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REPORT OF THE

Study Group on the Incorporation of Process Information into Stock-Recruitment Models

Lowestoft, UK
23–26 January 2001

International Council for the Exploration of the Sea

Conseil International pour l'Exploration de la Mer

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1 INTRODUCTION

1.1 Participants

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1.2 Terms of Reference

It was decided by Council (C.Res. 2000/2C01) at the 88th Statutory Meeting in September 2000 that:

The Study Group on Incorporation of Process Information into Stock Recruitment Models [SGPRISM] (Chair: Dr C. O'Brien, UK) will meet in Lowestoft, UK from 23–26 January 2001 to:

a) investigate and evaluate medium-term projection methodology for use in fishery assessment, taking account of characterisations (in space/time) of historical patterns in recruitment and the environment for specific case studies (cod and anchovy);
b) incorporate realistic variability in the parameters of management simulation models and evaluate more fully the potential of environmental studies to impact on management procedures;
c) investigate the variability and predictability of environmental conditions known or supposed to affect the dynamics of fish populations; and
d) consider the research activities of the STEREO project and investigate how the resultant information on the age, size and spatial structure of the North Sea/West of Scotland cod and haddock stocks should be incorporated into the extant methodology of stock assessment and projections.

SGPRISM will make its report available to the Working Group on Recruitment Processes (WGRP) and report to the Oceanography and Resource Management Committees at the 89th Statutory Meeting.

Scientific justification:

The relationship between spawning stock and recruitment is fundamental to the scientific approach to fisheries management. Considerations of environmental factors can make a difference to how one might manage a stock. Simulation models can play an important role in helping identify whether and where benefits to management are most likely to accrue and therefore where it would be best to focus attention in terms of other (e.g. process) studies. Results from simulation studies should be used to guide biological studies. Short-term focused studies aimed at identifying likely mechanisms are also crucial, but results from such studies can only be put to full use with information from longer-term observations. There is also benefit in long-term studies of the environment and underlying processes so that one is prepared if something unexpected happens. For example, if a process study reveals a strong relationship with some environmental variable, then it would be possible to incorporate this immediately if historic data are already available.

STEREO (An operational model of the effects of stock structure and spatio-temporal factors on recruitment, EU FAIR CT98–4122) is investigating the extent to which variations in dispersal and the spatial configuration of spawning affect the proportion of the total carrying capacity that can be occupied at different levels of stock abundance, and these results will be reported at the next meeting of the WGRP. However, it was also felt that the type of information considered in that project should be provided to the SGPRISM as an example case study which should be used to develop approaches for incorporation of process studies into stock-recruitment projections and advice.

1.3 Structure of the Report

The terms of reference (ToR) are addressed within the four main sections of the report. ToR a) and b) are addressed within Sections 3 and 4 of the report, ToR c) is addressed within Section 4 and ToR d) is addressed within Sections 2 and 3.

For a given level of spawning stock biomass there is often considerable variation in recruitment. This variation is frequently attributed to environment effects on survival. However, there is increasing evidence that the age, size and spatial structure of the spawning stock and the physiological condition of spawners can influence the number of surviving recruits. Section 2 reviews a number of these issues that have considerable potential for incorporation into medium-term recruitment forecasts.

In Section 3, background details are given of the WGMTERM projection program that is used for medium-term projections within the ICES stock assessment framework for North Sea gadoids. The effect of incorporating environmental variability (namely, sea surface temperature) into the Ricker stock-recruitment model for North Sea cod (*Gadus morhua* L.) and the results of a number of projections using WGMTERM are presented; together with modifications proposed at the last meeting of the Study Group (ICES, 2000a). Results from the short-term population and fishery projections of anchovy in the Bay of Biscay are presented in Section 4; together with a short-term prediction of recruitment in North Sea cod. The Section 5 consists mainly of a general discussion based on the results of a simulation study to investigate the potential of environmental studies to impact upon management procedures (e.g. harvest control rules).

Further work and the relevance of the Study Group to similar activities within ICES and NAFO are discussed in Section 6.

2 PROCESSES AND BIOLOGICAL ISSUES – AGE, GROWTH, SIZE AND SPATIAL STRUCTURE

2.1 Assessing the Effects of Incorporating Process Information in Assessments and Projections

Routine stock assessments are sometimes criticized for their lack of inclusion of biological information, particularly in relation to reproductive parameters (e.g. Trippel 1999). There are many cases where this is a valid criticism. While it seems intuitive that the inclusion of additional biological knowledge should improve the assessments, as with all assumptions made in the stock assessment process it is appropriate to verify that this assumption is correct.

To take first a hypothetical example, a fishery might be closed on the basis of the estimated SSB of the stock falling below some preset level. If a more biologically detailed measure of the stock's reproductive potential were used instead of SSB, then it is possible that the decision to close the fishery would have been reached at a different time. For subsequent management of the closed fishery, the two approaches could give different pictures of stock status. If the stock were rebuilt to some threshold SSB, it is possible that this level would correspond to a low reproductive potential due to the relatively high contribution of recently-recruited year classes. Hence decisions based on reproductive potential would tend to be more conservative and could delay the re-opening of the fishery until the actual reproductive potential had improved substantially (Scott *et al*. 1999, BD9).

While there is clear value in using a reproductive index rather than SSB in a management context, as in the above example, the situation is less clear-cut when the same information is used in a stock-recruitment relationship. The use of an index of stock reproductive potential in place of SSB on the X-axis of a stock-recruitment plot may result in an improvement in the coefficient of determination of the model fit. While this represents a statistical improvement in the assessment, it may not have a significant impact on the results of the assessment and projections. It is the latter which needs to be assessed to determine the contribution made by including the additional biological information.

The primary use of a stock-recruitment model within a routine stock assessment comes in predicting recruitment for the purposes of stock projections. These are generally used to estimate the uncertainty associated with the stock forecasts under different levels of F in medium-term projections. Hence an appropriate test for the effectiveness of additional biological information might be the extent to which it results in reduced uncertainty in recruitment forecasts. The approach developed by Patterson *et al*. (2000) to test medium-term projection methodology may have application in this context.

An analogous problem is the situation where a number of different recruitment models are available and criteria are needed to judge whether the choice of model will affect the management advice. An example of this is the stock-recruitment relationship for the east Baltic cod stock. Here, Sparholt (1996), Jarre-Teichman *et al*. (2000) and Köster *et al*. (1999) have all developed stock-recruitment models with varying degrees of complexity and which reflect environmental influence to differing extents. The stock-recruitment model used during stock assessments is different from all of these (ICES 2000c). In these cases it is desirable to have some criteria by which the 'best' model can be selected from among all these competing candidates. Again, thorough testing as performed by Patterson *et al*. (2000) may be appropriate.

2.2 Reproductive Indices

The assumption that spawner biomass is directly proportional to the reproductive potential of a stock (*sensu* total egg production) underlies most stock-recruit relationships. However, there is accumulating evidence to suggest that this assumption is invalid. The reproductive potential of a stock is determined by the age, size and spatial structure of the spawners as well as by their physiological condition. These findings have stimulated interest in re-evaluating the stock-recruit relationship using more precise estimates of reproductive potential (Solemdal 1997; Murawski *et al*. 1999).

The most direct approach to quantifying the reproductive potential of a stock is to multiply the age-specific biomass of mature females by the age-specific relative fecundity (no. of eggs g^{-1}) and integrate across age to give an estimate of total egg production. The data required for this calculation include:

1) assessment derived numbers-at-age;
2) age-specific values of the proportion of females;
3) age-specific values of the proportion mature;
4) age-specific weight; and
5) age-specific relative fecundity.

Total egg production estimates could also incorporate information about the intensity of atresia (resorption of oocytes) and age-specific egg viability.

For many stocks, detailed data on reproduction do not exist. Furthermore, existing sampling programs often do not collect basic data such as age-specific values of the proportion mature and weight (see Section 2.2.2). Treating any of these terms as constants will decrease the accuracy of the resulting estimate of reproductive potential. This is particularly true for stocks exhibiting large interannual variability in condition because condition affects maturity (Marshall *et al*. 1998), weight, fecundity (Kjesbu *et al*. 1998), atresia (Kjesbu *et al*. 1991), egg quality (Chambers and Waiwood 1996; Lambert and Dutil 2000), and larval quality (Marteinsdottir and Steinarsson 1998) simultaneously.

The approach taken to estimating the reproductive potential of a stock will necessarily differ among stocks as a consequence of inter-stock differences in data availability. The Baltic cod stock is an example of a data-rich stock by virtue of having data from ichthyoplankton surveys, historical fecundity data (Kraus *et al*. 2000) as well as maturity and weight information that is updated annually. These data have been used to reconstruct a time series of potential and realized daily egg production (Köster *et al*. 2000). In addition, a recruitment model has been developed which includes terms for daily egg production corrected for predation, oxygen content of the reproductive volume and larval transport (Köster *et al*. 2000).

Condition time series can also be used to indicate interannual variation in reproductive potential. For example, a long time series of liver weight observations was used to estimate the total lipid energy in the livers of mature females for the Northeast Arctic cod stock from 1946 to 1996 (see Section 2.2.1). Recruitment in some haddock stocks shows positive correlations with condition of spawners (Marshall and Frank 1999). In the case of data-poor stocks, improved estimates of reproductive potential can be obtained through relatively minor modifications to existing data. For example, the age-diversity index for Icelandic cod, estimated from the VPA numbers at age, shows a higher correlation with recruitment than spawner biomass (Marteinsdottir and Thorarinsson 1998). Excluding the first-time spawners from the spawner biomass estimate improved the fit of the stock-recruitment relationship for Georges Bank (Wigley 1999).

2.2.1 Reconstructing the stock-recruitment relationship for North-East Arctic cod using a bio-energetic index of reproductive potential

Liver weight observations for North-East Arctic cod have been recorded monthly since 1927 (Yaragina and Marshall 2000). Because the liver is the primary storage site of lipid energy in gadoids (Kjesbu *et al*. 1991), the database constitutes a highly resolved record of seasonal and inter-annual changes in surplus energy. Using these data, the total lipid energy (TLE, kJ) contained in the livers of mature females was estimated annually for a fifty-one year time period (1946-1996) and used as a proxy for total egg production by the North-East Arctic cod stock (Marshall *et al*. 2000). A significant linear relationships between TLE and recruitment to age-3 was observed ($n = 49$, $r^2 = 0.12$, $p = 0.013$). The TLE time series suggests that with the exception of 1982 the reproductive potential of the stock has been below 1 trillion kJ since the mid-1970s (Figure 2.2.1.1a). The temporal trend is quite different if the reproductive potential of stock is expressed as spawner biomass (Figure 2.2.1.1b).

This analysis illustrates how changes in the method of estimating the reproductive potential of North-East Arctic cod can alter the perception of stock status. In future, a general cod fecundity model will be developed and combined with the liver condition time series to generate year-specific fecundity-length relationships. Characteristics of the spawning stock that are likely to affect hatching success and larval survival (e.g. the proportion of repeat spawners) will also be included.

2.2.2 Collection of survey data

By nature, any reproductive index requires biological information. Even for a simple measure of SSB, the estimates of maturity and weight-at-age should ideally be updated annually. Research vessel surveys represent the key source of biological information, hence the scope for developing reproductive indices is limited by the information available from these surveys. Section 2.2 lists the biological data required to quantify the reproductive potential of a stock. Although, it would be desirable to collect all of this information on all surveys, this is typically not the case. This Study Group (SGPRISM) was aware that the existing sampling protocols for some surveys do not specify the collection of all of these data. As an example, the Study Group reviewed the protocol for one major survey within the ICES area.

The ICES International Bottom Trawl Survey (IBTS) is a major survey covering the North Sea. Minimum standards for length recording and otolith extraction for several species have been set for the IBTS by the WGBTS (Working Group on Bottom Trawl Surveys). This states that sex and maturity *may* be recorded, but the collection of these data is not mandatory. There is no requirement to collect individual weight data. In the absence of these data, the existing protocol restricts the ability to quantify the reproductive potential of the relevant stocks. While some nations do collect these data, they are often not available within the IBTS database.

In the light of this, the SG suggests that it would be desirable to review the sampling protocol of the IBTS and other surveys. The SG realises that time constraints at sea are the largest factor to consider when changing the mandatory sampling regimes. The recording of individual weights is already common practice amongst many nations and requires little time. However, those surveys not recording individual weights may have to adapt data recording procedures and even computerised data-bases to accommodate this.

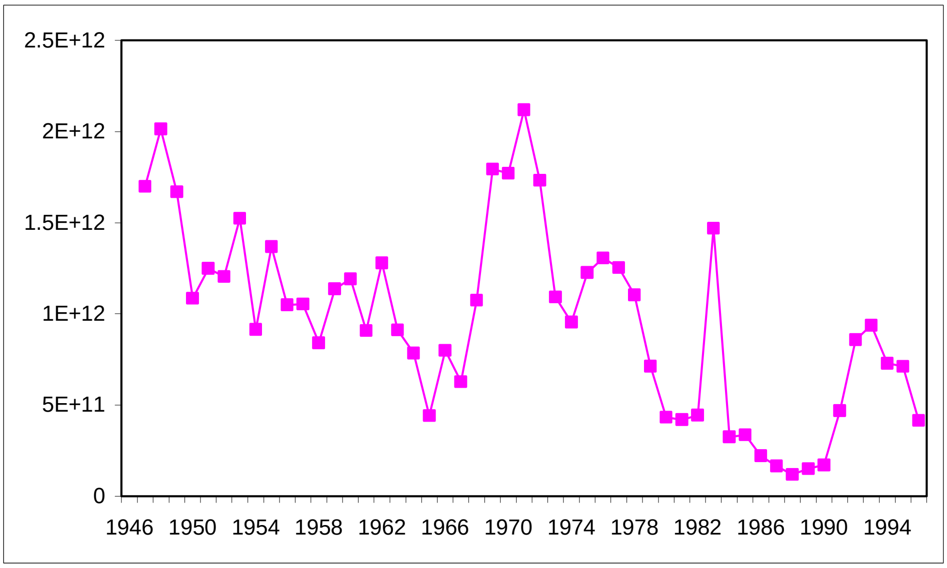
2.3 The STEREO Project (STock Effects on REcruitment relatiOnships, EU FAIR CT98-4122, December 1998-November 2001)

The last ToR d) of the Study Group requested that the research activities of the STEREO project should be considered within the context of SGPRISM and how information derived from the project could be incorporated into the extant methodology of stock assessment and projections. The study group felt that STEREO should also be considered within the larger management context and hence it investigated what additional information from the project would be of potential use to managers. Data on the reproductive potential of cod from the STEREO project were made available for stock projections and the results are described in Section 3.3.

2.3.1 Brief overview of the STEREO project

The STEREO project has been described and summarised in a number of ICES documents (CM 1999/Y:10, Theme Session on Cod and Haddock Recruitment Processes, ICES 2000b,d). Very briefly, the project involves field, laboratory, and modelling investigations of, on the one hand, the spatial and temporal patterns and magnitude of egg production by cod and haddock and the dependence of these on the age and length composition and condition of the spawning stock, and on the other hand, the dispersal, growth, mortality and settlement of eggs larvae and juveniles, including density dependent processes. The project has developed a bio-physical modelling approach which integrates the knowledge of demersal fish reproductive biology and early life history ecology. The basic philosophy of the project

a



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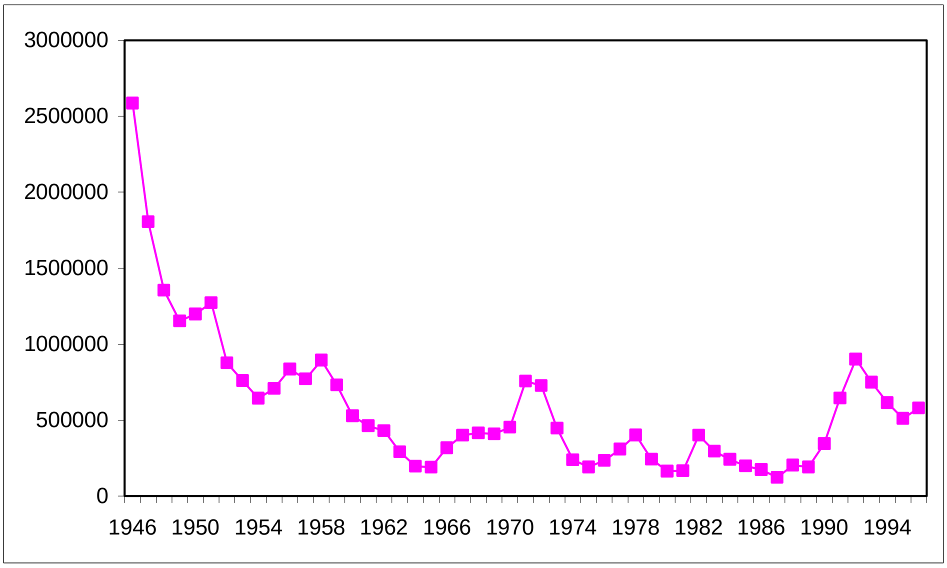


Figure 2.2.1.1. a) Time series of total lipid energy of North-East Arctic cod, and b) time series of spawner biomass for North-East Arctic cod

is that not all eggs have an equal probability of survival to recruitment. The whole modelling approach is intended to identify the relative contributions of different spatial, temporal, age and length components of the spawning stock to recruitment, and the effects of climatic conditions and spawning stock abundance on these outcomes. The model is capable of predicting the spatial distributions of surviving juveniles from an initial space-age-length-abundance distribution of spawning stock, and its success in this respect with respect to measured trawl survey data, is the major test of its performance. The case-study examples in the project are Icelandic cod, North Sea and west of Scotland cod and haddock.

