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Estimating uncertainty associated with acoustic surveys of spawning hoki (*Macruronus novaezelandiae*) in Cook Strait, New Zealand

Richard L. O'Driscoll

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Eleven acoustic surveys carried out between 1991 and 2002 provided estimates of the relative abundance of spawning hoki in Cook Strait, New Zealand. The precision and bias of each survey were estimated using a new Monte Carlo simulation method, which combined uncertainties associated with survey timing, sampling error, detectability, species composition, target strength, calibration coefficients, and missing strata. Because hoki have a long spawning season (more than 2 months) with turnover of fish in the survey area, survey timing was the most important source of uncertainty. Uncertainty was reduced by having a number of sub-surveys (snapshots) over a 4–6 week period, centred on the middle date of the spawning season. The other major source of uncertainty was the occurrence of 40–70% of hoki in mixed species: "hoki fuzz" marks. The acoustic analysis assumed all acoustic backscatter from hoki marks was hoki, so the presence of other species caused a positive bias in relative-abundance indices. The magnitude of this bias differed between years because the proportion of hoki in the "fuzz" marks was variable. There was additional uncertainty from the variability in the species composition of mixed marks that affected survey precision. The abundance indices were corrected for estimated bias, and the estimate of precision, expressed as the coefficient of variation or c.v., was applied to weight the results from each acoustic survey in the assessment model used to set commercial-catch limits.

Keywords: acoustic survey, hoki, Monte Carlo, target strength.

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R. L. O'Driscoll: National Institute of Water and Atmospheric Research, Private Bag 14-901, Kilbirnie, Wellington, New Zealand; tel: +64 4 386 0300; fax: +64 4 386 0574; e-mail: r.odriscoll@niwa.co.nz.

Introduction

Hoki (*Macruronus novaezelandiae*) form New Zealand's largest fishery, with annual catches of 160 000–270 000 t since 1987 (O'Driscoll *et al.*, 2002). Two stocks of hoki are recognized based on morphometric and growth-rate differences (Livingston and Schofield, 1996). The western stock resides primarily on the Campbell Plateau, south of New Zealand, and spawns on the west coast of the South Island (Figure 1). The eastern stock's "home ground" is the Chatham Rise, with spawning occurring in Cook Strait (Figure 1). Juvenile hoki of both stocks mix together on the shallower areas of the Chatham Rise, and are believed to recruit to their respective stocks at maturity at ages of 3–8 years (Livingston *et al.*, 1997).

On the spawning grounds hoki typically form large midwater aggregations. Commercial and research fishing on these aggregations results in very clean catches of hoki, with little or no bycatch. The occurrence of single-species spawning aggregations allows biomass estimation of hoki using acoustics. Acoustic surveys have provided abundance indices for spawning hoki on the west coast of South Island and in Cook Strait since 1988 (Coombs and Cordue, 1995; O'Driscoll, 2002), and these are an important input into the stock-assessment model used to set the total allowable commercial catch (Francis *et al.*, 2003).

Hoki acoustic-survey results are used in stock assessments as relative indices of spawning biomass. This is because hoki have a long spawning season of more than 2 months and it is thought that during this period there is a turnover of fish on the spawning grounds. The survey design devised to deal with this problem consists of a number of sub-surveys or "snapshots" spread over the spawning season. Each snapshot comprises a series of

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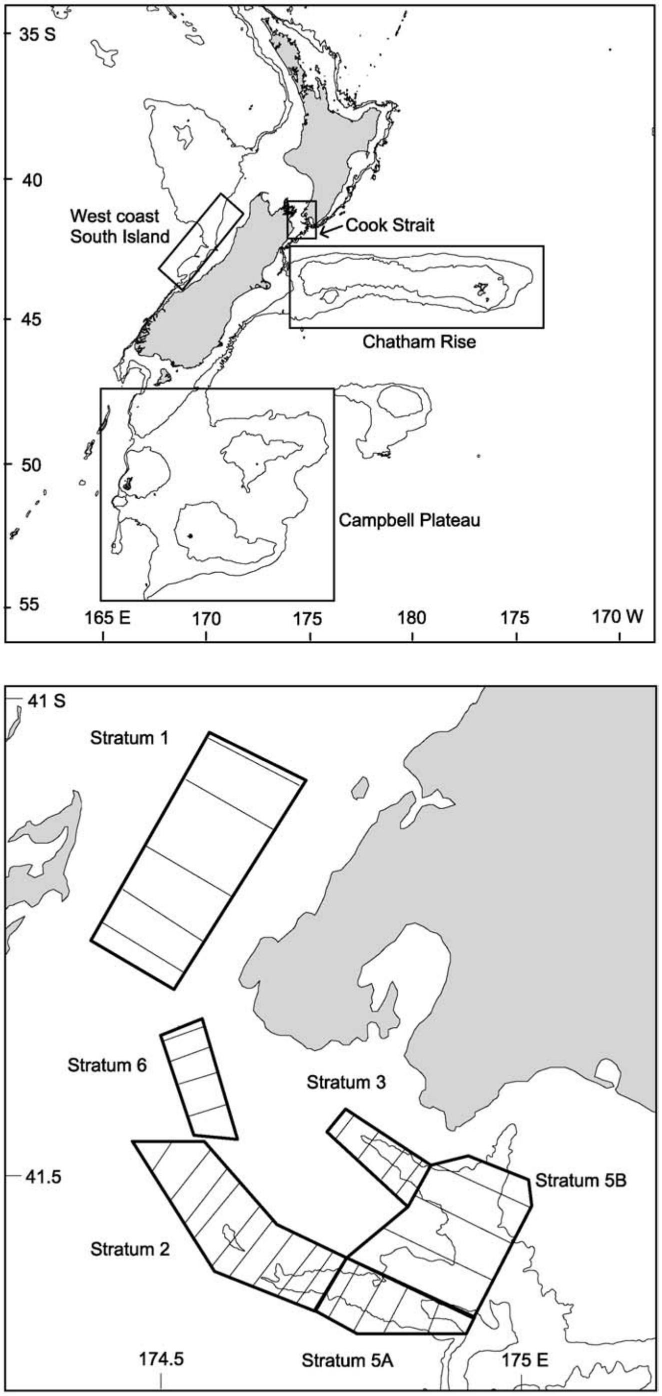

Figure 1. Map of New Zealand showing main spawning and feeding areas of hoki (upper panel), and the acoustic-survey area in Cook Strait with typical transect allocation (lower panel). Depth contours are 500 m and 1000 m.

random transects, following the design of Jolly and Hampton (1990), across strata covering the known distribution of the spawning hoki. Estimates of the spawning biomass are calculated for each of the snapshots, and these are then averaged to obtain an estimate of the "mean plateau height" i.e. the average biomass during the main spawning season. Under various assumptions about the timing and length of the spawning season (Coombs and Cordue, 1995), estimates of mean plateau height form a valid relative-abundance time-series.

