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Descriptive analysis and stock assessment model inputs of hake (*Merluccius australis*) in the Sub-Antarctic (HAK 1) for the 2020–21 fishing year

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Dunn, A.[1]; Mormede, S.[2]; Webber, D.N.[3] (2021). Descriptive analysis and stock assessment model inputs of hake (*Merluccius australis*) in the Sub-Antarctic (HAK 1) for the 2020–21 fishing year.

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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 Sub-Antarctic stock (hake in HAK 1 south of about 46° S) and the Sub-Antarctic fishery, with updated and revised catch-per-unit-effort (CPUE) indices up to the end of the 2019–20 fishing year.

The Sub-Antarctic fishery is concentrated off the south and east of the Stewart-Snares shelf. The total annual catch of hake in the last few years has declined in the Sub-Antarctic, with catches declining by half over the last decade. Formerly, the fishery caught hake in target hoki or hake trawls, but since about 2005 the fishery has been concentrated in a smaller area and catches are primarily from target hake trawls.

In CPUE analyses, estimates of relative year effects were obtained from a forward stepwise linear regression and then lognormal and binomial CPUE indices were combined. The data used for the analysis consisted of catch and effort records from the Sub-Antarctic from vessels targeting hoki, hake, or ling and reporting the catch and effort on trawl catch, effort and processing returns or electronic reporting system trawl forms for both tow-by-tow and daily summary data. Estimated standardised CPUE values were similar for the tow-by-tow data and the daily summary and showed a similar trend as the Sub-Antarctic trawl survey index over the same period. In general, the CPUE indices declined over the period of fishing, but levelled off in recent years as catches declined.

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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). Hake are caught mainly by deepwater demersal trawls usually as bycatch in hoki (*Macruronus novaezelandiae*) target fisheries and with some caught by direct targeting (Ballara 2018).

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) (see Figure 1). An administrative Fishstock (with no recorded landings) is also defined for the Kermadec FMA (HAK 10) (Fisheries New Zealand 2020). However, there are likely to be three main biological stocks of hake. These are the west coast of the South Island (WCSI, HAK 7), the Chatham Rise (HAK 4 and the northern regions in HAK 1), and the Sub-Antarctic (HAK 1) (Fisheries New Zealand 2020).

The length frequencies of hake were different between the west coast and both the Chatham Rise and the Sub-Antarctic. The growth parameters were also different between the three areas (Horn 1997) and juvenile hake are 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 like those from off the west coast South Island 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).

The reported catch history of hake in each of the Quota Management Area (QMA) is given in Table 1. 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 (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 2000, fishers were found to have misreported hake catches between Quota Management Areas. 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 (WCSI) 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. Probable levels of area misreporting prior to 1994–95 and between the WCSI and Sub-Antarctic were estimated as low (Dunn 2003a). There was 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 fishing year (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), and 2019–20 (Holmes 2021). The most recent stock assessment was for Sub-Antarctic hake for the 2020–21 fishing year and is described by Dunn et al. (2021).

Commercial catch and effort data were first analysed to produce 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. Most recently for the sub-Antarctic, Ballara (2018) updated the descriptive analyses of hake and estimates CPUE abundance indices, including data up to the end of 2016–17.

Estimates of age frequencies from the commercial catch, and age frequencies from resource surveys, are calculated under annual Fisheries New Zealand ageing projects that are reported elsewhere (e.g., Horn & Sutton 2019, Saunders et al. 2021), however they have not been summarised over the period of the Sub-Antarctic fishery.

This report fulfils Specific Objective 1 of Project HAK2020-01. 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 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 2019–20 (2020).

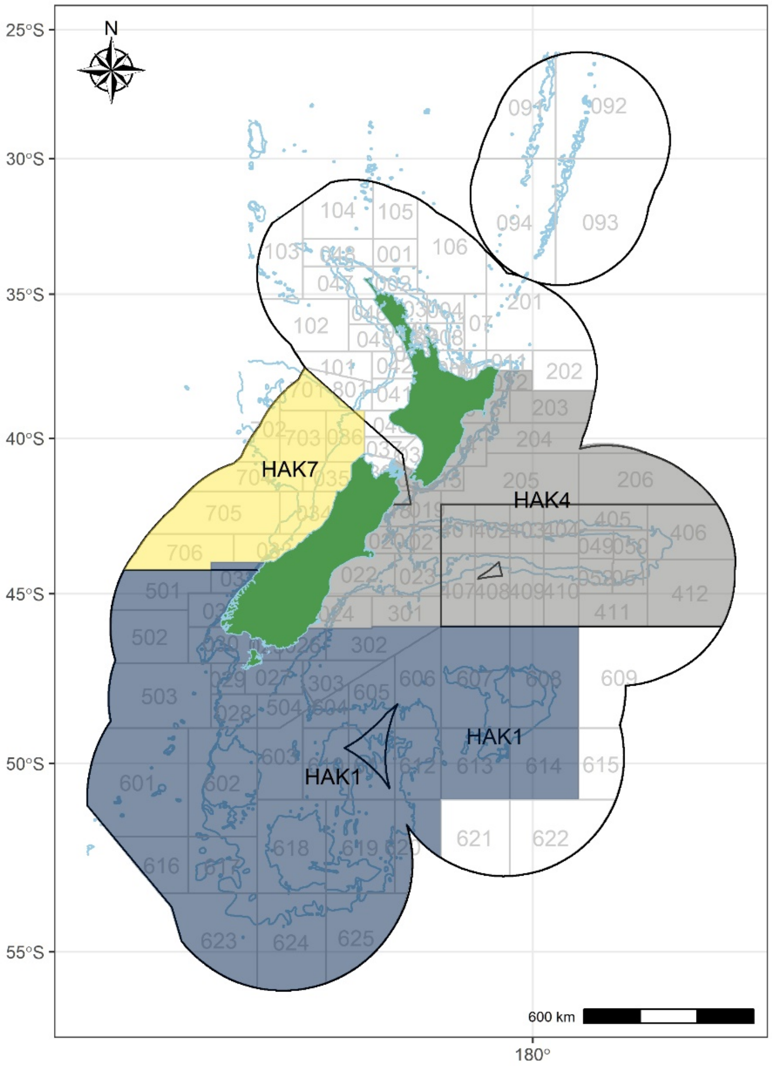

Figure 1: **Quota Management Areas (QMAs) HAK 1, 4, 7, and 10 (black lines), statistical areas (grey), and hake biological stock boundaries: West coast South Island (yellow), Chatham Rise (light grey), and Sub-Antarctic (dark grey).**

Table 1: Reported landings (t) of hake by Fishstock from 1983–84 to 2019–20 and actual total allowable commercial catches (TACCs) (t) for 1986–87 to 2020–21. Fisheries Statistics Unit (FSU) data from 1984–1986; QMS data from 1986 to the present (from Fisheries New Zealand 2021).

Fish stock	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	3 809	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	3 262	7 783
2020–21	–	3 701	–	1 800		2 272	–	10	–	7 783

[1] FSU data.

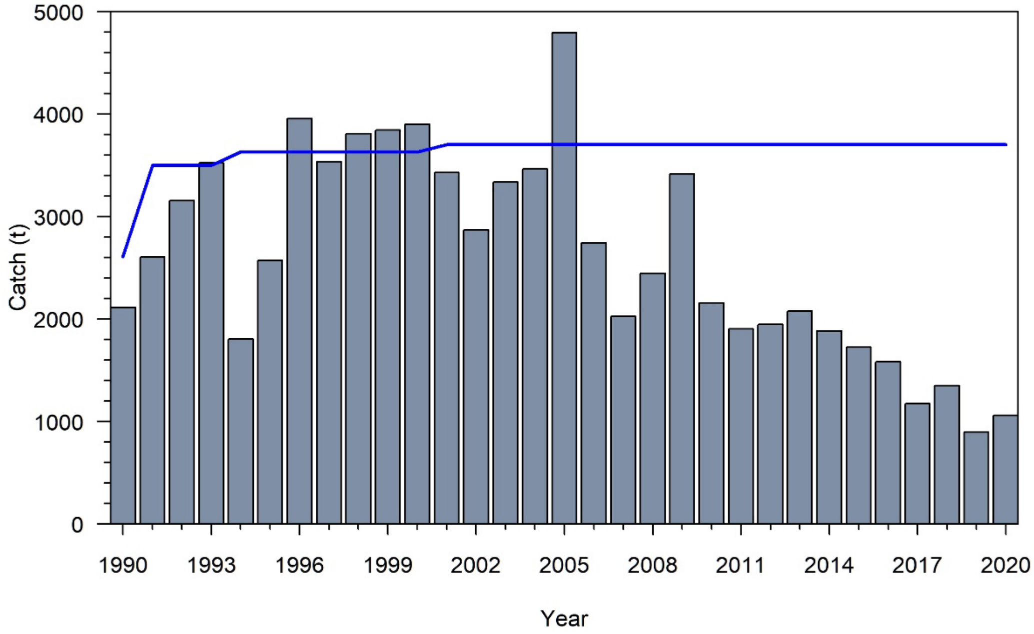

Figure 2: Annual reported catch of hake in HAK 1 (bars) and the TACC for hake (blue line) for the fishing years 1989–90 (1990) to 2019–20 (2020).

Table 2: Total (scaled) catches (t) by stock for hake from 1990–2020 for (left columns) the October–September definition of a fishing year (where 1990 is 1 October 1989–30 September 1990), and (right column) September–August model year (where 1990 is 1 September 1989–31 August 1990). 'Not assigned' includes catches from areas that had no fishing location or statistical area or were north of the boundaries used for the stock definitions.

	Oct-Sep fishing year					Sep-Aug fishing year
Year	Chatham Rise	Sub-Antarctic	WCSI	Not assigned	Total	Sub-Antarctic
1990	1 015	1 827	4 903	39	7 784	718
1991	963	2 366	6 147	73	9 549	2 318
1992	2 420	2 749	3 026	1	8 196	2 806
1993	2 801	3 265	7 121	37	13 225	3 919
1994	2 952	1 452	2 958	2	7 364	1 620
1995	4 097	1 844	8 839	9	14 789	1 982
1996	4 535	2 888	8 662	46	16 131	2 789
1997	4 790	2 274	6 111	48	13 222	1 919
1998	4 691	2 601	7 404	59	14 755	2 944
1999	4 381	2 792	8 159	6	15 338	2 871
2000	3 691	3 011	6 895	2	13 600	3 100
2001	2 965	2 787	8 357	7	14 117	2 816
2002	1 785	2 510	7 519	0	11 813	2 444
2003	1 407	2 741	7 432	1	11 581	2 780
2004	2 492	3 251	7 943	0	13 686	3 228
2005	3 532	2 530	7 314	0	13 377	2 591
2006	494	2 555	6 905	0	9 955	2 538
2007	1 112	1 812	7 668	2	10 594	1 706
2008	1 109	2 204	2 617	0	5 930	2 330
2009	1 845	2 427	5 953	1	10 226	2 445
2010	412	1 958	2 346	0	4 716	1 927
2011	975	1 288	3 574	1	5 838	1 319
2012	216	1 893	4 459	0	6 568	1 902
2013	373	1 883	5 434	1	7 690	1 878
2014	219	1 832	3 641	0	5 693	1 840
2015	390	1 639	6 219	0	8 248	1 608
2016	355	1 504	2 863	1	4 722	1 470
2017	406	1 037	4 701	1	6 145	1 042
2018	412	1 205	3 085	1	4 704	1 175
2019	443	636	1 562	0	2 642	662
2020	266	930	2 062	4	3 262	983
Total	57 546	65 691	171 880	344	295 460	65 670

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 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). The amount of catch misreported to HAK 1 in the Sub-Antarctic was relatively low (Dunn 2003a).

Catch and effort data were extracted by Fisheries New Zealand for the period from October 1989 to September 2020 (REPLOG 13300), along with all available Observer and resource survey data (REPLOG 13301), on 2nd November 2020. This included all data from trips where hoki, hake, or ling (*Genypterus blacodes*) were reported as either 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.

The extract of observed catch and effort data for hake from the Fisheries New Zealand observer sampling programme included all observer trips that reported hoki, hake, or ling. In addition, biological and length frequency information from these trips were also extracted, along with any otolith age readings associated with these trips.

Resource survey data (including data from the *Tangaroa* Sub-Antarctic standardised trawl survey and any other research voyage that reported hake) were 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 WCSI are given in Appendix A.

2.2 Data checks

Catch and effort data were checked for errors, using simple checking and imputation algorithms similar to those reported by Ballara (2018). These data were also groomed for errors using simple checking and imputation algorithms 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 a 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. General Statistical Areas were either assigned to the reported statistical area or were calculated from corrected positions, where specific position data were available. 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, using the estimates reported by Ballara (2018) according 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 on 2nd February 2021, 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).

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 catch limit 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. The current catch of hake across all areas (3262 t) was less than half of the available TACC (7783 t) in 2019–20.

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 subsequent data collection then switching to the newer ERS-trawl forms (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. Although hake caught from hoki target tows made up a significant proportion of the catch up to 2003–04, the catch from hoki target tows has reduced in frequency, and now most of the hake catch is taken from hake target tows (Figure 5).

Hake are caught mostly during the summer months in the Sub-Antarctic (Figure 6) from trawl vessels dominated by 60 to 70 m vessels. 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 as likely to be flagged to Japan and Norway by Ballara (2018). Hake have typically been caught at depths of 500 to 750 m depth, with the depth of fish caught remaining stable over time.

The location of catches has reduced in its spatial extent over time, with most of the change occurring with the change from hoki target catch to hake target catch from about 2004–05. Although the trawl fleet fished predominantly in Statistical Areas 028, 602, and 603 before 2004–05, there were still reasonable levels of catch from other areas (e.g., Statistical Areas 026, 027, 030, 504, and 618). Since the mid-2000s, catches are now concentrated in Statistical Areas 028 and 602, with catches from the most recent five years mostly in statistical area 602 (Figure 7).

To represent 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 a 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 was a small increase in 2017–18 in the number of 0.1° cells fished, which is likely to be a consequence of the change in reporting systems from TCEPR forms to the higher resolution position data reported on ERS-trawl data forms.

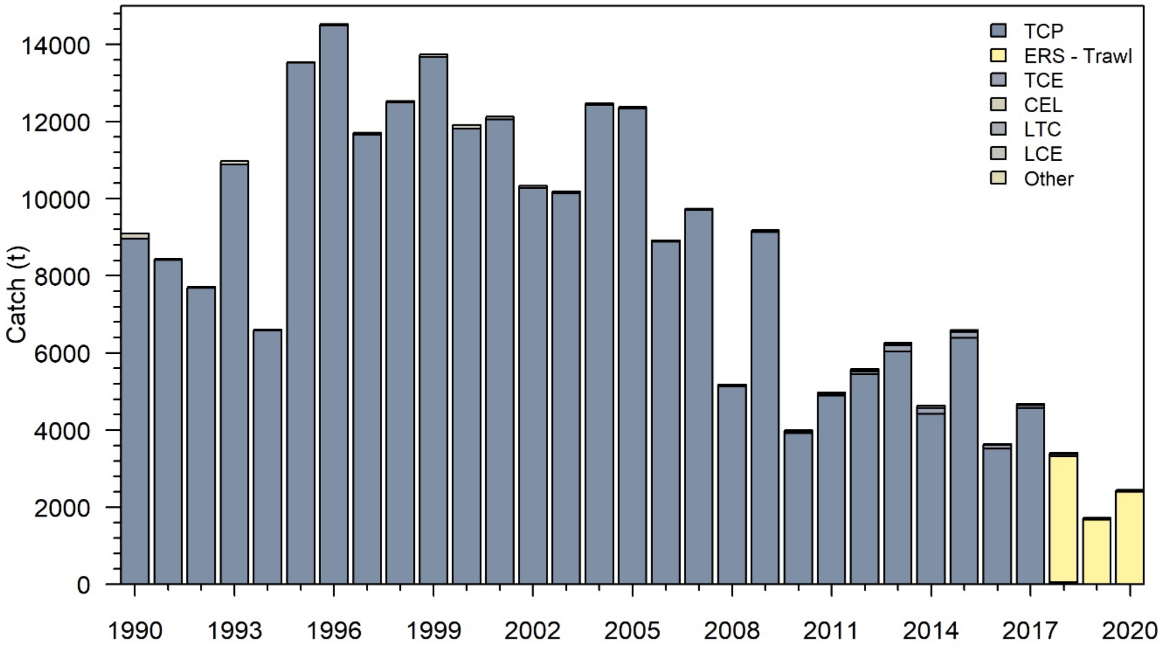

Figure 3: Total catch of hake (t) in the Sub-Antarctic by data reporting form type and fishing year from 1989–90 to 2019–20.

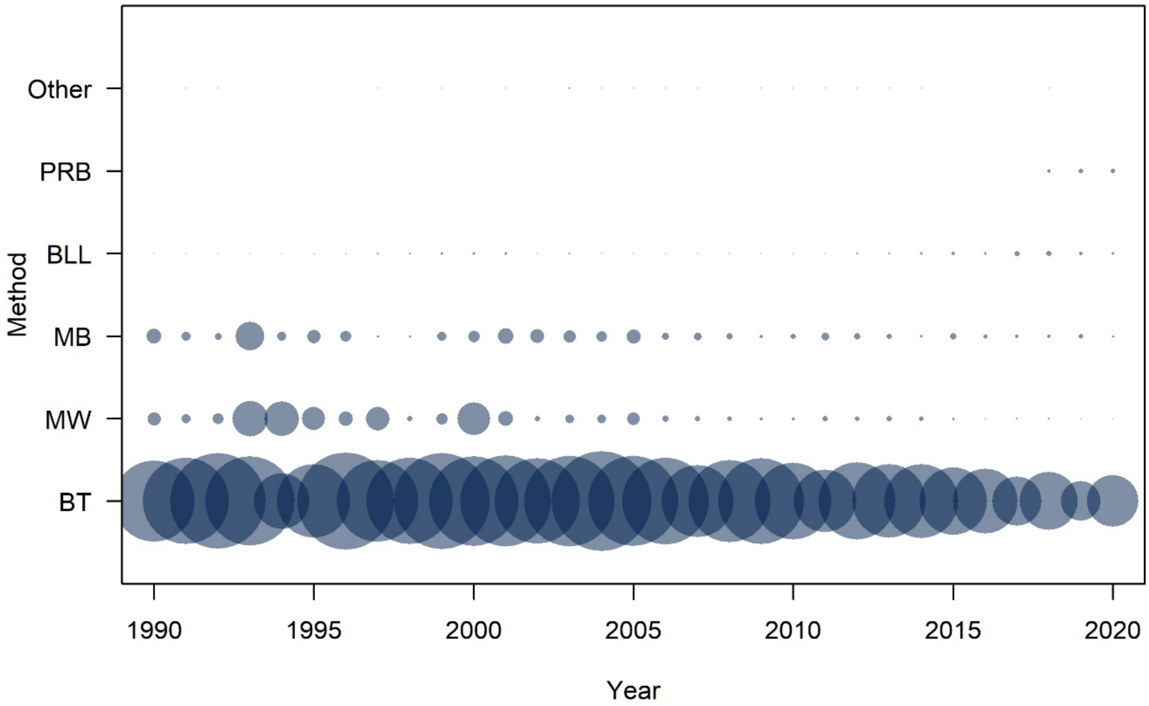

Figure 4: Relative proportion of hake catch in the Sub-Antarctic by gear type (BT = bottom trawl gear, MW = midwater trawl gear, and MB = midwater trawl gear fished near the sea floor, BLL = bottom longline, PRB = modular harvesting system bottom trawl gear, and other = all other gears combined) and fishing year, from 1989–90 to 2019–20.

