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Connecting Physical-Biological Interactions to Recruitment Variability, Ecosystem Dynamics, and the Management of Exploited Stocks

Including climate into the assessment of future fish recruitment, using multiple regression models.

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Abstract

Climate variability has generally not been included in the assessment of fish stocks in the Barents Sea and Norwegian Sea. However, in recent years there has been a focus on implementing climate variability in the assessment for several stocks in both areas. A promising approach, using linear multiple regression models, has been applied for short time projections of recruitment of Northeast Arctic cod, Norwegian spring spawning herring and Barents Sea capelin. Environmental factors influence the fish throughout their life history. Time lagged climate variables can be used in combination with stock abundance at younger ages to make models with predictive power 1-3 years ahead. The presented models describe 65-85 % of the variance in the recruitment data. The choice of variables in these kinds of models will always be a trade-off between best possible fit, the presences of a time lag and the possibility of updating the regressions/prognosis as close to the assessment as possible. But it is important that there is a plausible cause-and-effect link between the variables. The paper also discusses how this approach can be implemented in present and future assessment work.

Introduction

Today a large effort is put into the assessment of economically important fish stocks in the Barents Sea and the Norwegian Sea. These assessments are mainly based on commercial catch statistics and scientific survey data of the stocks. Climatic variability is generally not considered in the assessment models.

An assessment of a fish stock consists of statistical analyses of the available data, mainly for the purpose of predicting the consequences of various management options. An assessment gives the following products:

- An estimate of the present and historical stock abundance by age (and possibly also by length, sex etc.), preferably with associated uncertainty.
- A conditional short/medium-term prognosis for the development of catch, spawning stock, recruitment of young fish and other variables of interest to the managers, given a chosen management option. To fully allow for a precautionary approach to management, uncertainties should be quantified for the projected variables.

Climatic variables may be included in the estimate of present and historical stock abundance, by taking into account the effect of temperature on survey catchability, stomach evacuation rate (and hence predation) etc. However, the impact of climatic variables on such estimates will generally be much smaller than the impact of climatic variables on recruitment prognoses. Thus, we will only consider inclusion of climatic variables in stock prognoses in this paper.

A prognosis of stock development for a chosen management strategy depends on the current stock size as well as prognoses for recruitment, weight at age, maturity at age, exploitation pattern and natural mortality. Of these variables, recruitment usually has the highest variability. This is most probably due to a strong influence of climate condition, which is not accounted for in present assessment prognostic models. In this paper we will only consider methods for predicting recruitment, limited to year classes that already have been spawned, but have not yet entered the fishery.

Predictions are usually based mainly on regressions between survey indices of pre-recruit fish, and historical estimates of recruitment, i.e. of number of fish at the age it enters the fishery. One such approach commonly used by ICES Working Groups is the RCT3 model (Shepherd, 1997).

We extend such predictions to also include climatic factors by using a combination of recruitment indices and climate variables in a multiple regression model. In order to have predictive power, there has to be a time lag between the explanatory variables (e.g. temperature) and the response variable (i.e. recruitment). One advantage of such an approach is that it fits into the current assessment procedure and may easily be used by assessment working groups.

Three stocks are considered: Northeast Arctic cod (*Gadus morhua*), Norwegian spring spawning herring (*Clupea harengus*) and Barents Sea capelin (*Mallotus villosus*). For all these stocks recruitment is highly variable (Fig. 2).

Material and methods

There are four major considerations to take into account when building a multiple regression model that shall be used to make a prognosis of recruitment, which also incorporates effect of climate variability:

1) There should be a plausible cause-effect link between the response variable and all explanatory variables.
2) There must exist a time lag between the response variable and all the explanatory variables. This is what gives the prognostic power.
3) The number of explanatory variables should not be too high(“rule of thumb”: about 1 variable pr 10 data points).
4) The model must contain a combination of climate and fish stock variables.

Three ecologically and commercially important stocks were chosen for generating recruitment models by multiple regression; Northeast Arctic cod, Barents Sea capelin and Norwegian spring spawning herring. For each of the stocks several variables have been tested, all with different time lags, and the final chosen models are:

Model 1 (cod): $Rec3_t \sim TempKola_{t-3} + 1group_{t-2} + log(capmatb\ io_{t-2})$
Model 2 (capelin): $Rec1_t \sim TempSkinBS_{t-1} + 0group_{t-1} + capmatbio_{t-1}$
Model 3 (herring): $Rec3_t \sim TempSkinNS_{t-3} + 0group_{t-3}$

where the subscript denotes the time lag in years. The different variables are described in the following sections for each stock.

Recruits of Northeast Arctic cod
The main spawning is at the Norwegian coast, mainly north of 67°N, during March-April. Most of the larvae drift into the Barents Sea, where the cod spend the rest of its life (Fig.1), except for the spawning migration. Age of recruitment to the fisheries has been defined as age 3. The cod can reach an age of at least 20 years and a size above 130 cm. Economically it is the most important fish stocks in the area, with typical annual catches between 400 and 800 thousand tonnes. The cod is an opportunistic feeder, eating most available species of suitable size, however it seems that it prefers capelin where it is available. In years when capelin abundance is low or the cod density is high, cannibalism may cause a substantial mortality. Other important predators of cod are seals and whales.