An essential component of the acoustic-abundance index is the estimate of "uncertainty" associated with the results. This uncertainty is expressed as a coefficient of variation (c.v.) and used in the assessment model to weight the survey index (Francis *et al.*, 2003). The classical variance calculated from the mean transect densities (Jolly and Hampton, 1990) greatly underestimates total uncertainty because it is based solely on sampling error, and ignores the uncertainty associated with the acoustic methodology, in factors like acoustic target strength (TS), calibration, and mark identification (Rose *et al.*, 2000), and also the uncertainty in survey timing and plateau-model assumptions.

Rose *et al.* (2000) proposed a simulation-based method to estimate and diagnose the sources of uncertainty in acoustic-survey estimates of fish density. This method involves construction of probability distributions for all known sources of uncertainty. Random samples from each of the probability distributions are then selected and combined multiplicatively in Monte Carlo simulations of the process of acoustic-biomass estimation. In this paper I apply this new method to estimate uncertainty in acoustic surveys of hoki in Cook Strait (Figure 1). This application is more complex than the examples of cod (*Gadus morhua*) and redfish (*Sebastes* sp.) presented by Rose *et al.* (2000) because hoki are transient in the survey area and there is no time at which all of the fish are available to be surveyed. The estimates of survey uncertainty must, therefore, include consideration of survey timing.

Table 1. Hoki biomass estimates by stratum for Cook Strait hoki acoustic surveys. Stratum areas are shown in Figure 1. Strata 5A and 5B were combined prior to 1995. The average percentage of the estimated hoki biomass from school marks is also given.

	Biomass ('000 t)							
	1	2	3	5A	5B	6	Total	% Hoki in schools
1991	45	57	5	16		3	126	49
1992	33	37	3	16		3	93	43
1993	143	175	19	25		55	418	46
1994	110	112	13	133		52	420	30
1995	105	105	9	12	14	53	298	38
1996	22	74	7	17	3	15	138	59
1997	51	79	8	18	40	12	209	42
1998	37	35	7	9	13	13	115	37
1999	25	70	10	21	43	5	175	46
2001	15	85	7	21	25	2	155	59
2002	48	116	3	19	36	3	225	53

Methods

Hoki acoustic surveys

There were 11 acoustic surveys of hoki in Cook Strait from 1991 to 2002 (Table 1). The survey design and methods have been consistent over the time-series, but the vessels and hardware have changed, partly as a result of improvements in equipment and technology, and partly because of loss or damage. These changes were documented in a review of the acoustic time-series up to 2001 by O'Driscoll (2002).

The survey design followed the methods of Jolly and Hampton (1990) as adapted by Coombs and Cordue (1995) to obtain a biomass index for transient fish populations. Each survey comprised a number of sub-surveys (snapshots) spread over a 4–6 week period during the peak hoki spawning months of July and August (Figure 2). In each snapshot, 27–30 randomly allocated parallel transects normal to the depth contours were used to estimate the mean fish density within each of the six core strata (Figure 1). Each snapshot took 24–48 h to complete, depending on the number of mark-identification trawls carried out between transects. Acoustic transects were run day and night, as there is no evidence for systematic diurnal differences in the amount of backscatter. Biomass estimates and variances were obtained for each stratum in each snapshot using the formulae of Jolly and Hampton (1990). The stratum estimates were combined to produce snapshot estimates, and the snapshots were averaged to obtain the biomass index.

The acoustic data were collected with National Institute of Water and Atmospheric Research (NIWA) echosounder data-acquisition systems, initially FREDA (Fisheries Research Echo Data Acquisition) and more recently CREST (Computerised Research Echo Sounder Technology). These systems are based on the concept of a "software echosounder", which uses custom software to organise and edit data, and exercise overall control (Coombs, 1994). Simrad or EDO transducers with a nominal operating frequency of 38 kHz were used in all surveys. The transducers were usually deployed in a body towed at 30–50 m depth to reduce surface and vessel noise. The acoustic systems were calibrated regularly using a standard 38.1-mm tungsten-carbide sphere following the procedures of Foote *et al.* (1987). Measurements of temperature and salinity were made during the surveys with a conductivity, temperature, and depth probe (CTD). These were used to determine the appropriate sound velocity and absorption coefficient for each survey.

The acoustic data were processed using custom echosounding package (ESP) software (Cordue, 1990), and its successor ESP2 (McNeill, 2001). This software was used for plotting, checking, editing, bottom tracking, mark classification, echo integration, and the calculation of acoustic densities. The typical analysis routine involved an initial viewing of the file on screen and then editing-out any noise or bad data using a "bad transmit" function, which forces the analysis to ignore the selected bad pings. An automatic bottom-tracking algorithm was then run, which identifies the depth of the bottom in each ping. The

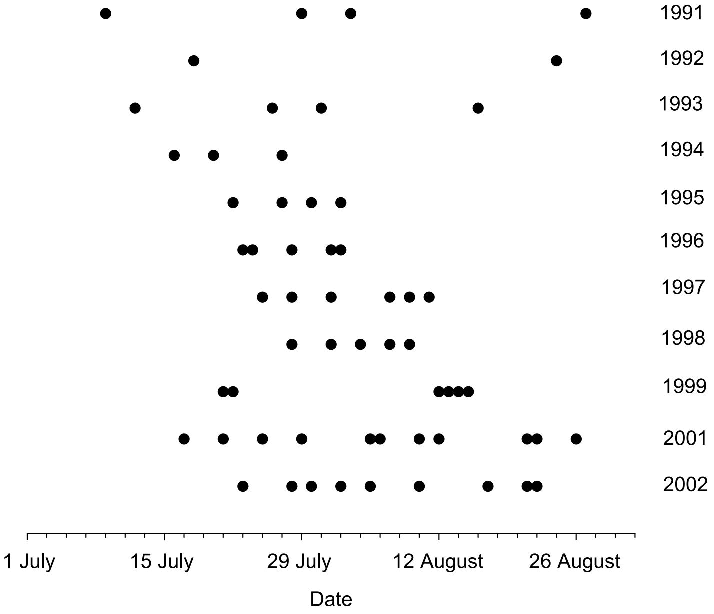

Figure 2. The timing of acoustic surveys for hoki in Cook Strait from 1991 to 2002. Circles show the median date of each snapshot.

operator viewed the results and manually edited the detected bottom if, for example, there were weak side-lobe echoes that were missed by the algorithm, or if the "automatic-bottom" cut through a dense school of fish. Regions corresponding to hoki marks were then defined.

Two main categories of hoki mark were recognised based on their appearance on the echogram (shape, structure, depth, strength, etc.), and using information from mark-identification trawls carried out during the survey with a hoki midwater trawl (O'Driscoll, 2002). Hoki "schools" were dense marks with clearly defined boundaries, usually occurring in 200−700-m depth, and often in midwater over canyon features (Figure 3). Hoki "fuzz" marks were lower density layers, either close to the bottom or in midwater (Figure 3). Acoustic backscatter from regions corresponding to hoki schools, and hoki fuzz were integrated to obtain acoustic-density estimates, and the results scaled by the appropriate calibration coefficients, sound speed and absorption, and beam-pattern corrections to give estimates of acoustic density. The estimates of acoustic density were then scaled by stratum area and hoki target strength to calculate biomass.