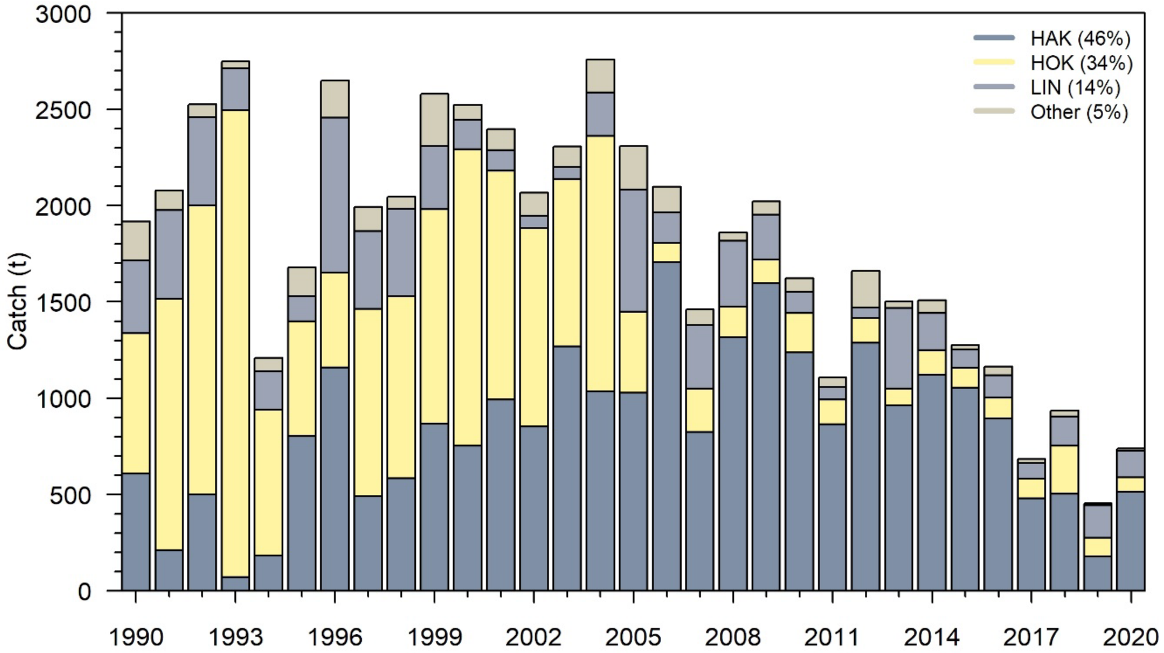

Figure 5: Total catch (t) of hake in the Sub-Antarctic by target species (hake, hoki, ling, and other species combined) by fishing year, from 1989–90 to 2019–20.

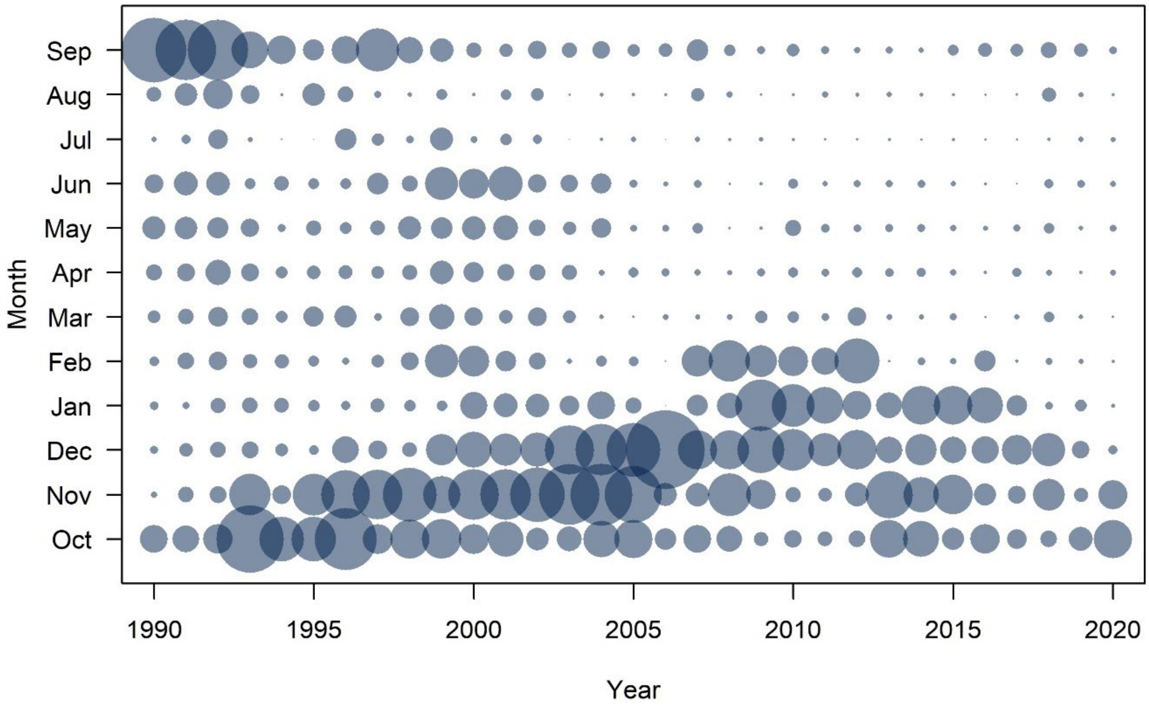

Figure 6: Relative catch of hake in the Sub-Antarctic by month and fishing year from 1989–90 to 2019–20.

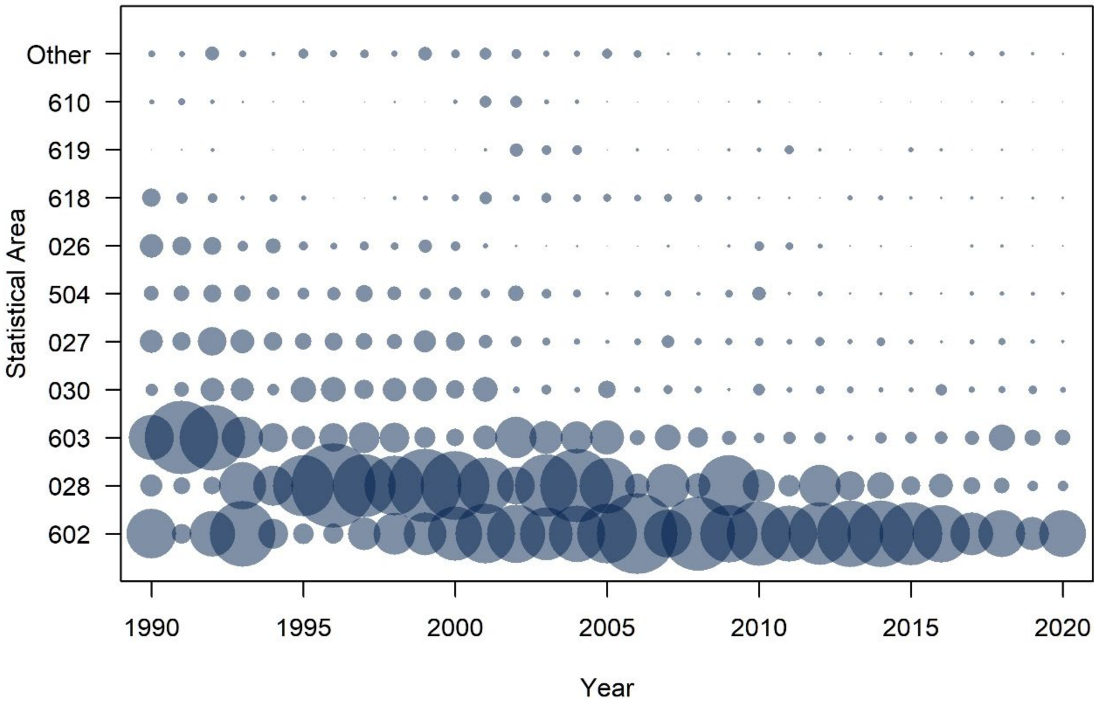

Figure 7: Relative catch of hake in the Sub-Antarctic, by statistical area and fishing year from 1989–90 to 2019–20.

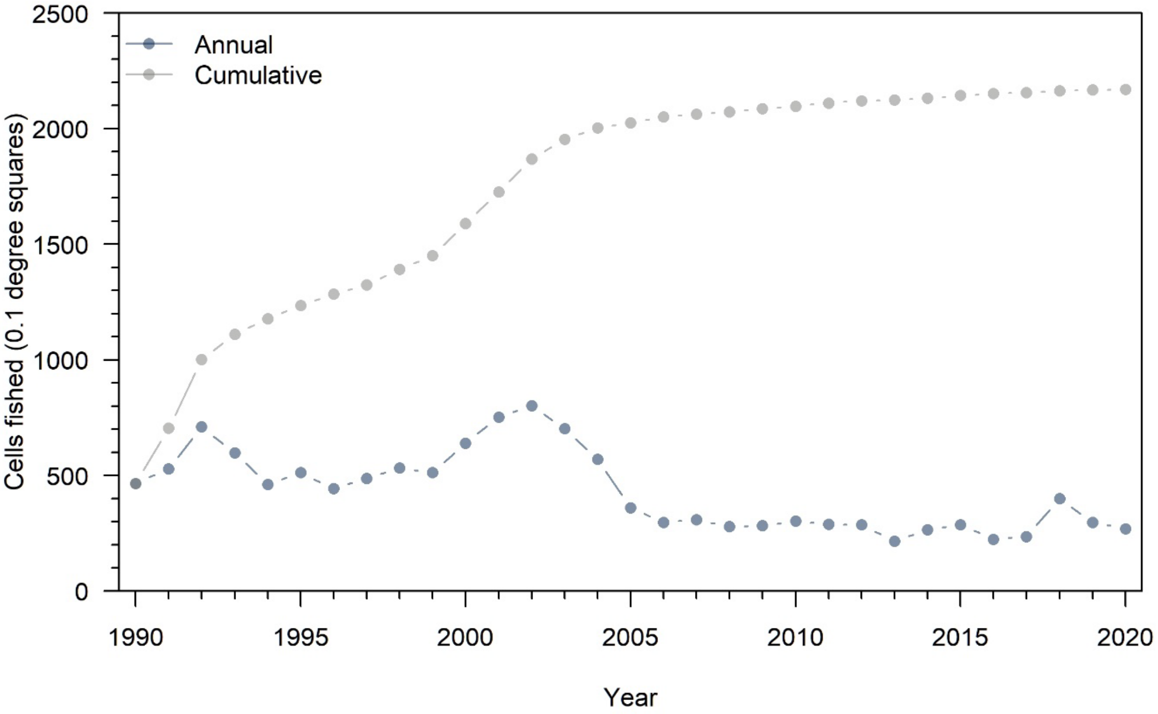

Figure 8: Annual and cumulative number of 0.1° cells in the Sub-Antarctic that had reported hake catch, by fishing year, from 1989–90 to 2019–20.

3. SPATIAL-TEMPORAL ANALYSES

Spatial-temporal analyses of the hake catch data in the Sub-Antarctic were undertaken to investigate if there were suitable sub-fleet, spatial, or temporal splits that would allow development of consistent fishing selectivity patterns or suitable subsets of data for CPUE analyses. For example, if hake were distributed differently by age or sex over spatial areas (for example, by depth or east/west in the Sub-Antarctic) then the changing pattern of the fishery would introduce changes in selectivity or in CPUE indices over time that an assessment model may interpret 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 a 2005 analysis by Horn (2008) and have been used since to scale age frequencies (Dunn 2019) and as a factor in the hake CPUE analyses (see Ballara 2018). Horn (2008) determined that there was one major and three minor spatially defined hake fisheries in the Sub-Antarctic area. Since then, this stratification has been used to generate the scaled length frequency and was applied to a single annual age-length key to produce a single area combined age frequency. This was used to estimate the selectivity for the single fishery within Sub-Antarctic hake stock assessments (Dunn 2019).

Describing and modelling of the spatial distribution of mean 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.

3.1 Methods

3.1.1 Tree regression

A series of tree regression analyses were carried out following a similar procedure to that used elsewhere, for example to establish the fisheries in the toothfish Ross Sea Region stock assessment (e.g., Mormede & Parker 2018). This analysis was implemented in the software package R (R Core Team 2019) using the R package *rpart*. A tree regression using the mean length of hake per fishing event was carried out for bottom trawl catch, with potential parameters offered to the regression detailed in Table 3. A similar tree regression analysis was also carried out for the sex ratio (expressed as the proportion of females) in each fishing event.

Tree regression was also carried out using the same methods but applied to the age data instead of the length data. Although the amount of age data was significantly lower than that for length, it was more likely to be able to resolve any patterns in the distribution of older fish than the length frequency analysis; however, this approach could introduce a bias due to the non-random selection of fish that were sampled by observers and then aged.

Table 3: Explanatory variables offered to the tree-regression model.

Variable	Type	Description
Month	Categorical	Month of the year
Week of year	Numeric	Week of the year, starting on 1 September
Day of year	Numeric	Julian date, starting at 1 on 1 September
Statistical area	Categorical	Statistical area
Start latitude	Numeric	Start latitude (absolute value)
Start longitude	Numeric	Start longitude (0–360)
Target	Categorical	Species targeted on the tow
Bottom depth	Numeric	Depth of the bottom in metres
Fishing duration	Numeric	Duration of the tow in hours

3.1.2 Bayesian spatial-temporal analysis

A spatial mesh (i.e., a spatial mesh made up of nodes connected by edges to delimitate 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 less than the number of observations, while still maintaining an appropriate spatial resolution). The analysis used all available length measurements (n = 95 134) and/or age measurements (n = 19 134). Each node was an estimated model parameter, constrained by the stochastic partial differential equation (SPDE) underpinning integrated nested Laplace approximation (INLA) spatial smoothers.

Two different data sets were used in this analysis: length frequency (LF) data, and age frequency (age) data. LF data were combined with the lengths available in the age data set (length is also recorded in the age data set); records with unknown sex were dropped; length was rounded down to the nearest integer; and eleven blocks consisting of length or age across three-yearly blocks were defined for the analysis. Records with unknown sex were also dropped from the age data, ages were rounded to the nearest integer, and eleven blocks of three-year periods were defined.

The length data were fitted assuming a normal distribution — the minimum length recorded was well away from zero — because models specified using the normal distribution can be run in reasonable time when using INLA. The age data were fitted assuming a Poisson distribution. The variables year, month, sex, and spatial structure (i.e., node) were offered to models for both data sets. Spatial structure was assumed to be either constant, sex-specific, or year-block specific, depending on the model run. Although there may be correlations within tows in the length and age data, any such correlations were ignored in these analyses, and it was assumed that each length was an independent sample from the population at that time in that location for each sex. Further development of this method could investigate the inclusion of the tow as a random-effect term within the model because this may better account for the variability and correlation of individual lengths within tows. The likely correlation between ages from the same tow less unlikely have a similar concern, because only a small number of otoliths are typically sampled within each tow, and a subset of these end up being aged.

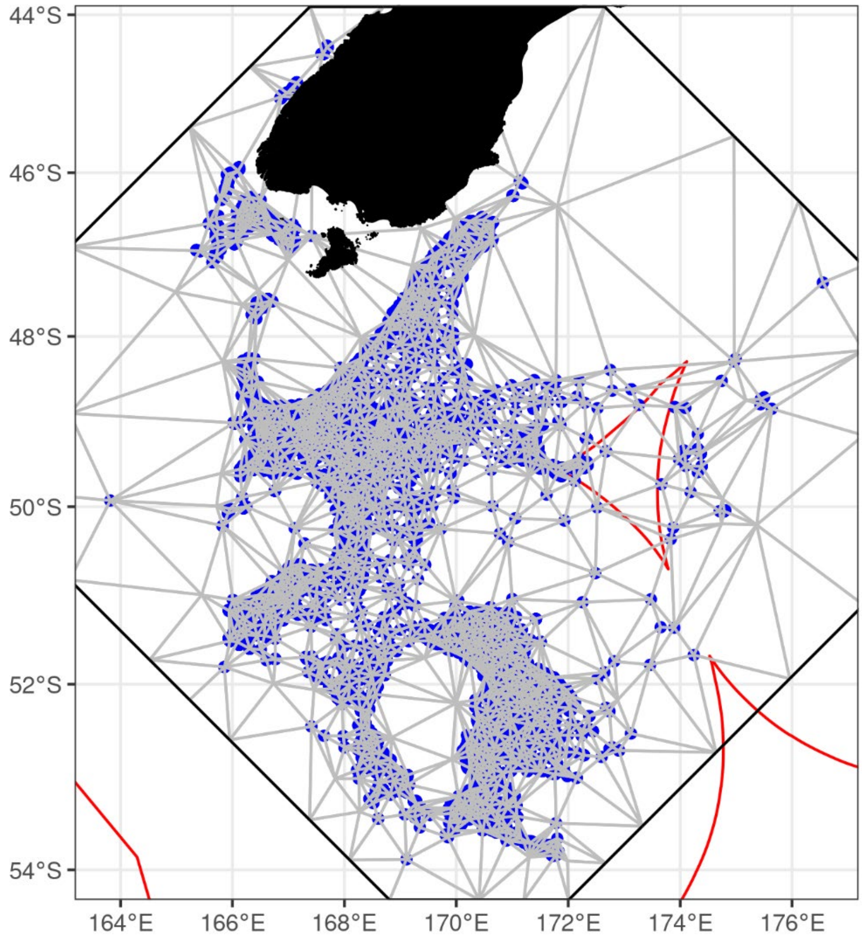

Figure 9: **Spatial mesh for hake spatial-temporal models showing the locations of data (blue points), the spatial mesh (grey lines), the extent of the spatial model (thick black lines), and the New Zealand EEZ (red lines).**

Both the deviance information criterion (DIC) and Watanabe-Akaike information criterion (WAIC) were used for model comparison. Both the DIC and WAIC suggested the most complex models were also the most parsimonious models (Table 4 and Table 5). The spatial effect for the chosen model of mean length is shown in Figure 10, for the sex-specific model of mean age in Figure 11, and for the time block model of mean age in Figure 12.

