Further work towards the assessment of the South African round herring (*Etrumeus whiteheadi*) resource using data from 1987 to 2010

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Introduction

Round herring (*Etrumeus whiteheadi*), commonly referred to as Red Eye, is exploited by the South African pelagic fishery. The fishery has been managed with a Precautionary Upper Catch Limit of 100 000t for at least the past eight years. An assessment of this resource is required in order to inform on any future decisions to the management of the round herring.

The assessment of round herring is complicated by the fact that the time series of hydroacoustic survey estimates of abundance have been obtained from surveys which were designed first for anchovy and secondly for sardine. However, Coetzee and Merkle (2009) recently proposed that the time series of survey estimates of abundance are comparable, paving the way for an assessment of this resource to be undertaken. de Moor and Butterworth (2010) presented some initial results from fitting a model to November survey estimates of total biomass, May survey estimates of recruitment numbers and commercial length frequency data.

This document presents further advancements in the assessment of the round herring resource and some results for discussion.

Population Dynamics Model

The population dynamics model used for the South African round herring resource is detailed in Appendix A. The data used in this assessment are listed in Appendix B.

Consideration of the initial assessment model results (de Moor and Butterworth 2010) together with the available round herring ageing and length frequency data (Durholtz et al. 2010) has resulted in a number of structural changes from the initial assessment model:

- The population is modelled as consisting of three annual (summer, winter and late spring) sub-cohorts. These are modelled to have birthdates of 1st March, 1st June and 1st September each year (equation A.1).
- The total biomass estimated by the May hydroacoustic survey is used in preference to the survey estimate of numbers of recruits only (equation A.17; Table B.1). A May survey selectivity at age is introduced to enable a lower selection of the older age groups to be modelled.

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- A parameter measuring the proportion of the round herring biomass for the fully selected age (age 1) as measured by the May survey in comparison to that measured by the November survey is introduced in order to estimate the bias associated with the expected lower coverage achieved by the May survey. All other forms of bias are included in the multiplicative factors k_N^{RH} and k_r^{RH}, and in respect of variance λ_N^{RH} and λ_r^{RH}.
- The length frequency data available from the November and May surveys are now used to assist estimate model parameters by their inclusion in the likelihood (equation A.17).

As before, the base case assumption of $M_j^{RH} = M_{ad}^{RH} = 1.3$ is based on unpublished data of Y. Geja and D. Durholtz.

Current Model Results

The model is able to fit the survey estimated November and May biomasses reasonably well (Figures 1 and 2). The multiplicative bias associated with these surveys is considered to be constant over time (Appendix A). This model estimates the survey coverage of round herring biomass in the May survey to be 22% of that obtained during the November survey (Table 1).

The model fits to the commercial proportions-at-length are provided in Figure 3, for the minus group, and Figure 4 for the remaining length classes. Figure 5 indicates a pattern of underestimation of the proportion-at-lengths 16-17cm and an overestimation of the higher and lower (excluding minus group) length classes.

The model fits to the November survey proportions-at-length are provided in Figure 6, for the minus group, and Figure 7 for the remaining length classes. The standardised residuals are plotted in Figure 8. The fit to these data appears better than that for the commercial catch data.

The model fits to the May survey proportions-at-length are provided in Figure 9, for the minus group, and Figure 10 for the remaining length classes. The standardised residuals are plotted in Figure 11.

The selectivities-at-age estimated by the model for the November and May surveys and commercial catch are plotted in Figure 12. This shows that the model allows for a small decrease in selectivity with increasing age in the November survey indicating the majority of the resource is covered in the survey. The sharp decrease in selectivity with increasing age in the May survey indicates that the majority of adults are not sampled in the May survey.

The model estimated length at age distributions are plotted in Figures 13 to 15. The estimated CV about the mean length at age, ϑ_a, is about 15% for age 0 and age 5+ and 11% for ages 1 to 4 (Table 1). 15% is on the upper boundary of that assumed *a priori* (Appendix A). The reason for this relatively high CV on the plus group will be due large fish. The reason for the relatively high CV on the 0 year olds likely arises because of a combination of their fast growth during their first year and the multiple sub-cohorts.

This initial run of the model estimates the proportion of recruitment occurring in the March sub-cohort to be 15% and the proportion occurring in the September sub-cohort to be 85% with no recruitment occurring in June. This is in contrast to the *a priori* information of June representing peak recruitment with the March and September sub-cohorts resulting from (lower) early and late spawning.

Discussion

This document has presented further work towards the assessment of South African round herring. The current model results are presented and comments and discussion on these results are welcomed.

Further work will need to test the following:

- Incorporating normal prior distributions on k_N^{RH} and k_r^{RH}, instead of fixed values.
- Although initial model runs suggested a zero selectivity in the commercial catch for ages 3+, this assumption may need to be retested.
- The current model results estimate the recruitment to occur in two pulses only; 15% in March and 85% in September. The CVs on the parameters p_1 and p_2 may be large. Some investigation into the effects of alternative values for p_1 and p_2, and their inter-annual variation will be conducted. In addition, smaller CVs on the age-to-length matrices for age 0 may result in $p_2 > 0$.
- In some years the model does not predict a peak of similar magnitude to that observed in the length frequency data. This results in an overestimation of proportion-at-length for lower and higher length classes and an underestimation of proportion-at-length around the observed peak. The possibility of introducing variability in time in selectivity at age to account for this will be considered.
- The model assumes that age 0 fish are at most 11cm long in November and 13cm long in March (the commercial catch). No such assumption is made in May. Instead the age 0 fish are proportioned by length according to the age-to-length matrix (equation A.15). Such a method did not work well for age 0 fish in the commercial catch in initial model runs without November and May survey length frequencies. Given the three sets of data, it may now be possible to estimate proportions-at-length for age 0 fish using the age-to-length matrix in November and March.

In addition, tests will also be carried out to check the robustness of the model results to assumptions of fixed natural mortality. The robustness of model results will also be tested using data from 1998 to 2010 only, with the recruit survey data extended to cover the area west of Port Alfred.

Acknowledgements

Janet Coetzee, Deon Durholtz, Yonela Geja, Dagmar Merkle and Jan van der Westhuizen are thanked for providing the data input to this assessment.

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Table 1. Key model parameters at the joint posterior mode and contributions of different likelihoods to the posterior mode.

Contributions to the joint posterior mode	
Joint posterior mode	-11.35
L(November biomass)	4.89
L(May biomass)	14.09
L(Commercial 13-cm)	-11.46
L(Commercial length frequency)	-1.02
L(November 11-cm)	-17.29
L(November length frequency)	-14.48
L(May 13-cm)	-11.56
L(May length frequency)	25.49
Model parameters	
$N_{1987,1}^{RH}$	22.6
$N_{1987,2}^{RH}$	31.0
$N_{1987,3}^{RH}$	0
$N_{1987,4}^{RH}$	0
$N_{1987,5+}^{RH}$	0
p_1	0.15
p_2	0
$1-p_1-p_2$	0.85
$k^{coverage}$	0.22
ϑ_0^2	0.15
ϑ_a^2, $a=1,2,3,4$	0.11
ϑ_{5+}^2	0.15

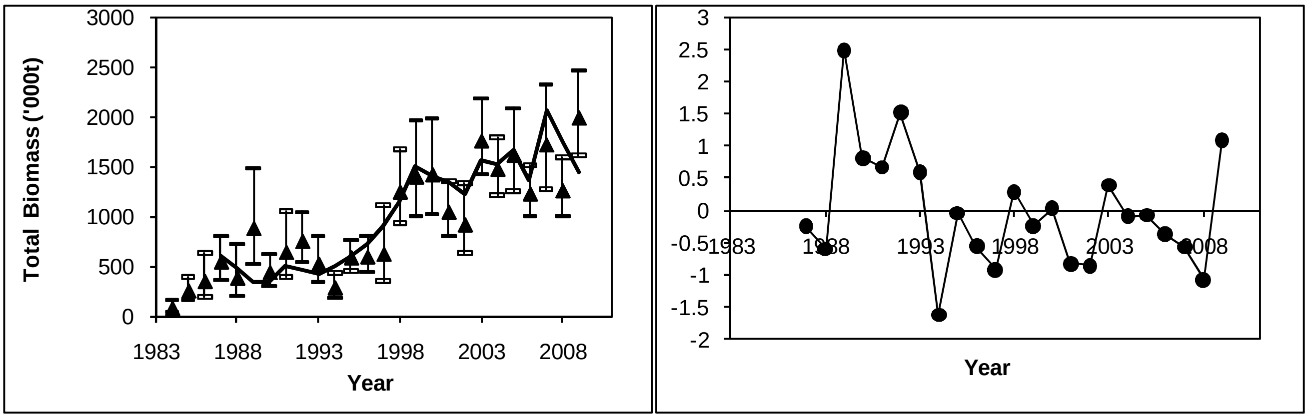

Figure 1. Acoustic survey observed and model estimated November round herring biomass from 1987 to 2009. The observed indices are shown with Hessian-based 95% confidence intervals. The standardised residuals from the fit are given in the right hand plot.

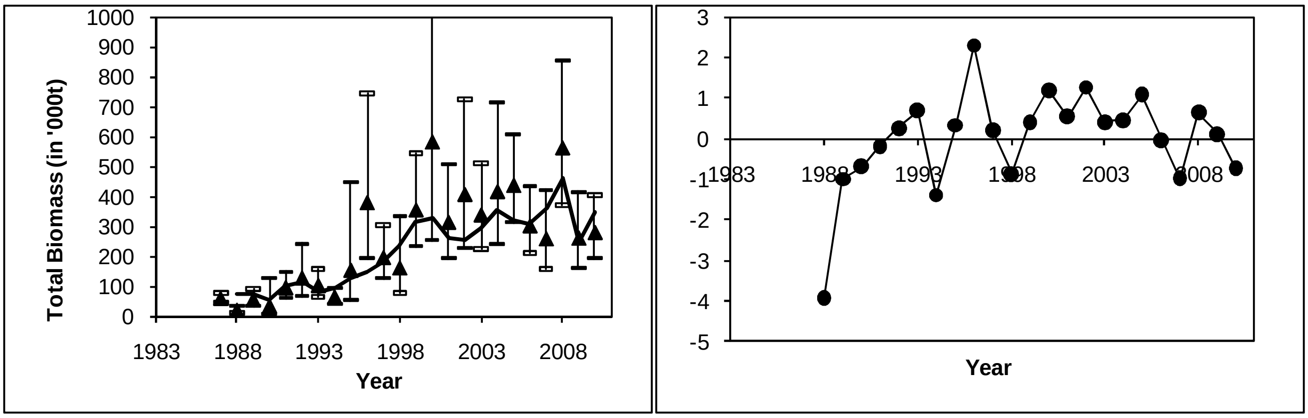

Figure 2. Acoustic survey observed and model estimated round herring biomass from May/June 1987 to 2010. The observed indices are shown with Hessian-based 95% confidence intervals. The standardised residuals from the fit are given in the right hand plot.

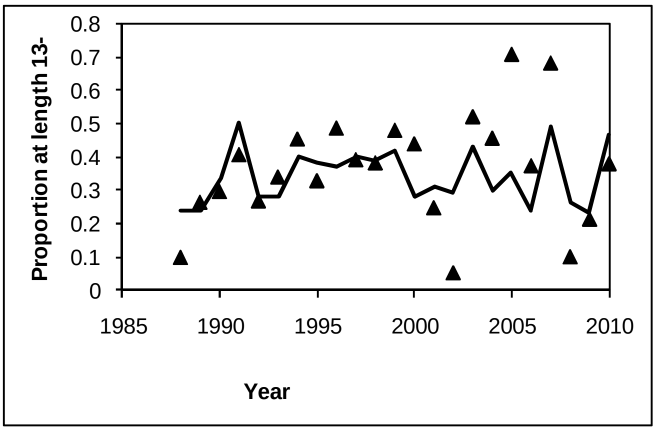

Figure 3. Observed (symbols) and model estimated (line) round herring proportion-at-length 13- in the commercial catch from 1988 (i.e. June 1987 to May 1988) to 2010 (i.e. June 2009 to May 2010).