Although midwater trawls caught a proportion of other species (Figure 4), all backscatter from hoki school and hoki fuzz marks was assumed to be from hoki. No species decomposition of acoustic backscatter was attempted because there was insufficient trawl sampling in the early surveys. Biomass estimates were determined separately for each mark type in each snapshot, and this was used to quantify the uncertainty in abundance indices due to the species mix (see below). On average, across all snapshots in all years, 51% of the estimated hoki biomass came from hoki schools and 49% from hoki fuzz (Table 1).

Quantifying uncertainty

I define "uncertainty" as variability that potentially affects the relative values of acoustic indices. This includes precision (the variability of repeated estimates, without reference to the true value) and bias (the systematic deviation of estimates from the true value), if the magnitude of bias can change between years. Bias which affects all annual indices in the same manner (e.g., the intercept of the TS−length relationship for hoki) is not included as part of the uncertainty because it will not affect the relative values.

Sources of uncertainty in hoki acoustic surveys include: survey timing and duration relative to the hoki spawning season, sampling error, species mix, detectability, hoki target strength, acoustic calibration, and missing strata. Probability distributions for each of these sources of uncertainty were constructed based on the best-available data and are summarized in Table 2. Details of how these distributions were derived are given below.

Survey timing

The number and timing of the snapshots varied considerably between surveys (see Figure 2). To assess the uncertainty associated with survey timing it is necessary to construct a model of changes in the actual hoki biomass in the survey area over the spawning season first. The survey design is based on a plateau-height model (Coombs and Cordue, 1995), which describes the build-up and decline of biomass

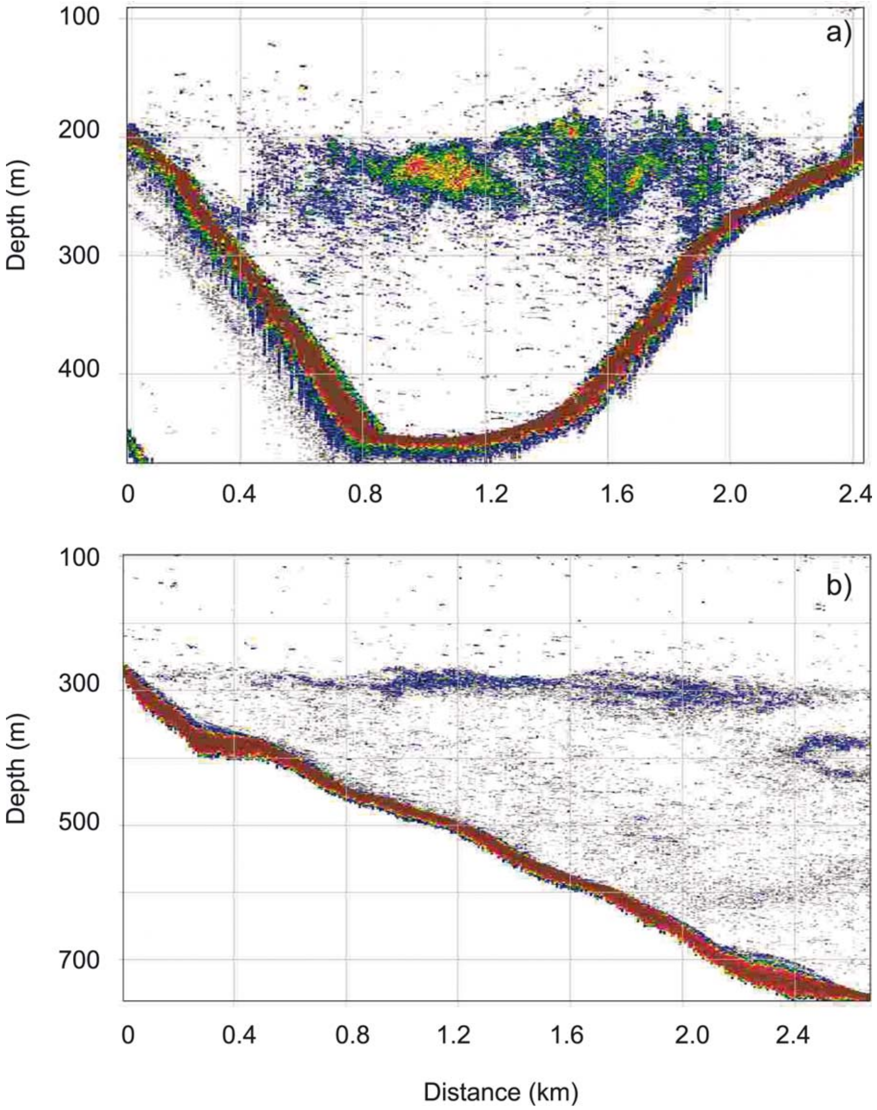

Figure 3. Acoustic echograms showing (a) hoki schools and (b) hoki fuzz, in Cook Strait during winter 2001.

in the spawning area for a transient fish population. The biomass B_t of fish in the spawning area at time t is defined as:

$$B_t = \sum_{i=1}^{n} w_i I_i(t) \tag{1}$$

where the population has n fish, w_i is the weight of the i-th fish and $I_i(t)$ is an indicator function which equals zero if the i-th fish is not in the area at time t and one if the i-th fish is in the area at time t. Fish i is in the spawning area for the period d_i to $d_i + r_i$, where d_i is the individual arrival date and r_i is the individual residence time.

Although Equation (1) is an individual-based model, the hoki population is made up of many millions of fish and it is not practical to simulate each individual. For speed of computation, the simulated population was assumed to comprise 100 "super-individuals", so that i in Equation (1) refers to a super-individual rather than a fish, and n equals 100. Each super-individual was 1% of the total population biomass (that is, w_i of each super-individual was constant) and all fish making up a super-individual had the same arrival date and residence time.

The plateau-height model is effectively described by two parameters. Mean arrival date ($\bar{d}$) determines the timing of the plateau, and mean residence time ($\bar{r}$) determines the shape of the build-up and decline of biomass during the spawning season (Figure 5). Estimates of $\bar{d}$ and $\bar{r}$ were given by Harley (2002), who modelled the spawning dynamics of hoki in Cook Strait from 1993 to 1999, based on the sex and gonad-stage composition of the commercial catch, commercial landings, and the acoustic-abundance estimates. Estimates of mean arrival time in Cook Strait

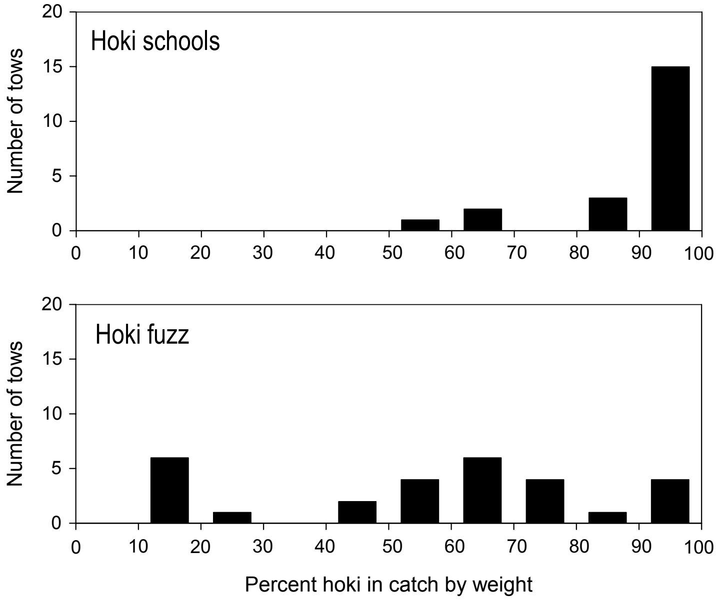

Figure 4. Catch composition in midwater trawls for mark identification targeted on hoki school and hoki fuzz mark types in 2001 and 2002.

varied from 1 July to 9 August, with a residence time of 24—47 days (Harley, 2002).

