A STOCHASTIC MODEL FOR THE BARENTS SEA CAPELIN STOCK WITH PREDATION FROM AN EXOGENOUS COD STOCK

by

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ABSTRACT

Based on the model CAPELIN used with management of the Barents
Sea capelin stock until 1986, a model that is structured on age and sex is
constructed. The predation on the mature part of the stock is connected
to the size of the cod stock, and predation parameters calculated by the
area-structured multispecies model MULTSPEC are used. The effect of
the geographical overlap of cod and capelin is modeled using a
scalar overlap index variable. The uncertainty connected to the
modeled biological processes are displayed and the future use of
the model for management of capelin briefly discussed.

INTRODUCTION

The Barents Sea capelin stock declined severely during the period 1983 to 1986, and did not start recovering until 1990. It is believed that the decline was initiated by an abrupt change of oceanographic conditions during the winter 1982–1983. An increase in the inflow of Atlantic water caused very good recruitment conditions for the Norwegian spring spawning herring and the Northeast Arctic cod stock. During the fall of 1983 it is likely that the 0–group herring caused a decline in capelin recruitment by predation (Moxness and Øiestad, 1979). As the 1983 year class of cod grew older, the natural mortality of adult capelin increased rapidly. Most likely as a consequence of the vanishing of the capelin as source of food, the individual growth of the cod decreased dramatically. The model used for management — CAPELIN — (Tjelmeland, 1985, Hamre and Tjelmeland, 1982) did not take into account these effects.

As the capelin stock now is at a level that it again can sustain fishery, the following issues must be dealt with:

1. What management measures should be taken in periods of much herring in the Barents Sea?

2. The predation from cod should be taken into account when the capelin quotas are set.

3. The importance of capelin as source of food for cod should be taken into account when the capelin quotas are set.

This paper addresses the above questions. A new model in which the predation from cod on mature capelin is evaluated using the actual size of the cod stock is presented. Also, a recruitment relation incorporating the significance of herring is implemented. An important goal of the paper is to reflect the uncertainty of management due to uncertain data and crude models.

In the paper the predation from cod on mature capelin is evaluated, using results from the model MULTSPEC presented in an accompanying paper to this symposium (Bogstad and Tjelmeland, 1992). Since the actual level of the cod stock is used in evaluating predation, the calculated size of the capelin spawning stock can not be compared to previously published figures, since the latter were based on a rather unsubstantiated and yearly constant M-value.

Only two biological processes are modeled in the sense that they are connected to other model variables: maturation of capelin and predation on mature capelin. The present version of CAPSEX is, so to speak, a multispecies minimum variant. The other processes important for management relevant modeling, i.e. growth, natural mortality on immature capelin and recruitment, are dealt with without any attempt of explaining these processes from other variables.

It is assumed that the reader has some familiarity with the Barents Sea ecosystem and its past management, especially for capelin.

BIOLOGY.

Figure 1 Distribution of cod and capelin, spawning migration of capelin.
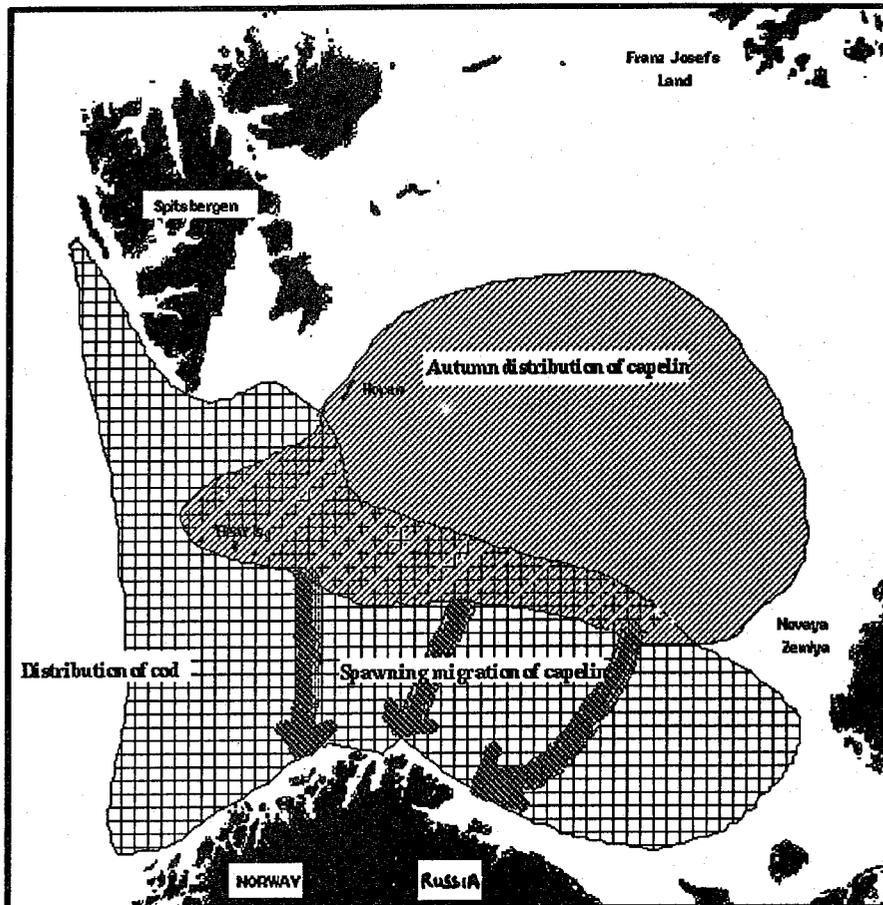
Life history of capelin.