Table 4: **Model comparison deviance information criterion (DIC) and Watanabe-Akaike information criterion (WAIC) for each of the LF model runs. The model term 'space' refers to the INLA SPDE term, and 'block' refers to the three-year time blocks.**

Model	DIC	WAIC	Comment
length ~ intercept + space	725 569	725 829	Worst model
length ~ intercept + year + month + sex + space	694 076	694 670	Chosen model
length ~ intercept + year + month + sex + (space × sex)	690 052	690 708	
length ~ intercept + month + sex + (space × block)	689 616	690 670	Best model

Table 5: Model comparison deviance information criterion (DIC) and Watanabe-Akaike information criterion (WAIC) for each of the age model runs. The model term 'space' refers to the INLA SPDE term, and 'block' refers to the three-year time blocks.

Model	DIC	WAIC	Comment
age ~ intercept + space	99 387	99 680	Worst model
age ~ intercept + year + month + sex + space	98 635	98 917	Chosen model
age ~ intercept + year + month + sex + (space × sex)	98 092	98 455	
age ~ intercept + month + sex + (space × block)	97 934	98 299	Best model

Finally, the R package *ClustGeo* was used to derive spatial fishery strata using hierarchical clustering with geographic constraints (Chavent et al. 2017). The *GeoClust* 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) compared to space (D1).

The value of alpha can be somewhat subjective and can radically change the clusters. However, a somewhat objective method for finding a good starting value for alpha involves:

1. defining the number of clusters (e.g., K = 5 clusters),
2. running 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. examining a plot of the proportion of explained inertia of the partitions in K clusters for each alpha value (e.g., Figure 13) and deciding on an alpha value.

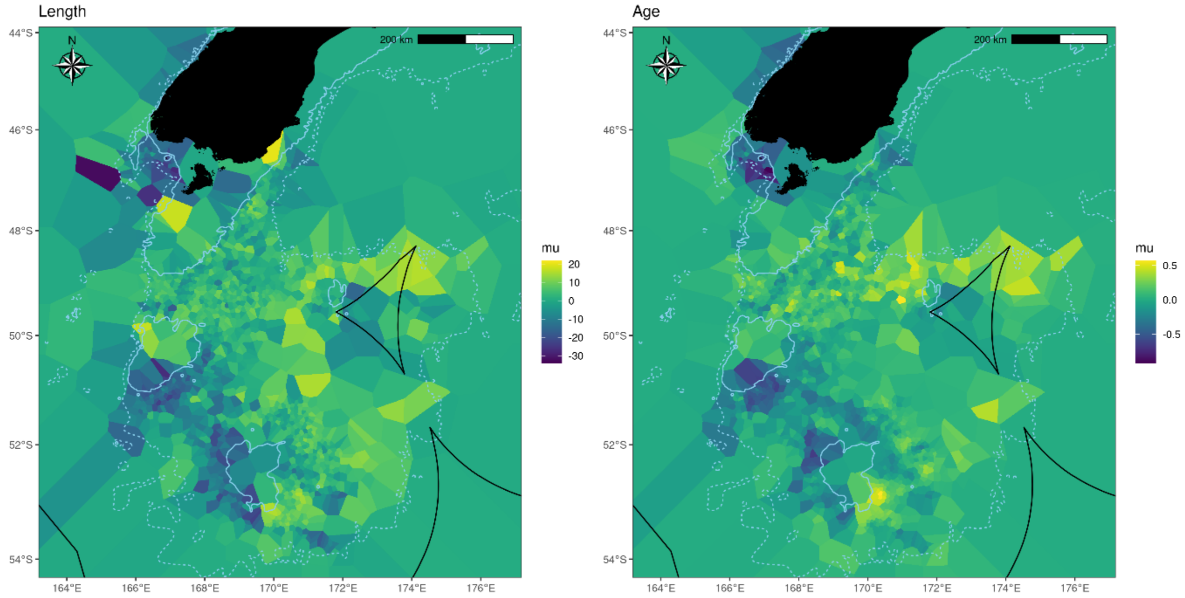

Figure 10: The spatial effect for the chosen model of mean length (length ~ intercept + year + month + sex + space) and the chosen model of mean age (age ~ intercept + year + month + sex + space).

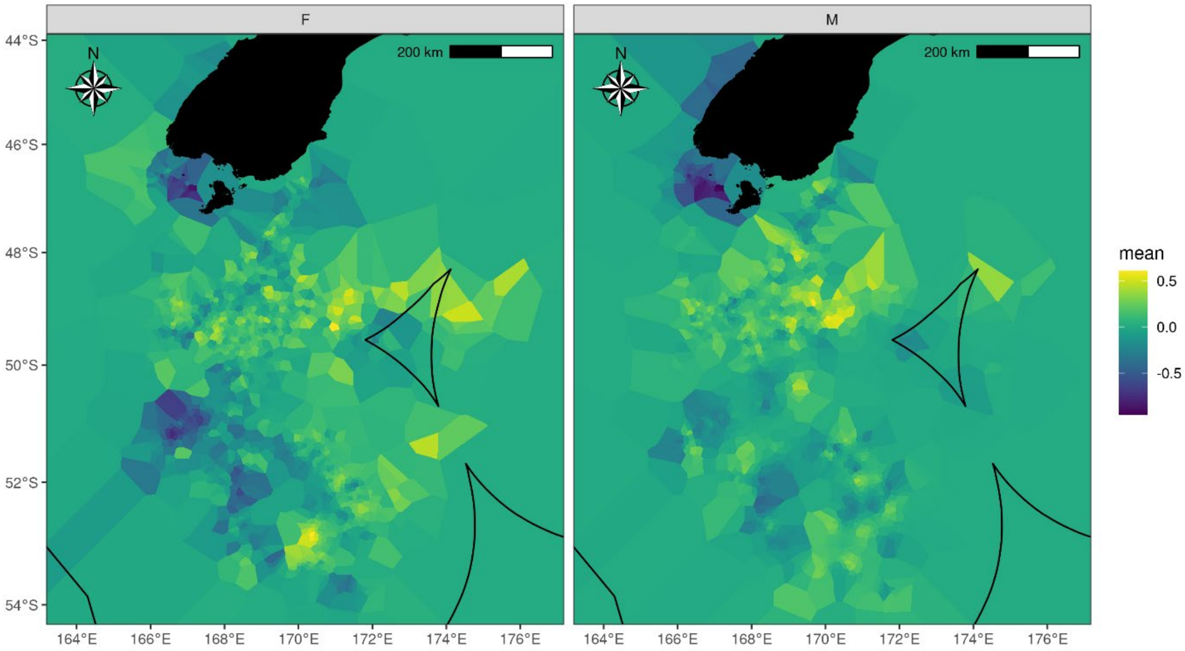

Figure 11: The spatial effect for the sex-specific model of mean age (age ~ intercept + year + month + sex + (space × sex)). Females (F) and males (M) are presented in the left panel and right panels, respectively.

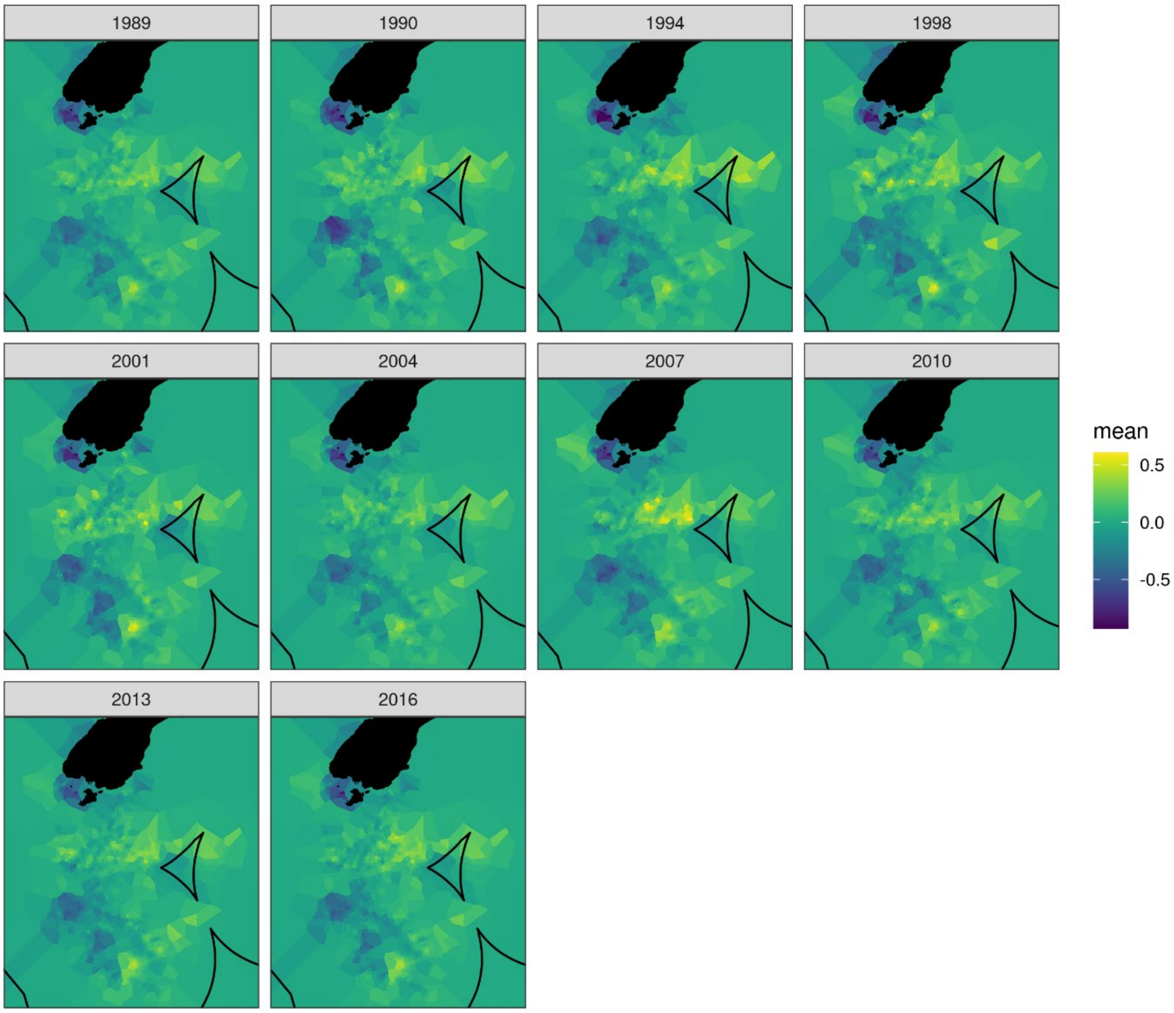

Figure 12: The spatial effect for the time block model of mean age (age ~ intercept + month + sex + (space × block)).

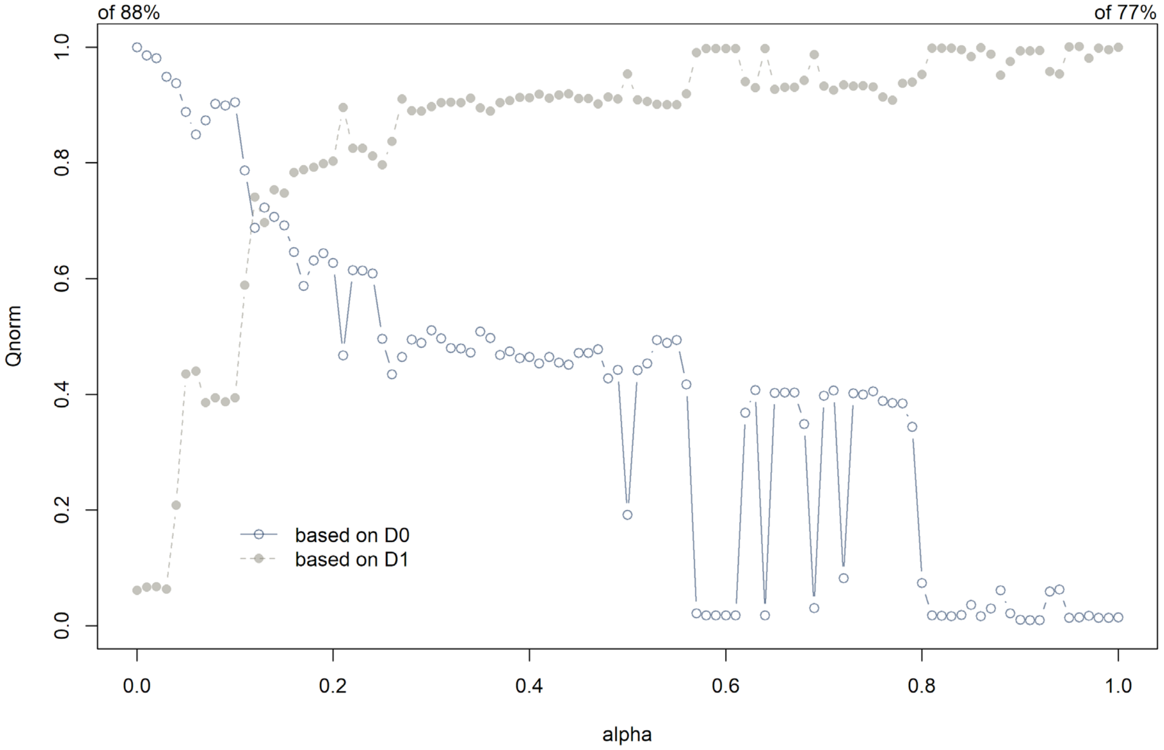

Figure 13: The proportion of explained inertia of the data (D0) and distance (D1) partitions (in K = 5 clusters) for different values of the mixing parameter alpha.

3.2 Results

An initial investigation of the length structure across the biological stocks was carried out. Unscaled length frequencies were plotted for all hake measured in HAK 1, HAK 4, and HAK 7. This suggested that although the largest fish were found in the Sub-Antarctic, most of the range of lengths were observed in each of the three assumed biological stock areas (WCSI, Chatham Rise, and the Sub-Antarctic) and that there was no evidence in the length frequencies that contradicted the current stock structure assumptions of hake for these three areas (Figure 14).

Tree regression analyses for the Sub-Antarctic suggested that the lengths could be clustered into three spatial strata, with no strong evidence of temporal splits (Figure 15). These three spatial strata suggested slightly smaller fish were located to the south of the Stewart-Snares shelf and to the west of Campbell Plateau in shallower depths, with the larger fish located to the east of the Sub-Antarctic in slightly deeper depths. The remaining (middle-sized fish) were allocated to Puysegur and on the Stewart-Snares shelf in the Sub-Antarctic. However, the fine scale patterns of lengths observed in the data (specially, the fine scale depth related structure along the Stewart-Snares shelf) were not well represented by the clusters generated by the tree regression. In addition, the spatial stratification resulting from the tree regression did not significantly modify the spatial strata of Horn (2008), with the majority of the catch coming from broadly the same region on the Stewart-Snares shelf.

Application of the Bayesian spatial-temporal analysis allowed the consideration of spatially non-contiguous areas (see Figure 16 and Figure 17), i.e., locations where the age and/or length structure was similar but was not located in a neighbouring location. Alpha levels of between 0.2 and 0.4 were considered optimal (Figure 13). Clustering was investigated for K = 3, 4, and 5 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 a single area (centred around the southern Stewart-Snares shelf), similar to that for the tree regression and the analysis of Horn (2008). However, the choice of five clusters split this region in deeper and shallower depths that were ‘spotted’ across the Stewart-Snares shelf area (see Figure 17). The relative catches were dominated by two clusters, both in and around the Stewart-Snares shelf, but suggested a pattern of similar proportions of catch from these two clusters up to the early 2000s, then diverging after about 2006 with an increasing proportion of catch in cluster 5, with cluster 2 reducing to nominal levels (Figure 18). The pattern of change in the relative proportions of catch from the length and age frequency Bayesian spatial-temporal analyses closely approximated the timing of the change in the targeting of hoki versus hake, and spatial contraction of effort catching hake from the mid-2000s (see, for comparison, Figure 5 and Figure 7 above).

Ideally, these clusters would be used to determine spatial structure of the commercial catch for use in an assessment model; however, only incomplete age data for the early years of the fishery were available at the time of this report and appropriate clustered age frequencies were not able to be developed for the consequential assessment. However, qualitative evaluation of the available age data did not suggest that ignoring the Bayesian stratification in determining spatially explicit age frequencies would have resulted in any significant bias in the Sub-Antarctic stock assessment (see Dunn et al. 2021).

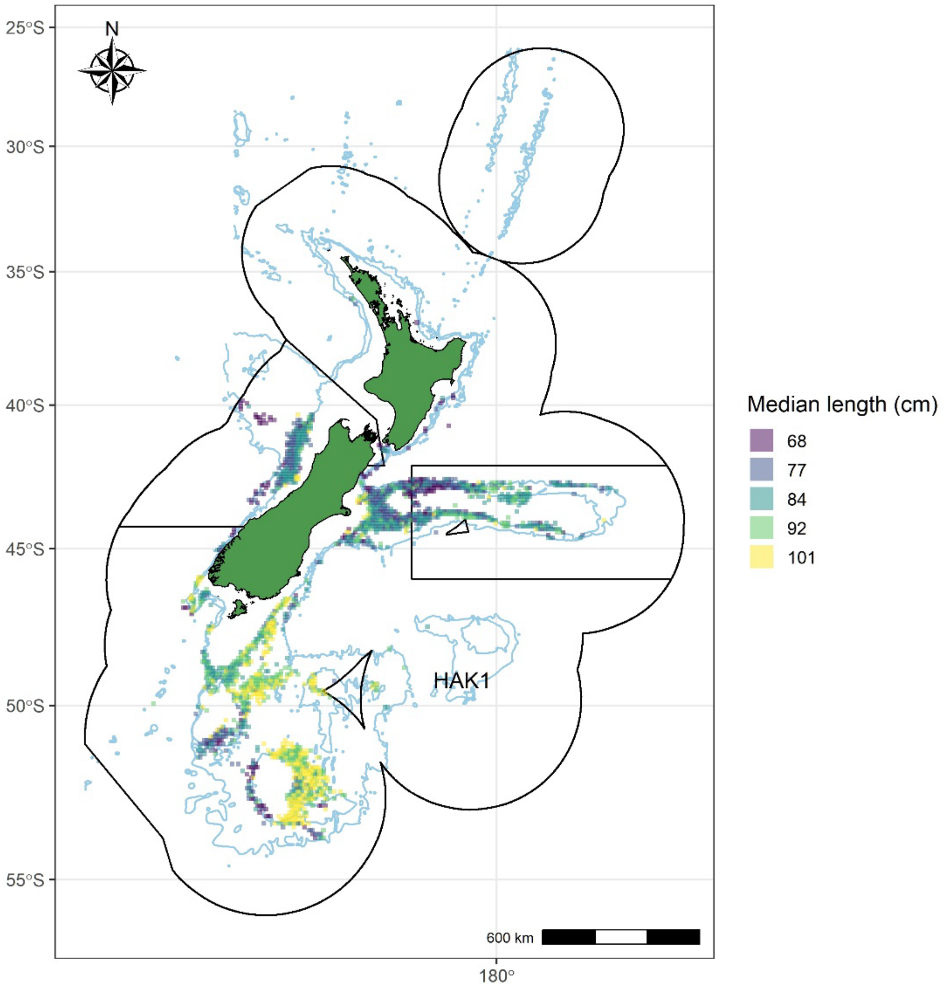

Figure 14: Observed median length of hake within the New Zealand EEZ by 0.1° cell, for males and females combined for years 1990–2020.

