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Short communication

Historical variations in the year-class strength of beaked redfish (*Sebastes mentella*) in the Barents Sea

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The present work provides the first quantitative estimate of the historical fluctuations in the year-class strength of beaked redfish in the Barents Sea. The year-class strength index is based on scientific survey data collected by Norway and Russia during the past three decades. It is defined as the effective number of 0-group fish that will eventually enter the fishery. Uncertainties in the year-class strength indices are estimated using a statistical modelling approach, which accounts for observation errors. The reconstructed series indicate clear periods of high recruitment (late 1980s–early 1990s) and 8 years of near complete recruitment failure (1996–2003). The apparent recovery in recent years is highly uncertain and needs to be confirmed by future observations. The modelling approach developed here can be applied to other fish stocks for which catch-at-age data are available from several surveys.

Keywords: age-structured model, observation uncertainties, population dynamics.

Introduction

The fishery for beaked redfish (*Sebastes mentella*) was traditionally conducted by Russia and other East European countries on grounds located south of Bear Island towards Spitsbergen. The highest landings of *S. mentella* (269 000 t in 1976) were followed by a rapid decline to 80 000 t in 1980/1981. Then, a second peak of 115 000 t in 1982 was followed by a decrease in the mid-1980s down to 10 500 t in 1987. Today, the only directed fisheries for *S. mentella* are pelagic trawl fisheries in the Norwegian Sea and beaked redfish in the Norwegian economic zone is classified as a threatened species on the Norwegian red-list (ICES, 2010).

The control of recruitment success of beaked redfish in the Barents Sea remains largely unknown, although data from scientific surveys exist back to several decades. Beaked redfish is characterized by slow life history (with age-at-50% maturity of 11 years and longevity estimated to more than 70 years), slow growth, and ovoviviparity. For these reasons, strong year classes only significantly contribute to the pelagic and demersal trawl fisheries (either as target or as bycatch) after a decade or more, but juveniles can already be caught as bycatch much earlier in the shrimp fishery of the Barents Sea.

Reconstructing the year-class strength history of redfish up to the age when individuals enter the fishery is of primary importance for management and conservation of the species. However, there is currently no analytical assessment for *S. mentella*, and only a non-analytical and qualitative assessment based on survey and catch data is carried out by the ICES Arctic Fisheries Working Group (ICES, 2011). One difficulty in reconstructing the population year-class strength is to assemble data from different sources, which target different age groups, with different gears and at different time of the year. Such problems can be overcome by statistical modelling as has already been demonstrated for Atlantic Mackerel (Simmonds *et al*., 2010).

Our intention is to provide the first quantitative estimate of the historical fluctuations in the year-class strength of beaked redfish in the Barents Sea, based on scientific survey data collected by Norway and Russia during the past three decades, while accounting for variations in the data collection procedure in individual surveys.

Data

Biological data were collected during four sets of surveys: (i) 0-group survey, (ii) winter survey, (iii) ecosystem survey, and (iv) autumn groundfish survey.

The 0-group survey has run since 1965 and is based on pelagic trawling. The winter, ecosystem, and autumn groundfish surveys have been conducted since 1981, 2004, and 1982, respectively, but can be extended further back in time using data from precursor surveys which have used similar gear, sampling design, and data processing. The 0-group survey data used in this study covers the period 1980–2010 (Figure 1). Data from the other three surveys cover the period 1992–2010 and age groups 2–15 (winter survey), 1996–2009 and age groups 2–15 (ecosystem survey), and 1979–2010 and age groups 2–11 (autumn groundfish survey).

Details of the 0-group survey protocols are found in ICES (1980), Dingsør (2005), and Eriksen *et al.* (2009). The winter survey is described in Jakobsen *et al.* (1997) and Johannesen *et al.* (2009). Details on sampling and results from the ecosystem survey can be found in the IMR/PINRO reports (see for 2009: Anon., 2010). Information on the autumn groundfish survey is given in Lepesevich and Shevelev (1997) and Shevelev *et al.* (1998).

The data used in the present study are taken from the ICES Arctic Fisheries Working Group report (ICES, 2011). Data tables are provided in the Supplementary material.

