	0.13
1994	1.20 (0.98–1.46)	0.10	0.53 (0.44–0.62)	0.08	1.81 (1.35–2.28)	0.13
1995	0.95 (0.79–1.16)	0.10	0.48 (0.39–0.56)	0.09	1.29 (0.95–1.63)	0.14
1996	1.05 (0.86–1.27)	0.10	0.33 (0.26–0.41)	0.12	0.98 (0.68–1.27)	0.15
1997	1.06 (0.87–1.28)	0.10	0.38 (0.30–0.46)	0.11	1.14 (0.81–1.46)	0.15
1998	1.07 (0.89–1.29)	0.10	0.52 (0.44–0.60)	0.08	1.57 (1.19–1.96)	0.13
1999	1.13 (0.93–1.36)	0.10	0.56 (0.48–0.64)	0.08	1.79 (1.36–2.22)	0.12
2000	1.29 (1.07–1.55)	0.10	0.50 (0.41–0.58)	0.08	1.81 (1.36–2.27)	0.13
2001	1.18 (0.98–1.42)	0.10	0.44 (0.36–0.52)	0.09	1.47 (1.09–1.86)	0.13
2002	1.12 (0.93–1.34)	0.09	0.39 (0.31–0.47)	0.10	1.23 (0.89–1.56)	0.14
2003	1.12 (0.93–1.36)	0.10	0.31 (0.25–0.39)	0.12	1.00 (0.71–1.29)	0.15
2004	1.38 (1.14–1.66)	0.10	0.35 (0.28–0.43)	0.11	1.37 (0.98–1.76)	0.15
2005	1.12 (0.92–1.35)	0.10	0.26 (0.20–0.33)	0.13	0.84 (0.57–1.10)	0.16
2006	1.51 (1.25–1.83)	0.10	0.19 (0.14–0.25)	0.14	0.82 (0.55–1.10)	0.17
2007	1.12 (0.93–1.36)	0.10	0.19 (0.14–0.24)	0.14	0.59 (0.40–0.79)	0.17
2008	1.04 (0.86–1.26)	0.10	0.26 (0.20–0.33)	0.13	0.78 (0.54–1.02)	0.16
2009	1.09 (0.90–1.32)	0.10	0.32 (0.25–0.40)	0.12	1.00 (0.70–1.30)	0.15
2010	1.12 (0.92–1.37)	0.10	0.31 (0.24–0.39)	0.13	0.99 (0.68–1.30)	0.16
2011	0.97 (0.79–1.19)	0.10	0.31 (0.24–0.39)	0.13	0.85 (0.58–1.12)	0.16
2012	0.97 (0.80–1.18)	0.10	0.36 (0.28–0.44)	0.12	0.98 (0.68–1.27)	0.15
2013	1.25 (1.03–1.52)	0.10	0.25 (0.19–0.31)	0.13	0.87 (0.59–1.15)	0.16
2014	0.88 (0.72–1.07)	0.10	0.19 (0.14–0.25)	0.14	0.47 (0.31–0.63)	0.17

2015	0.80 (0.66–0.98)	0.10	0.22 (0.17–0.29)	0.14	0.50 (0.34–0.67)	0.17
2016	0.98 (0.81–1.20)	0.10	0.23 (0.18–0.30)	0.14	0.65 (0.43–0.86)	0.17
2017	0.83 (0.68–1.01)	0.10	0.18 (0.13–0.23)	0.15	0.42 (0.27–0.57)	0.18
2018	0.81 (0.67–0.98)	0.10	0.42 (0.34–0.50)	0.10	0.96 (0.70–1.23)	0.14
2019	0.74 (0.61–0.89)	0.10	0.50 (0.41–0.58)	0.09	1.04 (0.77–1.31)	0.13
2020	0.69 (0.57–0.84)	0.10	0.38 (0.30–0.46)	0.11	0.74 (0.53–0.96)	0.15
2021	0.86 (0.71–1.05)	0.10	0.38 (0.30–0.46)	0.11	0.92 (0.66–1.19)	0.15
2022	0.69 (0.57–0.83)	0.10	0.46 (0.38–0.55)	0.10	0.90 (0.66–1.14)	0.14
2023	0.65 (0.54–0.79)	0.10	0.33 (0.26–0.41)	0.12	0.61 (0.43–0.79)	0.15
2024	0.59 (0.49–0.72)	0.10	0.33 (0.26–0.41)	0.12	0.55 (0.39–0.72)	0.15

Table 8: The parameters for the binomial tow-by-tow CPUE model, degrees of freedom (df) for each variable, the effective degrees of freedom (smooth terms, edf), log-likelihood (-logLik), AIC, and r^2 value for each term.

	Term	df	edf	-logLik	AIC	r^2
1	*Intercept*	0.00	0.00	-57376.5	114755.0	0.00
2	*Year*	34.00	0.00	-55853.5	111777.0	0.04
3	*Stratum*	3.00	0.00	-52622.3	105320.5	0.10
4	*Month*	10.47	10.47	-52073.2	104243.3	0.12
5	*Vessel*	39.36	39.36	-49667.8	99511.2	0.17
6	*Target*	1.99	-0.01	-48595.7	97371.0	0.19
7	*Bottom depth*	5.11	5.11	-46163.0	92515.8	0.24
8	*Fishing duration*	3.73	3.73	-45972.8	92142.8	0.24
9	*Long/lat*	32.38	32.38	-43543.4	87349.0	0.29

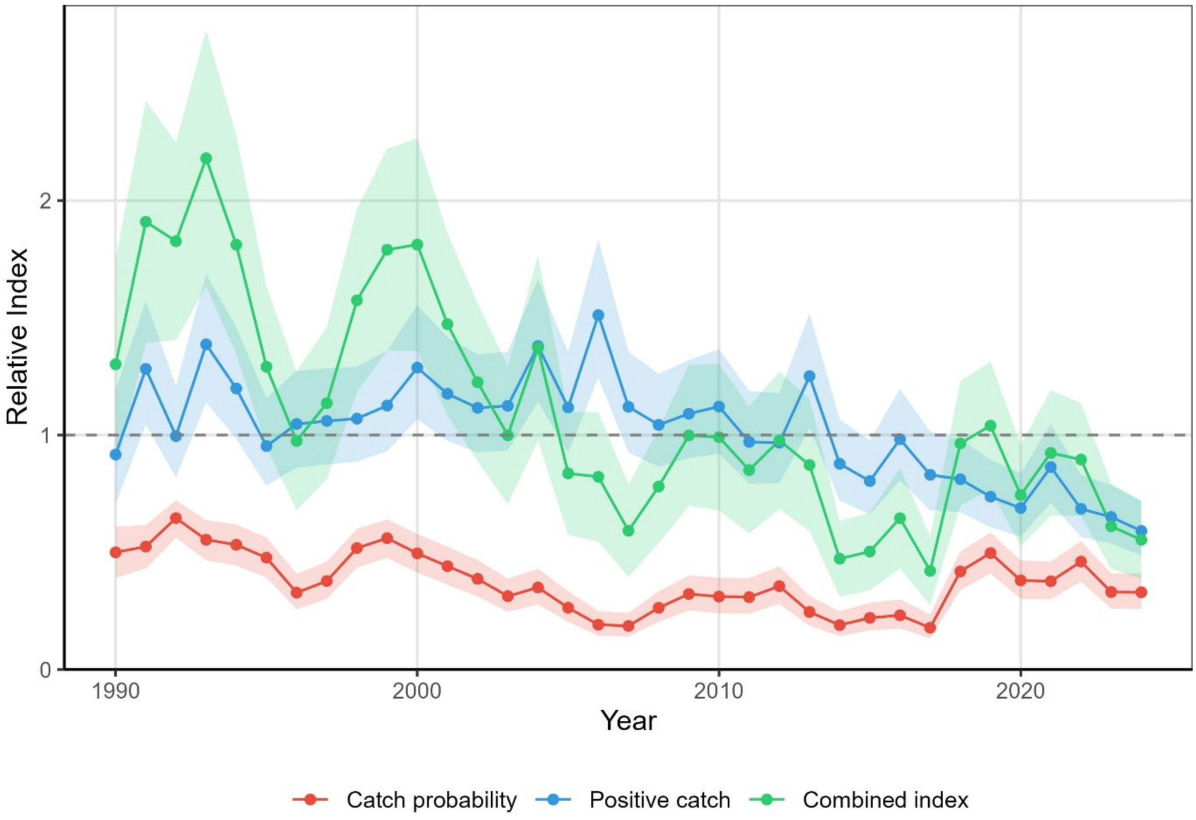

Figure 36: CPUE indices for the tow-by-tow analysis for the lognormal, binomial, and combined indices by fishing year, from 1990–91 to 2023–24.

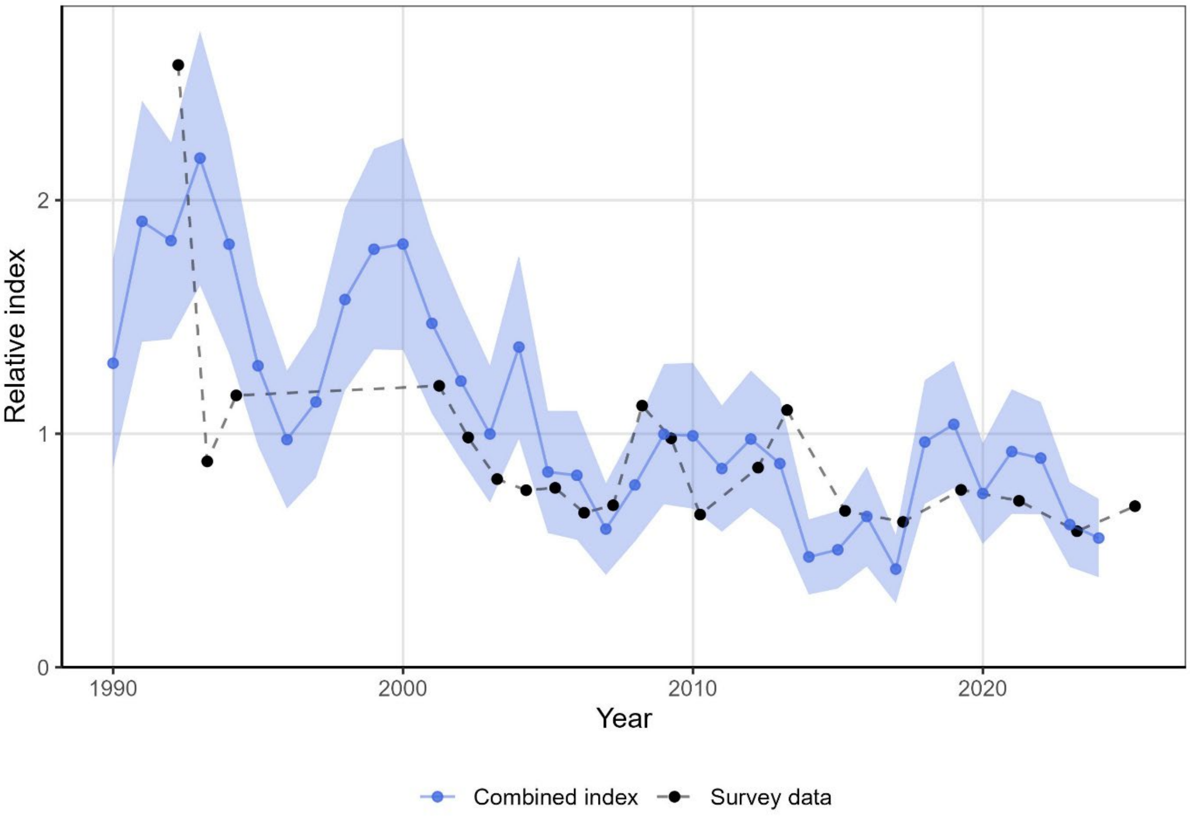

Figure 37: Combined CPUE indices for the tow-by-tow analysis, compared with the Sub-Antarctic trawl survey biomass index (survey) by fishing year, from 1990–91 to 2020–21.