2.3.2 Envisioned applications of the project outputs

From the inception of the project, it was never envisaged that the STEREO model system would ever be applied as a methodology in stock assessment and prediction. The system is too complex for that, and is fundamentally a research tool for integrating understanding of the processes which make up the stock-recruitment relationship, and assessing the extent to which uncertainty as to the details of some processes may cloud our perception of such relationships. However, the vision was very much that the model would allow us to resolve the fundamental shape of stock recruitment relationships given the various bio-physical relationships contributing to the overall process, and the way in which this shape should change in response to the structure of the spawning stock, and climatic factors. It was considered that this would be a valuable contribution to assessment methodology given a) the sensitivity of derived management reference points to the shape of stock recruitment relationships, and b) the extremely poor perception of such relationships gained from the common practice of statistically fitting simple equations such as those of Beverton-

Holt or Ricker to paired population level estimates of spawning stock abundance and recruitment from assessment time series. The first steps in this direction were reported by Heath and Gallego (2000, BD7).

The emphasis in the project on structural aspects of the stock recruitment relationship is important with respect to projections of the future state of stocks under different harvesting strategies using, for example the WGMTERM procedure. By structural aspects, we mean effects linked to the age and/or size composition of the spawning stock, and which are therefore potentially dynamic properties of the simulated population in WGMTERM, and do not rely on an ability to forecast any environmental conditions in the future. The biological rationale here is that large, old fish not only produce more eggs than small young fish, but more and larger eggs per unit body weight, usually spread over a longer period of the spawning season. The consequence is that, per unit weight of spawning biomass, large old females have the potential to make a disproportionately large contribution to recruitment. Heavily exploited stocks typically contain few such fish and would be expected to generate fewer potential recruits than a lightly exploited stock of the same spawning biomass. These relationships were explored in STEREO by Scott *et al.* (1999, BD9). In addition, it is clear from survey time series data for various groundfish stocks that biological properties such as size at age, weight:length, and maturity at age are dynamic properties of a fish population linked, presumably through some density dependent interactions, to the overall population abundance. The basic biological relationships underlying these properties of fish stocks are an important output from the field and laboratory investigations of STEREO, which can feed into assessment and management procedures.

Further applications of STEREO include providing advice on closed areas and seasons, particularly in relation to reducing fishing effort on spawning populations. Investigations into the carrying capacity of systems can offer insight into the processes that occur in years with extremely high survivorship and by inference years with high recruitment. As the model is further developed, applications may include analysis of essential fish habitats and other considerations within the context of the ecosystem approach to fisheries management.

2.4 Reference Points and Management

2.4.1 Life history and reproduction dynamics

The group discussed the use of reference points in light of STEREO and recent developments in process-related studies. It was clear that an understanding of the functional form of the stock/recruitment relationship is vital and that all reference points should be biologically consistent with this relationship. In cases where more sensitive measures of the reproductive potential of stocks are used to refine the stock-recruitment relationship, the reference points must be reviewed and in some cases revised. Reference points for SSB may prove to be inefficient in stock conservation or rebuilding when SSB is not indicative of the reproductive potential of the stock or when there are decadal changes in productivity. While the Study Group recognised the practical need for biomass-based reference points in formulating management advice it was felt that assessment working groups should consider new approaches.

In keeping with a biological perspective of a stock it is therefore necessary to consider developing additional reference points that are specific to reproductive potential. Several such measures are currently being evaluated by the NAFO Scientific Council Working Group on Reproductive Potential (BD1). The measures need to be biologically based and easily measured. It is clear that the underlying age structure of a population is important in determining the number of viable offspring produced (e.g. Scott *et al*. 1999 BD9, Marshall WD1). The use of an age-diversity index (Marteinsdottir and Thorarinsson 1998) is one possible index of reproductive potential that is easily calculated using numbers-at-age. Another example of an easily-computed index of stock reproductive potential is a measure of the viable number of eggs per kilogram of SSB, a measure utilised by Scott el al. (1999). Maximising the viable egg production per unit spawning stock biomass would seem to be a highly desirable objective for stock management as it reflects the age/size structure of the spawning stock and is a clear dynamic consequence of the balance between recruitment and mortality rates.

Fishing mortality reference points could also be used more effectively. The long-term consequences of sustained high rates of fishing mortality may be under-appreciated given that the link between fishing mortality and reproductive potential has not been accurately specified using SSB as a proxy for reproductive potential. The group used a specific stock (Northeast Arctic cod) to model the links between fishing mortality and reproductive potential. The reproductive potential of the stock was represented by the total lipid energy contained in livers of mature females in the stock (units of kJ; see Section 2.2.1). To quantify the removal of reproductive potential by the fishery the total amount of lipid energy contained in livers of mature females in the catch was also calculated using the catch numbers-at-age. The proportional removal of reproductive potential (PRR) was estimated as the ratio of the total amount of lipid energy contained in livers of mature females in the catch to the total amount of lipid energy contained in livers of mature females in the stock.

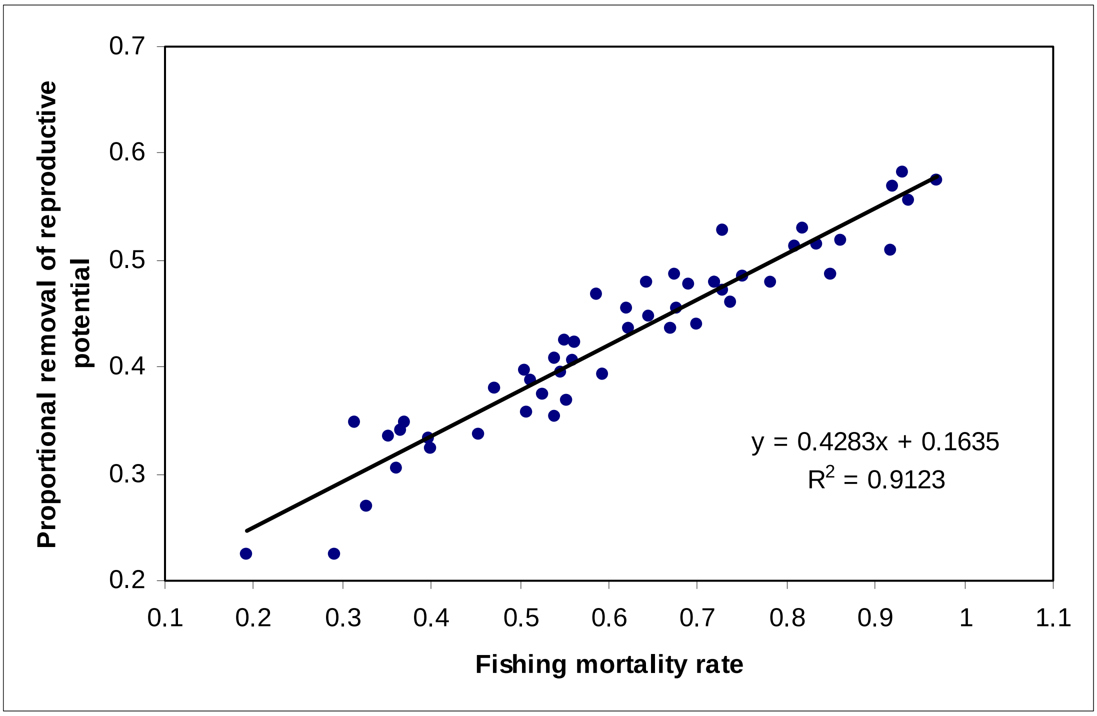


Figure 2.4.1.1. The relationship between fishing mortality rates (average values for cod age 5 through 10) and the proportional removal of reproductive potential by the fishery (1946–1996). A fishing mortality of 0.78 corresponds to the removal of 50% of the reproductive potential annually.

From 1946 to 1996, the PRR varied from 0.22 to 0.58 indicating that between twenty and sixty percent of the reproductive potential was being removed annually through fishing. The PRR was significantly, positively correlated ($r^2 = 0.91$, n = 51; Figure 2.4.1.1) with fishing mortality averaged across age-classes 5 to 10 (F_{5-10}). Values of F_{5-10} higher than 0.79 result in the removal of greater than 50% of the reproductive potential. The precautionary value of F ($\mathbf{F}_{pa}$ = 0.42) will remove 34% of the reproductive potential annually. Over the past five years between 46% and 61% of the reproductive potential has been removed annually. The results suggest that management advice should be formulated to achieve fishing mortality rates that are consistent with an acceptable level of PRR.

2.4.2 Spatial and fishery concerns

The role of spatial and fishery considerations whilst setting reference points was highlighted by the example of Celtic Sea herring. The 2000 Herring Assessment Working Group (HAWG) was charged with investigating the precautionary reference points for Celtic Sea Herring (ICES 2000e). This was in the light of an apparent regime shift in recruitment between 1968 and 1978. The issue had been raised and discussed by the HAWG and ACFM for a number of years. Previous HAWGs had noted that tagging investigations in the 1960s, recent acoustic surveys and ground fish surveys in the Irish Sea had shown a convincing link between the abundance of juvenile herring in the western Irish Sea and recruitment to the stock in the Celtic Sea.

From 1968 to 1978 an industrial fishery took place in the western Irish Sea and the catches were monitored by the Republic of Ireland. The occurrence of this fishery coincided temporally with the apparent regime shift in Celtic Sea herring recruitment (see Figure 4.7.1 in ICES 2000e). Previous HAWGs had looked into the likely impact of the fishery on Celtic Sea recruitment, and concluded that the catch was not sufficient to effect recruitment, i.e. the figures did not add up. However, recent ideas with regards to the non-random origin of recruits suggest that if the juveniles from the Irish Sea are more likely to recruit to the Celtic Sea stock than juveniles from other areas, the industrial fishery may have impacted on stock recruitment. In other words, if juveniles from the Irish Sea nursery area dominate the survivors to recruitment more than those from the Celtic Sea then the fishery was important. Further work is required to test this hypothesis. However, this case indicates that knowledge of the spatial patterns within the processes that govern recruitment is vital when considering management issues, such as the setting of reference points, ideas concerning regime shifts and the varying productivity of systems.

2.5 Related Issues for North-East Arctic Cod

2.5.1 Natural mortality

Tretyak (BD4) estimates natural mortality in North-East Arctic cod using a model which assumes a link between growth, maturity and natural mortality. To estimate coefficients of natural mortality for all ages and years, the measured mean weight-at-age of that year-class, and the average annual water temperature experienced by that year-class in its first three years are used in a regression model. A model linking growth and mortality in this way offers a way of reducing the number of parameters to be estimated for use in stock projections. However, in the case of North-East Arctic cod, growth and mortality appear to be closely linked to capelin abundance, so a multi-species approach might be more appropriate in this case.

2.5.2 Population fecundity

To estimate the population fecundity (or total egg production) for Northeast Arctic Cod, Tretyak (WD2) used fecundity data from Serebryakov *et al.* (1984) and from Kisaleva (2000). These only covered a limited year-range, so to estimate fecundity for earlier years Tretyak derived a relationship between weight-at-age and fecundity-at-age, which he used to estimate age-specific fecundities for other years. These were then used along with estimates of numbers-at-age from a recent stock assessment to estimate population fecundity for all years.

3 NUMERICAL APPROACHES TO QUANTIFYING UNCERTAINTY IN MEDIUM-TERM STOCK FORECASTS

3.1 Medium-Term Projections

Many strategic fishery management decisions in the ICES framework (such as estimates of precautionary fishing mortality rates) are based on stochastic projections of population dynamics over a medium-term (10-year) time-frame. The standard method of performing such projections for demersal species in the context of ICES is the WGMTERM package (Reeves and Cook 1994). The previous meeting of SGPRISM (ICES 2000a) proposed several modifications to WGMTERM to address concerns about autoregressive time-series structures in the recruitment model residuals used to

drive projections, and to attempt to implement in projection procedures stock-recruitment models mediated by hypothesised environmental and stock-structure influences. Inter-sessional work by Study Group members (Needle *et al.* 2000a, b) using ARMA time-series models and recruitment models with environmental covariates represented a first step towards meeting these requirements, and the analyses carried out therein were extended and augmented during the present meeting. Results are presented in Sections 3.2. Work was also initiated on the use of indices of potential egg production (as derived from outputs of the STEREO project, see Sections 2.3 and ToR d) in stock-recruitment-driven projections rather than SSB. The results of this are presented in Sections 3.3; the conclusion of which are discussed in Section 3.4.

The methodology of WGMTERM and it extension for inclusion of temperature as a covariate in the Ricker stock-recruitment relationship was summarised in the previous SGPRISM report (ICES 2000a). However, the principles of ARMA time-series modelling and how they have been applied to fishery population projections are less widely known and bear repeating. ARMA time-series modelling describes the behaviour of a data series in terms of a combination of autoregressive (AR) and moving-average (MA) effects. In order to conform to requirements for stationary, it may also be necessary in general to *difference* the series. For the analyses described here, however, this was not the case: because the series in question are residuals from a fitted parametric model, they tend to fluctuate around a stationary mean of zero without any requirement for further intervention. If a mean value is not being fitted, an ARMA(p,q) model fitted to a series x_i is given by

$$x_i - \Phi_1 x_{i-1} - \Phi_2 x_{i-2} - \ldots - \Phi_p x_{i-p} = a_t - \Theta_1 a_{i-1} - \Theta_2 a_{i-2} - \ldots - \Theta_q a_{i-q}, \qquad (3.1)$$

where p and q are the order of the AR and MA components of the model respectively, Φ_i and Θ_i are AR and MA parameters to be estimated, and $a_i \sim N\left(0, \sigma^2_{\mathrm{ARMA}}\right)$ are independent identically-distributed random variates known as *innovations*.

Time-series models for this study were fitted to $x_i = \ln(R/\hat{R})$, the logarithm of the ratio of observed to fitted recruitments, based on the Ricker stock-recruitment model. Model fitting was carried out using the S-PLUS statistical package (MathSoft 1999). For the purposes of demonstration at the present meeting, only first-order autoregressive models were fitted during the present meeting, although ideally a full investigation of the correct model choice would be performed (Needle *et al*. 2000a, 2000b). Thus the equation (3.1) reduces to

$$x_t = \phi x_{t-1} + a_t . \qquad (3.2)$$

For each simulation run, a vector $\mathbf{A} = [a_i]$ of innovations was created by random draws from a normal distribution with mean 0 and variance given by the variance of the ARMA model fit, so that $a_i \sim \mathrm{N}(0, \sigma^2_{\mathrm{ARMA}})$. North Sea cod recruit at age 1, so the first value of the projected time-series vector $\mathbf{X} = [x_i]$ was given by the logged residual ratio for the final historical assessment year. Subsequent values of **X** were generated from this point using the innovations vector. For the autoregressive ARMA(1,0) model with parameter ϕ_1 the *i*th projection value is

$$x_i = \phi_1 x_{i-1} + a_i , \qquad (3.3)$$

The required projected Ricker recruitment is then

$$R_i = \alpha S_{i-1}\, \mathrm{e}^{-\beta S_{i-1} + x_i} . \qquad (3.4)$$

Once recruitment is calculated, population dynamics are processed via the usual exponential decline equations.

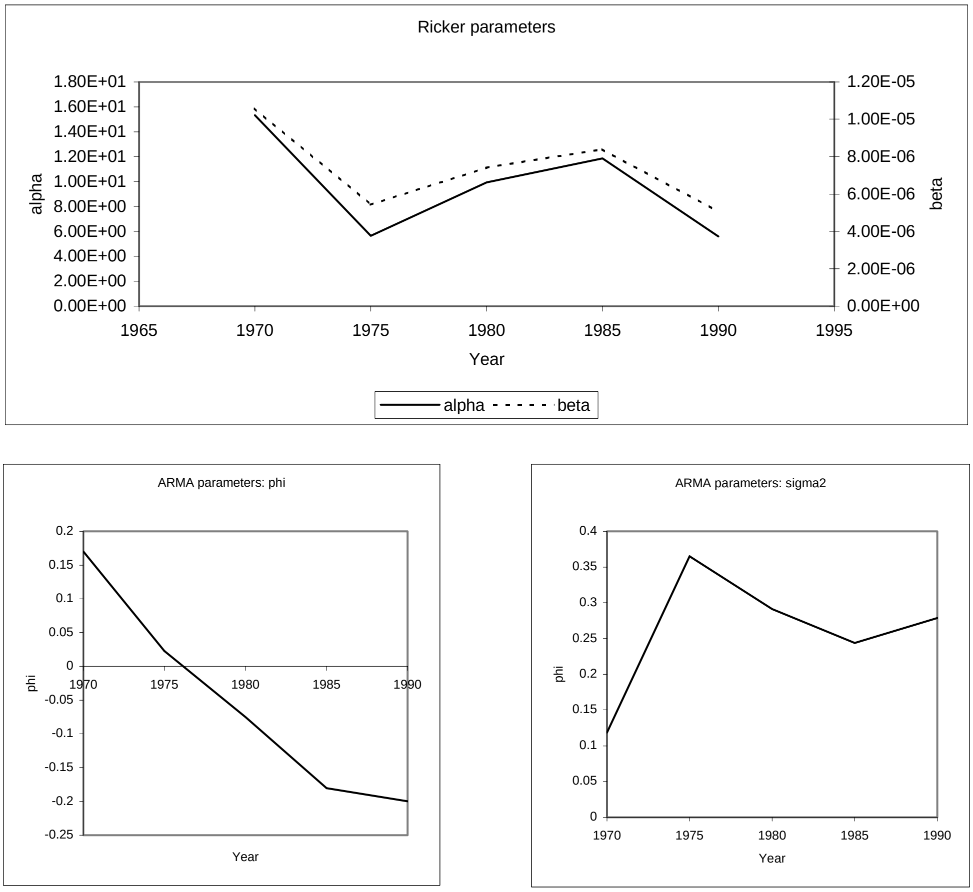


Figure 3.2.2.2. Parameters of the Ricker model for each of the distinct starting years, together with the time series model parameters.