The capelin was in focus at the second PINRO—IMR symposium, where the assessment and biology of the stock was described (Gjøsæter, 1985). Here, the main points relevant for the modeling work presented in this paper are mentioned.

In the autumn the capelin stock feeds in the northern parts of the Barents Sea, mainly north of 74°N in the western regions. In the eastern regions the capelin may be found far south also in the autumn but not in great abundance and consisting of mostly young fish. The capelin stock has been surveyed each year during September since 1972 in a joint Russian-Norwegian cruise using acoustic information combined with trawl data. These survey data are the foundation of the capelin modeling and management.

The geographical distribution in the autumn may vary strongly from year to year, in some periods being more southern and western and in other periods being more northern and eastern, see distribution maps in (Dommasnes and Røttingen, 1985).

At the end of the year and the following winter the mature part of the population moves southwards and will eventually spawn at the coast of Norway and Russia in April. In some years the capelin will have a westerly spawning migration, in other years an easterly spawning migration. The mechanisms governing the geographical variation of the spawning migration are poorly understood, although there have been some attempts to make conceptual models (Tjelmeland, 1987a), (Ozhigin and Luka, 1987).

It is believed that most of the mature capelin die after spawning.

The larvae will drift with the coastal and Atlantic currents into the central and southern Barents Sea. When the spawning is westerly, a significant portion of the larvae will drift to the west of Spitsbergen and may then be lost from the Barents Sea capelin stock.

The immature capelin may also migrate far southwards, but later than the mature component. The data for assessing the migration of the immature capelin are poor, but an overall impression is that the extent of the southwards migration may vary from year to year and that the most southern distribution may be in the months May and/or June. The northwards migration will take place in July and August.

Predation from cod.

During the spawning migration the capelin will overlap fully with the cod stock, and be subject to heavy predation. The magnitude of the predation will depend on the migration route, because there is an east-west gradient in both the abundance and age distribution of cod.

It is likely that the cod stock's predation on immature capelin is more variable than the predation on mature capelin, since the migration, and thereby the overlap, may be more variable. But there is no doubt that in some years the predation from cod also on immature capelin may be highly significant.

Predation from herring.

The pattern of herring abundance in the Barents Sea is that in some years of good recruitment herring juveniles may be entered in great quantities. The herring will grow up in the southeastern part and gradually move westwards as it grows older. It will leave the Barents Sea at age 3 or 4.

During the 0–group stage there may be considerable overlap between herring and capelin. Due to the size difference, the herring may prey on capelin, thus having an influence on capelin recruitment (Moxness and Øiestad, 1979). As the herring grows older, the predation on capelin larvae will depend on the overlap and in most cases probably will be of little significance, if not the geographical distribution of capelin larvae is extremely south— and easterly.

The fishery.

The capelin fishery is conducted in two seasons.

In the autumn season from August to December both immature and maturing capelin are caught. It is suspected that a considerable quantity of 1–group capelin may be killed

in the autumn fishery without being reported as catch. Thus, in periods where the 1–group capelin overlaps the older capelin in the autumn, there may be reason to suspect a somewhat reduced recruitment measured as 2 year old capelin the following year.

In the winter season from January to April mainly the migrating mature capelin is caught, although some immature capelin may be found in the catches.

Development of the capelin and cod stocks.

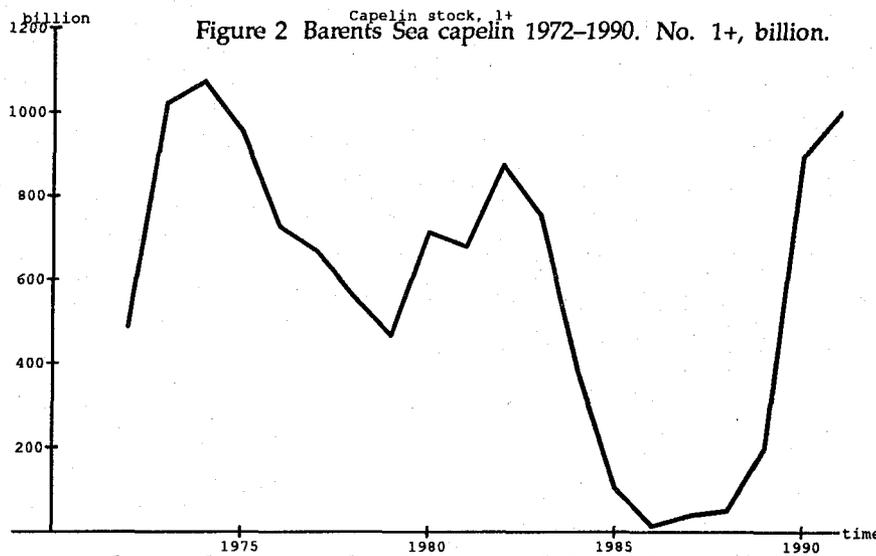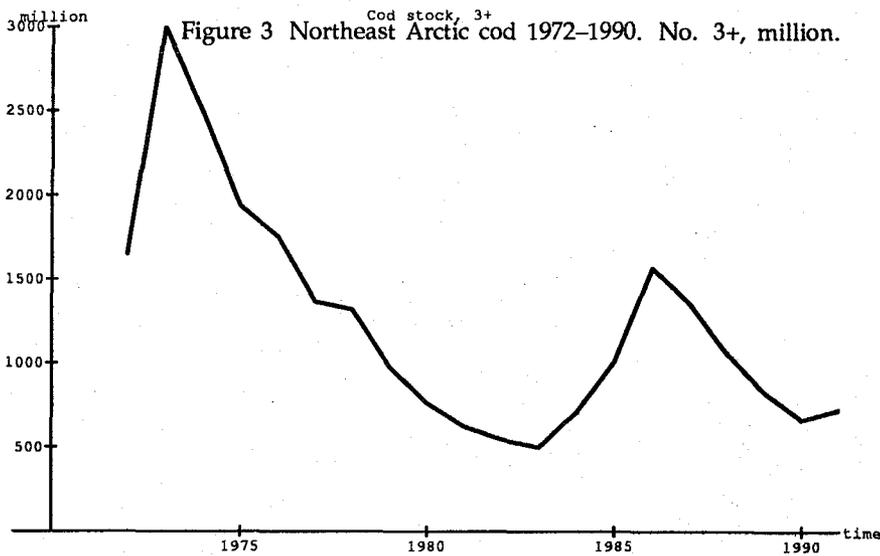Figure 2 shows the recent development of the capelin stock:

Figure 2 Barents Sea capelin 1972–1990. No. 1+, billion.

Figure 3 shows the recent development of the cod stock:

Figure 3 Northeast Arctic cod 1972–1990. No. 3+, million.

MANAGEMENT.

The management of the Barents Sea capelin up to 1984 is described by (Hamre, 1985). Prior to 1982 the stock was managed by using a spawning stock of 0.5 million tonnes as a lower safeguarding limit. This number was based on a comparison of historical calculations of the spawning stock and observed recruitment. In the autumn 1982 results from (Hamre and Tjelmeland, 1982) (CAPELIN model) was used to introduce MSY management. The optimal spawning stock calculated by the CAPELIN model did not differ much from the previous used safeguarding limit. It is worth noting that already in 1982 multispecies considerations were taken in the regulation of the capelin stock, since the value of the stock as source of food for predating organisms was explicitly considered (Anon, 1983).

In 1984 the first signs of capelin recruitment failure were manifest (Anon, 1985) as the number of one year old capelin was extremely low. The implications of this observation was not fully understood, to a large extent because the acoustic abundance estimate of the one-group had proven not to be reliable on earlier occasions.

In its 1985 meeting the Atlanto-Scandian Herring and Capelin Working Group (Anon, 1986) noted that the capelin stock had decreased far more that could be accounted for by the fishery. The conclusion was that environmental changes had taken place that invalidated the model. The working group did not recommend any fishing in 1986.

The stock was at a low level in 1986–1989, and retained its earlier strength in 1990, if measured in biomass units.

MODEL FORMULATION AND PARAMETER ESTIMATION.

Maturation and natural mortality on immature capelin.

In the following, a revised model will be described and the parameters will be estimated process by process. The natural starting point is the maturation, because in the present version of the model the estimated values of the maturation parameters will not be dependent on the values of other parameters. This follows from the conceptual model of the life history of capelin presented earlier and from the fact that the stock data are from September, prior to the separation of the stock into a mature and an immature component. The converse is not true. The estimated values of the parameters governing growth and natural mortality will be strongly dependent on the estimated values of the maturation parameters.

The maturation of capelin is believed to be above all a length-dependent process, although for a given length there might be a higher probability for maturation with higher age (Forberg and Tjelmeland, 1985).

Formulation

The maturation, applied on the September cruise data, is given by:

$$m(l) = \frac{1}{1 + e^{4 \times P_1^{sex} \times (P_2^{sex,age} - l)}}$$

where l is the fish length in cm.

The estimation of maturation parameters poses severe difficulties. A study of gonads reveal that maturation also may depend on age. With some support from (Forberg and Tjelmeland, 1985) we fix P_1^{sex} to 0.6 for both sexes. In (Tjelmeland, 1987b) a relation between maturation parameters between sex and age was assessed from gonadal data and an overall scaling was estimated by using the model. In (Tjelmeland, 1987a) the maturation was taken from gonadal data alone. Maturation studies should later be done using all collected gonadal data to lessen the burden on model estimations.

The natural mortality on immature capelin is supposed to be the same for all age groups and both sexes.

Estimation method.

The data inputs to the model are the acoustic estimate obtained during September each year, the catch in number and the weight in the catches by age and month, assuming all catch in the period January-April to be on mature capelin. The analysis will for the time being be restricted to utilizing only these data, although several other sources of data exist that may improve the basis for parameter estimation and that may be a foundation for refined models. For the moment disregarding recruitment, the biological processes affecting the population from one year to the next are the maturation and mortality. The parameters in the maturation and mortality models will be estimated by comparing the number of fish at age 3, 4 and 5 years simulated by starting the model in the previous autumn, to corresponding measured values.

In choosing the estimation method, assumptions on the stability of the parameters have been made:

1. The probability of a fish of given age, sex and length to mature is constant from year to year.
2. The mortality of immature capelin is regarded as stochastic, i.e. no pre-estimation assumptions on the mortality is made.

Thus, the following estimation scheme is adopted:

1. The maturation parameters are fixed throughout the whole time period of estimation.
2. The mortality is estimated year by year.
3. The estimation is performed by varying the maturation parameters until the least-squares goal function attains its minimum value.

The estimation is thus performed in a double iteration.

Uncertainty estimates.