In the model $Rec3_t$ is the number of 3 year old NEA cod from the last ICES Arctic Fisheries Working Group (AFWG) XSA-assessment with cannibalism (ICES CM 2005/ACFM: 20), $TempKola_{t-3}$ the yearly average temperature between 0 and 200m in the Kola section three years earlier, $1group_{t-2}$ is the age 1 bottom trawl index of NEA cod from the Norwegian-Russian bottom trawl survey in January/February two years earlier and c$apmatbio_{t-2}$ is the maturing biomass (individuals larger than 14 cm) of capelin from the Norwegian-Russian acoustic survey estimate of two years earlier. The data used for the model are from the period 1984-2002 for the response variable. The model gives a two-year prognosis of the cod recruitment. However, since all variable data are available before the AFWG meeting (April/May) it is possible to advance the prognosis one more year by using the prognosis estimate for the capelin maturing biomass from the capelin assessment (ICES CM 2005/ACFM:20) the previous autumn.

In the model equation the temperature from the Kola section (7030 N to 7230 N along 3330 E, Tereshchenko 1996 and PINRO pers. comm.) was chosen as climatic term. This section represents the climatic conditions in the southern Barents Sea (Ingvaldsen *et al.*, 2002). Temperature is a climatic variable that affects the cod directly through metabolism and indirectly through food production and availability and therefore has a large effect on the distribution of cod. The 1-group survey index is the link back to the parent population. Using one-group gives a population term, which on one hand is closer in time to the response variable (three year olds) than e.g. spawning stock biomass, and on the other hand still give a reasonable prognostic time lag. The capelin term most likely acts as an inverse cannibalism term, since it seems that older cod prefer capelin to younger cod. A logarithmic approach was chosen in order to dampen the large interannual variations and simulate a saturation level for the cod predation.

Recruits of Barents Sea capelin

The capelin spawns close to the shore on the North Norwegian and northwestern Russian coast during March-April. The east-west location of the main spawning may vary. Most years it occurs somewhere between Tromsø and Murmansk. The capelin has demersal eggs. After hatching the larvae rise from bottom and drift northeastward. The immature stock is typically distributed along the polar front. The maturation depends on the growth conditions, and age at maturity may vary from 2 to 5. After spawning most of the spawners die. The capelin is one of the major plankton feeders in the Barents Sea. It is an important food source for all the large fish species, as well as for seals, whales and sea birds. In years with high abundance of herring in the Barents Sea, the survival of capelin larvae tend to be low due to predation from herring. The capelin stock biomass may fluctuate widely between years (ICES CM 2005/ACFM:20). Annual catches of capelin have varied from zero to 3 million tonnes.

In the model $Rec1_t$ is the number of recruits (acoustic survey estimates back-calculated to 1 August), $TempSkinBS_{t-1}$ the skin temperature from the NCEP reanalysed database average from January to March and over the Barents Sea sub area between 30-45°E and 71-75°N one year earlier, $0group_{t-1}$ the capelin 0-group trawl survey index one year earlier (in August) and $capmatbio_{t-1}$ the capelin maturing biomass in tonnes (acoustic survey estimates of fish above 14 cm length) one year earlier. The data used for the model are from the period 1982-2004 for the response variable. The model gives a one-year prognosis of the capelin recruitment.
The surface temperature in the Southern part of the Barents Sea during winter was chosen as climatic parameter. The chosen area is occasionally partly covered in ice in this period, and thereby influencing the estimate of skin temperature. This climatic term is therefore a proxy for both heat conditions (temperature) and available area (ice cover). The 0-group term is the link back to the parent population. It is not obvious how the maturing biomass is coupled to the 1-group, since this is not the parent population that gives the one-group we are looking at. Most capelin dies after spawning (Gjøsæter, 1998) so there should not be a direct link between the maturing term on one side and the 0-group and 1-group term on the other side. However, this combination of parameters and time lag gave the best fit. If one should speculate about how they are coupled, two mechanisms are likely. First, feeding conditions would be equal for both the maturing and the 0-group populations, which gives the survival from 0-group to 1-group. Second, the maturing populations may act as a buffer for predation, i.e. cod, as a major predator (Mehl, 1989), prefer larger individuals to small ones (0-group/1-group), but will eat anything if large individuals are not accessible (years with low mature population).

Norwegian spring spawning herring

Since the 1970s most of the adult herring have over-wintered in fjords at the North Norwegian west coast. During the 1950s and 1960s over-wintering concentrations were observed in the Norwegian Sea. In late winter the herring migrates to the spawning cites along the Norwegian coast (mainly between 62 and 67° N in recent periods). After spawning the herring starts on a feeding migration into the Norwegian Sea, mainly feeding on copepods and euphausiids. The larvae hatch at the bottom and are advected along the Norwegian coast into the Barents Sea, where they spend the first three years. These juveniles feed mostly on zooplankton, but can also feed on capelin larvae and cod larvae. Important predators on the herring are seals, whales and to some extent cod, saithe and seabirds (Bogstad *et al.*, 2000, Johansen *et al*., 2003). The herring is one of the largest fish stocks in the Norwegian Sea/Barents Sea and is economically very important. Annual catches have varied from nearly zero to 2 million tonnes.