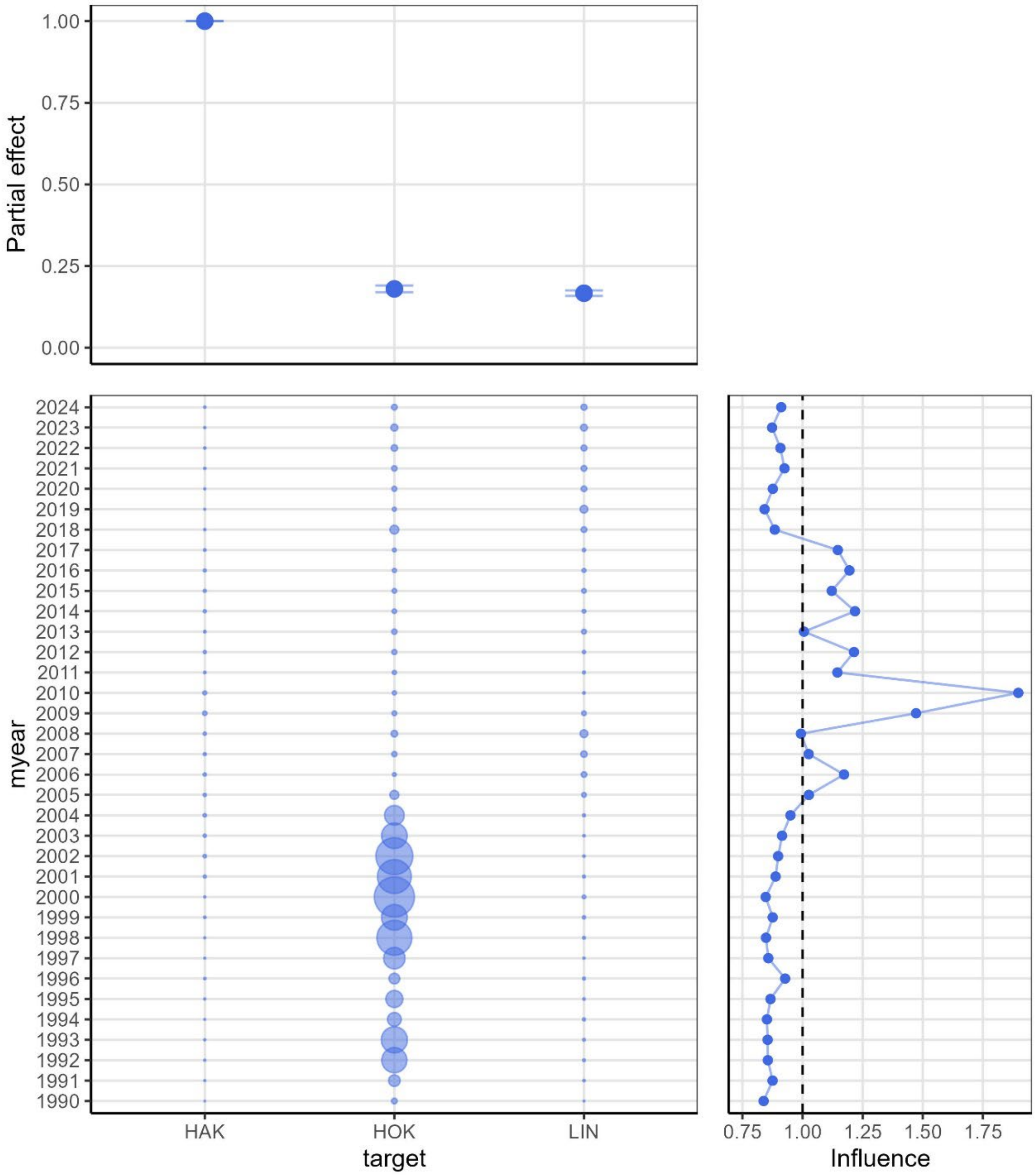

Figure 38: Influence plots of the effect of target species on the lognormal CPUE indices for the tow-by-tow analysis.

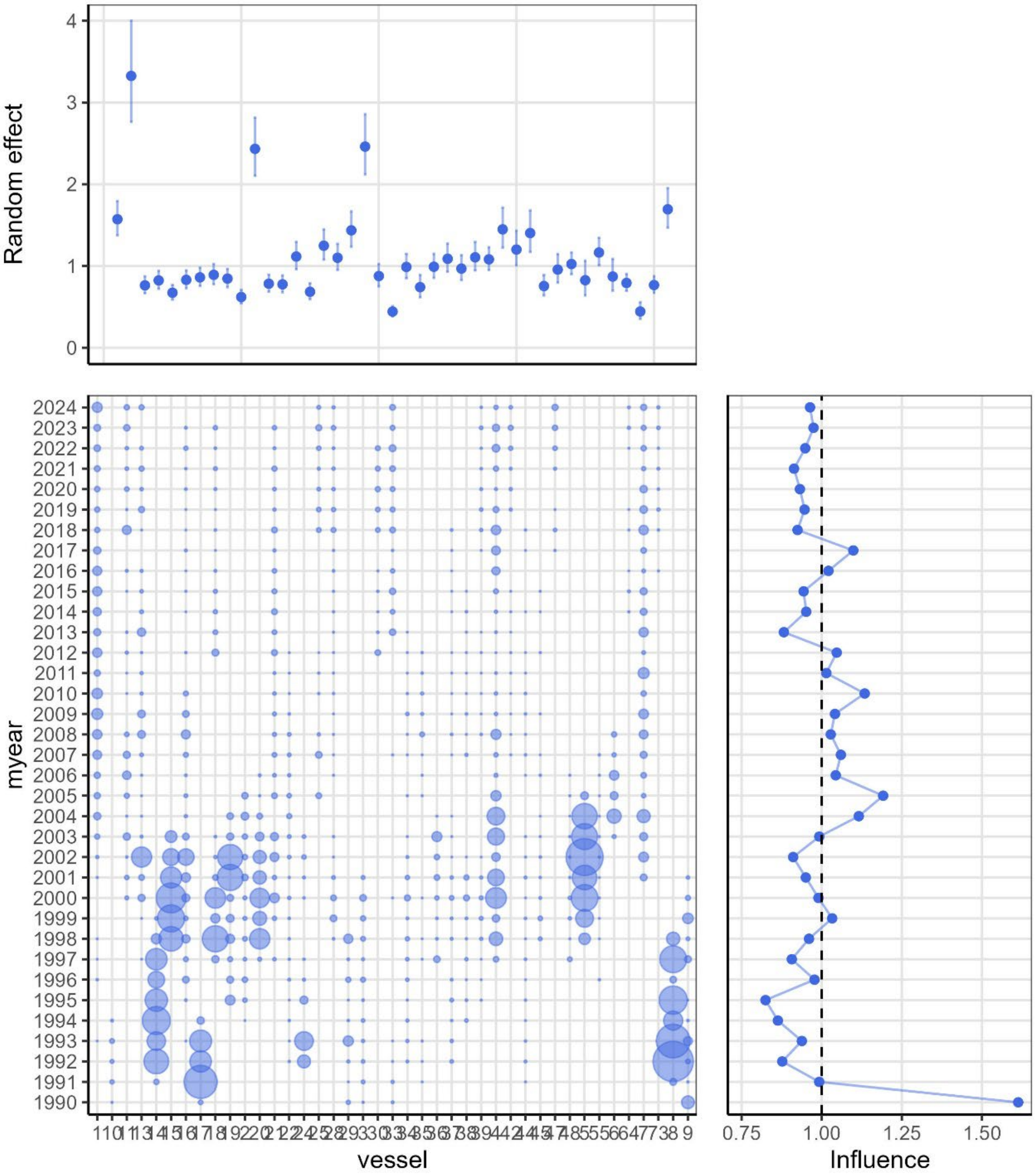

Figure 39: Influence plots of the effect of vessel on the lognormal CPUE indices for the tow-by-tow analysis.

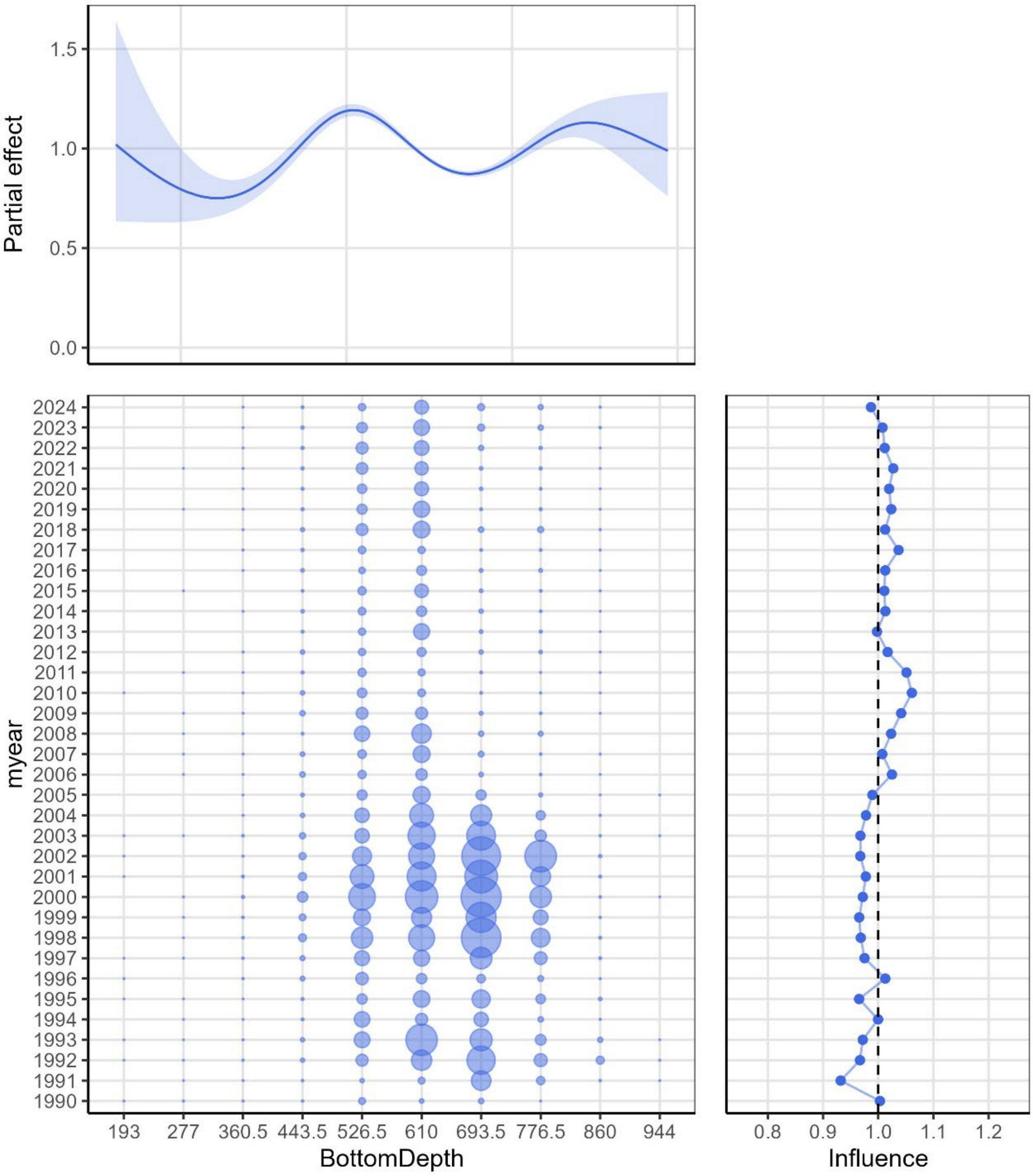

Figure 40: Influence plots of the effect of fishing depth (m) on the lognormal CPUE indices for the tow-by-tow analysis.

