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Acoustic survey of spawning hoki in Cook Strait and Pegasus Canyon during winter 2013

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An acoustic survey of spawning hoki abundance in Cook Strait was carried out from the industry vessels *Thomas Harrison* and *Aukaha* from 21 July to 3 September 2013 (voyage codes THH1303 and AUK1302). Nine acoustic snapshots of the main Cook Strait spawning grounds were completed. Both vessels participated in 8 of the 9 snapshots, coordinating their activities to carry out about half of the planned transects each. Acoustic data collection was supervised by vessel officers, but a NIWA staff member was on board *Thomas Harrison* for one trip from 5–16 August to direct mark identification trawling. During this trip, two acoustic snapshots were carried out, and biological data were collected from 25 trawls, including 8 mark identification tows and 17 commercial tows. An additional snapshot, with 9 transects, was carried out from *Thomas Harrison* in Pegasus Canyon on 20 August 2013.

Seven of the nine Cook Strait snapshots were carried out according to agreed protocols and met all the pre-survey criteria for estimating hoki abundance. Snapshot 6 was flawed because transects in strata 2 and 5A were not completed consecutively (increasing the risk of bias due to fish movement), and snapshot 9 was rejected because of incorrect echosounder power settings.

Acoustic estimates of hoki abundance ranged from 233 000 t on 8–10 August to 666 000 t on 20–21 August, with an average estimate over the seven accepted snapshots of 377 000 t. This was 20% higher than the equivalent estimate from 2011 (314 000 t). Absolute estimates of hoki abundance were sensitive to the length frequency data used to calculate the ratio of hoki weight to acoustic target strength (TS), and the choice of the TS-to-fish-length relationship, but relative acoustic indices were similar. The survey weighting (expressed as a coefficient of variation, CV) for the 2013 survey, which includes uncertainty associated with survey timing, sampling precision, acoustic detectability, mark identification, calibration, target strength was 30%.

About 78% of the hoki abundance in Cook Strait in 2013 was from hoki schools. Commercial trawls on hoki schools caught an average of 97% hoki by weight (17 trawls sampled, range 71–100%). The remaining hoki came from hoki 'fuzz' marks that also contained other species. The average proportion of hoki by weight from eight research trawls on fuzz marks in 2013 was 70% (range 13–99%).

Hoki from the Narrows Basin were predominantly male and were much smaller than hoki from the main Cook Strait Canyon, where commercial catches were dominated by females. Gonad staging showed that fish were actively spawning during the survey period, with 79% of female hoki sampled staged as ripening or ripe.

The acoustic abundance estimate from the single snapshot of Pegasus Canyon was 134 000 t, which was mainly (80%) from hoki school marks. This result confirms that substantial hoki spawning aggregations occur off the east coast South Island.

1. INTRODUCTION

The hoki fishery is New Zealand's largest finfish fishery with a TACC of 130 000 t in 2012–13, increasing to 150 000 t from 1 October 2013. Although managed as a single stock, hoki are assessed as two stocks, western and eastern. The hypothesis is that juveniles from both stocks mix on the Chatham Rise and recruit to their respective stocks as they approach sexual maturity. Spawning occurs in winter (June to September), with the major spawning areas on the west coast of the South Island (WCSI) for the western stock, and in Cook Strait for the eastern stock.

On the spawning grounds hoki typically form large midwater aggregations. The occurrence of readily identifiable, single species aggregations clear of the seabed allows for accurate abundance estimation using acoustics. Acoustic surveys of spawning hoki have been conducted regularly since a 1984 pilot survey of the WCSI spawning grounds (Coombs & Cordue 1995). The results of acoustic surveys of spawning hoki in Cook Strait and the WCSI have been used as inputs into hoki stock assessments for over 20 years (O'Driscoll 2002a).

The 10-year Deepwater Research Programme calls for acoustic surveys of the Cook Strait hoki spawning grounds every two years to update the abundance indices. Although the acoustic results from Cook Strait are not very influential on the results of the stock assessment model it is considered necessary to monitor the abundance of the eastern spawning stock independently of the Chatham Rise, where both eastern and western hoki are mixed together.

Previous acoustic surveys of Cook Strait were carried out on research vessels annually from 1991–2008 (except 2000, 2004, and 2007). Since 2007, industry vessels also surveyed part of Cook Strait during the hoki spawning season using the same (NIWA) protocols used for the research vessel surveys (O'Driscoll & Dunford 2008, O'Driscoll & Macaulay 2009, 2010). The most recent survey was in 2011 (O'Driscoll 2012). In 2013 the main fishing grounds in Cook Strait were surveyed throughout the spawning season from two industry vessels: *Thomas Harrison* and *Aukaha* (previously called *Independent 1*). The 2013 survey described here extends the time series of Cook Strait acoustic abundance indices used in the stock assessment (1991, 1993–99, 2001–03, 2005–09, 2011) from 17 to 18 points.

Although Cook Strait is the major spawning area for eastern hoki, some spawning also occurs on the east coast of the South Island (ECSI) in an area centred on Pegasus Canyon (Livingston 1990) (Figure 1). A fishery developed in this region, with catches of 500–7500 t in the last 17 years (Ministry for Primary Industries 2013). Two acoustic surveys of Pegasus Canyon were carried out from a commercial vessel in 2002 (O'Driscoll 2003b) and 2003 (O'Driscoll et al. 2004). These surveys indicated that the ECSI is a substantial satellite spawning area for the eastern hoki stock, with acoustic abundance estimates from Pegasus Canyon of 36 and 46% of the equivalent estimates from Cook Strait in 2002 and 2003 respectively. Research vessel surveys in 2006 and 2008 also included the east coast South Island (ECSI) areas of Pegasus and Conway Trough (O'Driscoll 2007, 2009). Pegasus Canyon was surveyed again as part of the 2013 acoustic survey.

1.1 Project objectives

This report fulfils the reporting requirements for Objectives 1 and 2 of Ministry of Fisheries Research Project HOK2010/03B:

1. To continue the time series of relative abundance indices of spawning hoki in Cook Strait using acoustic surveys, with a target coefficient of variation (CV) of the estimate of 30 %.

2. To calibrate acoustic equipment used in the acoustic survey.

2. METHODS

2.1 Survey design

Hoki have a long spawning season, from July to September. It is thought that during the spawning season there is a turnover of fish on the grounds. Therefore, there is no time at which all of the spawning fish are available to be surveyed. The survey design devised to deal with this problem consists of a number of subsurveys or "snapshots" spread over the spawning season. Each snapshot consists of a series of random transects (following the design of Jolly & Hampton (1990)) across strata covering the known distribution of spawning hoki. Estimates of spawning biomass are calculated for each of the snapshots, and these are then averaged to obtain an estimate of the "mean plateau height" (average biomass during the main spawning season). Under various assumptions about the timing and length of the spawning season (Cordue et al. 1992, Coombs & Cordue 1995), estimates of mean plateau height form a valid relative abundance time series.

The stratum boundaries and areas in Cook Strait (Figure 2, Table 1) were the same as in previous surveys, with six main strata (strata 1, 2, 3, 5A, 5B, and 6), covering the areas with depth greater than 200 m (or 180 m in stratum 2). The acoustic survey area in Cook Strait includes grounds which are not commercially fished by the fleet. For example, targeting of hoki by vessels greater than 28 m is not permitted in the Narrows Basin (stratum 1) under the industry agreed Operational Procedures for the Hoki Fishery (version 13), to reduce the catch of small hoki.

The stratum boundaries and area in Pegasus Canyon (Figure 1, Table 1) were based on the survey in 2003 from an industry vessel (O'Driscoll et al. 2004). As in Cook Strait, the strata included areas with depth greater than 200 m. Pegasus Canyon was subdivided into two strata, because the highest densities of hoki tended to occur in the southern part of the Canyon (PCB) in 2002 and 2003 (O'Driscoll 2003b, O'Driscoll et al. 2004).

2.2 Vessels and equipment

FV Thomas Harrison is a 42.5 m freezer trawler. The vessel is fitted with a Simrad ES70 echosounder with a hull-mounted split-beam 38 kHz transducer, and was used successfully to carry out research surveys of orange roughy on the Challenger Plateau in 2005, 2006, 2009, 2010, 2011, and 2013 (e.g., Clark et al. 2005), and hoki in Cook Strait in 2007, 2008, 2009, and 2011 (O'Driscoll & Dunford 2008, O'Driscoll & Macaulay 2009, 2010, O'Driscoll 2012). *FV Aukaha* is a 45.6 m freezer trawler, formerly known as *Independent 1*. *Aukaha* is also fitted with a Simrad ES70 echosounder and hull-mounted split-beam 38 kHz transducer, and was used previously to carry out research surveys for hoki around the South Island in 2002 and 2003 (O'Driscoll 2003b, O'Driscoll et al. 2004), and in Cook Strait in 2009 and 2011 (O'Driscoll & Macaulay 2010, O'Driscoll 2012), and for research surveys (using different acoustic equipment) in Oman. Both vessels are operated by Sealord Limited.

Echosounders on both vessels were calibrated by NIWA using standard scientific methods (MacLennan & Simmonds 1992). The ES70 on *Aukaha* was calibrated in Tasman Bay on 27 June 2013, and the ES70 on *Thomas Harrison* was calibrated in Tasman Bay on 15 November 2013. Calibration reports are provided as Appendices 1 and 2. Both calibrations were of good quality and indicated that the echosounders were functioning correctly. Estimated calibration coefficients, based on the mean sphere target strength (TS) were used in these analyses.

2.3 Acoustic data collection

NIWA provided start and finish positions for up to ten snapshots in Cook Strait, each consisting of 28 random transects in the six strata (see Table 1). Start and finish positions were also provided for up to three snapshots of Pegasus Canyon, each consisting of 9 random transects in two strata.

Key aspects of acoustic survey protocol provided to vessel officers were as follows:

- Acoustic data quality needs to be good. Weather is important (typically winds less than 25 knots, swell less than 2 m). All other echosounders and sonars need to be switched off to avoid acoustic interference.
- Vessel speed when running transects should be kept constant at 6–10 knots.
- A separate acoustic file should be recorded for each transect. It is not necessary to record the joining legs between transects. A logsheet should be completed.
- Estimates of species composition, hoki size, and spawning condition in commercial catches are needed (to estimate target strength), in addition to the requirement for targeted mark identification trawling (see Section 2.4).
- The ES70 echosounder needs to be set-up using scientific 'hoki' settings (key ones are power = 2000 W, pulse length = 1.024 ms, ping interval = 2 seconds, GPS position integrated into acoustic file).
- To generate an abundance index with a reasonable CV in Cook Strait requires six completed snapshots. These should be spread as evenly as possible between 15 July and 31 August.
- The entire snapshot needs to be completed within 48 hours (preferable, 72 hours absolute maximum) for it to be useful. All transects in the main Cook Strait Canyon (strata 5A and 2) need to be run sequentially (i.e., without breaks), because of fish movement related to tide in this area.

Acoustic data were stored on removable USB hard drives.

2.4 Mark identification trawling

Mark identification is one of the critical steps in acoustic analysis and requires directed trawling on different mark types. This was an integral part of the proposed survey, and eight targeted mark identification trawls were carried out on a trip on *Thomas Harrison* from 5–16 August, when a NIWA staff member (Dan MacGibbon) was on board.

Commercial tows and 4 of the 8 research tows were carried out using the *Thomas Harrison* 28-17 midwater hoki trawl, which was towed either in midwater or along the bottom. This trawl has a headline length of 88 m and wingspread of about 53 m, and was rigged with 150 m bridles. A 60 mm codend was fitted for the designated research tows. This is smaller than the mesh size legally required for hoki trawling (100 mm). All commercial tows were carried out using a 100 mm codend. The remaining four research tows (for mark identification in Narrows Basin and Terawhiti Sill) were carried out using a bottom trawl with ‘rockhopper’ ground-gear, also fitted with a 60 mm codend.

Associated with mark identification trawling, there is a requirement to collect biological data. This was carried out by the NIWA staff member on *Thomas Harrison*. For each trawl, all items in the catch were sorted into species and weighed (or estimated from processed weights when catch sizes were large). Where possible, fish, squid, and crustaceans were identified to species level, and other benthic fauna to family. A random sample of up to 200 individuals of each species from every tow was measured for length, and the sex and macroscopic gonad stage of all hoki in the length sample was also determined.

2.5 Other data collection

A Seabird SM-37 Microcat CTD datalogger (serial number 2958) was mounted to the headline of the net during 12 tows (7 research and 5 commercial) to estimate the absorption coefficient and speed of sound during the survey.

2.6 Acoustic data analysis

Acoustic data collected during the survey were analysed using standard echo integration methods (MacLennan & Simmonds 1992), as implemented in NIWA's Echo Sounder Package (ESP2) software (McNeill 2001). Echograms were visually examined, and the bottom determined by a combination of an in-built bottom tracking algorithm and manual editing. Regions corresponding to various acoustic mark types were then identified. Marks were classified subjectively (e.g. O'Driscoll 2002b), based on their appearance on the echogram (shape, structure, depth, strength and so on), and using information from mark identification trawls.

Backscatter from marks (regions) identified as hoki was then integrated to produce an estimate of acoustic density, expressed as the mean area backscattering coefficient (m^2 m^{-2}). During integration, acoustic backscatter was corrected for a systematic error in ES70 data (Ryan & Kloser 2004) and calculated sound absorption by seawater. In July 2013, an error was found in the software that applied the triangle wave correction for short files (less than 1360 pings), where the correction could not be established from the data. This bug led to a small negative bias in estimates of backscatter (i.e., abundance was underestimated) and affected previous Cook Strait surveys from industry vessels in 2007, 2009, and 2011. The bug was fixed before analysis of the 2013 data, but required the three previous surveys to be re-converted and integrated (see Section 2.9).

Acoustic density was output in two ways. First, average acoustic density over each transect was calculated. These values were used in abundance estimation (see Section 2.7). Second, acoustic backscatter was integrated over 10-ping bins to produce a series of acoustic densities for each transect (typically 30–100 values per transect). These data had a high spatial resolution, with each value (10 pings) corresponding to about 100 m along a transect, and were used to produce plots showing the spatial distribution of acoustic density.

Transect acoustic density estimates were converted to hoki biomass using a ratio, r, of mean weight to mean backscattering cross section (linear equivalent of target strength, TS) for hoki. The method of calculating r was based on that of O'Driscoll (2002a):

1. using the length frequency distribution of the commercial catch from the year of the survey;

2. using the generic length-weight regression of Francis (2003) to determine mean hoki weight (w in kilograms)

$$w = (4.79\times10^{-6})\, L^{2.89} \qquad (1)$$

3. using the most recent TS-length relationship for hoki (Macaulay 2006):

$$TS = 12.2 \log_{10}(L) - 63.9 \qquad (2)$$

where L is total fish length in centimetres.

2.7 Abundance estimation

Abundance estimates and variances were obtained for each stratum in each snapshot using the formulae of Jolly & Hampton (1990), as described by Coombs & Cordue (1995). Stratum estimates were combined to produce snapshot estimates, and the snapshots were averaged to obtain the abundance index for 2011.

The sampling precision of the abundance index was calculated in two ways, as described by Cordue & Ballara (2001). The first method was to average the variances from each snapshot. This method potentially underestimates the sampling variance as it accounts only for the observation error in each snapshot. The imprecision introduced by the inherent variability of the abundance in the survey area during the main spawning season is ignored. The second method assumes the snapshot abundance estimates are independent and identically distributed random variables. The sample variance of the snapshot means divided by the number of snapshots is therefore an unbiased estimator of the variance of the index (the mean of the snapshots).

2.8 Survey weighting for stock assessment

The sampling precision will greatly underestimate the overall survey variability, which also includes uncertainty in TS, calibration, and mark identification (Rose et al. 2000). The model weightings (expressed as coefficient of variation or CV) used in the hoki stock assessment model are calculated for individual surveys using a Monte Carlo procedure which incorporates these additional uncertainties (O'Driscoll 2004).

The simulation method used to combine uncertainties and estimate an overall weighting (CV) for each acoustic survey of Cook Strait was described in detail by O'Driscoll (2004), and is summarised below.

Six sources of variance are considered:

- plateau model assumptions about timing and duration of spawning and residence time
- sampling precision
- detectability
- mark identification
- fish weight and target strength
- acoustic calibration

The method has two main steps. First, a probability distribution is created for each of the variables of interest. Second, random samples from each of the probability distributions are selected and combined multiplicatively in Monte Carlo simulations of the process of acoustic abundance estimation.

In each simulation a biomass model was constructed by randomly selecting values for each variable from the distributions in Table 2. This model was then 'sampled' at dates equivalent to the mid dates of each snapshot (Table 3). The precision of sampling was determined by the snapshot CV, and the biomass adjusted for variability in detectability. The simulated biomass estimate in each snapshot was then split, based on the proportion of acoustic backscatter in 'school' and 'fuzz' marks (see Section 3.3), and mark identification uncertainties applied to each part. The biomass estimates were recombined and calibration and TS uncertainties applied in turn. The same random value for calibration and TS was applied to all snapshots in each simulated 'survey'. Abundance estimates from all snapshot estimates from the simulated survey were averaged to produce an abundance index. This whole process was repeated 1000 times (1000 simulated surveys) and the distribution of the 1000 abundance indices was output. The overall CV was the standard deviation of the 1000 abundance (mean biomass) indices divided by their mean.

2.9 Update of Cook Strait acoustic time-series

As noted in Section 2.6, an error was found in the software that applied the triangle wave correction for short files in July 2013. This bug led to a small negative bias in estimates of backscatter and affected the three previous Cook Strait hoki surveys from industry vessels in 2007, 2009, and 2011. Acoustic data from these previous surveys were therefore re-converted and integrated in November 2013 using updated (corrected) software.

At the same time, we also re-examined the calibration coefficients used for estimating abundance, and noted that there was inconsistency in the method used to estimate the peak transducer gain (G_0).

Estimates from 2007 used G_0 based on fitted sphere TS, while those from 2009 and 2011 used G_0 based on maximum sphere TS. This was due to a change in calibration software in 2008. Calibration values estimated using fitted or mean sphere TS are more consistent and stable than values based on maximum sphere TS (O'Driscoll et al. 2015), and we decided to re-calculate previous industry acoustic estimates in the Cook Strait time-series using G_0 values based on mean sphere TS. This change ensures consistency with acoustic methodology for industry surveys of other deepwater species (southern blue whiting, orange roughy), and those using towed acoustic equipment (including research vessel surveys in Cook Strait), which already use calibration values based on mean sphere TS.

The combined effect of these changes were negligible for the 2007 survey, increasing the acoustic abundance estimate by less than 1%. Acoustic estimates in 2009 and 2011 increased by 8% and 5% respectively.

3. RESULTS

3.1 2013 commercial fishery

A total catch of 19 400 t was taken from Cook Strait between 1 June and 30 September 2013, with most hoki caught between 15 July and 15 September (Figure 3). The acoustic survey was within the period of high catches. The hoki length frequency from the 2013 commercial fishery in Cook Strait based on scientific observer data and data from NIWA collected for this project is shown in Figure 4. The mean length of hoki was 79.7 cm (Table 4). Mean weight and mean backscattering cross-section (obtained by transforming the scaled length frequency distribution in Figure 4 by equations (2) and (3) and then calculating the means of the transformed distributions) were 1.57 kg and 0.0000853 m^2 (equivalent to –40.7 dB) respectively, giving a ratio, *r*, for Cook Strait in 2013 of 18 436 kg m^{-2} (Table 4).

As in 2011 (O'Driscoll 2012), there was considerable uncertainty associated with the estimated size distribution of the commercial catch from Cook Strait in 2013 because of poor observer sampling (Sira Ballara, NIWA, pers. comm.). Therefore, we calculated two alternative series of acoustic indices for Cook Strait: one series based on annual *r* values calculated from the commercial length frequency from the year of the survey, as was done in the past (see Section 2.6); and the other series calculated using the same *r* value for all surveys in the time-series. The assumed constant for *r* was the mean value from the individual surveys of 17 263 kg m^{-2} (Table 4).

A smaller commercial fishery occurred on the ECSI, which includes Pegasus Canyon, with 3300 t taken from this area during the spawning season, 1 June to 30 September 2013. The hoki length frequency from the 2013 ECSI commercial fishery estimated from scientific observer data is shown in Figure 5. The mean length of hoki was 74.3 cm. Mean weight and mean backscattering cross-section (obtained by transforming the scaled length frequency distribution in Figure 5 by equations (2) and (3) and then calculating the means of the transformed distributions) were 1.31 kg and 0.0000784 m^2 (equivalent to –41.1 dB) respectively, giving a ratio, *r*, for Pegasus Canyon of 16 675 kg m^{-2}.