3.2 Medium-Term Projections of North Sea Cod (*Gadus morhua* L.)

3.2.1 Simulation experiments

The Study Group decided that it would be a valuable exercise to investigate the validity of North Sea cod projections obtained from the three available methods (ARMA, WGMTERM-type, and WGMTERM-type with temperature). To this end, projections were performed from a series of starting points ($i = 1970, \ldots, 1990$ in steps of five years). In each case a Ricker stock-recruitment model (with or without a temperature covariate) was fitted to the scatterplot of recruitment R against spawning-stock biomass (SSB) for the years 1963 to i-2 from the 1999 ICES North Sea cod assessment (ICES 2000f). Projections were then begun from fixed numbers-at-age $N_{a,y}$ in year i, using a selection-at-age ogive $S_{a,y}$ and weights-at-age $W_{a,y}$ averaged over the years i-4 to i-2, and F-multipliers derived from the $\overline{F}$ estimates for the years i to 1998 from the 1999 assessment. 1000 stochastic simulations were performed for each combination of starting year and method, and percentiles of the resulting R and SSB projection envelopes were plotted against the historically-estimated values from the 1999 assessment. As an additional diagnostic test, plots were also produced which compared the median of projected R with a deterministic projected R: that is, the R that would result if there was no stochastic variation about the fitted stock-recruitment curve. Such plots highlight the existence of time-series structure in historical recruitment residuals if these have not been explicitly accounted for by the projection model (Needle *et al*. 2000a, b).

3.2.2 Results

Figure 3.2.2.1 (Appendix A) shows the Ricker stock-recruitment fits relating to each projection starting year: hence, for starting year 1990, stock-recruitment data from 1963–1988 are used to generate the fit. Figure 3.2.2.2 and Table 3.2.2.1 compare the parameters of the Ricker model for each of these starting years, along with the subsequently fitted time-series model parameters and temperature model parameters. These demonstrate that the characteristics of the fitted recruitment curves and the fitted time-series model change considerably over time. The effect of temperature is consistently negative and most marked for the fit using data up to and including 1973, which includes high recruitments of the 1969 and 1970 year classes. In the fit including data to 1988 the temperature effect is less strong, possibly because by this point SSB and recruitment are reduced and at low stock sizes the effect of temperature may be less significant upon recruitment. Figures 3.2.2.3 show the projections from each model for each starting year, for both R and SSB, while Figure 3.2.2.4 compares the projection diagnostics.

Projection year	**Ricker**		**ARMA**		**Ricker and temperature**		
	alpha	**beta**	**phi**	**Sigma2**	**alpha**	**beta**	**gamma**
1970	15.3018	1.06e-5	0.1702	0.1187	57.963	0.0094	-0.2076
1975	5.6474	5.43e-6	0.0228	0.3651	5842.195	0.0027	-0.9788
1980	9.9338	7.41e-6	-0.0753	0.2913	1099.279	0.0062	-0.6472
1985	11.8364	8.40e-6	-0.1805	0.2437	1694.920	0.0065	-0.6926
1990	5.5852	5.05e-6	-0.1998	0.2785	196.396	0.0036	-0.5007

Table 3.2.2.1. Tabulated parameter values for the models investigated.

3.2.3 Discussion

3.2.3.1 Projected recruitment

Table 3.2.3.1.1 compares projected recruitment with that perceived by the 1999 assessment. Note that feedback occurs in the projection and therefore projected recruitment is influenced by the preceding SSB, which may not be comparable, between each simulation and the 1999 assessment.

Projection year	WG	Temperature	ARMA
1970	wide simulation envelope – trend, along with high recruitment early in the series and later low recruitment, is not captured	tighter simulation envelope fails to capture the trend, early high recruitment and most of the later low points	very tight simulation envelope fails to capture the trend, and most of the observed recruitment points
1975	wide simulation envelope captures most of the recruitment data, but not the trend	tighter simulation envelope fails to capture most of the high recruitment values, although the trend is similar to the observed	tighter simulation envelope fails to capture some of the high and low recruitment values. The shift from high to low is smooth rather than sharp, as in the observed series
1980	wide simulation envelope fails to capture the trend and much of the late series low recruitment	tighter simulation envelope captures the trend and all but a few low recruitments in mid-series	tight simulation envelope fails to capture the trend, and most of the later low recruitment values
1985	wide simulation envelope fails to capture much of the late series low recruitment or the trend	variable simulation envelope captures the trend and all but a few low recruitments in the early series	tight simulation envelope fails to capture the trend, and most of the later low recruitment values
1990	wide simulation envelope captures most recruitment data, but not the trends	tighter simulation envelope fails to capture higher recruitment points, but does follow some of the observed trends	tighter simulation envelope fails to capture low recruitment values and the short-term trends

Table 3.2.3.1.1. Summary of projected recruitment under each of the three models.

The WG-type model produces a relatively smooth recruitment trajectory with a wide simulation envelope. Observed trends in recruitment are generally lost. The SRR and temperature model produces a more variable recruitment trajectory in which the simulation envelope is narrower and sometimes variable but follows the median more closely. Observed trends in recruitment are captured by this model, with the exception of the 1970 projection, in which the SRR model is fitted to data from 1963-1968 and the estimated temperature parameter is small. The ARMA model has the tightest simulation envelope and as a result many recruitments fall outside the envelope. The model does not predict the trends in recruitment well, particularly if abrupt changes in the level occur.

The standard WG-type model fails to capture the low recruitments in recent time for the projections started in 1970, 1980 and 1985. The temperature model fails to capture three low recruitments (1985, 1987 and 1989) in the 1970, 1980 and 1985 projections, but does capture them in the 1975 projection, although recruitment in this projection was generally low and few of the high recruitments are captured. The recruitments noted above occur during the transition between high and low (cool and warm) recruitment regimes. The ARMA model fails to capture the low recruitments in recent years in the projections started in 1970, 1980 and 1985, as well as, to some extent, in 1975, however it must be borne in mind that the simulation envelope for this model is much tighter.

3.2.3.2 Projected spawning stock biomass

Table 3.2.3.2.1 compares projected SSB with that perceived by the 1999 assessment.

The WG-type model tends to be over-optimistic with regards SSB in the recent past, except for the 1990 projection. The temperature model is inconsistent in its deviations from the perceived SSB trend. The 1970 projection over-estimates recent SSB, 1975 and 1990 projections underestimate the most recent SSB, whereas the 1980 and 1985 projections are roughly in accord with recent levels of SSB. The ARMA model tends to be over-optimistic in recent past, except for the 1990 projection and is generally similar in trend with the standard WG-type model but has much tighter simulation envelopes.

The earlier projections using all three models (and the temperature) consistently show high SSB in the early 1980s, a feature, which is supported by the historical series. The temperature model predicts high SSBs in the early 1990s in projections starting in years 1970, 1975, 1980 and 1985 which is absent from the historical series. This appears to be related to over-optimistic prediction of the 1985, 1987 and 1989 recruitments (see Section 3.2.3.1).

Projection year	WG	Temperature	ARMA
1970	The projection underestimates SSB in the first 5 years, loosely matches the level but not trend in the next 8 years and over-estimates for the most recent 10 years. The overall trend is down on the initial level and stable or rising in recent time.	The projection underestimates SSB in the first 5 years, loosely matches the level in the next 8 years and over estimates for the most recent 10 years. The overall trend is down on initial level and stable or rising in recent time.	The projection under estimates SSB in the first 5 years, loosely matches the level in the next 8 years and over estimates for the most recent 10 years. The overall trend is down on initial level and stable or rising in recent time.
1975	The simulation envelope encapsulates the historical trend, but is smoother and SSB tends to be over-estimated in recent years. The overall trend is well-down on initial level and rising after the series low in recent time.	The simulation envelope, which is tight at low SSB, fails to capture the historical data for much of the series and is generally more pessimistic. The overall trend is a continuous decline in SSB.	The simulation envelope encapsulates the historical trend, but is smoother and SSB tends to be over-estimated in recent years. The overall trend is well-down on initial level and rising after the series low in recent time.
1980	The projection tracks SSB for 5 years but is over-optimistic in the recent period. The overall trend is a recent recovery after a slight decline.	The projection is over-optimistic for most of the series, but declines sharply in the early 1990s and matches the historic in recent time. The overall trend is a decline followed by 10 years stability, then a further decline and slight recovery.	The projection tracks SSB for 5 years but is over-optimistic in the recent period. The overall trend is a recent recovery after a slight decline.
1985	The projection over-estimates SSB and the historic series is outside the simulation envelope in recent years. The trend is stable with a slight increase in recent time.	SSB is over-estimated initially, declines dramatically in the early 1990s and is in accord with the later part of the historical series. The trend is stable and rising followed by a sharp decline and recent slight recovery.	The projection over-estimates SSB and the historic series is outside the simulation envelope over the full time series. The trend is stable with an increase in recent time.
1990	The projected SSB follows the historical series closely. The trend is stable with some recovery in the most recent years.	The projected SSB simulation envelope fails to capture the historical series and under-estimates recent SSB. The trend is decline followed by stability and slight increase.	The projected SSB follows the historical series closely. The trend is stable with some recovery in the most recent years.

Table 3.2.3.2.1. Summary of projected SSB under each of the three models.

The relative levels of SSB from projection start to finish for the WG-type model are a decline in SSB for the 1970 and 1975 projections, level for the 1980 projection and 1985 projections and an increase for the 1990 projection. The first two and last projections are in agreement with the relative SSB levels in the 1999 assessment output. For the SRR and temperature model there is a decrease in SSB from projection start to finish in all cases which is in accord with perceived SSB apart for 1990. Relative SSB levels for the ARMA model are a decline in SSB for the 1970 and 1975 projections, level for the 1980 projection and increases for the 1985 and 1990 projections. The first two and last projections are in agreement with the perceived trend in SSB.

3.2.3.3 Diagnostic plots and bias

Figures 3.2.2.4 include plots of the median from the stochastic simulations with the deterministic projection and has been proposed as a diagnostic. Table 3.2.3.3.1 summarises some of the features of these plots.

	Deterministic >median			**Error and/or Bias**			**% negative residuals**		
Year	SRR and temperature	WG	ARMA	SRR and temperature	WG	ARMA	SRR and temperature	WG	ARMA
1970	91	100	76	-ve(<20%)	-ve(<15%)	<2%	50	67	n/a
1975	0	43	25	+ve(<20%)	5%	<5%	36	55	n/a
1980	0	100	84	+ve(<3%)	-ve(<15%)	<3%	44	56	n/a
1985	0	100	64	+ve(<5%)	-ve(<10%)	<3%	43	43	n/a
1990	0	75	30	+ve(<10%)	6%	<3%	46	50	n/a

Table 3.2.3.3.1. Summary of stochastic simulations.

For the temperature model it was notable that the median of the stochastic runs was biased, lying entirely to one side of the deterministic run, albeit on occasions close to the deterministic run. In four of the five projections the median was positively biased, the only occasion when this was not the case was when the residuals were evenly split between positive and negative (1970) and in this case a negative bias in the median resulted. In the other runs more positive residuals were present and a positive bias was noted.

For the WG-type model the situation was less clear with two of the projections showing variation rather than bias, and the remaining three runs all having the median negatively biased with respect to the deterministic run. Despite having mainly positive residuals the 1985 projection still showed a negative bias in the median. Negative biases also occurred in the 1970 and 1980 projections where there was a preponderance of negative residuals.

The ARMA model tended to show very little variation between the stochastic runs' median and the deterministic run with no systematic bias.

Interpretation of bias over time in the projection in this way is not straight forward due to feedback occurring through the SRR and also considerations regarding the distribution of residuals about the expected value.

3.2.3.4 Confounding of results due to changes in weight- and selectivity-at-age

Simulations of future SSB and recruitment for North Sea cod, carried out with the temperature and ARMA models (Section 3.2.2) established that the resulting trajectories were extremely sensitive to the choice of model. Figure 3.2.3.4.1 illustrates this using a prediction from the year 1990.

Figure 3.2.3.4.1.1 and 2 presents a WGMTERM forecast of recruitment and SSB starting from the *exact* 1989 population numbers, as estimated by the 1999 ICES North Sea cod assessment (ICES 2000f). In the forecast, selection-, weight- and maturity-at-age were the average of the years 1986–1988. To allow the model to follow the observed trends in the level of fishing mortality, the selection-at-age vector was scaled in each year to the average value estimated by the 1999 assessment. Projected recruitment was over-estimated in each year — the medians lie above the observed value. The trajectory of simulated SSB shows a good fit to the observed values.

Figure 3.2.3.4.1.3 and 4 show the trajectories for the projections using the stock and recruitment model with temperature effects. Recruitment is generally under-estimated and after the first few years SSB is under-estimated to the extent that the observed values fall outside the 95th percentiles of the simulation. The model is not predicting the trajectory of the observed SSB.

In order to investigate the under-estimation of SSB by the simulation model including temperature, the effect of the assumption of constant weight- and selection-at-age was examined. Simulations were carried out using the 1999 assessment weights-at-age, recorded for the years 1990–1997 and the fishing mortality-at-age estimated by that assessment. The results are presented in Figures 3.2.3.4.1.5 and 6 and 3.2.3.4.1.7 and 8. The results show that the under-estimation of recruitment by the model with temperature effects is still present and results in an increasing but gradual under-estimation of SSB as the starting population year-classes decrease in their contribution to SSB with increasing exploitation. The degree of under-estimation is reduced by including the weights observed for each year and also by the use of the assessment estimates of fishing mortality-at-age.

An examination of the relative weight-at-age for the period 1986–1997 (Figure 3.2.3.4.2) shows that the weight-at-age of the 1987 and subsequent year-classes were heavier, at the youngest ages, than the previous year-classes. This could be due to increased growth rates or changes in selection by the component fleets. The increases appear to be cohort dependent so that the former is more likely. The assessment estimates of fishing mortality and recruitment were relatively constant during the same period. Therefore, the gradual increase in SSB resulted primarily from the change in weight, a process that is not modelled within the medium-term forecasting process.

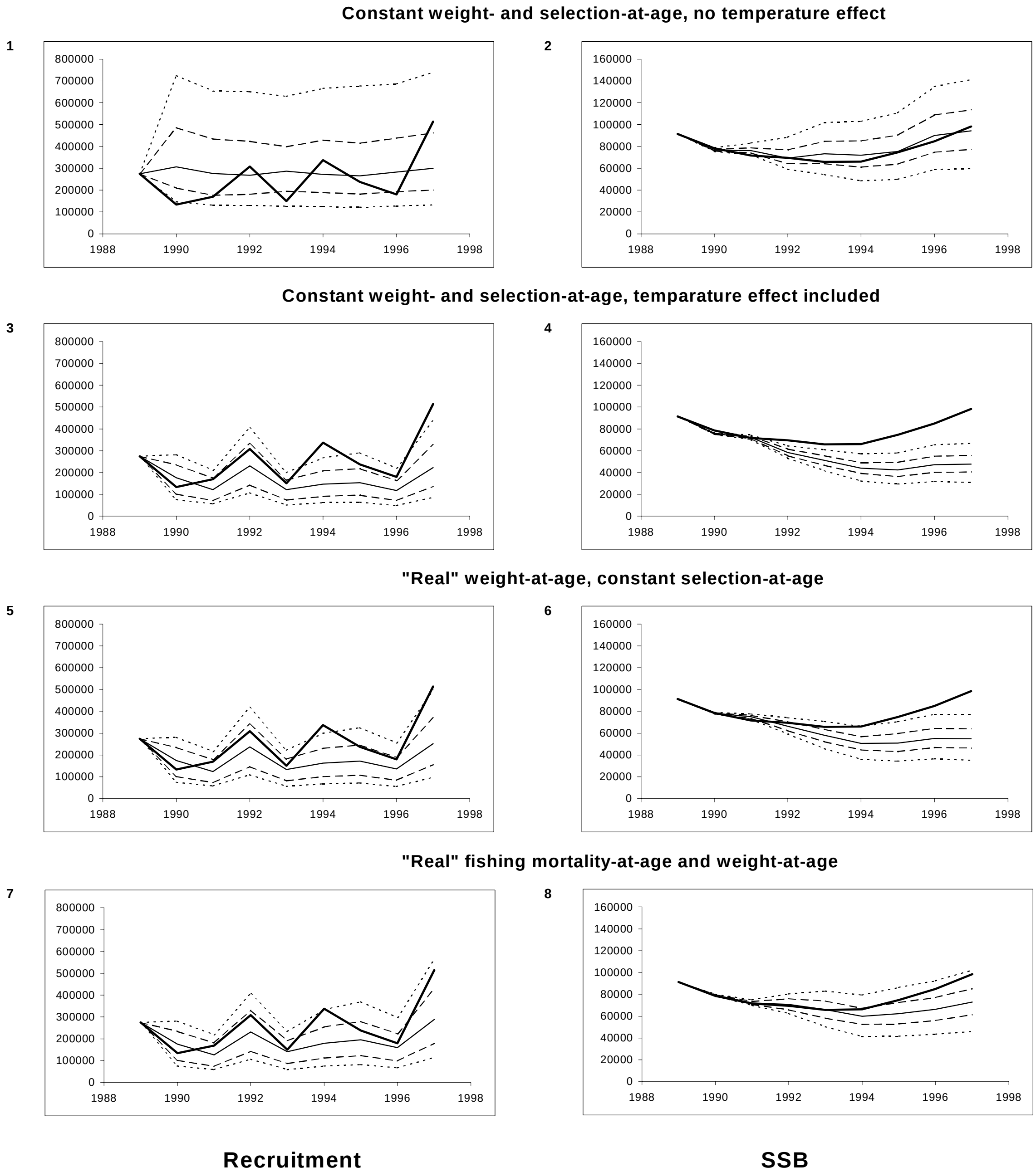


Figure 3.2.3.4.1. Simulations of North Sea cod recruitment and SSB for the years 1990-1997 compared with the values estimated by the 1999 ICES assessment.
3.2.3.4.1.1&2 Recruitment and SSB predicted by the stock and recruitment model without temperature effects.
3.2.3.4.1.3&4 Recruitment and SSB predicted by the stock and recruitment model with temperature effects and assuming constant weight and selection at age.
3.2.3.4.1.5&6 Recruitment and SSB predicted by the stock and recruitment model with temperature effects, constant selection and observed weights at age.
3.2.3.4.1.7&8 Recruitment and SSB predicted by the stock and recruitment model with temperature effects estimated fishing mortality at age and observed weight.