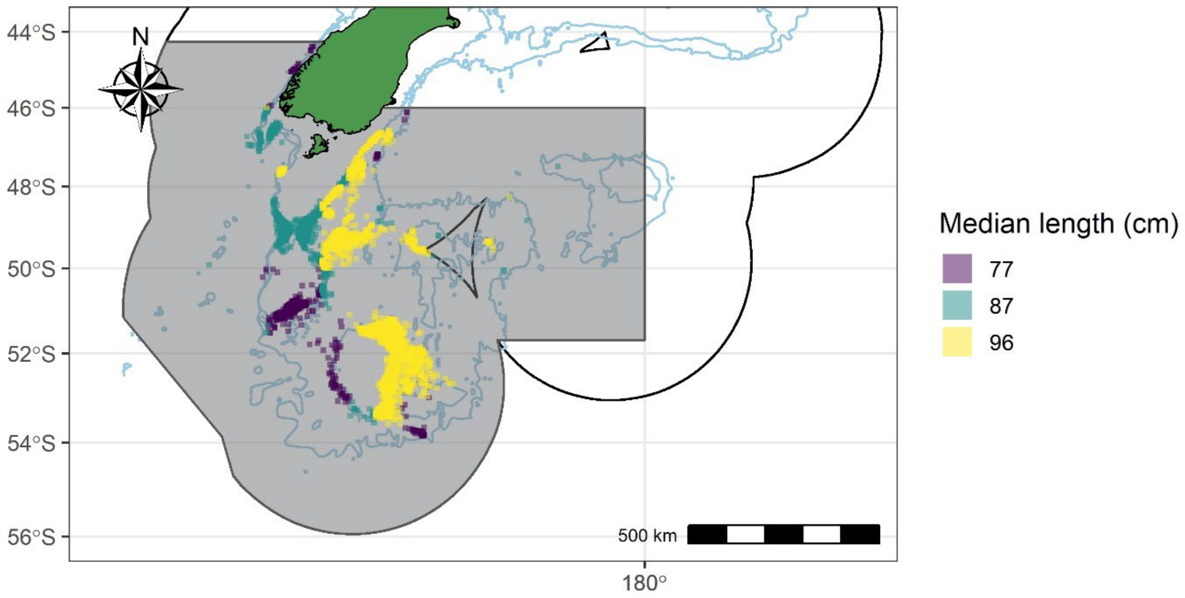

Figure 15: Estimated spatial strata using the tree-regression on the median length of hake within the New Zealand EEZ, for males and females combined for years 1990–2020.

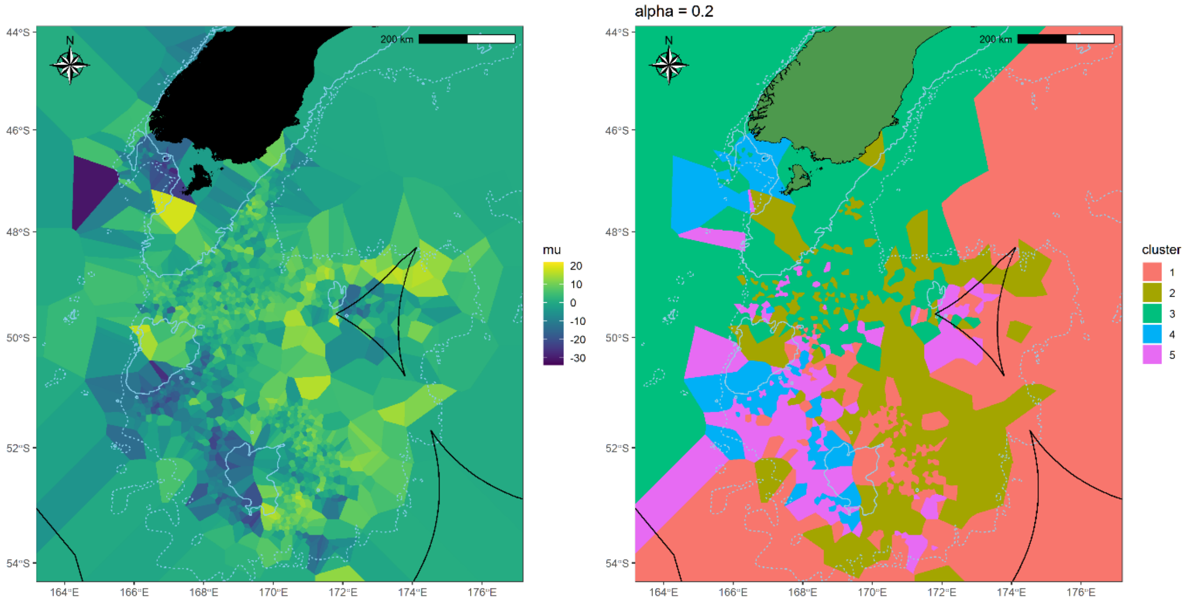

Figure 16: Clusters (for K = 5 clusters) for alpha = 0.2 levels for the age model.

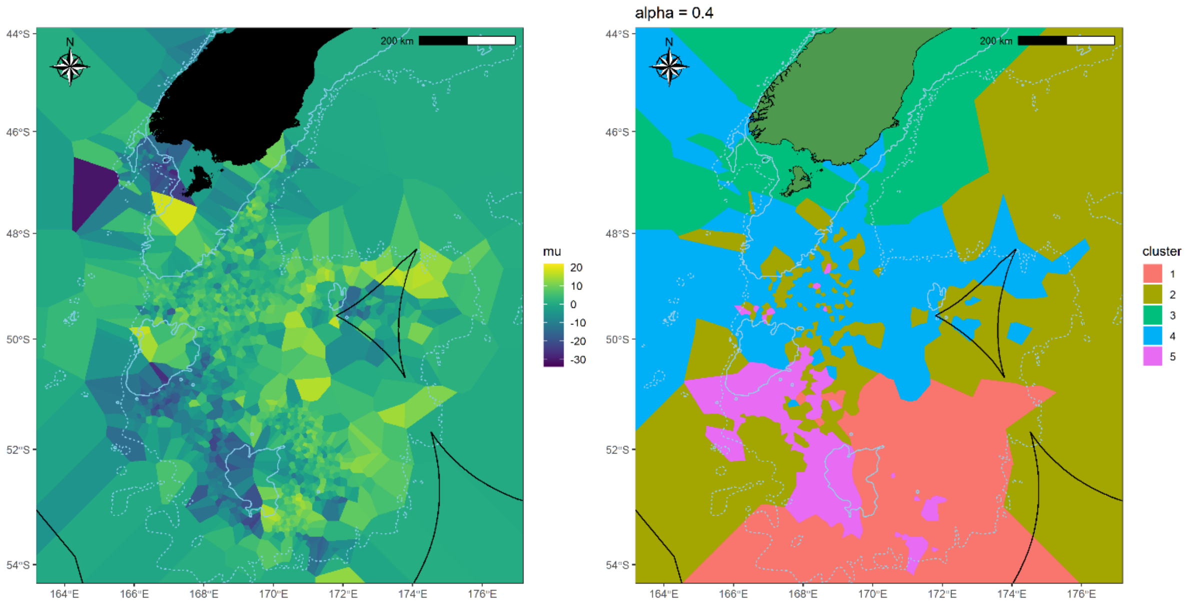

Figure 17: Clusters (for K = 5 clusters) for alpha = 0.4 levels for the age model.

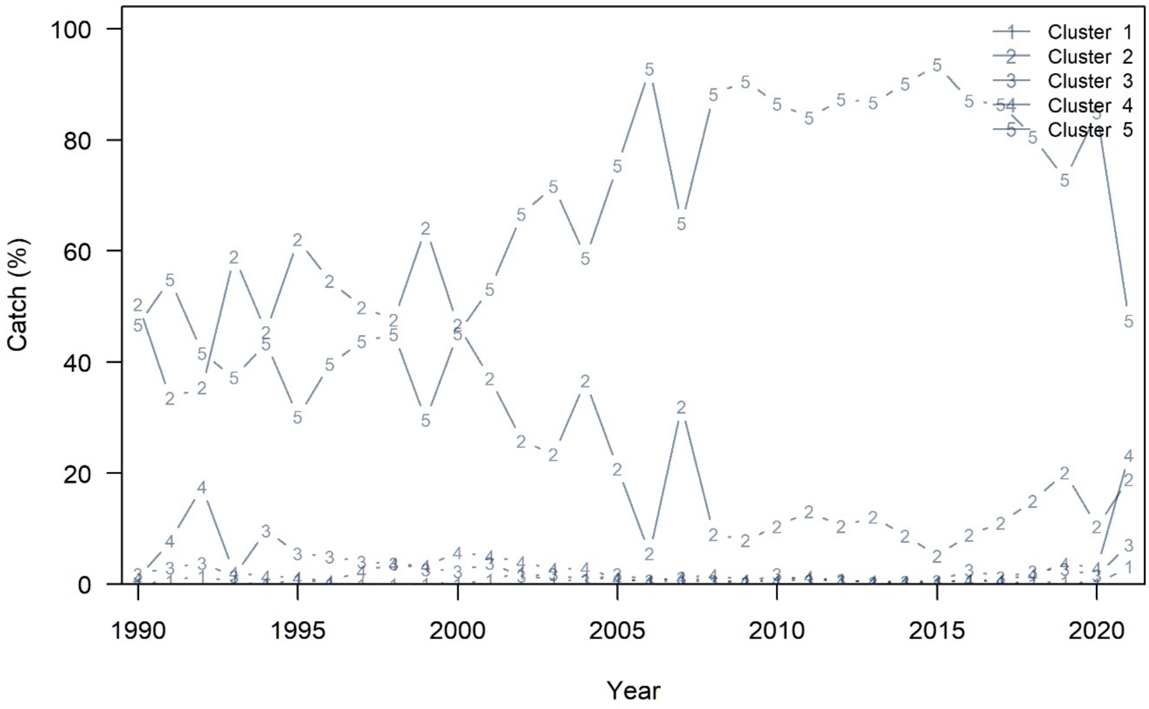

Figure 18: Relative catch of hake from allocation to the K = 5 clustering algorithm for the Bayesian spatial-temporal analysis of age and length by fishing year from 1989–90 to 2019–20.

4. BIOLOGICAL PARAMETERS

4.1 Length-weight parameters

Length-weight parameters for hake were last updated by Horn (2013a) based on data collected from resource surveys. Data from the resource surveys and other surveys from the Sub-Antarctic area were analysed to update the length-weight relationship ($n = 11\,635$). 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 $\text{Weight} = a \cdot (\text{length})^b$, to estimate the *a* and *b* parameters for each sex separately (see Table 6 and Figure 20). Plots of residuals indicated 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 there was little discernible change in the shape of the resulting length-weight curves.

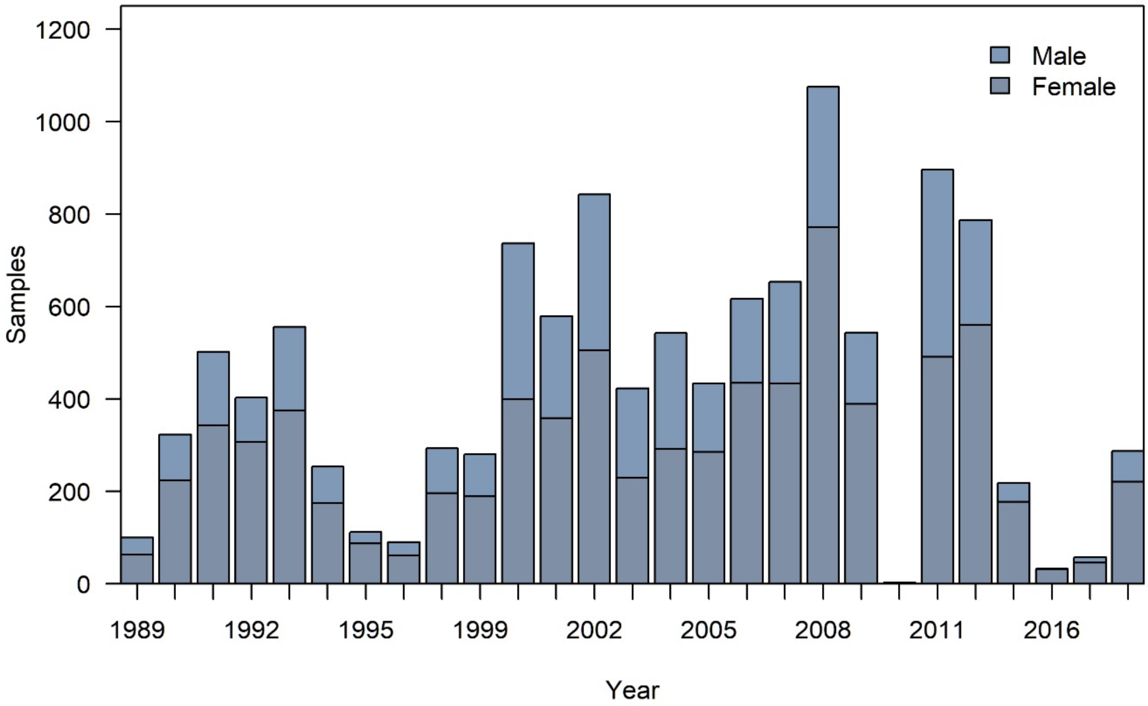

Figure 19: Number of length and weight observations for Sub-Antarctic hake by sex and fishing year from 1988–89 to 2017–18.

Table 6: Estimated length-weight parameters from Horn (2013a) and from this report.

Sex	N	Parameter	Horn (2013a)	This analysis
Male	3 992	*a*	2.13E-06	2.34E-06
		b	3.281	3.258
Female	7 643	*a*	1.83E-06	1.86E-06
		b	3.314	3.310

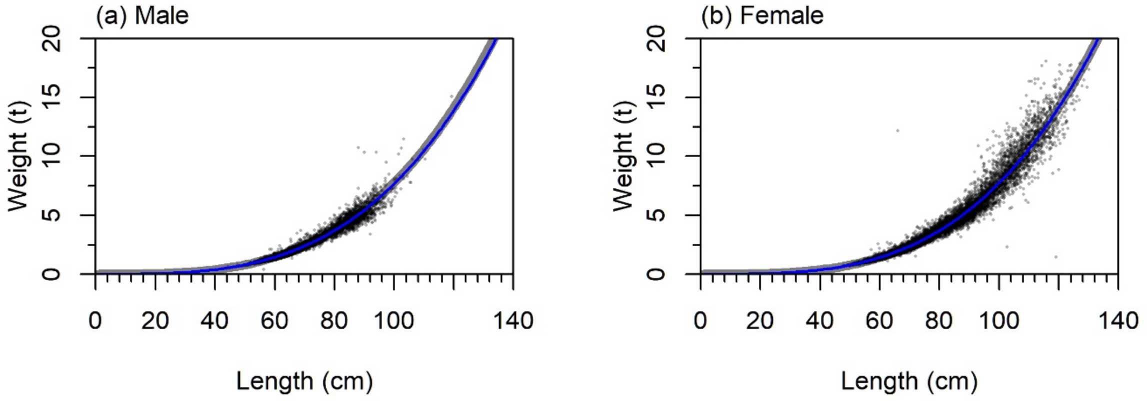

Figure 20: Observed and fitted length-weight relationship for (left) male and (right) female hake in the Sub-Antarctic.

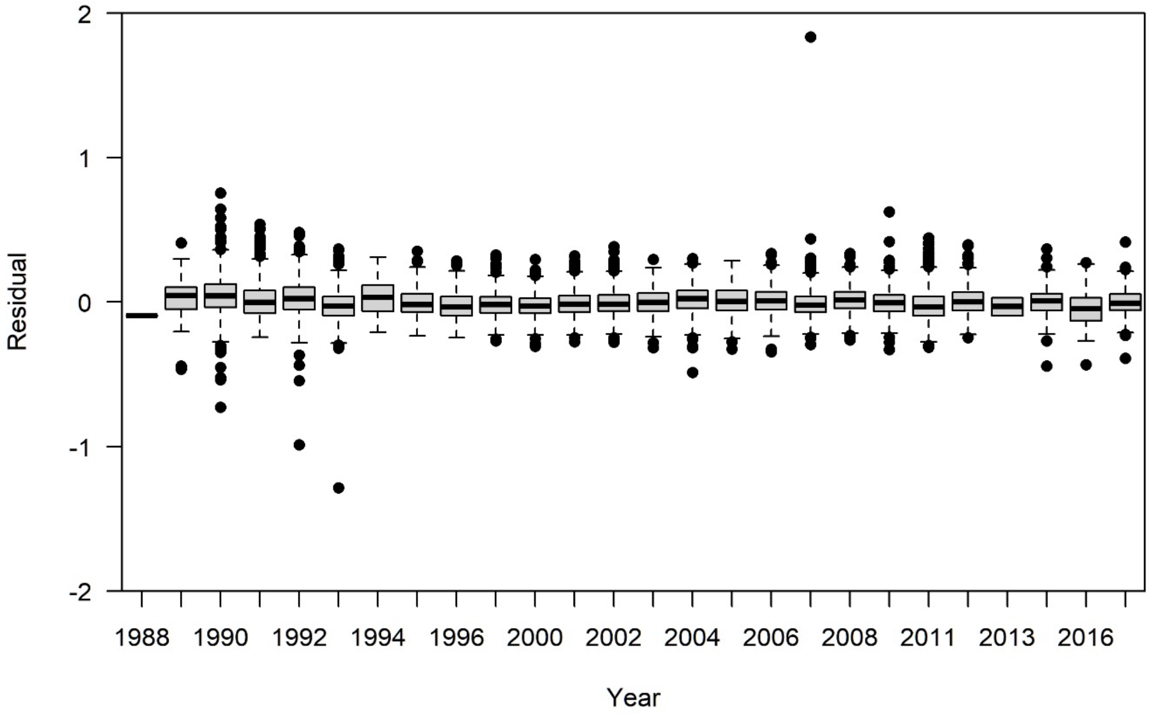

Figure 21: Boxplots of residuals (dark line = median; grey box = interquartile range; and values more than 1.5 times the interquartile range plotted as black circles) by fishing year, of the fitted the length-weight relationship for Sub-Antarctic hake, with the residuals for each sex combined.