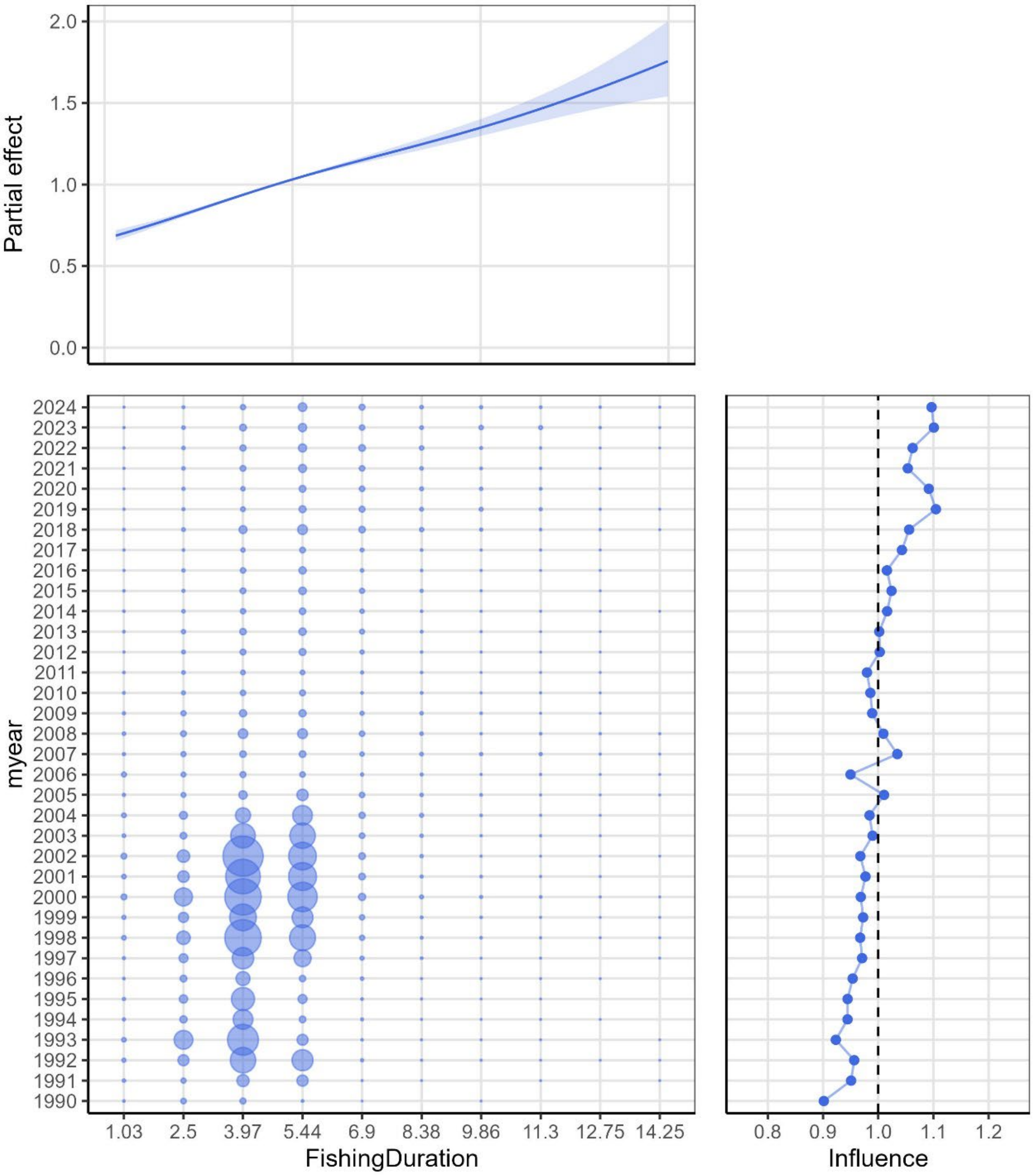

Figure 41: Influence plots of the effect of fishing duration (hr) on the lognormal CPUE indices for the tow-by-tow analysis.

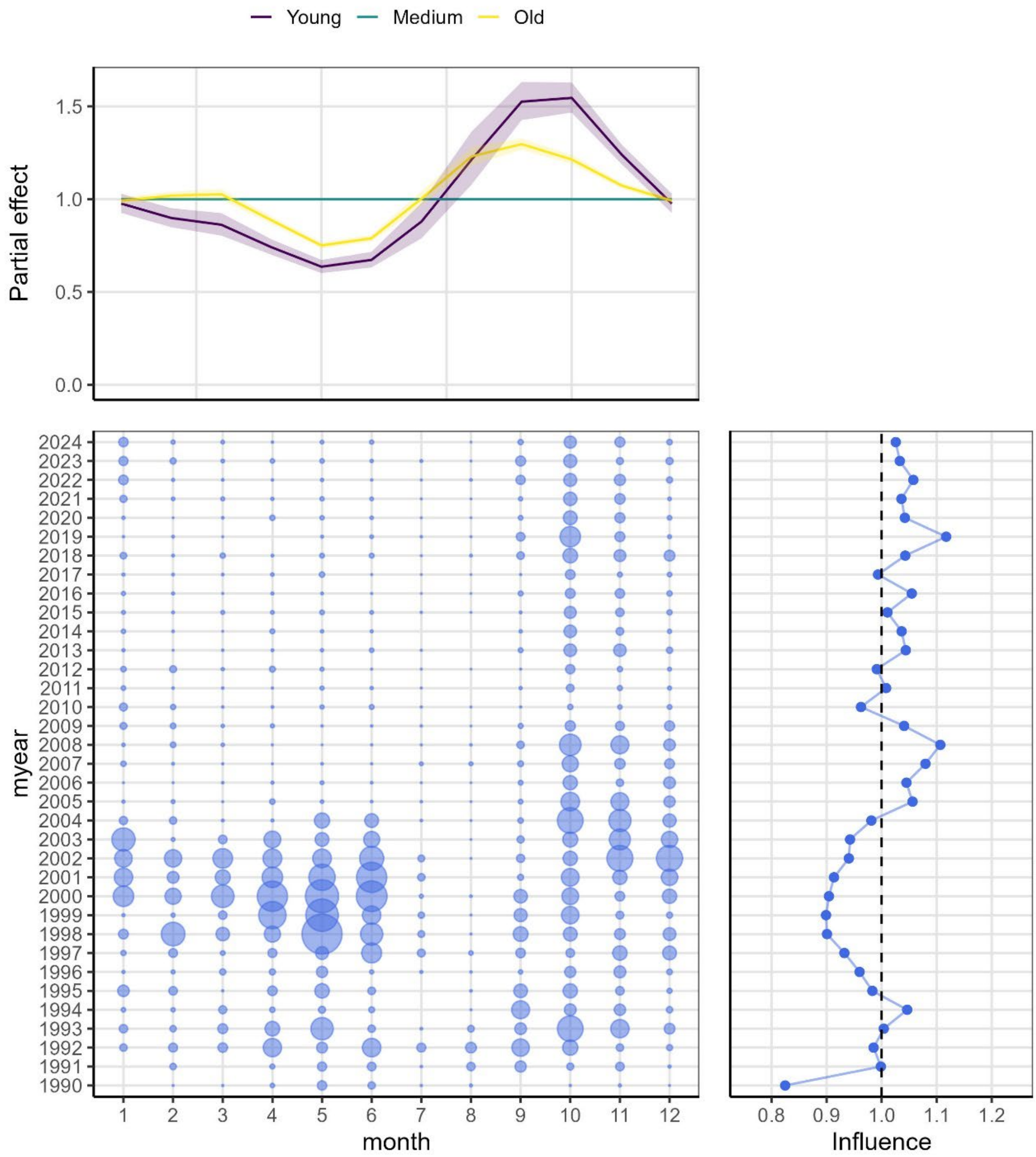

Figure 42: Influence plots of the effect of month on the lognormal CPUE indices for the tow-by-tow analysis.

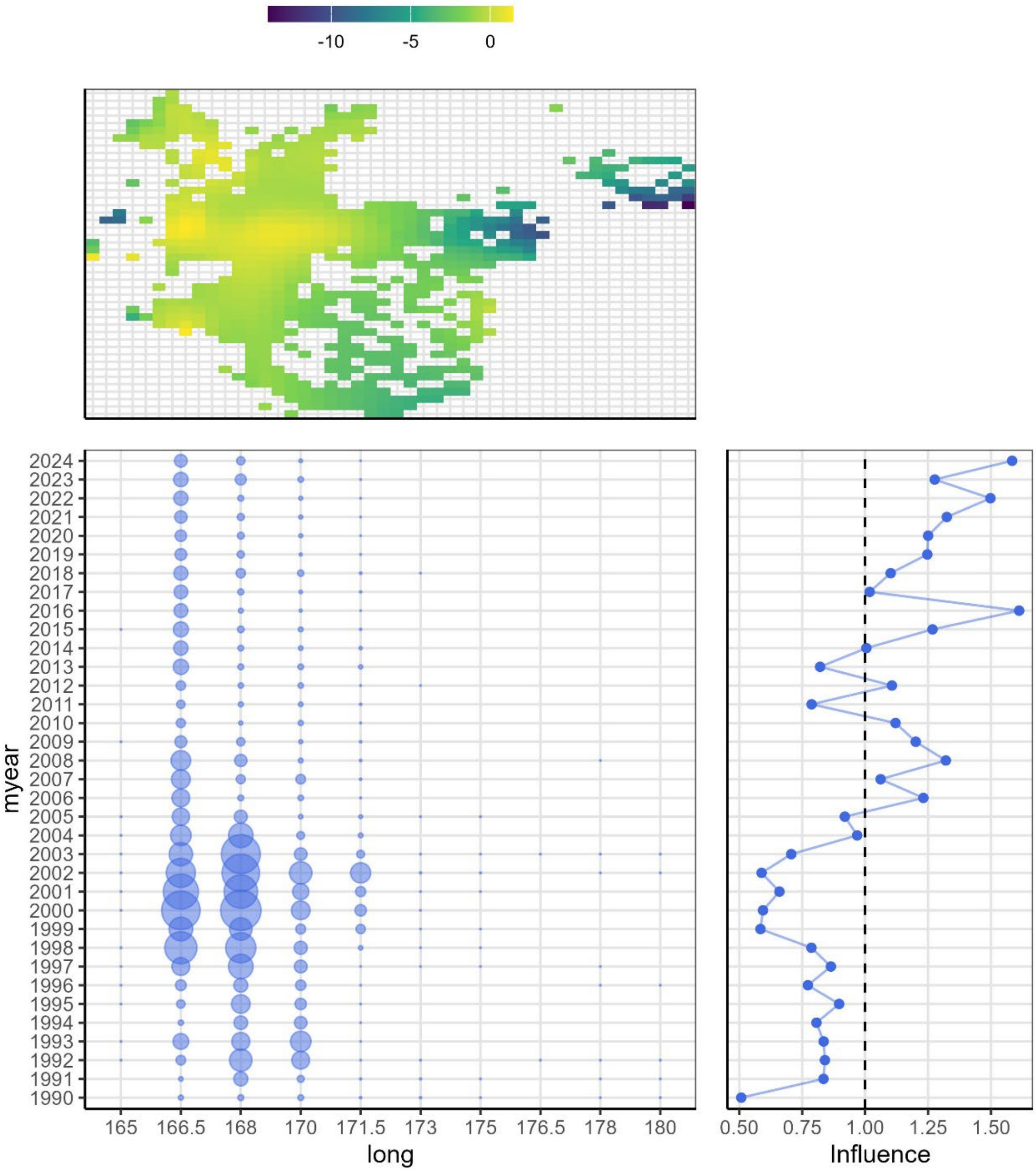

Figure 43: Influence plots of the effect of longitude on the lognormal CPUE indices for the tow-by-tow analysis.