In each simulation $\bar{d}$ and $\bar{r}$ were chosen randomly from uniform distributions within the estimated ranges (Table 2). I assumed that the arrival date (d_i) and residence time (r_i) of each super-individual on the spawning ground had normal distributions centred on the simulated mean values, with constant standard deviations, also derived from estimates by Harley (2002).

Sampling error

Classical sample variance was assessed for each snapshot using the formulae of Jolly and Hampton (1990). The snapshot coefficient of variations ranged between 12 and 62%. I assumed the sampling uncertainty was normally distributed with a standard deviation equal to the measured snapshot c.v.

Detectability

A proportion of hoki in the survey area will not be detected by acoustics because they occur close to the bottom within the acoustic deadzone (Ona and Mitson, 1996). This effect is worse in areas with steep bottom slopes. No deadzone correction is currently made for Cook Strait hoki because acoustic estimates are used as relative indices, and the distribution of fish is such that the estimated deadzone bias is relatively small. However, the variability of the

Table 2. Values of parameters and their distributions used in Monte Carlo uncertainty simulations. 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).

Term	Notation	Distribution	Values	Source
Mean arrival date	$\bar{d}$	Uniform	1 July—9 August	Harley (2002)
Mean residence time	$\bar{r}$	Uniform	24—47 days	Harley (2002)
Individual arrival date	d_i	Normal	$\bar{d}$ (5 days)	Harley (2002)
Individual residence time	r_i	Normal	$\bar{r}$ (10 days)	Harley (2002)
Sampling	s	Normal	1.0 (snapshot c.v.)	Individual surveys
Detectability	D	Uniform	0.85—0.97	This paper
Species mix: fuzz	id_{mix}	Lognormal	0.78 (0.72)	Figure 4
Species mix: schools	id_{hoki}	Lognormal	0.10 (0.16)	Figure 4
Calibration (1991—1999)	cal_{91-99}	Uniform	cal ± 0.5 dB	O'Driscoll (2002)
Calibration (2000—2001)	cal_{00-02}	Uniform	cal ± 0.2 dB	O'Driscoll (2002)
Target strength	TS	Uniform	TS ± 0.5 dB	O'Driscoll (2002)
Proportion biomass, Stratum 6 (1991 only)	$P_{biomass}$	Uniform	0.01—0.18	Table 1
Proportion biomass, Stratum 5 (1992 only)	$P_{biomass}$	Uniform	0.12—0.30	Table 1

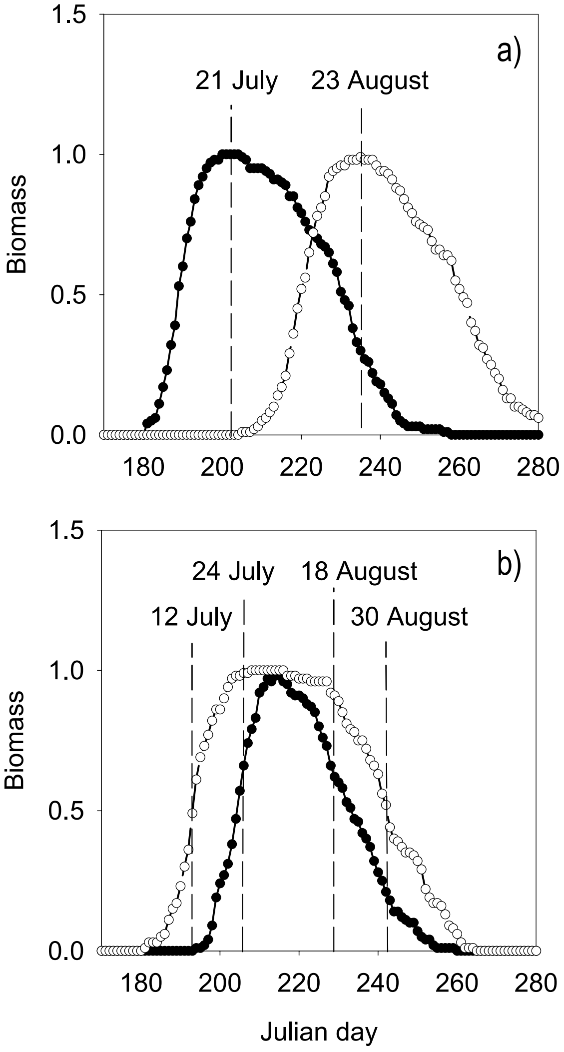

Figure 5. Simulated models of build-up and decline of hoki biomass on the Cook Strait spawning grounds showing the effect of varying (a) mean arrival date and (b) mean residence time parameters. In (a) mean arrival date was set at 9 July (solid symbols) and 9 August (hollow symbols) with a mean residence time of 40 days. In (b) mean arrival date was 20 July with mean residence time of 30 days (solid symbols) and 50 days (hollow symbols).

proportion of fish in the deadzone will contribute to the uncertainty of the abundance estimate.

The average height of the deadzone in the Cook Strait survey area, calculated using the method of R. Barr (NIWA, Wellington, unpublished report), was 2.6 m. I assumed that the density of the hoki in the deadzone was equal to the observed densities in the zone 0−2 m above the detected bottom, and calculated the appropriate correction factors (following Ona and Mitson, 1996) for all snapshots in the 2002 survey. The detectability for each snapshot, equal to one divided by the correction factor, ranged between 0.85 and 0.97. Because deadzone correction factors were not available for other surveys, I assumed that the variability in vertical distribution of hoki between snapshots in 2002 was representative of the overall variability in all surveys and modelled the uncertainty associated with detectability as a uniform distribution with bounds equal the observed range (Table 2).

Species mix

Uncertainties associated with the species mix were estimated from the catch composition of midwater trawls carried out for mark identification during the 2001 and 2002 surveys (see Figure 4). Trawls targeted at hoki schools caught 59−100% hoki by weight (number of trawls, n = 21). Tows on hoki fuzz marks caught 10−98% hoki (n = 28). Hoki biomass estimates from Cook Strait will be biased upwards because it is assumed that all backscatter from hoki schools and hoki fuzz is hoki. The magnitude of the bias is proportional to one divided by the acoustic proportion of hoki in the mark (P(hoki)).