In the model $Rec3_t$ is the number of 3 year old recruits of Norwegian spring spawning herring from the ICES Northern Pelagic and Blue Whiting Working Group (WGNPBW) 2004 SEASTAR assessment (ICES CM 2004/ACFM: 24), $TempSkinNS_{t-3}$ the NCEP skin (sea surface) temperature in degree C in the Norwegian Sea sub area between 64 -70°N and 6°W–8°E averaged from January to March three years earlier and $0group_{t-3}$ the 0-group logarithmic index of herring larvae from the 0-group survey in August three years earlier. The data used for the model are from the period 1983-2002 for the response variable. The model gives a three-year prognosis of the herring recruitment.

The winter surface temperature around the spawning sites was picked as the climatic term, while the 0-group was picked as the link back to the parent population. The latter is very closely linked to the number of three-year olds, and also optimises the time lag used in the prediction. Even if it is possible to go even further back in time, there is a large change in the distribution of young herring around 1983, when the stock started to recover.

Results (Table 5)

Recruits of Northeast Arctic cod

The model explains ~85 % of the variation in the recruitment (Tabs. 1-4, Fig. 3). Prognosis values are given in Table 5.

$$\mathrm{Re}\,c3_t = 2.8\times10^8 \times TempKola_{t-3} + 0.065\times 1group_{t-2} + 8.3\times10^7 \times \log(capmatbio_{t-2}) - 1.7\times10^9$$

Recruits of Barents Sea capelin

The model explains ~ 65 % of the variation in the recruitment (Tabs. 1-4, Fig. 4). Prognosis values are given in Table 5.

$$\mathrm{Re}\,c1_t = -3.7\times10^{10} \times TempskinBS_{t-1} + 4.1\times10^8 \times 0group_{t-1} + 1.1\times10^5 \times capmatbio_{t-1} - 6.9\times10^{10}$$

Norwegian spring spawning herring

The model describes ~80 % of the variation in the recruitment (Tabs. 1-4, Fig. 5). Prognosis values are given in Table 5.

$$\mathrm{Re}\,c3_t = 8.8\times10^9 \times TempskinNS_{t-3} + 1.6\times10^{10} \times 0group_{t-3} - 4.6\times10^{10}$$

The dominant variable in the model is the 0-group index, which has a correlation coefficient of 0.84 (Tab. 1) with the Recruitment (3 years later).

Discussion

Data quality
The quality for some of the input data series in the regressions is not the same throughout the entire time series. This is the case for the bottom trawl index used in the cod regression, where improvements in area coverage and trawl technology changed in the earlier part of the series. After 1994 this series are more consistent (Jakobsen *et al*., 1997).

The historical stocks are re-calculated each year in the relevant assessment groups. The back calculations of the historical stock size are based on knowledge of the whole cohort of a year class. Especially in the last 3-4 years the estimates of the younger age groups suffer from this and are more uncertain than the rest, where the whole cohort is available in the back calculation. In our regressions this is the case for cod and herring, but not for capelin since this is a pure acoustic survey estimate. A way to avoid this problem is to exclude the last years in the regression. However, this has to be evaluated against the need for longer time series. In our case we choose to leave out the last two years in the regression for cod and herring.

The resolution of the NCEP skin temperature data is about 1.9 degree latitude and longitude. To ensure robustness against influence from potential unrealistic data in a single data cell data are averaged over 3 months (January-March) and over an area over several grid cells. However, in the capelin regression ice occasionally enters the defined area, and influences the temperature term. In this case the skin term cannot be looked at as only a temperature term, but a more general climatic parameter that include heat content and available area. The capelin regression was tested against yearly average temperature in the Kola section, which do not have the mentioned ice influence in the data. The end result was about the same, though with lower R^2.

Results and statistical properties of retrospective runs are shown in Figs. 7 and 8. Fig. 7 shows that the results are reasonable for cod and herring, while for capelin there is a clear tendency of overestimation from 1997 onwards. In the assessment on cod carried out by AFWG the short-term recruitment prognosis is calculated by the RCT3 model (Shepherd, 1997). This model uses historical VPA (XSA) estimates and survey indices for the youngest age group(s), the survey indices also covering the last years up to the assessment year, in the calculations.

Considering that the multiple regression model statistically is better when adding more years to the time series, and that the VPA is less accurate the last 2-3 years the results are encouraging. The model may serve as a corrective to the “official” recruitment estimates, without having to drag along with earlier “errors” made in the calculations. It should be noted that for capelin and herring, the multiple regression models predict negative recruitment in some years (Fig. 6).