3.2 Data collection

3.2.1 Acoustic data

Nine acoustic snapshots of the main Cook Strait spawning grounds (see Figure 2) were completed from 21 July to 3 September 2013 (see Table 3). Acoustic data collection was supervised by vessel officers, but a NIWA scientist (Dan MacGibbon) was on board *Thomas Harrison* for one trip from 5–16 August to direct mark identification trawling (see Section 3.2.2). During this trip, two acoustic snapshots were carried out (snapshots 5 and 6 in Table 3).

Both vessels participated in eight of the nine snapshots in Cook Strait (see Table 3), coordinating their activities to carry out about half of the planned transects each. All snapshots were completed within the maximum of 72 hours and eight snapshots (all except snapshot 6) were completed within the recommended 48 hours (see Table 3). All transects in strata 2 and 5A were carried out sequentially to avoid potential bias due to fish movement, except in snapshot 6 when there was a 19 hour gap between completion of transects in stratum 2 and the start of transects in stratum 5A. All transects were carried out in suitable weather conditions, and there were few examples of missing pings or interference from wave-generated bubbles. There was no interference from other acoustic instruments. Echosounder settings followed NIWA recommendations except for four transects in stratum 2 of snapshot 9 that were carried out by the *Aukaha*, where the echosounder was set at 4 kW power and 2 ms pulse length. In summary, seven of the nine Cook Strait snapshots were carried out according to agreed protocols and met all the criteria for estimating hoki abundance. Snapshot 6 was flawed because transects in strata 2 and 5A were not completed consecutively, and snapshot 9 was rejected because of incorrect echosounder settings.

A single snapshot, with 9 transects, was carried out in Pegasus Canyon from 03:36 to 14:54 NZST on 20 August 2013 from *Thomas Harrison*. Acoustic data from this snapshot were suitable for estimating abundance.

3.2.2 Trawl data

There were 25 trawls for target identification purposes and to collect hoki length frequency and biological data during the trip on *Thomas Harrison* from 5–16 August (Table 5, Figure 6). Eight of these were specifically targeted on marks where the species composition was uncertain. These were designated as research tows. The remaining 17 were commercial tows which were sampled by the NIWA staff member on *Thomas Harrison*. Of the eight research tows, three were in the Narrows Basin (stratum 1), two in outer Cook Strait Canyon (stratum 5B), two in Nicholson Canyon (stratum 3), and one at Terawhiti Sill (stratum 6). Hoki made up 86% of the total catch of 6.5 t from research tows for mark identification (Table 6). Bycatch species included red cod, rattails, school shark, jack mackerels, spiny dogfish, rig, and tarakihi (Table 6).

A further 162 t of catch was sampled from the 17 commercial trawls, of which 99% was hoki (see Table 5). Another 21 commercial trawls were not sampled because the one NIWA person on board *Thomas Harrison* was unable to cover 24-hour operations. The original intention was that there would also be an observer on board on this trip, but this did not happen because of space limitations on the vessel.

A total of 5178 fish of 39 species were measured, including 4069 hoki measured for length, sex and macroscopic gonad stage. Otoliths were collected from 502 hoki.

There was no observer coverage on the two survey vessels to provide biological sampling during the other snapshots or from Pegasus Canyon.

3.2.3 CTD data

Twelve CTD profiles were obtained from Cook Strait, from seven research and five commercial tows. The average water temperature in Cook Strait over the entire depth range was 11.7 ºC, with an average salinity of 34.8 PSU. Estimates of sound absorption from individual CTD profiles in 2013 ranged from 8.82 to 9.11 dB km^{-1}, with an average of 8.97 dB km^{-1}. This was slightly lower than the average sound absorption estimated in Cook Strait in 2006–12 (9.09–9.12 dB km^{-1}), because the average water temperature was slightly warmer (by about 0.4 ºC) in 2013.

No CTD data were available for Pegasus Canyon in 2013, so the value of sound absorption from Cook Strait (8.97 dB km^{-1}) was used to estimated abundance in this area.

3.3 Mark identification

Marks in Cook Strait were similar to those observed in 2001–12. Example echograms of some of these mark types are shown in Figures 7–11. Further examples are provided by O'Driscoll (2002b, 2003a, 2007, 2009, 2012), O'Driscoll & Dunford (2008), and O'Driscoll & Macaulay (2009, 2010).

1. Hoki schools
Hoki schools were characterised by relatively dense marks with clearly defined edges, typically occurring at 200–700 m water depth, and often in midwater over canyon features. During the night, schools tended to disperse and descend to the bottom or to 350–600 m depth. In the day, schools were denser and higher in the water column, at 200–450 m depth. The densest hoki schools were observed in Cook Strait Canyon (e.g., Figures 7–8), but hoki schools were also observed over the Terawhiti Sill (e.g., Figure 9), in the deepwater between Cook Strait and Wairarapa Canyons (e.g., Figure 11), in Nicholson Canyon, and in Pegasus Canyon on the ECSI (e.g., Figure 12). All commercial trawls sampled on *Thomas Harrison* were targeted at hoki schools in Cook Strait Canyon (see Figure 6) and caught an average of 97% hoki by weight (see Table 5).

2. Hoki bottom fuzz
Hoki bottom fuzz occurred as bottom-referenced layers, sometimes extending more than 50 m above the seabed, and usually at water depths shallower than 300 m. This mark type was commonly observed in the Narrows Basin (e.g., Figure 10) and over the Terawhiti Sill. The four mark identification trawls on bottom fuzz marks in 2013 caught an average of 57% of hoki by weight (range 13–98%) (see Table 5).

3. Hoki pelagic fuzz
Hoki pelagic layers were relatively low density (diffuse), surface-referenced layers occurring at 200–700 m depth, typically over deep water (500–1000 m). Single targets are often visible in these layers. In 2013, these marks were common in outer Cook Strait Canyon, in the deepwater between Cook and Wairarapa Canyons (e.g., Figure 11), in Nicholson Canyon, and in Pegasus Canyon (e.g., Figure 12). The average proportion of hoki by weight from the four research trawls on pelagic fuzz marks was 83% (range 61–99%) (see Table 5).

4. Bottom non-hoki
Bottom non-hoki layers were bottom-referenced layers, which were typically denser and shallower (less than 200 m depth) than hoki bottom fuzz layers. Bottom non-hoki marks were occasionally observed in 2013 adjacent to Cook Strait Canyon. Previous research trawling on this mark type caught less than 10% hoki, with catches typically dominated by ling.

5. Jack mackerel
Jack mackerel were observed as strong surface-referenced layers consisting of small schools and strong single targets at depths of 50 to 200 m. As in previous surveys, jack mackerel marks were usually observed in the Narrows Basin (e.g., Figure 10). Previous research trawling on this mark type caught mainly jack mackerels and few hoki.

6. Pelagic layers
Strong surface-referenced pelagic layers usually occurring from 0 to 300 m, and exhibiting strong diurnal vertical migration patterns. Pelagic layers were widespread throughout the survey areas (e.g., Figures 7, 8, 11 and 12). Targeted trawling on this mark type in the past only caught a few very small (less than 30 cm) hoki.

7. Spiny dogfish
Spiny dogfish were characterised by surface-referenced layers similar to jack mackerel marks, and consisted of small schools and single targets at depths of 100–200 m, above hoki schools. Midwater spiny dogfish marks are sometimes observed in Cook Strait Canyon, but were not conspicuous during the 2013

survey. Livingston (1990) found that midwater aggregations of spiny dogfish above hoki schools were feeding on recently spawned hoki eggs.

Acoustic backscatter from regions corresponding to hoki schools, hoki bottom fuzz, and hoki pelagic fuzz were integrated to obtain acoustic density estimates. This is consistent with mark identification in previous years (O'Driscoll 2002a). Although we know that hoki fuzz marks contain a proportion of other species, all backscatter from these marks was assumed to be from hoki. Again, this is consistent with previous years. No species decomposition of acoustic backscatter in mixed layers was attempted because of the limited mark identification trawling. If there was a change in the proportion of hoki in fuzz marks over time (as suggested by O'Driscoll (2006) for bottom fuzz marks) this approach will lead to a bias in the relative abundance estimates. However, the Monte Carlo estimation of survey uncertainty will incorporate some of this potential bias because the lognormal distribution of uncertainty associated with species mix is very broad (see Table 2). In Section 3.6, abundance estimates are presented for hoki school marks only (where mark identification is relatively certain), as well as for hoki school and hoki fuzz marks combined.

3.4 Distribution of hoki backscatter

Expanding symbol plots show the spatial distribution of hoki backscatter along each transect during the nine snapshots of Cook Strait (Figure 13) and for Pegasus Canyon (Figure 14). The distribution of hoki in Cook Strait was generally similar to that observed in previous research and industry surveys in 2001–12 (O'Driscoll 2002b, 2003a, 2006, 2007, 2009, 2012, O'Driscoll & McMillan 2004, O'Driscoll & Dunford 2008, O'Driscoll & Macaulay 2009, 2010). Hoki densities were highest in Cook Strait Canyon. Fish were concentrated in the head (northern end) of the canyon during snapshots 4 and 5 on 3–10 August, but were more spread out through the canyon in the earlier and later snapshots (Figure 13).

Most of the acoustic backscatter in the deep water between Cook Strait and Wairarapa Canyons (stratum 5B) came from pelagic fuzz marks (e.g., Figure 11) and densities in this area were relatively low (Figure 13). Acoustic densities were also generally low in the Narrows Basin (stratum 1) and over the Terawhiti Sill (stratum 6), and most of the backscatter from these areas was from bottom fuzz marks (e.g., see Figure 10). Densities were higher over the Terawhiti Sill in snapshots 5 and 8 (Figure 13), when some hoki schools were present in this stratum (e.g., see Figure 9). No particularly dense marks were observed in Nicholson Canyon (stratum 3) during the 2013 survey (Figure 13). This was similar to 2011 (O'Driscoll 2012), but contrasts with some earlier surveys when hoki schools were abundant in this stratum.

Acoustic densities in Pegasus Canyon were higher on the northeast side of the southern canyon (stratum PCB) (Figure 14). This distribution was consistent with that observed in earlier ECSI surveys (O'Driscoll 2003b, 2007, 2009, O'Driscoll et al. 2004).

3.5 Hoki size and maturity

Unscaled length frequencies of hoki by strata are given in Figure 15. Although the number of mark identification trawls in 2013 was low (only eight tows), there appeared to be variation in hoki length frequencies between these tows and those from commercial trawls in the main Cook Strait Canyon. Hoki from the Narrows Basin (stratum 1) were predominantly male and were much smaller than hoki from the main Cook Strait Canyon (stratum 2), where commercial catches were dominated by large females. Modes at 23–32 cm and 40–50 cm in stratum 1 probably correspond to fish of ages 1 and 2 years respectively. The hoki sampled from strata 3, 5B, and 6 had a wide length distribution, but were also smaller on average than those from Cook Strait Canyon (Figure 15).

Gonad staging showed that fish were actively spawning during the survey period, with 79% of female hoki sampled staged as ripening (research stage 3) or ripe (research stage 4).

3.6 Hoki abundance estimates

Hoki abundance estimates by snapshot and strata for Cook Strait are given in Table 7 and plotted in Figure 16. Although estimates are provided for all snapshots, snapshots 6 and 9 were not included in the mean abundance index as they did not meet survey criteria (see Section 3.2.1). Estimates of hoki abundance in the seven accepted snapshots using the value of *r* calculated for 2013 ranged from 233 000 t (CV 19%) in snapshot 5 on 8–10 August to 666 000 t (CV 53%) in snapshot 7 on 20–21 August. There was a large drop in estimated biomass between snapshot 7 and snapshot 8, only two days later (Figure 16). It is unlikely that hoki abundance decreased by a factor of 2.5 over this period, and the difference between individual snapshots is probably due to sampling variability (transect location and fish behaviour) rather than changes in abundance. The high estimate in snapshot 7 also had a relatively high CV (53%). One or two very high snapshots were also observed in previous surveys, most recently in 2006, 2007, and 2011 (Figure 17).

When results from Table 7 were averaged over the seven accepted snapshots, 77% of the hoki biomass was in stratum 2, 9% in stratum 1, 6% in stratum 5A, 4% in stratum 5B, and 3% in stratum 6, and 1% in stratum 3. Hoki densities in strata 1 and 5B were generally low (see Figure 13), and the importance of these strata to the overall biomass was due to their relatively large areas. The contribution of biomass from outside Cook Strait Canyon (strata 2 and 5A) may also be overestimated because most of the estimated biomass in the other strata was from hoki fuzz marks which contain other species (Table 8).

The average proportion of the biomass from hoki schools in 2013 was 78% (Table 8). This was the highest proportion in in the time series (previous surveys had 30–74% of hoki in schools). Most (97%) of the hoki observed in stratum 2 were in schools (Table 8). Hoki schools were also observed in strata 3, 5A, 5B, and 6. As in previous surveys, changes in abundance over the survey period were driven mainly by changes in the biomass of hoki schools (see Figure 16). The biomass from hoki fuzz marks remained relatively constant between 32 000 and 87 000 t throughout the survey period.

The mean abundance from the seven accepted snapshots of Cook Strait was 377 000 t (see Table 7). The average of the snapshot variances was 17%. The variance of the abundance estimates from the seven snapshots was 15%.

The estimated abundance from the single snapshot of Pegasus Canyon was 134 000 t (CV 28%), with similar contributions from the two strata (67 000 t from each of PCA and PCB). As in Cook Strait, a high proportion (80%) of the estimated biomass in Pegasus Canyon was from hoki schools where mark identification is relatively certain.

3.7 Survey weighting for stock assessment

The overall survey weighting estimated from the Monte Carlo simulation model for Cook Strait was 30% (Table 9). As in previous Cook Strait surveys (O’Driscoll 2004), timing (including uncertainties about plateau timing and residence time), sampling error, and mark identification were the major sources of uncertainty (Table 9). Uncertainties due to calibration, detectability, and TS contributed relatively little to the overall CV However, incorrect choice of TS and calibration coefficients do have potential to introduce bias, which is not reflected in the CV in Table 9 (see Section 4).

4. DISCUSSION

Nine acoustic snapshots of the Cook Strait spawning grounds were completed from the industry vessels *Thomas Harrison* and *Aukaha* during winter 2013. Seven of these snapshots were suitable for abundance estimation. Snapshot 6 was flawed because transects in strata 2 and 5A were not completed consecutively, and snapshot 9 was rejected because of incorrect echosounder settings. Survey timing was appropriate, with all snapshots occurring within the timing of peak commercial catches (see Figure 3) and within the period of previous surveys (Figure 17). There was no obvious trend in the timing of peak abundance estimates from previous acoustic surveys to suggest that the main spawning season (plateau interval) has shifted over time (Figure 17).

The abundance index for 2013, calculated using the length frequency from the 2013 commercial fishery, was 377 000 t, which was 20% higher than the equivalent index from the 2011 industry survey, and the highest estimate since 1995 (Table 10, Figure 18). There was some uncertainty associated with the estimated size distribution of the commercial catch from Cook Strait in 2013 because of poor observer sampling. Following the recommendations of the Hoki Fishery Assessment Working Group in 2012 (O'Driscoll 2012), an alternative series of acoustic indices was also calculated for Cook Strait using the same (average) r value for all surveys in the time-series (see Table 4). The abundance index for 2013, calculated using a constant r value, was 353 000 t which was similar to the equivalent index from 2009, but still above average for the time series (Table 10). The overall CV of the 2013 estimate (30%) was equal lowest in the time-series, reflecting the good survey timing and coverage, and the relatively high proportion of hoki from school marks in 2013.

Recent work on the acoustic target strength (TS) of hoki raises concern that acoustic estimates based on the TS-length relationship of Macaulay (2006) may overestimate hoki biomass. Kloser et al. (2011) collected optically verified *in situ* measurements of Australian hoki (blue grenadier) and found that the TS was considerably higher than that predicted by equation (2). They provided a TS-to-standard length (SL) relationship for hoki of:

$$TS = 25.4 \log_{10}\mathrm{SL} - 81.5 \qquad (3)$$

O'Driscoll (2012) noted that if we apply this equation in place of Equation (1) in calculating the ratio of mean weight to mean backscattering cross section (after converting total length to standard length and adjusting for the larger cavity/swimbladder volume of Australian hoki using the relationship TL = 1.18 SL, from Kloser et al. (2011)), we obtain estimates of hoki biomass which are only 25–30% of those obtained using the TS-length relationship of Macaulay (2006). However, equation (3) was based on a relatively narrow length range of large hoki (17 fish of TL 84–110 cm), which are larger than those typically found in Cook Strait.

Further research on hoki TS was carried out using an acoustic-optical system (AOS) on the west coast South Island in June-July 2012 (O'Driscoll et al. 2014). Dunford et al. (2015) estimated a new TS-TL relationship based on a weighted non-linear least-squares fit to individual points in a combined Australian and New Zealand dataset:

$$TS = 30.7 \log_{10}\mathrm{TL} - 95.3 \qquad (4)$$

Equation (4) was based on a much greater sample size of 86 hoki from 35–110 cm TL. As a sensitivity analysis, we re-calculated acoustic abundance estimates for Cook Strait using this new TS-TL relationship. Estimates of mean TS and r are given in Table 4, and the alternative time-series is given in Table 10 and plotted in Figure 19. Absolute estimates of abundance were 40–47% of those obtained using the TS-TL relationship of Macaulay (2006), but higher than those estimated from Kloser et al. (2011). Because the alternative TS-length relationships in equations (1) and (4) have very different slopes, there is potential to bias relative indices of abundance where the size of hoki varies between surveys. However, the length of hoki caught in Cook Strait was quite similar over the acoustic time-series (see Table 4), and the choice of the TS-length relationship has relatively little impact on relative indices (Figure 19). It is notable, that because the slope of equation (4) is close to 30, there is relatively little variability in the ratio, r, of mean weight to mean backscattering cross section (Table 4), meaning that equation (4) is not as sensitive to the annual length frequency data.

The implication for stock assessment of adopting the new TS-TL relationship of Dunford et al. (2015) would be a change in the estimate of the acoustic *q*. This would also force us to reconsider our interpretation of, and priors on, *q*. The new TS-TL relationship would imply implausibly high exploitation rates in Cook Strait in some years (e.g., 1996, 1998) if $q = 1$. However, it is likely that *q* for this series will be less than 1 due to the turnover of fish on the spawning grounds (Harley 2002).

The estimated abundance of 134 000 t of hoki in Pegasus Canyon in 2013 was the highest in the time-series for this area (Table 11). However, it is difficult to interpret apparent changes in abundance because of the different timing and numbers of snapshots in the five surveys (Figure 20). The estimate from 2013 was similar to individual snapshot values with similar timing in 2003, and lower than some snapshots in 2002 (Figure 20). The estimate from Pegasus Canyon in 2013 was 36% of the acoustic abundance index from Cook Strait, which was similar to the proportion in 2002 (36%) and 2003 (46%), but higher than that in 2006 (26%) and 2008 (24%) (Table 11). The 2013 survey confirms that substantial hoki spawning aggregations occur off the east coast South Island, but there is no consistent time-series for this area, so results are probably of little value for stock assessment. Interpretation of acoustic data from Pegasus Canyon in 2013 is also hindered by the lack of associated biological sampling.

The survey approach in Cook Strait since 2008, using industry vessels rather than a dedicated research vessel, required compromises between scientists and industry participants. The requirement to complete an entire snapshot within 48 hours and to run all transects in the main Cook Strait Canyon (strata 5A and 2) involved considerable investment and commitment on the part of the vessel(s), as it was not possible to just carry out transects in the ‘down-time’ while processing between commercial trawls (e.g., O’Driscoll & Macaulay 2005). Rather, fishing activities needed to be suspended to collect acoustic data. The approach in 2013, where two vessels coordinated their activities to carry out about half of the planned transects each, appears to have been successful, reducing the burden on an individual vessel at the same time as ensuring near-synoptic sampling.