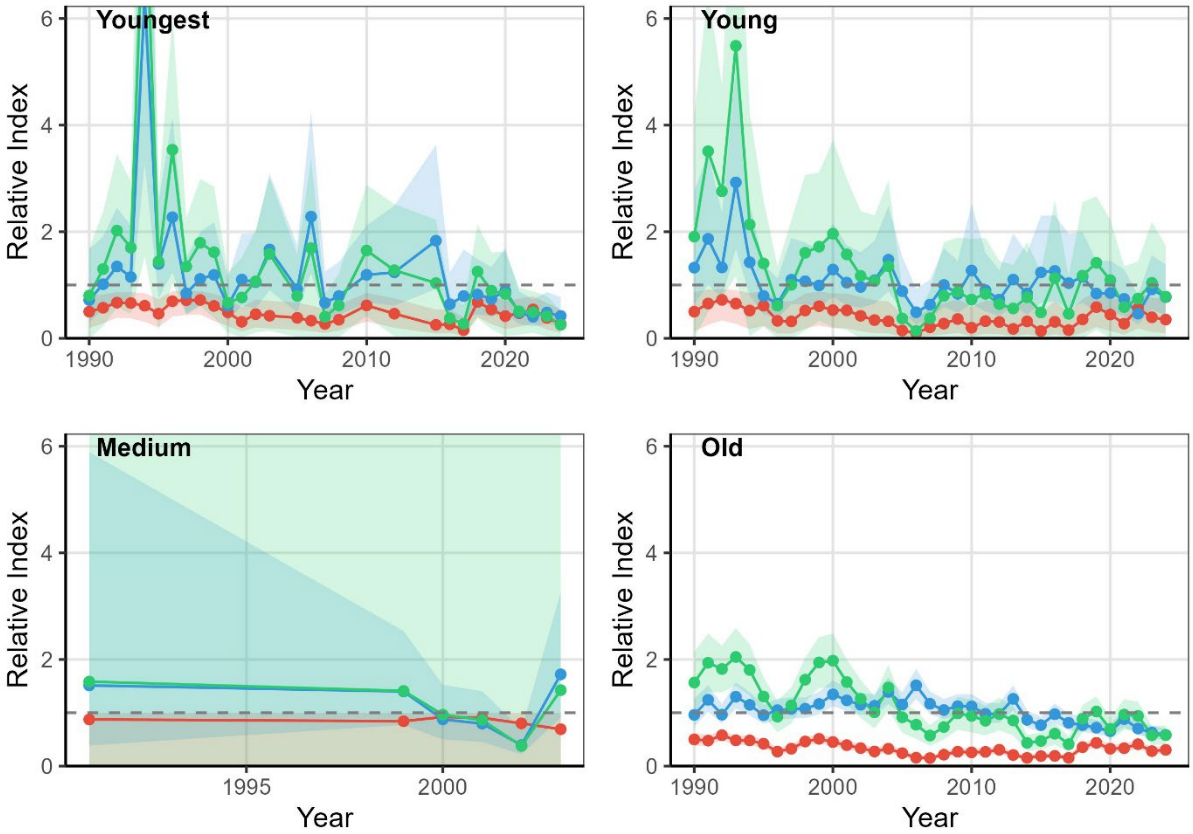

Figure 44: Combined CPUE indices for the four strata (youngest, young, medium, and old) for the tow-by-tow analysis for the lognormal (blue), binomial (red), and combined indices (green) by fishing year, from 1990–91 to 2023–24.

5.3 Monitoring of changes that may be due to climate change and environmental variability

Pinkerton et al. (2018, 2023) proposed methods for a qualitative evaluation of potential effects of environmental or climate change on the stock assessment. This approach evaluates where productivity may have changed due to environmental fluctuations or climate change and hence may be important to consider in the scientific or management advice for the stock. A summary of the qualitative evaluation determined by the Deepwater Working Group is given in Table 9.

Table 9: Summary of the changes that may be due to climate change and environmental variability for Sub Antarctic hake.

Parameter	Summary
Recruitment	There have potentially been changes in mean recruitment after the mid-1980s, but there was no evidence of strong change in mean recruitment since about 1985
Age-at-maturity	There was an observed drop in the age of maturity from the early 2000s. The age of 50% maturity reduced by almost 1.5 years between 2003 and 2012, before increasing again by about 1 year to 2023
Stock recruitment steepness and variability	It is not known if there have been changes in the stock-recruit steepness parameter (*h*). Variability in recruitment has remained relatively constant since about the mid-1980s, however, stock size has remained high and changes in steepness may not be apparent
Natural mortality	There was no information to determine if there have been changes in natural mortality over time
Growth	Growth model (von Bertalanffy) residuals by year of observation and year indicates some annual variability in growth, but there was no clear trend over time

Length-weight	There was some evidence for females that they were heavier fish at length in the early 1990s
Spatial distribution	Based on the trawl survey distributions, there was no evidence of spatial distribution changes over time. The fishery has concentrated into a smaller area since the mid-2000s, but is more likely to be the result of effort reduction and operational fishing patterns than changes in stock distribution
Stock structure	No studies have looked at stock structure since Horn (1998), and there was no evidence from age/length observations for changes in locations of young for adult fish
Locations of spawning and site fidelity	Unknown, as there were few data on which to draw conclusions. Spawning data (roe observations & maturity staging) do not suggest any evidence of a change in spawning locations or site fidelity over time, but there has been little roe data recorded in recent years

6. DISCUSSION

The population structure and life cycle of hake in the Sub-Antarctic is not well understood, but there is good evidence supporting the current stock structure assumptions. Analysis of morphometric data from the 1990s showed significant differences between Sub-Antarctic hake and those from other regions, including the Chatham Rise and west coast South Island (Colman, NIWA, unpublished data). Growth parameters also differ among the three main stock areas, with Sub-Antarctic hake exhibiting distinct biological characteristics (Horn 1997).

Sub-Antarctic hake exhibit a population structure with fish of all lengths and ages represented in both commercial catches and resource surveys (unlike on the west coast South Island), but with somewhat different age and sex structures. The spatio-temporal analyses conducted in this study revealed that smaller and younger fish are spatially separated from the main fishing grounds which catch larger, older fish, consistent with ontogenetic habitat shifts in distribution commonly observed in demersal fish species.

The Sub-Antarctic fishery has undergone significant changes since the early 2000s. Previously, hake were caught primarily as bycatch in hoki-targeted trawls, but following reductions in hoki availability and the hoki TACC in 2005–06, the fishery became increasingly concentrated in a smaller area near the Stewart-Snares shelf with catches primarily from hake-targeted trawls. This spatial concentration of fishing effort, combined with the decline in overall catch from about 3000 t in 2003–04 to less than 1000 t in recent years, has important implications for CPUE interpretation.

The CPUE standardisation results suggest that trends in the commercial fishery indices are more likely influenced by changes in fishing patterns, fleet dynamics, and market conditions rather than reflecting true changes in hake abundance. The concentration of fishing effort to the Stewart-Snares shelf area, the shift from hoki-targeted to hake-targeted fishing, and the substantial reduction in fleet participation all represent significant changes in the fishery that could affect catchability and CPUE interpretation.

Importantly, the estimated standardised CPUE values showed reasonable agreement with the Sub-Antarctic trawl survey biomass index over the overlapping time period, providing some validation of the CPUE standardisation. Both indices showed a declining trend in recent years, with both series suggesting a similar pattern of change over time.

The analysis of different spatial strata revealed that different age classes showed different temporal patterns in the CPUE indices. The 'youngest' and 'young' categories showed relatively flat indices over time with reductions only in recent years, while the 'old' stratum more closely reflected the trawl survey indices with a general decline since about 2005. This age-structured pattern in the indices provides some evidence that the CPUE standardisation is capturing meaningful biological signals rather than purely operational changes.

The biological parameters estimated in this study, including updated length-weight relationships, growth curves, and maturity ogives, were consistent with previous estimates and showed stable patterns over time. The von Bertalanffy growth parameters were similar to those reported by Horn (2008), with only slight differences that are unlikely to significantly affect stock assessment outcomes.

Overall, while the CPUE indices provide useful information about relative trends in the Sub-Antarctic hake fishery, they should be interpreted cautiously given the substantial changes in fishing patterns and fleet composition over the time series. The consistency between CPUE trends and survey biomass estimates provides some confidence in using these indices in stock assessments, particularly when combined with other data sources. Future CPUE analyses should focus on the development of spatio-temporal CPUE models to overcome these limitations. The spatial structure identified in this analysis could be useful for future stock assessments that incorporate spatial dynamics, though the concentration of commercial catch in the main Stewart-Snares shelf area limits the information available from the other wider area spatial strata.

7. FULFILMENT OF BROADER OUTCOMES

Whakapapa links all people back to the land, sea, and sky, and our obligations to respect the physical world. This research aims to ensure the long-term sustainability of hake stocks, for the good of the wider community (including stakeholders and the public) and the marine ecosystems that ling inhabit. This project supports Māori and regional businesses, diversity and inclusion, and our research is inextricably linked to the moana from the work it carries out and the tangata whenua it supports.

As part of this project, the team has continued to build capacity and capability in fisheries science and stock assessment, its commitment to zero waste and carbon neutrality, environmental stewardship and social responsibility.

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9. REFERENCES

Bagley, N.W.; Hurst, R.J. (1998). Trawl survey of hoki and middle depth species on the Chatham Rise January 1998 (TAN9801). *NIWA Technical Report 44*. 54 p.

Bagley, N.W.; Ladroit, Y.; O'Driscoll, R.L. (2017). Trawl survey of hoki, hake, and ling in the Southland and Sub-Antarctic areas, November-December 2014 (TAN1412). *New Zealand Fisheries Assessment Report 2017/58*. 69 p.

Bagley, N.W.; Livingston, M.E. (2000). Trawl survey of hoki and middle depth species on the Chatham Rise January 1999 (TAN9901). *NIWA Technical Report 81*. 52 p.

Bagley, N.W.; McMillan, P.J. (1999). Trawl survey of hake and middle depth species in the Southland and sub-Antarctic areas, April-May 1998 (TAN9805). *NIWA Technical Report 52*. 48 p.

Bagley, N.W.; O'Driscoll, R.L. (2012). Trawl survey of hoki, hake, and ling in the Southland and Sub-Antarctic areas, November-December 2009 (TAN0911). *New Zealand Fisheries Assessment Report 2012/5*. 70 p.

Bagley, N.W.; O'Driscoll, R.L.; Francis, R.I.C.C.; Ballara, S.L. (2009). Trawl survey of hoki, hake, and ling in the Southland and Sub-Antarctic areas, November-December 2007 (TAN0714). *New Zealand Fisheries Assessment Report 2009/9*. 63 p.

Bagley, N.W.; O'Driscoll, R.L.; Oeffner, J. (2013). Trawl survey of hoki, hake, and ling in the Southland and Sub-Antarctic areas, November-December 2011 (TAN1117). *New Zealand Fisheries Assessment Report 2013/23.* 70 p.

Bagley, N.W.; O'Driscoll, R.L.; Oeffner, J. (2014). Trawl survey of hoki, hake, and ling in the Southland and Sub-Antarctic areas, November-December 2012 (TAN1215). *New Zealand Fisheries Assessment Report 2014/12*. 69 p.

Ballara, S.L. (2012). Descriptive analysis of the fishery for hake (*Merluccius australis*) in HAK 1, 4 and 7 from 1989–90 to 2009–10, and a catch-per-unit-effort (CPUE) analysis for Sub-Antarctic hake. *New Zealand Fisheries Assessment Report 2012/02*. 47 p.

Ballara, S.L. (2013). Descriptive analysis of the fishery for hake (*Merluccius australis*) in HAK 1, 4 and 7 from 1989–90 to 2010–11, and a catch-per-unit-effort (CPUE) analysis for Sub-Antarctic hake. *New Zealand Fisheries Assessment Report 2013/45*. 81 p.