Method

As a first exploratory procedure, we investigated the consistency in the time-series for the different age groups by calculating correlation coefficients between them. The idea of this simple analysis was to explore how much the signal observed in one age group (e.g. year-to-year fluctuations in 3-year-old fish) was related to the signal observed the previous years on younger individuals of the same year class (i.e. year-to-year fluctuations in 2-year-old fish). Before calculation of the correlation coefficients, the data were transformed using a double square-root transformation. This transformation was preferred to log-transformation as it brought the data distribution closer to normality while limiting effects of uncertainty for small numbers usually associated with log-transformation.

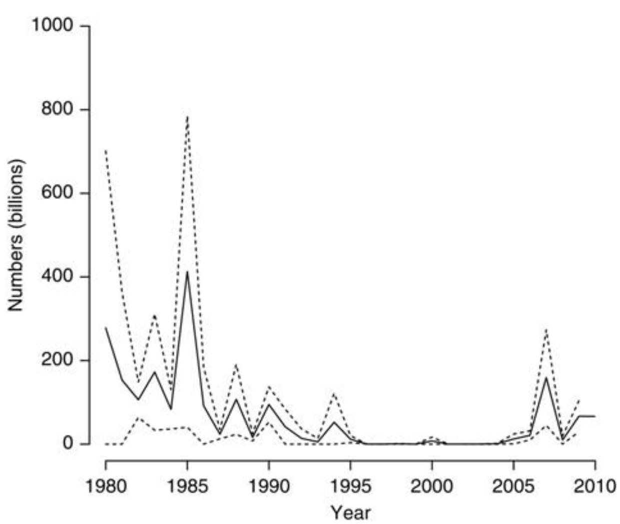

Figure 1. The 0-group survey index for *S. mentella* for the period 1980–2010 (in billions). Dotted lines indicate 95% confidence intervals.

We then constructed a statistical model to represent variations in numbers-at-age in the population and how these are observed by the four research surveys.

The first element of the model is the process model, which describes how the abundance of fish of a given year class and a given age depends on the abundance of fish of the same year class in the previous year:

$$N(y, a) = N(y, a-1)e^{-z(a-1)}, \quad (1)$$

where N is the number of individuals, "y" their year of birth, and "a" their age. The mortality coefficient $z(a-1)$ applies to the mortality between age $a-1$ and a. We assumed that the total mortality could vary between age groups, but not between years. This strong (and rather idealistic) assumption had to be made since one cannot simultaneously estimate varying mortalities for age groups and years from the current data alone. The result of this is that $N(y,0)$ does not represent the true number of recruits (0-group fish) in year y, but rather the effective number of 0-group fish. This quantity is defined as the number of 0-group fish which would have contributed to year-class strength, had the mortalities-at-age remained constant over time. We, therefore, noted this quantity $YCS(y)$, for year-class strength in year y, instead of $N(y,0)$. We found that this quantity is of particular interest because it provides information on the strength of the year class that will eventually enter the fishery. With this assumption on mortality, the equation can be re-written as

$$N(y, a) = YCS(y)e^{\sum_{i=0}^{a-1} -z(i)}. \quad (2)$$

The second part of the model is the observation model, which describes how observations from each survey are related to the true numbers of fish in the ocean. The generic form of the observation model used for the four surveys is

$$N_{obs}(y, a, s) = \frac{1}{Q(S)} G(a, s) N(y, a) \varepsilon_{obs}(s), \quad (3)$$

where $N_{obs}(y, a, s)$ is the number of individuals born in year "y" and of age "a" observed in survey "s". $Q(s)$ is a survey scaling factor. It is set to "1" for the 0-group survey and needs to be estimated for the other three surveys. $G(a,s)$ is a coefficient of gear selectivity at age. The selectivity G for the 0-group survey was unknown and set to 1. Values of G for the Campelen trawl used in the winter and ecosystem surveys were derived from Ajiad *et al.* (2005). Distinct selectivity curves were implemented for the periods before and after 1994 to reflect the implementation of the sorting grid in front of the trawl codend in 1994 and onwards. For the autumn groundfish survey, no selectivity data were available and we assumed a selectivity curve similar to the Campelen trawl before 1994. The observation error term $\varepsilon_{obs}(s)$ is assumed to follow a lognormal distribution of mean "1", the variance of which needs to be estimated separately for each survey s. The full model [combine Equations (2) and (3)] can be expressed in the linearized form:

$$\log(N_{\rm obs}(y, a, s)) = -\log(Q(s)) + \log(G(a,s)) + \log(YCS(y)) - \sum_{i=0}^{a-1} z(i) + \eta_{\rm obs}(s), \quad (5)$$

where the $\eta_{\rm obs}(s)$ follows normal distributions with mean zero and variance to be estimated. The estimates of mortalities (z's) were constrained using a penalized likelihood function. This procedure was equivalent to set a prior on z using the lognormal distribution so that

$$\log(z) \in N(\mu = -3, \sigma = 1.3). \quad (6)$$

The model was implemented in AD Model Builder (ADMB Project, 2009). Data preparation and plotting were done in R (R Development Core Team, 2004) using the R library *scapeMCMC* (Magnusson, 2005). In addition, we also implemented different model versions that included possible survey selectivity effects (in addition to the gear selectivity) and year effects. These models are presented in the Supplementary material together with the ADMB code and the corresponding input data files.

Results

Correlation between age groups

Positive correlations between the different age-group series (Figure 2) indicate that there is a degree of correspondence between successive years of observation. Correlations between the observations of an age group and the same year class the following year are on average highest for the ecosystem survey ($r \sim 0.7$). Similar values are found for the winter survey ($r \sim 0.65$) but the correlation seems to break down after 11 years of age. The temporal patterns recorded in the different age groups in the autumn groundfish survey are less coherent, as seen by the lower correlation coefficients ($r \sim 0.5$).

Synthetic year-class strength time-series

Estimates of year-class strength display large fluctuations during the period 1977–2009 (Figure 3). These are marked by a period of medium to high year-class strength in 1977–1995 followed by 8 years (1996–2003) of very poor year classes. The median estimates of year class since 2004 indicate a possible return to average levels, but estimates for recent years are based on fewer observations and are therefore highly uncertain.

Mortality-at-age

Mortality estimates were found to be highly uncertain. Estimated median mortality-at-age for 2–7-year-old juveniles was very low (Figure 4) with a value around 0.03. For older individuals, the median and the range of mortality estimates sharply increase with age. Although the former estimates are partly driven by the prior distribution set on mortality estimates, the latter estimates are highly uncertain, as indicated by the very large 95% confidence intervals. It was not possible to estimate mortality coefficients between 0-group and 2-year-old fish, since these are sampled in different surveys and the mortality estimates [$z(0)$ and $z(1)$] are confounded with the survey scaling factors (Q's). Overall, the precision of mortality estimates remain poor. Most conventional assessment models assume a fixed value for natural mortality, although there is generally little empirical evidence for the value chosen. The inclusion of mortality-at-age as free parameters in this model permits to account for uncertainty in year-class strength indices that results from uncertain mortality estimates.

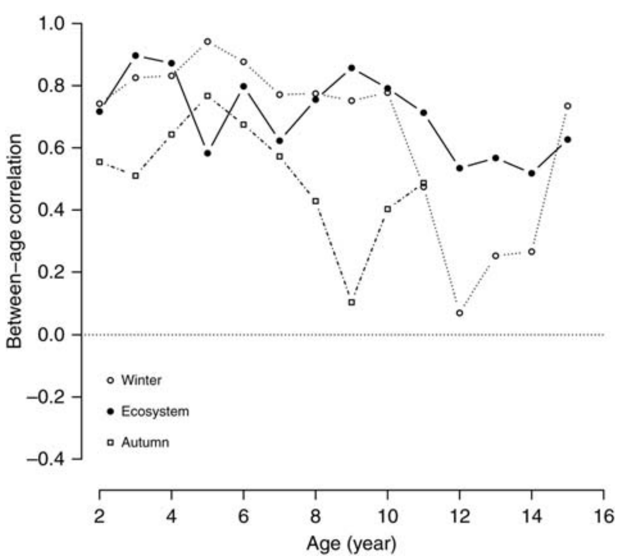

Figure 2. Correlation between time-series of number-at-age for consecutive age groups for the winter (dotted line with open circles), ecosystem (plain line with closed circles), and autumn groundfish (dash-dotted line with squares) surveys. The first point of each series (on the left) represents the correlation between age-2 fish and the 0-group index recorded 2 years previously. All series were transformed with double square root before the calculation of correlations.