Regression models are vulnerable for sudden changes in the mechanisms and processes that lay behind the couplings. The specific terms in the regression stands for the most dominant mechanisms/processes that influences the response variable. If a process/mechanism that is not included in the regression terms takes over as a dominant factor (e.g. regime shift) for the response variable, the regression fails. However, this should not prevent using the connection as long as it works. The challenge is then to look for signs of regime shifts. With time lag to the response there should be time enough get a warning (e.g. a decrease in the R^2).

Most stock assessments to day are carried out without taking climate into consideration. Regression models used in the way presented in this paper can easily be implemented into growth and recruitment short-term prognoses. The authors hope that this regression approach may be useful in taking climate considerations into assessment of fish stocks.

A key factor in this kind of correlation and regression analysis is to justify the relations through feasible cause-effect links. However, sometimes a coupling cannot be explained by present knowledge though it may still be valid. An important question is then: should we throw it away? In some cases this should not be done because correlation/regression results can act as a starting point for further investigations to clarify the processes that lay behind. The challenge is to find what to throw away as coincidental and what to keep in for further analysis.

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Tables and Figures

Table 1. Statistics of the models

Model	*P-value*	*Residual st.error*	*d.f.*	*R2*	*F-statistics*	*df (F)*
Cod 3	2.43E-06	105400000	15	0.846	27.47	3 and 15
Capelin 1	0.0001232	1.38E+11	19	0.6546	12	3 and 19
Herring 3	1.03E-06	4062000000	17	0.8025	34.54	2 and 17

Table 2. Statistics of the individual terms of the model

model	*variable*	*timelag*	*coefficients*	*st.dev of coeff.*	*t-value*	*P-value*
cod 3	Kola	-3	2.82E+08	6.18E+07	4.56E+00	4.00E-04
	rec1	-2	6.52E-02	1.32E-02	4.94E+00	2.00E-04
	capematbio	-2	8.31E+07	1.85E+07	4.48E+00	4.00E-04
	intercept		-1.73E+09	2.84E+08	-6.10E+00	0.00E+00
capelin 1	skin bs	-1	-3.70E+10	1.80E+10	-2.06E+00	5.35E-02
	ogroup	-1	4.07E+08	1.13E+08	3.58E+00	2.00E-03
	matbio	-1	1.07E+05	3.78E+04	2.82E+00	1.09E-02
	intercept		-6.86E+10	5.65E+10	-1.21E+00	2.39E-01
herring 3	skin ns	-3	8.85E+09	3.15E+09	2.80E+00	1.22E-02
	ogroup	-3	1.55E+10	2.02E+09	7.68E+00	0.00E+00
	intercept		-4.62E+10	1.64E+10	-2.81E+00	1.20E-02

Table 3. Correlations of the coefficients in the model

cod 3		(Intercept)	Kola	rec1
	Kola	-0.5727		
	rec1	-0.118	-0.1462	
	capmatbio	-0.5757	-0.3334	0.2157
capelin 1		(Intercept)	skin bs	ogroup
	skin bs	0.1971		
	ogroup	-0.425	0.4632	
	matbio	-0.6063	-0.4212	-0.2269
herring 3		(Intercept)	skin ns	
	skin ns	-0.9969		
	ogroup	-0.0062	-0.0493	

Table 4. Correlations of time series used in the models

cod 3		rec3	Kola	rec1
	Kola	0.69		
	rec1	0.47	0.08	
	capmatbio	0.55	0.31	-0.18
capelin 1		rec1	skin bs	ogroup
	skin bs	-0.41		
	ogroup	0.7	-0.42	
	matbio	0.32	0.37	0.04
		rec3	skin ns	
herring 3	skin ns	0.34		
	ogroup	0.84	0.05	

Table 5. Prognosis from the different multiple regression models.

Model \ prognosis year	**2005**	**2006**	**2007**
Cod age 3	$743*10^6$	$534*10^6$	$709*10^6$
Capelin age 1	$173*10^9$		
Herring age 3	$10.3*10^9$	$17.7*10^9$	$27.4*10^9$