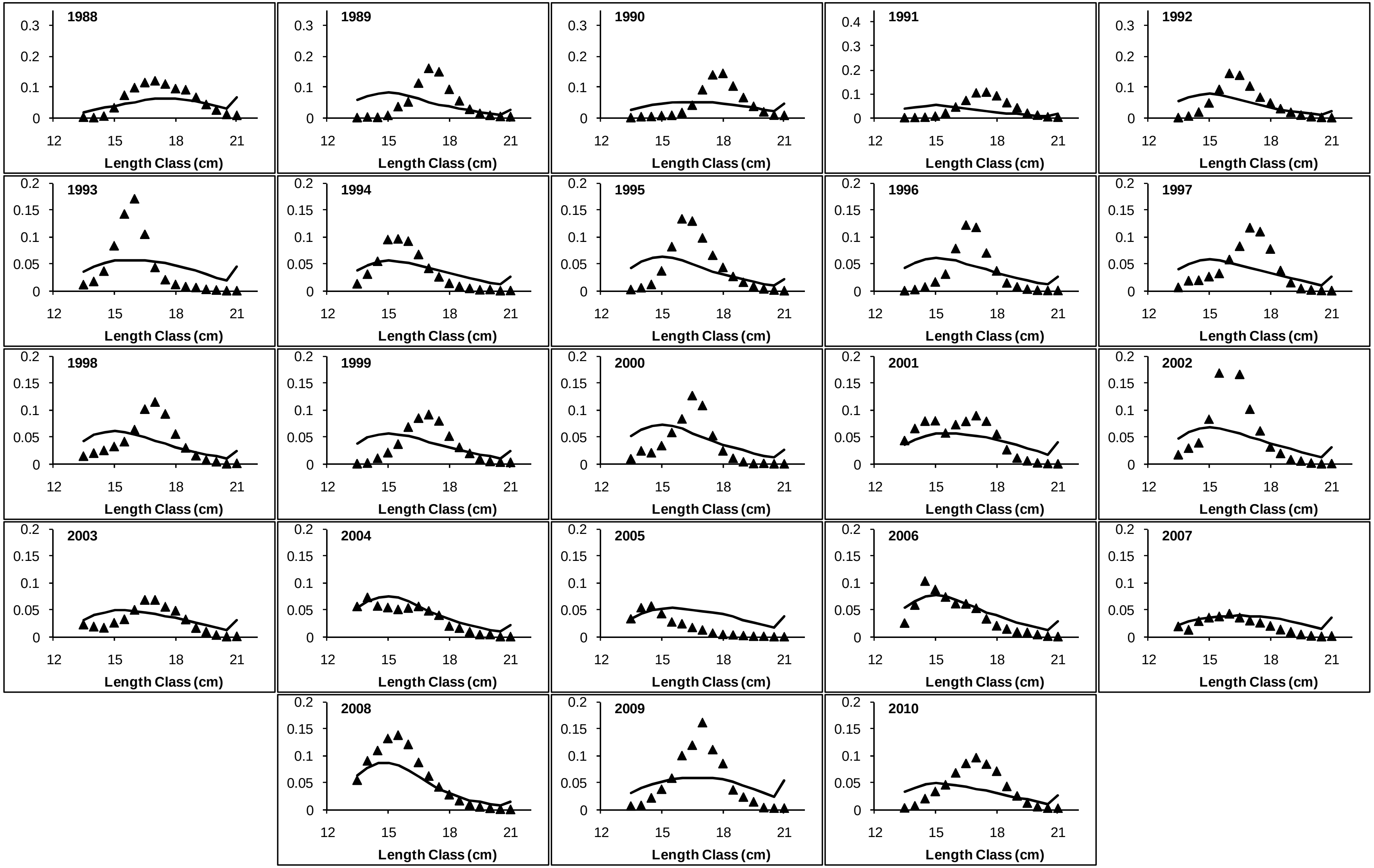

Figure 4. Observed and initial model estimated round herring proportion-at-length in the commercial catch from 1988 (i.e. June 1987 to May 1988) to 2010 (i.e. June 2009 to May 2010). Note that these proportions do not sum to 1 as they exclude the proportions-at-length 13-, plotted in Figure 3.

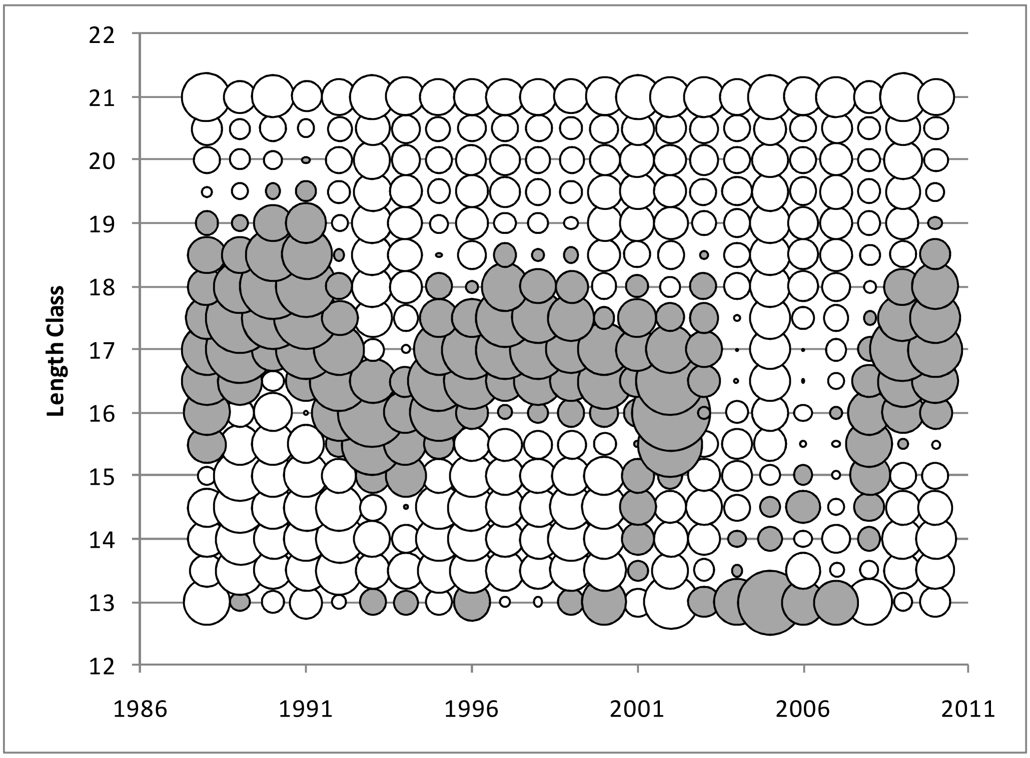

Figure 5. Bubble plot of the standardised residuals from the model fit to observed proportion-at-length in the round herring commercial catch from 1988 (i.e. June 1987 to May 1988) to 2010 (i.e. June 2009 to May 2010). Note that 13cm represents the 13- group and 21cm represents the 21+ group.

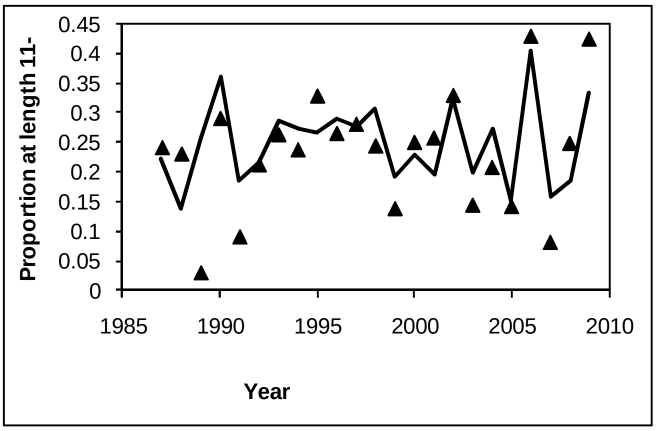

Figure 6. Observed (symbols) and initial model estimated (line) round herring proportion-at-length 11- in the November survey from 1987 to 2009.

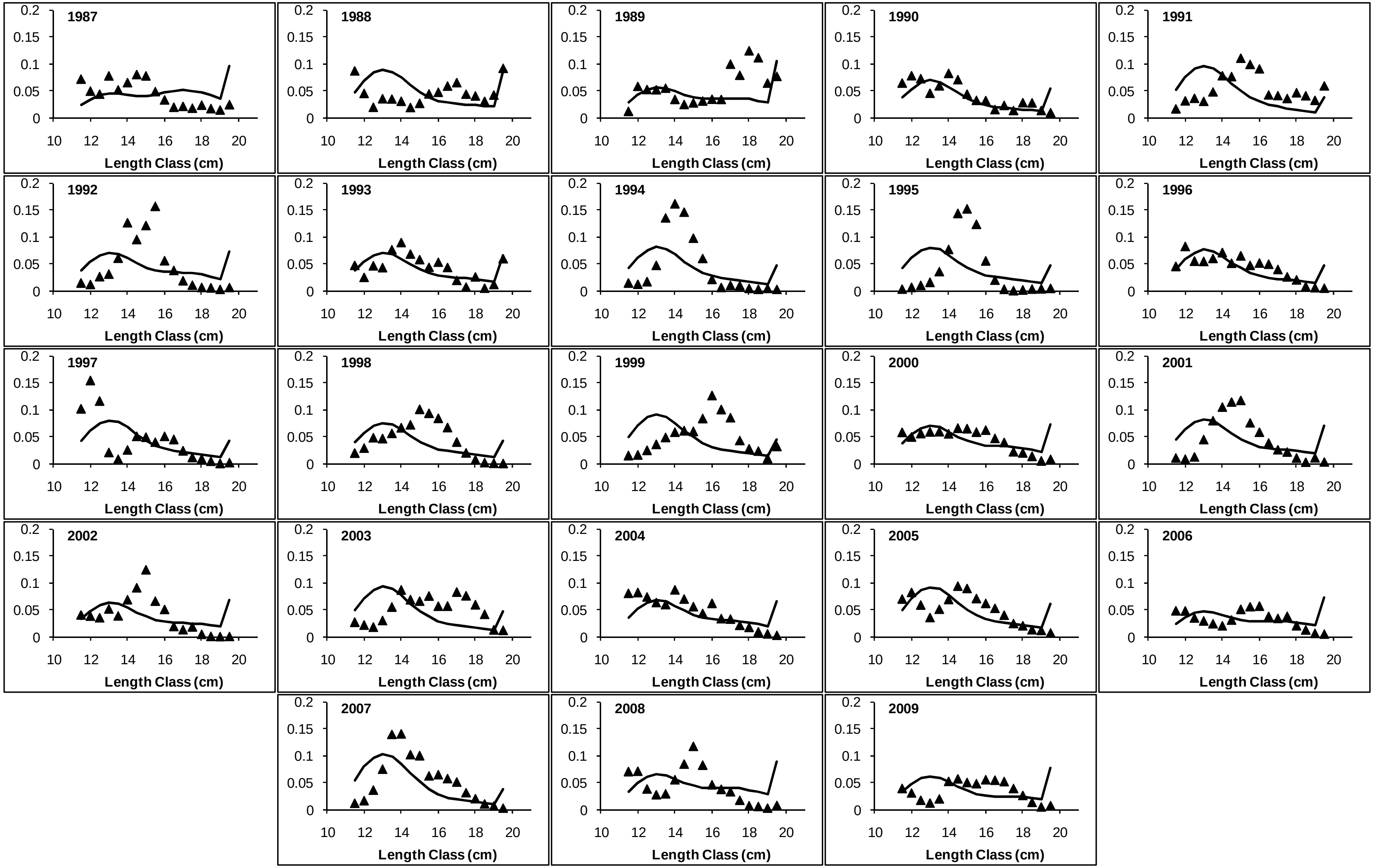

Figure 7. Observed and model estimated round herring proportion-at-length in the November survey from 1987 to 2009. Note that these proportions do not sum to 1 as they exclude the proportions-at-length 11-, plotted in Figure 6.

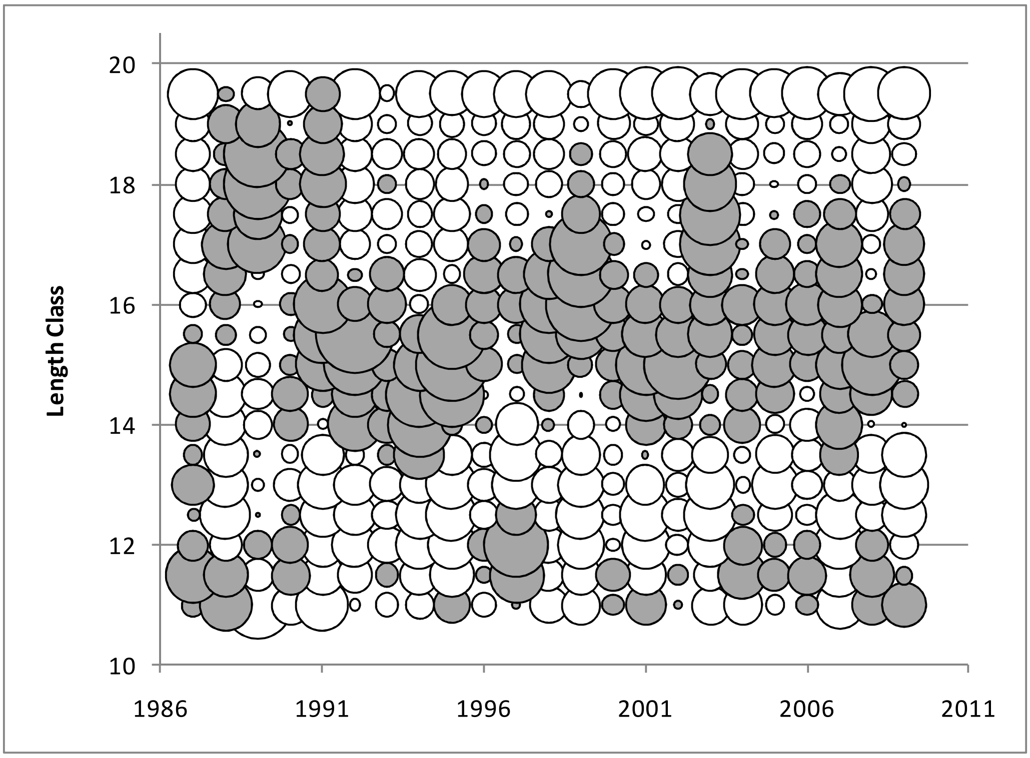

Figure 8. Bubble plot of the standardised residuals from the model fit to observed proportion-at-length in the round herring November survey from 1987 to 2009. Note that 11cm represents the 11- group and 19.5cm represents the 19.5+ group.

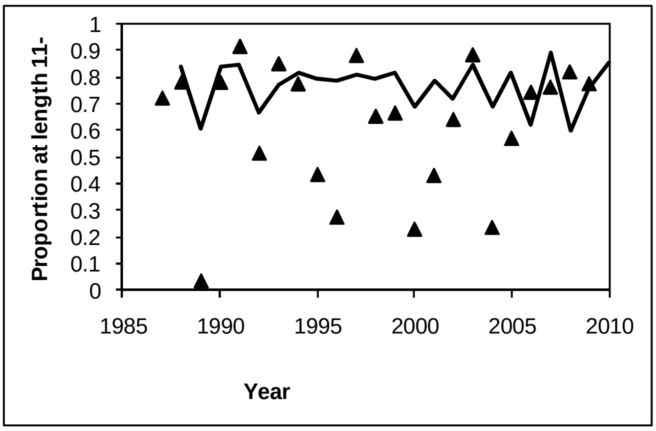

Figure 9. Observed (symbols) and initial model estimated (line) round herring proportion-at-length 13- in the May survey from 1988 to 2010.