There is not enough knowledge of the uncertainties connected to the acoustic estimate to construct a goal function that gives the probability of obtaining the actual measurements given that the model is true, i.e. a maximum likelihood method for constructing the parameter confidence intervals cannot be used. Therefore, resampling is used. From the period of available data, 18 one-year periods are picked at random and the estimation of maturation and mortality parameters is performed. 85 estimations are performed and the parameter confidence intervals and correlation are calculated from these estimates (table 2).

Goal functions.

Two different goal functions have been tried, both using unweighted least squares:

1. Comparing absolute simulated number of fish in each age group and for each sex to absolute measured number of fish in each age group and for each sex.
2. Comparing the ratio of simulated number of fish to measured number of fish to 1.0 in each age group and for each sex.

Given that the maturation and mortality models both are correct, the two goal functions should give the same estimated values for the parameters. However, both the maturation model and the mortality model are highly idealized. Thus, differences in the estimated values tell us something about how the model assumptions deviate from the realities. For instance, goal function 1 put more weight on the more numerous 3 year old fish than on older fish. If there is something wrong with the assumptions on age dependence, we will get different estimates.

It is not straightforward to determine how simple the models of maturation, spawning survival and mortality can be. We have made 24 series of estimations using the two different goal functions, ages 3 and 4 or ages 3, 4 and 5, increased length at maturity for 2 year old fish for females, males and both sexes, and no spawning survival or some spawning survival of females.

None of the 24 estimations performed significantly better than one of the simplest: Using goal function 2, ages 3 and 4, no spawning survival and no age dependence of maturation parameters.

In later versions of the model, it might prove possible to utilize a relation between observed energy content of the fish and spawning survival being worked upon at PINRO (Lebskaya, pers. comm.).

Consistency with weight at age in the catches of mature capelin.

Once the maturation parameters are determined, the mean weight at age of the maturing population is determined. During the estimation of the maturation parameters, the simulated individual weight of the maturing capelin from October 1. to spawning at April 1. is not changed. The mean weight at age is compared to the mean weight at age in the catches of mature capelin in the period January-April. If the simulated weight is higher than the measured weight there is an inconsistency if no real weight decrease has taken place. In this case, the goal function has been increased with a (somewhat arbitrary) penalty function, which is the quadratic deviation of the ratio between simulated and measured weight from unity.

The weight at age data from the catches in the mature population may be difficult to interpret. Some of the catch may have been taken on immature capelin. Also, it is difficult to construct reliable weight at age because the geographical distribution of the catch may differ from the geographical distribution of the mature stock. Hence, a weight at age gradient may cause errors in the estimate. The data used are weighted averages between Russian and Norwegian catches.

We consider the use of weight at age data from the catch statistics to be the weakest part of the analysis presented in this paper.

Estimation results.

The parameter estimate obtained fixing the maturation over the whole time period is shown in table 1:

Table 1 Basic maturation parameter estimate.

Length at maturity females	13.68
Length at maturity males	14.00

To investigate the uncertainty associated with the maturation parameter estimates, a series of 85 estimations each using 18 one-year periods drawn at random (with replacement) from the available data were run. The result is shown in table 2:

Table 2 Bootstrap parameter estimates and covariance matrix.

	Length at maturity, females	Length at maturity, males
Means	13.65	14.04
Covariance	matrix	
	0.078	0.438
		0.125

The estimates in table 1 are reasonably close to the estimates in table 2, in view of the bootstrap-estimated variances.

Natural mortality and growth of immature capelin.

As for the natural mortality, a model relating growth to model variables has not been used, although such a model is implemented into the CAPSEX software. Instead, the growth per year has been estimated year by year for males and females separately. An ordinary least squares goal function has been used, without measurement error. There is no need for estimating growth with a confidence interval because the statistical uncertainty the variation in growth imposes on the overall model results will be found by drawing estimated growth at random from the estimated growth by year. Table 3 shows the results.

Table 3 Estimated growth of immature capelin.

	Natural mortality, month^{-1}	Females length, cm year^{-1}	Males length, cm year^{-1}	Females weight, g year^{-1}	Males weight, g year^{-1}
1972 - 1973	0.108	2.18	3.04	7.88	14.89
1973 - 1974	0.044	1.43	3.51	2.51	14.34
1974 - 1975	0.040	2.72	2.41	7.64	8.07
1975 - 1976	0.058	2.27	2.70	6.08	8.61
1976 - 1977	0.035	2.31	3.00	8.37	12.08
1977 - 1978	0.050	2.08	2.96	6.12	10.19
1978 - 1979	0.090	2.47	2.67	-	7.25
1979 - 1980	0.037	2.77	3.70	8.59	16.02
1980 - 1981	0.066	2.48	3.12	7.54	12.32
1981 - 1982	0.064	2.77	3.66	7.99	14.39
1982 - 1983	0.202	2.41	3.95	8.37	-
1983 - 1984	0.066	2.73	3.55	7.53	14.37
1984 - 1985	0.173	2.18	2.64	5.54	8.34
1985 - 1986	0.215	1.83	3.12	2.71	8.61
1986 - 1987	0.249	2.38	3.38	-	-
1987 - 1988	0.079	-	-	-	-
1988 - 1989	0.209	3.15	3.82	-	2.71
1989 - 1990	-0.046	2.59	-	10.52	-

With one exception (1974–1975) the growth in length has been estimated at a higher value for males than for females. Without exception the growth in weight has been estimated at a higher value for males than for females.