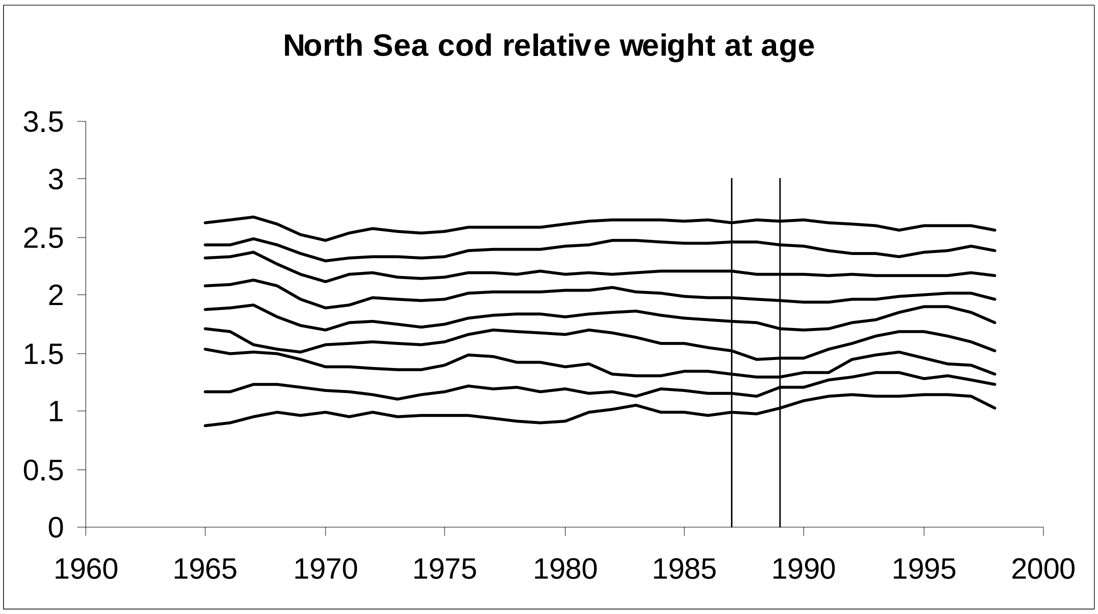


Figure 3.2.3.4.2. Relative weights-at-age observed for North Sea cod (ages 1 to 9) in the years 1965–1999. The vertical lines indicate the years used for the calculation of the average weight-at-age in the simulations.

The results of the exploratory simulations have established that the over-estimation of recruitment by the model without temperature (i.e. WGMTERM-type) has compensated for the use of an average weight-at-age which is lower than that subsequently recorded. This combination resulted in the SSB trajectory being followed closely - a case of two wrongs making a right! The model including temperature under-estimated recruitment and when combined with the low weight-at-age, resulted in the simulated SSB being severely under-estimated (c.f. Figure 3.2.3.4.3 in Appendix A).

Uncertainty about the initial stock size and recruitment variability are generally considered to be the primary causes of uncertainty in the trajectory of future population and yield trajectories. The simulations carried out at this Study Group have established that changes in weight-at-age can also be important components in the uncertainty and models taking account of such changes should be considered. This is particularly important if changes are systematic, rather than random, the former often being likely in response to environmental changes and heavy exploitation.

3.3 Medium-term Projections of North Sea Cod (*Gadus morhua* L.) Incorporating STEREO Output

3.3.1 Background

The changes in age structure that have occurred in the North Sea cod stock since the 1960’s, suggest that spawning stock biomass may be a poor index of annual egg production. Under these circumstances, it is possible that the stock-recruitment relationship might be better resolved if the spawning biomass term was recast in terms of egg production (MacKenzie *et al*. 1998; Marshall *et al*. 1998; Marteinsdottir and Thorarinsson 1998).

Cod are determinate batch spawners. This means that the total annual potential egg production of an individual is set by the number of vitellogenic oocytes present at the start of the spawning season. During the season, a proportion of these oocyctes may be resorbed (a process referred to as atresia) due to a variety of reasons. Hence the realised fecundity may differ from the potential fecundity.

Potential fecundity is typically a high (exponent >4) power function of body length in cod (Kjesbu 1988; Marteinsdottir and Thorarinsson 1998), and a weak (exponent <2) power function of body weight. Recent studies indicate that inter-annual variations in potential fecundity to body weight and potential fecundity to body length relationships are small compared to those in the growth rate of year-classes. Thus, meaningful estimates of potential population fecundity can be calculated from year-specific data on population numbers-, and length-, at-age and a constant fecundity-length relationship. However, data on population abundance at length are not typical outputs from the usual age-based stock assessment procedures. As an alternative, data on numbers-at-age, mean weight-at-age, and a constant fecundity-weight relationship should provide a credible alternative.

Data on annual atresia in cod stocks are only recently available and not widespread in the literature. The data that do exist indicate a high degree of inter-annual variability linked to changes in fish condition. Hence, estimation of realised population fecundity from standard stock assessment outputs is not possible unless accompanying data on year-specific weight-length relationships are available.

3.3.2 Data for estimating population potential fecundity in North Sea cod (*Gadus morhua* L.)

The routine outputs from the stock assessment procedure for North Sea cod are: numbers-at-age, and mean weight-at-age in the catch. The additional data needed to estimate population potential fecundity are: sex ratio, proportion mature at age, and a potential fecundity–weight relationship.

Data on sex and maturity are collected from each fish dissected for otolith extraction during the North Sea IBTS in February each year. However, no analysis of the results has been incorporated into the routine assessment, which assume a constant maturity-at-age based on data collected at some indeterminate time in the past. However, Poulding (1997) describes an analysis of the data on cod and haddock from the 1980–1995 surveys. A smoothed version of the data was combined with the assessment numbers-at-age to estimate the number of mature fish at age in each year. In this case, estimate of maturity for years outside the period presented by Poulding (1997) were generated by a) linear interpolation between 1963 and 1980 assuming that the existing assessment values applied in 1963, and constant extrapolation from 1995 to the last year in the assessments.

age	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95
1	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01
2	0.10	0.04	0.03	0.03	0.06	0.04	0.09	0.02	0.05	0.13	0.19	0.09	0.21	0.07	0.14	0.05
3	0.08	0.16	0.17	0.20	0.25	0.10	0.18	0.15	0.27	0.24	0.54	0.39	0.52	0.42	0.43	0.30
4	0.56	0.52	0.64	0.50	0.42	0.45	0.35	0.60	0.53	0.59	0.73	0.50	0.85	0.70	0.77	0.82
5	1.00	0.85	0.93	0.96	0.81	0.56	0.63	0.76	0.90	0.77	0.93	0.89	0.85	0.88	0.98	1.00
6+	0.88	0.87	1.00	0.99	0.98	0.91	0.90	0.98	0.95	0.97	0.99	0.98	1.00	0.96	1.00	0.97

Table 3.3.2.1. The observed proportion of cod mature at age [combined sexes, total North Sea] (source: Poulding 1997).

age	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95
1	0.00	0.01	0.00	0.00	0.01	0.02	0.02	0.01	0.01	0.03	0.06	0.04	0.06	0.03	0.03	0.00
2	0.01	0.05	0.02	0.02	0.06	0.05	0.06	0.05	0.06	0.10	0.20	0.11	0.20	0.13	0.13	0.04
3	0.08	0.18	0.17	0.17	0.19	0.15	0.16	0.19	0.23	0.27	0.48	0.30	0.52	0.37	0.42	0.30
4	0.57	0.51	0.64	0.64	0.48	0.36	0.37	0.52	0.57	0.56	0.78	0.60	0.82	0.71	0.78	0.82
5	0.96	0.83	0.94	0.94	0.79	0.65	0.65	0.84	0.86	0.81	0.93	0.84	0.95	0.91	0.95	0.98
6+	1.00	0.96	0.99	0.99	0.94	0.86	0.86	0.96	0.96	0.94	0.98	0.95	0.99	0.98	0.99	1.00

Table 3.3.2.2. Smoothed proportion of cod mature at age [combined sexes, total North Sea] (source: Poulding 1997).

The STEREO project has not studied cod fecundity in the North Sea, and few recent data are available in the literature. During this Study Group, we therefore applied a potential fecundity – eviscerated body weight relationship estimated for Icelandic cod during STEREO (Anon. 1998; Scott *et al*. 1999). The original formulation of the relationship was linear: fecundity = -1396801 + 1044446 * weight (in kg.). However, this formulation gives unrealistic fecundity estimates at low body weights, and visual inspection of the pattern of residuals from the raw data indicates that a linear form is probably not appropriate. An alternative power function was therefore fitted-by-eye to the data (fecundity = 5.2E5 * $(\text{weight})^{1.25}$). In this case, the weight term refers to eviscerated weight, so a factor of 1.15 was applied as a conversion from gutted to whole weight (estimate from sampling data collected by Marine Laboratory Aberdeen).

The application of fecundity data from Icelandic cod in the North Sea should be regarded as a temporary arrangement borne out of the lack of immediate to hand North Sea data during the Study Group. However, it is expected that fecundity-weight should be less variable between stocks and regions than fecundity-age, which will depend also on weight-at-age. The error introduced should therefore be limited, and the results adequate for the demonstration of methodology undertaken by the Study Group.

3.3.3 Results

A 10-year projection was performed with the ARMA and WGMTERM model using a STEREO-derived index of potential egg production *E* using 1985 as a starting year, thus allowing for comparison with observed *E* for the years 1986–1995. Results are given in Figure 3.3.3.1.

3.3.4 Discussion

Many of the relevant data sources are already sampled at sea or on the commercial fish markets and inclusion of maturity-at-age data on an annual basis, along with a weight based fecundity relationship, would not be a major problem for many stocks. This would enable improved SRR fitting, but given existing methodology would not necessarily result in improved projections (see confounding due to weights above). Improved projections require that growth, maturity and fecundity be coherently modelled and extrapolated into the future rather than assumed to be arbitrary averages either with or without random variation.

4 NUMERICAL APPROACHES TO QUANTIFYING UNCERTAINTY IN SHORT-TERM STOCK FORECASTS

4.1 Anchovy Recruitment and Environment in the Bay of Biscay

4.1.1 Ecological background

The Bay of Biscay anchovy, a short-lived species, experiences large annual fluctuations in biomass from one year to the next mainly as a result of recruitment variability. Spawning takes place in the Bay of Biscay between April and July. The population spawns in areas where there is potential for increased biological production (Motos *et al.* 1996); those being in river plumes, at shelf break fronts and in oceanic gyres. In general, spawning is limited to the French and Spanish coasts (south of 46º 30' N and east of 05º 00' W). Anchovy eggs and larvae develop from April through to August. After metamorphosis, anchovy juveniles appear from August up to the first winter when they disperse in the area. Oceanographic events happening in concurrent periods and areas during the early development stages are likely to play a fundamental role in their dynamics and in the determination of subsequent recruitment strength.

Borja *et al.* (1996, 1998) have shown that for the period 1967–1996, oceanographic conditions caused by north-easterly winds of medium and low intensity in spring/summer in the Bay of Biscay are related to good levels of recruitment to the anchovy population. The major oceanographic events originating from north-easterly winds that probably cause enhancement of the surviving of larvae and early juveniles are identified by these authors as:

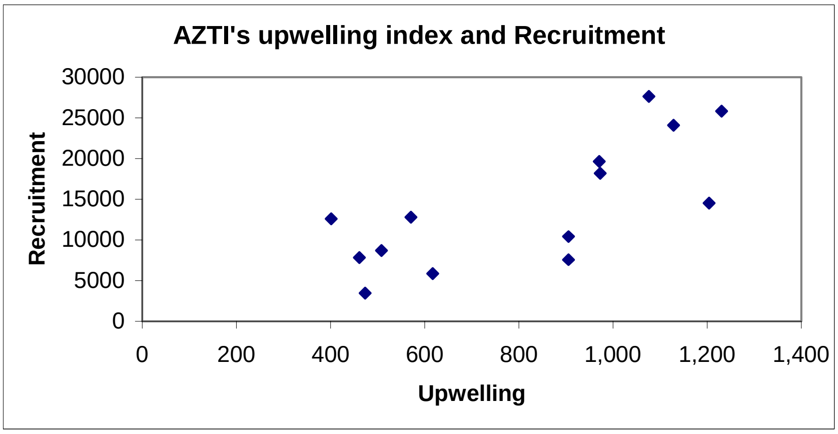
- weak upwelling conditions, with a low degree of turbulence, that usually do not break out at surface layers but push up the thermocline close to it. Thus light is more accessible to this rich fringe of water and increase subsurface chlorophyll and the general productivity in the area. The joint effect is a weak upwelling, stability and shallow but pronounced stratification, all this matching well with the ideas of Lasker (1978), Bakun and Parrish (1982) and Roy (1993) – amongst others.
- Expansion of the areas influenced at surface by the outflow of the major French river plumes over the continental shelf, which are known as important spawning sites probably due to the enrichment associated to those areas. The expansion of those areas supposes an expansion of the natural spawning habitats and of the enrichment influence of the rivers. In addition eggs and larvae will be gradually disperse in that rich environment and less subject to massive predation.

On the contrary, the north-western winds are stronger, provoking downwelling and turbulence in the area, pushing the areas of influence of rivers towards the coasts and reducing the production and suitable spawning habitat for the spawning to anchovy.

Turbulence itself during spawning period or for the whole year were initially found to be significant by Borja *et al.* (1996) but were finally rejected as statistically significant in their most recent revision (1998). The explanatory power of that variable has always been placed at the boundaries between being significant or not.

The north-easterly wind conditions in the Bay of Biscay are summarised in an upwelling index calculated from March to July each year (Borja *et al*. 1996, 1998). Figure 4.1.1.1a summarises the relationship between the upwelling index and recruitment estimates from the assessment performed in 2000 by ICES (2001). The upwelling index used to explain about 55–60% of the inter-annual variability of the recruitment from 1987–1998. However the addition of the most recent recruitment estimates 1999/2000 dropped that value down to about 45%, without considering any stock-recruitment relationship.

a



b

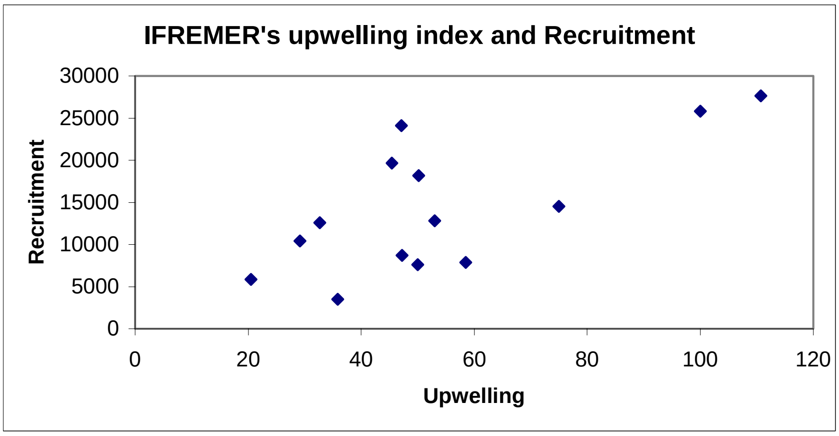


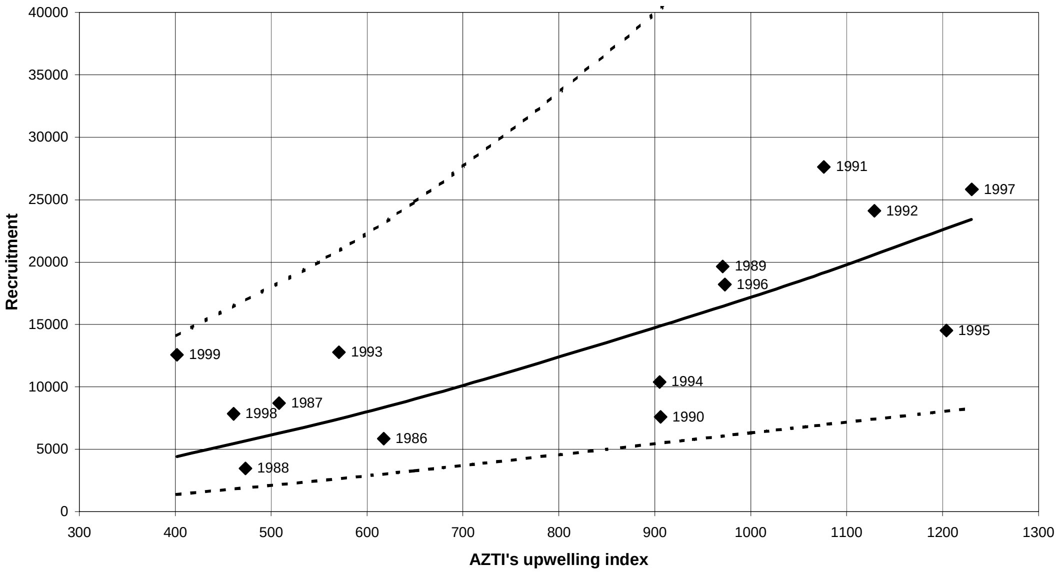
Figure 4.1.1.1: Relationship between the Upwelling indexes and Recruitment estimates

Recently, Allain *et al*. (1999) and Petitgas *et al*. (2000) have improved the previous relationship between wind and recruitment for the period 1987–98 by simulating the oceanographic processes that are expected to be directly linked to the life-history of larvae. This was made by a 3-D hydrodynamic physical model (IFREMER, Brest) that simulates processes occurring over the French Biscay continental shelf. Two of these variables were retained by the authors because in total they explained about 75% of the recruitment inter-annual variability between 1987–98. These two variables are by order of importance:

- An upwelling index which correspond to the sum of mean weakly vertical currents from bottom to surface over the period March-July along the Landes coast (SW of France). These upwelling events are caused by the moderate and intermittent North-eastern winds. This variable, as AZTI's upwelling index, has a positive effect in determining anchovy recruitment (Figure 4.1.1.1b)
- Stratification Break down index (or destratification): This is a binary variable describing stratification breakdown events in June-July concerning the waters above the whole continental shelf. These are phenomena linked to strong westerly winds (>15 m/s) that may cause important larvae mortality just after peak spawning.