4.2 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), parameterised as a Schnute growth curve (Schnute 1981) rather than the von Bertalanffy curve (von Bertalanffy 1938) generally used for deepwater species. Both the von Bertalanffy curve and Schnute curve were investigated using frequentist (maximum likelihood estimation, MLE) methods, as well as consideration of Bayesian von Bertalanffy and Bayesian non-parametric monotonically increasing mean length-at-age growth relationships (e.g., Dunn & Parker 2019). A total of 19 144 age length observations were available (*n* = 11 711 female and *n* = 7433 male) for Sub-Antarctic hake, over the years 1990–2019 (Figure 22), with most of the data collected from the Sub-Antarctic trawl survey. Fewer ages were available from the Fisheries New Zealand database than had been previously reported because, at the time of this analysis, not all historical data had been loaded into the database. However, the amount of data available to determine the age length relationship was reasonably large, and the inclusion of the additional data is unlikely to significantly modify the estimates made here.

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.

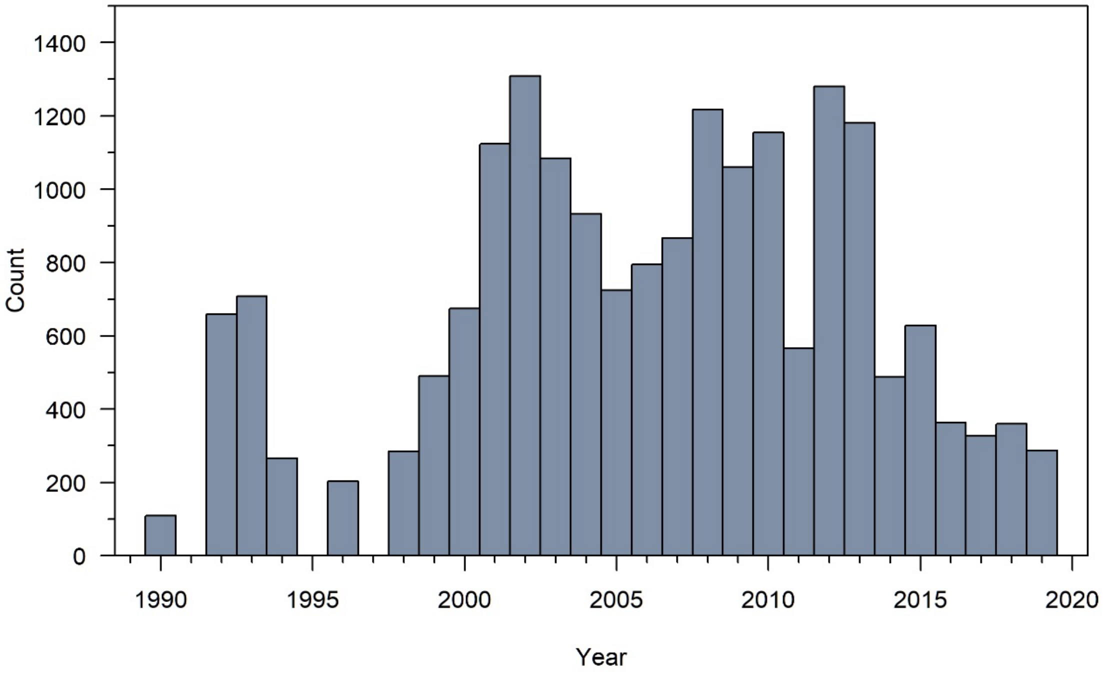

Figure 22: Number of length and age observations for Sub-Antarctic hake by fishing year from 1989–90 to 2019–20.

Initially, the available data for Sub-Antarctic hake were used to estimate the growth curve parameters using maximum likelihood estimation (MLE) and Bayesian methods. 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. Here, the length-at-age data are assumed to consist of length *L* and age *t* observations for *n* fish of sex i, i.e.,

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

The MLE and Bayesian von Bertalanffy growth parameters are given in Table 7, and the MLE von Bertalanffy curves and raw data are plotted in Figure 23. Diagnostic plots of the fits to all ages suggested significant departure from the normal distributional assumptions for fish of ages under 4, likely due to length-based selectivity effects at younger ages where small fish were less likely to be caught or sampled, and hence the von Bertalanffy growth models were refitted using only age data for ages four and over.

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 24). Comparison of Schnute model fits (Table 7) with von Bertalanffy models did not suggest any evidence for choosing one relationship over the other, and both had similar residual diagnostics. Model estimates of growth from both equations produced very similar relationships between length and age, and both models did not adequately fit the length data for younger ages (i.e., under 4 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-at-age for each age was estimated, but constrained to be monotonically increasing, with a constant CV (as a function of the mean length-at-age) with normally distributed errors.

Table 7: Revised growth parameters (MLE von Bertalanffy, MLE Schnute, 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)	88.8	90.1	89.4	89.3
		k (y^{-1})	0.295	0.260	0.297	0.260
		t_0 (y)	0.06	-0.52	0.12	-0.71
		CV	–	0.08	0.08	0.07
	Female	L_∞ (cm)	107.3	115.2	113.1	114.5
		k (y^{-1})	0.220	0.158	0.178	0.160
		t_0 (y)	0.01	-1.074	-0.500	-1.33
		CV	–	0.08	0.08	0.09
Schnute	Male	y_1	22.3	40.5	24.5	
		y_2	89.8	88.7	89.1	
		a	0.249	0.389	0.306	
		b	1.243	-1.576	0.760	
		A_1	1	1	1	
		A_2	20	20	20	
		CV	–	0.08	0.08	
	Female	y_1	22.9	43.4	42.8	
		y_2	109.9	108.3	108.3	
		a	0.147	0.319	0.311	
		b	1.457	-1.872	-1.689	
		A_1	1	1	1	
		A_2	20	20	20	
		CV	–	0.08	0.08	

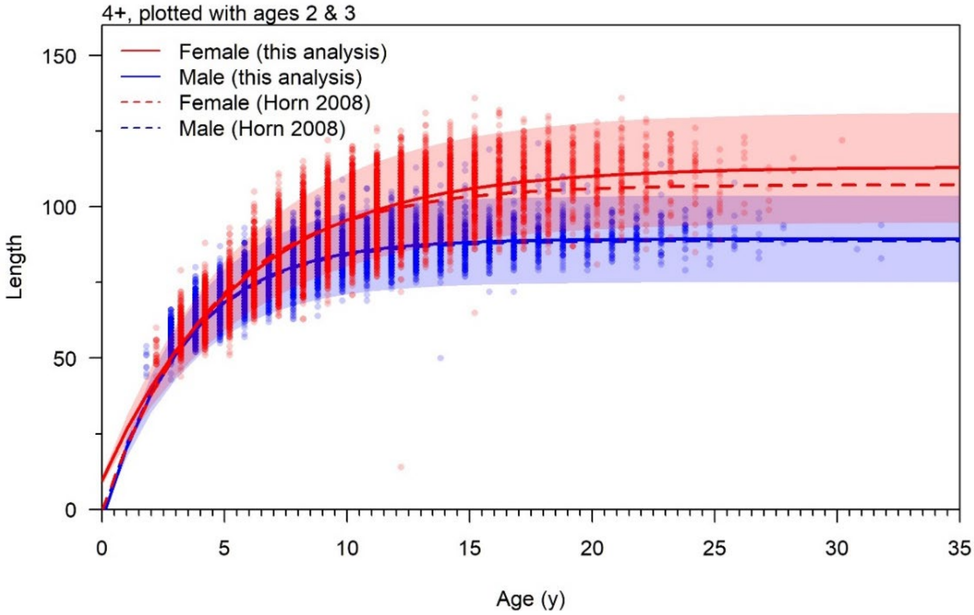

Figure 23: MLE von Bertalanffy growth curves for males (blue) and females (red) for Sub-Antarctic hake, with points showing the observations of age-at-length for males (blue points, offset by -0.2 years) and females (red points, offset by +0.2 years). Shaded regions show 95% confidence intervals.

Growth models were developed using the R package *brms* which uses Stan (Stan Development Team 2020) to estimate the Bayesian von Bertalanffy and the mean length-at-age 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. The mean length-at-age model was defined as:

$$
\begin{aligned}
&\tau \sim N(0, 100^2)\\
&L_t \sim N(\eta_t, \sigma^2)\\
&\eta_t = f(t) + f(m)\\
&\sigma = \tau\eta_t
\end{aligned}
$$

where $f(t)$ is a monotonic increasing term for each age and $f(m)$ is a monotonic increasing term for each month within each age. The models were run independently for each sex (i.e., there were no shared parameters across sexes).

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 Bayesian von Bertalanffy model (Table 8). Posterior predictive distributions for the mean length-at-age model showed some improvement over the Bayesian von Bertalanffy model (see Figure 25 and Figure 26). Further, the standardised residuals suggest that the mean length-at-age model fitted the data better across the full range of observed ages.

However, without any constraint, the mean length-at-age model estimates of mean length (Table 9) 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. Despite this, the non-linear monotonic model did have some advantages over the more standard von Bertalanffy model in that it allowed exploration of monthly changes in expected length—and hence used to estimate the cumulative proportion of growth that occurs throughout the year and growth proportions across time steps in the annual cycle of a stock assessment (Table 10).

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 8: The leave-one-out information criterion (LOO IC) for the Bayesian von Bertalanffy and mean length-at-age models (smaller 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

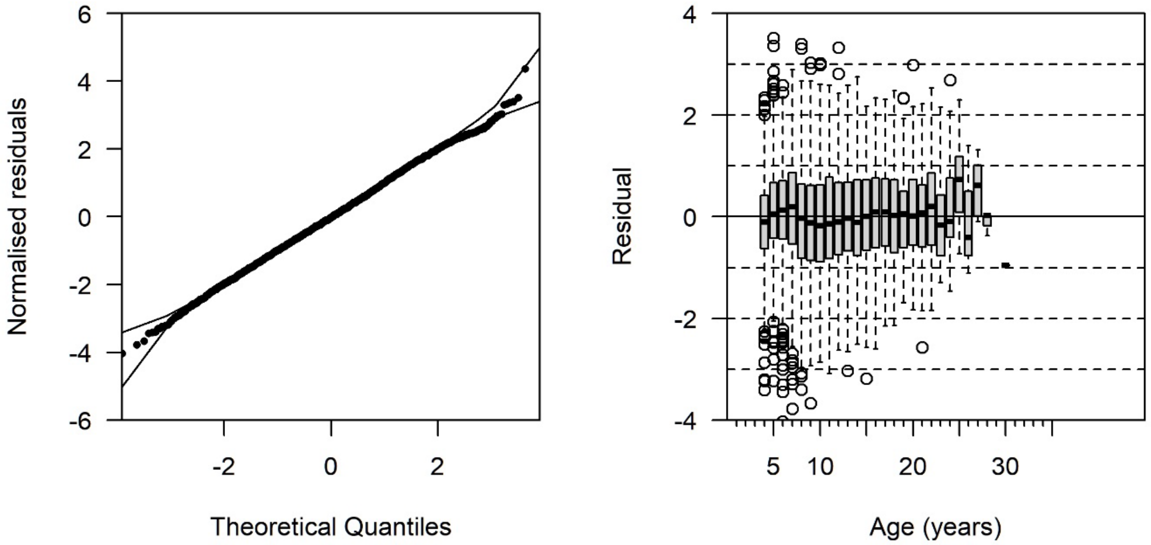

Figure 24: Diagnostic plots for the MLE von Bertalanffy growth curves for males and females: (left) quantile-quantile plot of normalised residuals with 95% confidence envelopes; and (right) boxplot of the normalised residuals by age.

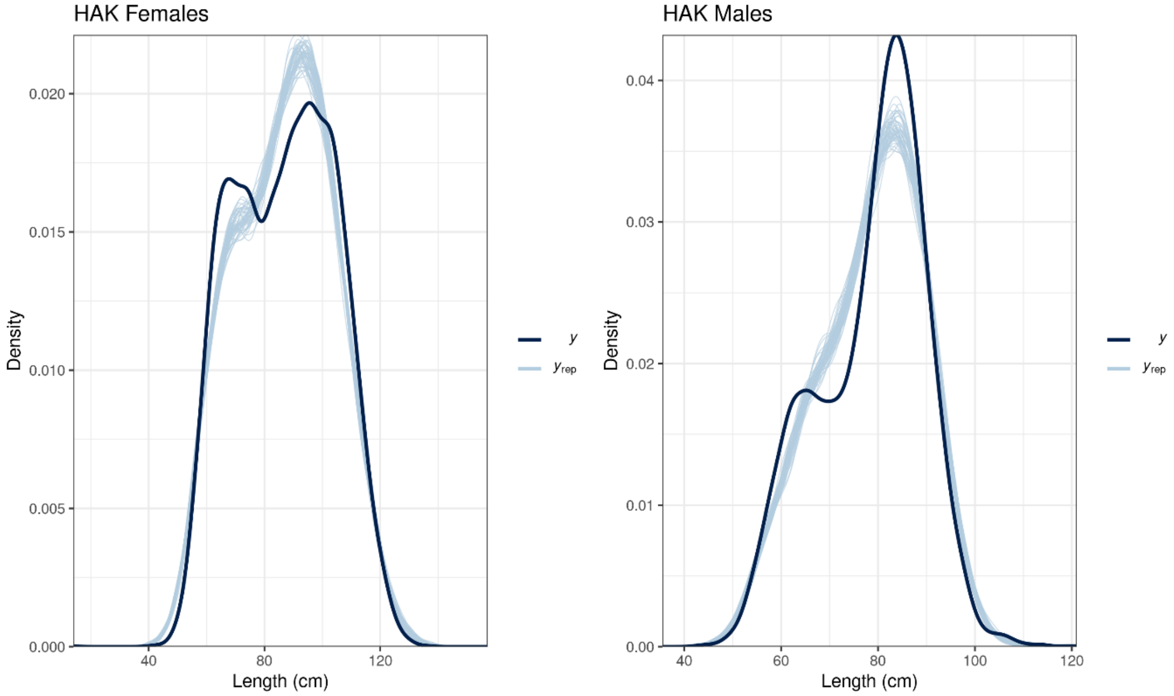

Figure 25: Comparison of the empirical distribution of the data (y) to the posterior predictive distributions of simulated data (y_{rep}) from the Bayesian von Bertalanffy model by sex.

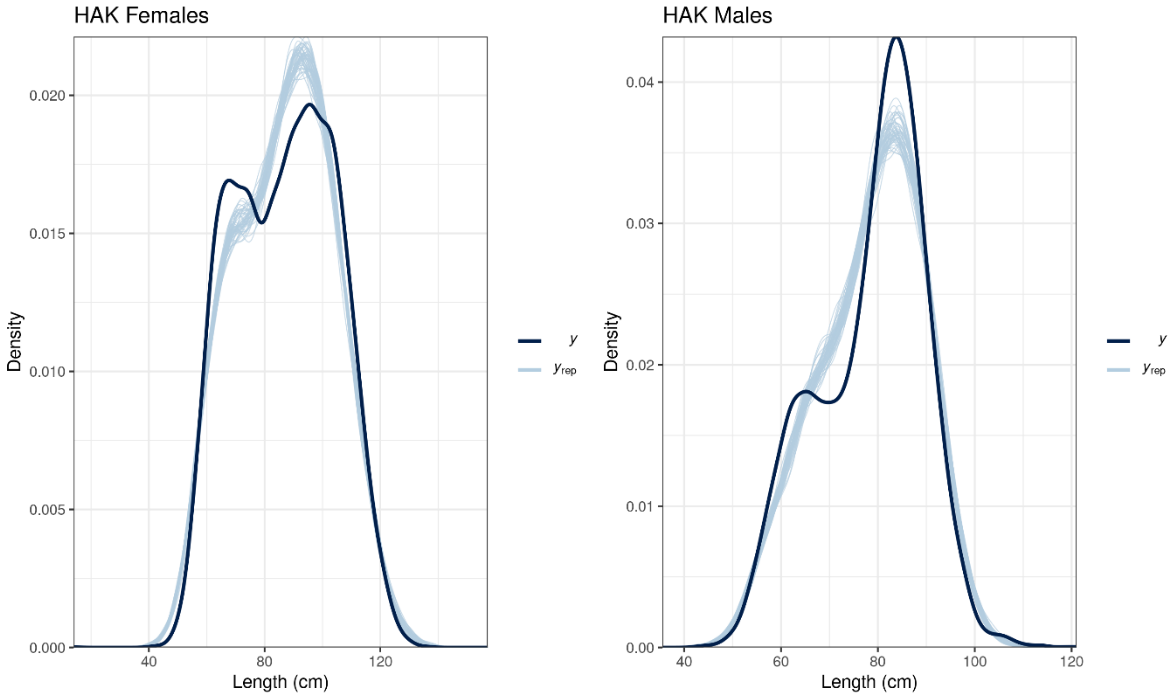

Figure 26: Comparison of the empirical distribution of the data (y) to the posterior predictive distributions of simulated data (y_{rep}) from the mean length-at-age model by sex.

Table 9: Estimated length-at-age (calculated for October = month 10) using the monotonic growth model.

Age						Female						Male
	Estimate	Est Error	2.5%	50%	97.5%	CV	Estimate	Est Error	2.5%	50%	97.5%	CV
2	50.56	4.34	42.25	59.04	50.56	0.0848	49.88	3.50	43.13	56.89	49.88	0.0675
3	58.48	5.02	48.44	68.25	58.48	0.0848	57.34	3.81	50.33	64.76	57.34	0.0675
4	64.63	5.48	54.46	75.28	64.63	0.0848	63.20	4.23	54.93	71.30	63.20	0.0675
5	71.17	5.95	59.66	82.77	71.17	0.0848	69.23	4.58	60.01	77.96	69.23	0.0675
6	77.40	6.59	64.26	90.26	77.40	0.0848	74.53	5.08	64.34	84.38	74.53	0.0675
7	82.81	7.04	69.57	96.64	82.81	0.0848	79.10	5.31	68.62	89.07	79.10	0.0675
8	88.74	7.59	74.25	103.44	88.74	0.0848	81.32	5.50	70.36	92.18	81.32	0.0675
9	92.87	7.77	77.85	108.21	92.87	0.0848	83.53	5.54	73.27	94.78	83.53	0.0675
10	96.52	8.05	80.92	112.81	96.52	0.0848	83.84	5.89	72.03	95.19	83.84	0.0675
11	97.92	8.46	81.60	114.65	97.92	0.0848	84.70	5.90	73.25	96.26	84.70	0.0675
12	100.04	8.51	83.73	116.82	100.04	0.0848	85.54	5.65	74.46	96.87	85.54	0.0675
13	102.12	8.78	84.91	119.27	102.12	0.0848	86.21	5.90	74.22	97.53	86.21	0.0675
14	103.32	8.93	85.55	121.35	103.32	0.0848	86.83	5.89	75.33	98.74	86.83	0.0675
15	104.19	8.78	87.21	121.11	104.19	0.0848	87.26	5.70	76.25	98.58	87.26	0.0675
16	105.34	8.90	87.89	122.66	105.34	0.0848	87.79	6.02	75.96	100.03	87.79	0.0675
17	105.90	8.76	88.69	122.89	105.90	0.0848	88.39	6.03	76.93	100.13	88.39	0.0675
18	107.13	9.15	89.04	124.45	107.13	0.0848	88.78	6.05	76.86	100.69	88.78	0.0675
19	107.49	9.13	89.36	125.52	107.49	0.0848	89.33	5.91	77.78	101.31	89.33	0.0675
20	107.59	9.01	90.16	125.12	107.59	0.0848	89.56	6.03	77.75	101.12	89.56	0.0675
21	108.21	9.03	90.19	125.89	108.21	0.0848	89.72	6.16	77.36	101.82	89.72	0.0675
22	108.32	9.20	90.59	127.04	108.32	0.0848	90.21	6.09	78.33	102.60	90.21	0.0675
23	109.20	9.37	90.92	127.52	109.20	0.0848	90.53	5.99	78.42	101.82	90.53	0.0675
24	109.69	9.46	90.62	128.07	109.69	0.0848	90.81	6.26	78.38	102.98	90.81	0.0675
25	110.02	9.27	91.68	128.43	110.02	0.0848	91.14	6.30	78.28	103.48	91.14	0.0675
26	111.28	9.47	92.88	129.23	111.28	0.0848	92.03	6.16	80.74	104.61	92.03	0.0675
27	111.99	9.71	92.71	131.10	111.99	0.0848	92.13	6.28	80.06	104.52	92.13	0.0675
28	114.24	9.79	95.21	133.20	114.24	0.0848	92.94	6.35	81.00	105.65	92.94	0.0675
30	119.53	10.78	99.25	142.20	119.53	0.0848	94.49	6.71	80.67	107.56	94.49	0.0675

Table 10: Cumulative proportion of growth by month (calendar month for the period October to September) estimated using the mean length-at-age growth model.