The acoustic backscatter contributed by each species j caught in the trawl is the product of its catch weight in kg (c_j), its mean acoustic-backscatter cross-section per kg (σ_j, where target strength in dB $\text{kg}^{-1} = 10 \log \sigma$), and its relative vulnerability to the trawl and acoustic gear (v_j). Therefore:

$$P(\text{hoki}) = \frac{c_{\text{hoki}}\sigma_{\text{hoki}}v_{\text{hoki}}}{\sum_{j=1}^{N} c_j \sigma_j v_j} \qquad (2)$$

where N is the number of species caught in the trawl. Because the target strength (TS) of many bycatch species is poorly understood and there is considerable uncertainty associated with the relative catchabilities of different species in the trawl (O'Driscoll, 2003), I assumed that the acoustic proportion of hoki was equal to the proportion of hoki by weight in the catch:

$$P(\text{hoki}) \approx \frac{c_{\text{hoki}}}{\sum_{j=1}^{N} c_j} \qquad (3)$$

that is, $\sigma_j v_j \approx \sigma_{\text{hoki}} v_{\text{hoki}}$. This is a reasonable assumption because the TS per kg of hoki (which have a swimbladder) is intermediate between best estimates of TS for associated species (hoki ≈ −41 dB kg^{-1}; other common species such as ling, *Genypterus blacodes*, jack mackerel, *Trachurus* spp., and spiny dogfish, *Squalus acanthias* ≈ −35 to −45 dB kg^{-1}). O'Driscoll (2003) also found that the acoustic:trawl vulnerability ratio (v) for hoki in a bottom trawl was near the median of the range for other species caught on the Chatham Rise and Campbell Plateau.

Separate uncertainty distributions were determined for school and fuzz mark types. The distributions of $1/P(\text{hoki})_t$ where $P(\text{hoki})_t$ is the proportion of hoki in trawl t (from Equation (2)) were modelled as lognormal with the parameters given in Table 2.

Target strength

Uncertainty associated with TS arose from the variation in fish size, and from differences in the slope of alternative TS−length relationships. Potential bias due to the intercept of the alternative TS−length model was ignored because it will not affect the relative values of indices. By comparing TS obtained from the alternative TS−length models of Coombs and Cordue (1995) and Macaulay (2001) over the range of fish-length distributions observed in the commercial fishery, O'Driscoll (2002) estimated an uncertainty of ±0.5 dB associated with mean TS. I modelled the TS uncertainty as a uniform distribution within these bounds, but sensitivity analyses with normal distributions indicated that the distributional assumption did not affect the results.

Calibration

Calibration uncertainty includes uncertainties associated with source level, receive sensitivity, pulse duration, and sound speed, which were treated separately by Rose *et al.* (2000). Uncertainty associated with calibration and acoustic hardware was estimated to be ±0.5 dB in 1991−1999, and ±0.2 dB in 2000−2002 (O'Driscoll, 2002). Uncertainty decreased over time with the advances in technology and calibration methods. Again, I modelled this as a uniform distribution (Table 2), but sensitivity analyses indicated that the distributional assumption did not have a major effect.

Missing strata

An additional uncertainty was included in the simulations of the 1991 and 1992 Cook Strait surveys because not all core strata were surveyed in those years: Stratum 6 was not surveyed in 1991; and Stratum 5 was not surveyed in 1992. Biomass estimates for missing strata were based on results from the surveys in adjacent years: in 1991, all snapshots used the 1992 estimate for Stratum 6; and in 1992, all snapshots used the 1991 estimate for Stratum 5. This introduces uncertainty because there was significant variation in the proportion of biomass in these strata between years (see Table 1). In surveys from 1993 to 2002 between 1 and 18% of the total survey biomass was in Stratum 6, and 12−30% in Stratum 5 (Table 1). In each simulation of the 1991 and 1992 surveys, the proportion of the biomass in the missing stratum was estimated by selecting from a uniform distribution within these observed ranges.

Sensitivity to estimated parameters

Probability distributions for the main sources of uncertainty were somewhat subjective and were often estimated from poor data. However, the range of values presented in Table 2 is probably reasonable given current understanding about the fish and the acoustic methods. To test the sensitivity of the calculated coefficient of variations to the chosen uncertainty distributions, parameter values in Table 2 were arbitrarily halved and doubled.

Combining uncertainty

A thousand Monte Carlo simulations were carried out for each acoustic survey using Matlab. Each time a biomass model was constructed by randomly selecting values of arrival date and residence time from the distributions in Table 2. This simulated population was then "sampled" at dates equivalent to the mid-dates of each snapshot (see Figure 2). The precision of sampling was determined by the snapshot c.v., and the biomass adjusted for variability in detectability. The simulated biomass estimate in each snapshot was then split, based on the observed proportion of acoustic backscatter in school and fuzz marks, and species mix uncertainties applied to each part. The estimates were then recombined and the TS and calibration uncertainties applied in turn. The same random values for TS and calibration were applied to all snapshots in each simulated "survey" because I felt these factors would be consistent within a survey. Biomass estimates from all snapshots in the simulated "survey" were averaged to produce an abundance index, and additional uncertainty applied to surveys with missing strata.

The mean of the 1000 biomass indices provides a measure of their bias relative to the known (simulated) abundance. The c.v. (the standard deviation of the 1000 biomass indices divided by their mean) assesses survey precision. The distribution of the simulated indices was also monitored after each component of uncertainty was added to assess which sources of uncertainty were the most important in each year.

Improving survey design

Survey design can be optimized under the simulated model conditions. Simulations were carried out to investigate the effects of survey timing, duration and the number of snapshots on bias and precision due to the uncertainties associated with the timing of hoki spawning (arrival date and residence time). In these simulations a sampling error (snapshot c.v.) of 25% was used for all snapshots, with 51% of the hoki biomass in schools and no missing strata.

Results

Estimated uncertainty

Figure 6 shows the probability distributions of simulated biomass as uncertainties associated with each step of the acoustic analysis are accumulated, using the 1999 survey as an example. The results from all 11 surveys are summarized in Table 3. Survey timing and species mix were the major sources of uncertainty in Cook Strait hoki surveys, reducing precision and introducing bias. Imprecision due to sampling error, detectability, calibration, and TS contributed relatively little to the overall uncertainty.