After the addition of the latest two estimates of recruitment 1999/2000, the coefficient of determination (r^2) of IFREMER model drops down to about 65% (and to 59% when adjusted for d.f.).

Figure 4.1.1.2: Predictive model applied in 1999 and recruitment estimates obtained in 2000 (ICES 2001)



In 1999 AZTI's upwelling index, the only environmental index available, was used for the first time to correct upward the 1998 year class strength estimated by the assessment and to predict the 1999 recruitment at age 0 (ICES 2000g). Two bad recruitments were expected to occur in 1998 and 1999 and hence the average spawning biomass predicted for 2000 (about 25000) was below $\mathbf{B}_{pa}$ (=36000t). However the SSB estimate obtained during 2000 was actually of about 47000 t, as result of better than expected recruitment in 1999. The management measures adopted in 1999 to protect the stock given the low predicted SSB turned out to be unnecessary and that caused a lot of unrest of the management bodies with the scientific advisers. The recruitment estimates resulting from the 2000 assessment were not outside the confidence limits of the AZTI's upwelling index model (Figure 4.1.1.2) but the deviates of the 1998 and 1999 were both of the same sign and lead to a SSB projection with only about 2–3% probabilities of occurring at random. That situation served to focus attention on the uncertainties associated with the predictions and to look for enhancing their predictive capability. Although IFREMER model seems to have a better predictive power, ICES (2001) decided in 2000 not to make use of the environmental indices when recommending a catch level for 2001, although endorsed further investigation on them in order to improve their reliability and predictive power. Part of that analysis is shown here in the subsequent Sections of this report.

4.1.2 Stock-recruitment models and the potential role of environment and parental stock

The results from fitting stock recruitment models including and excluding an environmental index are presented in this section. The number of recruits fitted (*R*) and the spawning stock biomass (*S*) are the ones estimated by the most recent assessment performed (ICES 2001) and correspond to the period 1987–2000. The environmental variable (*E*) corresponds to the upwelling index described in Borja *et al.* (1998) and in Petitgas *et al*. (2000). For the purposes of the current analysis it was considered that this index may suffice and would represent the role that environment may play in modifying the stock–recruitment relationship.

Ricker and Beverton-Holt models of S-R relationships were fitted using Generalized Linear Models as in O'Brien (1999). The Ricker model fitted is the following:

$$R = a \cdot S \cdot \exp(-b \cdot S + c \cdot E)$$

where *a*, *b* and *c* are model parameters to be determined. The environmental index corresponds to the deviate of every year upwelling from the average value since 1967 (= 869). The results from fitting the Ricker model with and without an environmental index are shown in Table 4.1.2.1 and Figure 4.1.2.1. The environmental index was set equal to 0 to plot a Ricker curve that would include the environment under average conditions. However, different levels of upwelling will result in different Ricker curves.

Table 4.1.2.1 Fitting by GLM of the S-R Ricker model including environment:

```
Coefficients:
 (Intercept)            SSB Desviupwelling
   -0.183708 -0.00001944675    0.001290152
Degrees of Freedom: 13 Total; 10 Residual
Residual Deviance: 2.217639
Analysis of Deviance Table
Quasi-likelihood model: family = quasi(link = log, variance = "mu^2")
Response: Recruits0
Terms added sequentially (first to last)
               Df Deviance Resid. Df Resid. Dev
          NULL                    12   6.962860
           SSB  1 3.158140        11   3.804720
Desviupwelling  1 1.587081        10   2.21763
```

The results from fitting the Beverton-Holt model of the form:

$$R = \frac{1}{a + b/SSB}$$

resulted in a negative value of the *b* parameter which is a strong indication that this model is not appropriate for the current set of anchovy data.

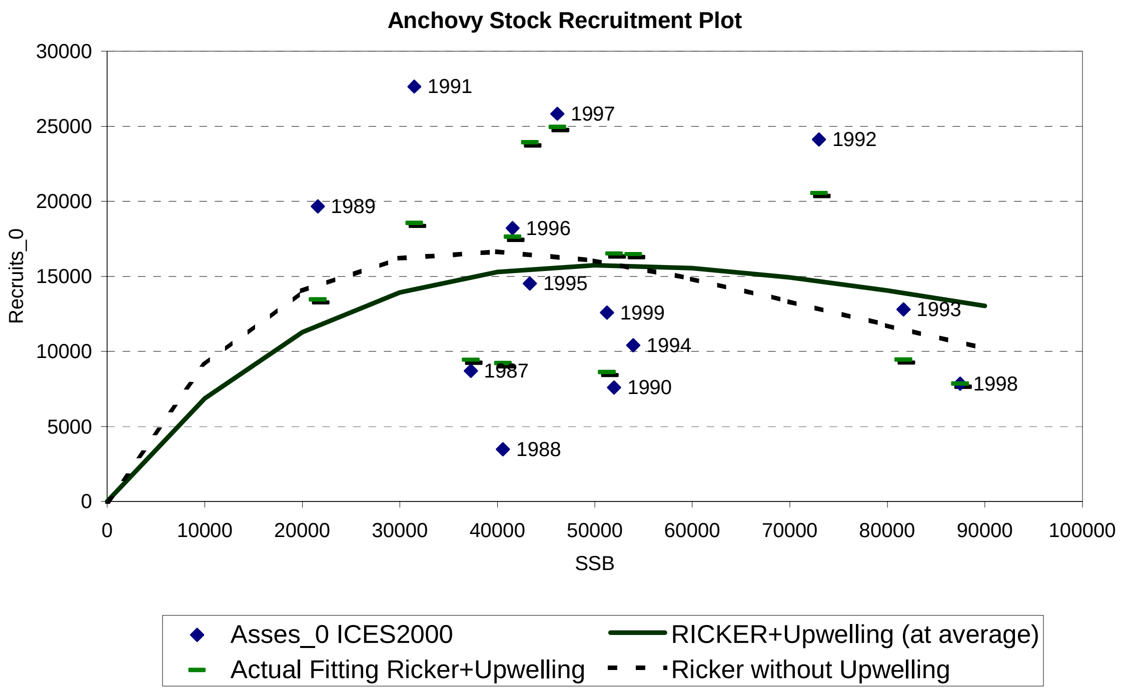


Figure 4.1.2.1. Ricker model fits both with and without the inclusion of an environmental index.

Finally, the relationship between recruitment and the environment was investigated by using three environmental indices: the AZTI index of upwelling (Borja *et al.* 1998), the IFREMER environmental index (based on an upwelling index plus destratification - Allain *et al.* 1999) and a combination of the two (the way this index was computed is explained in the following section). For simplicity, the relationships between the environmental indexes and recruitment were assumed log-linear. A comparison of goodness-of-fit in terms of r^2 between the two Ricker models, with and without environment, and from directly relating recruitment to the environmental indices is presented in Table 4.1.2.2. In all cases, the dependent variable *R* is the log-transformed number of recruits. The time series of fitting values are presented in Figure 4.1.2.2.

Table 4.1.2.2 Comparison in terms of Coefficient of Determination of the fitting of S-R models and of direct Environment-Recruitment (log) models.

r^2 at original scale

	Environment inclusion	
	Without	With
Ricker	1%	44%
UpwellingAZTI		56%
Env.IFREMER		65%
Synthesis of Env.Indexes		75%

The above results indicate that including an environmental index results in a significant increase in the amount of variability explained by the Ricker model. In addition, incorporating the environment in the Ricker model results in a smoother curve which approaches an horizontal line crossing the S-R points by their average level. Based on the r^2 value and for the range of stock biomasses observed modelling recruitment as a function of the environmental index only gives better results than the alternatives that include the spawning stock biomass. This does not imply that the level of spawning stock biomass does not influence recruitment of anchovy in the Bay of Biscay, it simply indicates that for the limited number of data points available this relationship is not shown. The strong influence of the environment during the period considered in the analysis may well be masking any real relationship between spawning stock biomass and recruitment.

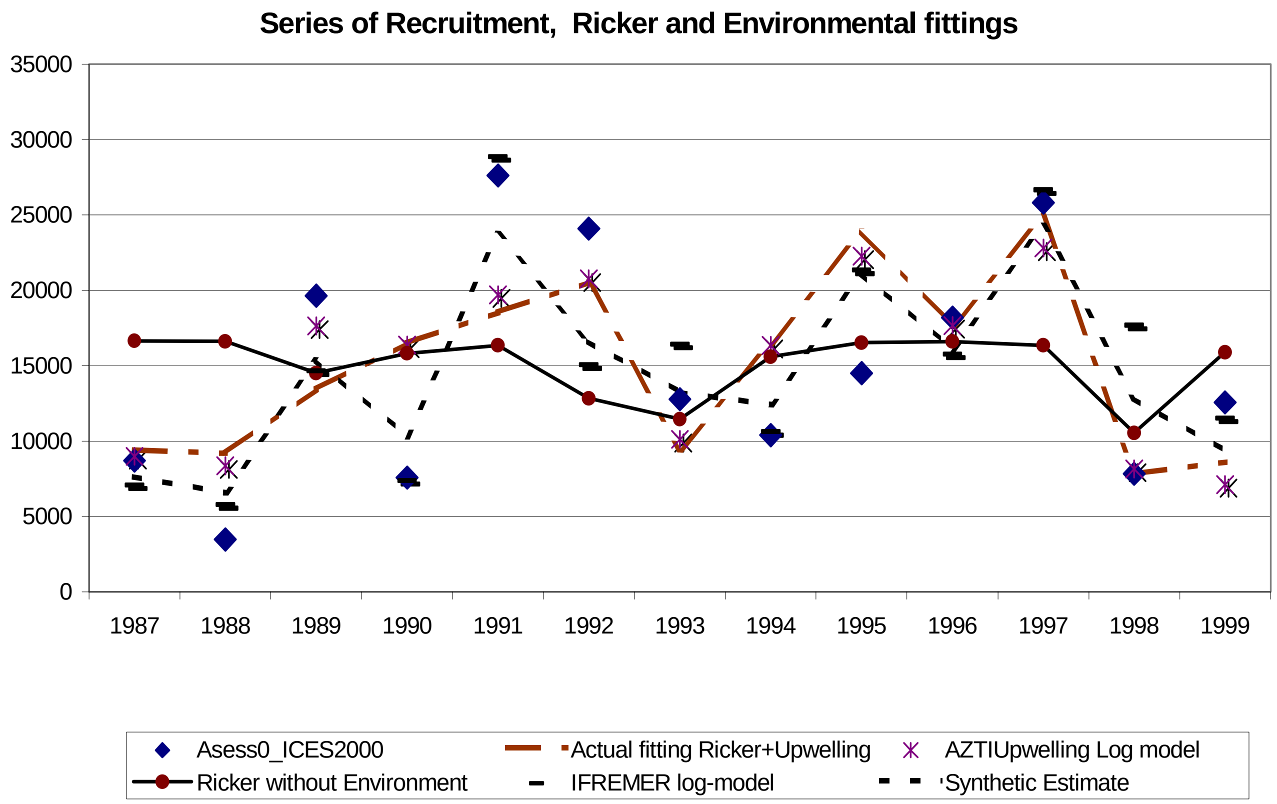


Figure 4.1.2.2. Time series of recruitment values.

We should stress that the environmental indices can only be used to predict recruitment at age 0 for the year when the assessment is made and that the environmental index cannot be forecasted a year ahead. In fact, once the average is removed from the time-series of upwelling what is left is essentially white noise. Figure 4.1.2.3 presents the autocorrelation plot of the AZTI's upwelling index since 1967 which demonstrate no significant autocorrelation of the index in time.

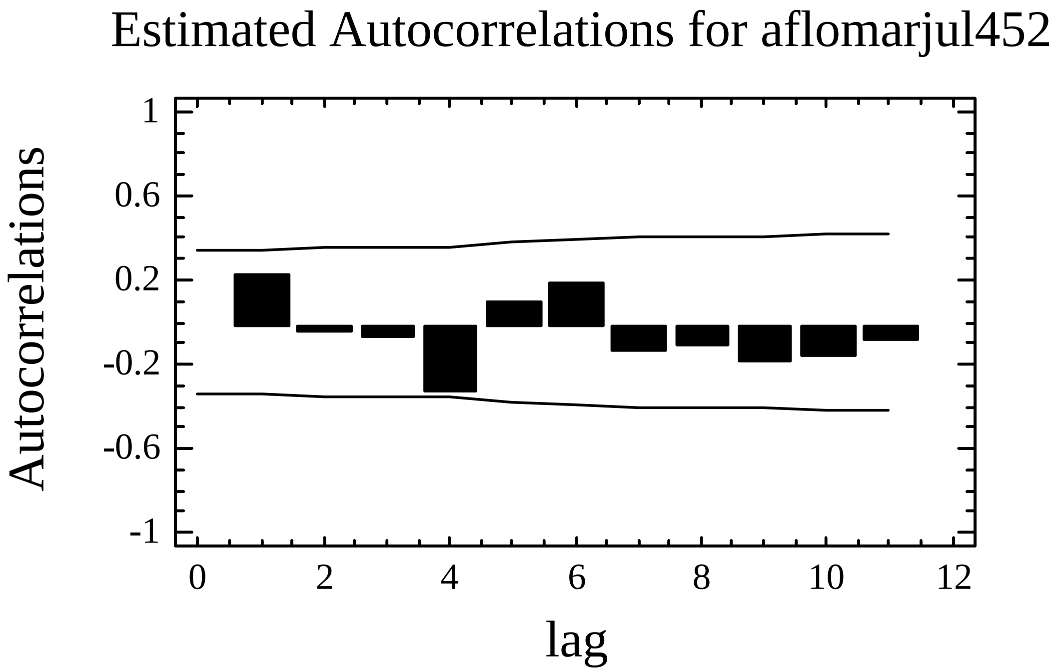


Figure 4.1.2.3: Auto-correlation analysis of the AZTI's upwelling estimate since 1967 (n=34).

4.1.3 Procedures for forecasting

In this section, since there is no clear relationship between anchovy spawning stock biomass and recruitment for the short period when data are available, simple relationships between environment and recruitment are used directly for forecasting purposes. Two environmental indices have been developed: one by AZTI (Borja *et al*. 1996, 1998) and the other by IFREMER (Allain *et al.* 1999). They are both indices of wind induced phenomena (upwelling and de-stratification) which show significant relationships with the estimates of anchovy recruitment. As both are based on measurements of northeasterly winds they are not, as predictors of anchovy recruitment, independent from each other.

Two procedures to forecast anchovy recruitment for short-term predictions (1 year ahead) of the anchovy fishery and population were devised; a quantitative method and a semi-quantitative one. A quantitative approach based on the AZTI upwelling index which was the only available, was performed in 1999 (ICES 2000g). Now that two models are available a synthesis of both methods is required to obtain the recruitment forecast. On the other hand, given the large deviance between forecasted and estimated population for 2000, a general feeling of this Study group was the convenience of setting up a semi-quantitative approach to forecast the level of recruitment from the two aforementioned models. Here below follow the definition of the two approaches followed by the Study Group:

a) Quantitative estimate: recruitment is forecasted as the weighted average of the two predictions available from AZTI and IFREMER models respectively, with weighting factors proportional to the inverse of their prediction variances. This is a fair procedure to synthesize the estimates of different models. It is also worth mentioning that the difference between index variances is small for any given year, therefore the weighted average would not be strongly dominated by any particular index. The variance of such estimate is taken as the variance of a weighted sum of correlated variables.

Model estimates of Recruitment at age 0

WG2000			UpwellAZTI		3D IFREMER		**SYNTHETIC Estimate**	
Year	Asses-R_0	Qualification	Age_0 Serie	CV	Age_0 Serie	CV	Age_0 Serie	CV
1986	5,845	BA	10,964	51%	8,276	46%	9,150	41%
1987	8,703	BA	8,996	52%	7,089	45%	7,640	41%
1988	3,473	BA	8,371	53%	5,782	45%	6,585	41%
1989	19,652	AA	17,637	51%	14,656	41%	15,380	38%
1990	7,587	BA	16,377	51%	7,396	45%	10,280	40%
1991	27,632	AA	19,711	52%	28,876	45%	23,760	40%
1992	24,103	AA	20,757	52%	15,062	40%	16,616	38%
1993	12,789	Av	10,118	51%	16,434	40%	13,236	38%
1994	10,405	Av	16,359	51%	10,627	43%	12,422	39%
1995	14,514	Av	22,272	53%	21,351	42%	21,135	39%
1996	18,197	AA	17,678	51%	15,769	40%	16,088	38%
1997	25,830	AA	22,810	53%	26,672	44%	24,300	40%
1998	7,841	BA	8,155	53%	17,685	41%	12,850	38%
1999	12,582	Av	7,120	55%	11,522	42%	9,344	40%
2000		Prediction	*6,929*	56%	*16,012*	40%	*11,531*	39%

b) Semi-quantitative estimate: the quantitative forecast based on the upwelling indices as in a) above, is then classified as above average, average or below average depending upon its position within the historical estimates of recruitment provided by the most recent assessment. The percentiles of reference to qualify such recruitment in one of the above categories are 66% and 33% of the historical set of recruitment estimates. This qualifying method is given as a first tentative approach and may be improved in future. Further, this approach may most likely result in a change in the definition of the recruitment strength categories from one year to the next, however a more stable approach would not be realistic. The recruitment values as estimated by the WG in 2000 and the corresponding percentiles of reference are shown in Figure. 4.1.3.1.