Month	Female	Male
10	0.000	0.000
11	0.007	0.010
12	0.011	0.015
1	0.239	0.270
2	0.257	0.296
3	0.268	0.308
4	0.278	0.319
5	0.318	0.343
6	0.501	0.659
7	0.605	0.869
8	0.765	0.927
9	1.000	1.000

5. CPUE ANALYSES

Standardised CPUE indices were generated for hake in the Sub-Antarctic following the method described by Ballara (2018). CPUE indices were calculated for two data sets: the tow-by-tow data (HOK/HAK/LIN target TCEPR and ERS-trawl tows); and daily summaries derived from the daily processed data from target HOK/HAK/LIN TCPER and ERS-trawl data.

Because a substantial proportion of the catch was taken during September of the early years when catch and effort data were available for the fishery (1990–1994), and this proportion was more likely to be similar in characteristics to the catch taken in October–December (the period of the year that more than three quarters of the catch was taken), catch and effort from September was assigned to the following fishing year.

Unstandardised CPUE indices were calculated as the mean of catch (t) per tow for the tow-by-tow data or mean catch (t) per day for the daily summaries. 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).

Models were run using forward stepwise multiple regression (Chambers & Hastie 1991) implemented in R (R Core Team 2019). The stepwise regression iteratively added terms to a base model initialised with *year* only, where the addition of a term resulted in a reduction in residual deviance of at least 1%. 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) were made for each accepted variable in the CPUE standardisation, which show the effect of each variable on the standardisations and the annual influence of each variable.

5.1 Tow-by-tow CPUE analysis

Tow-by tow CPUE indices were estimated using TCEPR and ERS-trawl data, with the dependent variable catch (t) and using the explanatory variables in Table 11. These included variables for year, vessel, location of the tow, tow duration, characteristics of the gear, and spatial variables such as the longitude and latitude, spatial grid cell (0.5° cells), and the subarea from Horn (2008). The explanatory variables were classified as either categorical or continuous. *Year* was treated as a categorical value to derive an annual index from the CPUE indices, with resulting indices standardised to have mean one over the years of the model. For the indices, CVs were calculated from the standard error, and 95% confidence intervals were also calculated for each index.

Categorical variables were modelled as factors in the analysis, and continuous variables were modelled as third-order polynomials. Vessel was included to account for potential differences in fishing efficiency between vessels and was assumed to be a constant effect over time, with target, gear characteristics, and depth used to account for potential differences in the fishing efficiency of the gear or other operational aspects related to depth or the reported target species. Spatial covariates were used to allow for potential differences between locations, and these were also assumed to be constant over time.

Table 11: Description of variables used in the Sub-Antarctic CPUE analysis for the tow-by-tow data. Continuous variables were fitted as third order polynomials.

Variable	Type	Description
Year	Categorical	Year (defined as September to August)
Vessel	Categorical	Vessel identification number
Statistical area	Categorical	Statistical area
Tow duration	Continuous	Duration of tow (h)
Catch	Continuous	Estimated green weight of hake (t) caught
Target species	Categorical	Target species (HOK/HAK/LIN)
Date	Continuous	Start date of the tow
Month	Categorical	Month of the year
Day of year	Continuous	Day of the year, starting at 1 January
Time start	Continuous	Start time of tow
Time mid	Continuous	Time at the midpoint of the tow
Method	Categorical	Fishing gear (BT = bottom trawl; MB = midwater trawl within 5 m of the seabed; MW = midwater trawl)
Tow distance	Continuous	Distance of tow (km)
Distance (duration)	Continuous	Distance of tow (calculated as speed in knots × duration)
Headline height	Continuous	Headline height (m) of the net
Bottom depth	Continuous	Seabed depth (m)
Net depth	Continuous	Net depth (m) (i.e., depth of ground rope)
Speed	Continuous	Vessel speed (knots)
Vessel experience	Continuous	Number of years the vessel has been involved in the fishery
Twin trawl	Categorical	T/F variable for a vessel that has used twin trawl
Subarea	Categorical	Defined by fishing effort distribution and depth
Longitude	Continuous	Longitude
Latitude	Continuous	Latitude
Grid number	Categorical	0.5° square based on start latitude and longitude

Analysis was conducted on a subset of all data defined by 'core' set of data, i.e., the subset that comprised vessels with a consistent presence in the fishery, using a consistent method, over a consistent area. The definition of the core data was all effort recorded on TCEPR or ERS-trawl forms from bottom trawl tows from vessels with length > 28 m (to ensure consistency between the TCEPR data and ERS-trawl data); effort that targeted either hoki, hake, or ling; fished in Statistical Areas 026, 027, 028, 030, 504, 602, 603, 604, 610, or 618; and had reported a minimum of 20 tows in each year. Tows that reported a total catch of > 50 t; reported a bottom depth outside the range between 150 and 1000 m; or had a total event duration less than 0.2 hours or greater than 15 hours were excluded to remove reporting errors and potential outliers. In addition, vessels that had been identified as a vessel that misreported catch by Ballara (2018) were also excluded. Further, a core vessel data set was then created from all those vessels with a presence of at least eight years in the fishery (comprising 80% of the total reported catch). This resulted in a data set comprising 30 unique vessels (Figure 27), and the relative contribution of effort in each year of each vessel is shown in Figure 28.

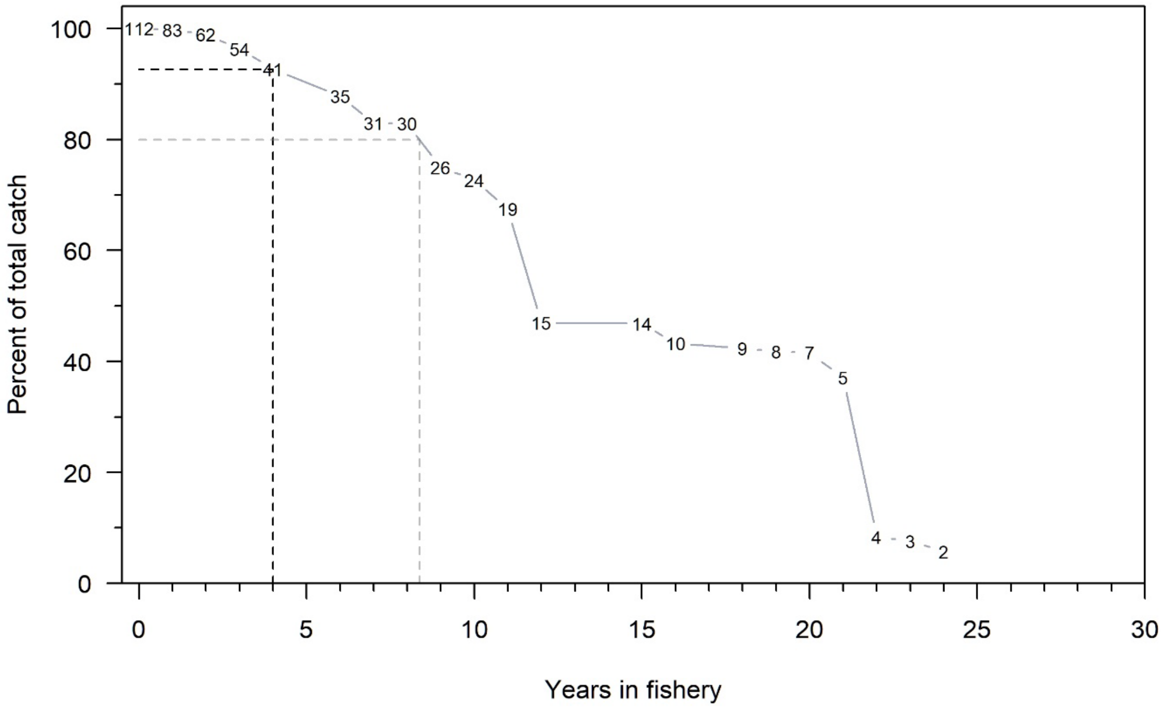

Figure 27: **Percentage of catch for different numbers of years in the fishery used to determine core vessels in the tow-by-tow CPUE standardisation.**

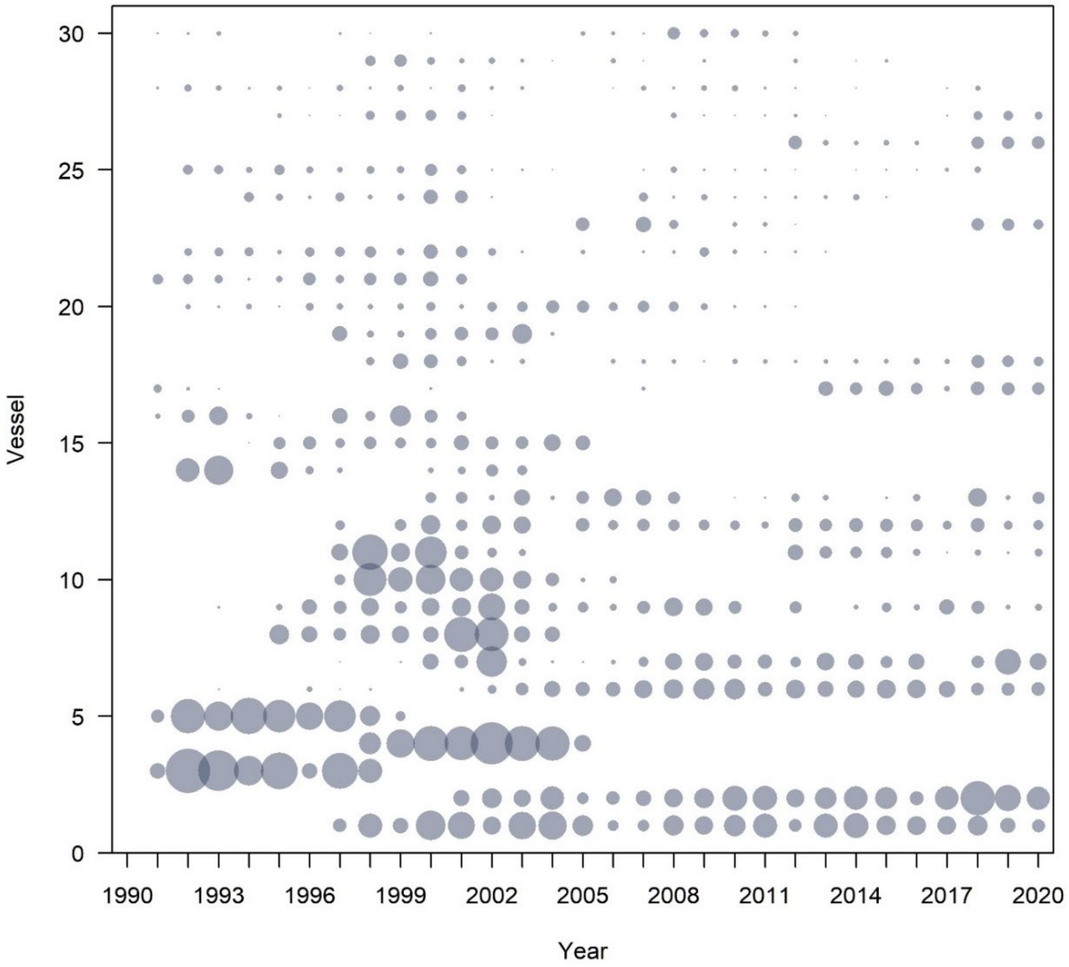

Figure 28: **Relative effort by vessel and fishing year for the core data used in the tow-by-tow CPUE standardisation, for 1989–90 to 2019–20.**

5.1.1 Results

The model terms accepted into the lognormal CPUE model for the tow-by-tow model included *year*, *target species*, *grid cell* (0.5° cell), *vessel*, and *month*. The model had an r^2 of 47% (Table 12). The standardised lognormal CPUE indices suggested a decline in relative abundance (Table 13) up to about 2015 and a small increase after and were similar to the lognormal indices obtained by Ballara (2018). The model terms accepted into the binomial CPUE model for the tow-by-tow model were similar: *year*, *grid cell* (0.5° cell), *vessel*, *target species*, and *bottom depth*. The model had an r^2 of 19% (Table 14). The binomial indices fluctuated for most of the series before reducing to a low in about 2017, and then increasing again in the most recent three years. The effect of the binomial on the overall index was to moderate the recent increase observed in the lognormal.

The combined index is given in Table 13 and Figure 29. Trends in the combined indices were similar to that reported by Ballara (2018) for the period where these indices overlapped, and similar 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 30) and grid cell (Figure 31) corresponded to a significant change in the influence on the index in about 2004.

In the tow-by-tow CPUE indices, the variable describing twin trawls was not selected as significant; however, additional analyses were undertaken that excluded twin trawls to evaluate the sensitivity of resulting CPUE indices. The use of twin trawls has been reported on the catch and effort forms since 2009, but only a small proportion of the hake catch in the tow-by-tow data (7% of hake catch reported on TCEPR forms since 2009) was from a twin trawl. There was a higher proportion in the ERS-trawl data from the most recent three years—13% of hake catch reported on ERS-trawl forms was from a twin trawl. However, the resulting lognormal, binomial, and combined indices were almost identical to the combined tow-by-tow CPUE indices that included twin trawls.

Table 12: The parameters included into the lognormal tow-by-tow CPUE model, degrees of freedom (df) for each variable, log-likelihood, AIC, r^2 value, and cumulative r^2 with the addition of each term.

	Term	df	logLike	AIC	r^2	Cumulative r^2
1	Intercept	1	-69138.2	–	–	–
2	*Year*	29	-68219.2	136500.3	0.04	0.04
3	*Target species*	2	-60451.4	120968.8	0.30	0.34
4	*Grid cell*	120	-58299.0	116904.0	0.07	0.41
5	*Vessel*	29	-56542.3	113448.7	0.05	0.46
6	*Month*	11	-56025.8	112437.6	0.01	0.47

Table13: Lognormal, binomial, and combined indices (with 95% confidence intervals and CV) for the tow-by-tow CPUE index.

Year	Lognormal		Binomial		Combined	
	Index (95% CIs)	CV	Index (95% CIs)	CV	Index (95% CIs)	CV
1991	0.37 (0.33-0.43)	0.06	0.66 (0.60-0.71)	0.03	0.24 (0.10-0.39)	0.06
1992	0.41 (0.38-0.45)	0.03	0.87 (0.86-0.89)	0.01	0.36 (0.28-0.45)	0.03
1993	0.45 (0.42-0.49)	0.03	0.85 (0.83-0.87)	0.01	0.38 (0.30-0.47)	0.03
1994	0.34 (0.31-0.37)	0.04	0.82 (0.80-0.85)	0.01	0.28 (0.18-0.37)	0.04
1995	0.33 (0.30-0.36)	0.04	0.79 (0.77-0.81)	0.01	0.26 (0.18-0.34)	0.04
1996	0.36 (0.33-0.40)	0.04	0.68 (0.65-0.71)	0.02	0.25 (0.16-0.34)	0.04
1997	0.36 (0.33-0.39)	0.03	0.70 (0.67-0.72)	0.01	0.25 (0.17-0.33)	0.03
1998	0.34 (0.32-0.37)	0.03	0.84 (0.82-0.85)	0.01	0.29 (0.22-0.35)	0.03
1999	0.41 (0.39-0.44)	0.03	0.84 (0.82-0.86)	0.01	0.35 (0.28-0.42)	0.03
2000	0.37 (0.35-0.39)	0.03	0.81 (0.79-0.82)	0.01	0.30 (0.24-0.36)	0.03
2001	0.39 (0.36-0.41)	0.03	0.79 (0.77-0.80)	0.01	0.30 (0.24-0.37)	0.03
2002	0.33 (0.31-0.35)	0.03	0.76 (0.74-0.78)	0.01	0.25 (0.19-0.31)	0.03
2003	0.35 (0.33-0.38)	0.03	0.71 (0.68-0.73)	0.01	0.25 (0.18-0.32)	0.03
2004	0.41 (0.38-0.44)	0.02	0.73 (0.71-0.75)	0.01	0.30 (0.23-0.37)	0.03
2005	0.38 (0.35-0.40)	0.03	0.65 (0.62-0.68)	0.02	0.24 (0.16-0.32)	0.04
2006	0.31 (0.28-0.34)	0.05	0.52 (0.48-0.56)	0.03	0.16 (0.06-0.26)	0.06
2007	0.32 (0.30-0.35)	0.04	0.51 (0.48-0.54)	0.02	0.16 (0.08-0.25)	0.05
2008	0.31 (0.29-0.33)	0.04	0.64 (0.61-0.67)	0.02	0.20 (0.12-0.28)	0.04
2009	0.28 (0.26-0.30)	0.04	0.67 (0.64-0.70)	0.02	0.19 (0.11-0.27)	0.05
2010	0.30 (0.27-0.32)	0.04	0.68 (0.65-0.71)	0.01	0.20 (0.12-0.28)	0.04
2011	0.26 (0.24-0.28)	0.05	0.65 (0.62-0.68)	0.02	0.17 (0.08-0.26)	0.05
2012	0.25 (0.23-0.27)	0.05	0.71 (0.69-0.74)	0.01	0.18 (0.09-0.26)	0.05
2013	0.31 (0.28-0.33)	0.04	0.64 (0.61-0.67)	0.02	0.20 (0.12-0.27)	0.04
2014	0.22 (0.21-0.24)	0.05	0.54 (0.51-0.57)	0.02	0.12 (0.04-0.20)	0.05
2015	0.18 (0.17-0.20)	0.07	0.56 (0.53-0.59)	0.02	0.10 (0.02-0.19)	0.07
2016	0.22 (0.21-0.24)	0.06	0.60 (0.57-0.63)	0.02	0.13 (0.04-0.22)	0.06
2017	0.24 (0.22-0.26)	0.06	0.50 (0.47-0.53)	0.02	0.12 (0.03-0.21)	0.06
2018	0.21 (0.20-0.23)	0.05	0.80 (0.78-0.82)	0.01	0.17 (0.10-0.24)	0.05
2019	0.20 (0.18-0.21)	0.06	0.85 (0.84-0.87)	0.01	0.17 (0.09-0.25)	0.06
2020	0.21 (0.20-0.23)	0.06	0.79 (0.77-0.82)	0.01	0.17 (0.09-0.25)	0.06

Table 14: The parameters included into the binomial tow-by-tow CPUE model, degrees of freedom (df) for each variable, log-likelihood, AIC, r^2 value, and cumulative r^2 with the addition of each term.