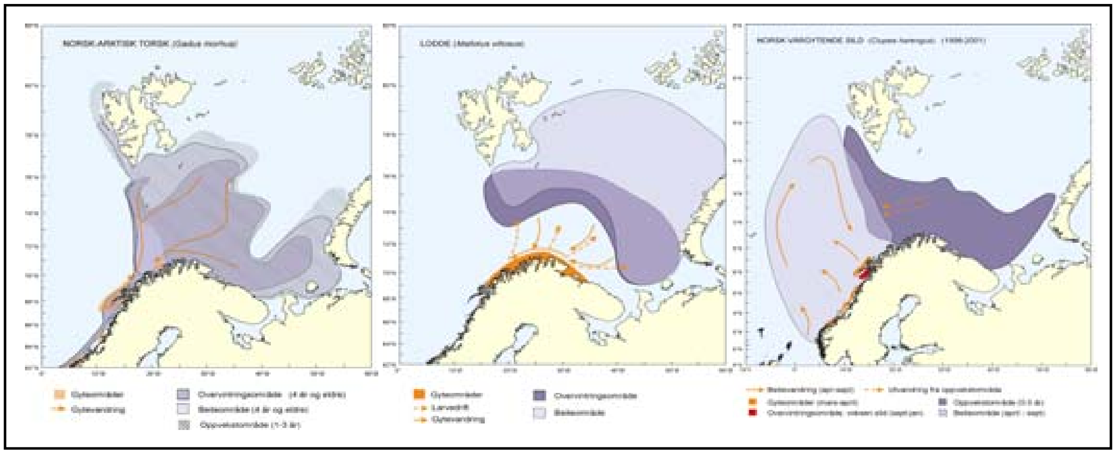

Figure 1. Spawning, hatchery and feeding area of the three modelled species. From left NEA cod, BS capelin and NSS herring.

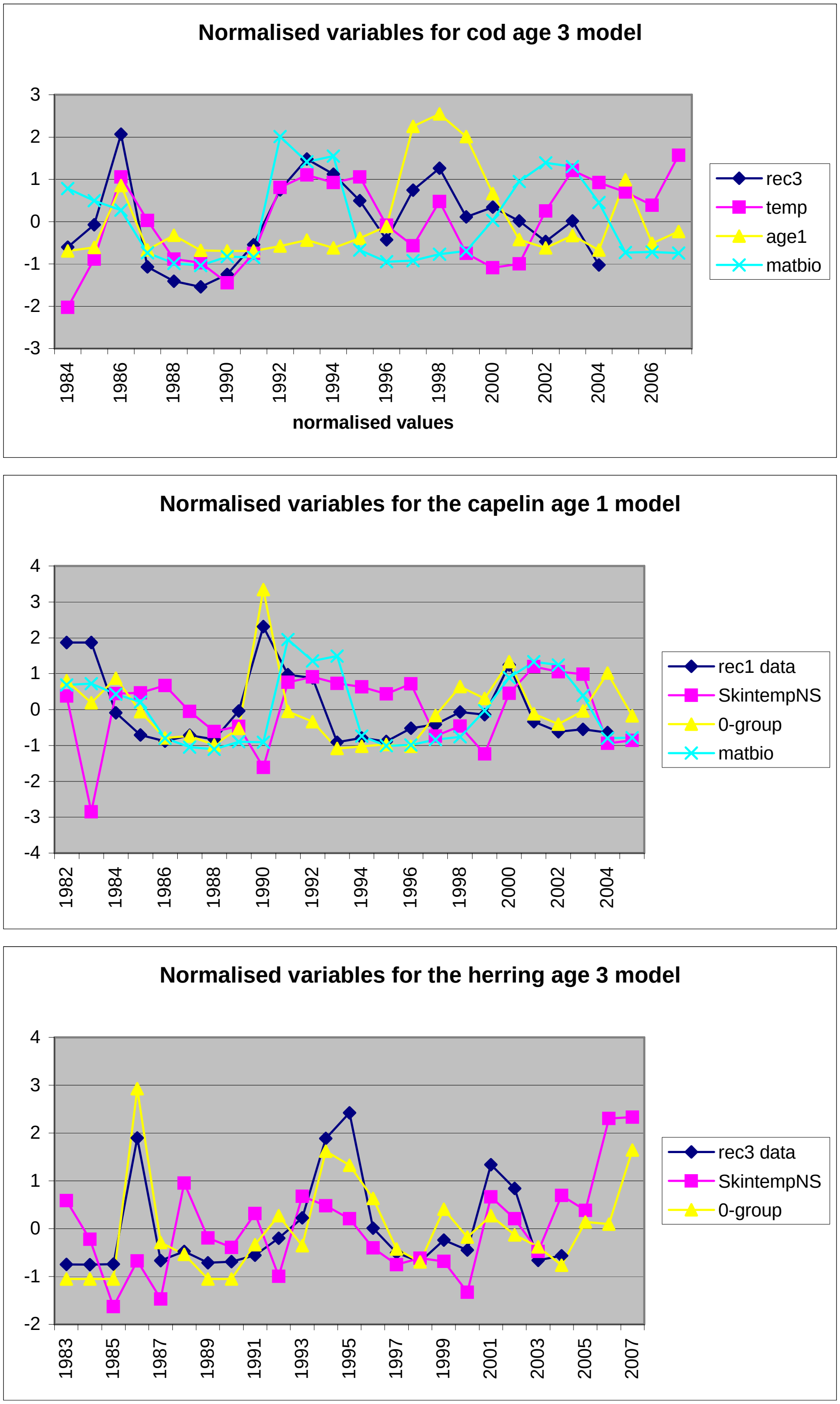

Figure 2. Normalised time series of the response variable and the explanatory variables in the models. Upper panel is the cod model, middle panel is the capelin model and lower panel is the herring model.