If recruitment was classified as above average, then recruitment is forecasted as the average of recruitment above the historical median. If below, then recruitment is forecasted as the average of recruitment below the historical median. And if average then recruitment is forecasted as the historical mean.

In summary:

if $R \geq 66\%\ (9{,}269)$ then $\hat{R} = \text{Avg}\,[R \geq 50\%]$

if $R < 33\%\ (16{,}966)$ then $\hat{R} = \text{Avg}\,[R < 50\%]$

if $66\% > R \geq 33\%$ then $\hat{R} = \text{Avg}\,[R]$

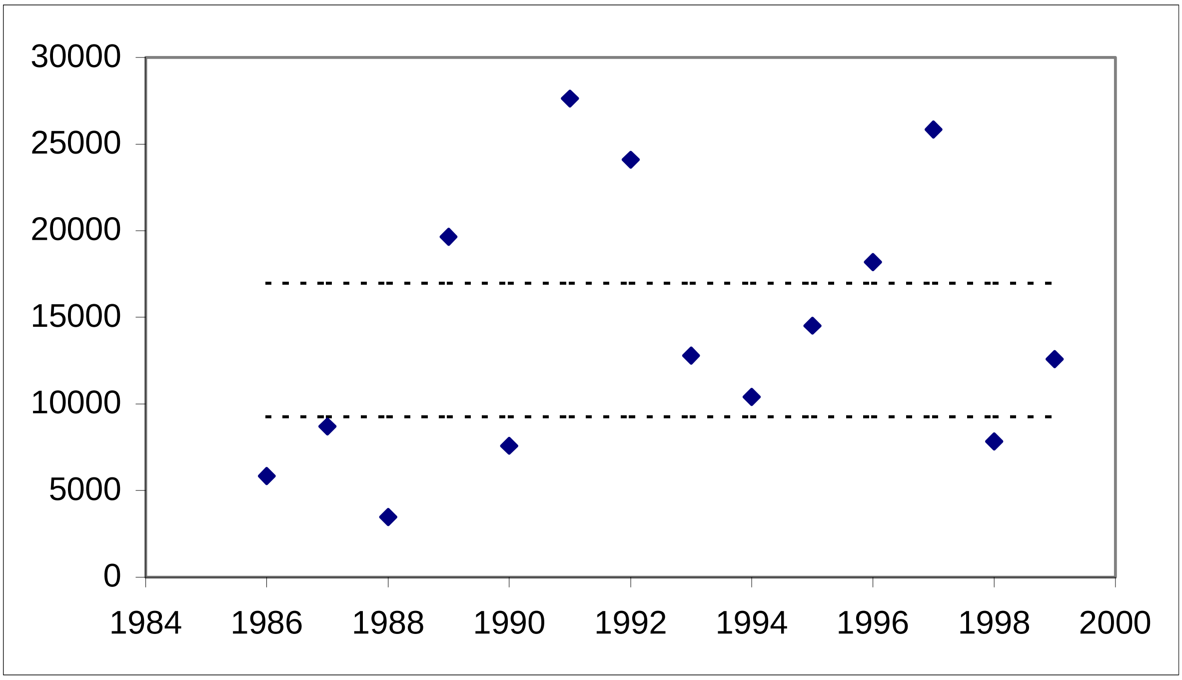


Fig. 4.1.3.1: Time-series of number of recruits as estimated by the WG REF in 2000, and 33% and 66% percentiles.

The average adopted was the geometric mean of series of data within the range selected, which results in the following estimates of recruitment:

QUALITATIVE ESTIMATES OF RECRUITMENT

Log estimates	Below	Average	Above
Counts	7	14	7
Wmean	8.93	9.41	9.89
Wvariance	0.18	0.37	0.09
St.Error	0.42	0.61	0.29
Geom.Mean (NoLog)	7,533	12,174	19,676
Cv	44%	67%	30%

4.1.4 Retrospective analyses

4.1.4.1 Methods

A retrospective analysis to test the predictive ability of the quantitative and semi-quantitative methods outlined above for setting new incoming recruitments was performed for the period 1996–2000. Each year the recruitment prediction at age 0 was obtained by fitting over the previous years the environmental recruitment indices and the recruitment levels as estimated by the WG assessment of that same year. The resulting recruitment predictions were then used to produce probability profiles of recruitment at age 0 in the year of the assessment and biomasses for the following year, constrained to the catch actually achieved those two years. The projections were made using the program Wgfran4.exe of Cook(1993) and using constant weight at ages in the stock and in the catches for the whole period of retrospective analysis (equal to the most recent available averages) (see the input values in Table 4.1.4.1, Appendix B).

Note: The 1999 survey did not render estimates of numbers at age, as a result the 1998 recruitment estimate resulting from the ICA assessment (Patterson and Melvin 1996) performed in 1999 is based only on the catch data and on the 1999 spawning biomass estimate from the survey. Therefore the 1998-year class as estimated by ICA in 1999 was considered unreliable and it was corrected with an ad hoc procedure (ICES 2000g). In the retrospective analysis that follows (period 1996 to 1999), only the 0-year-olds in the year of the assessment are forecasted and for the biomass projection for 2000 the same input used by the WG in 1999 concerning the 1998-year class was used.

4.1.4.2 Results

In Figure 4.1.4.1 is shown the time series of the quantitative estimates of recruitment in comparison with the most recent recruitment estimates obtained in the assessment performed in 2000 (ICES 2001). This synthetic environmental index fits better these recruitment estimates than each index alone (arriving to an r^2 of 75%, see table 4.1.2.3). The quantitative retrospective forecast of the recruitments since 1996 is shown in Figure 4.1.4.2 (including +/- 1 CV). In the two former years the predictions performed better than in the latter's. The semi-quantitative retrospective forecast is shown in Figure 4.1.4.3 with confidence intervals corresponding to the CVs of the recruitment estimates used to compute the forecast. The performance over the three first years seems to be good, although in 1999 there is still an under estimation of the actual recruitment. For both methods, in no case the most recent estimates were outside the 95% confident limits.

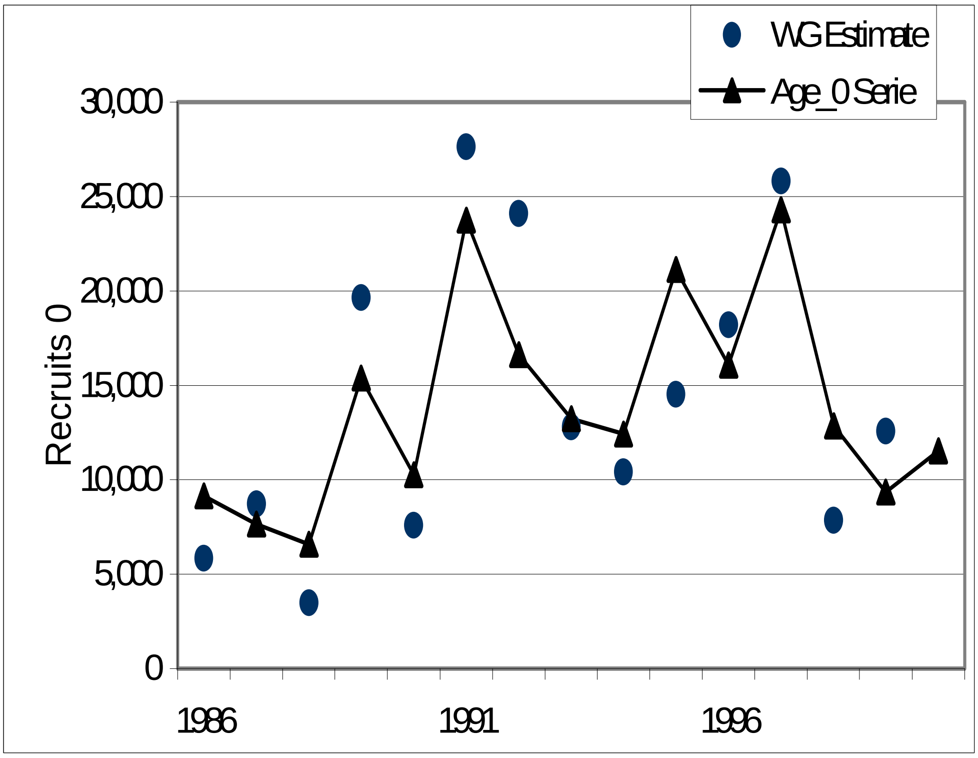


Fig. 4.1.4.1: Time-series of recruitment synthetic and WG 2000 estimates.

The results concerning the biomass projected a year ahead of the respective assessments (constrained to the known catches that occurred in those years) are shown in Figure 4.1.4.4 (Appendix B). The retrospective analysis show that in the first three years SSB biomasses fall within the confident limits of the predictions, but for year 2000 the probability of getting the actual estimate of SSB is very low (about 1%). The probability of observing the actual biomass in year 2000 is very low even in the case of letting F at status quo (in this case of about 6%). The performances of the quantitative and semi quantitative approaches are rather similar. The failure for predicting year 2000 would have happened with either of both methods equally. The projection for SSB in 2001 is presented in Figure 4.1.4.5 (Appendix B).

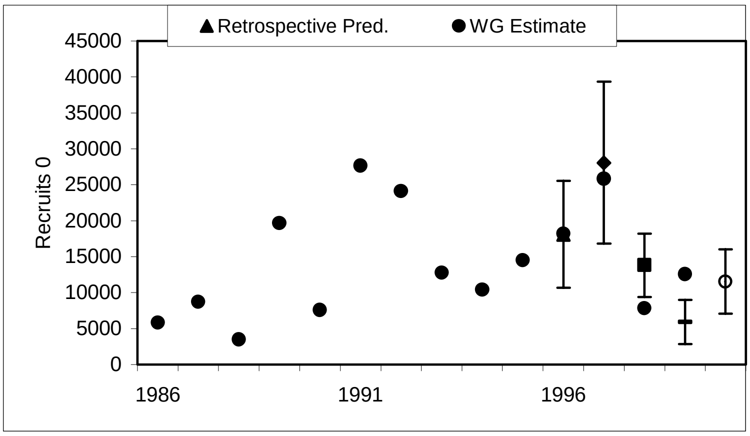


Fig. 4.1.4.2 : Time-series of WG 2000 recruitment estimates and retrospective quantitative predictions with corresponding CVs.

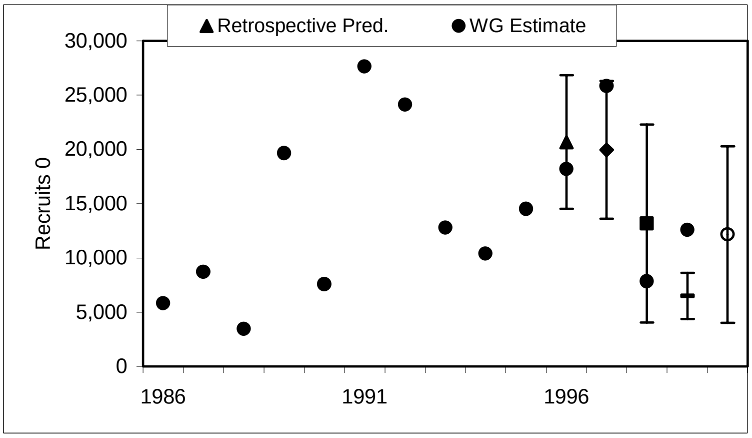


Fig. 4.1.4.3 : Time-series of WG 2000 recruitment estimates and retrospective semi-quantitative predictions with corresponding CVs.

4.1.5 Discussion

The current indexes of anchovy recruitment available from environment monitoring (Borja *et al*. 1996, 1998) and from hydrodynamic models (Allain 1999) contain valuable information to predict the recruitment occurring in the year of the assessments, which can be beneficial to the provision of short-term forecast for the anchovy fishery. Now that both indexes are available by September each year, a synthesis of both indexes seems to perform better than each index alone over the range of recruitment estimates available. The role of the parental stock is not yet evidenced in the short series of data available and, because of this, direct recruitment-environment models perform as well or better than stock-environment-recruitment models. All these must be reviewed as new data become available on this population.

However the predictive power of the current models is limited (between 44% and 75% coefficient of determination, see Table 4.1.2.2). This suggest that a semi quantitative use of these indexes can perform as well as a pure quantitative one. This is shown in the retrospective analysis of the performance of the synthetic estimate of Recruitment and the semi quantitative use of such estimate since 1996.

Despite the imprecise forecasts of recruitment and biomass provided by these indexes and methods the current retrospective exercise show that in 3 out of 4 years the probability of falling below $\mathbf{B}_{pa}$ (=36000 t) was low. In this sense the current methods can be used to split safe years from risky years concerning the probabilities of falling below threshold limits. This use of the models fits well with the requirements set by the STECF in year 2000 to ICES for triggers to switch between a constant annual TACs and two step TAC provisions (in season update of starting TACs).

Although the current analysis is far from being complete, it provides a starting point for further research on the best use of the environment to forecast stock levels. Retrospective analysis could be brought back to 1993 (hence 8 retrospective comparisons), to better evaluate the relative performance of both methods for forecasting as outlined above. Other semi quantitative approaches can also be devised and checked over such range of years. Improvements can also arise by analysis of residuals to the models outlined above (ARMA and time series models) or further exploring non-linear relationships of the environmental indexes with recruitment (Cury and Roy 1989, Roy 1993).

In future it is also advisable to come out with some synthetic environmental index instead of two independent ones, *via* better comprehension and simulation of the abiotic and biotic factors affecting the onset of recruitment. For instance, other measures of the physical processes more directly related with larvae survival than upwelling, or better indices of reproductive biomass rather than current SSB estimates, etc. Studies on this line of research should be promoted since they may greatly improve current ability to predict recruitment.

4.2 Short-term Prediction of Recruitment in North Sea Cod Using Temperature Forecasts

Several studies have demonstrated a correlative link between recruitment success and sea temperature during the time of spawning for cod in the North Sea and Irish Sea. This information can be used in medium-term projections of the stock under varying environmental scenarios (see Section 3.2). There may be the potential to use this link in short-term projections and hence feed into the assessment procedure. Such an approach would increase the lead-time of recruitment predictions available and the time horizon for the implementation of management decisions.

In collaboration with the Benfield Greig Hazard Prediction Centre, UK, the forecasting abilities of a statistically based climate prediction model using an extension of the ENSO-CLIPPER prediction model were examined. The model is able to generate SST forecasts, up to four months ahead, with greater skill than a random persistence model. For a stock assessment working group meeting in October, a forecast for SST in the following spring is therefore available. Recruitment to the North Sea cod stock is defined as numbers of fish at age 1. It was demonstrated that forecasts of recruitment can be made by incorporating SST information into a stock-recruitment based prediction scheme (Planque *et al.* 2000, BD3). When compared with the observed recruitment patterns over the past 10 years, the predictions were poorly related to the observations. Problems are thought to arise due to the difficulties in forecasting SST with this length of lead-time.

Actual observations on the SST from the period January-June for the year in which the stock assessment working group is meeting are available by October. Hence investigations were made into generating a now-cast of cod recruitment based upon the early year observations. There was relatively good agreement between predicted recruitment and observed recruitment at age 1; i.e. for the following year, using this approach. The present, simple stock-recruitment-SST model appears to capture the inter-annual pattern in recruitment, although the variance is only partially captured. This is a standard feature of regression based models and the result is not unexpected.

Producing forecasts of next-year recruitment for North Sea cod following an October working group is possible but the prediction skill appears relatively weak. However, producing now-casts of recruitment for the present year of a working group using observed SST from that spring is relatively easy and performs reasonably well. The prediction can be made one year in advance of the recruitment predictions made using data from the young-fish surveys. Whether such environmentally based short-term predictions are of practical use in the management process is a separate issue.

The group believes that ICES must be kept abreast of the latest developments in climate and meteorological forecasting in order to evaluate methods by which information on links between environment, stocks and recruitment can be utilised in fisheries management.

5 POTENTIAL OF ENVIRONMENTAL STUDIES TO IMPACT ON MANAGEMENT PROCEDURES

5.1 Reference Points and Environmental Factors: Should They be Linked?

One question regarding management in the context of productivity which exhibits cycles or *regime shifts*, is whether to (and how to) change biological reference points. This question is considered in Basson (2000, BD8). The work was motivated by the observation that North Sea surface temperatures (SST) have been above the long-term average for most of the past decade. There is increasing evidence of a link between cod recruitment and SST (Planque and Frédou 1999). In the North Sea, for example, above average temperatures appear to impair recruitment (O’Brien *et al*. 2000). It is therefore relevant to ask whether current reference points would remain appropriate if above-average temperatures were to persist.

Theoretical considerations and simulation studies were used to explore potential problems with, and merits of, adjusting reference points according to an environmental factor. Theoretical considerations highlighted the following.

- Model choice is important:
  - e.g. Ricker or Beverton-Holt formulation
  - how the environmental effect is incorporated into the formulation.
- When analysing real stock-recruitment data it is usually impossible to distinguish statistically between different candidate models.
- Ignoring the environmental effect could lead to fishing mortality (F) being too high if there is a trend or pattern in the environmental series.
- There are potential conceptual difficulties with a $\mathbf{B}_{MSY}$-based threshold since it suggests a *lower* threshold when R is low than when R is average or high.