Ballara, S.L. (2018). Descriptive analysis of the fishery for hake (*Merluccius australis*) in HAK 1, 4 and 7 from 1989–90 to 2014–15, and a catch-per-unit-effort (CPUE) analysis for Chatham Rise and WCSI hake. *New Zealand Fisheries Assessment Report 2018/55*. 57 p.

Ballara, S.L.; Barnes, T.C. (2024). Catch-at-age from commercial fisheries and trawl surveys for hake (*Merluccius australis*) and ling (*Genypterus blacodes*) in 2021–22. *New Zealand Fisheries Assessment Report 2024/14*. 87 p.

Ballara, S.L.; Barnes, T.C.; Hart, A.C.; Sutton, C.; O'Maolagain, C.; Spong, K. (2024). Catch-at-age from commercial fisheries and trawl surveys for hake (*Merluccius australis*) and ling (*Genypterus blacodes*) in 2022–23 and a trawl survey in 2024. *New Zealand Fisheries Assessment Report 2024/74*. 87 p.

Ballara, S.L.; O'Driscoll, R.L.; Saunders, R.J. (2022). Catch-at-age for hake (*Merluccius australis*) and ling (*Genypterus blacodes*) for the 2020–21 fishing year and from research trawl surveys in 2021–22, and a summary of the available data sets from the New Zealand EEZ. *New Zealand Fisheries Assessment Report 2022/56*. 94 p.

Bentley, N.; Kendrick, T.H.; Starr, P.J.; Breen, P.A. (2012). Influence plots and metrics: tools for better understanding fisheries catch-per-unit-effort standardizations. *ICES Journal of Marine Science 69*, 84–88.

Chatterton, T.D.; Hanchet, S.M. (1994). Trawl survey of hoki and associated species in the Southland and sub-Antarctic areas, November–December 1991 (TAN9105). *New Zealand Fisheries Data Report 41*. 55 p.

Chavent, M.; Kuentz-Simonet, V.; Labenne, A.; Saracco, J. (2018). ClustGeo: an R package for hierarchical clustering with spatial constraints. *Computational Statistics 33*, 1799–1822. https://doi.org/10.1007/s00180-018-0791-1

Colman, J.A. (1997). Stock assessment of hake (*Merluccius australis*) for the 1997–98 fishing year. *New Zealand Fisheries Assessment Research Document 97/19*. 15 p.

Colman, J.A. (1998). Spawning areas and size and age at maturity of hake (*Merluccius australis*) in the New Zealand Exclusive Economic Zone. *New Zealand Fisheries Assessment Research Document 98/2*. 17 p.

Colman, J.A.; Stocker, M.; Pikitch, E. (1991). Assessment of hake (*Merluccius australis*) stocks for the 1991–92 fishing year. *New Zealand Fisheries Assessment Research Document 91/14*. 29 p.

Colman, J.A.; Vignaux, M. (1992). Assessment of New Zealand hake (*Merluccius australis*) stocks for the 1992–93 fishing year. *New Zealand Fisheries Assessment Research Document 92/17*. 23 p.

Devine, J.A.; Stevens, D.W.; Ballara, S.L. (2022). Trawl survey for middle depth fish species on the west coast South Island, July–August 2021 (TAN2107). New Zealand Fisheries Assessment Report 2022/53. Ministry for Primary Industries, Wellington, New Zealand, 131 p.

Dunn, A. (1998). Stock assessment of hake (*Merluccius australis*) for the 1998–99 fishing year. *New Zealand Fisheries Assessment Research Document 98/30*. 19 p.

Dunn, A. (2001). Stock assessment of hake (*Merluccius australis*) for the 2000–01 fishing year. *New Zealand Fisheries Assessment Report 2001/22*. 31 p.

Dunn, A. (2003a). Revised estimates of landings of hake (*Merluccius australis*) for the west coast South Island, Chatham Rise, and Sub-Antarctic stocks in the fishing years 1989–90 to 2000–01. *New Zealand Fisheries Assessment Report 2003/39*. 36 p.

Dunn, A. (2003b). Stock assessment of hake (*Merluccius australis*) for the 2002–03 fishing year. *New Zealand Fisheries Assessment Report 2003/38*. 57 p.

Dunn, A. (2004). Stock assessment of hake (*Merluccius australis*) for the 2003–04 fishing year. *New Zealand Fisheries Assessment Report 2004/34*. 62 p.

Dunn, A. (2006). Stock assessment of hake (*Merluccius australis*) in HAK 1 & 4 for the 2005–06 fishing year. Final Research Report for Ministry of Fisheries Project HAK2003-01. NIWA, Wellington, New Zealand, 47 p.

Dunn, A. (2025a). Stock assessment of hake (*Merluccius australis*) off the west coast South Island (HAK 7) for the 2022–23 fishing year. *New Zealand Fisheries Assessment Report 2025/03*. 68 p.

Dunn, A. (2025b). gamInflu: Influence Analysis for Generalized Additive Models. Wellington, New Zealand, https://github.com/alistairdunn1/gamInflu.

Dunn, A.; Ballara, S.L.; Phillips, N.L. (2006). Stock assessment of hake (*Merluccius australis*) in HAK 1 & 4 for the 2004–05 fishing year. *New Zealand Fisheries Assessment Report 2006/11*. 63 p.

Dunn, A.; Horn, P.L.; Cordue, P.L.; Kendrick, T.H. (2000). Stock assessment of hake (*Merluccius australis*) for the 1999–2000 fishing year. *New Zealand Fisheries Assessment Report 2000/50*. 50 p.

Dunn, A.; Mormede, S.; Webber, D.N. (2021a). Descriptive analysis and stock assessment model inputs of hake (*Merluccius australis*) in the Sub-Antarctic (HAK 1) for the 2020–21 fishing year. *New Zealand Fisheries Assessment Research Document 2021/74*. 52 p.

Dunn, A.; Mormede, S.; Webber, D.N. (2021b). Stock assessment of hake (*Merluccius australis*) in the Sub-Antarctic (HAK 1) for the 2020–21 fishing year. *New Zealand Fisheries Assessment Report 2021/75*. 37 p.

Dunn, A.; Mormede, S.; Webber, D.N. (2023a). Stock assessment of hake (*Merluccius australis*) off the west coast South Island (HAK 7) for the 2021–22 fishing year. *New Zealand Fisheries Assessment Report 2023/48.* 45 p.

Dunn, A.; Mormede, S.; Webber, D.N. (2023b). Descriptive analysis and model inputs for the 2022 stock assessment of hake (*Merluccius australis*) off the west coast South Island (HAK 7) for the 2020–21 fishing year. *New Zealand Fisheries Assessment Report 2023/44*. 56 p.

Dunn, A.; Mormede, S.; Webber, D.N. (2025). Stock assessment of hake (*Merluccius australis*) in the subantarctic (HAK 1) for the 2023–24 fishing year. *New Zealand Fisheries Assessment Report 2025/xx*. xx p.

Dunn, A.; Parker, S.J. (2019). Revised biological parameters for Antarctic toothfish in the Ross Sea region (881 & 882AB). WG-FSA-2019/11. CCAMLR, Hobart, Australia, 14 p.

Dunn, M.R. (2019). Stock assessment of Sub-Antarctic hake (part of HAK 1) for 2018. *New Zealand Fisheries Assessment Report 2019/52.* 33 p.

Finucci, B. (2019). Descriptive analysis and a catch-per-unit-effort (CPUE) analysis of the West Coast South Island (HAK 7) fishery for hake (*Merluccius australis*). *New Zealand Fisheries Assessment Report 2019/55.* 49 p.

Fisheries New Zealand (2024). Report from the Fishery Assessment Plenary, May 2024: stock assessments and stock status. Compiled by the Fisheries Science Team, Fisheries New Zealand. Ministry for Primary Industries, Wellington, New Zealand, 1941 p.

Gavaris, S. (1980). Use of a multiplicative model to estimate catch rate and effort from commercial data. *Canadian Journal of Fisheries and Aquatic Sciences 37*, 2272–2275.

Holmes, S.J. (2021). Stock assessment of hake (*Merluccius australis*) on Chatham Rise for the 2019–20 fishing year. *New Zealand Fisheries Assessment Report 2021/22*. 55 p.

Horn, P.L. (1994a). Trawl survey of hoki and middle depth species on the Chatham Rise, December 1991–January 1992 (TAN9106). New Zealand Fisheries Data Report No. 43. MAF (Fisheries), Wellington, 38 p.

Horn, P.L. (1994b). Trawl survey of hoki and middle depth species on the Chatham Rise, December 1992–January 1993 (TAN9212). New Zealand Fisheries Data Report No. 44. MAF (Fisheries), Wellington, 43 p.

Horn, P.L. (1997). An ageing methodology, growth parameters, and estimates of mortality for hake (*Merluccius australis*) from around the South Island, New Zealand. *Marine and Freshwater Research 48*, 201–209.

Horn, P.L. (2008). Stock assessment of hake (*Merluccius australis*) in the Sub-Antarctic for the 2007– 08 fishing year. *New Zealand Fisheries Assessment Report 2008/49*. 66 p.

Horn, P.L. (2011). Stock assessment of hake (*Merluccius australis*) off the west coast of South Island (HAK 7) for the 2010–11 fishing year. *New Zealand Fisheries Assessment Report 2011/33*. 46 p.

Horn, P.L. (2013a). Stock assessment of hake (*Merluccius australis*) in the Sub-Antarctic (part of HAK 1) for the 2011–12 fishing year. *New Zealand Fisheries Assessment Report 2013/5*. 52 p.

Horn, P.L. (2013b). Stock assessment of hake (*Merluccius australis*) on the Chatham Rise (HAK 4) and off the west coast of South Island (HAK 7) for the 2012–13 fishing year. *New Zealand Fisheries Assessment Report 2013/31*. 58 p.

Horn, P.L. (2015). Stock assessment of hake (*Merluccius australis*) in the Sub-Antarctic (part of HAK 1) for the 2014–15 fishing year. *New Zealand Fisheries Assessment Report 2015/29*. 55 p.

Horn, P.L. (2017). Stock assessment of hake (*Merluccius australis*) on the Chatham Rise (HAK 4) and off the west coast of South Island (HAK 7) for the 2016-17 fishing year. *New Zealand Fisheries Assessment Report 2017/47.* 70 p.

Horn, P.L.; Dunn, A. (2007). Stock assessment of hake (*Merluccius australis*) on the Chatham Rise for the 2006–07 fishing year. *New Zealand Fisheries Assessment Report 2007/44*. 62 p.

Horn, P.L.; Francis, R.I.C.C. (2010). Stock assessment of hake (*Merluccius australis*) on the Chatham Rise for the 2009–10 fishing year. *New Zealand Fisheries Assessment Research Document 2010/14*. 65 p.

Horn, P.L.; Sutton, C.P. (2019). Catch-at-age for hake (*Merluccius australis*) and ling (*Genypterus blacodes*) in the 2017–18 fishing year and from research trawl surveys in 2018, with a summary of all available data sets from the New Zealand EEZ. *New Zealand Fisheries Assessment Report 2019/63*. 81 p.

Hurst, R.J.; Bagley, N.W.; Anderson, O.F.; Francis, M.P.; Griggs, L.H.; Clark, M.R.; Paul, L.J.; Taylor, P.R. (2000). Atlas of juvenile and adult fish and squid distributions from bottom and midwater trawls and tuna longlines in New Zealand waters. *NIWA Technical Report 84*. 162 p.

Hurst, R.J.; Schofield, K.A. (1995). Winter and summer trawl surveys of hoki and associated species in the Southland and sub-Antarctic areas 1990. *New Zealand Fisheries Technical Report 43*. 55 p.

Ingerson, J.K.V.; Hanchet, S.M.; Chatterton, T.D. (1995). Trawl survey of hoki and associated species in the Southland and sub-Antarctic areas, November–December 1992 (TAN9211). *New Zealand Fisheries Data Report 66*. 43 p.