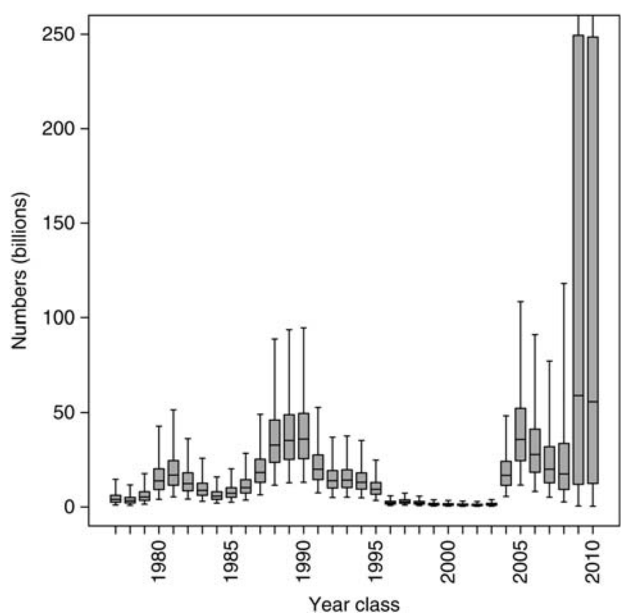

Figure 3. Modelled index of year-class strength (in billions) for the period 1977–2010. The median estimate is indicated by the horizontal line in each box. Box edges outline the 25 and 75% distribution percentiles and whiskers show the 2.5 and 97.5% percentiles. In 2009 and 2010, the upper part of the distribution is off scale.

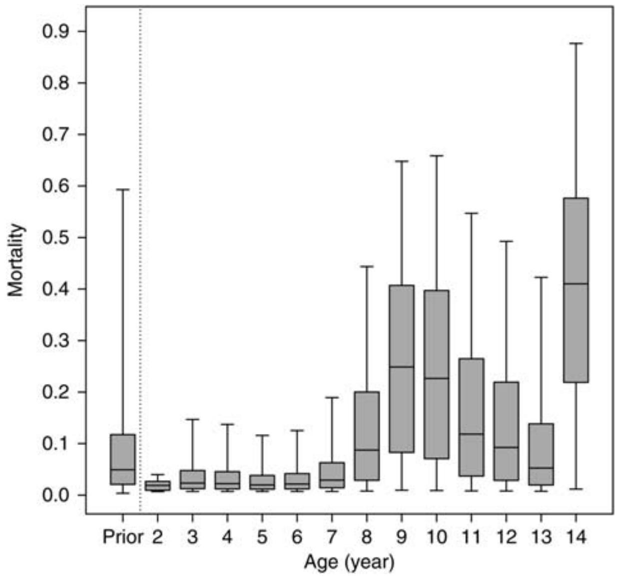

Figure 4. Modelled mortality-at-age for ages 2 – 14.The median and the percentiles are represented as in Figure 3. The first box on the left shows the prior distribution of mortality.