There are some problems with the present version of the data base used, leading to the growth in some years not being estimated or estimated at an unreasonably low value. In these cases the estimate is not given in table 3 and the growth has been set to a lower limit of 2.0 for growth in length for females, and 2.5 cm for males. This probably gives a biased growth when the model is used, but the effect should be small.

Growth of mature capelin.

No model relating the weight of mature capelin at time of spawning to model variables have been applied. A constant rate of growth in the period October 1 to April 1 has been assumed. Once the maturation parameters have been estimated the growth of mature capelin is determined. The relative weight increase from October 1 to April 1 is shown in table 4.

Table 4 Weight increase factors from October to April for mature capelin, using weight at age in the catch.

	2-3 years	3-4 years	4-5 years
1973-1974	1.75	1.18	1.18
1974-1975	2.00	1.61	0.99
1975-1976	2.00	1.62	1.35
1976-1977	2.00	0.74	1.34
1977-1978	1.13	1.14	0.53
1978-1979	0.88	1.30	1.39
1979-1980	1.42	1.39	1.17
1980-1981	2.00	1.30	1.15
1981-1982	2.00	0.72	1.31
1982-1983	1.27	1.09	1.15
1983-1984	1.07	0.93	1.15
1984-1985	1.60	1.21	1.10
1985-1986	1.91	1.26	1.76

During the estimation an upper limit of 2.00 has been set, and it is seen from table 4 that the weight increase has been determined to the upper limit in several cases for capelin 2-3 years. Such high growth seems unlikely and may be connected either to a bias in data or to the maturation model being wrong. A greater length at maturity for 2 year old fish, as suggested in (Forberg and Tjelmeland, 1985) would lower the estimated weight increase. This problem might be dealt with either by introducing a new parameter to be estimated for each sex or by estimating relations between maturation parameters, as was attempted in (Tjelmeland, 1987b).

If the data for weight at age in the mature population consists of more males than females the we would also obtain a too large growth in weight.

In some cases there is a decrease in weight in spite of the penalty used in estimating the maturation parameters, see page —146—. How much this penalty should be weighted is a trade-off between belief in the model for immature capelin and the model for the mature capelin, as well as the trust in the autumn acoustic data and the weight at age data for the mature stock. It appears from table 4 that the penalty might have been weighted more, giving a lower length at maturity (and hence a greater spawning stock and a lower natural mortality for immature capelin). However, this would also have increased the estimated growth of mature 2-3 year old capelin which already is unlikely high.

In future versions of the model, weight at age data split on sex should be used.

Predation from cod on mature capelin.

Formulation.

The effect of predation on mature capelin is evaluated by using parameters estimated by the area-distributed model MULTSPEC. The results using data from 1984 to 1989 are given in an accompanying paper to this symposium (Bogstad and Tjelmeland, 1992). The MULTSPEC predation equations are formulated in an area-integrated form as follows (details concerning different units in MULTSPEC and CAPSEX are omitted):

The capelin abundance is transformed to capelin density:

$$Capelin\ concentration = \frac{Capelin\ abundance}{Area\ size}$$

Total food concentration is given by:

$$Total\ food = Capelin\ concentration + Other\ food\ concentration$$

The capelin length part of the suitability is neglected.

The individual cod's predation ability is made dependent on the age. The mature cod at this time of the year migrating towards the spawning grounds is supposed not to prey on capelin. The maximum consumption of cod on capelin then becomes:

$$Cod = P_4 \times Temp \times \sum_{age=3}^{10} N_{Year}^{Cod}(age) \times \left(1 - Ogive_{Year}^{Cod}(age)\right) \times W_{Year}^{Cod}(age)^{0.802}$$

where the cod length part of the suitability has been implemented by starting the summation at age 3.

The temperature effect is given by:

$$Temp = e^{0.104 \times T_{Year} - 0.000112 \times T_{Year}^3 - 1.5}$$

where the temperature T_{year} is the April temperature from the Kola section, integrated in depth and along the section (PINRO, pers. comm.)

The feeding level is given by:

$$f = \frac{Total\ food}{Total\ food\ + P_3}$$

The consumption on capelin then becomes:

$$Cons = Overlap \times Cod \times f \times \frac{Capelin\ concentration}{Total\ food\ concentration}$$

The variable *Overlap* is a measure of the difference between CAPSEX and MULTSPEC given the same data and parameters. This difference stems from MULTSPEC having a geographical dimension, thus taking into account the overlap between the species and how the temperature is distributed geographically.

The natural mortality becomes:

$$M = \frac{Cons}{Capelin\ concentration}$$

The cod stock abundance and cod maturity ogives are taken from the work of the Arctic Fisheries Working Group, and the data files are the same as used by MULTSPEC. The parameters P_3, P_4 and the other food concentration are taken from estimation work with MULTSPEC (Bogstad and Tjelmeland, 1992). The area size used in converting abundance to concentration is set to the sum of the sizes of MULTSPEC areas 2, 3, 4 and 5, in which the capelin occurs during the spawning migration.

Cod model.