Simulation studies used a relatively simple age-based projection model. A distinction was made between the stock-recruitment model used to generate the underlying recruitment series (called the *correct* model), and that used for calculation of reference points, $\mathbf{F}_{MSY}$ in particular. This allowed performance evaluation of a management strategy based on a *wrong* model (i.e. a model differing from the so-called *correct* model). An imaginary SST series with a distinct *regime shift* to above-average temperatures was used to drive recruitment, in scenarios where recruitment was linked to SST. It is important to note that the simulations did *not* attempt to predict year-to-year recruitment, did *not* include any management inaccuracies, and did *not* incorporate assessment bias or error. It is therefore not a reflection of the existing ICES *modus operandi* for advising on TACs, for example, and neither is it a full-scale management evaluation. The main aim of this particular exercise was to explore the implications of model uncertainty and environmentally driven recruitment for four different management strategies.

Some of the main conclusions drawn from the simulation model are as follows. If target harvest rate ($\mathbf{F}_{MSY}$) is adjusted as a response to changes in SST, then:

- the model formulation used for the adjustments is important;
- there is a need to predict SST, and if a recent average is used, a lag in response can develop;
- adjustment of F, particularly upward adjustments, has effort implications; and
- model performance is poor if recruitment is *not* really affected by SST.

When a harvest control rule which does not respond to changes in SST, but which reduces F linearly between $\mathbf{F}_{MSY}$ and 0 for $0.5\mathbf{B}_{MSY}<SSB<\mathbf{B}_{MSY}$, is used, then:

- performance is good even if the model choice is wrong (and recruitment is affected by SST);
- there is no need to predict SST;
- adjustment in F still has effort implications, but there is an upper limit at $\mathbf{F}_{MSY}$; and
- performance is good if recruitment is *not* affected by SST.

One of the main reasons why the harvest control rule performs well under these scenarios, is because it maintains SSB at a higher level than the strategies which adjust the reference points (to lower $\mathbf{B}_{MSY}$) as SST increases. The harvest control rule and the adjusted reference point strategies all lead to increased variability in catches compared to a fixed $\mathbf{F}_{MSY}$ strategy (as one might expect). The average catches are, however, very similar under the different scenarios when the model choice is correct.

The paper concludes that one approach to management of a system that may be subjected to substantial changes in productivity (e.g. regime shifts or cycles) is to design robust, *smooth* harvest strategies. Such a strategy may *not* even directly incorporate a factor such as SST, but it is crucial that robustness tests are performed for a wide range of hypotheses about, or scenarios for, the environmental driver.

There are many details and issues which are not considered in the simulation study, and which would need to be explored in a case-specific context. Issues such as assessment error and bias, management inaccuracies (e.g. catches not being equal to the TAC) have already been mentioned. Other issues include testing with a wide range of environmental scenarios. For example, not just *regime shifts* that lead to reduced recruitment, but also ones that lead to increased recruitment should be considered.

5.2 Discussion

During discussion, it was noted that although knowledge and an understanding of the underlying process and mechanisms are necessary for the construction of an operating model (which reflects how the real system works), the management procedure, or strategy, itself *need* not be complex. There is an increasing body of work (e.g. Parma 2000) showing that very simple management strategies or harvest control rules can perform well. The key issue is that proposed strategies have to be tested for robustness and performance.

Some of the key characteristics of simple (or in fact complex!) management strategies were identified as: robustness to a wide range of issues (environmental effects, model uncertainty, estimation error and bias etc); *smoothness* to minimise large year-to-year changes in catch – ideally, the strategy should have maximum capability of tracking signals, and only minimum response to noise. Although greater responsiveness usually leads to higher inter-annual variability in catches, a strategy could be designed with a limit on the percentage change in catch from one year to the next. It was, however, pointed out that in some cases (heavily or over-exploited stocks) it may be difficult to achieve a sustainable fishery with a harvest strategy which limits year-to-year changes in catches.

The potentially large differences between a system which is at or close to its *target* exploitation level (as modelled in the simulations), and a system which is over-exploited (outside safe biological limits) was also noted. For most of the ICES stocks which are outside safe biological limits, TACs are dominated by incoming recruitment, and the stock dynamics are similar to the dynamics of short-lived species. Such stocks may initially require different, and special, management approaches until stock levels are rebuilt to include a wider age range and their stronger buffering effect to fluctuating recruitment. These issues can usefully be investigated within a simulation context.

6 RECOMMENDATIONS

A discussion took place on the relevance and utility of the Study Group to ICES in the wider context of stock assessments and a desire to understand biological issues when contemplating fisheries management. It was considered that the Study Group had afforded an opportunity for biologists and stock assessment practitioners to meet under a common theme and to begin the, much needed, process of integrating biological knowledge and stock assessment methods/techniques.

The first meeting of the Study Group (ICES, 2000a) had concentrated mainly on environmental issues as drivers of recruitment variability; whilst this second meeting jointly considered possible environmental and biological causes for recruitment fluctuations. Whilst the Study Group had addressed its terms of reference at both meetings, it was felt that much work still remained to be undertaken and that a third meeting should be held.

6.1 Future Work and Terms of Reference

The Study Group meet for 4 days during the period 14–18 January 2002 (Chair: Dr C.M. O'Brien, UK) in Lowestoft, UK to:

- further consider the two case studies (North Sea cod and Bay of Biscay anchovy);
- further develop the modelling and testing of process and recruitment relationships for incorporation into management procedures; and
- consider the compilation and acquisition of data for estimating the reproductive potential of fish stocks; together with ensuring either the continued, or future additional collection, of relevant data for the construction of pertinent biological time series (e.g. fish condition based upon individual fish weights).

6.2 Links to Other Groups and Activities

In this section is a partial listing of on-going international collaborative groups investigating aspects of the reproductive variability of marine fish stocks, biological processes contributing to recruitment and numerical approaches to quantifying uncertainty in medium-term stock forecasts.

6.2.1 NAFO Working Group on Reproductive Potential

Methods for quantifying the reproductive potential of individuals and stocks are currently being reviewed and summarized by the NAFO Working Group on Reproductive Potential (Chair: E.A. Trippel, Canada). The terms of reference for this group are to:

a) explore and review availability of information and existing data on reproductive potential by area and species;
b) explore possibilities to develop standard internationally co-ordinated research protocols to estimate egg and larval production;
c) explore and evaluate alternative methods to estimate reproductive potential annually as part of routine in monitoring and sampling schemes (such as hepatosomatic index, HSI); and
d) review possibilities to develop methods and opportunities to estimate stock reproductive potential for assessment and management.

It is anticipated that the information compiled by the working group will benefit fisheries management by developing methods for incorporating relevant information on stock structure into conventional assessment. A final report will be available by the end of 2001.

6.2.2 ICES Working Group on Recruitment Processes

The ICES Working Group on Recruitment Processes (Co-chairs: P. Pepin, Canada, and R. Nash, Isle of Man) will work by correspondence in 2001 and prepare for a meeting in 2002. The next meeting of the working group will consider the results of the SGPRISM's examination of the STEREO project, along with concurrent and subsequent investigations, in order to refine the present approach to incorporating stock structure and environmental information into assessment and projection procedures (ICES, 2000b).

6.2.3 ICES Working Group on Methods on Fish Stock Assessments

The ICES Working Group on Methods on Fish Stock Assessments (Chair: to be decided) has been re-established to meet in June 2001 to address the following tasks.

a) Develop diagnostics and testing procedures for the evaluation of methods used for producing stock assessments, short-term forecasts and medium-term projections.
b) Apply such testing procedures to the methods routinely used by ICES at present. Such testing should pay particular attention to:
    - bias detection and correction;
    - the form of error distributions in stock-recruit relationships taking into account input from SGPRISM; and
    - other concerns that may be raised by ACFM from time to time based on input from assessment working groups.
c) Identify strengths and weaknesses in the methods and propose modifications to assessment models or new models as appropriate.
d) Use its diagnostic and testing procedures in order to evaluate the performance of new methodological proposals.
e) Present its results in a form that can be readily implemented in the assessments, e.g. through the development of computer software.

The work of the current SGPRISM has relevance to the first and second terms of reference of the ICES Working Group on Methods on Fish Stock Assessments; specifically in respect of diagnostic tests and procedures applicable to medium-term stock projections.

7 WORKING DOCUMENTS AND BACKGROUND MATERIAL PRESENTED TO THE STUDY GROUP

At the Study Group two working documents (WD1, WD2) and nine background documents (BD1-BD9) were presented and discussed. These are listed below, together with the reference codes used in the text of this report.

Working document: WD1
Marshall, C.T. (2001). A review of recent research related to quantifying the reproductive potential of marine fish.

Working document: WD2
Tretyak, V.L. (2001). On the possibility of North East Arctic cod recruitment modelling.

Background document: BD1
Report of the Working Group meeting *NAFO Scientific Council Working Group on Reproductive Potential*, 10–13 October 2000, AZTI, San Sebastian, Spain.

Background document: BD2
Needle, C.L., O'Brien, C.M., Darby, C.D. and Smith, M.T. (2000). Incorporating time-series structure and environmental information in medium-term stock projections. Submitted to *Sci. Mar*.

Background document: BD3
Planque, B., Fox, C.J., Hamilton, T and Saunders, M.A. (2000). On the statistical prediction of short term changes in the recruitment of North Sea cod (*Gadus morhus*) using temperature forecasts. Submitted to *Sci. Mar*.

Background document: BD4
Tretyak, V.L. (2000). Modelling of age-dependent instantaneous coefficients of natural mortality for Northeast Arctic cod. ICE CM 2000/V:09.

Background document: BD5
Tretyak, V.L. (1999). On possibility of the use of the Ricker's model "stock-recruitment" for estimation of recruitment of North-Eastern Arctic cod population. ICES CM 1999/Y:12.

Background document: BD6
Borja, A., Skreslet, S, Wyatt, T and Hansen, G. (2000). Environmental and climatic factors affecting recruitment of the Northeast Arctic cod (*Gadus morhua* L.) along the Norwegian coasts. Submitted to *Fisheries Oceanography* (abstract supplied).

Background document: BD7
Heath, M. and Gallego, A. (2000). Modelling the spatial and temporal structure of survivorship to settlement in North Sea and West of Scotland haddock. ICES CM 2000/N:11.

Background document: BD8
Basson, M. (2000). Reference points and environmental factors: should they be linked? Presented at the symposium: *Targets, Reference Points and the Burden of Proof in Fishery Management* (31 October – 2 November 2000, MOTE Marine Laboratory, Sarasota, Florida) and submitted to *Bulletin of Marine Science*.

Background document: BD9
Scott, B., Marteinsdottir, G. and Wright, P. (1999). Potential effects of maternal factors on spawning stock-recruitment relationships under varying fishing pressure. *Canadian Journal of Fisheries and Aquatic Sciences*, **56**: 1882–1890.

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ICES 2000f. Report of the Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak. ICES CM 2000/ACFM:7.

ICES 2000g. Report of the Working Group on the Assessment of Mackerel, Horse Mackerel, Sardine and Anchovy. ICES CM 2000/ACFM:5.

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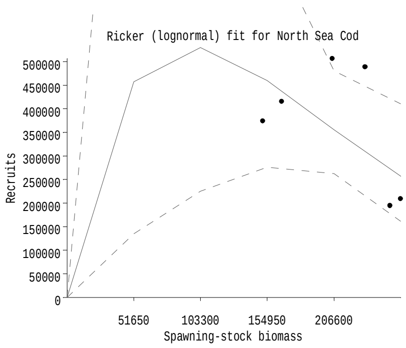
APPENDIX A – FIGURES SHOWING FITTED RICKER MODELS, PROJECTIONS OF RECRUITMENT, PROJECTIONS OF SPAWNING STOCK BIOMASS AND PROJECTIONS OF REALISED EGG PRODUCTION FOR NORTH SEA COD; TOGETHER WITH DIAGNOSTIC PLOTS FOR THE MEDIUM-TERM PROJECTION MODELS INVESTIGATED

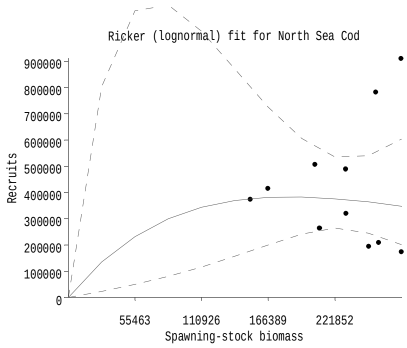
This Appendix A contains the graphs and plots that comprise Figures 3.2.2.1, 3.2.2.3, 3.2.2.4, 3.2.3.4.3 and 3.3.3.1.

Figure 3.2.2.1. Ricker model fits $R = \alpha S\,\mathrm{e}^{-\beta S}$ used to generate residuals for ARMA and WGMTERM projections, with starting dates and fitted parameters as noted. Fitting was done by non-linear least-squares minimisation using the RecAn 2.0 program (Needle, unpublished data), assuming log-normal variance of residual errors. The dotted lines in each plot are the approximate upper and lower 95% confidence bounds on the (solid) fitted function.

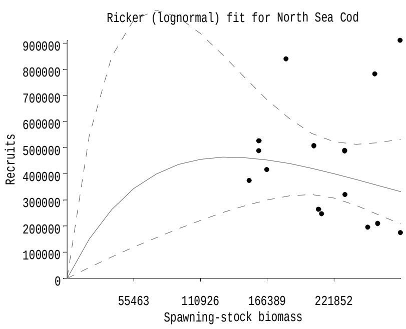
1970: $\alpha = 1.5301e1, \beta = 1.0582e-5$



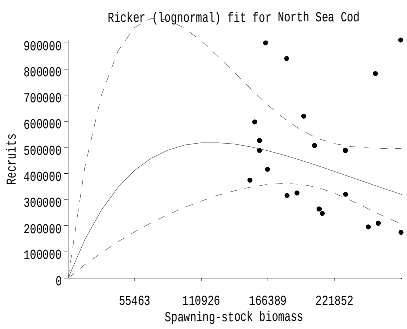
1975: $\alpha = 5.6474e0, \beta = 5.4273e-6$



1980: $\alpha = 9.9338e0, \beta = 7.4075e-6$



1985: $\alpha = 1.1836e1, \beta = 8.3952e-6$



1990: $\alpha = 5.5852e0, \beta = 5.0483e-6$

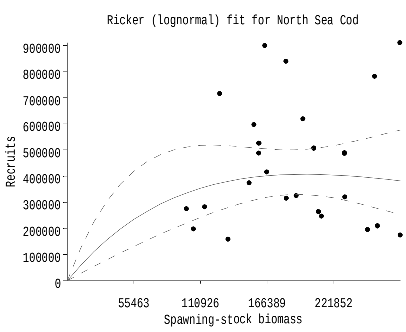
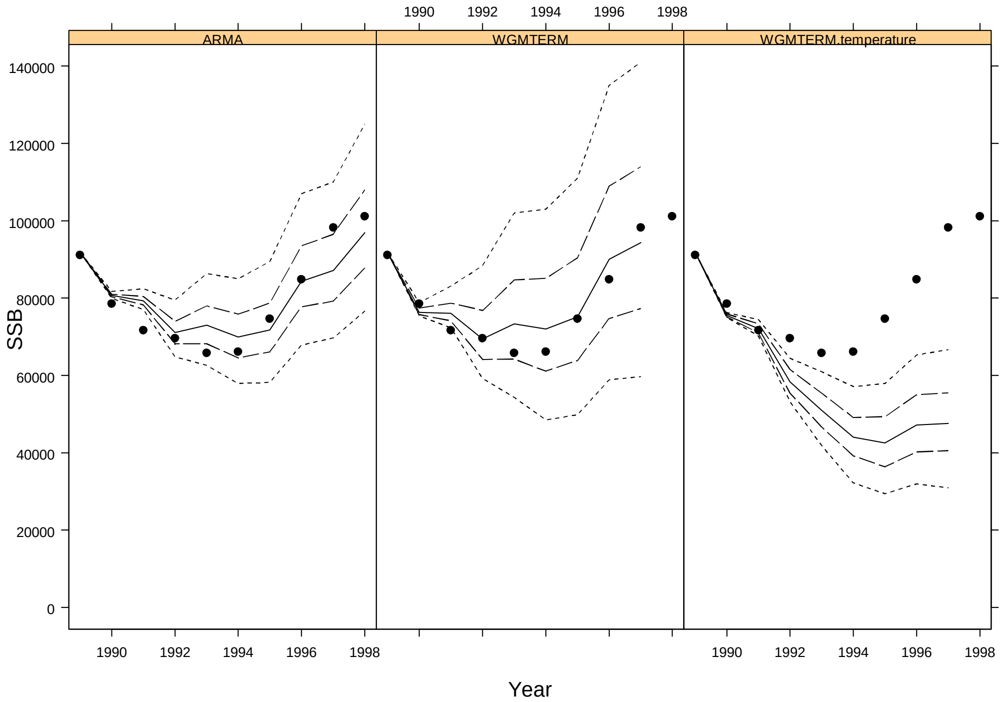


Figure 3.2.2.3. Projections of spawning stock biomass (a) and recruitment (b) for three different models (ARMA, WGMTERM-type, and WGMTERM-type with a temperature covariate), with starting dates as noted. Lines give percentiles (5th, 25th, 50th, 75th and 95th) of stochastic projection distributions, and points show the estimated spawning stock biomass (a) and recruitment (b) from the 1999 ICES assessment. Projections use *F*-multipliers from the assessment, with fixed weights-at-age and selectivity ogives.