The survey design of averaging biomass estimates from a number of snapshots over the spawning season

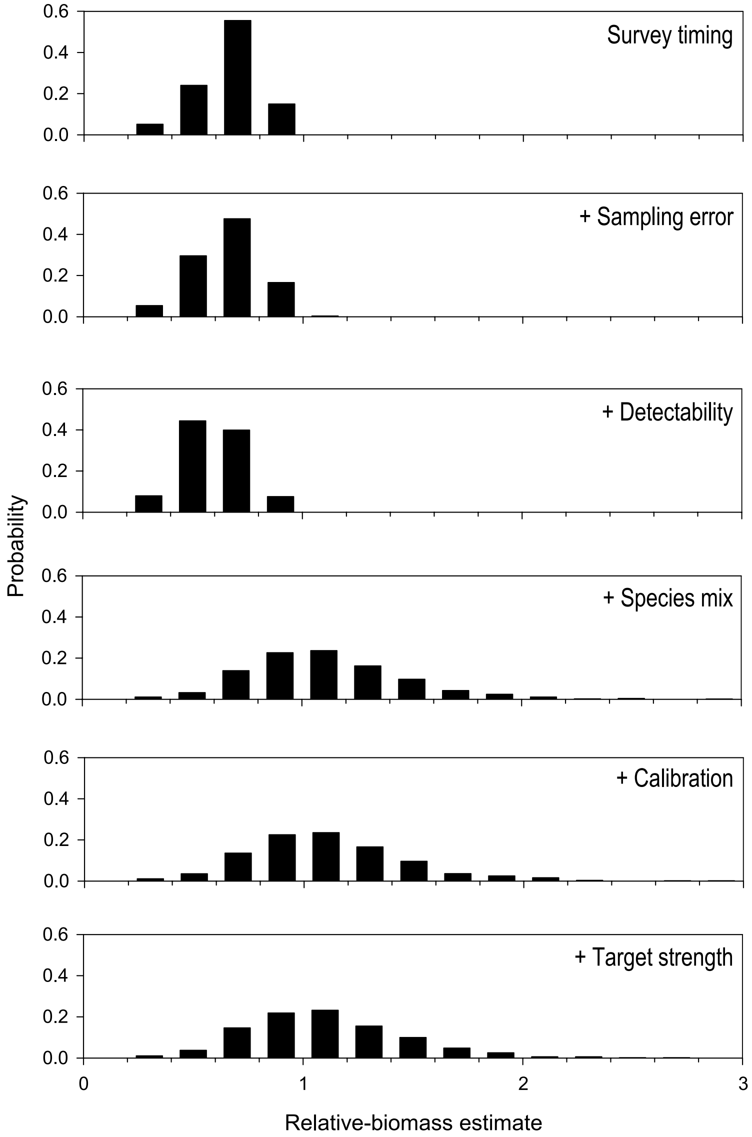

Figure 6. Probability distributions of the 1000 simulated biomass indices as each component of uncertainty was added for the 1999 Cook Strait hoki survey.

underestimates absolute-spawning hoki biomass because there is no, or only a very short, time when all fish are available to the survey (see Figure 5). The magnitude of this underestimation (negative bias) is dependent on the timing of the survey. Potential bias arising from survey timing was greatest in 1992, when the average estimate was only 47% of the simulated biomass before other sources of uncertainty were considered (Table 3). The 1992 survey had only two snapshots which were early and late in the spawning season (see Figure 2), and probably missed the period of peak abundance. Bias from survey timing was also large in 1991, when two of the four snapshots were probably outside the main spawning season, and in 1994, when all three snapshots were before the end of July (Figure 2, Table 3). Survey timing has been more consistent since 1995, with biomass estimates over the time of the surveys averaging 62—74% of the simulated population size (Table 3).

Survey timing also leads to imprecision, due to uncertainties associated with the timing of hoki spawning. The estimated c.v. from Monte Carlo simulations produced by survey timing alone ranged from 0.21 in 1999 and 2001 to 0.72 in 1994 (Table 3). Timing was particularly poor in 1994—1996 (high c.v.), when the surveys were less than 2 weeks and finished before 4 August (see Figure 2).

Uncertainty associated with species mix introduces a positive bias because the acoustic analysis assumes all

Table 3. The results of Monte Carlo simulations to determine survey uncertainty for Cook Strait acoustic surveys. The simulated relative-biomass estimate (and c.v. in parentheses) for each survey is given in a stepwise fashion to allow the contribution of each component of the overall uncertainty to be assessed. Survey timing refers to uncertainties associated with the timing of snapshots relative to the plateau-height model, and includes uncertainties associated with fish arrival date and residence time.

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2001	2002
Survey timing	0.53 (0.23)	0.47 (0.24)	0.58 (0.31)	0.51 (0.72)	0.66 (0.46)	0.64 (0.49)	0.72 (0.27)	0.74 (0.27)	0.66 (0.21)	0.62 (0.21)	0.67 (0.23)
+Sampling error	0.53 (0.26)	0.47 (0.33)	0.57 (0.35)	0.51 (0.74)	0.66 (0.51)	0.64 (0.51)	0.72 (0.29)	0.74 (0.29)	0.66 (0.23)	0.62 (0.23)	0.67 (0.26)
+Detectability	0.48 (0.26)	0.43 (0.33)	0.52 (0.35)	0.47 (0.74)	0.60 (0.51)	0.58 (0.51)	0.65 (0.29)	0.68 (0.29)	0.60 (0.23)	0.57 (0.23)	0.61 (0.26)
+Species mix	0.88 (0.39)	0.77 (0.58)	1.01 (0.52)	1.04 (0.91)	1.22 (0.59)	0.97 (0.56)	1.24 (0.39)	1.38 (0.42)	1.12 (0.35)	0.96 (0.29)	1.15 (0.34)
+Calibration	0.88 (0.40)	0.77 (0.59)	1.01 (0.52)	1.04 (0.91)	1.22 (0.59)	0.97 (0.57)	1.25 (0.40)	1.38 (0.43)	1.13 (0.36)	0.96 (0.29)	1.16 (0.34)
+Target strength	0.88 (0.41)	0.77 (0.60)	1.01 (0.52)	1.04 (0.91)	1.22 (0.61)	0.97 (0.57)	1.25 (0.40)	1.38 (0.44)	1.13 (0.36)	0.96 (0.30)	1.16 (0.35)
+Missing strata	0.82 (0.41)	0.73 (0.61)	–	–	–	–	–	–	–	–	–
Total	0.82 (0.41)	0.73 (0.61)	1.01 (0.52)	1.04 (0.91)	1.22 (0.61)	0.97 (0.57)	1.25 (0.40)	1.38 (0.44)	1.13 (0.36)	0.96 (0.30)	1.16 (0.35)

Table 4. The sensitivity of Monte Carlo estimates of simulated relative biomass (and c.v. in parentheses) in 1999 to halving and doubling each of the uncertainty parameters. Only one parameter was changed in each sensitivity test, with all other parameters held at the values in Table 2. Best estimates for this survey were 1.13 (0.36).

Parameter	Halve	Double
$\bar{d}$	1.24 (0.32)	0.75 (0.70)
$\bar{r}$	1.14 (0.32)	1.05 (0.46)
d_i	1.14 (0.37)	1.05 (0.34)
r_i	1.14 (0.38)	1.04 (0.34)
s	1.13 (0.33)	1.14 (0.40)
D	1.12 (0.36)	1.11 (0.36)
id_{mix}	0.97 (0.28)	1.98 (0.88)
id_{hoki}	1.10 (0.35)	1.11 (0.34)
cal_{91-99}	1.12 (0.36)	1.13 (0.39)
TS	1.13 (0.36)	1.12 (0.37)

backscatter from hoki schools and hoki fuzz is from hoki. This positive bias balanced the negative bias caused by the sampling design to some extent, and the distribution of biomass estimates from Monte Carlo simulations were centred close to one (e.g., Figure 6). The magnitude of the positive bias caused by species mix varied between years, depending on the proportion of hoki in the school marks. Bias was greatest in 1994, 1995, and 1998, when less than 40% of hoki were in schools, and lowest in 1996 and 2001, when 59% of hoki were in schools (see Table 1). Because there was considerable variability in catch composition from hoki fuzz marks (see Figure 4), the species-mix assumption also introduces imprecision, increasing the c.v. (Table 3). Again, increases in c.v. from species mix were highest in years when a low proportion of hoki were in schools.