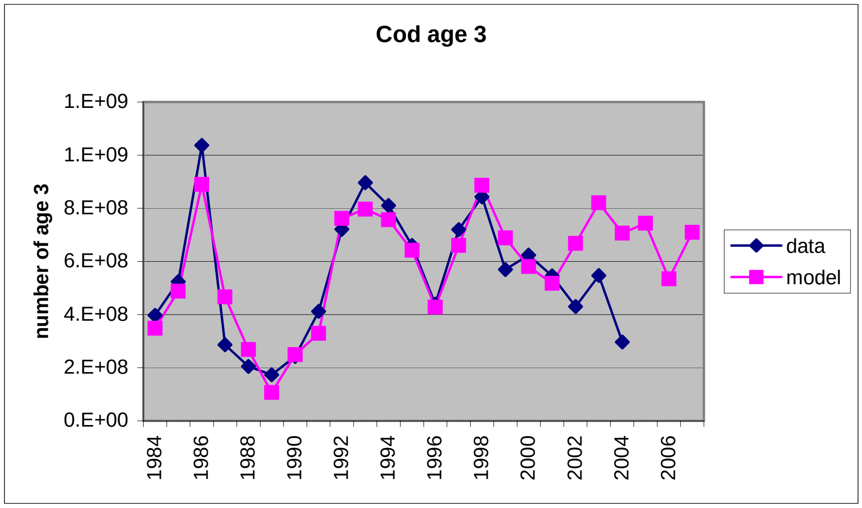

Figure 3. The figure shows the number of recruits (three year olds) of North East Arctic cod (blue) and the model fit (red).

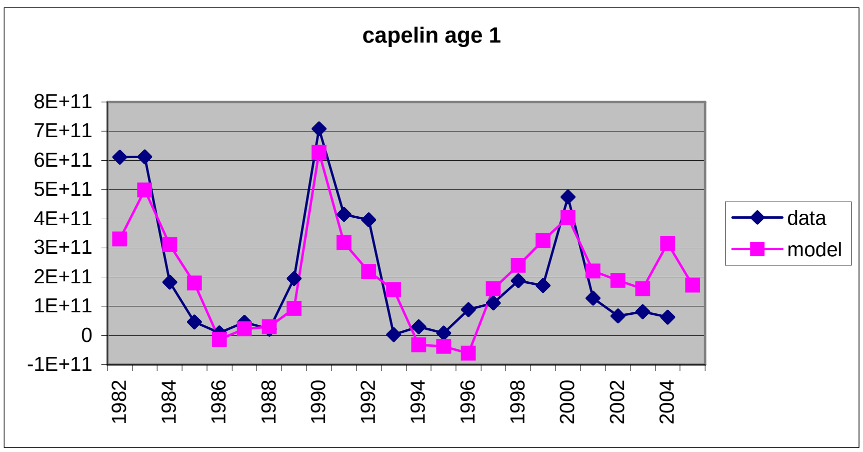

Figure 4. The figure shows the number of recruits (1 year olds) of Barents Sea Capelin (blue) and the model fit (red).

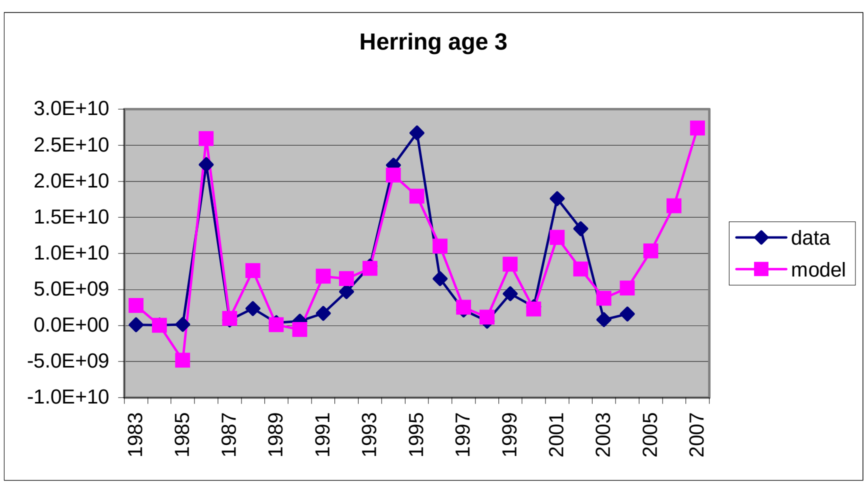

Figure 5. The figure shows the number of recruits (3 year olds) of Norwegian spring spawning herring (blue) and the model fit (red).