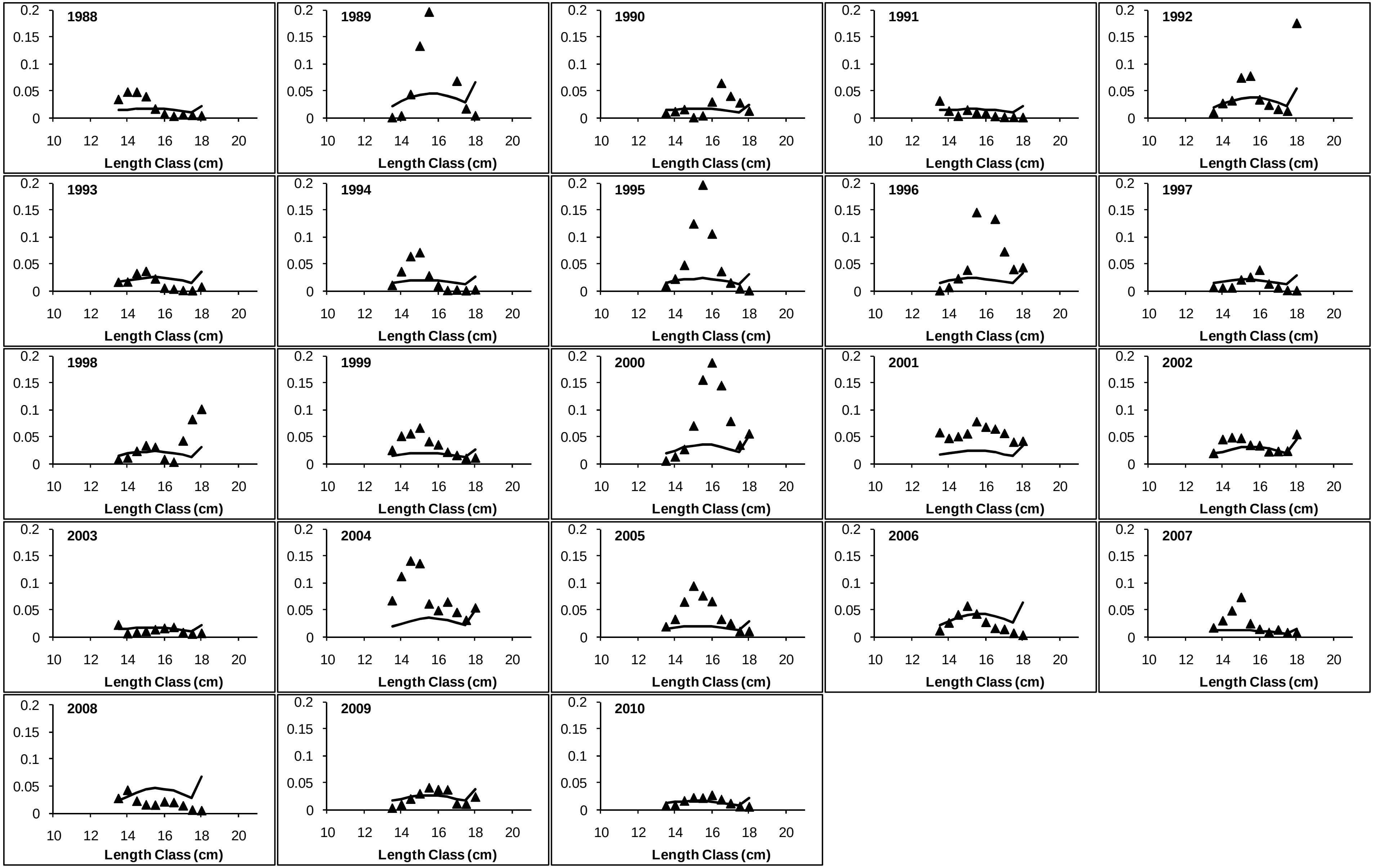

Figure 10. Observed and model estimated round herring proportion-at-length in the May survey from 1988 to 2010. Note that these proportions do not sum to 1 as they exclude the proportions-at-length 13-, plotted in Figure 9.

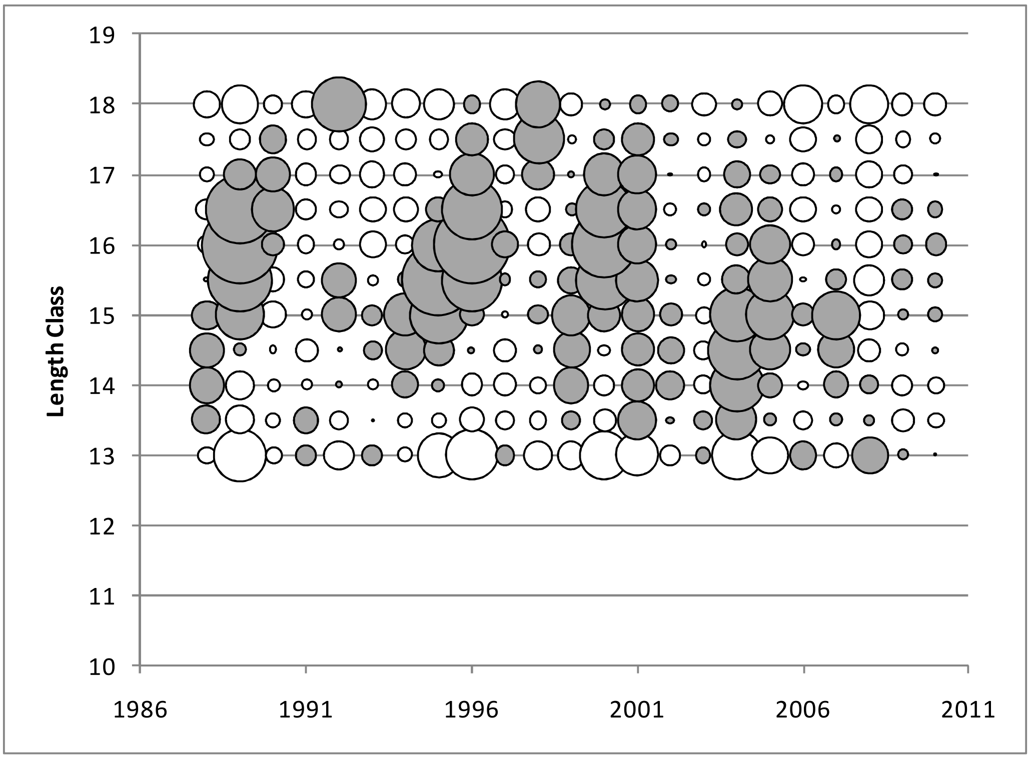

Figure 11. Bubble plot of the standardised residuals from the model fit to observed proportion-at-length in the round herring May survey from 1988 to 2010. Note that 13cm represents the 13- group and 18cm represents the 18+ group.

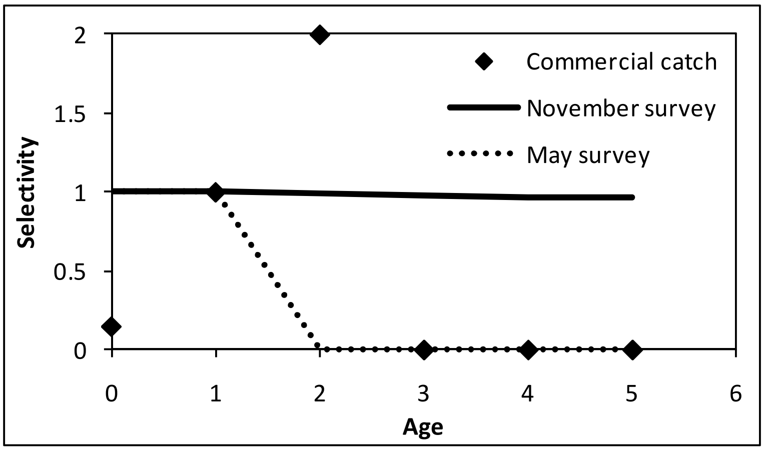

Figure 12. Fixed and model estimated selectivity-at-age in the commercial catch, the November survey and the May survey.

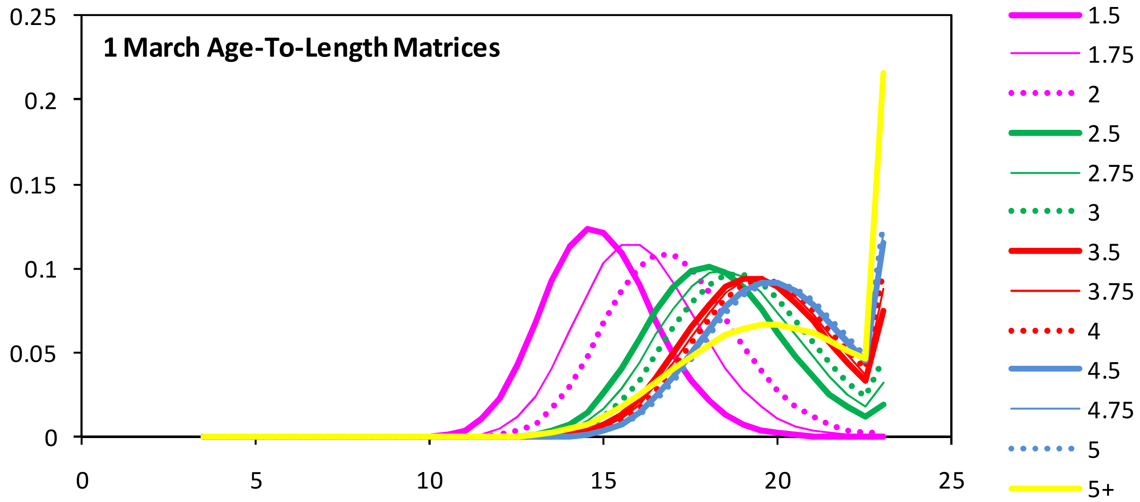

Figure 13. The model estimate age to length matrix, $A_{a,l}^{com}$, representing the proportion of round herring catch-at-age a that fall in the length group l.

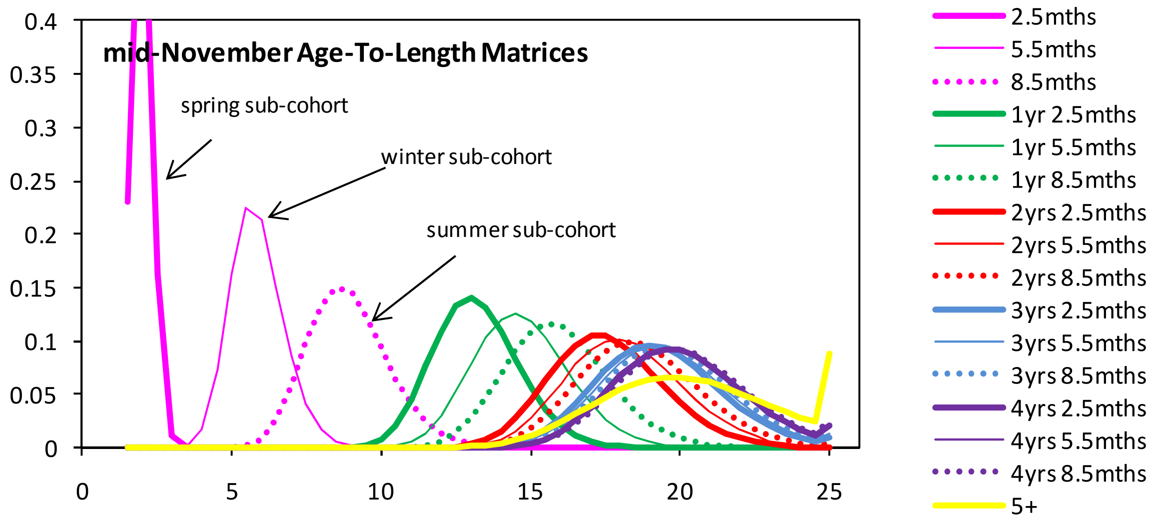

Figure 14. The model estimate age to length matrix, $A_{a,l}^{Nov}$, representing the proportion of round herring of age a that fall in the length group l in mid-November.

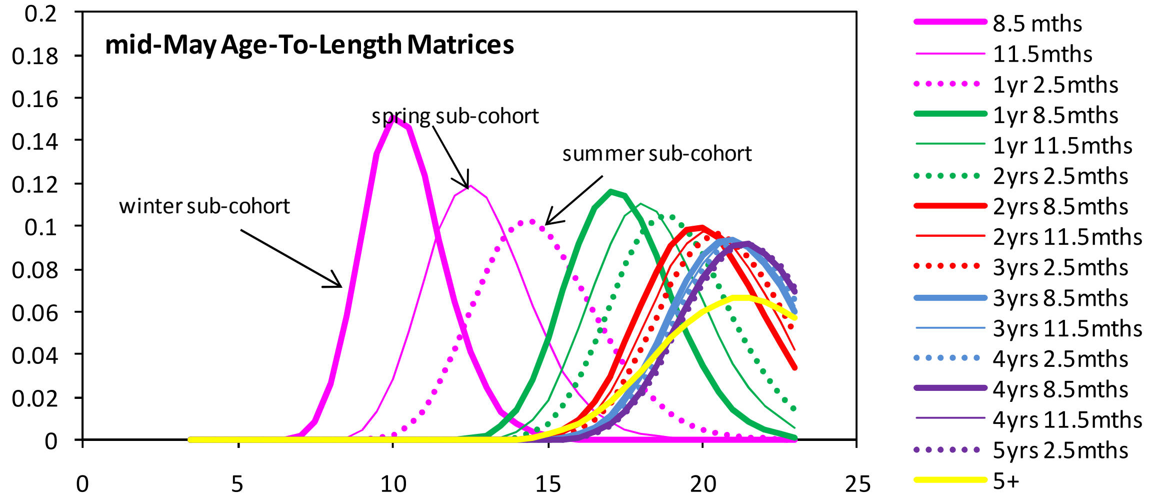

Figure 15. The model estimate age to length matrix, $A_{a,l}^{May}$, representing the proportion of round herring of age a that fall in the length group l in mid-May.