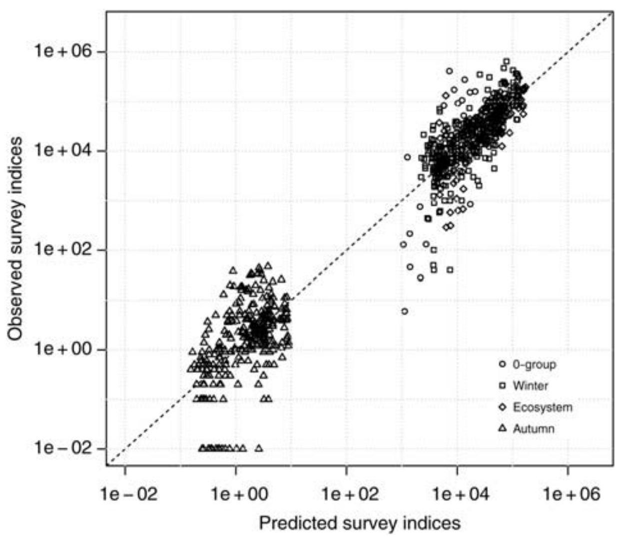

Figure 5. Scatterplot of observed vs. predicted survey indices. The dotted line indicates 1:1 correspondence between observed and predicted indices.

Model fit and contribution of individual surveys

The general fit of the model to individual observations is illustrated in Figure 5. There is overall a good agreement between observations and model predictions except for some of the observations for the 0-group survey and for the very low abundance indices in the autumn groundfish survey. The contribution of the different surveys to the final year-class-strength estimate can be derived from the estimated observation error for each survey. The estimated standard deviations of observation error terms for log-transformed abundances in each survey are as follows: 2.2 (0-group), 1.1 (winter), 0.8 (ecosystem), and 1.6 (autumn groundfish). This indicates that individual observations collected during the ecosystem survey (which has the lowest s.d. and therefore the lowest observation error) are well described by the current model, followed by the winter, autumn groundfish, and 0-group surveys. Observations from the 0-group survey strongly deviate from model predictions as can be seen by comparing Figures 1 and 3. The models' residuals (differences between observations and model predictions) by age and year are well distributed for the ecosystem survey—i.e. they show little patterns with age or time—and to a lesser extent for the winter survey (Figure 6). For the 0-group survey, the pattern of residuals shows a downward trend over time. The residuals from the autumn groundfish survey are not distributed randomly but instead show clear patterns with age and year of observation. There appears to be a change in the residual patterns at the beginning of the 1990s, which suggests change in the survey selectivity at the time, but the possible reasons for such changes are not documented. The contribution of each survey to the final index depends on the number of observations provided so that the contribution of the 0-group survey is reduced (only one observation per year), whereas the contribution of the autumn survey is higher at the beginning of the period when data from the other surveys were only available for a restricted number of age-groups (the oldest fish collected since 1990). Although the ecosystem survey had the lowest observation error, the series remains short and is not sufficient on its own to reconstruct year-class strength fluctuations back to 1977.

Discussion

Currently, there is no analytical population dynamic model for *S. mentella* in the Norwegian and Barents Seas, and consequently no estimates of demographic fluctuations over time. The model presented here does not attempt to fully fill this gap but rather to synthesize historical variations in year-class strength observed from multiple scientific surveys at sea. The reconstructed series indicates clear periods of high recruitment (late 1980s–early 1990s) and 8 years of near complete recruitment failure (1996–2003). The apparent recovery in recent years is highly uncertain and will need to be confirmed by the collection of additional data in future years.

The correlation analysis indicates that year-class strength is already determined to a large extent at the age of two and possibly already for the young of the year fish, as monitored in the 0-group survey. However, it is interesting that the high indices in the 0-group survey in the early 1980′s did not materialize into strong year classes. There is evidence that consumption of juvenile redfish (5–15 cm) by cod (*Gadus morhua*) was high from the late 1980s throughout the 1990s (Figure 6.9 in ICES, 2011) and that the bycatch of redfish in the shrimp fishery was high from the early 1980s to the mid 1980s (Figure 6.3 in ICES, 2007). Whether the high mortalities for young age groups during the early part of the studied period resulted from high predation, high discard rates from the shrimp fishery, or another cause is still unresolved.