A major limitation of acoustic surveys of Cook Strait from industry vessels in 2007 and 2009 was the lack of targeted mark identification trawls (O’Driscoll & Macaulay 2009). Regular sampling of all mark types is important to understand species composition, especially as this can change over time (e.g., O’Driscoll 2007). This is particularly important for hoki fuzz marks, which typically contribute 30–50% of the hoki biomass in Cook Strait, but which are not usually targeted commercially because of low fish density. This was addressed in 2011 and 2013 with provision in the survey design for a limited number of mark identification trawls with a scientist present on board. A disadvantage of this strategy is that mark type and composition may change during the spawning season, so that mark types during the trip with targeted trawling may have differed from those in snapshots at the start and end of the spawning period. However, we believe that the risks are reduced by having at least some dedicated mark identification tows. It is important to retain mark identification trawling on future surveys, and to extend this to other survey areas (e.g., Pegasus Canyon). It is also important to ensure adequate sampling by scientific observers throughout the survey period to provide adequate biological data to estimate size distribution of hoki and progression of maturity stages to allow interpretation of acoustic survey results.

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7. TABLES

Table 1: Stratum boundaries, areas and transect allocation for the 2013 acoustic survey of spawning hoki in Cook Strait and Pegasus Canyon. Stratum locations are shown in Figures 1–2.

Area	Stratum	Name	Boundary	Area (km^2)	No. of transects
Cook Strait	1	Narrows Basin	200–200 m	330	4
	2	Cook Strait Canyon	180–180 m	220	9
	3	Nicholson Canyon	200–200 m	55	4
	5A	Cook Strait Canyon extension	position to 200 m	90	4
	5B	Deep water	position to 200 m	215	3
	6	Terawhiti Sill	200–200 m	65	4
Pegasus	PCA	North Pegasus Canyon	position to 200 m	270	5
Canyon	PCB	South Pegasus Canyon	200–200 m	63	4

Table 2: Values of parameters and their distributions used in Monte Carlo uncertainty simulations to determine model weighting (from O'Driscoll 2004).

Term	Notation	Distribution	Values*
Mean arrival date	$\overline{d}$	Uniform	1 July–9 August
Mean residence time	$\overline{r}$	Uniform	24–47 days
Individual arrival date	d_i	Normal	$\overline{d}$ (5 days)
Individual residence time	r_i	Normal	$\overline{r}$ (10 days)
Sampling	s	Normal	1.0 (snapshot c.v)
Detectability	D	Uniform	0.85–0.97
Mark identification – 'fuzz' marks	Id_{fuzz}	Lognormal	0.78 (0.72)
Mark identification – 'school' marks	Id_{school}	Lognormal	0.10 (0.16)
Calibration	cal	Uniform	cal ± 0.2 dB
Target strength+	TS	Uniform	TS ± 0.5 dB

* For uniform distribution, values are ranges; for normal distributions, values are means with standard deviations (in parentheses); for lognormal distributions, values are the mean and standard deviation (in parentheses) of $\log_e$(variable).

+ Uncertainty associated with TS arose from variation in fish size, and from differences in the slope of alternative TS-length relationships. Potential bias due to differences in the intercept of alternative TS-length models was ignored because it will not affect the relative values of acoustic indices (see O'Driscoll 2004 for details).

Table 3: Summary of snapshots carried out during the 2013 Cook Strait hoki acoustic survey. Times are NZST.

Snapshot	Vessel	Start time	End time	No. of transects
1	*Thomas Harrison* & *Aukaha*	21 Jul 04:54	22 Jul 22:06	28
2	*Thomas Harrison* & *Aukaha*	24 Jul 05:30	25 Jul 21:34	28
3	*Thomas Harrison* & *Aukaha*	27 Jul 04:10	28 Jul 08:16	28
4	*Thomas Harrison* & *Aukaha*	3 Aug 03:17	4 Aug 08:52	28
5	*Thomas Harrison*	8 Aug 10:01	10 Aug 04:56	28
6	*Thomas Harrison* & *Aukaha*	15 Aug 02:08	17 Aug 20:16	28
7	*Thomas Harrison* & *Aukaha*	20 Aug 16:36	21 Aug 22:49	28
8	*Thomas Harrison* & *Aukaha*	22 Aug 00:48	23 Aug 04:15	28
9	*Thomas Harrison* & *Aukaha*	2 Sep 02:57	3 Sep 15:38	28

Table 4: Estimates of the ratio *r* for converting hoki acoustic backscatter to biomass using acoustic TS derived from commercial length frequency data using the TS-length relationships of Macaulay (2006), and the unpublished relationship derived from AOS data (Dunford et al. 2015).

			Macaulay (2006)		Dunford et al. (2015)	
Year	Mean length (cm)	Mean weight (kg)	Mean TS (dB)	*r* (kg m^{-2})	Mean TS (dB)	*r* (kg m^{-2})
1991	73.1	1.25	-41.1	16 289	-37.8	7 477
1993	74.7	1.29	-41.0	16 406	-37.6	7 485
1994	76.9	1.40	-40.9	17 129	-37.3	7 453
1995	78.4	1.50	-40.8	17 931	-36.9	7 412
1996	77.4	1.46	-40.8	17 773	-37.0	7 414
1997	74.9	1.33	-41.0	16 838	-37.5	7 455
1998	75.7	1.38	-41.0	17 250	-37.3	7 433
1999	75.6	1.37	-41.0	17 090	-37.4	7 444
2001	76.9	1.43	-40.9	17 479	-37.2	7 428
2002	78.5	1.50	-40.8	17 948	-36.9	7 412
2003	76.8	1.43	-40.9	17 551	-37.1	7 424
2005	78.7	1.54	-40.8	18 323	-36.8	7 389
2006	74.7	1.34	-41.0	17 039	-37.4	7 438
2007	73.8	1.30	-41.1	16 669	-37.6	7 455
2008	72.9	1.23	-41.2	16 101	-37.8	7 489
2009	73.3	1.25	-41.1	16 281	-37.8	7 480
2011	79.1	1.54	-40.7	18 202	-36.8	7 400
2013	79.7	1.57	-40.7	18 436	-36.7	7 390
Mean				17 263		7 438

Table 5: Summary and catch information from mark identification trawls and commercial tows where NIWA collected biological data during the 2013 hoki acoustic survey. Mark type refers to the categories described by O'Driscoll (2002b): HOK = hoki school; PMIX = hoki pelagic fuzz; BMIX = hoki bottom fuzz.

				Catch (kg)						
Station	Type	Stratum	Mark type	Hoki	Jack mackerels	Spiny dogfish	Ling	Rattails	Other	% hoki
1	Commercial	2	HOK	5 777	0	0	0	2	27	100
2	Commercial	2	HOK	17 405	0	12	1	2	9	100
3	Commercial	2	HOK	23 998	0	1	0	0	45	100
4	Commercial	2	HOK	14 108	0	0	0	1	25	100
5	Research	3	PMIX	1 706	13	3	0	1	6	99
6	Research	3	PMIX	802	33	3	1	0	0	96
7	Research	5B	PMIX	36	3	0	0	0	20	61
8	Research	5B	PMIX	273	29	0	0	31	21	77
9	Research	6	BMIX	891	5	3	0	11	54	92
10	Research	1	BMIX	1 767	1	12	0	3	14	98
11	Research	1	BMIX	99	2	12	2	68	253	23
12	Research	1	BMIX	46	2	12	1	69	233	13
13	Commercial	2	HOK	8 405	0	0	0	5	109	99
14	Commercial	2	HOK	5 257	0	5	0	0	23	99
15	Commercial	2	HOK	545	0	198	3	0	19	71
16	Commercial	2	HOK	9 950	42	5	0	0	52	99
17	Commercial	2	HOK	5 673	13	3	13	1	119	97
18	Commercial	2	HOK	7 841	5	0	0	1	78	99
19	Commercial	2	HOK	13 187	0	0	0	0	22	100
20	Commercial	2	HOK	9 249	0	0	2	2	84	99
21	Commercial	2	HOK	11 613	3	0	0	0	82	99
22	Commercial	2	HOK	5 970	0	159	2	0	44	97
23	Commercial	2	HOK	9 237	0	101	1	0	53	98
24	Commercial	2	HOK	8 346	0	0	0	1	126	99
25	Commercial	2	HOK	4 366	0	1	0	1	56	99

Table 6: Total catch by species for the eight designated research tows carried out in the 2013 hoki acoustic survey.

Code	Common name	Catch (kg)
BSH	Seal shark	2.8
BYS	Alfonsino	0.8
CAR	Carpet shark	2.7
CBI	Two saddle rattail	151.2
CBO	Bollons's rattail	25.0
COL	Oliver's rattail	7.6
CON	Conger eel	13.1
CSQ	Leafscale gulper shark	0.5
CYP	Longnosed velvet dogfish	8.1
DCS	Dawson's catshark	0.1
DIS	Discfish	0.1
ETL	Lucifer's dogfish	3.2
FRO	Frostfish	1.0
GSH	Dark ghost shark	38.9
HAK	Hake	0.8
HJO	Johnson's cod	0.4
HOK	Hoki	5 620.9
JMD	Greenback jack mackerel	41.1
JMM	Slender jack mackerel	47.2
LAN	Lanternfishes	0.2
LIN	Ling	3.5
NMP	Tarakihi	37.2
OPE	Orange perch	14.5
RCO	Red cod	243.6
RHY	Common roughy	0.7
RSO	Gemfish	7.5
RUD	Rudderfish	0.7
SBK	Spineback	12.2
SCH	School shark	150.3
SND	Shovelnosed dogfish	0.2
SPD	Spiny dogfish	44.3
SPE	Sea perch	0.1
SPO	Rig	43.4
SQU	Arrow squid	1.3
SSI	Silverside	0.1
SWA	Silver warehou	10.5
TSQ	*Todarodes filippovae* (squid)	0.4
VSQ	Violet squid	0.4
WAR	Blue warehou	4.1
	Total	6 540.7

Table 7: Hoki acoustic abundance estimates from the 2013 Cook Strait survey by snapshot and stratum.

	Stratum biomass (‘000 t)						Total	Snapshot
Snapshot	1	2	3	5A	5B	6	(‘000 t)	CV
1	39	314	4	15	16	6	395	19
2	29	184	5	18	18	9	263	12
3	39	323	5	18	17	9	412	14
4	27	316	8	28	22	4	404	64
5	41	145	4	19	14	9	233	19
6*	15	142	6	14	16	5	197	28
7	19	590	6	23	19	9	666	53
8	39	167	4	26	11	20	267	28
9*	10	115	8	14	10	0	157	43
Mean	33	291	5	21	17	10	377	17

* Snapshots 6 and 9 were not included in the mean as they did not meet all survey criteria.

Table 8: Percentage of the hoki abundance estimate from hoki school marks in each snapshot and strata for the 2013 Cook Strait survey. Percentages were calculated in relation to abundance estimates in Table 7.

	Percentage of biomass in schools						
Snapshot	1	2	3	5A	5B	6	Total
1	0	97	64	0	0	0	78
2	0	97	43	37	0	0	71
3	0	98	0	57	0	0	79
4	0	99	64	78	48	0	87
5	0	95	34	81	0	36	68
6	0	96	26	48	0	0	73
7	0	99	52	81	10	0	92
8	0	94	0	66	0	67	70
9	0	96	60	70	0	0	80
Mean	0	97	38	58	6	11	78

Table 9: Results of Monte Carlo simulations to determine model weighting for the 2013 Cook Strait acoustic survey (see O’Driscoll 2004 for details). The CV for the survey is given in a stepwise cumulative fashion to allow the contribution of each component of the abundance estimation process to be assessed. ‘Timing’ refers to uncertainties associated with the timing of snapshots relative to the plateau height model and includes uncertainties associated with assumptions about fish arrival date and residence time.

Timing	0.220
+ Sampling	0.263
+ Detectability	0.264
+ Mark identification	0.287
+ Calibration	0.289
+ TS	0.296
Total	0.296

Table 10: Alternative acoustic indices of hoki abundance for Cook Strait 1988–2013. Biomass values with annual *r* use acoustic TS derived from commercial length frequency data in each survey year using the TS-length relationships of Macaulay (2006) and the relationship derived from New Zealand and Australian AOS data (Dunford et al. 2015) (see Table 4). Values with constant *r* use an average ratio of hoki TS to fish weight (calculated from the mean of annual values estimated using Macaulay TS).

		Biomass ('000 t)			
Year	No of snapshots	Annual *r* Macaulay TS	Constant *r* Macaulay TS	Annual *r* Dunford TS	CV
1991	4	180	191	83	0.41
1993	4	583	614	266	0.52
1994	3	592	597	258	0.91
1995	4	427	411	176	0.61
1996	5	202	196	84	0.57
1997	6	295	303	131	0.40
1998	5	170	170	73	0.44
1999	6	243	245	106	0.36
2001	11	220	218	94	0.30
2002	9	320	308	132	0.35
2003	9	225	222	95	0.34
2005	9	132	125	53	0.32
2006	7	126	128	55	0.34
2007*	4	217	225	97	0.46
2008	7	167	179	78	0.30
2009*	5	339	359	156	0.39
2011*	6	314	298	128	0.35
2013*	7	377	353	151	0.30

* Surveys from industry vessels. Indices from 2007, 2009, and 2011 were re-calculated in 2013 to correct for a bug in the conversion programme and inconsistencies in the estimation of calibration parameters (see Section 2.9 for details).

Table 11: Acoustic indices of hoki abundance for Pegasus Canyon 2002–13. All biomass values were estimated using the TS-length relationships of Macaulay (2006). % Cook Strait indicates the abundance in Pegasus Canyon as a percentage of the equivalent estimate from Cook Strait (see Table 10).

Year	No of snapshots	Biomass ('000 t)	% Cook Strait
2002*	7	116	36
2003*	4	97	43
2006	3	33	26
2008	2	40	24
2013*	1	134	36

* Surveys from industry vessels.

8. FIGURES

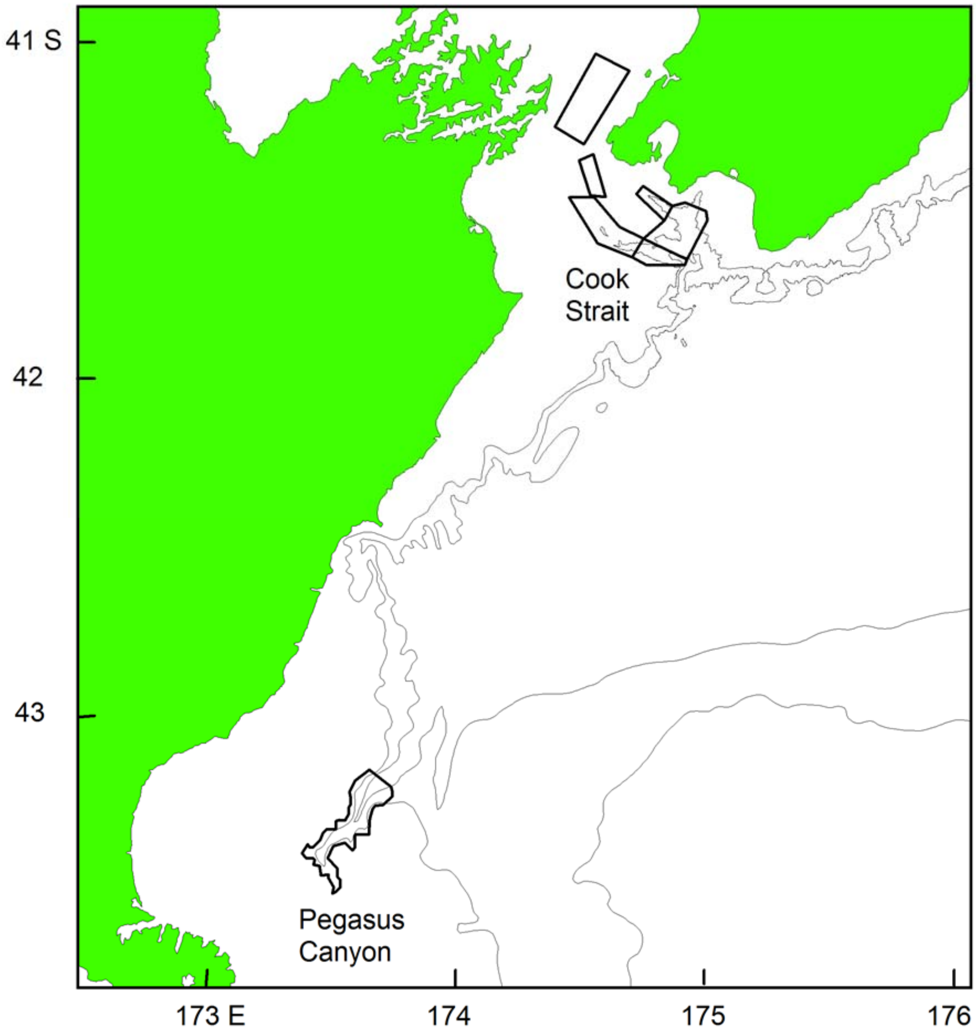

Figure 1: Map showing location of survey area in Pegasus Canyon relative to Cook Strait. Depth contours (grey lines) are 500 and 1000 m isobaths.

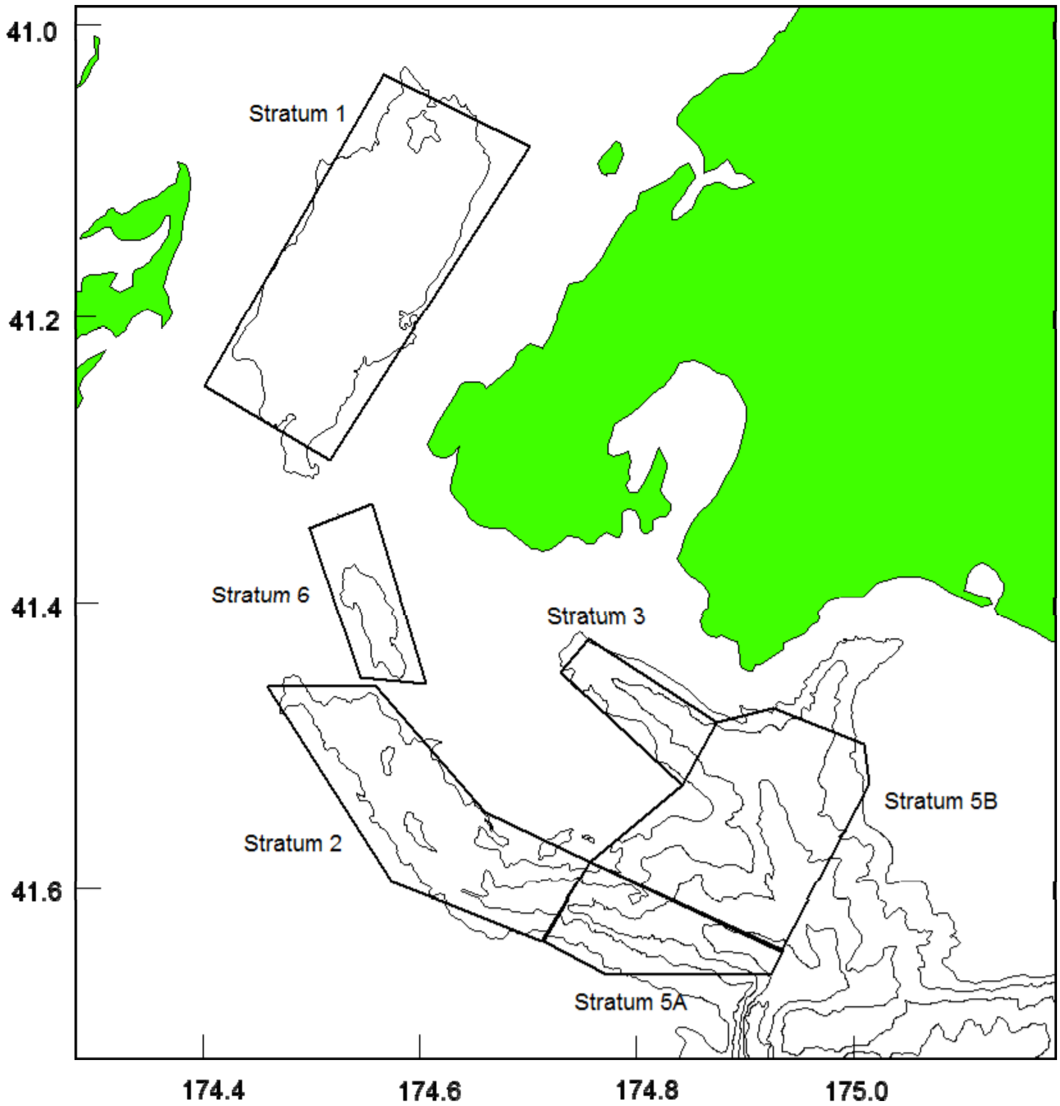

Figure 2: Stratum boundaries for the 2013 acoustic survey of Cook Strait spawning hoki: 1, Narrows Basin; 2, Cook Strait Canyon; 3, Nicholson Canyon; 5A, Cook Strait Canyon extension; 5B, Deepwater outside Nicholson and Wairarapa Canyons; 6, Terawhiti Sill. Depth contours are 250, 500, 750, and 1000 m.