APPENDIX A: Bayesian assessment model for the South African round herring ("red eye") resource

Model Assumptions

1) Fish are modelled to be in one of three sub-cohorts, corresponding to summer recruitment (1 March), winter recruitment (1 June) and spring recruitment (1 September).
2) A plus group of age 5 is used. No males older than 4 have been observed, though females up to 8 years of age have been observed (Y. Geja and D. Durholtz pers. comm.).
3) Two acoustic surveys are held each year: the first takes place in November and surveys all fish except the 0 year olds of the September sub-cohort; the second is in May/June and targets 0 year old round herring from the September and June sub-cohorts[1], but also surveys older fish with lower selectivity.
4) The November acoustic survey provides a relative index of abundance of unknown bias.
5) The May survey provides a relative index of abundance of unknown bias.
6) The survey designs have been such that they result in survey estimates of abundance whose bias is invariant over time (Coetzee and Merkle 2009).
7) Pulse fishing occurs on 1st March for all ages (higher round herring catches have historically been recorded between January and May, with a peak in March).
8) Catches are measured without error.
9) Age 0 fish are at most 11cm long in November and 13cm long in March (the commercial catch).
10) Selectivity is assumed to be year, but not age, invariant.
11) Natural mortality is year-invariant for juvenile and adult fish, and age-invariant for adult fish.

Population Dynamics

The basic dynamic equations for round herring, based on Pope's approximation (Pope, 1972), are as follows, where $y_1 = 1987$ and $y_n = 2010$. The numbers-at-age of the sub-cohorts represent the numbers of round herring at the time of the sub-cohorts 'birthdate', i.e. 1 March, 1 June or 1 September. The plus group is modelled to age on 1 June each year.

Numbers-at-age

$$\hat{N}sub_{y,a,1}^{RH} = \hat{N}sub_{y-1,a-1,1}^{RH} e^{-M_{a-1}} - \hat{C}sub_{y,a-1,1}^{RH} \qquad y_1 + 1 \le y \le y_n\,,\ 1 \le a \le 4$$

$$\hat{N}sub_{y,a,2}^{RH} = (\hat{N}sub_{y-1,a-1,2}^{RH} e^{-9M_{a-1}/12} - \hat{C}sub_{y,a-1,2}^{RH}) e^{-3M_{a-1}/12} \qquad y_1 + 1 \le y \le y_n\,,\ 1 \le a \le 4$$

$$\hat{N}sub_{y,a,3}^{RH} = (\hat{N}sub_{y-1,a-1,3}^{RH} e^{-6M_{a-1}/12} - \hat{C}sub_{y,a-1,3}^{RH}) e^{-6M_{a-1}/12} \qquad y_1 + 1 \le y \le y_n\,,\ 1 \le a \le 4$$

$$\begin{aligned}\hat{N}_{y,5+}^{RH} = {} & (\hat{N}sub_{y-1,4,1}^{RH} e^{-M_4} - \hat{C}sub_{y,4,1}^{RH}) e^{-3M_4/12} + (\hat{N}sub_{y-1,4,2}^{RH} e^{-9M_4/12} - \hat{C}sub_{y,4,2}^{RH}) e^{-3M_4/12} + \\ & (\hat{N}sub_{y-1,4,3}^{RH} e^{-6M_4/12} - \hat{C}sub_{y,4,3}^{RH}) e^{-3M_4/12} + (\hat{N}_{y-1,5+}^{RH} e^{-9M_{5+}/12} - \hat{C}_{y,5+}^{RH}) e^{-3M_{5+}/12} \\ & y_1 + 1 \le y \le y_n \qquad \text{(A.1)}\end{aligned}$$

[1] It is assumed that the current year's March sub-cohort would be too small to be picked up in the survey.

where

$\hat{N}sub_{y,a,c}^{RH}$ is the number (in billions) of the March ($c=1$), June ($c=2$) or September ($c=3$) spawning sub-cohort round herring of age *a* at 1 March ($c=1$), 1 June ($c=2$) or 1 September ($c=3$) in calendar year *y*;

$\hat{N}_{y,5+}^{RH}$ is the number (in billions) of round herring of age 5+ at 1 June in year *y*;

$\hat{C}sub_{y,a,c}^{RH}$ is the number (in billions) of the March ($c=1$), June ($c=2$) or September ($c=3$) spawning sub-cohort round herring of age *a* caught from 1 June in year $y-1$ to 31 May in calendar year y;

$\hat{C}_{y,5+}^{RH}$ is the number (in billions) of round herring of age 5+ caught from 1 June in year $y-1$ to 31 May in year y; and

M_a is the natural mortality (in year^{-1}) of round herring of age a.

Biomass associated with the November survey

$$\hat{N}sub_{Nov,y,a,1}^{RH} = (\hat{N}sub_{y,a,1}^{RH} e^{-6M_a/12} - \hat{C}sub_{Nov,y,a,1}^{RH})e^{-2.5M_a/12} \qquad y_1 \le y \le y_n - 1,\ 0 \le a \le 4$$

$$\hat{N}sub_{Nov,y,a,2}^{RH} = (\hat{N}sub_{y,a,2}^{RH} e^{-3M_a/12} - \hat{C}sub_{Nov,y,a,2}^{RH})e^{-2.5M_a/12} \qquad y_1 \le y \le y_n - 1,\ 0 \le a \le 4$$

$$\hat{N}sub_{Nov,y,a,3}^{RH} = (\hat{N}sub_{y,a,3}^{RH} - \hat{C}sub_{Nov,y,a,3}^{RH})e^{-2.5M_a/12} \qquad y_1 \le y \le y_n - 1,\ 0 \le a \le 4$$

$$\hat{N}_{Nov,y,5+}^{RH} = (\hat{N}_{y,5+}^{RH} e^{-3M_{5+}/12} - \hat{C}_{Nov,y,5+}^{RH})e^{-2.5M_{5+}/12} \qquad y_1 \le y \le y_n - 1$$

$$\hat{B}_{Nov,y}^{RH} = \sum_{c=1}^{2}\left(S_0^{Nov} \times \hat{N}sub_{Nov,y,0,c}^{RH} w_{0,c}^{Nov}\right) + \sum_{a=1}^{4}\sum_{c=1}^{3}\left(S_a^{Nov} \times \hat{N}sub_{Nov,y,a,c}^{RH} w_{a,c}^{Nov}\right) + S_{5+}^{Nov} \times \hat{N}_{Nov,y,5+}^{RH} w_{5+}^{Nov}$$

$$y_1 \le y \le y_n - 1 \qquad \text{(A.2)}$$

where

$\hat{N}sub_{Nov,y,a,c}^{RH}$ is the number (in billions) of the March ($c=1$), June ($c=2$) or September ($c=3$) spawning sub-cohort round herring of age *a* at mid-November in calendar year *y*;

$\hat{N}_{Nov,y,5+}^{RH}$ is the number (in billions) of round herring of age 5+ at mid-November in year *y*;

$\hat{C}sub_{Nov,y,a,c}^{RH}$ is the number (in billions) of the March ($c=1$), June ($c=2$) or September ($c=3$) spawning sub-cohort round herring of age *a* caught from 1 June to mid-November in calendar year y;

$\hat{C}_{Nov,y,5+}^{RH}$ is the number (in billions) of round herring of age 5+ caught from 1 June to mid-November in year y;

$\hat{B}_{Nov,y}^{RH}$ is the biomass (in thousand tons) of 1+ round herring at mid-November in year *y*, which is taken to be associated with the November survey in year *y*;

$w_{a,c}^{Nov}$ is the mean mass (in grams) of March ($c=1$), June ($c=2$) or September ($c=3$) spawning sub-cohort round herring of age *a* during the November survey (see Table B.2d); and

w_{5+}^{Nov} is the mean mass (in grams) of round herring of age 5+ during the November survey (see Table B.2d).

Biomass associated with the May survey

$$\hat{N}sub_{May,y,a,1}^{RH} = (\hat{N}sub_{y-1,a,1}^{RH} e^{-M_a} - \hat{C}sub_{y,a,1}^{RH}) e^{-2.5M_a/12} \qquad y_1+1 \le y \le y_n,\ 0 \le a \le 4$$

$$\hat{N}sub_{May,y,a,2}^{RH} = (\hat{N}sub_{y-1,a,2}^{RH} e^{-9M_a/12} - \hat{C}sub_{y,a,2}^{RH}) e^{-2.5M_a/12} \qquad y_1+1 \le y \le y_n,\ 0 \le a \le 4$$

$$\hat{N}sub_{May,y,a,3}^{RH} = (\hat{N}sub_{y-1,a,3}^{RH} e^{-6M_a/12} - \hat{C}sub_{y,a,3}^{RH}) e^{-2.5M_a/12} \qquad y_1+1 \le y \le y_n,\ 1 \le a \le 4$$

$$\hat{N}_{May,y,5+}^{RH} = (\hat{N}_{y-1,5+}^{RH} e^{-9M_{5+}/12} - \hat{C}_{y,5+}^{RH}) e^{-2.5M_{5+}/12} \qquad y_1+1 \le y \le y_n$$

$$\hat{B}_{May,y}^{RH} = \sum_{a=0}^{4}\sum_{c=1}^{3}\left(S_a^{May} \times \hat{N}sub_{May,y,a,c}^{RH} w_{a,c}^{May}\right) + S_{5+}^{May} \times \hat{N}_{May,y,5+}^{RH} w_{5+}^{May}$$

$$y_1+1 \le y \le y_n \qquad \text{(A.3)}$$

where

$\hat{N}sub_{May,y,a,c}^{RH}$ is the number (in billions) of the March ($c=1$), June ($c=2$) or September ($c=3$) spawning sub-cohort round herring of age *a* at mid-May in calendar year *y*;

$\hat{N}_{May,y,5+}^{RH}$ is the number (in billions) of round herring of age 5+ at mid-May in year *y*;

$\hat{B}_{May,y}^{RH}$ is the biomass (in thousand tons) of 1+ round herring at mid-May in year *y*, which are taken to be associated with the May survey;

$w_{a,c}^{May}$ is the mean mass (in grams) of the March ($c=1$), June ($c=2$) or September ($c=3$) spawning sub-cohort round herring of age *a* during the May survey (see Table B.2b); and

w_{5+}^{May} is the mean mass (in grams) of round herring of age 5+ during the May survey (see Table B.2b).

Catch at age

The annual catch at age by number is given by:

$$\hat{C}sub_{y,a,1}^{RH} = \hat{N}sub_{y-1,a,1}^{RH} e^{-M_a} S_a F_y \qquad y_1+1 \le y \le y_n,\ 0 \le a \le 4$$

$$\hat{C}sub_{y,a,2}^{RH} = \hat{N}sub_{y-1,a,2}^{RH} e^{-9M_a/12} S_a F_y \qquad y_1+1 \le y \le y_n,\ 0 \le a \le 4$$

$$\hat{C}sub_{y,a,3}^{RH} = \hat{N}sub_{y-1,a,3}^{RH} e^{-6M_a/12} S_a F_y \qquad y_1+1 \le y \le y_n,\ 0 \le a \le 4$$

$$\hat{C}_{y,5+}^{RH} = \hat{N}_{y-1,5+}^{RH} e^{-9M_{5+}/12} S_{5+} F_y \qquad y_1+1 \le y \le y_n \qquad \text{(A.4)}$$

where

S_a is the commercial selectivity at age a, which is assumed to be year-independent; and

F_y is the fished proportion in year y for a fully selected age class.

In the equations above the difference in the year subscript between the catch-at-age and initial numbers-at-age is because these numbers-at-age pertain to March/June/September of the previous year, while the catch is assumed to be taken in a pulse on 1st March.