The correlation analysis further suggests that fluctuations in abundance within age groups are best captured by the winter and ecosystem surveys, which display highest correlation between age groups. This indicates that the sampling design and protocols used for these surveys (e.g. age reading methodology, geographical coverage, number of sampling stations, etc.) are appropriate to track demographic fluctuations and that the mortality-at-age does not greatly vary between years, at least for fish of age 3 or more. The lower degree of internal consistency in the autumn groundfish survey data may be explained by

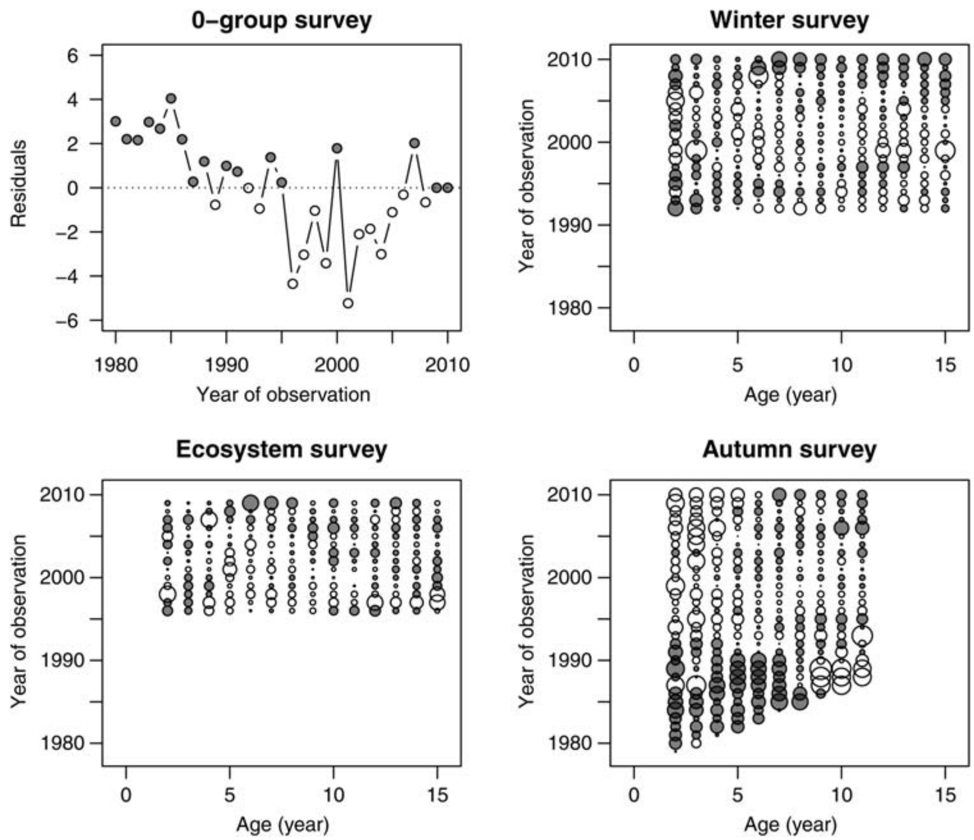

Figure 6. Model residuals (observed minus predicted values) by year and age for each survey. For the winter, ecosystem, and autumn groundfish surveys, closed circles indicate the positive residuals and open circles represent the negative residuals. The area of circles is proportional to the residual values.

changes in area coverage or age reading uncertainties, which would need to be investigated further.

The estimates of mortality-at-age are uncertain and must be considered with caution, nonetheless the 95% distribution intervals provide a good indication of the range of mortality values that can be expected. Although these are low for fish below 7 years, they appear to be higher at later ages. Higher mortalities beyond 7 years can possibly result from higher fishing mortality or increased natural mortality related to migration of older individuals out of the Barents Sea and into the Norwegian Sea. Although these estimates of mortality-at-age are based on the idealistic assumption of stable mortality-at-age from year to year, they can provide a first baseline for the mortality-at-age required for the development of age-structured assessment models.

Overall, the modelling approach developed here for the particular case of beaked redfish can be applied to other fish stocks for which catch-at-age data are available from several surveys.

Conclusions

The methodology used in this study shows that despite high uncertainties and some discrepancies between individual survey data, it is possible to reconstruct a synthetic time-series of year-class strength of beaked redfish in the Barents Sea for the period 1977–2010. The statistical model used includes the formal description of the observation uncertainties. This allows for direct evaluation of the probability distribution for the year-class strength index, but also for the other parameters of the model (survey scaling factors, standard error in survey observation, mortalities). Despite large uncertainties in year-class-strength index estimates, we show that a period of high recruitment in the late 1980s and early 1990s was followed by a rapid decline and 8 consecutive years of recruitment failure (1996–2003). The recovery recorded in recent years (2004 onwards) is still highly uncertain because supported by few observations of the youngest age groups only. This will need to be confirmed by additional years of data.