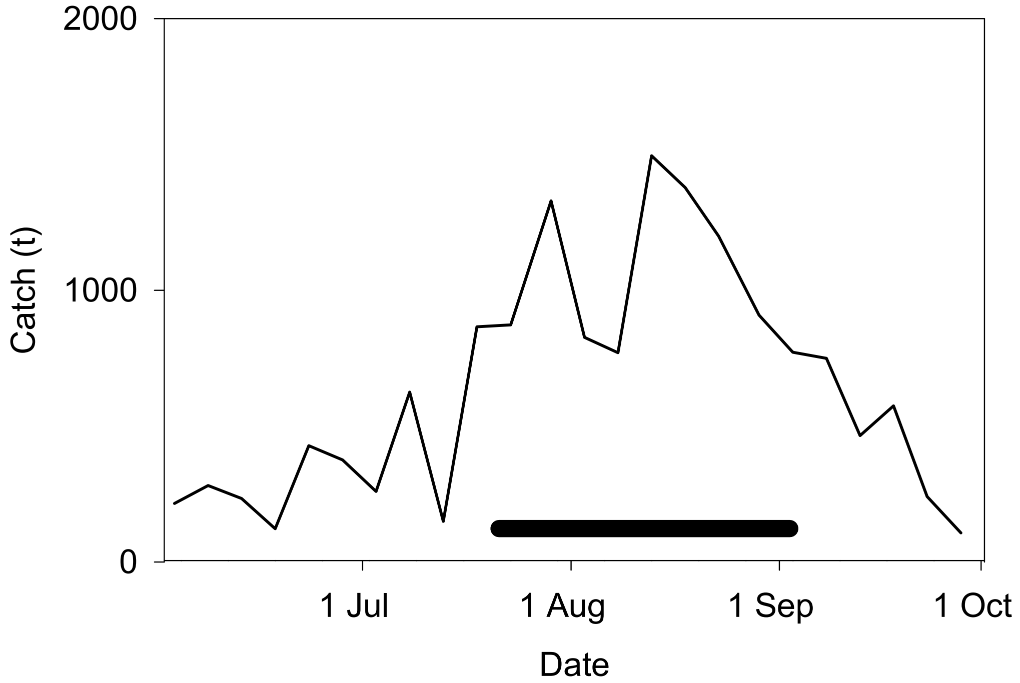

Figure 3: Timing of acoustic survey in 2013 (bar along the x axis) in relation to the commercial hoki catch from Cook Strait in 5-day periods.

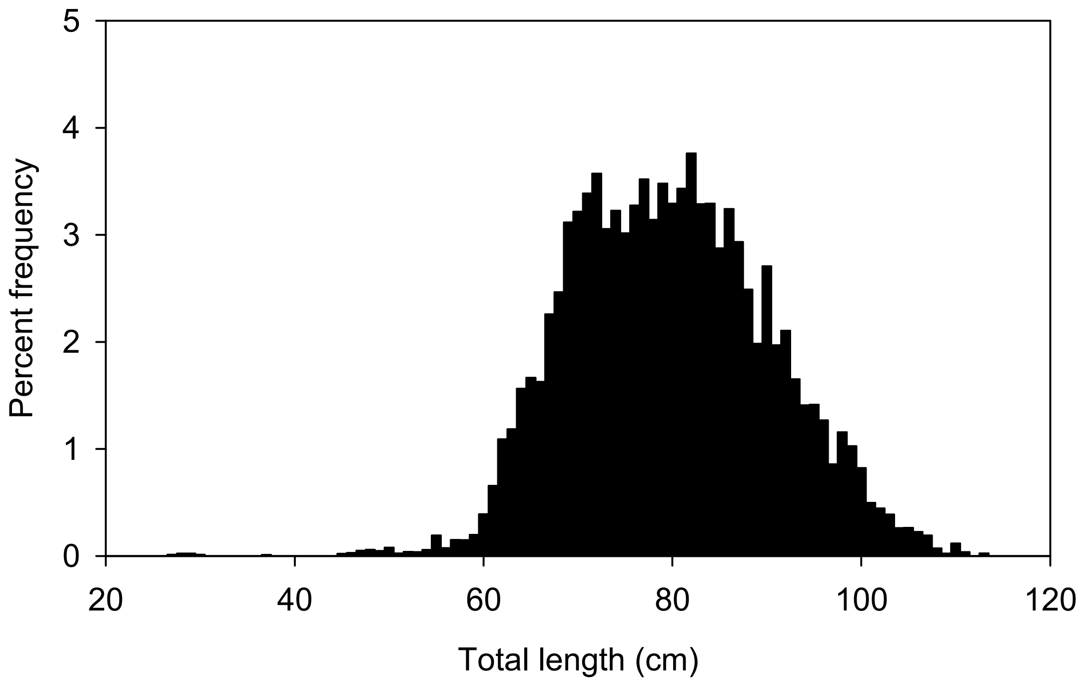

Figure 4: Scaled unsexed length frequencies of hoki caught in the commercial fishery in Cook Strait in 2013 based on at-sea observer sampling and sampling by NIWA on *Thomas Harrison*. Data were used to estimate the ratio, *r*, of mean weight to mean backscattering cross-section for Cook Strait hoki.

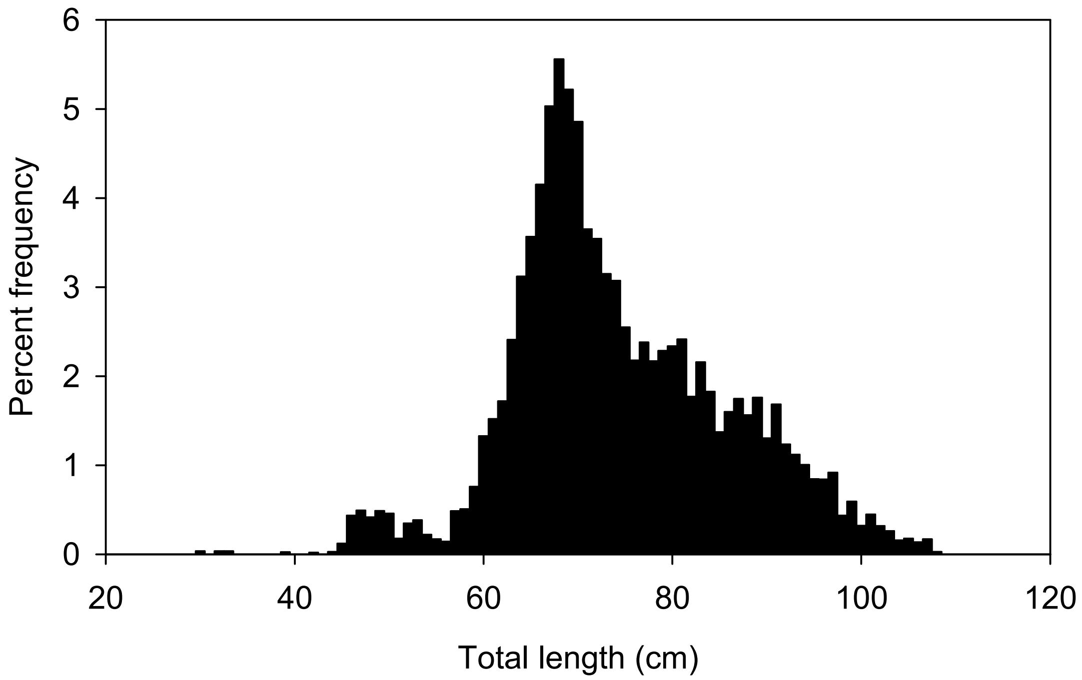

Figure 5: Scaled unsexed length frequencies of hoki caught in the commercial fishery on the east coast South Island in 2013. Data were used to estimate the ratio, *r*, of mean weight to mean backscattering cross-section for Pegasus Canyon hoki.

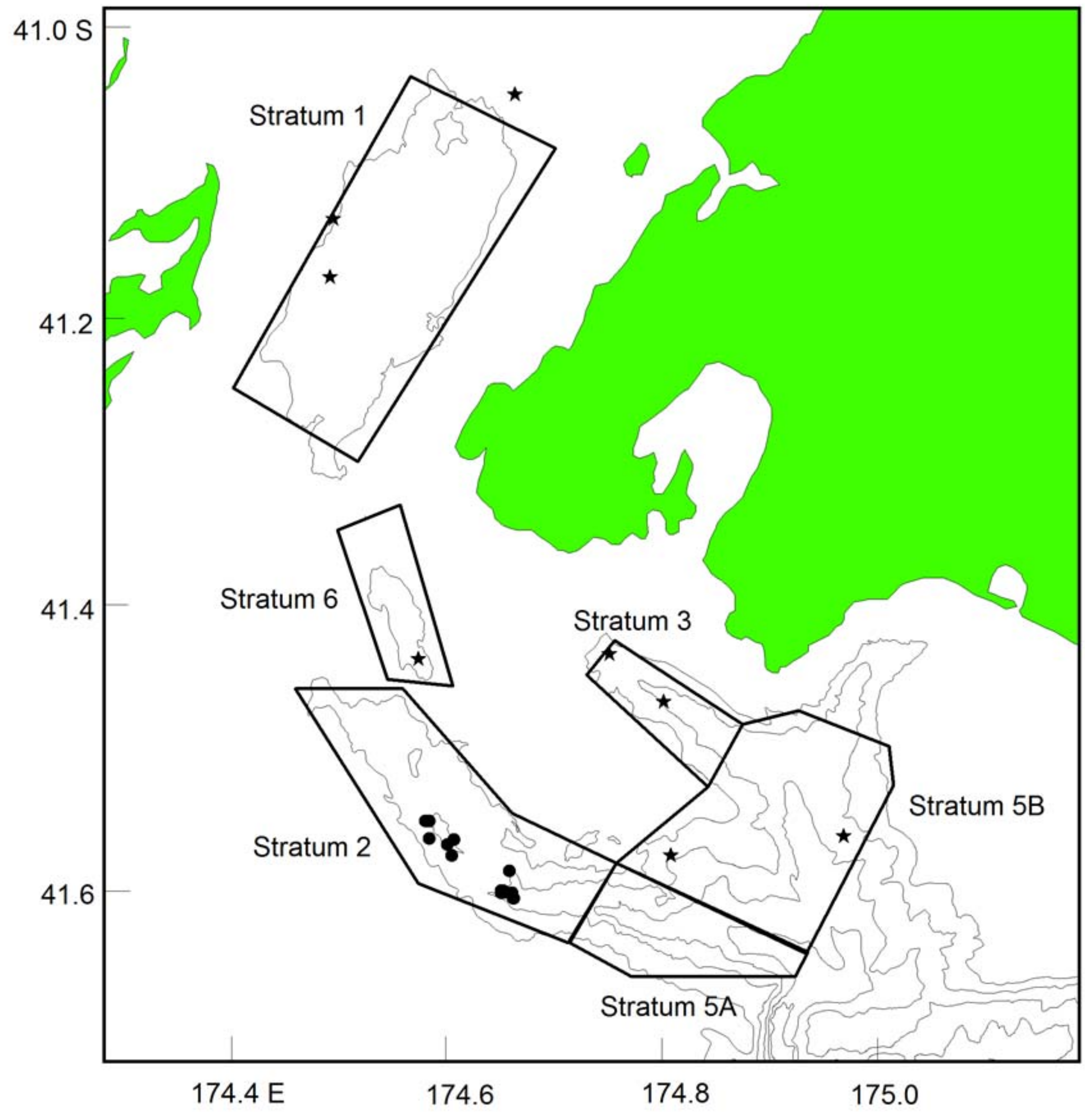

Figure 6: Location of trawls sampled on *Thomas Harrison* from 5–16 August 2013: stars show research tows; and circles show commercial tows.

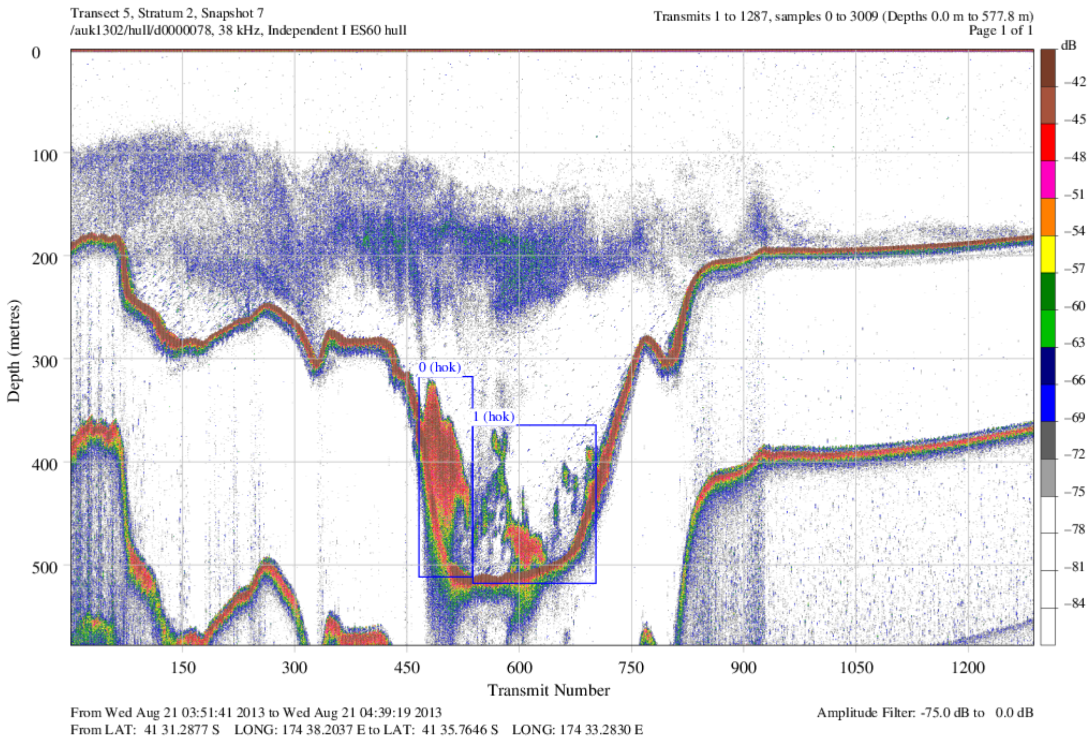

Figure 7: Acoustic echogram from Cook Strait Canyon (stratum 2) during snapshot 7 showing a very dense hoki school close to the bottom on the northern side of the canyon at night. The dispersed layer from 100 to 250 m is probably mesopelagic fish.

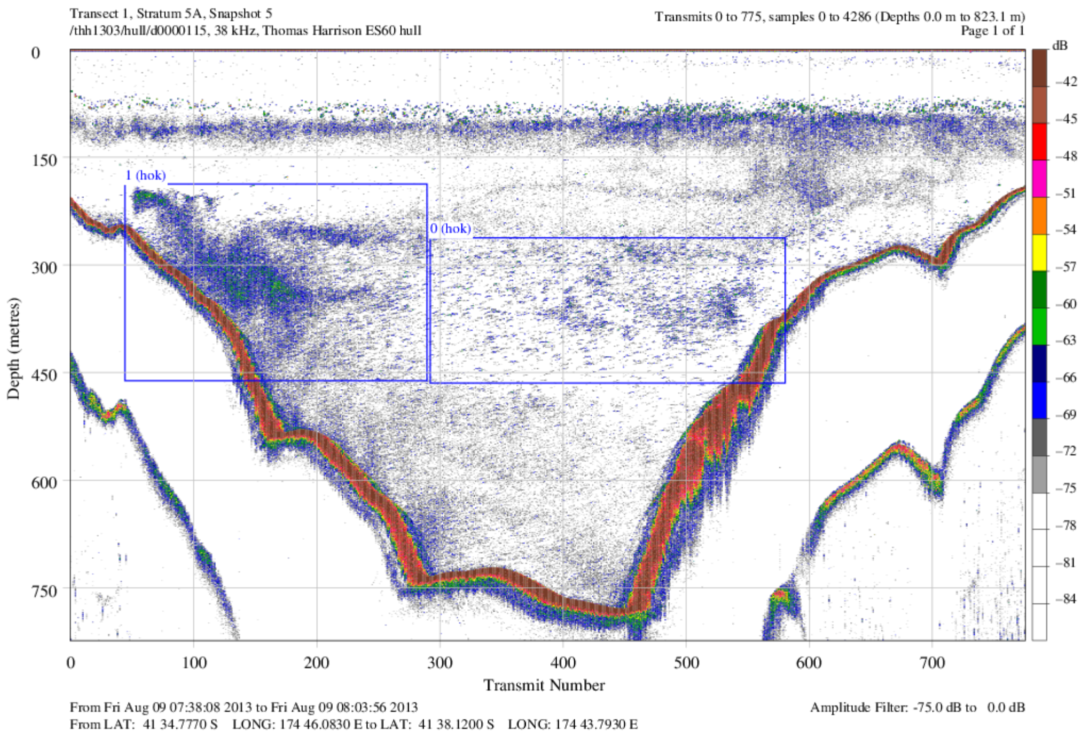

Figure 8: Acoustic echogram from outer Cook Strait Canyon (stratum 5A) during snapshot 5 showing hoki schools in midwater. The layer from 70–150 m is probably mesopelagic fish.

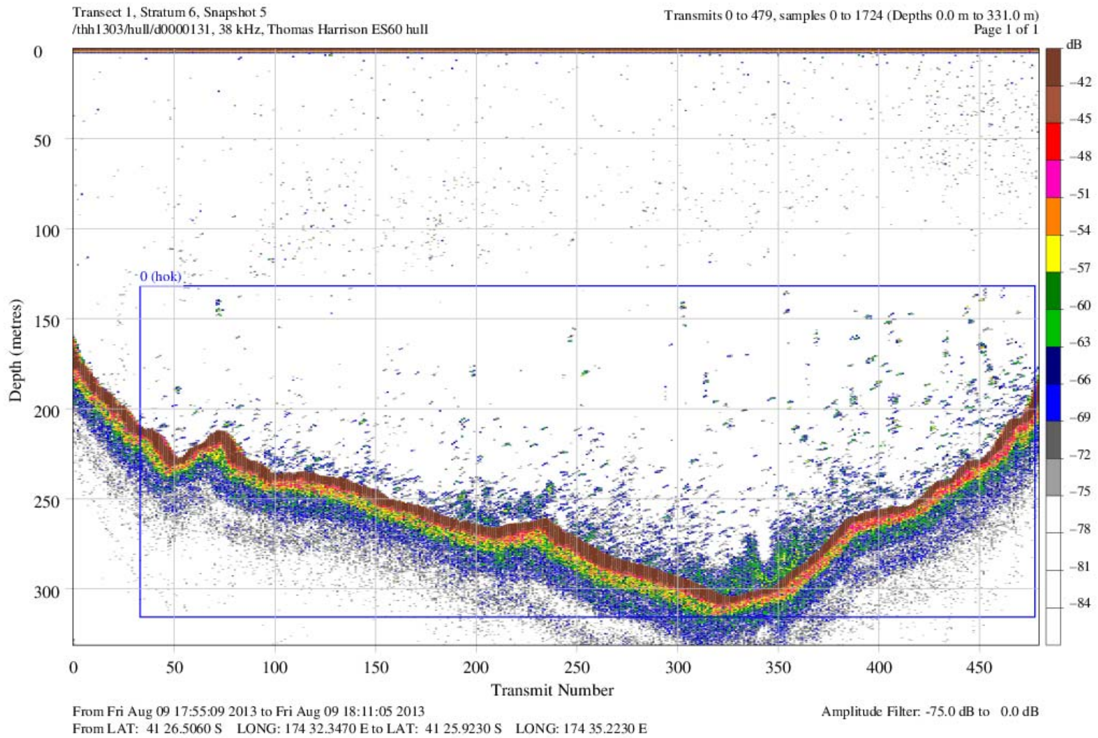

Figure 9: Acoustic echogram from Terawhiti Sill (stratum 6) during snapshot 5 showing hoki on or near the bottom.