The catch at age by number from 1 June to mid-November, for use in calculating the round herring biomass surveyed, is calculated as follows:

$$\hat{C}sub^{RH}_{Nov,y,a,1} = \hat{N}sub^{RH}_{Nov,y,a,1} e^{-6M_a/12} S_a F^{Nov}_y \qquad y_1 \le y \le y_n - 1,\ 0 \le a \le 4$$

$$\hat{C}sub^{RH}_{Nov,y,a,2} = \hat{N}sub^{RH}_{Nov,y,a,2} e^{-3M_a/12} S_a F^{Nov}_y \qquad y_1 \le y \le y_n - 1,\ 0 \le a \le 4$$

$$\hat{C}sub^{RH}_{Nov,y,a,3} = \hat{N}sub^{RH}_{Nov,y,a,3} S_a F^{Nov}_y \qquad y_1 \le y \le y_n - 1,\ 1 \le a \le 4$$

$$\hat{C}^{RH}_{Nov,y,5+} = \hat{N}^{RH}_{y,5+} e^{-3M_{5+}/12} S_{5+} F^{Nov}_y \qquad y_1 \le y \le y_n - 1 \qquad \text{(A.5)}$$

The fished proportion for the full year (from 1 June of year $y-1$ to 31 May of year y) is estimated by:

$$F_y = C^{ObsTon}_y \Bigg/ \left[\sum_{a=0}^{4} \left(w^{Mar}_{a,1} \hat{N}sub^{RH}_{y-1,a,1} e^{-M_a} S_a + w^{Mar}_{a,2} \hat{N}sub^{RH}_{y-1,a,2} e^{-9M_a/12} S_a + w^{Mar}_{a,3} \hat{N}sub^{RH}_{y-1,a,3} e^{-6M_a/12} S_a \right) + w^{Mar}_{5+} \hat{N}^{RH}_{y-1,5+} e^{-9M_{5+}/12} S_{5+} \right]$$

$$y_1 + 1 \le y \le y_n \qquad \text{(A.6)}$$

And for the catch prior to the November survey (1 June y to mid-November y) is estimated by:

$$F^{Nov}_y = C^{ObsTon,Nov}_y \Big/ \Big[w^{Sep}_{0,1} \hat{N}sub^{RH}_{y,0,1} e^{-6M_0/12} S_0 + w^{Sep}_{0,2} \hat{N}sub^{RH}_{y,0,2} e^{-3M_0/12} S_0 + \sum_{a=1}^{4} \left(w^{Sep}_{a,1} \hat{N}sub^{RH}_{y,a,1} e^{-6M_a/12} S_a + w^{Sep}_{a,2} \hat{N}sub^{RH}_{y,a,2} e^{-3M_a/12} S_a + w^{Sep}_{a,3} \hat{N}sub^{RH}_{y,a,3} S_a \right) + w^{Sep}_{5+} \hat{N}^{RH}_{y,5+} e^{-3M_{5+}/12} S_{5+} \Big]$$

$$y_1 \le y \le y_n - 1 \qquad \text{(A.7)}$$

where

C^{ObsTon}_y	is the observed catch tonnage of year y (June $y-1$ to May y, see Table B.3).
$C^{ObsTon,Nov}_y$	is the observed catch tonnage prior to the November survey of year y (June y to mid-November y, see Table B.3).
$w^{Mar}_{a,c}$	is the mean mass (in grams) of the March ($c=1$), June ($c=2$) or September ($c=3$) spawning sub-cohort round herring of age a in the commercial catch (see Table B.2a).
w^{Mar}_{5+}	is the mean mass (in grams) of round herring of age 5+ in the commercial catch (see Table B.2a).
$w^{Sep}_{a,c}$	is the mean mass (in grams) of the March ($c=1$), June ($c=2$) or September ($c=3$) spawning sub-cohort round herring of age a in the commercial catch taken prior to the November survey (see Table B.2c).
w^{Sep}_{5+}	is the mean mass (in grams) of round herring of age 5+ in the commercial catch taken prior to the November survey (see Table B.2c).

Catch at length

Given the predicted proportion-at-age in the quarterly commercial catch

$$\hat{p}sub^{com}_{y,a,c} = \frac{\hat{C}sub^{RH}_{y,a,c}}{\sum_{a=0}^{4}\sum_{c=1}^{3}\hat{C}sub^{RH}_{y,a,c} + \hat{C}^{RH}_{y,5+}} \qquad y_1+1 \le y \le y_n,\ 0 \le a \le 4,\ c = 1,\ldots,3$$

$$\hat{p}^{com}_{y,5+} = \frac{\hat{C}^{RH}_{y,5+}}{\sum_{a=0}^{4}\sum_{c=1}^{3}\hat{C}sub^{RH}_{y,a,c} + \hat{C}^{RH}_{y,5+}} \qquad y_1+1 \le y \le y_n \qquad \text{(A.8)}$$

and the assumption that all age 0 fish are at most 13cm L_c, the predicted proportion-at-length is then estimated as follows:

$$\hat{p}^{com}_{y,13-} = \sum_{c=1}^{3}\hat{p}sub^{com}_{y,0,c} + \sum_{l=3.5}^{13}\left(\sum_{a=1}^{4}\sum_{c=1}^{3}\hat{p}sub^{com}_{y,a,c}A^{com}_{a,l,c} + \hat{p}^{com}_{y,5+}A^{com}_{5+,l}\right) \qquad y_1+1 \le y \le y_n$$

$$\hat{p}^{com}_{y,l} = \sum_{a=1}^{4}\sum_{c=1}^{3}\hat{p}sub^{com}_{y,a,c}A^{com}_{a,l,c} + \hat{p}^{com}_{y,5+}A^{com}_{5+,l} \qquad y_1+1 \le y \le y_n,\ l = 13.5,\ldots,20.5\,\text{cm}$$

$$\hat{p}^{com}_{y,21+} = \sum_{l=21}^{23}\left(\sum_{a=1}^{4}\sum_{c=1}^{3}\hat{p}sub^{com}_{y,a,c}A^{com}_{a,l,c} + \hat{p}^{com}_{y,5+}A^{com}_{5+,l}\right) \qquad y_1+1 \le y \le y_n \qquad \text{(A.9)}$$

where the length groups are in 0.5cm L_c and

$A^{com}_{a,l,c}$ is the proportion of the March ($c=1$), June ($c=2$) or September ($c=3$) spawning round herring catch-at-age *a* that fall in the length group l (thus $\sum_{l=l\min}^{l\max}A^{com}_{a,l,c}=1$).

$A^{com}_{5+,l}$ is the proportion of round herring catch-at-age 5+ that fall in the length group l (thus $\sum_{l=l\min}^{l\max}A^{com}_{5+,l}=1$).

A plus group of 21cm was chosen to ensure that all observations were non-zero. The matrix A^{com} is calculated under the assumption that length-at-age is normally distributed about a von Bertalanffy growth curve:

$$L^{com}_{a,1} \sim N\left(L_\infty\left(1-e^{-\kappa(a+1-t_0)}\right), \vartheta^2_a\right) \qquad 1 \le a \le 4$$

$$L^{com}_{a,2} \sim N\left(L_\infty\left(1-e^{-\kappa(a+9/12-t_0)}\right), \vartheta^2_a\right) \qquad 1 \le a \le 4$$

$$L^{com}_{a,3} \sim N\left(L_\infty\left(1-e^{-\kappa(a+6/12-t_0)}\right), \vartheta^2_a\right) \qquad 1 \le a \le 4$$

$$L^{com}_{5+} \sim N\left(L_\infty\left(1-e^{-\kappa(6-t_0)}\right), \vartheta^2_a\right)_2 \qquad \text{(A.10)}$$

where

L_∞ denotes the maximum length of the individual;

κ denotes the annual growth rate;

t_0 denotes the age at which the growth rate is zero; and

ϑ_a^2 denotes the variance about the mean length for age a.

Proportion at length in November

Given the predicted proportion-at-age in mid-November of:

$$\hat{p}sub_{y,a,c}^{Nov} = \frac{S_a^{Nov} \times \hat{N}sub_{Nov,y,a,c}^{RH}}{S_0^{Nov} \times \left(\hat{N}sub_{Nov,y,0,1}^{RH} + \hat{N}sub_{Nov,y,0,2}^{RH}\right) + \sum_{a=1}^{4}\sum_{c=1}^{3}\left(S_a^{Nov} \times \hat{N}sub_{Nov,y,a,c}^{RH}\right) + S_{5+}^{Nov} \times \hat{N}_{Nov,y,5+}^{RH}}$$

$$y_1 \le y \le y_n - 1,\ a = 0,\ c = 1,2$$

$$\hat{p}sub_{y,a,c}^{Nov} = \frac{S_a^{Nov} \times \hat{N}sub_{Nov,y,a,c}^{RH}}{S_0^{Nov} \times \left(\hat{N}sub_{Nov,y,0,1}^{RH} + \hat{N}sub_{Nov,y,0,2}^{RH}\right) + \sum_{a=1}^{4}\sum_{c=1}^{3}\left(S_a^{Nov} \times \hat{N}sub_{Nov,y,a,c}^{RH}\right) + S_{5+}^{Nov} \times \hat{N}_{Nov,y,5+}^{RH}}$$

$$y_1 \le y \le y_n - 1,\ 1 \le a \le 4,\ c = 1,\ldots,3$$

$$\hat{p}_{y,5+}^{Nov} = \frac{S_{5+}^{Nov} \times \hat{N}_{Nov,y,5+}^{RH}}{S_0^{Nov} \times \left(\hat{N}sub_{Nov,y,0,1}^{RH} + \hat{N}sub_{Nov,y,0,2}^{RH}\right) + \sum_{a=1}^{4}\sum_{c=1}^{3}\left(S_a^{Nov} \times \hat{N}sub_{Nov,y,a,c}^{RH}\right) + S_{5+}^{Nov} \times \hat{N}_{Nov,y,5+}^{RH}}$$

$$y_1 \le y \le y_n - 1 \qquad \text{(A.11)}$$

and the assumption that all age 0 fish are at most 11cm L_c, the predicted proportion-at-length is then estimated as follows:

$$\hat{p}_{y,13-}^{Nov} = \sum_{c=1}^{2}\hat{p}sub_{y,0,c}^{Nov} + \sum_{l=1.5}^{11}\left(\sum_{a=1}^{4}\left(\sum_{c=1}^{3}\hat{p}sub_{y,a,c}^{Nov}A_{a,l,c}^{Nov}\right) + \hat{p}_{y,5+}^{Nov}A_{5+,l}^{Nov}\right) \qquad y_1 \le y \le y_n - 1$$

$$\hat{p}_{y,l}^{Nov} = \sum_{a=1}^{4}\sum_{c=1}^{3}\hat{p}sub_{y,a,c}^{Nov}A_{a,l,c}^{Nov} + \hat{p}_{y,5+}^{Nov}A_{5+,l}^{Nov} \qquad y_1 \le y \le y_n - 1,\ l = 11.5,\ldots,19\,\text{cm}$$

$$\hat{p}_{y,19.5+}^{Nov} = \sum_{l=19.5}^{25}\left(\sum_{a=1}^{4}\sum_{c=1}^{3}\hat{p}sub_{y,a,c}^{Nov}A_{a,l,c}^{Nov} + \hat{p}_{y,5+}^{Nov}A_{5+,l}^{Nov}\right) \qquad y_1 \le y \le y_n - 1 \qquad \text{(A.12)}$$

where the length groups are in 0.5cm L_c and

$A_{a,l,c}^{Nov}$ is the proportion of the March ($c=1$), June ($c=2$) or September ($c=3$) spawning round herring catch-at-age a that fall in the length group l (thus $\sum_{l=1.5}^{25} A_{a,l,c}^{Nov} = 1$) in mid-November.

$A_{5+,l}^{Nov}$ is the proportion of round herring catch-at-age 5+ that fall in the length group l (thus $\sum_{l=1.5}^{25} A_{5+,l}^{Nov} = 1$) in mid-November.

A plus group of 19.5cm was chosen to ensure that all observations were non-zero. The matrix A^{Nov} is calculated under the assumption that length-at-age is normally distributed about the same von Bertalanffy growth curve mentioned above:

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[2] Age 6 is used here to account for the greater average age of the plus group.

$$L_{a,1}^{Nov} \sim N\left(L_\infty\left(1-e^{-\kappa(a+8.5/12-t_0)}\right), \vartheta_a^2\right) \qquad 1 \le a \le 4$$

$$L_{a,2}^{Nov} \sim N\left(L_\infty\left(1-e^{-\kappa(a+5.5/12-t_0)}\right), \vartheta_a^2\right) \qquad 1 \le a \le 4$$

$$L_{a,3}^{Nov} \sim N\left(L_\infty\left(1-e^{-\kappa(a+2.5/12-t_0)}\right), \vartheta_a^2\right) \qquad 1 \le a \le 4$$

$$L_{5+}^{Nov} \sim N\left(L_\infty\left(1-e^{-\kappa(6-t_0)}\right), \vartheta_a^2\right)^{3} \qquad \text{(A.13)}$$

Proportion at length in May

Given the predicted proportion-at-age in mid-May of:

$$\hat{p}sub_{y,a,c}^{May} = \frac{S_a^{May} \times \hat{N}sub_{May,y,a,c}^{RH}}{\sum_{a=0}^{4}\sum_{c=1}^{3}\left(S_a^{May} \times \hat{N}sub_{May,y,a,c}^{RH}\right) + S_{5+}^{May} \times \hat{N}_{May,y,5+}^{RH}}$$

$$y_1 + 1 \le y \le y_n, \; 0 \le a \le 4, \; c = 1, \ldots, 3$$

$$\hat{p}_{y,5+}^{May} = \frac{\hat{N}_{May,y,5+}^{RH}}{\sum_{a=0}^{4}\sum_{c=1}^{3}\left(S_a^{May} \times \hat{N}sub_{May,y,a,c}^{RH}\right) + S_{5+}^{May} \times \hat{N}_{May,y,5+}^{RH}}$$

$$y_1 + 1 \le y \le y_n \qquad \text{(A.14)}$$

the predicted proportion-at-length is then estimated as follows:

$$\hat{p}_{y,13-}^{May} = \sum_{l=2}^{13}\left(\sum_{a=0}^{4}\left(\sum_{c=1}^{3}\hat{p}sub_{y,a,c}^{May} A_{a,l,c}^{May}\right) + \hat{p}_{y,5+}^{May} A_{5+,l}^{May}\right) \qquad y_1 + 1 \le y \le y_n$$

$$\hat{p}_{y,l}^{May} = \sum_{a=1}^{4}\sum_{c=1}^{3}\hat{p}sub_{y,a,c}^{May} A_{a,l,c}^{May} + \hat{p}_{y,5+}^{May} A_{5+,l}^{May} \qquad y_1 + 1 \le y \le y_n, \; l = 13, \ldots, 18\text{cm}$$

$$\hat{p}_{y,18+}^{May} = \sum_{l=18}^{23}\left(\sum_{a=1}^{4}\sum_{c=1}^{3}\hat{p}sub_{y,a,c}^{May} A_{a,l,c}^{May} + \hat{p}_{y,5+}^{May} A_{5+,l}^{May}\right) \qquad y_1 + 1 \le y \le y_n \qquad \text{(A.15)}$$

where the length groups are in 0.5cm L_c and

$A_{a,l,c}^{May}$ is the proportion of the March ($c = 1$), June ($c = 2$) or September ($c = 3$) spawning round herring catch-at-age *a* that fall in the length group l (thus $\sum_{l=2}^{23} A_{a,l,c}^{May} = 1$) in mid-May.