For the historic runs used to estimate the parameters of the CAPSEX model, the VPA-estimates made by the Arctic Fisheries Working Group are used (Anon, 1991). The area distribution is based on the Norwegian young cod survey in February. It is assumed that only immature cod eats capelin during January-March, and the immature part of the cod stock is calculated using the maturity ogive given by the Working Group. The weight at age data for cod are those used by the Working Group, which makes an arithmetic average of the weight at age from these two surveys. However, it is evident from the working group report that there is a larger discrepancy in weight at age between the Russian late autumn cod survey and the Norwegian young cod survey the following winter than can be accounted for by growth. This discrepancy may to a large extent be due to differences in age reading, and this matter is now under investigation (Anon, 1993)

For the runs into the future, a cod model dynamic in number at age has been used, with the following assumptions:

1. The natural mortality equals 0.2 for all age groups.
2. The fishing mortality equals 0.3 times the fishing pattern for 1990 given by the Working Group.
3. A constant maturity ogive and weight at age given by the Working Group for 1990 is used.
4. The recruitment is made stochastic with a uniform probability between 200 and 600 million individuals.

These assumptions bring the biomass of the immature cod stock up to about 1 million tonnes in about 10 years of simulation time.

Estimation of the overlap variable.

The overlap variable has been estimated by demanding that the capelin spawning biomass should be the same using MULTSPEC and CAPSEX for the years 1984–1989, provided the predation parameters, growth of mature capelin and capelin maturation parameters are the same. The result is:

Table 5 Overlap variable, CAPSEX adjustment to MULTSPEC.

1984	2.04
1985	1.82
1986	2.12
1987	2.56
1988	2.71
1989	1.55

In using the immature capelin to estimate the maturation parameters and the MULT-SPEC parameters to evaluate predation on mature capelin it is assumed that the amount of late maturing capelin (i.e. capelin spawning in June-July) is negligible.

Recruitment.

A recruitment model incorporating the influence from herring was used:

$$R = P_5 \frac{B}{B_{\frac{1}{2}} + P_6 \times H_0 + P_7 \times H_{1+} + B}$$

$$where:$$

$$B = Spawning\ stock\ biomass\ (million\ tonnes)$$

$$R = Number\ of\ recruits\ (2\ year\ old, billion)$$

$$B_{\frac{1}{2}} = Spawning\ stock\ biomass\ halfvalue\ neglecting\ influence\ from\ herring$$

$$H_0 = Index\ of\ 0 - group\ herring$$

$$H_{1+} = index\ of\ older\ herring$$

The index used for older herring is the acoustic estimate for the 1983 year class in the Barents Sea herring and shown in table 6.

Table 6 Index for herring (billion).

1984	1985	1986	1987
40	23	8	4

The index used for 0-group herring is the exponential of the logarithmic 0-group index. The data used are shown in table 7.

Table 7 Index for 0-group herring.

1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
0.0	0.05	0.01	0.00	0.00	0.01	0.02	0.09	0.00	0.00	0.00	4.87	0.40	0.26	0.00	0.00	0.38	0.80	0.38

The model will not account for more of the variance in the data if 0-group of cod is included.

The parameter estimates are:

Table 8 Recruitment parameter estimates.

P_5	274 billion
P_6	0.55
P_7	0.80 - estimated at limit
$B_{1/2}$	0.0033 million tonnes

The influence from a 1983–type herring event will dominate the dynamics of the capelin totally. The spawning biomass half value is extremely small, giving very good recruitment in absence of herring.

This model accounts for 2/3 of the variance in the data.

The above recruitment model has the property that even if there may be great variation in recruitment due to fluctuation in the amount of herring, an additional amount of spawning capelin will always give an additional amount of recruits.

When this model is being used stochastically:

1. The index of 0-group herring is drawn at random from the 0-group indices calculated from the yearly 0-group survey.
2. The index of older herring is calculated by drawing a 1983–type herring event with a probability of two instances in an 18–year period.
3. The recruitment is calculated by using the above model and adding a stochastic term drawn from a uniform probability density function with a range given by the standard deviation of the residuals.

Some important processes have been neglected:

1. Influence from 0-group cod on recruitment.
2. Influence of larval drift on capelin recruitment.
3. Influence on recruitment of killing of 1–group capelin during the autumn fishery.
4. Cheating on the reports on catch of mature capelin. Some capelin may have been discarded in connection with roe production and fishing for roe capelin for the consumption market.

Also, the stock-recruitment results are strongly dependent on the stock data for cod being correct. Several tuned VPAs for cod with different values of M should be run to check the sensitivity towards M.

With improved area coverage of the Barents Sea the later years, to a great extent due to an increased effort both from the Norwegian and Russian side, it might be possible to use the estimate of the 1 group as recruitment. However, we feel that at present the time series of reliable data is somewhat short.

Fishing.

The catch data used are numbers caught by age and month. The same data files as in the older model CAPELIN are used. The catch is converted to fishing mortality, assumed to be the same for females and males.

In the period January to April all catch is assumed to occur on mature capelin.

Running the model into the future, it is supposed that the same F-value apply in all catching months, and that the F-value is the same for all age groups. The catching months for runs into the future are October-December (autumn fishery) and January-March (winter fishery, mature capelin only).

RANKING SOURCES OF UNCERTAINTY — LONG TIME SIMULATIONS.

In order to get a feeling of how much the uncertainty in each of the modeled processes contributes to the overall uncertainty 30 runs from 1990 to 2040 have been made, drawing only one process at random each time. For the other processes mean values have been used. It turned out that if the influence from herring were averaged, the capelin stock would vanish in the course of 10–15 years due to the increased predation pressure from the growing cod stock. If the influence from herring is random the capelin stock turns out to be sustainable because in years of low herring influence the recruitment will be good even if the spawning biomass is poor due to the low $B_{1/2}$ value, see table 8. In order to compare the uncertainties of the other processes, in all runs the same sequence of herring events have been used. In all runs the spawning stock biomass (million tonnes) only is plotted. The baseline run is shown in figure 4.