Sampling error decreased survey precision slightly (increased c.v. 2–9%) without contributing to bias (Table 3). Conversely, detectability added a small negative bias because there was a small proportion of hoki in the acoustic deadzone that is not included in the abundance estimate; there was no change in c.v. because the proportion of fish in the deadzone was relatively consistent between surveys. Uncertainties in calibration and target strength had little effect. Uncertainty as a result of not surveying Stratum 6 in 1991 and not surveying Stratum 5 in 1992 introduced additional negative bias because it was assumed that there was a low proportion of biomass in the missing strata relative to the proportions observed in subsequent surveys.

Sensitivity to estimated parameters

The simulation model was most sensitive to the choice of parameters for mean arrival date and the proportion of hoki in fuzz marks. Halving and doubling the best estimates of these parameters (from Table 2) resulted in large changes in the estimates of relative biomass and c.v. (Table 4). The model was relatively insensitive to the parameters of other uncertainty distributions (Table 4).

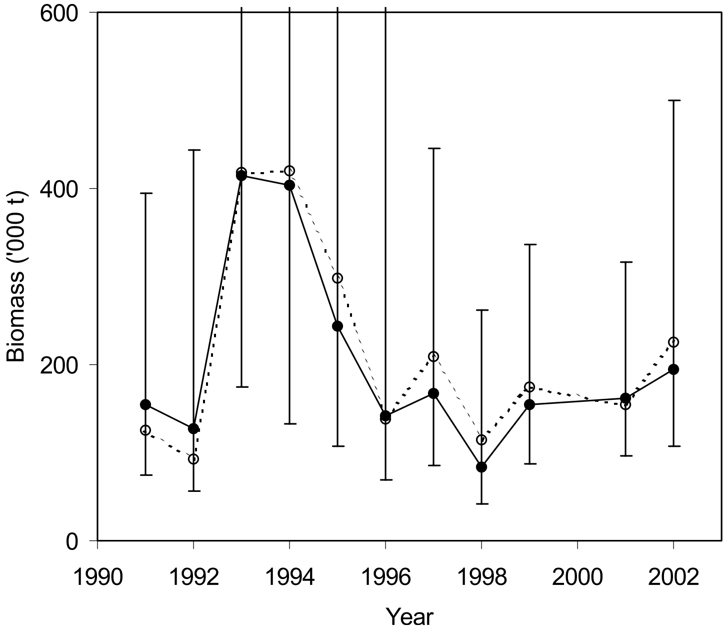

Figure 7. Hoki biomass indices from acoustic surveys of Cook Strait 1991−2002. Raw indices (dotted line) were adjusted for bias, and 95% confidence intervals calculated, based on the results of the Monte Carlo simulations of uncertainty (solid line). Note that the upper confidence bounds for surveys from 1993 to 1996 were greater than 600 000 t.

Abundance indices

Abundance indices from Cook Strait hoki acoustic surveys in 1991−2002 were adjusted for bias by dividing the original biomass estimates by the mean relative estimate from the Monte Carlo simulations (see Table 3). The adjusted indices were similar to the original indices, but there were changes in the relative time-series, with minimum biomass occurring in 1998 for the adjusted indices compared to 1992 in the original series (Figure 7). The 95% confidence intervals based on the distribution of the 1000 simulated estimates were broad, reflecting high uncertainty, especially in the period 1992−1996 (Figure 7).

Survey design

Timing was the most important consideration in survey design. The simulations indicated that acoustic surveys of Cook Strait should have a mid-date of about 7 August (Figure 8). Negative bias increased (lower relative biomass) and precision decreased (higher c.v.) if surveys were either later or earlier. The rate of change in the survey uncertainty away from the optimal timing was related to survey duration. Longer surveys were more stable than shorter ones. For example, a 41-day survey gave a c.v. less than 0.40 with survey mid-dates between 29 July and 14 August, while a 16-day survey only gave a c.v. less than 0.40 if it was centred between 6 and 8 August (Figure 8). This was because a short survey increased the probability of missing the period of peak abundance if there was some variation in the timing of the spawning season.

Increasing the number of snapshots reduced bias and increased precision (Figure 9). However, the gains, in terms of the reduction in uncertainty, from increasing the number of snapshots were small relative to those that could be obtained by improving survey timing (Figure 8). The simulations suggested there was little advantage in having a survey with more than six snapshots (Figure 9).

Discussion

The Monte Carlo simulation approach used in this paper allows all sources of uncertainty associated with the acoustic-survey method to be combined and provides estimates of the bias and precision of individual surveys. This is a significant advance for surveys of New Zealand hoki. Previously, the weightings of abundance indices from hoki acoustic surveys used in stock assessment were based on an arbitrary c.v. (0.5), that was assigned to the survey with the median number of snapshots (4). This arbitrary c.v. was then scaled according to the number of snapshots in a particular survey (Cordue *et al.*, 1992). This method did not include information about the sampling variability of individual snapshots, nor did it incorporate factors such as survey timing or mark identification, which may affect the uncertainty of the different surveys independent of the number of snapshots. Indeed, the results in this paper indicate that the number of snapshots is less important than the survey timing in determining uncertainty.