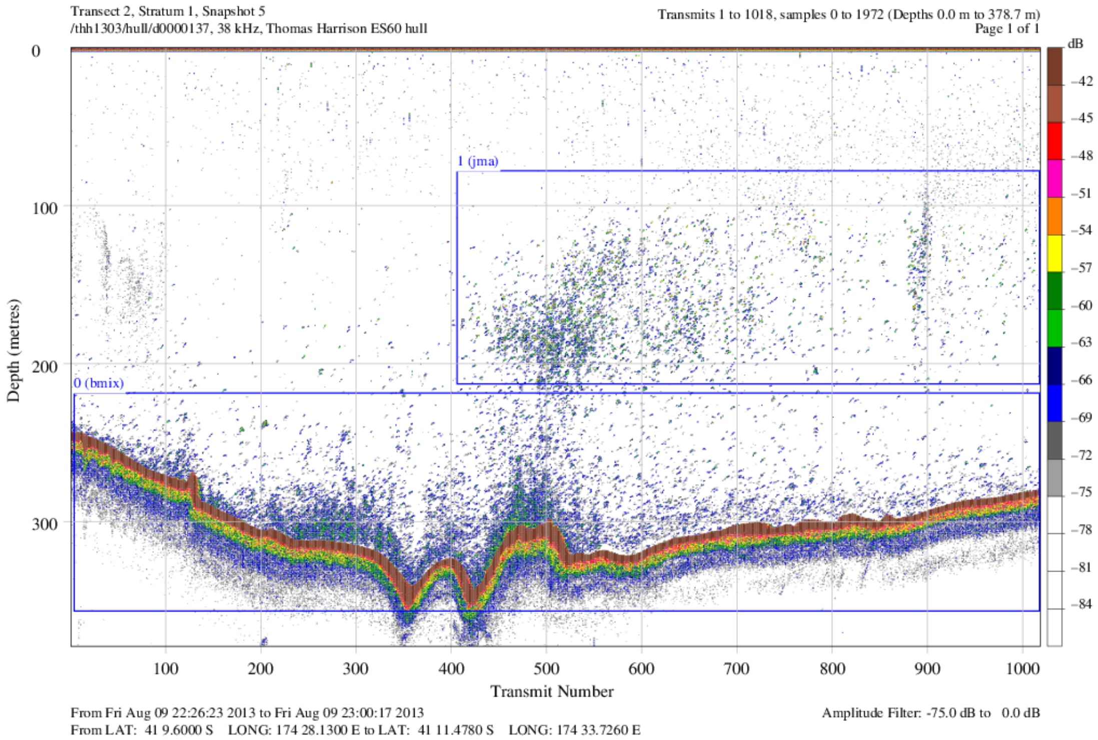

Figure 10: Acoustic echogram from Narrows Basin (stratum 1) during snapshot 5 showing hoki bottom fuzz within 100 m of the bottom and jack mackerel above at 100–200 m.

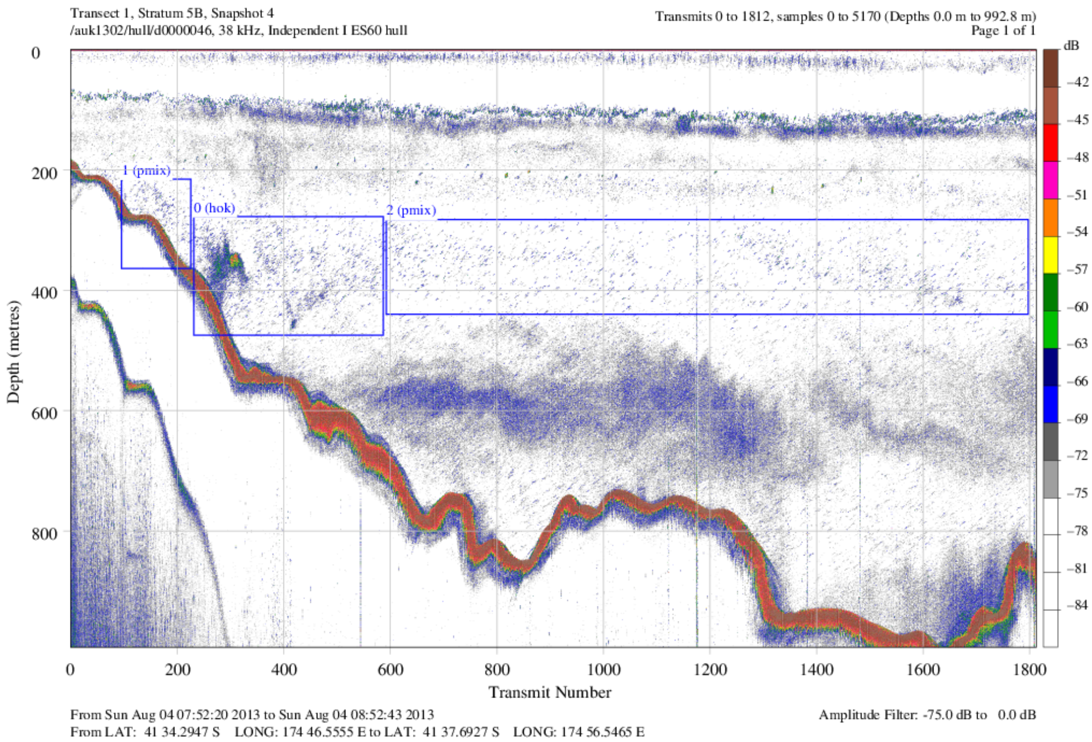

Figure 11: Acoustic echogram from the deepwater between Cook Strait and Wairarapa Canyons (stratum 5B) during snapshot 4 showing a hoki school surrounded by dispersed hoki pelagic fuzz marks. The layers above and below are probably mesopelagic fish.

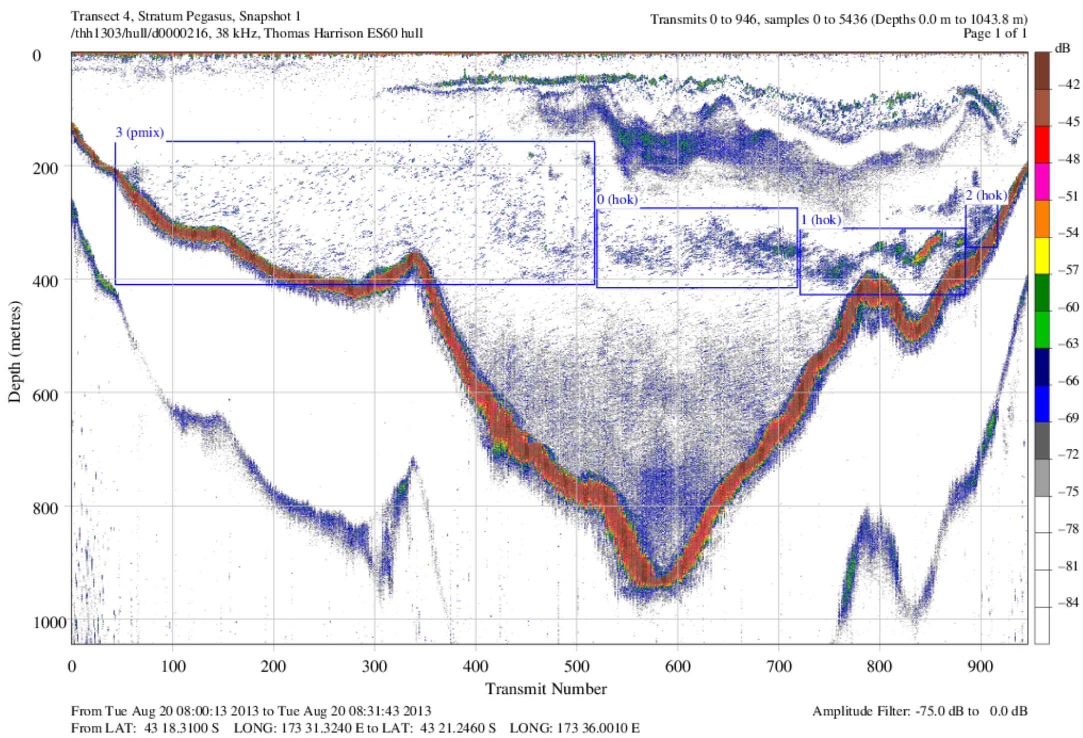

Figure 12: Acoustic echogram from the north Pegasus Canyon (stratum PCA) showing a hoki school on the southeast side of the canyon surrounded by dispersed hoki pelagic fuzz marks. The layers above and below are probably mesopelagic fish.

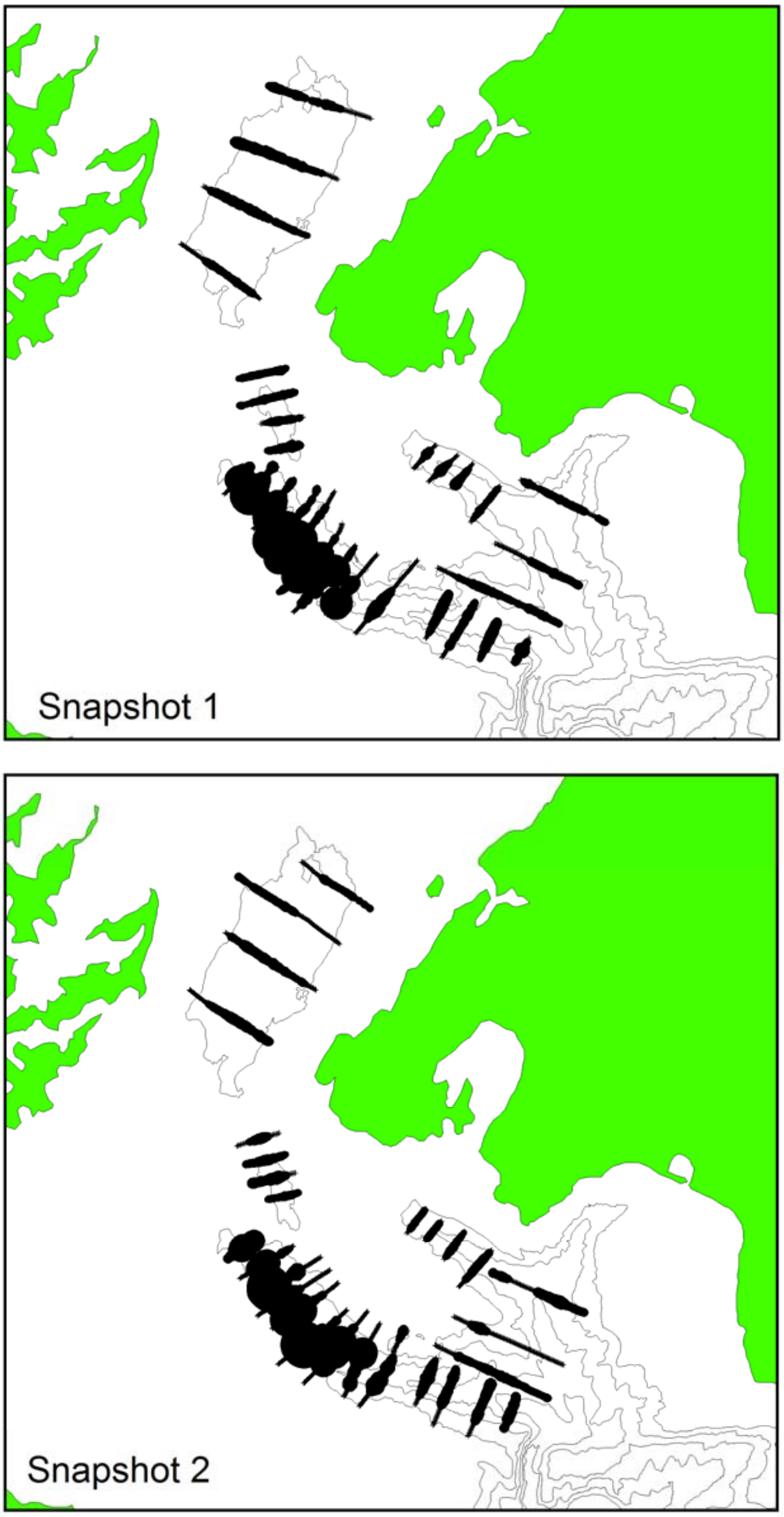

Figure 13: Spatial distribution of hoki acoustic backscatter plotted in 10 ping (~100 m) bins for snapshots 1–2 of Cook Strait. Symbol size is proportional to the log of the acoustic backscatter.

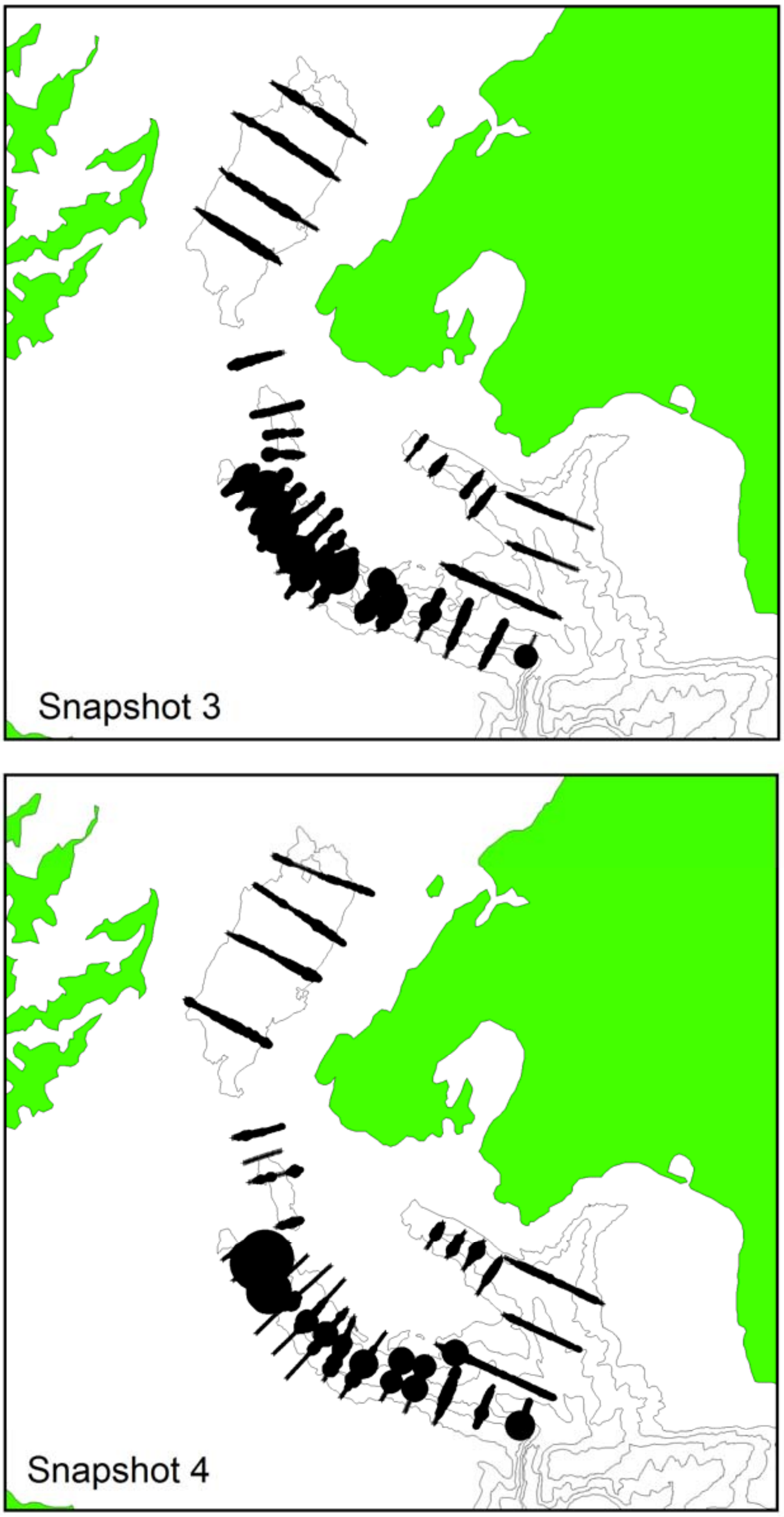

Figure 13 ctd: Spatial distribution of hoki acoustic backscatter plotted in 10 ping (~100 m) bins for snapshots 3–4 of Cook Strait. Symbol size is proportional to the log of the acoustic backscatter.

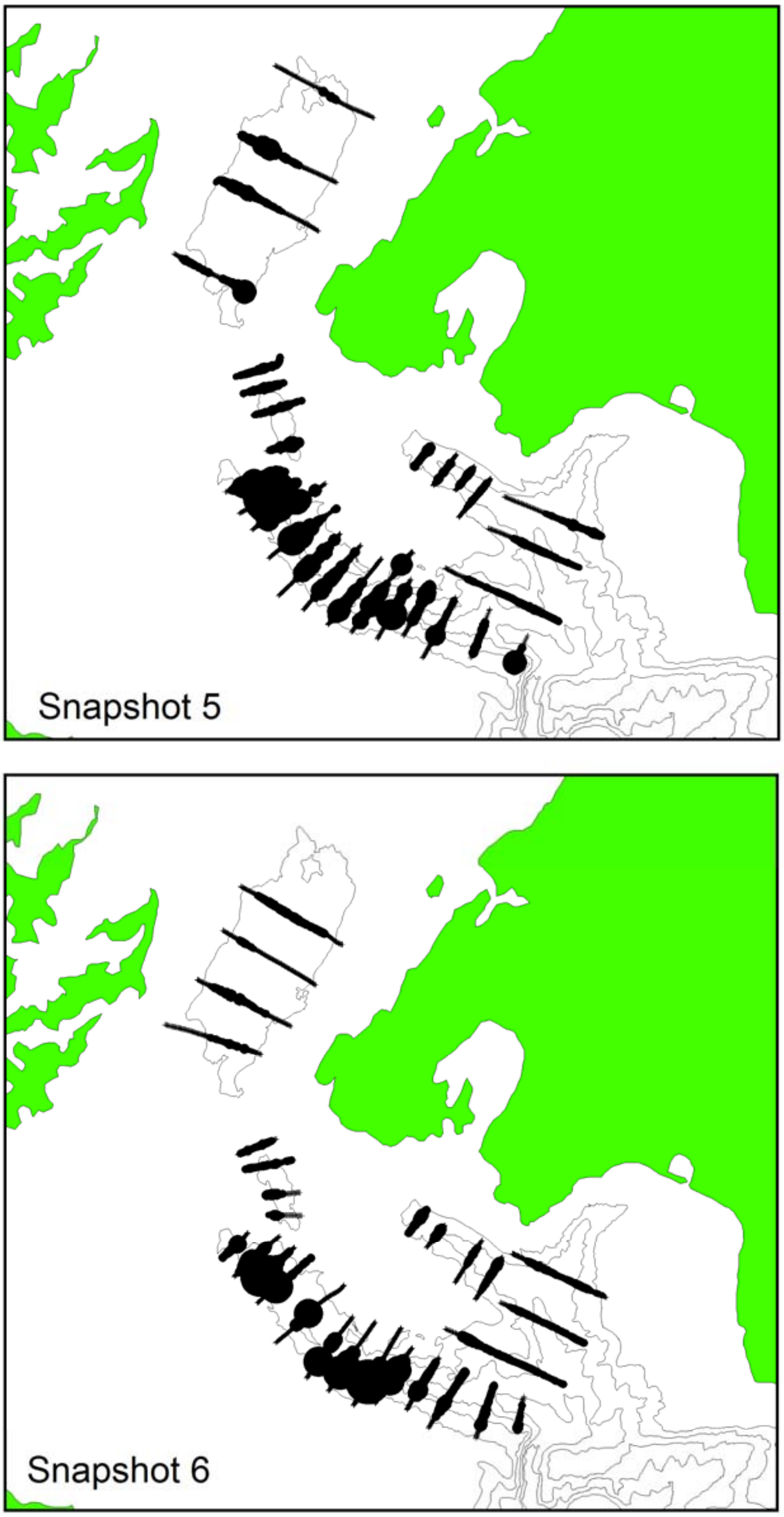

Figure 13 ctd: Spatial distribution of hoki acoustic backscatter plotted in 10 ping (~100 m) bins for snapshots 5–6 of Cook Strait. Symbol size is proportional to the log of the acoustic backscatter.