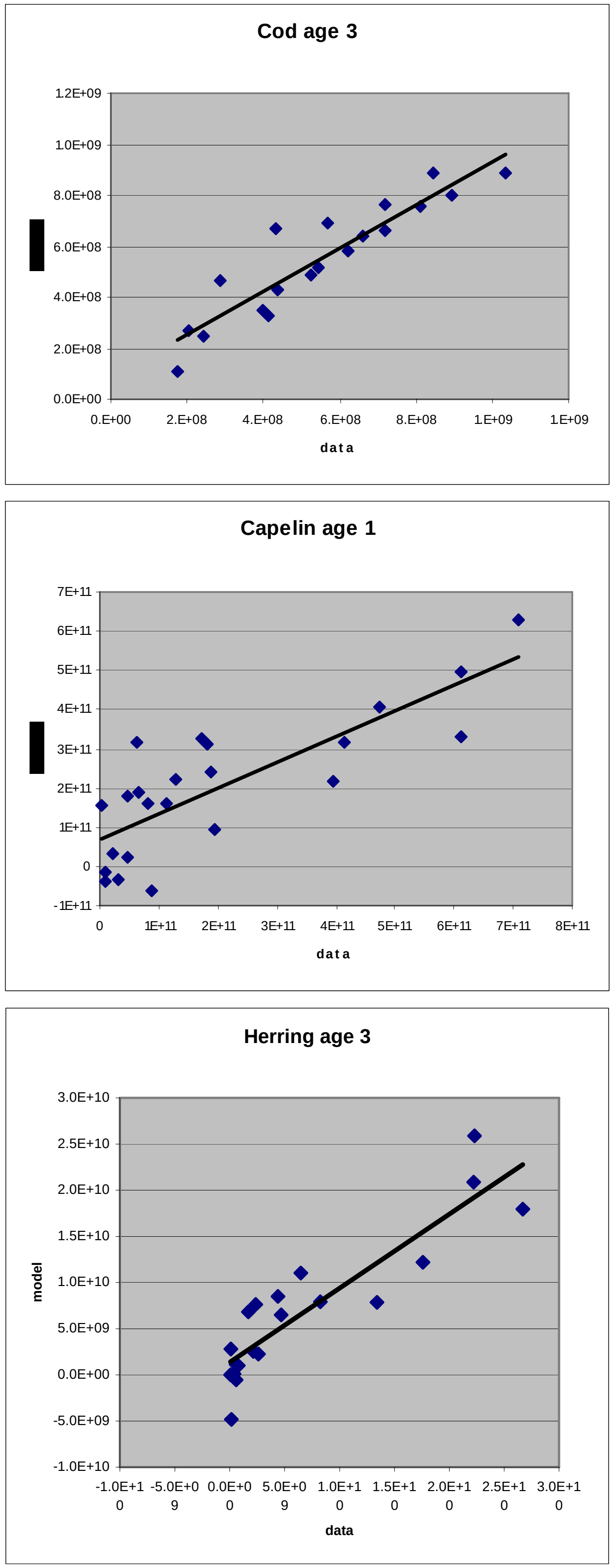

Figure 6. Model vs. data for the multiple regression models. Upper panel is for the cod model, middle panel is for the capelin model and lower panel is for the herring model.