	Term	df	logLike	AIC	r^2	Cumulative r^2
1	Intercept		-49550	–	–	–
2	*Year*	29	-48273	96606	0.03	0.03
3	*Grid cell*	154	-42719	85805	0.11	0.14
4	*Vessel*	29	-41514	83454	0.02	0.16
5	*Target species*	2	-40815	82060	0.02	0.18
6	*Bottom depth (m)*	3	-40118	80672	0.01	0.19

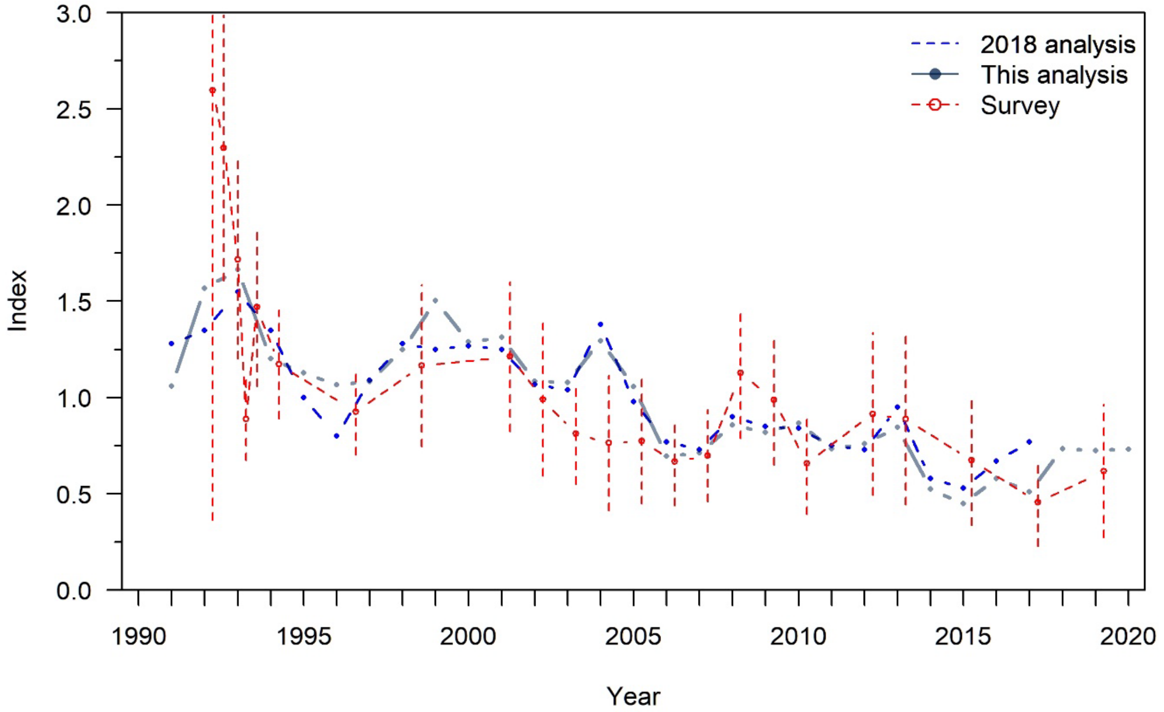

Figure 29: Combined CPUE indices for the tow-by-tow analysis, compared with the analysis of Ballara (2018), and the Sub-Antarctic trawl survey biomass index by fishing year, from 1990–91 to 2019–20.

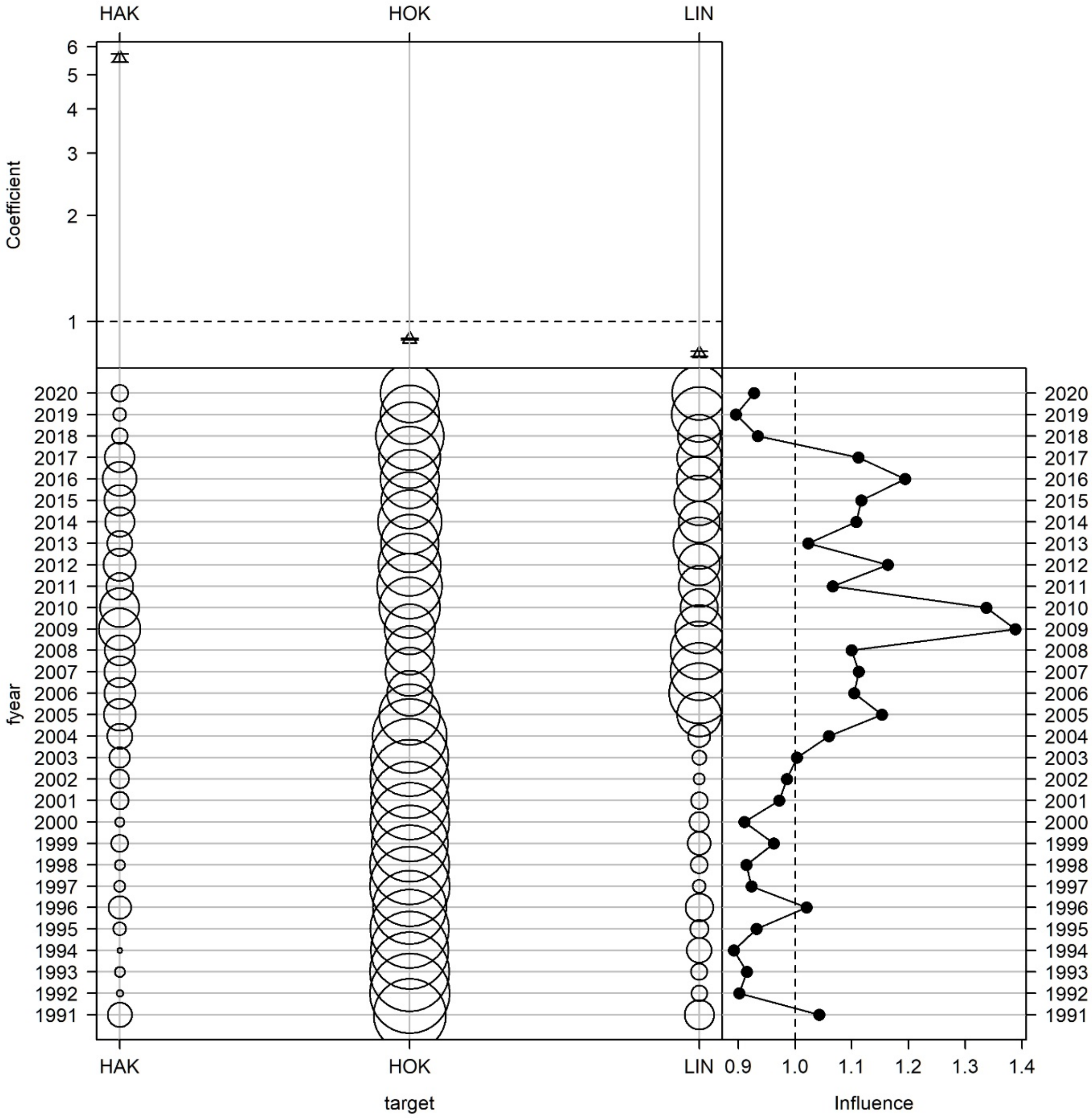

Figure 30: Influence plots of the effect of target species on the lognormal CPUE indices for the tow-by-tow analysis.

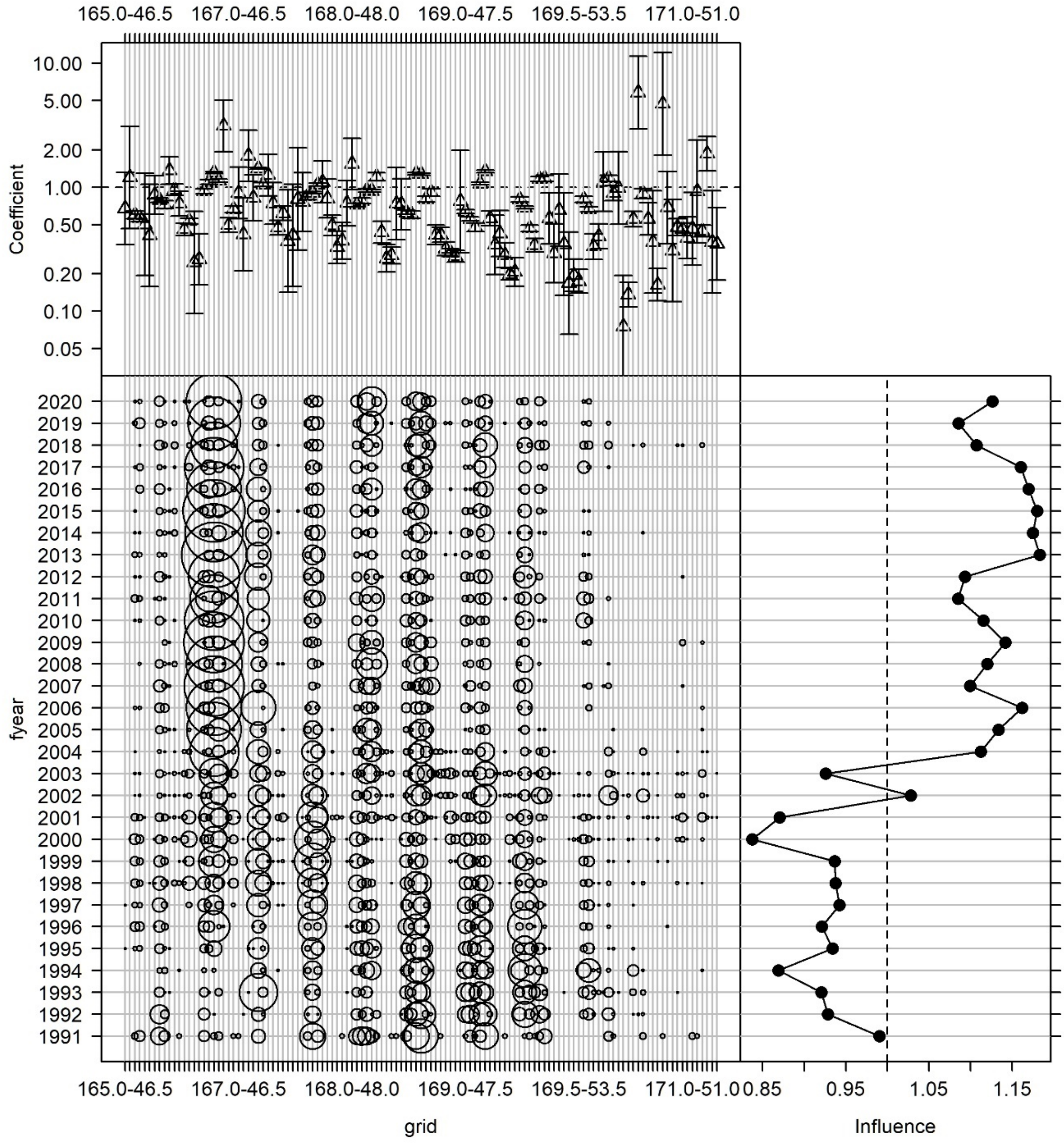

Figure 31: Influence plots of the effect of grid cell on the lognormal CPUE indices for the tow-by-tow analysis.

5.1.2 Daily summary CPUE analysis

Daily summary CPUE indices were estimated using daily processed forms from the TCEPR and ERS-trawl data, with the dependent variable catch (t) per day. The explanatory variables offered to the standardisation were similar to the tow-by-tow data above, but daily values for variables were estimated as the median values on each day for location and gear specific parameters (Table 15). The explanatory variables were classified as either categorical or continuous. *Year* was treated as a categorical value to derive an annual index from the CPUE indices, with resulting indices standardised to have mean one over the years of the model. For the indices, CVs were calculated from the standard error, and 95% confidence intervals were also calculated for each index.

Categorical variables were modelled as factors in the analysis, and continuous variables were modelled as third-order polynomials. Vessel was included to account for potential differences in fishing efficiency between vessels and was assumed to be a constant effect over time, with target, gear characteristics, and depth used to account for potential differences in the fishing efficiency of the gear or other operational aspects related to depth or the reported target species. Spatial covariates were used to allow for potential differences between locations, with these also assumed to be constant over time.

Analysis was conducted on a subset of all data defined by ‘core’ set of data, i.e., the subset that comprised vessels with a consistent presence in the fishery, using a consistent method, over a consistent area. The definition of the core data was all effort recorded on TCEPR or ERS-trawl forms from bottom trawl tows from vessels with length > 28 m (to ensure consistency between the TCEPR data and ERS-trawl data); effort that targeted either hoki, hake, or ling; and fished in Statistical Areas 026, 027, 028, 030, 504, 602, 603, 610, or 618. Daily catches that had: a total catch of > 80 t; a median bottom depth outside the range between 150 and 1000 m; or a combined event duration for a day of less than 0.2 hours or greater than 24 hours were excluded to remove reporting errors and potential outliers. In addition, vessels that had been identified as a vessel that misreported catch by Ballara (2018) were also excluded. Further, a core vessel data set was then created from all those vessels with a presence of at least seven years in the fishery (comprising 80% of the total reported catch). This resulted in a data set comprising 24 unique vessels (Figure 32), and the relative contribution of effort in each year of each vessel is shown in Figure 33.

Table 15: Description of variables used in the Sub-Antarctic CPUE analysis for the daily summary data. Continuous variables were fitted as third order polynomials.

Variable	Type	Description
Year	Categorical	Year (defined as September to August)
Vessel	Categorical	Vessel identification number
Statistical area	Categorical	Statistical area
Effort	Continuous	Number of tows in each day
Tow duration	Continuous	Duration of all tows in each day (h)
Catch	Continuous	Estimated green weight of hake (t) caught
Target species	Categorical	Main target species (HOK/HAK/LIN)
Date	Continuous	Date the fish were processed
Month	Categorical	Month of the year
Day of year	Continuous	Day of the year, starting at 1 January
Method	Categorical	Fishing gear (BT = bottom trawl; MB = midwater trawl within 5 m of the seabed; MW = midwater trawl)
Tow distance	Continuous	Distance of all tows on each day
Distance (duration)	Continuous	Distance (calculated as speed × duration) of all tows on each day
Headline height	Continuous	Median headline height (m) of the net on each day
Bottom depth	Continuous	Median seabed depth (m) on each day
Net depth	Continuous	Median net depth (m) on each day (depth of ground rope)
Speed	Continuous	Median vessel speed (knots) on each day
Vessel experience	Continuous	Number of years the vessel has been involved in the fishery
Twin trawl	Categorical	T/F variable for a vessel that has used twin trawl on each day
Subarea	Categorical	Defined by fishing effort distribution and depth
Longitude	Continuous	Median longitude of the vessel on each day
Latitude	Continuous	Median latitude of the vessel on each day
Grid number	Categorical	0.5° square based on start latitude and longitude

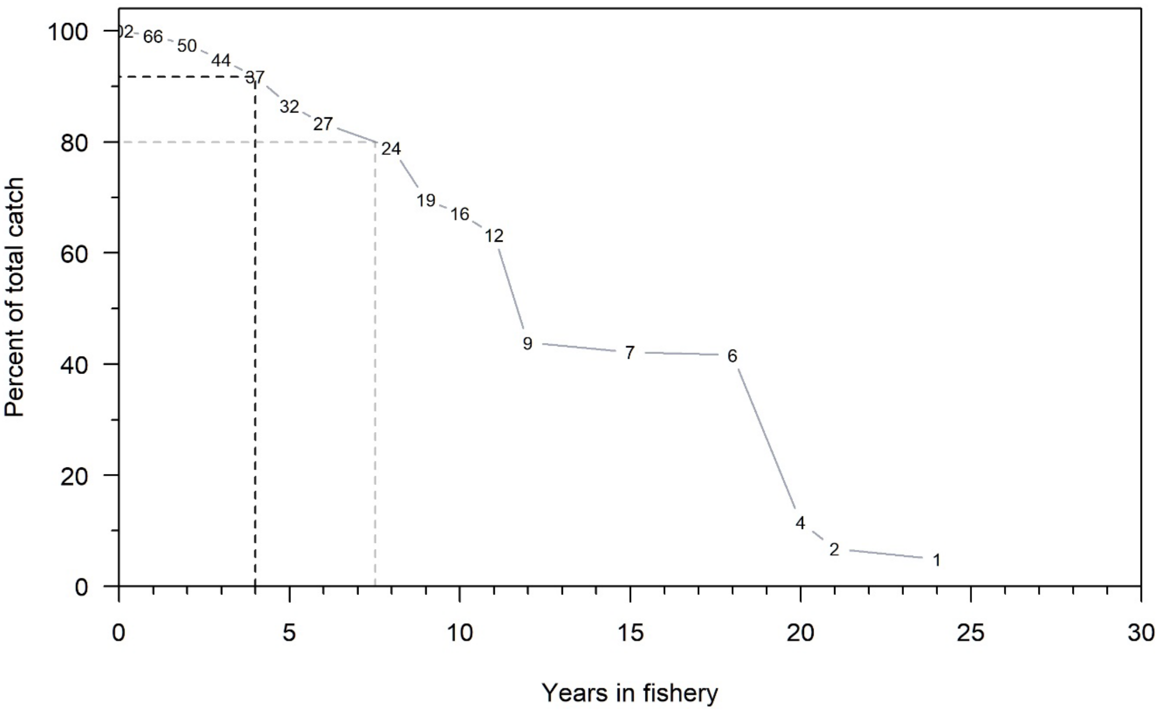

Figure 32: Percentage of catch for different numbers of years in the fishery used to determine core vessels in the daily summary CPUE standardisation.