$A_{5+,l}^{May}$ is the proportion of round herring catch-at-age 5+ that fall in the length group l (thus $\sum_{l=1.5}^{25} A_{5+,l}^{Nov} = 1$) in mid-May.

A plus group of 18cm was chosen to ensure that all observations were non-zero. The matrix A^{May} is calculated under the assumption that length-at-age is normally distributed about the same von Bertalanffy growth curve mentioned above:

$$L_{a,1}^{May} \sim N\left(L_\infty\left(1-e^{-\kappa(a+14.5/12-t_0)}\right), \vartheta_a^2\right) \qquad 0 \le a \le 4$$

[3] Age 6 is used here to account for the greater average age of the plus group.

$$L_{a,2}^{May} \sim N\left(L_\infty\left(1-e^{-\kappa(a+11.5/12-t_0)}\right), \vartheta_a^2\right) \qquad 0 \le a \le 4$$

$$L_{a,3}^{May} \sim N\left(L_\infty\left(1-e^{-\kappa(a+8.5/12-t_0)}\right), \vartheta_a^2\right) \qquad 0 \le a \le 4$$

$$L_{5+}^{May} \sim N\left(L_\infty\left(1-e^{-\kappa(6-t_0)}\right), \vartheta_a^2\right)^4 \qquad \text{(A.16)}$$

Fitting the Model to Observed Data (Likelihood)

The survey observations are assumed to be log-normally distributed, and sampling CVs (squared) of the untransformed survey observations are used to approximate the "sampling" component of the total variance of the corresponding log-distributions. The commercial proportions at length from the raised length frequencies are assumed to be lognormally distributed. Thus we have:

$$\begin{aligned}
-\ln L = {} & \tfrac{1}{2}\sum_{y=y1}^{yn-1}\left\{\frac{\left(\ln B_{Nov,y}^{RH} - \ln(k_N^{RH}\hat{B}_{Nov,y}^{RH})\right)^2}{(\sigma_{y,N}^{RH})^2 + (\lambda_N^{RH})^2} + \ln\left[2\pi\left((\sigma_{y,N}^{RH})^2 + (\lambda_N^{RH})^2\right)\right]\right\} \\
& + \tfrac{1}{2}\sum_{y=y1+1}^{yn}\left\{\frac{\left(\ln B_{May,y}^{RH} - \ln(k^{coverage}k_r^{RH}\hat{B}_{May,y}^{RH})\right)^2}{(\sigma_{y,r}^{RH})^2 + (\lambda_r^{RH})^2} + \ln\left[2\pi\left((\sigma_{y,r}^{RH})^2 + (\lambda_r^{RH})^2\right)\right]\right\} \\
& + w_{com,\min}\sum_{y=y1+1}^{yn}\left\{\frac{p_{y,l\min}^{com}\left(\ln p_{y,l\min}^{com} - \ln \hat{p}_{y,l\min}^{com}\right)^2}{2\left(\sigma_{com,\min}\right)^2} + \ln\left(\frac{\sigma_{com,\min}}{\sqrt{p_{y,l\min}^{com}}}\right)\right\} \\
& + w_{com}\sum_{y=y1+1}^{yn}\sum_{l=l\min+1}^{l\max}\left\{\frac{p_{y,l}^{com}\left(\ln p_{y,l}^{com} - \ln \hat{p}_{y,l}^{com}\right)^2}{2\left(\sigma_{com}\right)^2} + \ln\left(\frac{\sigma_{com}}{\sqrt{p_{y,l}^{com}}}\right)\right\} \\
& + w_{Nov,\min}\sum_{y=y1}^{yn-1}\left\{\frac{p_{y,l\min N}^{Nov}\left(\ln p_{y,l\min N}^{Nov} - \ln \hat{p}_{y,l\min N}^{Nov}\right)^2}{2\left(\sigma_{Nov,\min}\right)^2} + \ln\left(\frac{\sigma_{Nov,\min}}{\sqrt{p_{y,l\min N}^{Non}}}\right)\right\} \\
& + w_{Nov}\sum_{y=y1}^{yn-1}\sum_{l=l\min N+1}^{l\max N}\left\{\frac{p_{y,l}^{Nov}\left(\ln p_{y,l}^{Nov} - \ln \hat{p}_{y,l}^{Nov}\right)^2}{2\left(\sigma_{Nov}\right)^2} + \ln\left(\frac{\sigma_{Nov}}{\sqrt{p_{y,l}^{Nov}}}\right)\right\} \\
& + w_{May,\min}\sum_{y=y1+1}^{yn}\left\{\frac{p_{y,l\min M}^{May}\left(\ln p_{y,l\min M}^{May} - \ln \hat{p}_{y,l\min M}^{May}\right)^2}{2\left(\sigma_{May,\min}\right)^2} + \ln\left(\frac{\sigma_{May,\min}}{\sqrt{p_{y,l\min M}^{May}}}\right)\right\} \\
& + w_{May}\sum_{y=y1+1}^{yn}\sum_{l=l\min M+1}^{l\max M}\left\{\frac{p_{y,l}^{May}\left(\ln p_{y,l}^{May} - \ln \hat{p}_{y,l}^{May}\right)^2}{2\left(\sigma_{May}\right)^2} + \ln\left(\frac{\sigma_{May}}{\sqrt{p_{y,l}^{May}}}\right)\right\}
\end{aligned}$$

(A.17)

where

$B_{Nov,y}^{RH}$ is the acoustic survey estimate (in thousand tons) of round herring biomass from the November survey in year y, with associated CV $\sigma_{y,N}^{RH}$ and constant of proportionality (multiplicative bias[5]) k_N^{RH};

[4] Age 6 is used here to account for the greater average age of the plus group.

$B^{RH}_{May,y}$ is the acoustic survey estimate (in thousands of tons) of round herring biomass from the May survey in year y, with associated CV $\sigma^{RH}_{y,r}$ and constant of proportionality k_r^{RH} [6];

$(\lambda^{RH}_{N/r})^2$ is the additional variance (over and above the survey sampling CV $\sigma^{RH}_{y,N/r}$ that reflects survey inter-transect variance) associated with the November/recruit surveys (see Appendix C);

$k^{coverage}$ is the multiplicative bias associated with the May survey denoting the proportion of the biomass for the fully selected age (age = 1) that is covered by the survey, in comparison to the proportion of the biomass surveyed in November – note that this is not incorporated in k_r^{RH};

$p^{com}_{y,l}$ is the observed proportion (by number) of the commercial catch in length group l during year y (June $y-1$ to May y);

$p^{Nov/May}_{y,l}$ is the observed proportion (by number) of length group l fish during the November/May survey in year y;

$w_{com,\min}$ is the weighting applied to the commercial proportion at length 13cm (the minus group);

w_{com} is the weighting applied to the remainder of the commercial proportion at length data;

$w_{Nov/May,\min}$ is the weighting applied to the November/May proportion at length 11/13cm (the minus group);

w_{May} is the weighting applied to the remainder of the November/May proportion at length data;

$\sigma_{com,\min}$ is the standard deviation associated with the proportion-at-length 13cm (minus group) data in the commercial catch, which is estimated in the fitting procedure by:

$$\sigma_{com,\min} = \sqrt{\sum_{y=y1+1}^{yn} p^{com}_{y,l\min}\left(\ln p^{com}_{y,l\min} - \ln \hat{p}^{com}_{y,l\min}\right)^2 \Big/ \sum_{y=y1+1}^{yn} 1}\,.$$

σ_{com} is the standard deviation associated with the remaining proportion-at-length data in the commercial catch, which is estimated in the fitting procedure by:

$$\sigma_{com} = \sqrt{\sum_{y=y1+1}^{yn}\sum_{l=l\min+1}^{l\max} p^{com}_{y,l}\left(\ln p^{com}_{y,l} - \ln \hat{p}^{com}_{y,l}\right)^2 \Big/ \sum_{y=y1+1}^{yn}\sum_{l=l\min+1}^{l\max} 1}\,.$$

$\sigma_{Nov,\min}$ is the standard deviation associated with the proportion-at-length 11cm (minus group) data in the November survey data, which is estimated in the fitting procedure by:

$$\sigma_{Nov,\min} = \sqrt{\sum_{y=y1}^{yn-1} p^{Nov}_{y,l\min N}\left(\ln p^{Nov}_{y,l\min N} - \ln \hat{p}^{Nov}_{y,l\min N}\right)^2 \Big/ \sum_{y=y1}^{yn-1} 1}\,.$$

σ_{Nov} is the standard deviation associated with the remaining proportion-at-length data in the November survey data, which is estimated in the fitting procedure by:

[5] This includes an estimate of all bias associated with the survey, including the bias introduced due to the use of a target strength for a species other than round herring (see Appendix C).

$$\sigma_{Nov} = \sqrt{\sum_{y=y1}^{yn-1} \sum_{l=l\min N+1}^{l\max N} p_{y,l}^{Nov} \left(\ln p_{y,l}^{Nov} - \ln \hat{p}_{y,l}^{Nov}\right)^2 \Big/ \sum_{y=y1}^{yn-1} \sum_{l=l\min N+1}^{l\max N} 1} \; .$$

$\sigma_{May,\min}$ is the standard deviation associated with the proportion-at-length 13cm (minus group) data in the May survey data, which is estimated in the fitting procedure by:

$$\sigma_{May,\min} = \sqrt{\sum_{y=y1+1}^{yn} p_{y,l\min M}^{May} \left(\ln p_{y,l\min M}^{May} - \ln \hat{p}_{y,l\min M}^{May}\right)^2 \Big/ \sum_{y=y1+1}^{yn} 1} \; .$$

σ_{Nov} is the standard deviation associated with the remaining proportion-at-length data in the November survey data, which is estimated in the fitting procedure by:

$$\sigma_{May} = \sqrt{\sum_{y=y1+1}^{yn} \sum_{l=l\min M+1}^{l\max M} p_{y,l}^{May} \left(\ln p_{y,l}^{May} - \ln \hat{p}_{y,l}^{May}\right)^2 \Big/ \sum_{y=y1+1}^{yn} \sum_{l=l\min M+1}^{l\max M} 1} \; .$$

The raw commercial catch data are in 0.5cm length classes of caudal length, L_c.

Fixed Parameters

The following parameters are fixed externally in this assessment:

Natural mortality: $M_a^{RH} = 1.3$, $0 \le a \le 5+$.

There are 16 length classes in the commercial catch data, 18 in the November survey data and 11 in the May survey data. However, these length classes are not all independent as there are only about 5 age groups. Therefore dividing the length data contribution to the likelihood by 3 gives it a weighting close to the 5 age groups. Thus $w_{com} = w_{|Nov} = w_{May} = 0.33$.

The assumption is made that $w_{com,\min} = w_{Nov,\min} = w_{May,\min} = 1$ as it represents a single age group.

It is assumed that age 1 fish are fully selected in the commercial catch, i.e. $S_1 = 1$.

Initial model fits with additional parameters indicated a negligible selectivity for ages 2+ and thus these are fixed at 0, i.e. $S_3 = S_4 = S_{5+} = 0$.

It is assumed that age 0 (March and June sub-cohorts) and age 1 fish are fully selected in the November survey, i.e. $S_0^{Nov} = S_1^{Nov} = 1$

It is assumed that age 0 (all sub-cohorts) fish are fully selected in the May survey, i.e. $S_0^{May} = 1$

The multiplicative bias on the November survey estimate of abundance and on the May recruitment estimate were fixed at $k_N^{RH} = 0.340$ and $k_r^{RH} = 0.427$, respectively, corresponding to the means of normal distributions fitted to pdfs of all individual constant bias factors (Appendix C). Additional (inter-transect) variance on the November and May surveys were fixed at $\left(\lambda_N^{RH}\right)^2 = 0.076$ and $\left(\lambda_r^{RH}\right)^2 = 0.052$, respectively, corresponding to the means of normal distributions fitted to pdfs of all individual variable and random bias factors (Appendix C).

Estimable Parameters and Prior Distributions

Annual recruitment: $\hat{N}^{RH}_{y,0} \sim U(0{,}5000)$ billion, $y_1 \leq y \leq y_n - 1$

Initial numbers at age: $\hat{N}^{RH}_{1987,1} \sim U(0{,}500)$ and $\hat{N}^{RH}_{1987,a} \sim U(0{,}50)$, $2 \leq a \leq 5+$

Split of recruitment by sub-cohort: $p_1 = q_1 q_2$, $p_2 = q_2 - p_1$, with $q_1, q_2 \sim U(0{,}1)$

With $\hat{N}sub^{RH}_{1987,a,1} = p_1 \times \hat{N}^{RH}_{1987,a}$, $1 \leq a \leq 4$

$\hat{N}sub^{RH}_{1987,a,2} = p_2 \times \hat{N}^{RH}_{1987,a}$, $1 \leq a \leq 4$

$\hat{N}sub^{RH}_{1987,a,3} = (1 - p_1 - p_2) \times \hat{N}^{RH}_{1987,a}$, $1 \leq a \leq 4$

And $\hat{N}sub^{RH}_{y,0,1} = p_1 \times \hat{N}^{RH}_{y,0}$

$\hat{N}sub^{RH}_{y,0,2} = p_2 \times \hat{N}^{RH}_{y,0}$

$\hat{N}sub^{RH}_{y,0,3} = (1 - p_1 - p_2) \times \hat{N}^{RH}_{y,0}$

Selectivity at age: $S_0, S_2 \sim U(0{,}1)$

November survey selectivity at age: $S^{Nov}_a = e^{-x(a-1)}$, $2 \leq a \leq 5+$, with $x \sim U(0{,}5)$ estimated

May survey selectivity at age: $S^{May}_a = e^{-z(a-1)}$, $1 \leq a \leq 5+$ with $z \sim U(0{,}10)$ estimated

May Survey coverage compared to November survey coverage: $k^{coverage} \sim U(0{,}2)$

Variance about the mean length at age 0: $\vartheta^2_0 \sim U(0{,}0.15)$

Variance about the mean length at age: $\vartheta^2_a \sim U(0{,}0.15)$, $a = 1, \ldots, 4$

Variance about the mean length at age 5+: $\vartheta^2_{5+} \sim U(0{,}0.15)$

APPENDIX B: Data and standard inputs used in the South African Round Herring Assessment

November acoustic survey

A time series of estimates of annual biomass from November 1984 to November 2009 are available, together with CVs (Table B.1). The assumption is made that these estimates of abundance are comparable. Coetzee and Merkle (2009) compared visually survey effort and biomass, noting too the general correlation between increased survey estimated recruitment (which should be less influenced by offshore extensions of survey effort) and subsequent increased survey November biomass, and concluded that the increase in biomass for the duration of the time series was ‘real’ and not correlated to the increase in survey effort.