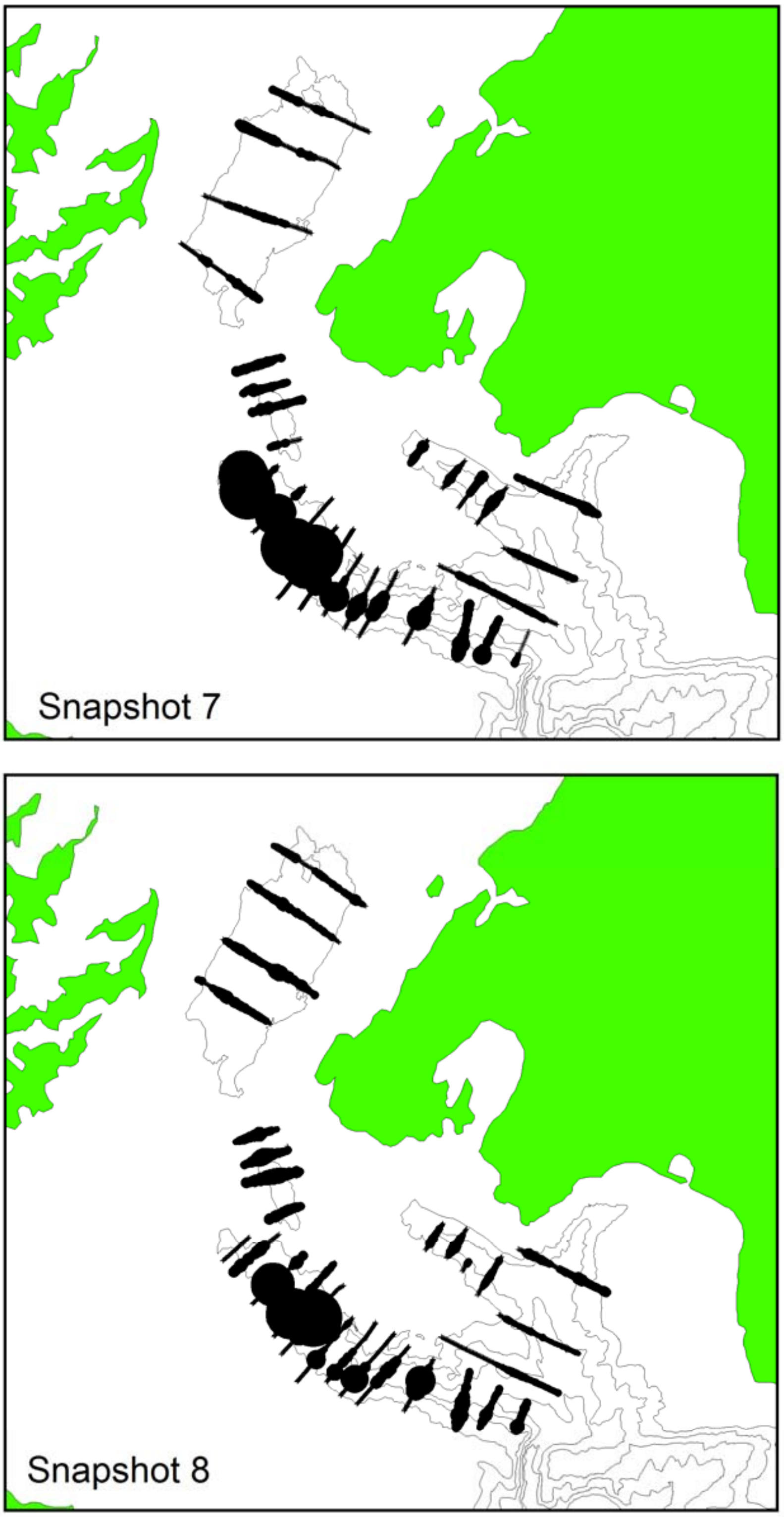

Figure 13 ctd: Spatial distribution of hoki acoustic backscatter plotted in 10 ping (~100 m) bins for snapshots 7–8 of Cook Strait. Symbol size is proportional to the log of the acoustic backscatter.

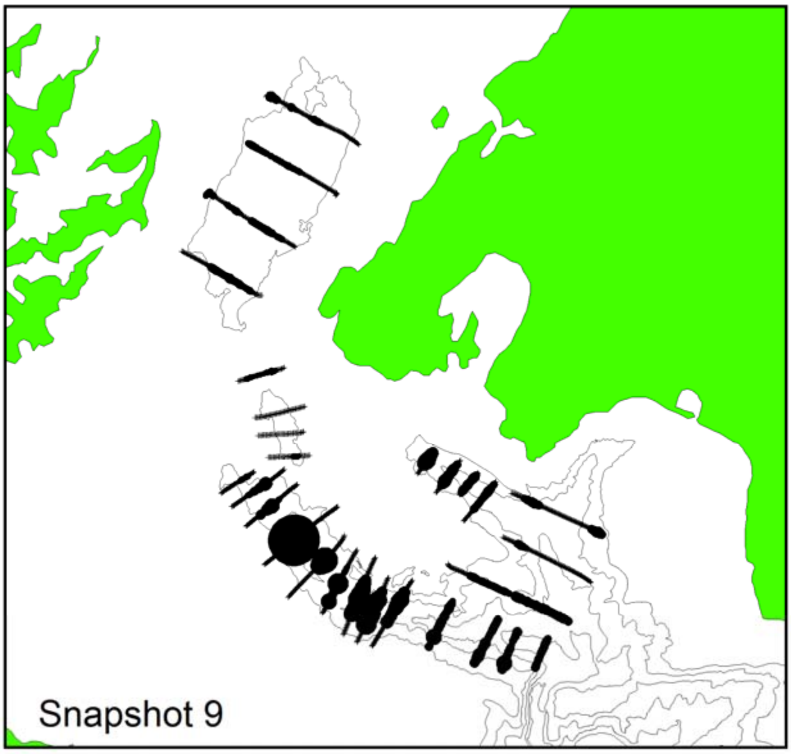

Figure 13 ctd: Spatial distribution of hoki acoustic backscatter plotted in 10 ping (~100 m) bins for snapshot 9 of Cook Strait. Symbol size is proportional to the log of the acoustic backscatter.

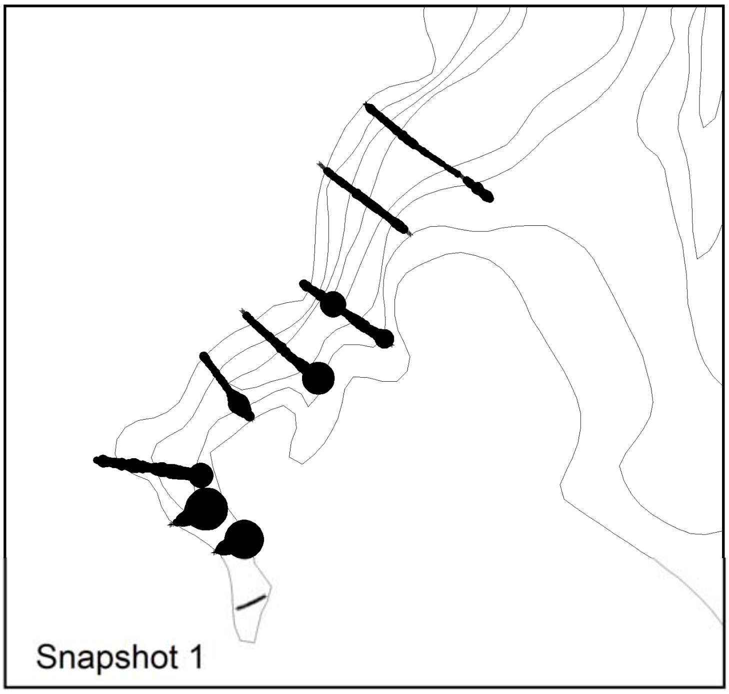

Figure 14: Spatial distribution of hoki acoustic backscatter plotted in 10 ping (~100 m) bins for snapshot 1 of Pegasus Canyon. Symbol size is proportional to the log of the acoustic backscatter.

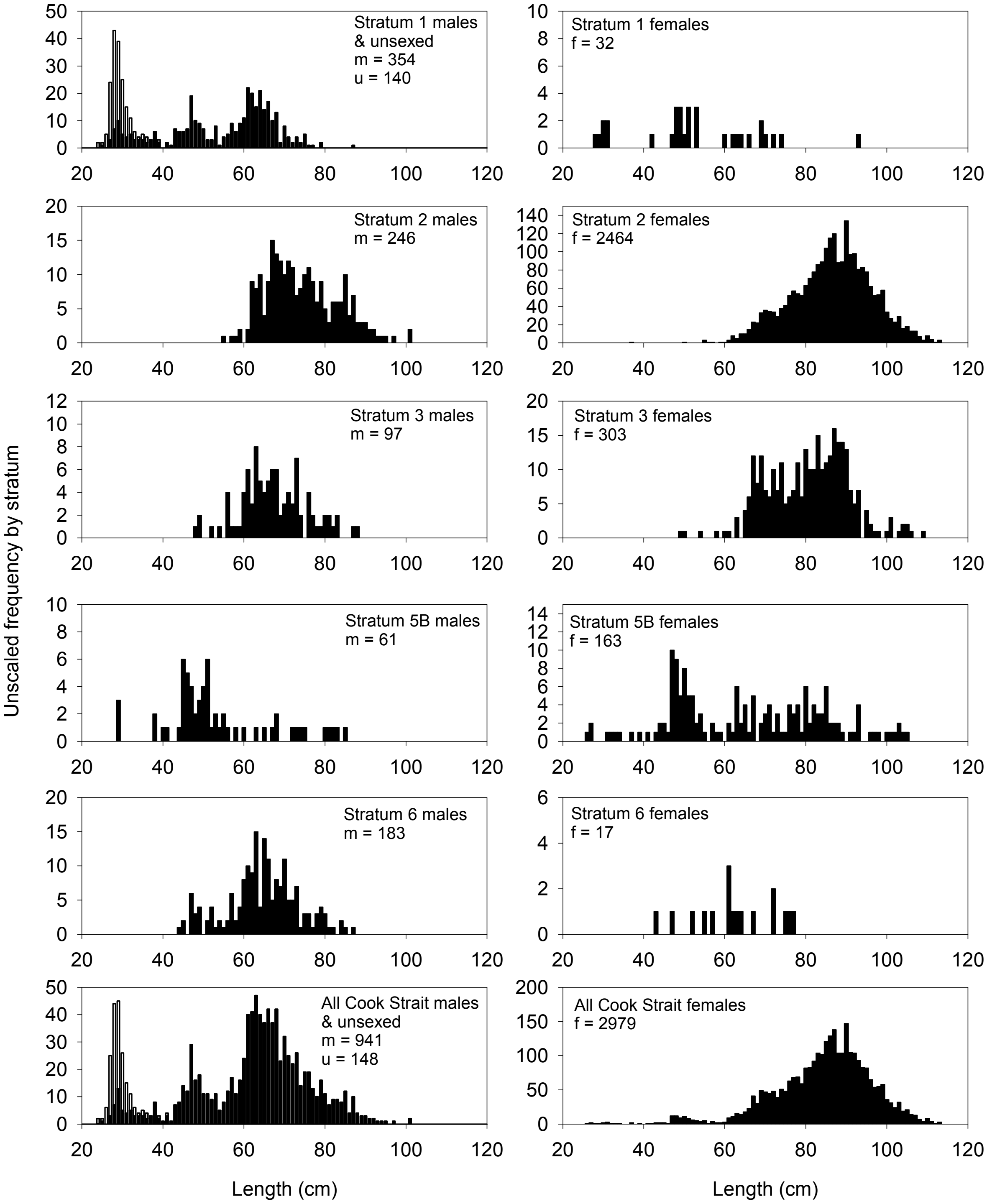

Figure 15: Unscaled length frequencies of hoki by sex and stratum from sampling in Cook Strait by *Thomas Harrison* in winter from 5–16 August 2013. m (male), f (female), and u (unsexed) values refer to the numbers of fish measured. Some small (less than 40 cm) hoki were not measured in stratum 1 and these are shown as white bars on male plots. Hoki in stratum 2 were taken in commercial tows. Hoki in all other strata were from designated research tows (see Figure 6).

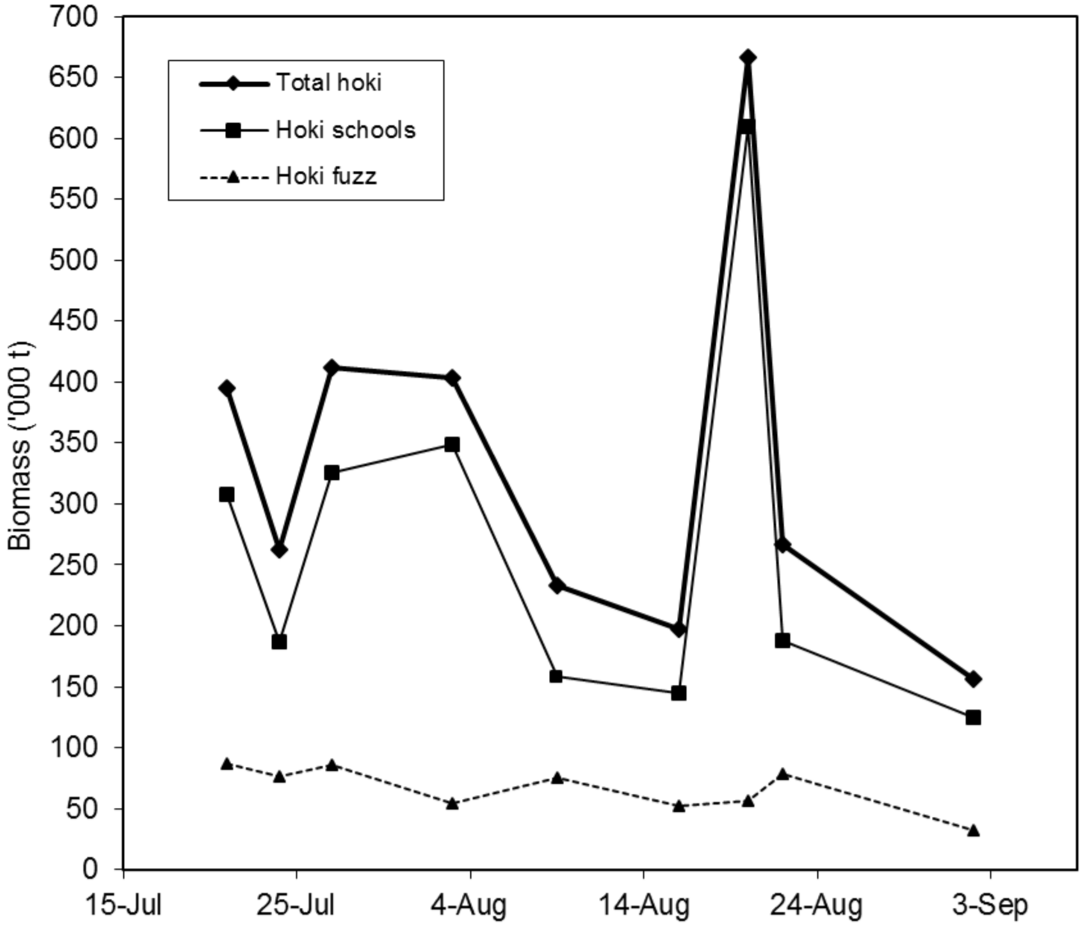

Figure 16: Estimated hoki abundance in Cook Strait by snapshot (1–9) from the 2013 survey.

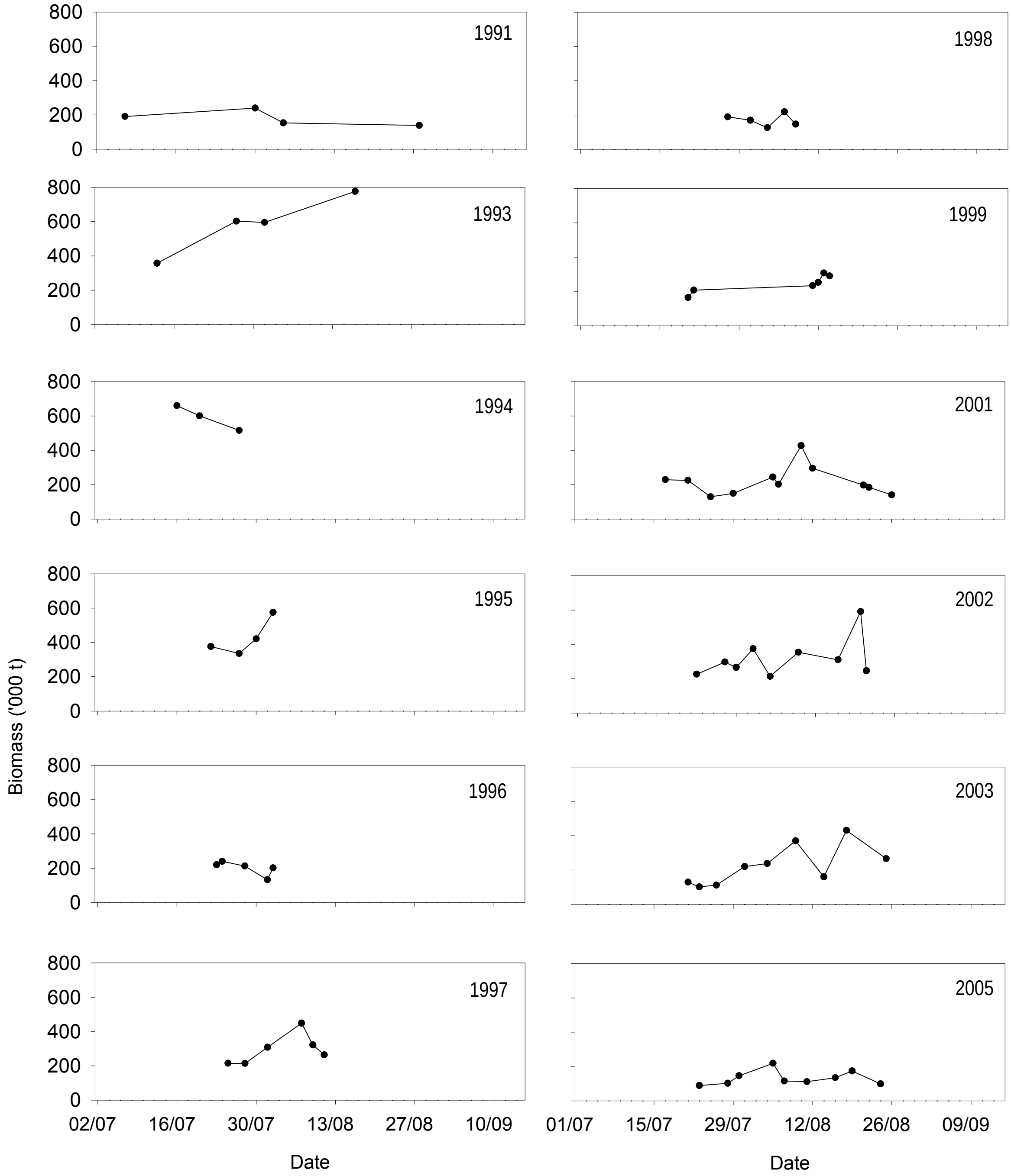

Figure 17: Estimated hoki abundance by snapshot for acoustic surveys in the Cook Strait time series from 1991 to 2005.