Kendrick, T.H. (1998). Feasibility of using CPUE as an index of stock abundance for hake. *New Zealand Fisheries Assessment Research Document 1998/27*. 22 p.

Kerstan, M.; Sahrhage, D. (1980). Biological investigations on fish stocks in the waters off New Zealand. *Mitteilungen aus dem Institut für Seefischerei der Bundesforschungsanstalt für Fischerei No, 29.* 287 p.

Kienzle, M.; McGregor, V.; Dunn, M.R. (2019). Stock assessment of hake (*Merluccius australis*) on the west coast of South Island (HAK 7) for the 2018-19 fishing year. *New Zealand Fisheries Assessment Report 2019/66.* 47 p.

Livingston, M.E.; Schofield, K.A. (1993). Trawl survey of hoki and associated species south of New Zealand, October-November 1989. *New Zealand Fisheries Technical Report 36*. 39 p.

Livingston, M.E.; Stevens, D.W. (2005). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2004 (TAN0401). *New Zealand Fisheries Assessment Report 2005/21*. 62 p.

Livingston, M.E.; Stevens, D.W.; O'Driscoll, R.L.; Francis, R.I.C.C. (2004). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2003 (TAN0301). *New Zealand Fisheries Assessment Report 2004/16.* 71 p.

MacGibbon, D.; Ballara, S.L.; Schimel, A.C.G.; O'Driscoll, R.L. (2019). Trawl survey of hoki and middle-depth species in the Southland and Sub-Antarctic areas, November–December 2018 (TAN1811). *New Zealand Fisheries Assessment Report 2019/71*. 96 p.

MacGibbon, D.J. (2019). Inshore trawl survey of the west coast South Island and Tasman and Golden Bays, March-April 2019 (KAH1902). *New Zealand Fisheries Assessment Report 2019/64*. 87 p.

MacGibbon, D.J.; Walsh, C.; Buckthought, D.; Bian, R. (2022). Inshore trawl survey off the west coast South Island and in Tasman Bay and Golden Bay, March–April 2021 (KAH2103). *New Zealand Fisheries Assessment Report 2022/11*. 97 p.

MacGibbon, D.J.; Walsh, C.; Buckthought, D.; Bian, R. (2024). Inshore trawl survey off the west coast South Island and in Tasman Bay and Golden Bay, March–April 2023 (KAH2302). *New Zealand Fisheries Assessment Report 2024/06*. 95 p.

Marra, G.; Wood, S.N. (2011). Practical variable selection for generalized additive models. *Computational Statistics & Data Analysis 55*, 2372–2387. https://doi.org/10.1016/j.csda.2011.02.004

McGregor, V.L.; Dunn, M.R.; Langley, A.D.; Dunn, A. (2022). Assessment of hoki (*Macruronus novaezelandiae*) in 2021. *New Zealand Fisheries Assessment Report 2022/43*. 247 p.

O’Driscoll, R.L.; Bagley, N.W. (2001). Review of summer and autumn trawl survey time series from the Southland and sub-Antarctic areas, 1991–98. *NIWA Technical Report 102*. 115 p.

O’Driscoll, R.L.; Bagley, N.W. (2003a). Trawl survey of middle depth species in the Southland and sub-Antarctic areas, November-December 2002 (TAN0219). *New Zealand Fisheries Assessment Report 2003/46*. 57 p.

O’Driscoll, R.L.; Bagley, N.W. (2003b). Trawl survey of middle depth species in the Southland and sub-Antarctic areas, November-December 2001 (TAN0118). *New Zealand Fisheries Assessment Report 2003/01*. 53 p.

O’Driscoll, R.L.; Bagley, N.W. (2004). Trawl survey of middle depth species in the Southland and sub-Antarctic areas, November-December 2003 (TAN0317). *New Zealand Fisheries Assessment Report 2004/49*. 58 p.

O’Driscoll, R.L.; Bagley, N.W. (2006a). Trawl survey of middle depth species in the Southland and sub-Antarctic areas, November-December 2004 (TAN0414). *New Zealand Fisheries Assessment Report 2006/02*. 60 p.

O’Driscoll, R.L.; Bagley, N.W. (2006b). Trawl survey of middle depth species in the Southland and sub-Antarctic areas, November-December 2005 (TAN0515). *New Zealand Fisheries Assessment Report 2006/45*. 64 p.

O’Driscoll, R.L.; Bagley, N.W. (2008). Trawl survey of hoki, hake, and ling in the Southland and Sub-Antarctic areas, November-December 2006 (TAN0617). *New Zealand Fisheries Assessment Report 2008/30*. 61 p.

O’Driscoll, R.L.; Bagley, N.W. (2009). Trawl survey of hoki, hake, and ling in the Southland and Sub-Antarctic areas, November-December 2008 (TAN0813). *New Zealand Fisheries Assessment Report 2009/56*. 67 p.

O’Driscoll, R.L.; Bagley, N.W.; Bull, B. (2001). Trawl survey of middle depth species in the Southland and sub-Antarctic areas, November-December 2000 (TAN0012). Final Research Report for Ministry of Fisheries Research Project MDT2000/01 Objectives 1 & 2. National Institute of Water and Atmospheric Research, Wellington, 78 p.

O’Driscoll, R.L.; Ballara, S.L. (2018). Trawl survey of middle depth fish abundance on the west coast South Island, August 2016 (TAN1609). *New Zealand Fisheries Assessment Report 2018/47*. 74 p.

O’Driscoll, R.L.; Ballara, S.L. (2019). Trawl survey of middle depth fish abundance on the west coast South Island, July-August 2018 (TAN1807). *New Zealand Fisheries Assessment Report 2019/19*. 120 p.

O'Driscoll, R.L.; Ballara, S.L.; MacGibbon, D.J.; Schimel, A.C.G. (2018). Trawl survey of hoki and middle-depth species in the Southland and Sub-Antarctic areas, November-December 2016 (TAN1614). *New Zealand Fisheries Assessment Report 2018/39.* 84 p.

Pinkerton, M.; Devine, J.; Dunn, A.; Mormede, S. (2023). Monitoring the effects of environmental variability and climate change on toothfish assessments. WS-CC-2023/20. CCAMLR, Hobart, Australia, 10 p.

Pinkerton, M.; Dunn, A.; Mormede, S.; Parker, S. (2018). Monitoring and managing the effects of environmental change on toothfish assessments. WG-SAM-18/22. CCAMLR, Hobart, Australia, 14 p.

R Core Team (2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing. https://www.R-project.org/. Vienna, Austria.

Rue, H.; Martino, S.; Chopin, N. (2009). Approximate Bayesian inference for latent Gaussian models by using integrated nested Laplace approximations. *Journal of the Royal Statistical Society: Series B (Statistical Methodology) 71*, 319–392. http://doi.wiley.com/10.1111/j.1467-9868.2008.00700.x. https://doi.org/10.1111/j.1467-9868.2008.00700.x

Saunders, R.; Hart, A.C.; Horn, P.L.; Sutton, C.P. (2021). Catch-at-age for hake (*Merluccius australis*) and ling (*Genypterus blacodes*) for the 2018–19 fishing year and from a research trawl survey in 2020, and a summary of the available data sets from the New Zealand EEZ. *New Zealand Fisheries Assessment Report 2021/15*. 97 p.

Schnute, J. (1981). A versatile growth model with statistically stable parameters. *Canadian Journal of Fisheries and Aquatic Sciences 38*, 1128–1140.

Schofield, K.A.; Horn, P.L. (1994). Trawl survey of hoki and middle depth species on the Chatham Rise, January 1994 (TAN9401). *New Zealand Fisheries Data Report No. 53*. 54 p.

Schofield, K.A.; Livingston, M.E. (1994a). Trawl survey of hoki and associated species in the Southland and sub-Antarctic areas, April–May 1992 (TAN9204). *New Zealand Fisheries Data Report 47.* 38 p.

Schofield, K.A.; Livingston, M.E. (1994b). Trawl survey of hoki and associated species in the Southland and sub-Antarctic areas, September–October 1992 (TAN9209). *New Zealand Fisheries Data Report 46.* 43 p.

Schofield, K.A.; Livingston, M.E. (1994c). Trawl survey of hoki and associated species in the Southland and sub-Antarctic areas, May–June 1993 (TAN9304). *New Zealand Fisheries Technical Report 47.* 39 p.

Schofield, K.A.; Livingston, M.E. (1995). Trawl survey of hoki and middle depth species on the Chatham Rise, January 1995 (TAN9501). *New Zealand Fisheries Data Report No. 59.* 53 p.

Schofield, K.A.; Livingston, M.E. (1996). Trawl survey of hoki and middle depth species on the Chatham Rise, January 1996 (TAN9601). *New Zealand Fisheries Data Report No. 71.* 50 p.

Schofield, K.A.; Livingston, M.E. (1997). Trawl survey of hoki and middle depth species on the Chatham Rise, January 1997 (TAN9701). *NIWA Technical Report 6.* 51 p.

Stan Development Team (2020). Stan Modelling Language: User's Guide and Reference Manual Version 2.24. Stan Governing Body.

Stevens, D.W.; Ballara, S.; Maurice, A.; Escobar-Flores, P.C.; Yeoman, J. (2024a). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2024 (TAN2401). *New Zealand Fisheries Assessment Report 2024/77*. 118 p.

Stevens, D.W.; Ballara, S.L.; Escobar-Flores, P.C.; O'Driscoll, R.L. (2023). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2022 (TAN2201). New Zealand Fisheries Assessment Report 2023/24. Ministry for Primary Industries, Wellington, New Zealand, 126 p.

Stevens, D.W.; Livingston, M.E. (2003). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2002 (TAN0201). *New Zealand Fisheries Assessment Report 2003/19.* 57 p.

Stevens, D.W.; Livingston, M.E.; Bagley, N.W. (2001). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2000 (TAN0001). *NIWA Technical Report 104.* 55 p.

Stevens, D.W.; Livingston, M.E.; Bagley, N.W. (2002). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2001 (TAN0101). *NIWA Technical Report 116.* 61 p.

Stevens, D.W.; MacGibbon, D.; Ballara, S.; Escobar-Flores, P.C.; O'Driscoll, R.L. (2022). Trawl survey of hoki and middle-depth species in the Southland and Sub-Antarctic areas, November–December 2020 (TAN2014). *New Zealand Fisheries Assessment Report 2022/08.* 111 p.

Stevens, D.W.; MacGibbon, D.; Ballara, S.; Wieczorek, A.M.; Barnes, T.C. (2024b). Trawl survey of hoki and middle-depth species in the Southland and Sub-Antarctic areas, November–December 2022 (TAN2215). *New Zealand Fisheries Assessment Report 2024/15.* 105 p.

Stevens, D.W.; O'Driscoll, R.L. (2006). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2005 (TAN0501). *New Zealand Fisheries Assessment Report 2006/13.* 73 p.

Stevens, D.W.; O'Driscoll, R.L. (2007). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2006 (TAN0601). *New Zealand Fisheries Assessment Report 2007/5.* 73 p.

Stevens, D.W.; O'Driscoll, R.L.; Ballara, S.L.; Ladroit, Y. (2017). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2016 (TAN1601). *New Zealand Fisheries Assessment Report 2017/8.* 131 p.

Stevens, D.W.; O'Driscoll, R.L.; Ballara, S.L.; Schimel, A.C.G. (2018). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2018 (TAN1801). *New Zealand Fisheries Assessment Report 2018/41.* 111 p.

Stevens, D.W.; O'Driscoll, R.L.; Ballara, S.L.; Schimel, A.C.G. (2021). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2020 (TAN2001). *New Zealand Fisheries Assessment Report 2021/33.* 122 p.

Stevens, D.W.; O'Driscoll, R.L.; Dunn, M.R.; Ballara, S.L.; Horn, P.L. (2012). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2011 (TAN1101). *New Zealand Fisheries Assessment Report 2012/10.* 98 p.