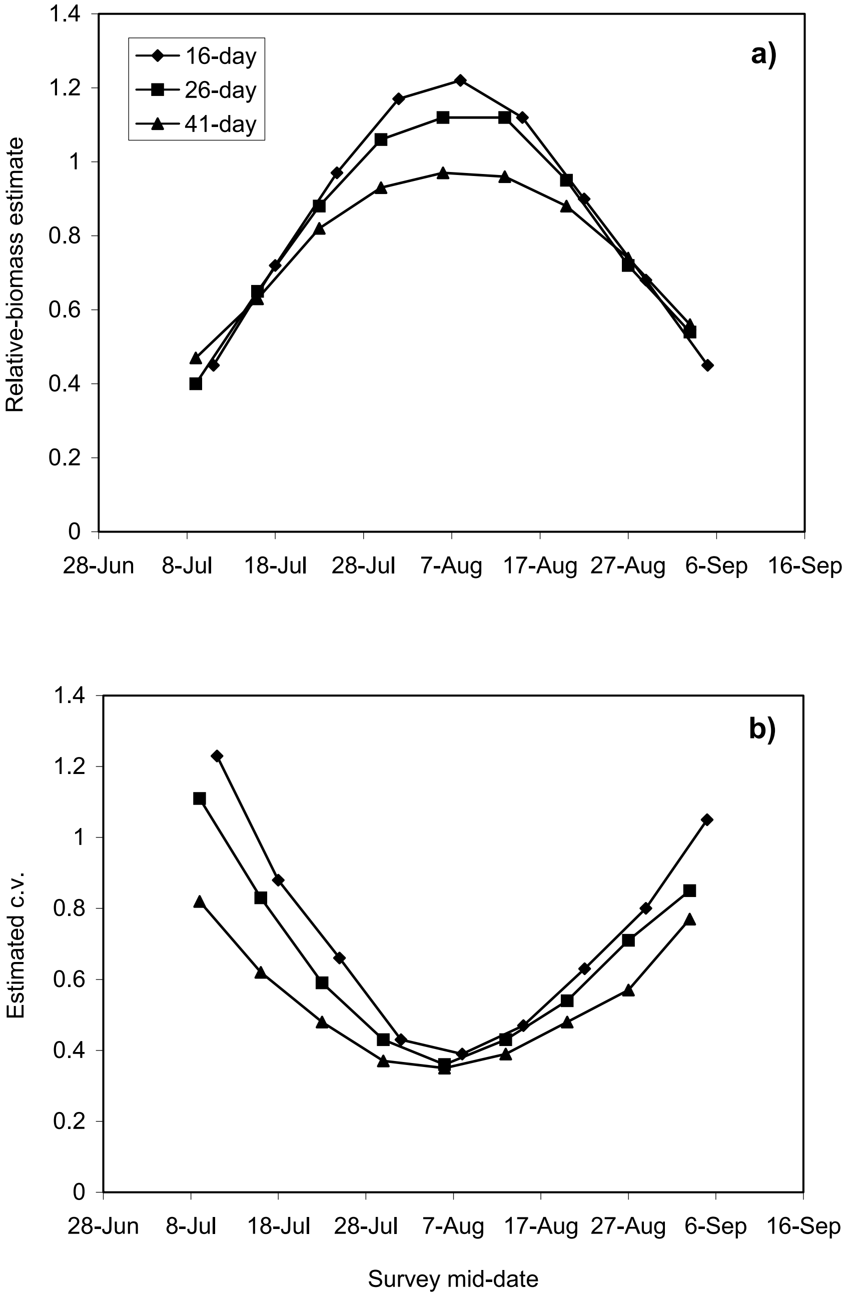

Figure 8. The effects of survey timing and duration on simulated estimates of (a) relative biomass and (b) precision. Simulated surveys comprised six snapshots evenly spaced over 16 (diamonds), 26 (squares), or 41 days (triangles), with different timing. A sampling c.v. of 25% was assumed for all snapshots, with 51% of hoki in schools.

Estimates of mean plateau height, obtained by averaging biomass estimates over a number of snapshots, only form a valid relative-abundance time-series if: first, all snapshots are within the plateau interval (main spawning season); second, the mean residence time is constant between years; third, the duration of the plateau interval is constant; and finally, the ratio of the plateau interval to the duration of the total spawning season is constant (Coombs and Cordue, 1995). These assumptions are unrealistic, given our knowledge of hoki reproductive biology and behaviour (Harley, 2002). The method presented here incorporates uncertainty in the timing of spawning and residence time, and enables the potential bias in the relative biomass index arising from survey timing to be quantified and the indices

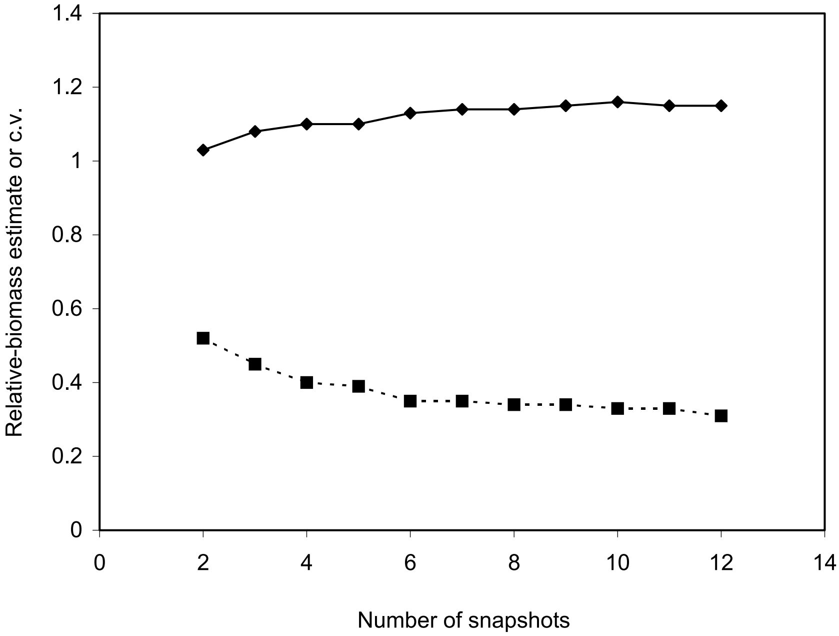

Figure 9. The effect of the number of snapshots on simulated estimates of relative biomass (solid line) and precision (dotted line). The simulated survey was 26 days centred on 5 August with the snapshots spaced evenly over the survey period. A sampling c.v. of 25% was assumed for all snapshots, with 51% of hoki in schools.

adjusted. As knowledge of the timing and duration of hoki spawning grows, it may be possible to improve on the current method of estimating mean plateau height as the raw average of the snapshots. For example, a better estimate of mean abundance might be obtained by fitting a parametric curve to snapshot biomass estimates.

The current analysis methods overestimate hoki biomass present during the survey because all backscatter from hoki school and hoki fuzz marks is assumed to be from hoki. Trawling for mark identification shows that this is not the case, with hoki making up an average of only 56% of the catch by weight from hoki fuzz marks and 91% from hoki school marks. This bias affects relative-abundance indices because the proportion of hoki in schools varies between years. This variation is also included and accounted for in the simulation process.

Confidence intervals for the acoustic indices of hoki abundance in Cook Strait were very wide. One of the advantages of the Monte Carlo simulation approach is that it allows the major sources of uncertainty to be identified, so that these can be reduced (Rose *et al.*, 2000). In Cook Strait, most uncertainty was due to survey timing relative to the timing of hoki spawning and the presence of other species in hoki acoustic marks. Survey precision could be increased by improving survey design and analysis methods, and by improving the estimates of parameters defining uncertainty distributions.

The simulations suggested that the optimal survey design was a relatively long survey of more than 26 days centred about 7 August, with at least six snapshots. Species decomposition, where acoustic backscatter is partitioned based on catch composition (MacLennan and Simmonds, 1992), would reduce the bias arising from treating all backscatter as hoki. However, this would not avoid uncertainty related to variability in catches which can only be reduced by more trawling. Species decomposition would also introduce additional uncertainties associated with the TS and acoustic:trawl vulnerability ratio of bycatch species (O'Driscoll, 2003).

The simulations were particularly sensitive to the choice of parameters describing the range of the mean date at which hoki arrive on the spawning ground, and the variability in the proportion of hoki in hoki fuzz marks. Improved estimates of these parameters would increase survey precision and decrease bias. Future work will focus on refining the estimates of arrival date in Harley (2002), and carrying out more trawling to determine species composition in hoki fuzz marks.

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