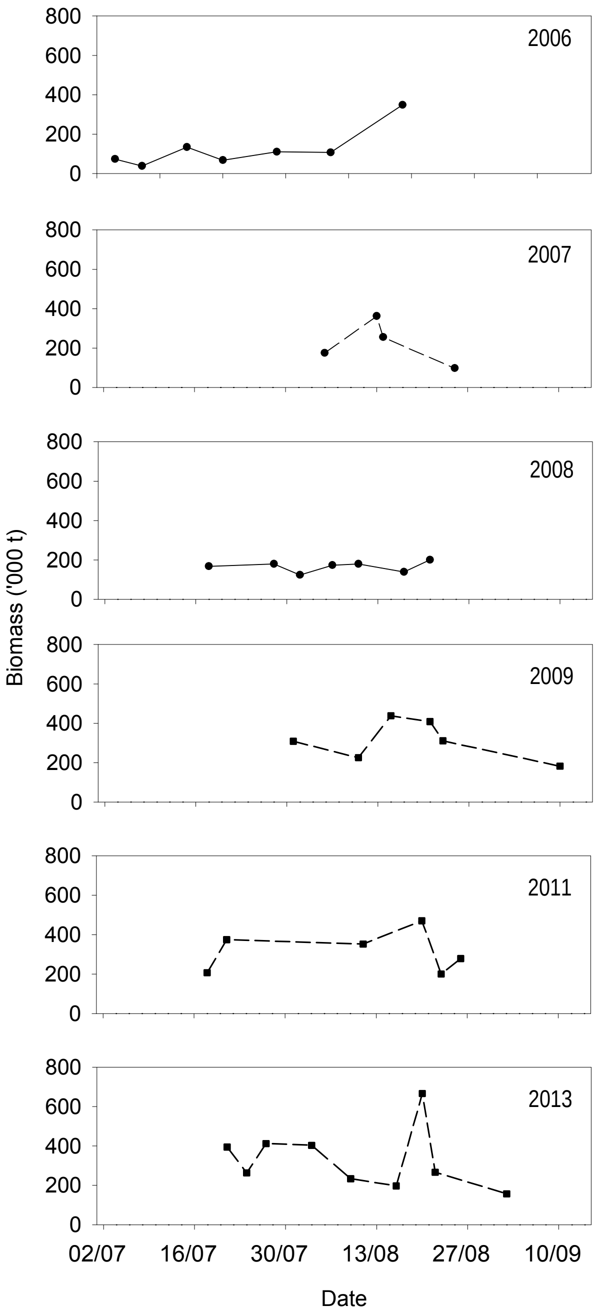

Figure 17 ctd: Estimated hoki abundance by snapshot for acoustic surveys in the Cook Strait time series from 2006 to 2013. Dotted lines show surveys carried out from commercial vessels.

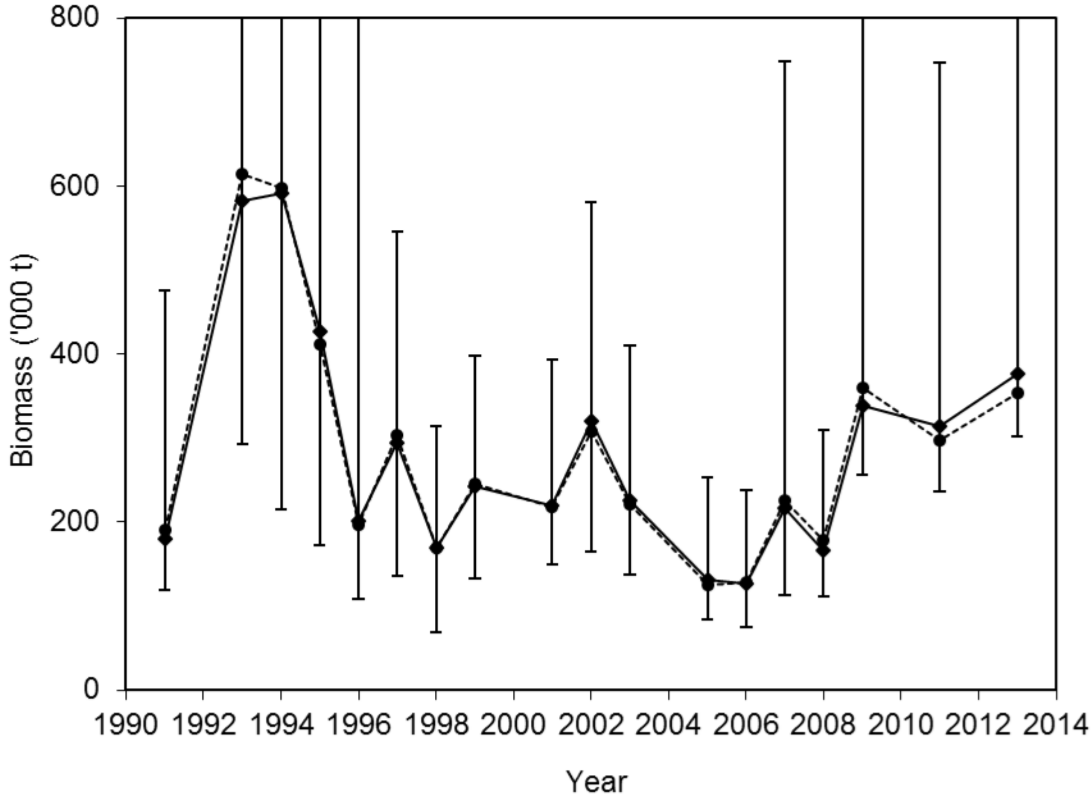

Figure 18: Relative time series of acoustic abundance estimates for spawning hoki in Cook Strait. Diamonds (with 95% confidence intervals based on Monte Carlo estimates of uncertainty) connected by solid line show indices calculated using annual estimates of the ratio of hoki weight to acoustic target strength (*r*) from commercial length frequency data. Circles connected by dashed line show indices calculated using a constant *r*.

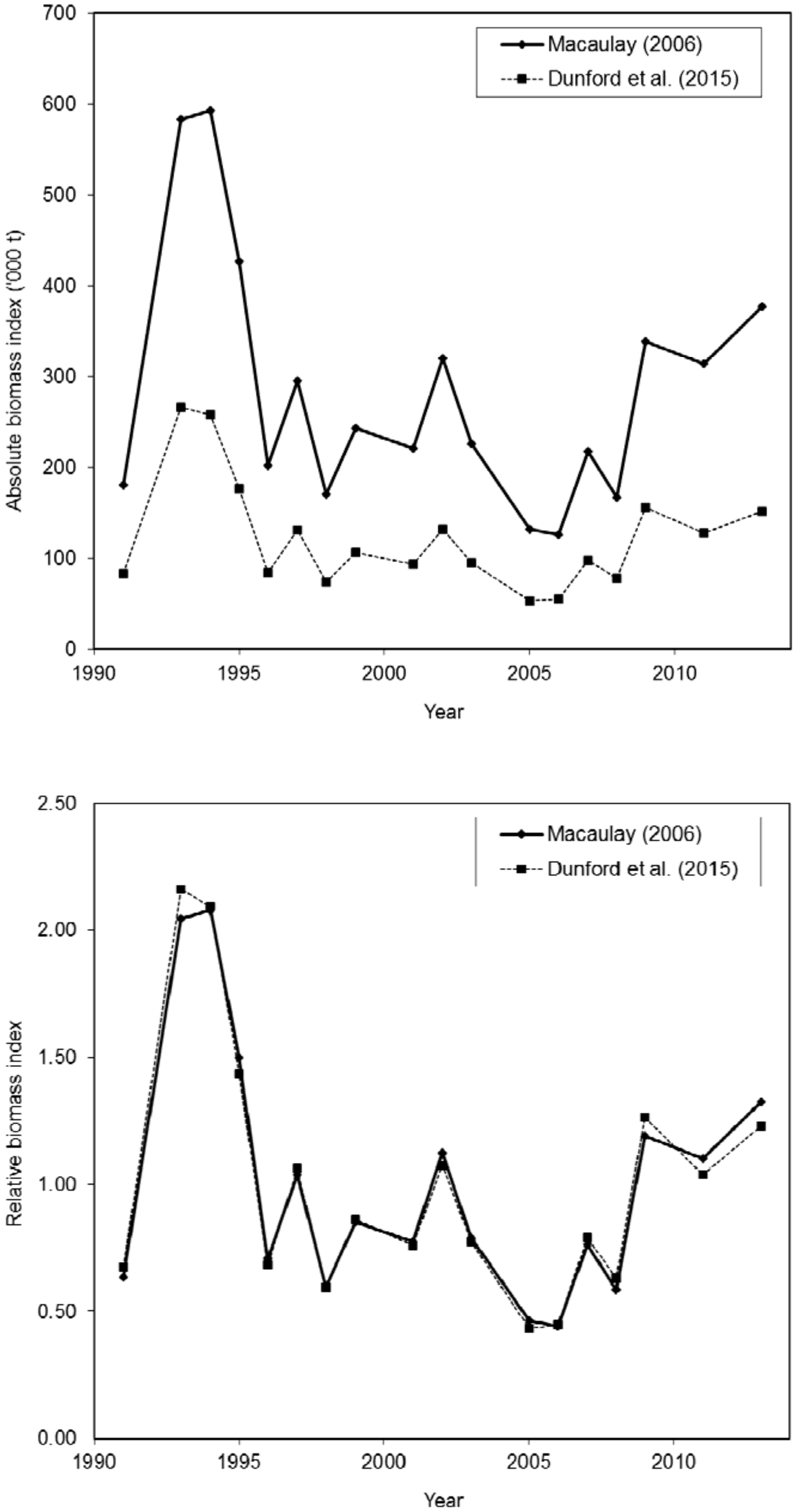

Figure 19: Comparison of absolute (upper panel) and relative (lower panel) time series of acoustic abundance estimates for spawning hoki in Cook Strait estimated with the TS-length relationship of Macaulay (2006) and the TS-length relationship derived from AOS data (Dunford et al. 2015).

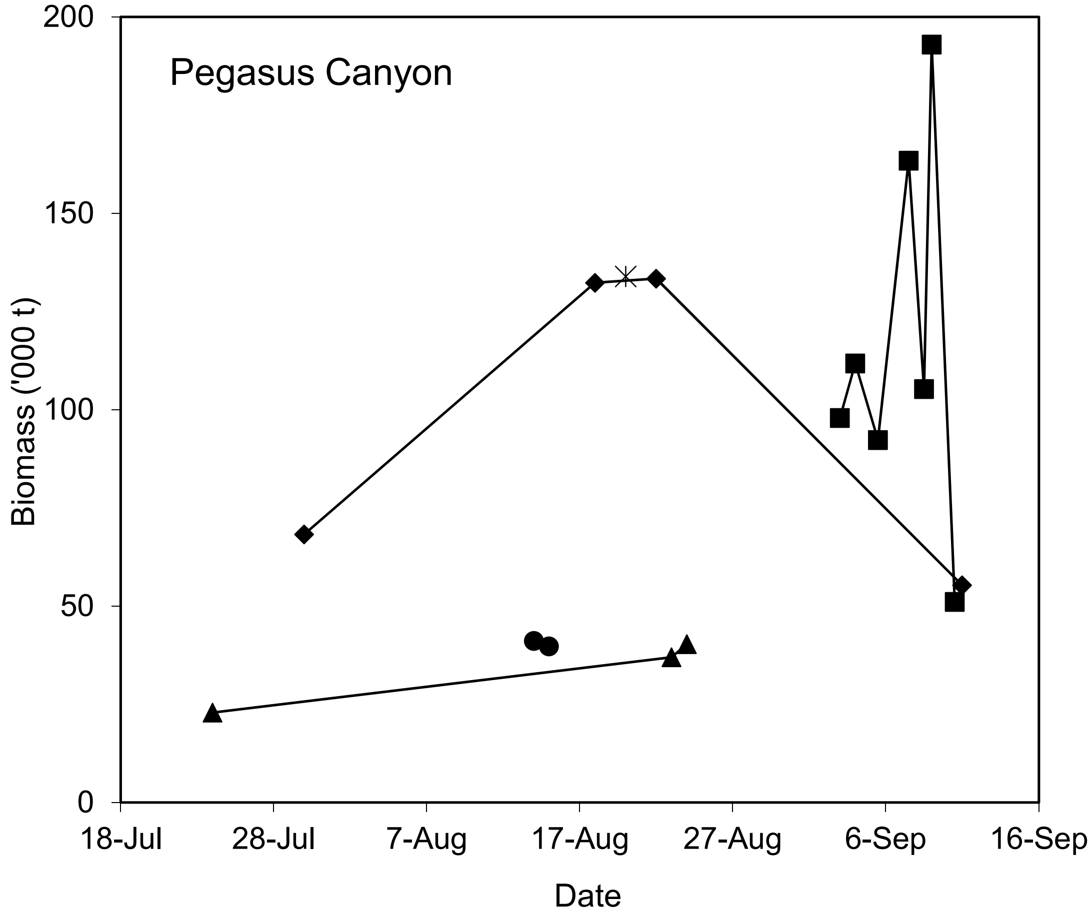

Figure 20: Estimated hoki abundance by snapshot in Pegasus Canyon from 2002–13. Results from the single snapshot in 2013 (asterix) compared to abundance estimates from previous ECSI surveys in 2002 (squares), 2003 (diamonds), and 2006 (triangles), and 2008 (circles).

APPENDIX 1: Calibration Report *Aukaha*

Calibration of the Simrad ES70 echosounder on FV *Aukaha* took place in Tasman Bay (41° 07.53' S 173° 08.02' E) on 27 June 2013. Water depth was about 27 m (below the transducer). This vessel was formerly known as *Independent 1*, and this was the fifth time that the echosounder on this vessel has been calibrated by NIWA, with the most recent calibration on 25 July 2011. The many calibrations carried out on *Independent 1* as part of the Oman fisheries survey were with an EK60 connected to the transducer and are not directly comparable to the ES60/ES70 calibrations. The calibration was conducted broadly as per the procedures in MacLennan & Simmonds (1992).

Richard O'Driscoll was picked up from the Sealord Rescue Centre in Nelson by the vessel's MOB boat at 11:00 NZST and was onboard *Aukaha* by 11:20. The vessel then steamed out into deeper water in Tasman Bay. The ES70 was configured to recommended settings (2000 W power and 1.024 ms pulse) and the time of the ES70 was adjusted to the GPS. A keyboard was available (installed on the wall under the bridge console).

The calibration started at 12:45 NZST. A weighted line was passed under the keel to facilitate setting up the three lines and calibration sphere. The sphere and associated lines were immersed in a soap solution prior to entering the water. A lead weight was also deployed about 3 m below the sphere to steady the arrangement of lines. There is something on the keel immediately aft of the transducer and this fouled the weighted line on the first attempt. The three lines were set up successfully on the second attempt, but (as in 2011) the port aft line became entangled. However it was still possible to manipulate the sphere in the beam between the port forward and starboard lines.

The weather was good with a 5–10 knot southwest wind, no swell, and slight seas. The propeller was not de-clutched because the engineers were reluctant to do this, and the vessel moved in reverse at 0.5 knots when at 0% pitch, so a slight forward pitch was applied. The vessel was allowed to drift, and the drift speed was about 0.6 knots. The sphere was first observed in the beam at 13:20 and was centred to obtain data for the on-axis calibration at 13:38. After on-axis data were collected, the sphere was then moved around the beam to obtain data for the beam shape calibration. Calibration data were recorded into a single ES70 raw format file (Aukaha-D20130627-T011839.raw). Raw data are stored in the NIWA Fisheries Acoustics Database. The ES70 transceiver settings in effect during the calibration are given in Table A1.1.

Water temperature measurements were taken using an RBR-2050 temperature depth probe, serial number 11817. The water column was stratified, with a temperature of 11.9º at the surface, increasing to 13.2º at the depth of the sphere (22 m). The salinity was not measured and was assumed to be 35 PSU. An estimate of acoustic absorption was calculated using the formulae in Doonan et al. (2003) and an estimate of sound speed was calculated using the formulae of Fofonoff & Millard (1983).

The calibration was completed at 14:15 NZST. The vessel steamed towards Nelson and the MOB boat took Richard O'Driscoll ashore to the Sealord Rescue Centre at 15:45.

The data in the ES70 file were extracted using custom-written Matlab software. The amplitude of the sphere echoes was obtained by filtering on range, and choosing the sample with the highest amplitude. Instances where the sphere echo was disturbed by fish echoes were discarded. The alongship and athwartship beam widths and offsets were calculated by fitting the sphere echo amplitudes to the Simrad theoretical beam pattern:

$$compensation = 6.0206\left(\left(\frac{2\theta_{fa}}{BW_{fa}}\right)^2 + \left(\frac{2\theta_{ps}}{BW_{ps}}\right)^2 - 0.18\left(\frac{2\theta_{fa}}{BW_{fa}}\right)^2\left(\frac{2\theta_{ps}}{BW_{ps}}\right)^2\right),$$

where θ_{ps} is the port/starboard echo angle, θ_{fa} the fore/aft echo angle, BW_{ps} the port/starboard beamwidth, BW_{fa} the fore/aft beamwidth, and *compensation* the value, in dB, to add to an uncompensated echo to yield the compensated echo value. The fitting was done using an unconstrained nonlinear optimisation (as implemented by the Matlab fminsearch function).

The Sa correction was calculated from:

$$S_{a,corr} = 5\log_{10}\left(\frac{\sum P_i}{4P_{\max}}\right),$$

where P_i is the sphere echo power measurement and P_{max} the maximum sphere echo power measurement. A value for $S_{a,corr}$ is calculated for all valid sphere echoes and the mean over all sphere echoes is used to determine the final $S_{a,corr}$.

A correction for the triangle wave error in ES60/ES70 data (Ryan & Kloser 2004) was also applied as part of the analysis.

Results

The mean range of the sphere and the sound speed and acoustic absorption between the transducer (about 6 m deep) and the sphere are given in Table A1.2.

The calibration results are given in Table A1.3. The estimated beam pattern and sphere coverage are given in Figure A1.1. The symmetrical nature of the pattern and the zero centre of the beam pattern indicate that the transducer and ES70 transceiver were operating correctly. The fits between the theoretical beam pattern and the sphere echoes is shown in Figure A1.2 and confirms that the transducer beam pattern is correct. The root mean square (RMS) of the difference between the Simrad beam model and the sphere echoes out to 3.6° off axis was 0.21 dB (Table A1.3), indicating that the calibration was of good quality (<0.4 dB is poor, <0.3 dB good, and <0.2 dB excellent).

Calibration coefficients in 2013 were similar to those obtained in the four previous calibrations (Table A1.3), indicating consistent system performance. The estimated peak gain (G_0) in 2013 was 0.11 dB higher than that estimated in 2011 and 0.08 dB higher than that in 2009 (Table A1.3). The Sa corrections estimated from the three most recent calibrations were all within 0.05 dB (Table A1.3).

Table A1.1. ES60 transceiver settings and other relevant parameters during the calibration of *Aukaka*.

Parameter	Value
Echosounder	ES70
ES70 software version	1.1.0.0
Transducer model	ES38B
Transducer serial number	Not recorded
GPT serial number	GPT 38 kHz 009072033fc2 1 ES38B
GPT software version	040120
Sphere type/size	tungsten carbide/38.1 mm diameter
Operating frequency (kHz)	38
Transducer draft setting (m)	0.0
Transmit power (W)	2000
Pulse length (ms)	1.024
Transducer peak gain (dB)	26.5
Sa correction (dB)	0.0
Bandwidth (Hz)	2425
Sample interval (m)	0.192
Two-way beam angle (dB)	–20.60
Absorption coefficient (dB/km)	9.75
Speed of sound (m/s)	1500
Angle sensitivity (dB) alongship/athwartship	21.90/21.90
3 dB beamwidth (º) alongship/athwartship	7.10/7.10
Angle offset (º) alongship/athwartship	0.0/0.0

Table A1.2. Auxiliary calibration parameters derived from depth/temperature measurements.

Parameter	Value
Mean sphere range (m)	16.4
S.D. of sphere range (m)	1.5
Mean sound speed (m/s)	1 499
Mean absorption (dB/km)	9.20
Sphere TS (dB re $1m^2$)	–42.41

Table A1.3: Calculated echosounder calibration parameters for *Independent 1/Aukaha*. Values from 2009 and 2011 differed slightly from those reported by O'Driscoll (2012), because the latest version of the Matlab calibration code (7045) was used. Transducer peak gain estimated from mean sphere TS was used for estimating abundance.