Although the November survey length frequencies indicate that some recruits (<12cm L_c) are sampled by the survey, the numbers are low (Janet Coetzee pers. comm.). The weight of these recruits and their contribution to the total biomass would therefore be small. Thus the survey estimates of abundance are assumed to measure the relative 1+ biomass.

May recruit acoustic survey

A time series of estimates of annual recruitment numbers and biomass is available from May 1987 to May 2010, together with CVs (Table B.1). The assumption is made that these estimates of biomass and recruitment are comparable.

Von Bertalanffy Growth Curve

The von Bertalanffy parameters are: $L_\infty = 20.30$ L_c, $\kappa = 0.937$, $t_0 = 0.1$. The derivation of this growth curve is detailed in Durholtz et al. (2010).

Weight at age

A length-weight relationship has been calculated from the 5 years of November survey data between 2005 and 2009 (Y. Geja and D. Durholtz pers. comm.):

$W = 0.0084 \times L_c^{3.0883}$

where weight is in grams and caudal length (L_c) in cms. This length-weight relationship was applied to the length-at-age calculated by the mean von Bertlanffy relationship assumed for the model to give the weight-at-age values listed in Tables B.2a-d. The weight-at-age 5+ was calculated as $w_{5+} = \frac{\sum_{a=5}^{8} w_a prop_a}{\sum_{a=5}^{8} prop_a}$, where

$prop_a = e^{-(a-5)M_{ad}}$ denotes the relative proportion at age, assuming a low fishing mortality on older ages.

Commercial catch

Commercial catch raised length frequencies are available by month from 1987 onwards. The annual data listed in Table B.3 is the sum of the months of June of the previous year to May of the reported year.

Table B.1. Time series of annual estimates of 1+ biomass from the November acoustic survey (in tons), with CVs, and estimates of recruitment from the May acoustic survey (in billions), with CVs.

Year	November survey		May survey up to Cape Infanta	
	Biomass	CV	Biomass	CV
1984	80 546	0.337		
1985	253 750	0.227		
1986	349 282	0.305		
1987	545 522	0.201	58 214	0.152
1988	380 531	0.323	18 711	0.277
1989	881 286	0.264	54 286	0.267
1990	440 117	0.181	33 095	0.689
1991	642 954	0.250	93 830	0.235
1992	751 462	0.170	126 229	0.334
1993	523 388	0.220	100 967	0.225
1994	284 887	0.213	62 609	0.217
1995	586 870	0.135	152 197	0.548
1996	596 511	0.156	378 938	0.345
1997	624 054	0.295	195 492	0.224
1998	1 247 966	0.149	160 525	0.376
1999	1 398 329	0.171	355 087	0.217
2000	1 420 454	0.169	582 579	0.424
2001	1 045 517	0.131	312 982	0.247
2002	917 853	0.189	406 132	0.296
2003	1 761 631	0.108	337 754	0.212
2004	1 475 464	0.100	415 721	0.275
2005	1 616 260	0.130	436 840	0.169
2006	1 228 446	0.106	301 534	0.185
2007	1 720 865	0.153	257 984	0.250
2008	1 260 460	0.118	562 608	0.212
2009	1 990 831	0.108	260 185	0.239
2010			278 731	0.189

Table B.2a. The weight-at-age (in grams) corresponding to the pulse of commercial catch at 1 March, $w_{a,c}^{Mar}$, $a=0,\ldots,4$ and w_{5+}^{Mar}.

Age	March sub-cohort ($c=1$)	June sub-cohort ($c=2$)	September sub-cohort ($c=3$)
0	16.15	8.13	2.53
1	51.88	43.78	34.82
2	74.29	70.09	65.02
3	84.60	82.78	80.52
4	88.89	88.15	87.22
5+		89.40	

Table B.2b. The weight-at-age (in grams) corresponding to the May survey, $w_{a,c}^{May}$, $a=0,\ldots,4$ and w_{5+}^{May}.

Age	March sub-cohort ($c=1$)	June sub-cohort ($c=2$)	September sub-cohort ($c=3$)
0	23.81	14.70	7.00
1	57.86	50.60	42.34
2	77.20	73.64	69.31
3	85.83	84.32	82.44
4	89.38	88.77	88.01
5+		89.40	

Table B.2c. The weight-at-age (in grams) corresponding to the pulse of commercial catch taken prior to the November survey at 1 September, $w_{a,c}^{Sep}$, $a=0,\ldots,4$ and w_{5+}^{Sep}.

Age	March sub-cohort ($c=1$)	June sub-cohort ($c=2$)	September sub-cohort ($c=3$)
0	2.53	0.17	N/A
1	34.82	25.39	16.15
2	65.02	58.97	51.88
3	80.52	77.73	74.29
4	87.22	86.05	84.60
5+		89.40	

Table B.2d. The weight-at-age (in grams) corresponding to the November survey, $w_{a,c}^{Nov}$, $a=0,\ldots,4$ and w_{5+}^{Nov}.

Age	March sub-cohort ($c=1$)	June sub-cohort ($c=2$)	September sub-cohort ($c=3$)
0	7.00	1.91	N/A
1	42.34	33.27	23.81
2	69.31	64.08	57.86
3	82.44	80.10	77.20
4	88.01	87.04	85.83
5+		89.40	

Table B.3. The numbers at length (in thousands) in the commercial catch, and the corresponding catch (in tons). Note that the catch for year y consists of the catch from 1st June $y-1$ to 31st May y. The catch (in tons) from 1 June $y-1$ to mid-November $y-1$ is also tabled.

Length Class (L_c in cm)	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Tonnage to mid-Nov	293	156	273	225	245	1383	12357	5934	958	4701	6922	2095
Tonnage	64582	44600	46276	33550	47005	46054	60448	81819	43512	90107	57663	57336
3.5	0	0	0	0	0	0	0	1210	0	0	0	0
4.0	0	0	188	136	344	933	0	4033	0	0	0	0
4.5	0	20	1590	3802	42	1396	3	5451	264	0	1027	1142
5.0	9	436	1560	18107	644	11656	3278	17966	5717	1402	2918	91752
5.5	132	1312	4112	24879	32578	72276	31932	13226	28412	2044	14124	3812
6.0	1228	20776	12596	37549	9808	43569	88839	82300	28940	3703	35206	30732
6.5	15795	21662	10209	63102	25452	29200	119539	113561	55497	6037	54445	21765
7.0	22868	127778	55153	57340	36893	35559	88063	88795	72965	36038	61051	59664
7.5	12226	22966	45484	45462	34696	26987	63975	65737	119077	148602	40950	88257
8.0	6729	2988	40204	33918	26483	22613	283301	68331	111041	132460	32035	156403
8.5	3058	4870	36379	20096	22533	28108	95722	66983	49106	83287	39678	124366
9.0	4708	9780	22763	9712	20849	26834	47427	50800	37392	132225	43534	76824
9.5	6509	12952	13304	8572	18682	28838	42161	47815	38429	105417	34327	54855
10.0	7500	11244	6010	3053	17083	25657	24391	39363	51578	101222	19499	49394
10.5	6659	4814	3893	384	18878	24017	12950	28011	41749	45901	22480	17651
11.0	5038	2168	1764	219	13731	19798	9684	13505	17607	43712	27557	18421
11.5	2526	1785	463	148	8272	17082	4497	5061	5926	27754	32206	7219
12.0	2346	1833	626	2097	6143	11738	4581	2605	1740	8444	39926	4293
12.5	1867	165	422	289	2630	9134	5238	2263	783	5476	44173	470
13.0	2267	927	1221	492	2109	11601	9803	3634	713	21051	27825	924
13.5	2235	1435	777	337	922	15123	27055	5910	938	16216	22024	1889
14.0	968	3114	3350	662	6293	23003	63718	13002	3907	44289	30556	4016
14.5	5979	2354	3910	1905	21313	48125	113041	26941	10425	46367	38148	18667
15.0	34697	8311	6808	5852	54216	110940	196053	82506	23207	61819	48845	36325
15.5	76580	34783	7315	16042	103608	188813	198565	181847	43286	75067	62061	62604
16.0	102302	49349	15379	36821	161932	226282	189852	296054	108218	134197	95323	115229
16.5	119760	106594	35935	59041	154602	138816	139083	286859	167712	190492	151824	142682
17.0	125465	151644	80222	84928	115861	57493	86520	217875	161957	269486	171789	153853
17.5	114880	141090	122301	87714	75105	27162	53894	146720	96829	252920	138899	133992
18.0	99058	87488	126588	74923	54165	15541	29239	96800	51393	178824	83154	87150
18.5	95477	52635	90429	51736	33495	10290	17069	59433	20568	87594	44962	52519
19.0	69588	26878	57948	33950	20346	8032	9292	35549	10703	35864	23275	33807
19.5	45410	14189	32785	15663	10240	3657	4045	19385	4770	11312	11404	16563
20.0	26329	8321	17370	8845	4508	1909	5103	8588	1965	5176	6800	8898
20.5	11553	4694	8119	2999	1921	383	779	3788	1167	2542	1297	7085
21.0	5192	2560	4315	1246	683	175	179	885	501	1944	1472	3990
21.5	2433	1293	1804	242	172	0	193	79	616	234	416	2133
22.0	806	568	889	156	121	0	23	162	132	0	570	195
22.5	358	37	202	144	33	0	97	0	186	0	0	0
23.0	124	3	28	0	12	0	670	0	0	0	0	65

Table B.3 (continued).

Length Class (L_c in cm)	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Tonnage to mid-Nov	3216	4461	1890	739	8230	15231	3829	7526	1683	699	4247
Tonnage	36346	56703	56815	34941	40171	39444	37814	53650	66651	36989	89152
3.5	0	0	0	0	0	0	0	0	0	0	0
4.0	0	275	0	4	196	0	0	74	0	0	257
4.5	1192	688	0	1523	3321	0	134	496	0	0	3376
5.0	11450	321	4	4438	14270	6207	6030	6577	712	378	18651
5.5	35039	125	11	19670	183961	33083	5678	41347	100	1087	99617
6.0	63035	6432	14	24780	26944	82217	8543	127469	315	6098	102628
6.5	84150	37148	547	40858	36528	108793	23529	183168	4417	16971	84844
7.0	78973	43545	2413	54890	40369	125373	40999	218400	11669	23122	224061
7.5	26290	41098	6409	48228	49446	167992	67744	172644	18771	19210	167132
8.0	29705	6405	5258	29945	56747	125025	68441	267471	11324	13098	111732
8.5	38184	30105	7231	23683	47262	88430	75416	235538	18666	6450	34107
9.0	24748	7949	6412	31420	30321	55699	57736	86507	6597	11662	27878
9.5	8632	26369	4196	40279	14053	82027	35880	30578	7562	6664	13358
10.0	5364	27965	16714	12369	5434	116156	15237	20868	8279	3714	10293
10.5	6427	23672	646	11671	4837	130120	9070	34572	2280	7932	7691
11.0	16943	9648	668	19239	5773	122409	7029	49602	2621	5503	6071
11.5	7215	9781	384	39320	12406	92964	6470	29637	1294	13035	10353
12.0	7965	27725	226	57984	15463	60157	4783	89153	6305	6364	6521
12.5	6192	20581	1106	58749	24343	65392	5530	89402	7637	12429	1667
13.0	14955	27998	9166	40492	55310	60594	8973	54335	46794	15098	5018
13.5	10318	61858	20629	25414	77530	73402	31605	48990	85095	5038	9613
14.0	26121	93757	35362	21438	100981	118835	71706	33521	140802	5940	19121
14.5	22166	113375	47090	19203	78765	125703	124276	73678	170200	17159	52565
15.0	36337	114009	99863	28821	75099	94089	105847	90036	204847	29836	85427
15.5	62425	81671	202682	35635	70288	60513	89128	95659	214324	46223	116385
16.0	89618	103865	253809	53999	73909	53355	74529	107805	187902	79515	170832
16.5	135751	112680	199878	73355	77908	37704	74136	90062	135926	94850	214739
17.0	116358	127691	122076	73376	66474	28054	64269	76487	96997	128300	241224
17.5	56383	112969	73704	60171	55146	15520	41053	66708	65951	88425	211322
18.0	26062	78831	37771	52317	27437	9804	25769	51371	43888	67805	179034
18.5	11273	37670	23546	35419	22215	7510	18671	35062	26616	28851	108929
19.0	4232	15546	9521	18854	13175	5020	11949	24049	15292	18296	64755
19.5	792	8283	6436	11327	5865	2615	11102	11869	8729	11344	32209
20.0	1067	2763	2095	4995	5780	2083	6318	6340	4847	2706	15368
20.5	414	607	418	2133	745	475	2794	2880	2181	1872	8788
21.0	203	93	515	1822	72	367	1216	2157	972	1739	5690
21.5	0	96	164	439	650	3	667	1647	315	294	1462
22.0	174	40	0	117	0	103	0	694	88	0	782
22.5	0	0	0	67	0	0	0	350	0	0	183
23.0	0	0	0	33	0	0	0	170	0	0	31

APPENDIX C: Calculating the bias in estimates of round herring abundance from the November and May hydro-acoustic surveys

Probability density functions (pdfs) for the overall biases in the November and May surveys, k_N^{RH} and k_r^{RH}, were calculated by drawing ten thousand samples from the individual pdfs for each source of constant error, together with the median values of the individual pdfs of each source of variable and random error (see Tables C.1 and C.2 with reasons given by Janet Coetzee in the Annex). Pdfs of the inter-transect variance, $(\lambda_N^{RH})^2$ and $(\lambda_r^{RH})^2$, were then calculated by drawing ten thousand samples from the individual pdfs for each source of variable and random error. The resultant pdfs on the model predicted biomass (i.e. the inverse of the pdfs calculated using the errors provided), together with normal distributions fitted to these pdfs are given in Figures C.1 to C.4.