Figure 4 Stochastic runs — baseline.
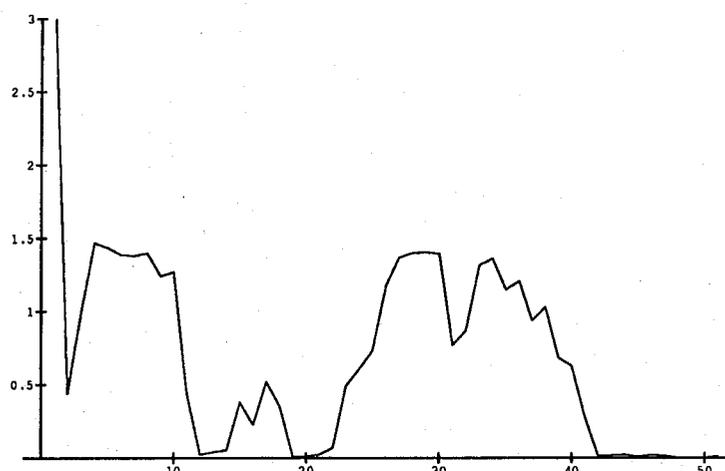
During the baseline run, herring events occurred in years 6, 13, 36 and 42. This leads to two long periods of capelin and two shorter periods where the capelin stock is very poor or almost absent from the Barents Sea.
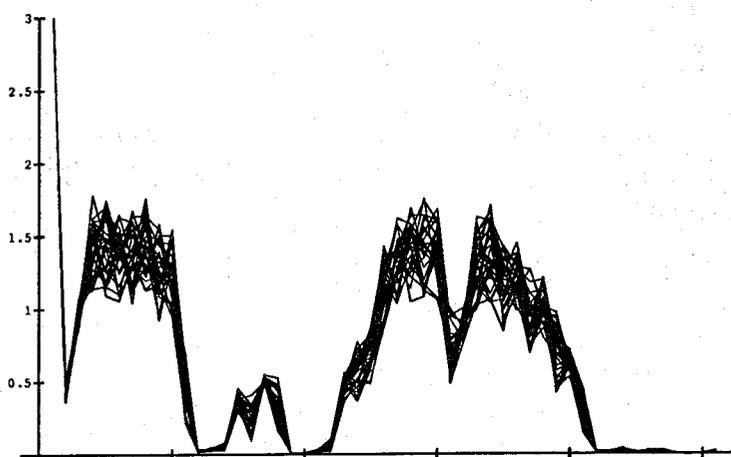
The influence of variation in natural mortality (table 3) on the development of the spawning stock biomass is shown in figure 5.

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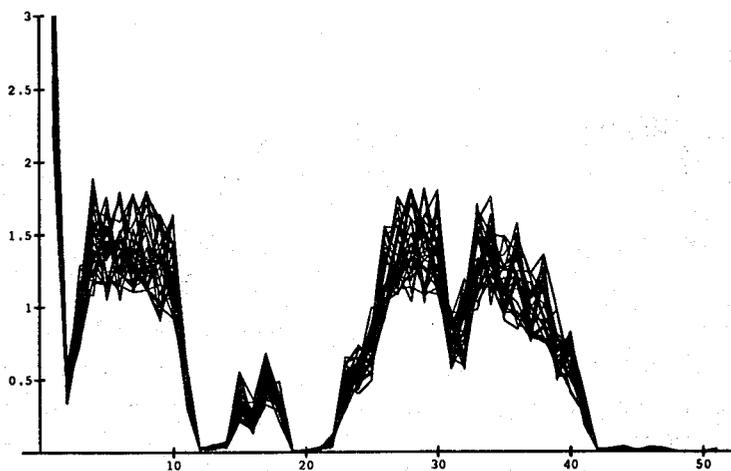Figure 5 Stochastic runs — natural mortality.
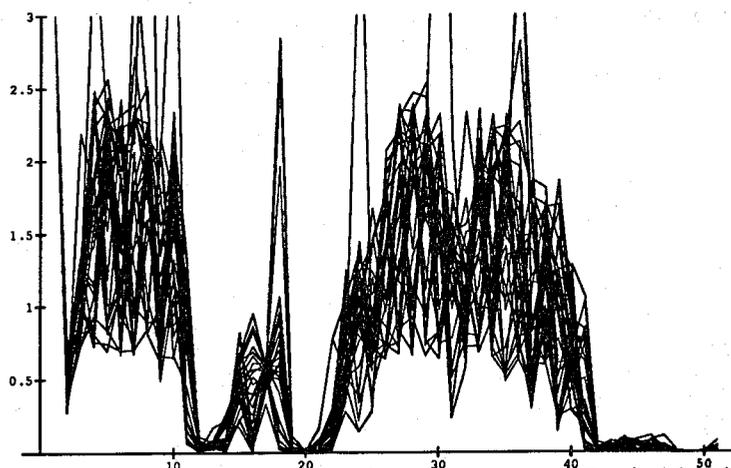
The influence of variation in growth of immature capelin (table 3) on the development of the spawning stock biomass is shown in figure 6.