Stevens, D.W.; O'Driscoll, R.L.; Dunn, M.R.; Ballara, S.L.; Horn, P.L. (2013). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2012 (TAN1201). *New Zealand Fisheries Assessment Report 2013/34.* 103 p.

Stevens, D.W.; O'Driscoll, R.L.; Dunn, M.R.; MacGibbon, D.J.; Horn, P.L.; Gauthier, S. (2011). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2010 (TAN1001). *New Zealand Fisheries Assessment Report 2011/10.* 112 p.

Stevens, D.W.; O'Driscoll, R.L.; Gauthier, S. (2008). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2007 (TAN0701). *New Zealand Fisheries Assessment Report 2008/52.* 81 p.

Stevens, D.W.; O'Driscoll, R.L.; Horn, P.L. (2009a). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2008 (TAN0801). *New Zealand Fisheries Assessment Report 2009/18.* 86 p.

Stevens, D.W.; O'Driscoll, R.L.; Horn, P.L. (2009b). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2009 (TAN0901). *New Zealand Fisheries Assessment Report 2009/55.* 91 p.

Stevens, D.W.; O'Driscoll, R.L.; Ladroit, Y.; Ballara, S.L.; MacGibbon, D.J.; Horn, P.L. (2015). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2014 (TAN1401). *New Zealand Fisheries Assessment Report 2015/19.* 119 p.

Stevens, D.W.; O'Driscoll, R.L.; Oeffner, J.; Ballara, S.L.; Horn, P.L. (2014). Trawl survey of hoki and middle depth species on the Chatham Rise, January 2013 (TAN1301). *New Zealand Fisheries Assessment Report 2014/2.* 110 p.

Vehtari, A.; Gelman, A.; Gabry, J. (2017). Practical Bayesian model evaluation using leave-one-out cross-validation and WAIC. *Statistics and Computing 27,* 1413–1432. https://doi.org/10.1007/s11222-016-9696-4

Vignaux, M. (1994). Catch per unit effort (CPUE) analysis of west coast South Island and Cook Strait spawning hoki fisheries, 1987–93. *New Zealand Fisheries Assessment Research Document 94/11.* 29 p.

von Bertalanffy, L. (1938). A quantitative theory of organic growth (Inquiries on growth laws. II). *Human Biology 10,* 181–213.

Wood, S.N. (2003). Thin-plate regression splines. *Journal of the Royal Statistical Society (B) 65*, 95–114.

Wood, S.N. (2004). Stable and efficient multiple smoothing parameter estimation for generalized additive models. *Journal of the American Statistical Association 99*, 673–686.

Wood, S.N. (2011). Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. *Journal of the Royal Statistical Society (Series B) 73*, 3–36.

Wood, S.N. (2017). Generalized Additive Models: An Introduction with R, 2nd ed. Chapman and Hall/CRC.

Wood, S.N.; Pya, N.; Säfken, B. (2016). Smoothing parameter and model selection for general smooth models (with discussion). *Journal of the American Statistical Association 111*, 1548–1575.

10. APPENDIX A: RESOURCE SURVEY BIOMASS INDICES FOR HAKE

Table 10: Biomass indices (t) and coefficients of variation (CV) for hake from resource surveys of the Sub-Antarctic. (Estimates assume that the areal availability, vertical availability, and vulnerability are equal to one.). (Continued on next three pages)

Vessel	Date	Series	Trip code	Depth	Notes	Biomass	CV	Reference
Wesermünde	Mar–May 1979	Autumn	–	–	*1*			(Kerstan & Sahrhage 1980)
Wesermünde	Oct–Dec 1979	Summer	–	–	*1*			(Kerstan & Sahrhage 1980)
Shinkai Maru	Mar–Apr 1982	Autumn	SHI8201	200–800 m		6 045	0.15	(Horn 2017)
Shinkai Maru	Oct–Nov 1983	Summer	SHI8303	200–800 m		11 282	0.22	(Horn 2017)
Amaltal Explorer	Oct–Nov 1989	Summer	AEX8902	200–800 m		2 660	0.21	(Livingston & Schofield 1993)
Amaltal Explorer	Jul–Aug 1990	Winter	AEX9001	300–800 m	*2*	4 343	0.19	(Hurst & Schofield 1995)
Amaltal Explorer	Nov–Dec 1990	Summer	AEX9002	300–800 m	*3*	2 460	0.16	(Horn 2017)
Tangaroa	Nov–Dec 1991	Summer	TAN9105	Reported	*4*	5 686	0.43	(Chatterton & Hanchet 1994)
				300–800 m	*5*	5 553	0.44	(O'Driscoll & Bagley 2001)
				1991 area	*2*	5 686	0.43	(O'Driscoll & Bagley 2001)
				1996 area		–	–	*Not surveyed*
Tangaroa	Apr–May 1992	Autumn	TAN9204	Reported	*4*	5 028	0.15	(Schofield & Livingston 1994a)
				300–800 m	*3*	5 028	0.15	(O'Driscoll & Bagley 2001)
				1991 area	*5*	–	–	*Not surveyed*
				1996 area		–	–	*Not surveyed*
Tangaroa	Sep–Oct 1992	September	TAN9209	Reported	*4*	3 762	0.15	(Schofield & Livingston 1994b)
				300–800 m		–	–	*Not surveyed*
				1991 area	*3*	3 760	0.15	(O'Driscoll & Bagley 2001)
				1996 area		–	–	*Not surveyed*
Tangaroa	Nov–Dec 1992	Summer	TAN9211	Reported	*4*	1 944	0.12	(Ingerson et al. 1995)
				300–800 m	*5*	1 822	0.12	(O'Driscoll & Bagley 2001)
				1991 area	*2*	1 944	0.12	(O'Driscoll & Bagley 2001)
				1996 area		–	–	*Not surveyed*
Tangaroa	May–Jun 1993	Autumn	TAN9304	Reported	*4*	3 602	0.14	(Schofield & Livingston 1994c)
				300–800 m	*3*	3 221	0.14	(O'Driscoll & Bagley 2001)
				1991 area		–	–	*Not surveyed*
				1996 area		–	–	*Not surveyed*
						–	–	*Not surveyed*
Tangaroa	Nov–Dec 1993	Summer	TAN9310	Reported	*2*	2 572	0.12	(O'Driscoll & Bagley 2001)
				300–800 m	*3*	2 286	0.12	(O'Driscoll & Bagley 2001)

Vessel	Date	Series	Trip code	Depth	Notes	Biomass	CV	Reference
				1991 area	*4*	2 567	0.12	(O'Driscoll & Bagley 2001)
				1996 area		–	–	*Not surveyed*
Tangaroa	Mar–Apr 1996	Autumn	TAN9605	Reported	*2*	3 946	0.16	(O'Driscoll & Bagley 2001)
				300–800 m	*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	(Bagley & McMillan 1999)
Tangaroa	Apr–May 1998	Autumn	TAN9805	Reported	*2*	2 554	0.18	(O'Driscoll & Bagley 2001)
				300–800 m	*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 et al. 2001)
Tangaroa	Nov–Dec 2000	Summer	TAN0012	300–800 m	*3*	2 194	0.17	(O'Driscoll et al. 2001)
				1991 area	*4*	2 657	0.16	(O'Driscoll et al. 2001)
				1996 area	*5*	3 103	0.14	(O'Driscoll & Bagley 2003a)
Tangaroa	Nov–Dec 2001	Summer	TAN0118	300–800 m	*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 2003b)
Tangaroa	Nov–Dec 2002	Summer	TAN0219	300–800 m	*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 2004)
Tangaroa	Nov–Dec 2003	Summer	TAN0317	300–800 m	*3*	1 335	0.24	(O'Driscoll & Bagley 2004)
				1991 area	*4*	1 672	0.23	(O'Driscoll & Bagley 2004)
				1996 area	*7*	1 898	0.21	(O'Driscoll & Bagley 2006a)
Tangaroa	Nov–Dec 2004	Summer	TAN0414	300–800 m	*3*	1 250	0.27	(O'Driscoll & Bagley 2006a)
				1991 area	*4*	1 694	0.21	(O'Driscoll & Bagley 2006a)
				1996 area	*7*	1 774	0.20	(O'Driscoll & Bagley 2006b)
Tangaroa	Nov–Dec 2005	Summer	TAN0515	300–800 m	*3*	1 133	0.20	(O'Driscoll & Bagley 2006b)
				1991 area	*4*	1 459	0.17	(O'Driscoll & Bagley 2006b)
				1996 area	*7*	1 624	0.17	(O'Driscoll & Bagley 2008)
Tangaroa	Nov–Dec 2006	Summer	TAN0617	300–800 m	*3*	998	0.22	(O'Driscoll & Bagley 2008)
				1991 area	*4*	1 530	0.17	(O'Driscoll & Bagley 2008)
				1996 area	*7*	1 588	0.16	(Bagley et al. 2009)
Tangaroa	Nov–Dec 2007	Summer	TAN0714	300–800 m	*3*	2 188	0.17	(Bagley et al. 2009)
				1991 area	*4*	2 470	0.15	(Bagley et al. 2009)
				1996 area	*7*	2 622	0.15	(O'Driscoll & Bagley 2009)

Vessel	Date	Series	Trip code	Depth	Notes	Biomass	CV	Reference
Tangaroa	Nov–Dec 2008	Summer	TAN0813	300–800 m	*3*	1 074	0.23	(O'Driscoll & Bagley 2009)
				1991 area	*4*	2 162	0.17	(O'Driscoll & Bagley 2009)
				1996 area	*7*	2 355	0.16	(Bagley & O'Driscoll 2012)
Tangaroa	Nov–Dec 2009	Summer	TAN0911	300–800 m	*3*	992	0.22	(Bagley & O'Driscoll 2012)
				1991 area	*4*	1 442	0.20	(Bagley & O'Driscoll 2012)
				1996 area	*7*	1 602	0.18	(Bagley et al. 2013)
Tangaroa	Nov–Dec 2011	Summer	TAN1117	300–800 m	*3*	1 434	0.30	(Bagley et al. 2013)
				1991 area	*4*	1 885	0.24	(Bagley et al. 2013)
				1996 area	*7*	2 004	0.23	(Bagley et al. 2014)
Tangaroa	Nov–Dec 2012	Summer	TAN1215	300–800 m	*3*	1 943	0.23	(Bagley et al. 2014)
				1991 area	*4*	2 428	0.23	(Bagley et al. 2014)
				1996 area	*7*	2 443	0.22	(Bagley et al. 2017)
Tangaroa	Nov–Dec 2014	Summer	TAN1412	300–800 m	*3*	1 101	0.32	(Bagley et al. 2017)
				1991 area	*4*	1 477	0.25	(Bagley et al. 2017)
				1996 area	*7*	1 485	0.25	(O'Driscoll et al. 2018)
Tangaroa	Nov–Dec 2016	Summer	TAN1614	300–800 m	*3,8*	1 000	0.25	(O'Driscoll et al. 2018)
				1991 area	*4,8*	–	–	*Not available*
				1996 area	*8*	1 373	0.34	(MacGibbon et al. 2019)
Tangaroa	Nov–Dec 2018	Summer	TAN1811	300–800 m	*3*	1 354	0.28	(MacGibbon et al. 2019)
				1991 area		1 675	0.25	(MacGibbon et al. 2019)
				1996 area	*7*	1 785	0.24	D. MacGibbon (pers. comm)
Tangaroa	Nov–Dec 2020	Summer	TAN2014	300–800 m	*3*	1 309	0.23	(Stevens et al. 2022)
				1991 area	*4*	1 572	0.20	D. MacGibbon (pers. comm)
				1996 area	*7*	1 619	0.20	(Stevens et al. 2022)
Tangaroa	Nov–Dec 2022	Summer	TAN2215	300–800 m	*3*	983	0.21	(Stevens et al. 2024b)
				1991 area	*4*	1 285	0.18	(Stevens et al. 2024b)
				1996 area	*7*	1572	0.20	(Stevens et al. 2024b)
Tangaroa	Nov–Dec 2024	Summer	TAN2413	300–800 m	*3*	–	–	*Not available*
				1991 area	*4*	1 521	0.16	J. Devine (pers. comm)
				1996 area	*7*	–	–	*Not available*

1. Although surveys by *Wesermünde* were carried out in the Sub-Antarctic in 1979, biomass estimates for hake were not calculated.
2. The depth range, biomass, and CV in the original report.
3. The biomass and CV 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 CV 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 CV calculated from source records using the equivalent 1996 region, which includes the 800–1000 m strata in Puysegur region but excludes the Bounty Platform strata. (The 1996 region added additional 800–1000 m strata to the north and to the south of the Sub-Antarctic to the 1991 region).
6. Doorspread data not recorded for this survey. Analysis of source data with average of all other survey doorspread estimates resulted in a new estimate of biomass.
7. The biomass and CV calculated from source records using the equivalent 1996 region, which includes the 800–1000 m strata in Puysegur region but excludes the Bounty Platform strata. (The 1996 region added additional 800–1000 m strata to the north and to the south of the Sub-Antarctic to the 1991 region). However, in 2003, stratum 26 (the most southern 800–1000 m strata) was not surveyed. In previous years this stratum yielded either a very low or zero hake biomass. The yield in 2003 from stratum 26 was assumed to be zero.
8. Due to bad weather, the core survey strata were unable to be completed in 2017; biomass estimates were scaled up based on the proportion of hake biomass in those strata in previous surveys from 2000 to 2014. This introduced additional uncertainty into the 2017 biomass estimate (see Dunn 2019). Biomass for the 1996 area was not estimated.