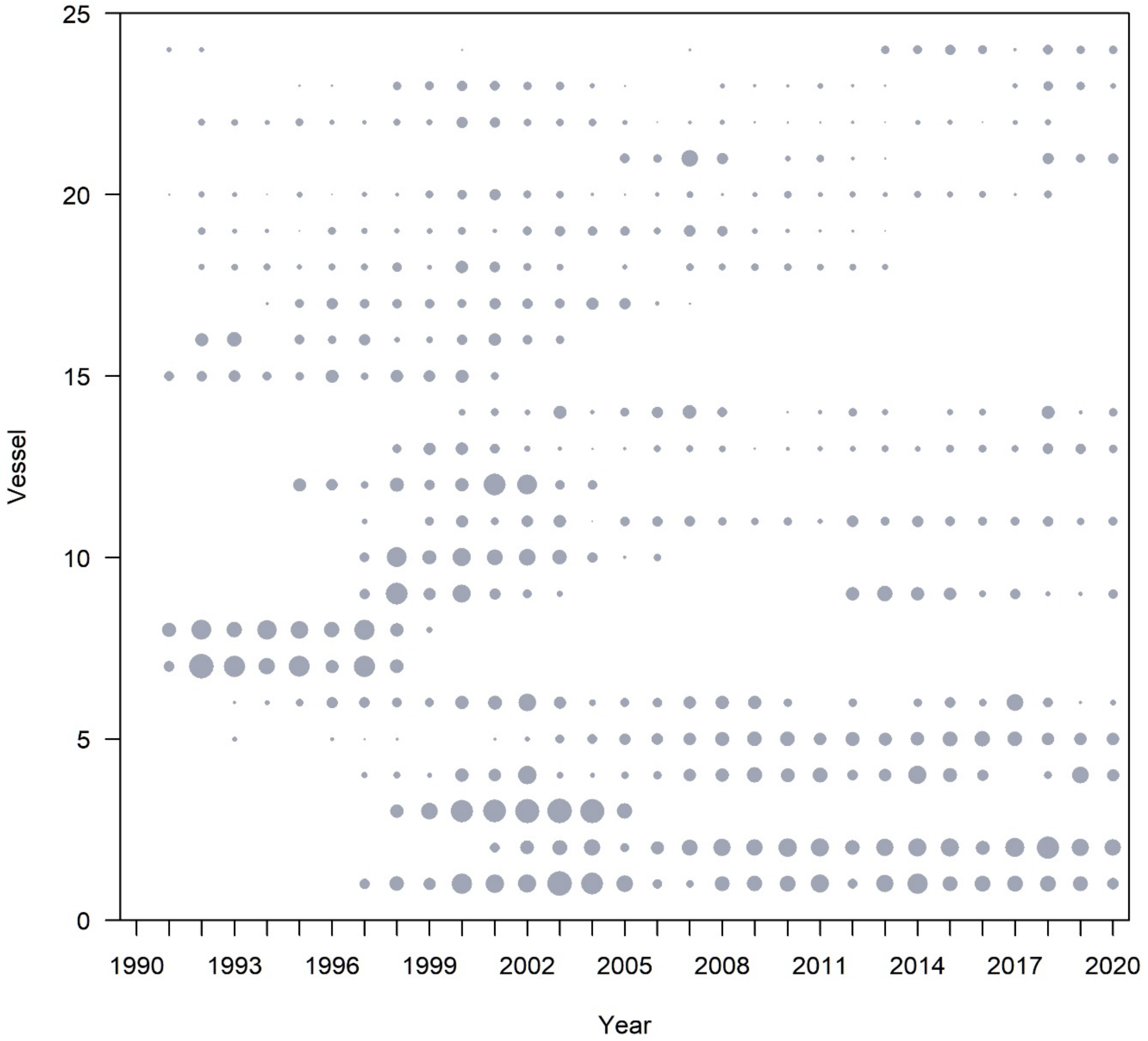

Figure 33: Relative effort by vessel and year for the core data used in the daily summary CPUE standardisation by fishing year, from 1990–91 to 2019–20.

5.1.3 Results

The model terms accepted into the lognormal CPUE model for the daily summary data included *year*, *grid cell* (0.5° cell), *target species*, *month*, and *vessel*. The model had an r^2 of 50% (Table 16). The standardised lognormal CPUE indices suggested a decline in relative abundance (Table 17) up to about 2015 and the small increase after and were similar to the lognormal indices obtained by Ballara (2018). The model terms accepted into the binomial CPUE model for the tow-by-tow model were similar: *year*, *grid cell* (0.5° cell), *bottom depth*, *month, vessel*, and *fishing duration*. The model had an r^2 of 26% (Table 18). The binomial indices fluctuated for most of the series before reducing to a low in about 2017, and then increasing again in the most recent 3 years. The effect of the binomial on the overall index was to moderate the recent increase observed in the lognormal.

The combined index is given in Table 17 and Figure 34. Trends in the combined indices were similar to that reported by Ballara (2018) for the period where these indices overlapped, and similar to the observed trend in the trawl survey biomass index over the same period. The combined daily summary index was also similar to the tow-by-tow index, suggesting a gradual decline in relative abundance over the time period of the indices.

Table 16: The parameters included into the lognormal daily summary CPUE model, degrees of freedom (df) for each variable, log-likelihood, AIC, r^2 value, and cumulative r^2 with the addition of each term.

	Term	df	logLike	AIC	r^2	Cumulative r^2
1	Intercept		19123	–	–	–
2	*Year*	29	19094	69187	0.03	0.03
3	*Grid cell*	123	18971	62635	0.29	0.32
4	*Target species*	2	18969	57671	0.15	0.47
5	*Month*	11	18958	57298	0.02	0.48
6	*Vessel*	23	18935	56885	0.01	0.50

Table 17: Lognormal, binomial, and combined indices (with 95% confidence intervals and CV) for the daily summary CPUE index.

Year	Lognormal		Binomial		Combined	
	Index (95% CIs)	CV	Index (95% CIs)	CV	Index (95% CIs)	CV
1991	1.56 (1.27-1.91)	0.07	0.94 (0.90-0.98)	0.02	1.47 (1.26-1.68)	0.07
1992	1.76 (1.53-2.02)	0.04	0.97 (0.95-0.98)	0.01	1.70 (1.55-1.84)	0.04
1993	1.55 (1.34-1.79)	0.05	0.91 (0.87-0.95)	0.02	1.41 (1.26-1.56)	0.05
1994	1.42 (1.21-1.67)	0.06	0.97 (0.95-0.99)	0.01	1.38 (1.22-1.54)	0.06
1995	1.28 (1.12-1.46)	0.06	0.97 (0.95-0.98)	0.01	1.24 (1.10-1.37)	0.06
1996	1.24 (1.08-1.42)	0.06	0.96 (0.94-0.98)	0.01	1.19 (1.06-1.33)	0.06
1997	1.23 (1.08-1.39)	0.05	0.96 (0.93-0.98)	0.01	1.17 (1.05-1.29)	0.05
1998	1.32 (1.19-1.47)	0.04	0.98 (0.97-0.99)	0.00	1.30 (1.19-1.40)	0.04
1999	1.64 (1.46-1.84)	0.04	0.98 (0.97-0.99)	0.00	1.61 (1.49-1.72)	0.04
2000	1.44 (1.31-1.59)	0.04	0.98 (0.97-0.99)	0.00	1.41 (1.31-1.51)	0.04
2001	1.36 (1.23-1.50)	0.04	0.98 (0.97-0.99)	0.00	1.33 (1.23-1.43)	0.04
2002	1.14 (1.03-1.26)	0.05	0.98 (0.97-0.99)	0.01	1.11 (1.01-1.21)	0.05
2003	1.10 (1.00-1.22)	0.05	0.98 (0.97-0.99)	0.00	1.08 (0.98-1.18)	0.05
2004	1.30 (1.17-1.44)	0.04	0.98 (0.97-0.99)	0.01	1.27 (1.16-1.37)	0.04
2005	1.03 (0.91-1.15)	0.06	0.97 (0.96-0.98)	0.01	1.00 (0.88-1.11)	0.06
2006	0.77 (0.67-0.88)	0.09	0.97 (0.96-0.99)	0.01	0.75 (0.61-0.88)	0.09
2007	0.75 (0.67-0.84)	0.08	0.98 (0.97-0.99)	0.00	0.74 (0.62-0.85)	0.08
2008	0.81 (0.73-0.91)	0.07	0.99 (0.98-0.99)	0.00	0.80 (0.69-0.92)	0.07
2009	0.95 (0.84-1.07)	0.07	0.99 (0.98-1.00)	0.00	0.94 (0.82-1.06)	0.07
2010	1.03 (0.92-1.16)	0.06	0.99 (0.98-0.99)	0.00	1.02 (0.90-1.14)	0.06
2011	0.81 (0.72-0.92)	0.08	0.99 (0.98-0.99)	0.00	0.80 (0.68-0.92)	0.08
2012	0.97 (0.86-1.10)	0.07	0.99 (0.99-1.00)	0.00	0.97 (0.84-1.09)	0.07
2013	0.90 (0.80-1.01)	0.07	0.99 (0.98-0.99)	0.00	0.89 (0.77-1.00)	0.07
2014	0.62 (0.55-0.69)	0.09	0.99 (0.98-1.00)	0.00	0.61 (0.50-0.72)	0.09
2015	0.57 (0.51-0.64)	0.10	0.99 (0.99-1.00)	0.00	0.57 (0.46-0.68)	0.10
2016	0.73 (0.65-0.82)	0.09	0.99 (0.98-0.99)	0.00	0.72 (0.60-0.84)	0.09
2017	0.58 (0.52-0.65)	0.11	0.99 (0.99-1.00)	0.00	0.57 (0.46-0.69)	0.11
2018	0.65 (0.58-0.72)	0.09	0.98 (0.98-0.99)	0.00	0.64 (0.53-0.75)	0.09
2019	0.66 (0.58-0.74)	0.10	0.99 (0.98-0.99)	0.00	0.65 (0.53-0.77)	0.10
2020	0.58 (0.51-0.65)	0.11	0.99 (0.98-0.99)	0.00	0.57 (0.45-0.69)	0.11

Table 18: The parameters included into the binomial daily summary CPUE model, degrees of freedom (df) for each variable, log-likelihood, AIC, r^2 value, and cumulative r^2 with the addition of each term.

	Term	df	logLike	AIC	r^2	Cumulative r^2
1	Intercept		20619	–	–	–
2	*Year*	29	20485	9296.6	0.02	0.02
3	*Grid cell*	134	20482	8929.8	0.16	0.18
4	*Bottom depth*	3	20471	8683.6	0.03	0.21
5	*Month*	11	20448	8546.7	0.02	0.23
6	*Vessel*	23	20445	8439.3	0.02	0.25
7	*Fishing duration*	3	20619	10726.3	0.01	0.26

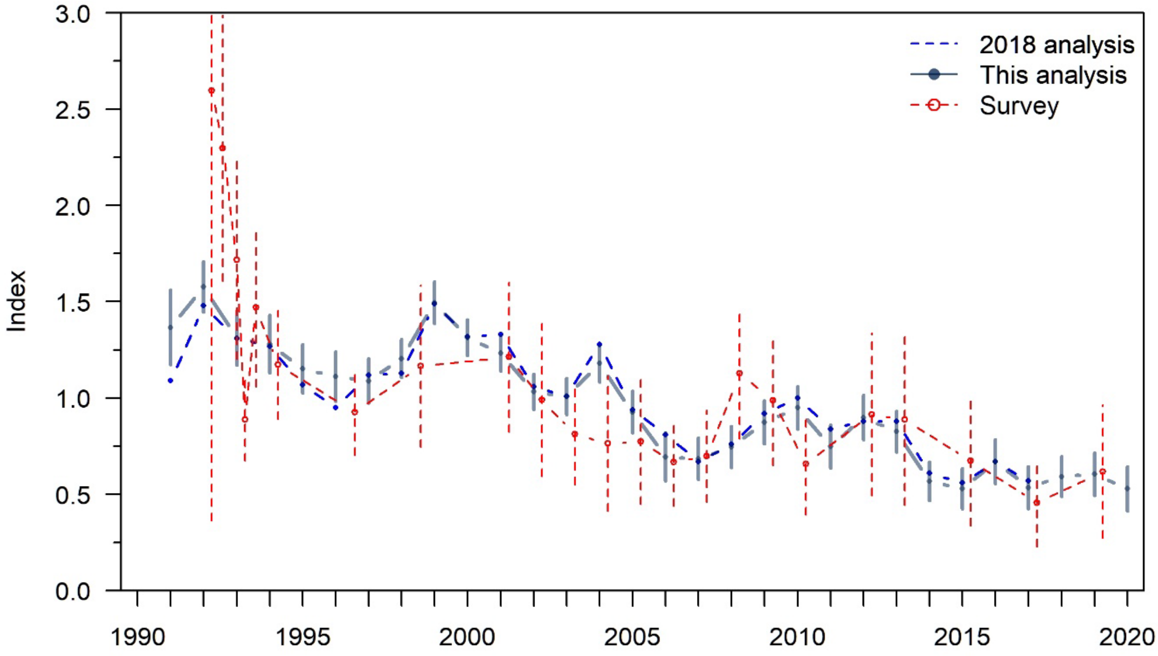

Figure 34: Combined CPUE indices for the tow-by-tow analysis, compared with the analysis of Ballara (2018), and the Sub-Antarctic trawl survey biomass index, for the years 1991–2020.

5.2 Discussion

The bottom trawl standardised CPUE for hake in relative abundance since the beginning of the series. However, the tow-by-tow was slightly more optimistic in recent years, increasing slightly, whereas the daily summary indices were slightly flatter over that time. Both indices were similar to the trend in the trawl survey series for Sub-Antarctic hake.

Diagnostic plots of the two different sets of indices (tow-by-tow and daily summary indices) were similar, with little to choose between them, although the quantile-quantile plots for the lognormal model using the daily summary data was marginally better than the tow-by-tow lognormal model. 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. The use of daily summary data may alleviate some differences in reporting (for example, reporting of the top five versus top eight species on the TCEPR and ERS-trawl forms respectively; and the reporting of the top five QMS species and top three non-QMS for vessels over 28 m on the ERS-trawl forms, versus the top eight species for all other vessels). However, although there was little to choose between them, the daily processed indices may be a slightly more robust index than the tow-by-tow data.

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8. APPENDIX A: RESOURCE SURVEY BIOMASS INDICES FOR HAKE

Table 19: 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.). Model year and time step refer to the assumed model year and time step in 2021 stock assessment (Dunn et al. 2021). (Continued on next three pages

Vessel	Date	Series	Time step	Model year	Trip code	Depth	Notes	Biomass	CV	Reference
Wesermünde	Mar–May 1979	Autumn	–	1979	–	–	*1*			(Kerstan & Sahrhage 1980)
Wesermünde	Oct–Dec 1979	Summer	–	1980	–	–	*1*			(Kerstan & Sahrhage 1980)
Shinkai Maru	Mar–Apr 1982	Autumn	1	1982	SHI8201	200–800 m		6 045	0.15	(Horn 2017)
Shinkai Maru	Oct–Nov 1983	Summer	1	1984	SHI8303	200–800 m		11 282	0.22	(Horn 2017)
Amaltal Explorer	Oct–Nov 1989	Summer	1	1990	AEX8902	200–800 m		2 660	0.21	(Livingston & Schofield 1993)
Amaltal Explorer	Jul–Aug 1990	Winter	2	1990	AEX9001	300–800 m	*2*	4 343	0.19	(Hurst & Schofield 1995)
Amaltal Explorer	Nov–Dec 1990	Summer	1	1991	AEX9002	300–800 m	*3*	2 460	0.16	(Horn 2017)
Tangaroa	Nov–Dec 1991	Summer	1	1992	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		–	–	
Tangaroa	Apr–May 1992	Autumn	2	1992	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*	–	–	
						1996 area		–	–	
Tangaroa	Sep–Oct 1992	September	1	1992	TAN9209	Reported	*4*	3 762	0.15	(Schofield & Livingston 1994b)
						300–800 m		–	–	
						1991 area	*3*	3 760	0.15	(O’Driscoll & Bagley 2001)
						1996 area		–	–	
Tangaroa	Nov–Dec 1992	Summer	1	1993	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		–	–	
Tangaroa	May–Jun 1993	Autumn	2	1993	TAN9304	Reported	*4*	3 602	0.14	(Schofield & Livingston 1994c)
						300–800 m	*3*	3 221	0.14	(O’Driscoll & Bagley 2001)
						1991 area		–	–	
						1996 area		–	–	

Vessel	Date	Series	Time step	Model year	Trip code	Depth	Notes	Biomass	CV	Reference
Tangaroa	Nov–Dec 1993	Summer	1	1994	TAN9310	Reported	*2*	2 572	0.12	(Ingerson & Hanchet 1995)
						300–800 m	*3*	2 286	0.12	(O'Driscoll & Bagley 2001)
						1991 area	*4*	2 567	0.12	(O'Driscoll & Bagley 2001)
						1996 area		–	–	
Tangaroa	Mar–Apr 1996	Autumn	2	1996	TAN9605	Reported	*2*	3 946	0.16	(Colman 1996)
						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	(O'Driscoll & Bagley 2001)
Tangaroa	Apr–May 1998	Autumn	2	1998	TAN9805	Reported	*2*	2 554	0.18	(Bagley & McMillan 1999)
						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 & Bagley 2001)
Tangaroa	Nov–Dec 2000	Summer	1	2001	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 et al. 2001)
Tangaroa	Nov–Dec 2001	Summer	1	2002	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 2003a)
Tangaroa	Nov–Dec 2002	Summer	1	2003	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 2003b)
Tangaroa	Nov–Dec 2003	Summer	1	2004	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 2004)
Tangaroa	Nov–Dec 2004	Summer	1	2005	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 2006a)
Tangaroa	Nov–Dec 2005	Summer	1	2006	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 2006b)
Tangaroa	Nov–Dec 2006	Summer	1	2007	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	(O'Driscoll & Bagley 2008)

Vessel	Date	Series	Time step	Model year	Trip code	Depth	Notes	Biomass	CV	Reference
Tangaroa	Nov–Dec 2007	Summer	1	2008	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	(Bagley et al. 2009)
Tangaroa	Nov–Dec 2008	Summer	1	2009	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	(O'Driscoll & Bagley 2009)
Tangaroa	Nov–Dec 2009	Summer	1	2010	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 & O'Driscoll 2012)
Tangaroa	Nov–Dec 2011	Summer	1	2012	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. 2013)
Tangaroa	Nov–Dec 2012	Summer	1	2013	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. 2014)
Tangaroa	Nov–Dec 2014	Summer	1	2015	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	(Bagley et al. 2017)
Tangaroa	Nov–Dec 2016	Summer	1	2017	TAN1614	300–800 m	*3,8*	1 000	0.25	(O'Driscoll et al. 2018)
						1991 area	*4,8*	1 373	0.34	(O'Driscoll et al. 2018)
						1996 area	*8*	–	–	*Not available*
Tangaroa	Nov–Dec 2018	Summer	1	2019	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	(MacGibbon et al. 2019)
Tangaroa	Nov–Dec 2020	Summer	1	2021	TAN2014	300–800 m	*3*	1 310	0.23	MacGibbon (NIWA, pers. comm)
						1991 area	*4*	1 572	0.20	MacGibbon (NIWA, pers. comm)
						1996 area	*7*		–	*Not yet 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 20: 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)
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)

Vessel	Date	Series	Trip code	Depth	Notes	Biomass	CV	Reference
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)

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 21: 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)
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)
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)
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)