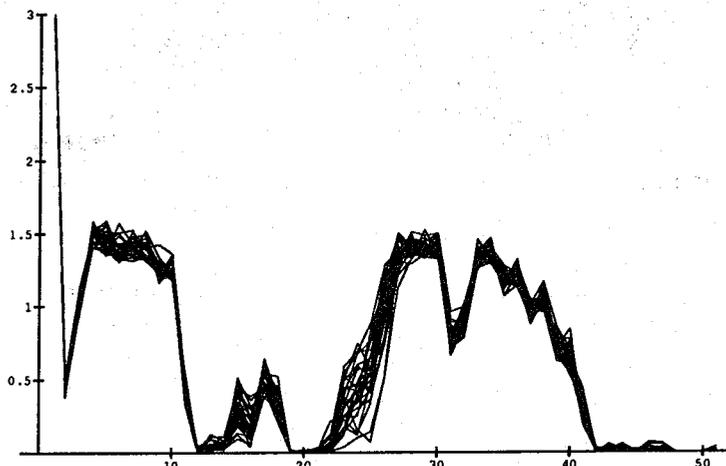Figure 6 Stochastic runs — growth of immature capelin.

The influence of variation in growth of mature capelin (table 4) on the development of the spawning stock biomass is shown in figure 7.
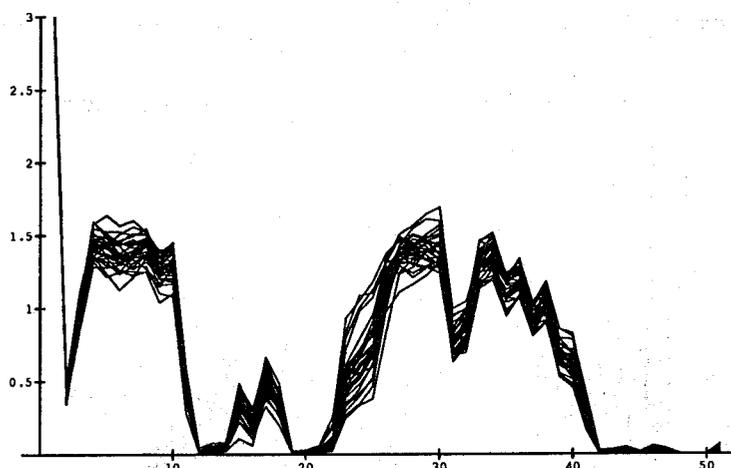
Figure 7 Stochastic runs — growth of mature capelin.

The influence of variation in the index for overlap between capelin and cod (table 5) on the development of the spawning stock biomass is shown in figure 8.

Figure 8 Stochastic runs — overlap index.

The influence of variation in the recruitment of cod on the development of the spawning stock biomass is shown in figure 9.

Figure 9 Stochastic runs — overlap index.

The influence of variation in the recruitment of capelin other than the variation due to random fluctuation of predating herring on the development of the spawning stock biomass is shown in figure 10.

Figure 10 Stochastic runs — recruitment index.
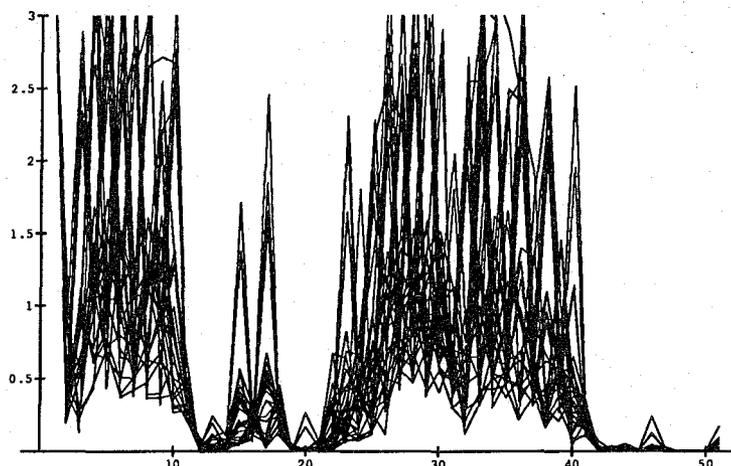
The variation in recruitment and natural mortality of immature capelin are by far the most dominating sources of uncertainty. Thus, the future work of constructing models for the CAPSEX processes which are not modeled should focus on these two processes. An obvious starting point would be to look for environmental variables that could explain some of the variation in recruitment and connect natural mortality also on immature capelin to the cod stock.

FUTURE WORK:
1: —IMPLEMENTING THE MODEL INTO MANAGEMENT OF CAPELIN.

In order to utilize the CAPSEX model for management of capelin, one should use long time simulations to find operational management decision rules, for instance if there is some value of the spawning stock that in the long runs yields the largest catch. Even if there is rather large uncertainty in the model such rules may be found. The line of work might be:

1. Find an optimal management criterion for a fixed series of random events.
2. Repeat for a large number of distinct series of events to find the precision of the management criterion.

Also, one might try to make the management decision rule adaptive. For instance, it may well prove more effective to allow a different quantity to spawn in cases of a rich year class of herring coming up than when the sea is more or less empty of herring.

2: —IMPROVEMENTS OF THE MODEL.

The present paper presents a minimum model. Future improvements might be:

1. Working out a better stock-recruitment relationship. (See page —153—).
2. The natural mortality on immature capelin should be modeled, with one component due to the cod stock and one residual component.
3. The growth should, if possible, be modeled by seeking relations between growth, temperature and capelin abundance. In the CAPSEX software there is built in a possibility for relating growth to observed plankton abundance.

4. It should be explored whether the overlap variable could be related to temperature or trends in temperature.
5. Before the results from the model are taken into use for management, extensive sensitivity analysis should be done, including:

   a. Temperature.
   b. Development of the cod stock (M and F values, individual growth).
   c. Maturation parameters.

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