Supplementary material

Supplementary material is available at the *ICESJMS* online version of the paper. The supplementary material includes (i) data tables for the 0-group, winter, ecosystem, and autumn groundfish surveys, (ii) the table of gear selectivity coefficients, (iii) description of additional model runs and results which include survey selectivity that is independent from gear selectivity and year effects, (iv) point estimates and s.d. of model parameters, (v) the ADMB code, and (vi) the input data files necessary for running the ADMB code.

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References

ADMB Project. 2009. AD Model Builder: automatic differentiation model builder. Developed by David Fournier. http://admb-project.org.

Ajiad, A., Aglen, A., and Nedreaas, K. 2005. Bycatch estimates of redfish (*Sebastes* spp.) in the Norwegian Barents Sea shrimp fisheries during 1983–2002. Working Document of the ICES Arctic Fisheries Working Group, 18. 8 pp.

Anon. 2010. Survey report from the joint Norwegian/Russian Ecosystem survey in the Barents Sea in August–September 2009. IMR/PINRO Joint Report Series, 2/2010. 118 pp.

Dingsør, G. E. 2005. Estimating abundance indices from the international 0-group fish survey in the Barents Sea. Fisheries Research, 72: 205–218.

Eriksen, E., Prozorkevich, D. V., and Dingsør, G. E. 2009. An evaluation of 0-group abundance indices of the Barents Sea fish stocks. The Open Fish Science Journal, 2: 6–14.

ICES. 1980. Preliminary Report of the International 0-Group Fish Survey in the Barents Sea and Adjacent Waters in August/September 1980. ICES Document CM 1980/G: 53. 7 pp.

ICES. 2007. Report of the Arctic Fisheries Working Group (AFWG). ICES Document CM 2007/ACFM: 16. 598 pp.

ICES. 2010. Report of the Arctic Fisheries Working Group (AFWG). ICES Document CM 2010/ACOM: 05. 664 pp.

ICES. 2011. Report of the Arctic Fisheries Working Group (AFWG). ICES Document CM 2011/ACOM: 05. 659 pp.

Jakobsen, T., Korsbrekke, K., Mehl, S., and Nakken, O. 1997. Norwegian combined acoustic and bottom trawl surveys for demersal fish in the Barents Sea during winter. ICES Document CM 1997/Y: 17. 8 pp.

Johannesen, E., Wenneck, T., Høines, Å., Aglen, A., Mehl, S., Mjanger, H., Halland, T. I., *et al.* 2009. Egner vintertoktet seg til overvåking av endringer i fiskesamfunnet i Barentshavet? -en gjennomgang av metodikk og data fra 1981–2007. Fisken og Havet s7/2009. 29 pp.

Lepesevich, Y. M., and Shevelev, M. S. 1997. Evolution of the Russian survey for demersal fish: from ideal to reality. ICES Document CM 1997/Y: 09.

Magnusson, A. 2005. R goes fishing: Analyzing fisheries data using AD Model Builder and R. Proceedings of the 5th International Workshop on Distributed Statistical Computing. http://www.hafro.is/~arnima/uw/s/pdf/dsc.pdf.

R Development Core Team. 2004. R: a Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-00-3, http://www.R-project.org.

Shevelev, M. S., Mamylov, V. S., Ratushny, S. V., and Gavrilov, E. N. 1998. Technique of Russian bottom trawl and acoustic surveys of the Barents Sea and how to improve them. NAFO Scientific Council Studies, 31: 13–19.

Simmonds, E. J., Portilla, E., Skagen, D., Beare, D., and Reid, D. G. 2010. Investigating agreement between different data sources using Bayesian state-space models: an application to estimating NE Atlantic mackerel catch and stock abundance. ICES Journal of Marine Science, 67: 1138–1153.

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