Parameter	2013	2011	2009	2003	2002
Mean TS within 0.21° of centre	-44.87	-45.10	-45.02	-	-
Std dev of TS within 0.21° of centre	0.35	0.35	0.36	-	-
Max TS within 0.21° of centre	-44.31	-44.64	-44.55	-	-
No. of echoes within 0.21° of centre	112	73	33	-	-
On axis TS from beam-fitting	-44.61	-44.86	-44.82	-	-
Transducer peak gain from mean (dB)	25.27	25.16	25.19		
Transducer peak gain from max (dB)	25.55	25.39	25.43	25.43	25.17
Sa correction (dB)	-0.71	-0.72	-0.66	–0.78	–0.68
Beamwidth (º) alongship/athwarthship	6.86/6.67	6.95/7.01	7.30/7.24	7.1/6.9	7.0/7.0
Beam offset (º) alongship/athwarthship	0.00/0.00	0.02/0.17	-0.00/0.00	0.0/0.1	0.0/0.2
RMS deviation	0.21	0.14	0.16	0.27	0.39
Echoes used to estimate the beam shape	12 076	11 558	25 146	333	143

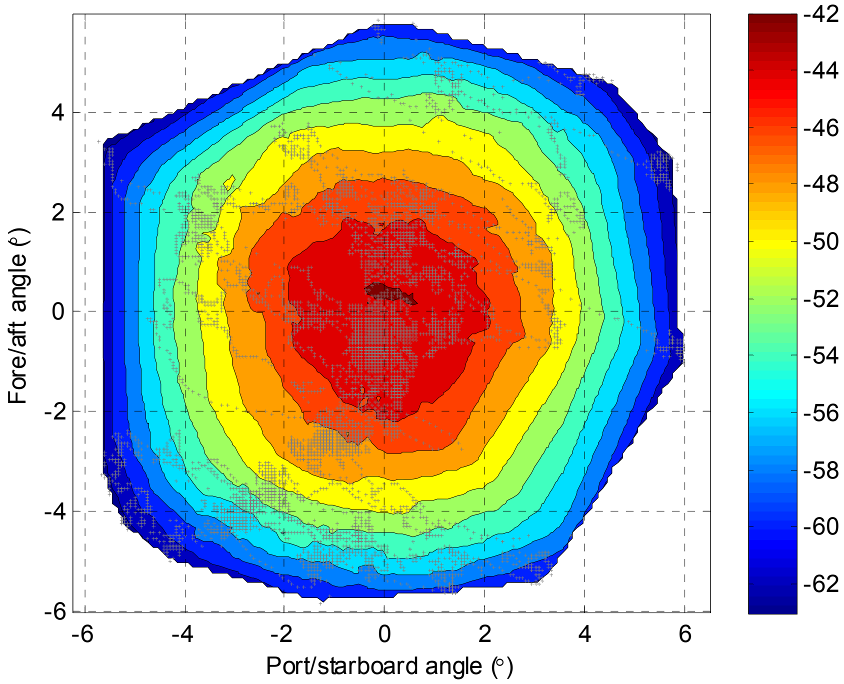

Figure A1.1. The estimated beam pattern from the sphere echo strength and position for the calibration of *Independent 1*. The '+' symbols indicate where sphere echoes were received. The colours indicate the received sphere echo strength in dB re 1 m^2.

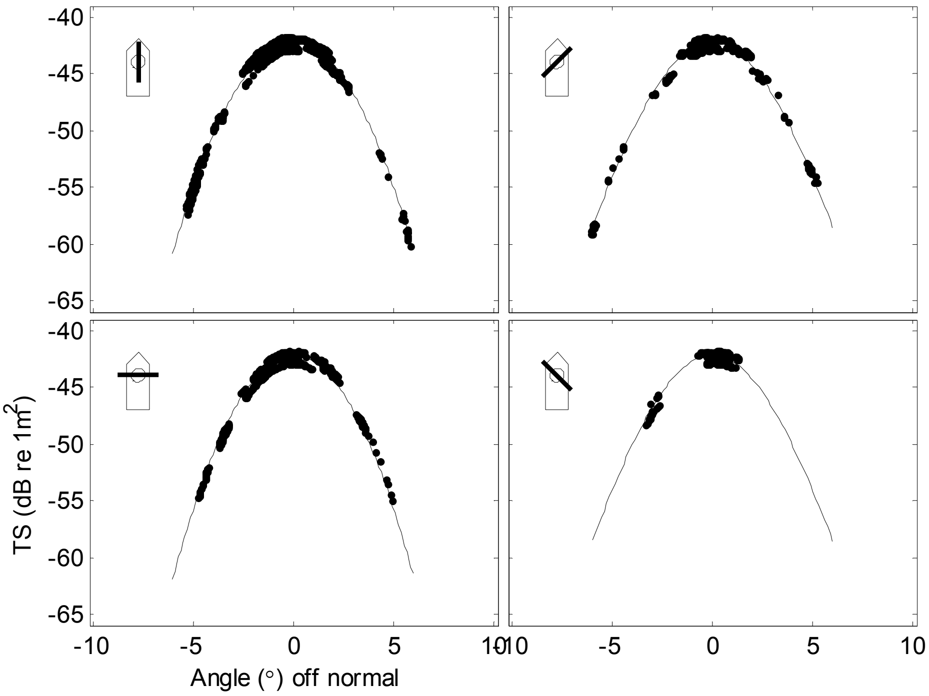

Figure A1.2. Beam pattern results from the calibration analysis for *Aukaha*. The solid line is the theoretical beam pattern fit to the sphere echoes for four slices through the beam.

APPENDIX 2: Calibration Report *Thomas Harrison*

Calibration of the Simrad ES70 echosounder on *Thomas Harrison* was carried out by Yoann Ladroit (NIWA) on 15 November 2013. This was the eleventh time that the Simrad echosounder on this vessel has been calibrated since 2005, but the first four calibrations were with an older transducer (that failed in 2008). A new ES70 computer and software were installed on *Thomas Harrison* in December 2010 and connected to the same 38-kHz GPT and transducer as the ES60 used previously. Because the ES60 and ES70 use the same hardware, the calibrations with the two software systems are identical within the measurement uncertainty. A previous calibration of this echosounder was carried out by NIWA on 27 March 2013, but one of the circuit boards in the transceiver (GPT) was replaced by CSIRO in June 2013, which may have affected system performance. All calibrations were conducted broadly as per the procedures in MacLennan & Simmonds (1992).

The calibration took place in Tasman Bay (41°04.93’ S 173°15.67’E) in about 30 m of water. The vessel left Nelson at 9:30 NZDT and was on calibration site at 11:00 NZDT. A weighted line was passed under the keel to facilitate setting up the three lines and calibration sphere. The transducer on *Thomas Harrison* is located near the bow, and a 5-m long pole was used to place one of the lines forward of the transducer position. The sphere and associated lines were immersed in a soap solution prior to entering the water. A lead weight was also deployed about 2 m below the sphere to steady the arrangement of lines. The sphere was centred in the beam to obtain data for the on-axis calibration, and was then moved around the beam to obtain data for the beam shape calibration.

The weather during the calibration was excellent – the wind was variable 5 knots, with very little swell. The operation was first attempted without unclutching the shaft and with only zero pitch, with little success since the vessel still went forward at about 1.5 knots. Once unclutched, the vessel was allowed to drift and drift speed was about 0.4 knots. The sphere was first located in the beam at 11:20 NZDT, and the recording was stopped at 12:28 NZDT. Calibration data were recorded into a single ES70 raw format file (thh_D20131114-T221354.raw). The ES70 transceiver settings in effect during the calibration are given in Table A2.1.

Water temperature measurements were taken using an RBR-2050 temperature depth probe, serial number 11817. The salinity at the calibration site was assumed to be 35 PSU. An estimate of acoustic absorption was calculated using the formulae in Doonan et al. (2003) and an estimate of sound speed was calculated using the formulae of Fofonoff & Millard (1983).

The data in the ES70 files were extracted using custom-written software. The amplitude of the sphere echoes was obtained by filtering on range, and choosing the sample with the highest amplitude. The alongship and athwartship beam widths and offsets were calculated by fitting the sphere echo amplitudes to the Simrad theoretical beam pattern:

$$compensation = 6.0206\left(\left(\frac{2\theta_{fa}}{BW_{fa}}\right)^2 + \left(\frac{2\theta_{ps}}{BW_{ps}}\right)^2 - 0.18\left(\frac{2\theta_{fa}}{BW_{fa}}\right)^2\left(\frac{2\theta_{ps}}{BW_{ps}}\right)^2\right),$$

where θ_{ps} is the port/starboard echo angle, θ_{fa} the fore/aft echo angle, BW_{ps} the port/starboard beamwidth, BW_{fa} the fore/aft beamwidth, and *compensation* the value, in dB, to add to an uncompensated echo to yield the compensated echo value. The fitting was done using an unconstrained nonlinear optimisation (as implemented by the Matlab fminsearch function). The Sa correction was calculated from:

$$S_{a,corr} = 5\log_{10}\left(\frac{\sum P_i}{4P_{\max}}\right),$$

where P_i is the sphere echo power measurement and P_{max} the maximum sphere echo power measurement. A value for $S_{a,corr}$ is calculated for all valid sphere echoes and the mean over all sphere echoes is used to determine the final $S_{a,corr}$.

A correction for the triangle wave error in ES60 data (Ryan & Kloser 2004) was also applied as part of the analysis.

Results

The mean range of the sphere and the sound speed and acoustic absorption between the transducer (about 6 m deep) and the sphere are given in Table A2.2.

The calibration results are given in Table A2.3 along with the results from previous NIWA calibrations. The symmetrical nature of the estimated beam pattern (Figure A2.1) centred on zero indicates that the transducer and ES70 transceiver were operating correctly. The fits between the theoretical beam pattern and the sphere echoes (Figure A2.2) also confirms that the transducer beam pattern is correct. The RMS of the difference between the Simrad beam model and the sphere echoes out to 3.5° off axis was 0.09 dB (Table A2.3), indicating that this calibration was of excellent quality (<0.4 dB is poor, <0.3 dB good, and <0.2 dB excellent).

There has been a trend of declining G_0 for this transducer and GPT since the new transducer was installed in 2008 (see Figure A2.3). Other long-term time series of echosounder calibrations also observed gradual declines in peak gain, possibly as a function of transducer ageing (Knudsen 2009).

Two calibrations of the echosounder on *Thomas Harrison* were carried out by Fisheries Resource Surveys (FRS) as part of the 2013 survey of Challenger orange roughy on 27 June and 14 July. Calibration parameters estimated from the Simrad Lobe calibration software were provided to NIWA by Mike Soule (FRS). Both calibrations gave G_0 and Sa values within 0.05 dB of those estimated from the NIWA calibration in November 2013.

Table A2.1. ES70 transceiver settings and other relevant parameters during the calibration of *Thomas Harrison*.

Parameter	Value
Echosounder	ES70
ES70 software version	1.0.0
Transducer model	ES38B
Transducer serial number	n/a
ES70 GPT serial number	GPT-Q38(4) 1.0 0090720179e5
GPT software version	040120
Sphere type/size	tungsten carbide/38.1 mm diameter
Operating frequency (kHz)	38
Transducer draft setting (m)	0.0
Transmit power (W)	2000
Pulse length (ms)	1.024
Transducer peak gain (dB)	26.5
Sa correction (dB)	0.0
Bandwidth (Hz)	2425
Sample interval (m)	0.192
Two-way beam angle (dB)	–20.60
Absorption coefficient (dB km^{-1})	9.7
Speed of sound (m s^{-1})	1500
Angle sensitivity (dB) alongship/athwartship	21.90/21.90
3 dB beamwidth (º) alongship/athwartship	7.10/7.10
Angle offset (º) alongship/athwartship	0.0/0.0

Table A2.2. Auxiliary calibration parameters derived from depth/temperature measurements.

Parameter	
Mean sphere range (m)	16.9
S.D. of sphere range (m)	3.4
Mean sound speed (m s^{-1})	1514
Mean absorption (dB km^{-1})	8.32
Sphere TS (dB re $1m^2$)	–42.41

Table A2.3: Calculated echosounder calibration parameters for *Thomas Harrison*. Calibrations prior to 2008 are not reported here as the transducer was found to be faulty during the 2008 calibration and replaced prior to the 2009 calibrations. Values from 2009 and 2011 differ slightly from those reported by O'Driscoll (2012), because the latest version of the Matlab calibration code (7045) was used. Transducer peak gain estimated from mean sphere TS was used for estimating abundance.

Parameter	15 Nov 13	27 Mar 13	15 Aug 11	24 Jun 10	7 Aug 09	25 Jun 09
Mean TS within 0.21° of centre	-47.28	-47.79	-46.52	-46.64	-45.06	-45.31
Std dev of TS within 0.21° of centre	0.12	0.22	0.35	0.24	0.11	0.31
Max TS within 0.21° of centre	-47.19	-47.12	-46.14	-46.05	-44.93	-44.45
No. of echoes within 0.21° of centre	67	277	14	176	119	2 738
On axis TS from beam-fitting	-47.33	-47.55	-46.39	-46.46	-44.81	-45.19
Transducer peak gain (dB) (mean)	24.07	23.81	24.41	24.39	25.17	25.05
Transducer peak gain (dB) (max)	24.11	24.14	24.62	24.68	25.23	25.48
Sa correction (dB)	-0.58	-0.55	-0.52	-0.59	-0.60	-0.64
Beamwidth (º) alongship/athwarthship	6.95/6.95	7.05/7.05	6.90/6.81	7.07/6.98	6.68/6.69	6.94/7.04
Beam offset (º) alongship/athwarthship	0.00/0.00	-0.01/0.01	0.00/0.00	0.00/0.00	-0.05/-0.00	0.00/0.00
RMS deviation	0.09	0.18	0.21	0.18	0.18	0.17
Number of echoes	8692	16 825	3 613	22 728	18 221	34 909

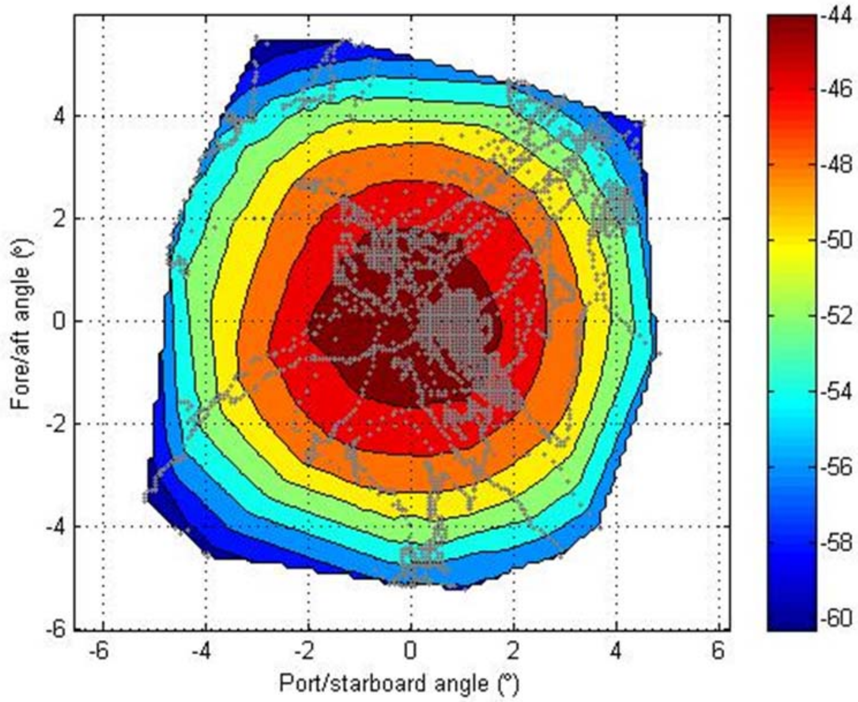

Figure A2.1. The estimated beam pattern from the sphere echo strength and position for the calibration of *Thomas Harrison*. The '+' symbols indicate where sphere echoes were received. The colours indicate the received sphere echo strength in dB re 1 m^2.

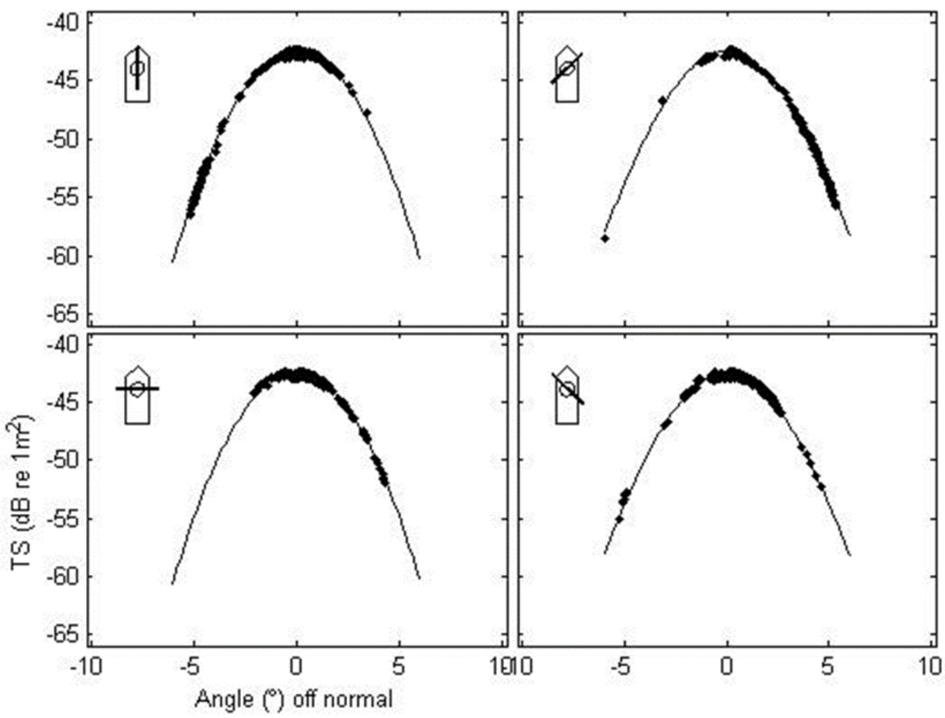

Figure A2.2. Beam pattern results from the calibration analysis for *Thomas Harrison*. The solid line is the theoretical beam pattern fit to the sphere echoes for four slices through the beam.

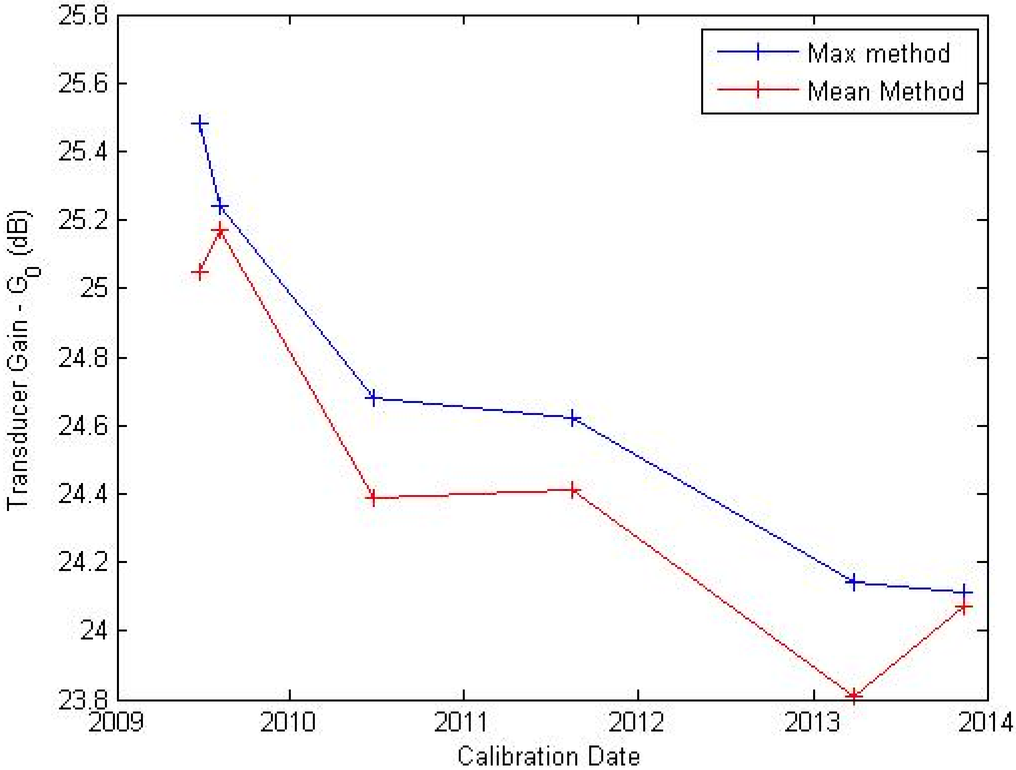

Figure A2.3: The trend in transducer gain (G_0) for the Simrad ES38B transducer installed on *Thomas Harrison*. For comparability only calibrations carried out and analysed by NIWA are shown.