Table 11: Biomass indices (t) and coefficients of variation (CV) for hake from resource surveys of the Chatham Rise. (Estimates assume that the areal availability, vertical availability, and vulnerability are equal to one.) (Continued next page)

Vessel	Date	Series	Trip code	Depth	Notes	Biomass	CV	Reference
Wesermünde	Mar–May 1979	Autumn		–	*1*			(Kerstan & Sahrhage 1980)
Wesermünde	Oct Dec 1979	Spring		–	*1*			(Kerstan & Sahrhage 1980)
Shinkai Maru	Mar 1983	Autumn	SHI8301	200–800 m		11 327	0.12	(Horn 2017)
Shinkai Maru	Nov–Dec 1983	Summer	SHI8304	200–800 m	*2*	8 160	0.12	(Horn 2017)
Shinkai Maru	Jul 1986	Winter	SHI8602	200–800 m		7 630	0.13	(Horn 2017)
Amaltal Explorer	Nov–Dec 1989	Summer	AEX8903	200–800 m		3 576	0.19	(Horn 2017)
Tangaroa	Jan 1992	Summer	TAN9106	200–800 m		4 180	0.15	(Horn 1994a)
Tangaroa	Jan 1993	Summer	TAN9212	200–800 m		2 950	0.17	(Horn 1994b)
Tangaroa	Jan 1994	Summer	TAN9401	200–800 m		3 353	0.10	(Schofield & Horn 1994)
Tangaroa	Jan 1995	Summer	TAN9501	200–800 m		3 303	0.23	(Schofield & Livingston 1995)
Tangaroa	Jan 1996	Summer	TAN9601	200–800 m		2 457	0.13	(Schofield & Livingston 1996)
Tangaroa	Jan 1997	Summer	TAN9701	200–800 m		2 811	0.17	(Schofield & Livingston 1997)
Tangaroa	Jan 1998	Summer	TAN9801	200–800 m		2 873	0.18	(Bagley & Hurst 1998)
Tangaroa	Jan 1999	Summer	TAN9901	200–800 m		2 302	0.12	(Bagley & Livingston 2000)
Tangaroa	Jan 2000	Summer	TAN0001	200–800 m		2 090	0.09	(Stevens et al. 2001)
				200–1000 m		2 152	0.09	(Stevens et al. 2001)
Tangaroa	Jan 2001	Summer	TAN0101	200–800 m		1 589	0.13	(Stevens et al. 2002)
Tangaroa	Jan 2002	Summer	TAN0201	200–800 m		1 567	0.15	(Stevens & Livingston 2003)
				200–1000 m		1 905	0.13	(Stevens & Livingston 2003)
Tangaroa	Jan 2003	Summer	TAN0301	200–800 m		888	0.16	(Livingston et al. 2004)
Tangaroa	Jan 2004	Summer	TAN0401	200–800 m		1 547	0.17	(Livingston & Stevens 2005)
Tangaroa	Jan 2005	Summer	TAN0501	200–800 m		1 048	0.18	(Stevens & O'Driscoll 2006)
Tangaroa	Jan 2006	Summer	TAN0601	200–800 m		1 384	0.19	(Stevens & O'Driscoll 2007)
Tangaroa	Jan 2007	Summer	TAN0701	200–800 m		1 824	0.12	(Stevens et al. 2008)
				200–1000 m		1 976	0.12	(Stevens et al. 2008)

Vessel	Date	Series	Trip code	Depth	Notes	Biomass	CV	Reference
Tangaroa	Jan 2008	Summer	TAN0801	200–800 m		1 257	0.13	(Stevens et al. 2009a)
				200–1000 m		1 323	0.13	(Stevens et al. 2009a)
Tangaroa	Jan 2009	Summer	TAN0901	200–800 m		2 419	0.21	(Stevens et al. 2009b)
Tangaroa	Jan 2010	Summer	TAN1001	200–800 m		1 701	0.25	(Stevens et al. 2011)
				200–1300 m		1 862	0.25	(Stevens et al. 2011)
Tangaroa	Jan 2011	Summer	TAN1101	200–800 m		1 099	0.15	(Stevens et al. 2012)
				200–1300 m		1 201	0.14	(Stevens et al. 2012)
Tangaroa	Jan 2012	Summer	TAN1201	200–800 m		1 292	0.15	(Stevens et al. 2013)
				200–1300 m		1 493	0.13	(Stevens et al. 2013)
Tangaroa	Jan 2013	Summer	TAN1301	200–800 m		1 793	0.15	(Stevens et al. 2014)
				200–1300 m		1 874	0.15	(Stevens et al. 2014)
Tangaroa	Jan 2014	Summer	TAN1401	200–800 m		1 377	0.15	(Stevens et al. 2015)
				200–1300 m		1 510	0.14	(Stevens et al. 2015)
Tangaroa	Jan 2016	Summer	TAN1601	200–800 m		1 299	0.19	(Stevens et al. 2017)
				200–1300 m		1 512	0.16	(Stevens et al. 2017)
Tangaroa	Jan 2018	Summer	TAN1801	200–800 m		1 660	0.34	(Stevens et al. 2018)
				200–1300 m		1 813	0.32	(Stevens et al. 2018)
Tangaroa	Jan 2020	Summer	TAN2001	200–800 m		1 037	0.20	(Stevens et al. 2021)
				200–1300 m		1 126	0.19	(Stevens et al. 2021)
Tangaroa	Jan 2022	Summer	TAN2201	200–800 m		1 651	0.20	(Stevens et al. 2023)
				200–1300 m		1 766	0.19	(Stevens et al. 2023)
Tangaroa	Jan 2024	Summer	TAN2401	200–800 m		2 088	0.48	(Stevens et al. 2024a)
				200–1300 m		2 242	0.45	(Stevens et al. 2024a)

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

Table 12: Biomass indices (t) and coefficients of variation (CV) for hake from resource surveys of the West Coast South Island. (Estimates assume that the areal availability, vertical availability, and vulnerability are equal to one.)

Vessel	Date	Series	Trip code	Depth	Biomass	CV	Reference
Tangaroa	Jul–Aug 2000	Winter	TAN0007	300–650 m	803	0.13	(O'Driscoll & Ballara 2018)
				200–800 m	–	–	*Not surveyed*
				200–1000 m	–	–	*Not surveyed*
Tangaroa	Jul–Aug 2012	Winter	TAN1210	300–650 m	583	0.13	(O'Driscoll & Ballara 2018)
				200–800 m	1103	0.13	(O'Driscoll & Ballara 2018)
				200–1000 m	–	–	*Not surveyed*
Tangaroa	Jul–Aug 2013	Winter	TAN1308	300–650 m	331	0.17	(O'Driscoll & Ballara 2018)
				200–800 m	747	0.21	(O'Driscoll & Ballara 2018)
				200–1000 m	–	–	*Not surveyed*
Tangaroa	Jul–Aug 2016	Winter	TAN1609	300–650 m	221	0.24	(O'Driscoll & Ballara 2018)
				200–800 m	355	0.16	(O'Driscoll & Ballara 2018)
				200–1000 m	502	0.13	(O'Driscoll & Ballara 2018)
Tangaroa	Jul–Aug 2018	Winter	TAN1807	300–650 m	229	0.33	(O'Driscoll & Ballara 2019)
				200–800 m	559	0.18	(O'Driscoll & Ballara 2019)
				200–1000 m	899	0.14	(O'Driscoll & Ballara 2019)
Tangaroa	Jul–Aug 2021	Winter	TAN2107	300–650 m	507	0.34	(Devine et al. 2022)
				200–800 m	747	0.25	(Devine et al. 2022)
				200–1000 m	939	0.20	(Devine et al. 2022)
Tangaroa	Jul–Aug 2024	Winter	TAN2407	300–650 m	139	0.34	(J. Devine, NIWA, pers. comm)
				200–800 m	891	0.45	(J. Devine, NIWA, pers. comm)
				200–1000 m	–	–	*Not available*

Table 13: Biomass indices (t) and coefficients of variation (CV) for hake from inshore resource surveys of Tasman and Golden Bays and the West Coast South Island. (Estimates assume that the areal availability, vertical availability, and vulnerability are equal to one.)

Vessel	Date	Series	Trip code	Depth	Biomass	CV	Reference
Kaharoa	Mar–Apr 1992	Autumn	KAH9204	20–400 m	390	0,.25	(MacGibbon 2019)
Kaharoa	Mar–Apr 1994	Autumn	KAH9404	20–400 m	99	0.31	(MacGibbon 2019)
Kaharoa	Mar–Apr 1995	Autumn	KAH9504	20–400 m	5 197	0.27	(MacGibbon 2019)
Kaharoa	Mar–Apr 1997	Autumn	KAH9701	20–400 m	1 019	0..46	(MacGibbon 2019)
Kaharoa	Mar–Apr 2000	Autumn	KAH0004	20–400 m	15	0.36	(MacGibbon 2019)
Kaharoa	Mar–Apr 2003	Autumn	KAH0304	20–400 m	55	0.47	(MacGibbon 2019)
Kaharoa	Mar–Apr 2005	Autumn	KAH0503	20–400 m	1 673	0.30	(MacGibbon 2019)
Kaharoa	Mar–Apr 2007	Autumn	KAH0704	20–400 m	359	0.35	(MacGibbon 2019)
Kaharoa	Mar–Apr 2009	Autumn	KAH0904	20–400 m	212	0.56	(MacGibbon 2019)
Kaharoa	Mar–Apr 2011	Autumn	KAH1104	20–400 m	44	0.36	(MacGibbon 2019)
Kaharoa	Mar–Apr 2013	Autumn	KAH1304	20–400 m	36	0.41	(MacGibbon 2019)
Kaharoa	Mar–Apr 2015	Autumn	KAH1503	20–400 m	81	0.37	(MacGibbon 2019)
Kaharoa	Mar–Apr 2017	Autumn	KAH1703	20–400 m	217	0.61	(MacGibbon 2019)
Kaharoa	Mar–Apr 2019	Autumn	KAH1902	20–400 m	111	0.33	(MacGibbon 2019)
Kaharoa	Mar–Apr 2021	Autumn	KAH2103	20–400 m	179	0.63	(MacGibbon et al. 2022)
Kaharoa	Mar–Apr 2023	Autumn	KAH2302	20–400 m	<1	1.00	(MacGibbon et al. 2024)