Table C.1. Individual error factors for November hydro-acoustic surveys of round herring biomass, where the values define trapezium form pdfs. Note that these error factors apply to the observed biomass, i.e. they reflect the inverse of the multiplicative bias (applied to predicted biomass) in this document.

Error	Minimum	Likely (lower)	Likely (midpoint)	Likely (upper)	Maximum	Nature
Target Strength	0.50	1.10	1.40	1.70	2.00	Constant
Depth dependence on target strength	1.00	1.25	1.50	1.75	2.00	Variable
Calibration						
(On-axis sensitivity)	0.90	0.95	1.00	1.05	1.10	Random[6]
(Beam factor)	0.75	0.90	1.00	1.10	1.25	Constant
Attenuation	1.00	1.05	1.075	1.10	1.15	Variable
Target Identification	0.50	0.80	1.00	1.20	1.50	Random
Weather Effects	1.00	1.10	1.20	1.30	1.50	Variable

[6] Note that for the purposes of this simulation, 'random' and 'variable' factors are treated in the same manner.

Table C.2. Individual error factors for May hydro-acoustic surveys of round herring recruitment, where the values define trapezium form pdfs. Note that these error factors apply to the observed recruitment, i.e. they reflect the inverse of the multiplicative bias (applied to predicted recruitment) in this document.

Error	Minimum	Likely (lower)	Likely (midpoint)	Likely (upper)	Maximum	Nature
Target Strength	0.50	1.10	1.40	1.70	2.00	Constant
Depth dependence on target strength	1.00	1.125	1.25	1.375	1.50	Variable
Calibration						
(On-axis sensitivity)	0.90	0.95	1.00	1.05	1.10	Random
(Beam factor)	0.75	0.90	1.00	1.10	1.25	Constant
Attenuation	1.00	1.025	1.05	1.075	1.10	Variable
Target Identification	0.60	0.85	1.00	1.15	1.40	Random
Weather Effects	1.00	1.005	1.10	1.15	1.50	Variable

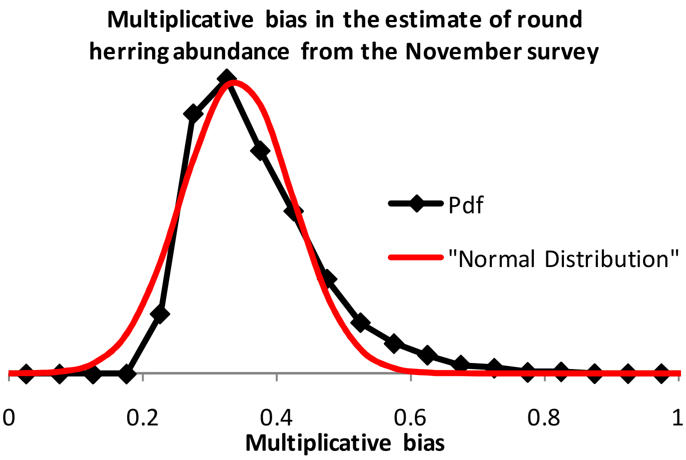

Figure C.1. The probability density function for the overall bias in the estimate of round herring abundance from the November survey, calculated by drawing 10 000 samples from the individual probability distribution functions for each source of constant error, together with the median values of the individual probability distribution functions for each source of variable and random error. The normal distribution fitted to this pdf is $k_N^{RH} \sim N\left(0.3404, 0.083^2\right)$.

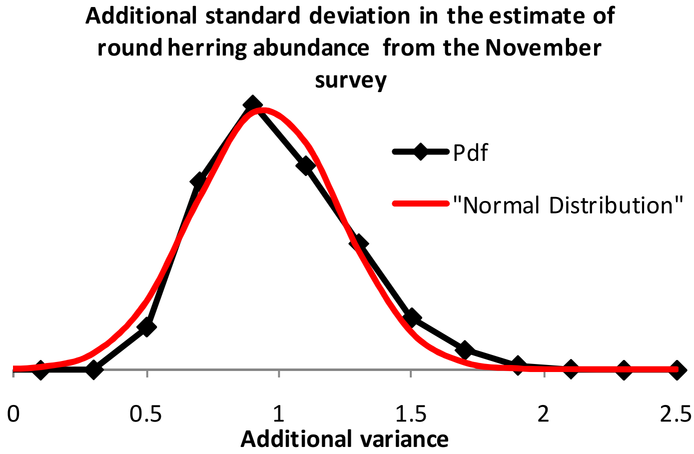

Figure C.2. The probability density function for the additional standard deviation in the estimate of round herring abundance from the November survey, calculated by drawing 10 000 samples from the individual probability distribution functions for each source of variable and random error. The normal distribution fitted to this pdf is $\lambda_N^{RH} \sim N\left(0.2763, 0.954^2\right)$.

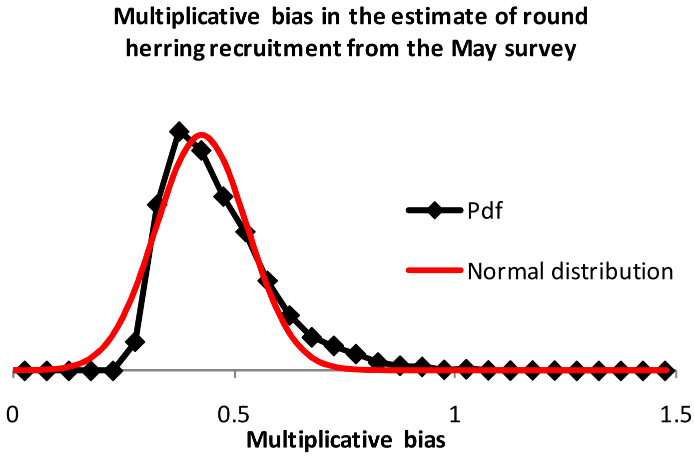

Figure C.3. The probability density function for the overall bias in the estimate of round herring recruitment from the May survey, calculated by drawing 10 000 samples from the individual probability distribution functions for each source of constant error, together with the median values of the individual probability distribution functions for each source of variable and random error. The normal distribution fitted to this pdf is $k_r^{RH} \sim N\left(0.4269, 0.103^2\right)$.

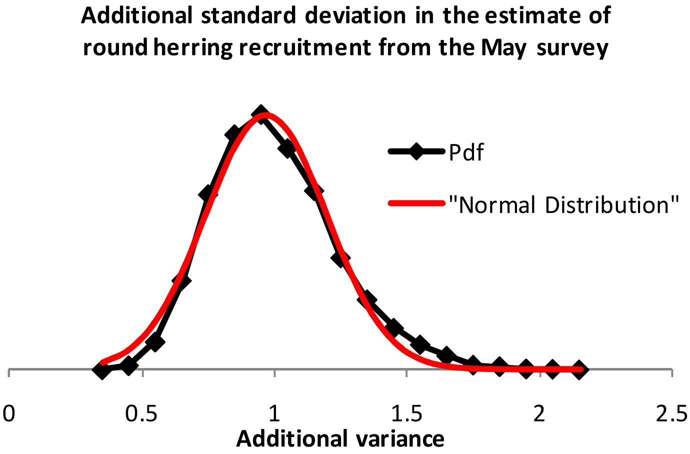

Figure C.4. The probability density function for the additional standard deviation in the estimate of round herring recruitment from the May survey, calculated by drawing 10 000 samples from the individual probability distribution functions for each source of variable and random error. The normal distribution fitted to this pdf is $\lambda_r^{RH} \sim N\left(0.2284, 0.966^2\right)$.

ANNEX: Estimating the likely ranges of individual error factors of round herring abundance from the November and May hydro-acoustic surveys

Janet Coetzee

A BENEFIT workshop held in December 2000 summarised the most likely sources of error relevant to acoustic estimates of fish biomass (Anon 2000) and estimated their likely ranges based on expert opinion and available data. Although these error factors pertained mainly to surveys of anchovy and sardine, they are also pertinent to acoustic surveys of round herring although the effect of the individual errors may differ. Consequently, an initial attempt has been made to update the parameter estimates that define the likely, and minimum and maximum ranges of these errors for round herring. Where necessary, new errors factors have been added and their effects estimated based on available knowledge. It is likely that these may be improved as more data become available. Rationale for the derivation of parameters describing each error factor is provided below and should be read in conjunction with those published in the Survey errors workshop report.

November surveys

- Target Strength

The TS of round herring is unknown and no published data on round herring TS exists. Currently the target strength of round herring is assumed to be the same as that currently used for similar sized sardine (Barange et al. 1996). A general published TS for clupeoids (Foote 1987) would result in a biomass that is 1.38 times higher. Preliminary unpublished data suggests that the TS of round herring should be higher than that of anchovy, but lower than that of sardine. Some recent published TS data for anchovy (Sawada et al. 2009), however, suggests that the TS of anchovy is much higher than previously thought, and we have therefore opted for a relatively high minimum of 0.5. It is unlikely that the maximum error associated with TS can be higher than 2, given the generally similar size and morphology of round herring and sardine and similar acoustic signature at high density. A study is currently being initiated to estimate the TS of round herring from in-situ data and it is likely that the effect of this bias on estimate of round herring biomass will be more accurately determined in the near future.

- Depth dependence on Target Strength

This error was not considered important for anchovy and sardine at the time that the Survey errors workshop was held and is therefore an additional error that has been considered important in the context of round herring biomass estimation. Published findings for herring (Ona 2003) suggests a strong depth dependence on target strength, with halving of TS between the surface and a depth of 200m with the steepest decrease in TS in the first few (upper 50) meters of the water column. Round herring are close to the surface at night only, migrating to deeper water before dawn and staying close to the bottom during the day. At dusk they again migrate up in the water column. Additionally, our surveys are conducted by day and night, so round herring should be deep for approximately 50 % of the time and the max error (factor of 2) should therefore be applicable for half of the acoustic intervals only. But, during migration (up and down in the water column) the tilt angle will be substantially increased and lead to a reduction in TS. For this reason, we have opted to use the max error range and not only applied it for half the time.

- Calibration

Calibration errors are likely to be similar to those of anchovy and sardine and have therefore not been changed from those agreed on at the Survey errors workshop.

- Attenuation

The effect of attenuation on round herring estimates has not been determined. This error factor is, however, most likely substantially less than that of denser schooling sardine (which averages at around 1.15 for November surveys). We have therefore opted to use 1.15 for the maximum error and 1 (cannot be less) for the minimum error and a symmetrical distribution around the likely value of 1.075. It is possible to estimate the effect of attenuation on round herring biomass estimates using a similar method to that used for quantifying attenuation effects in dense schools of sardine.

- Target Identification

The same parameters estimated for the minimum and maximum Target Identification error for anchovy have been applied, but the likely range has been increased. This is to account for larger overestimation of round herring (when the assumption is made that deep targets during the day are most likely to be round herring, but could possibly include horse mackerel). Conversely, diving behaviour at dawn may result in (larger relative to other pelagic species) under-sampling of round herring in some trawls, and consequent underestimation of biomass.

- Weather effects

Weather effects are likely to play a larger role when fish are deeper (vessel pitch and roll effects are amplified at depth) and as such we have opted for a slightly wider likely range compared to that for anchovy, but have suggested that the maximum effect is the same. Again it is likely that the effect of this error may be more accurately estimated in the future.

May surveys

The rationale for the derivation of parameters describing error factors that differ in range from that applicable to November surveys, is provided below; these should again be read in conjunction with those published in the aforementioned Survey errors workshop report:

- Depth dependence on Target Strength

Juvenile round herring tend to be distributed closer inshore during the recruit survey than adults during the November survey and therefore the maximum error is likely to be lower. However, given that the largest reduction in TS occurs within the first 50 m of the water column, it is still considered to be an important source of negative bias. Further analyses on the mean depth of round herring recruits during the May survey may improve estimates of the likely effect.

- Attenuation

As for sardine recruits, attenuation biases are likely to be smaller than those applicable to denser schooling adults. No information on the likely reduction in this effect for round herring recruits is available, but we have assumed that the maximum error is 10% and that the distribution of the error is symmetrical around the likely midpoint of 5%.

- Target Identification

The range of this error should be smaller than that for November surveys, given the closer inshore distribution and smaller overlap between round herring recruits and adult horse mackerel. Similarly the under-sampling of round herring during trawling is likely to be less than that for adults because slower swimming juvenile round herring are less likely to avoid capture than adults. The maximum and minimum ranges have therefore been reduced, although the distribution is still centred on 1 (equal chance of under- or over estimation).

- Weather effects

The maximum range for this error is assumed to be similar for May and November surveys, although the likely range has been halved to account for the more inshore distribution of recruits relative to adults, and consequent reduction in mean depth distribution during the day.

Annex References:

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