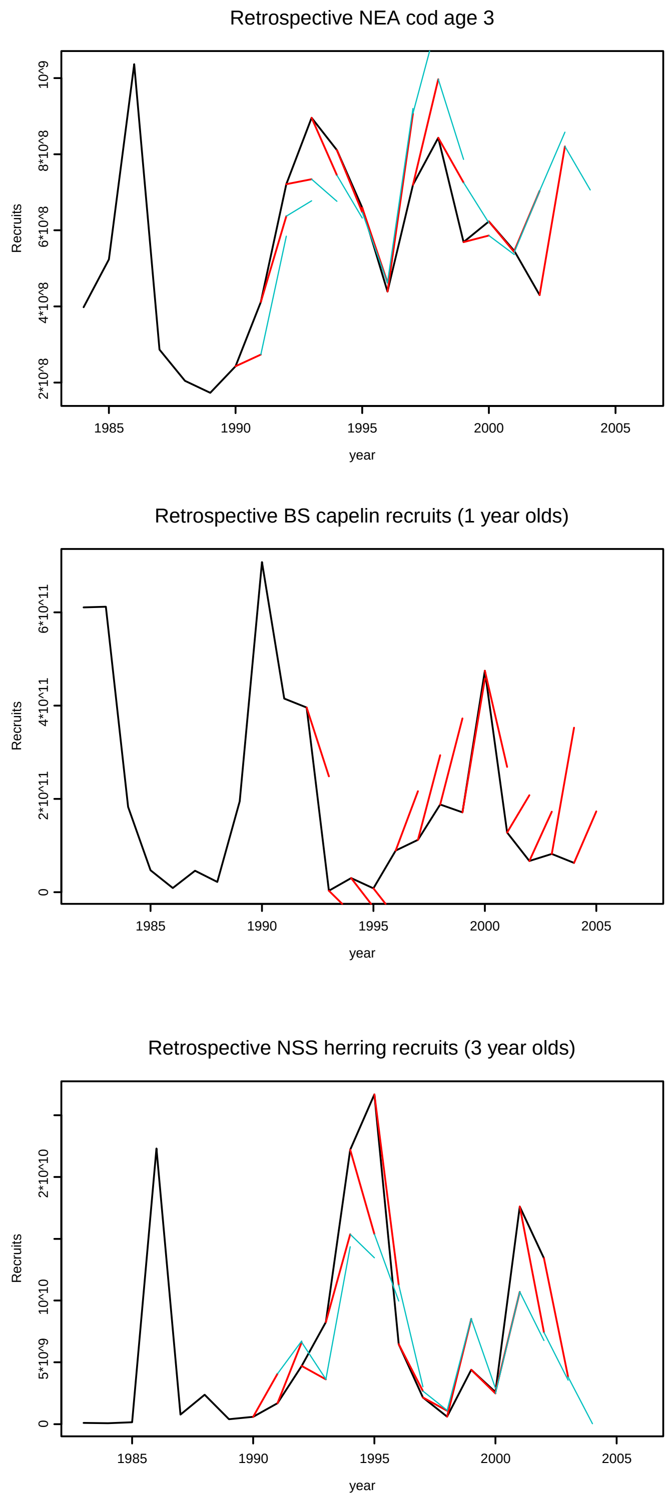

Figure 7. Retrospective run of the different multiple regression models. Upper panel is the cod model, middle panel is the capelin model and lower panel is the herring model. Note that the coefficients of the models changes as the time series is shorten.

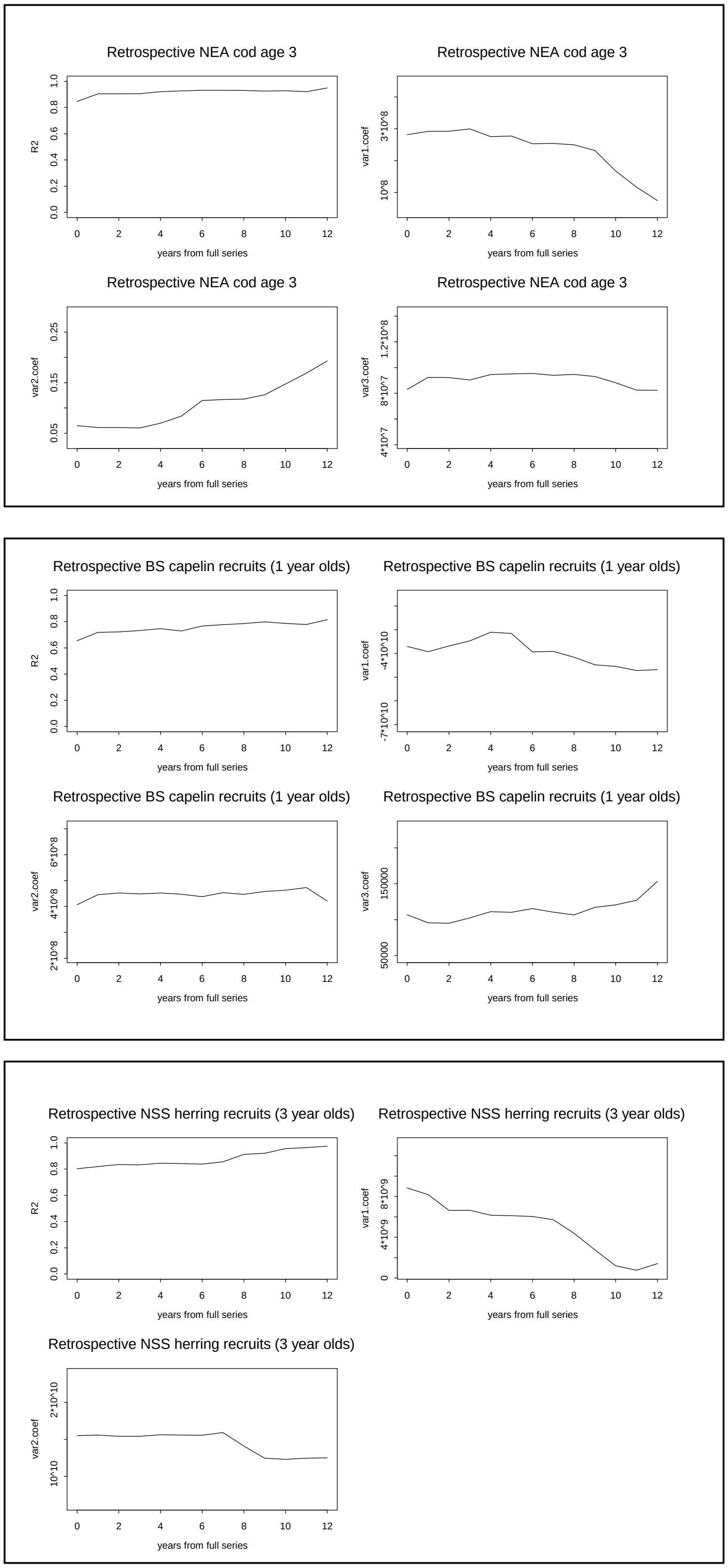

Figure 8. Development of R^2 and the model coefficients in the retrospective run due to shortening of the time series. This figure indicates the stability of the models. The upper panel is for the cod model, the middle panel is for the capelin model and the lower panel is for the herring model.