1990: SSB



1990: Recruitment

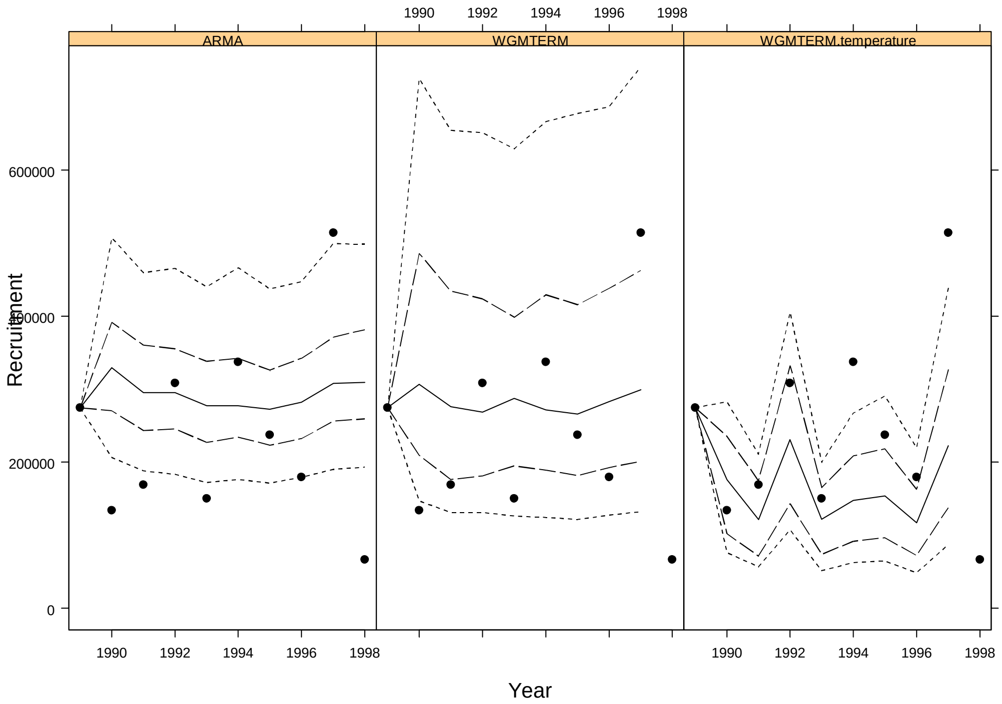
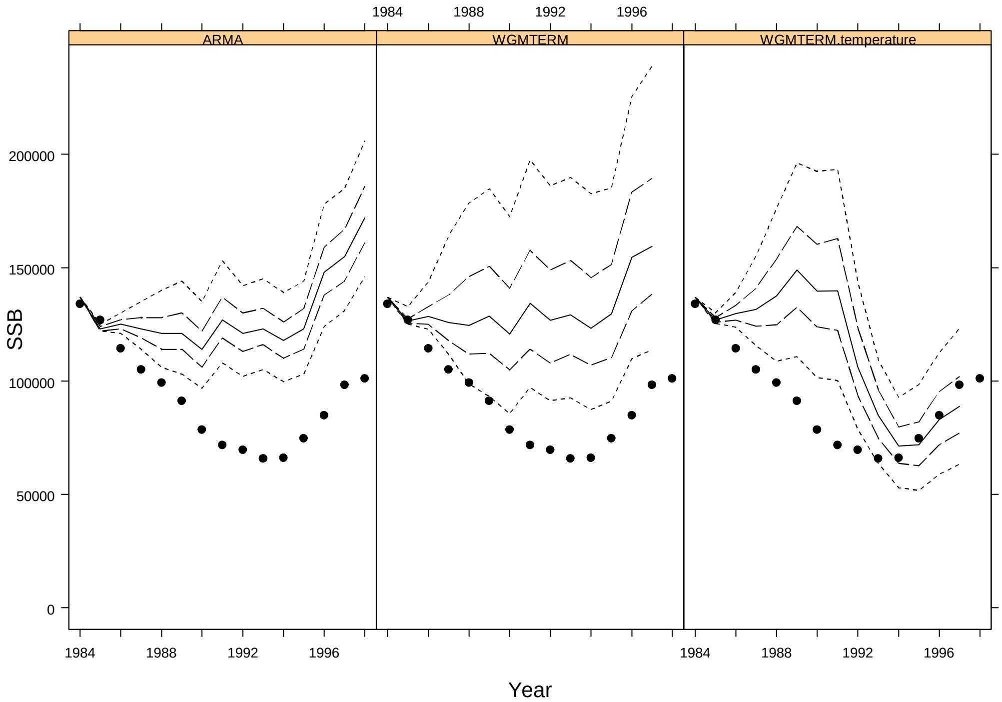


Figure 3.2.2.3 Continued

1985: SSB



1985: Recruitment

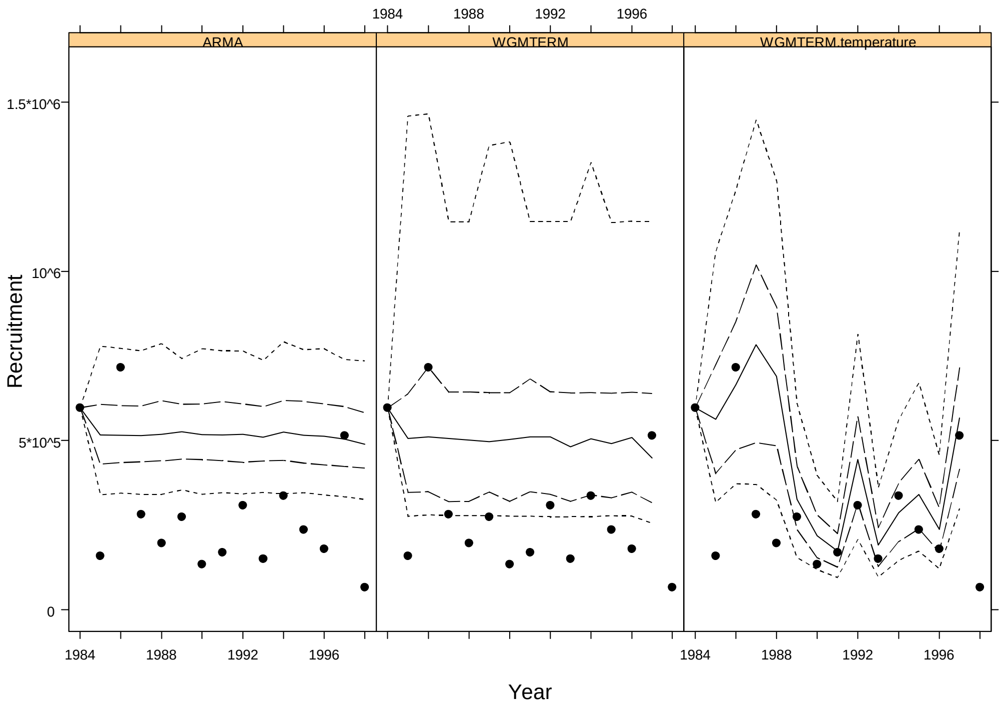
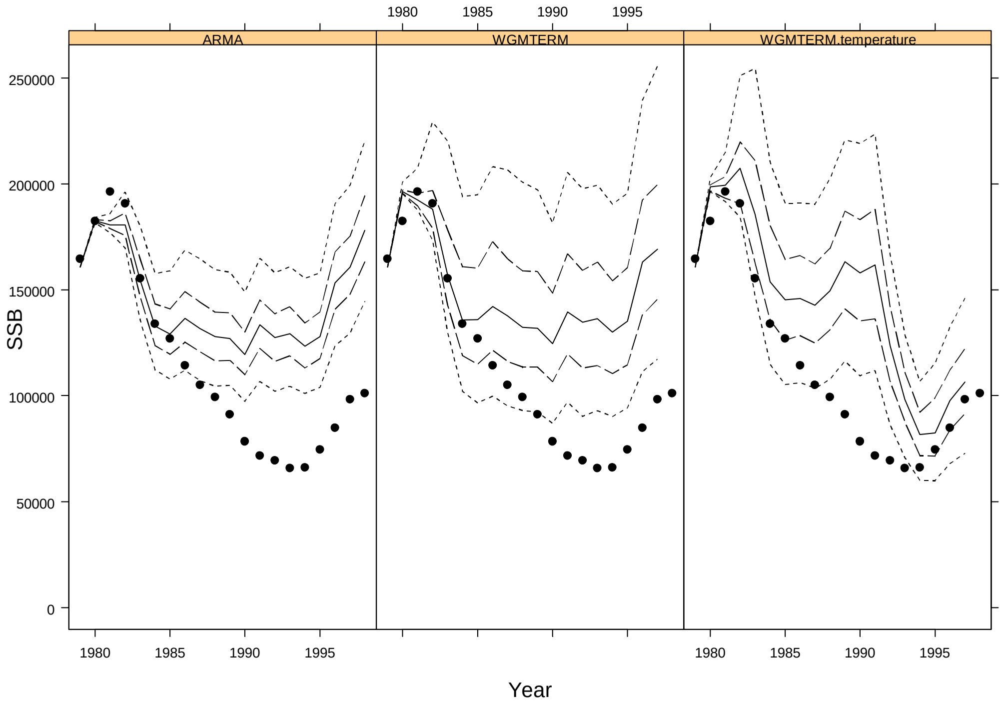


Figure 3.2.2.3 Continued

1980: SSB



1980: Recruitment

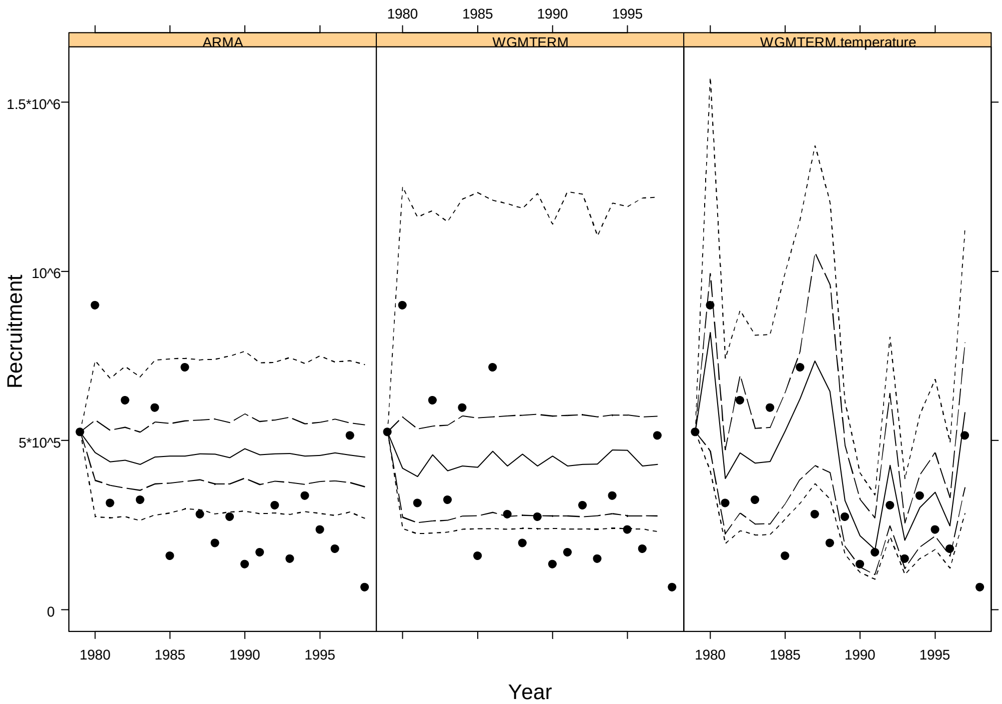
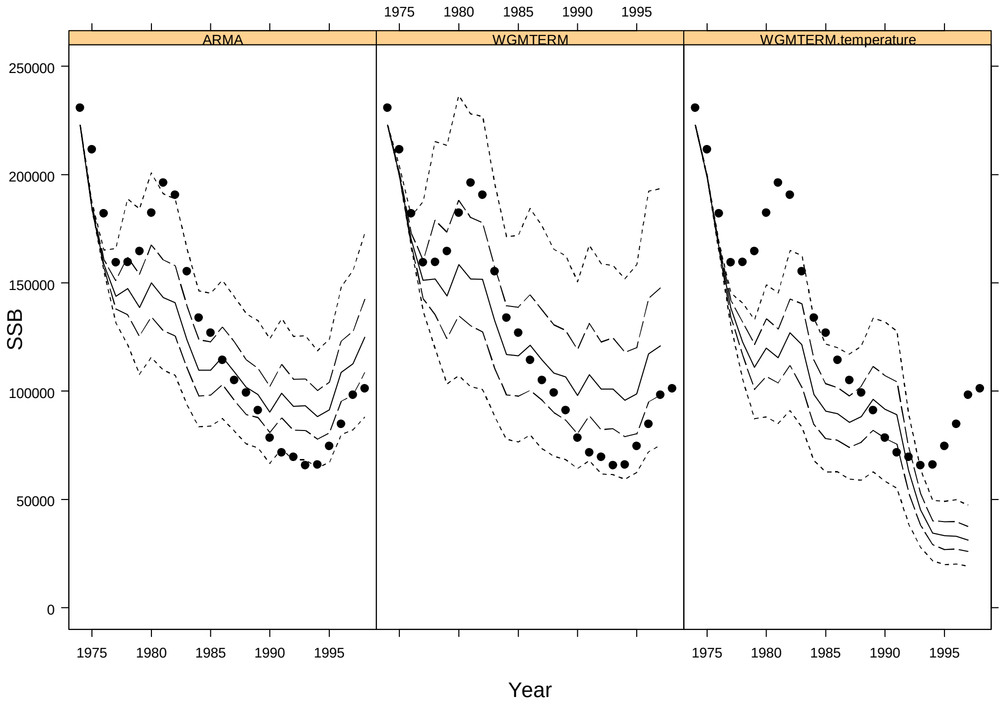


Figure 3.2.2.3 Continued

1975: SSB



1975: Recruitment

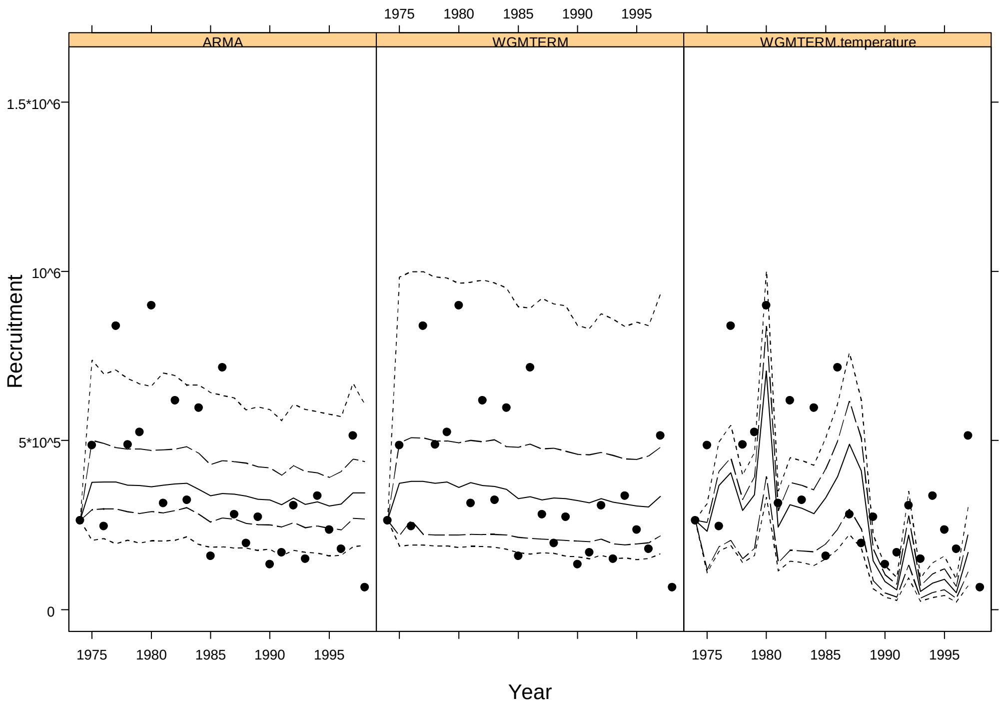
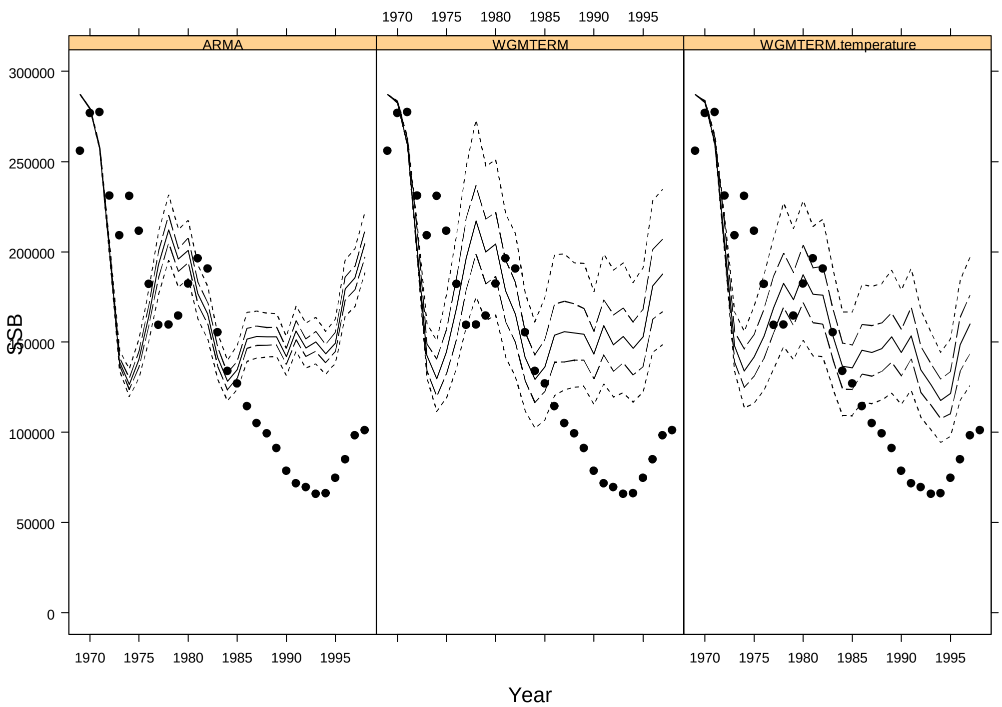


Figure 3.2.2.3 Continued

1970: SSB



1970: Recruitment

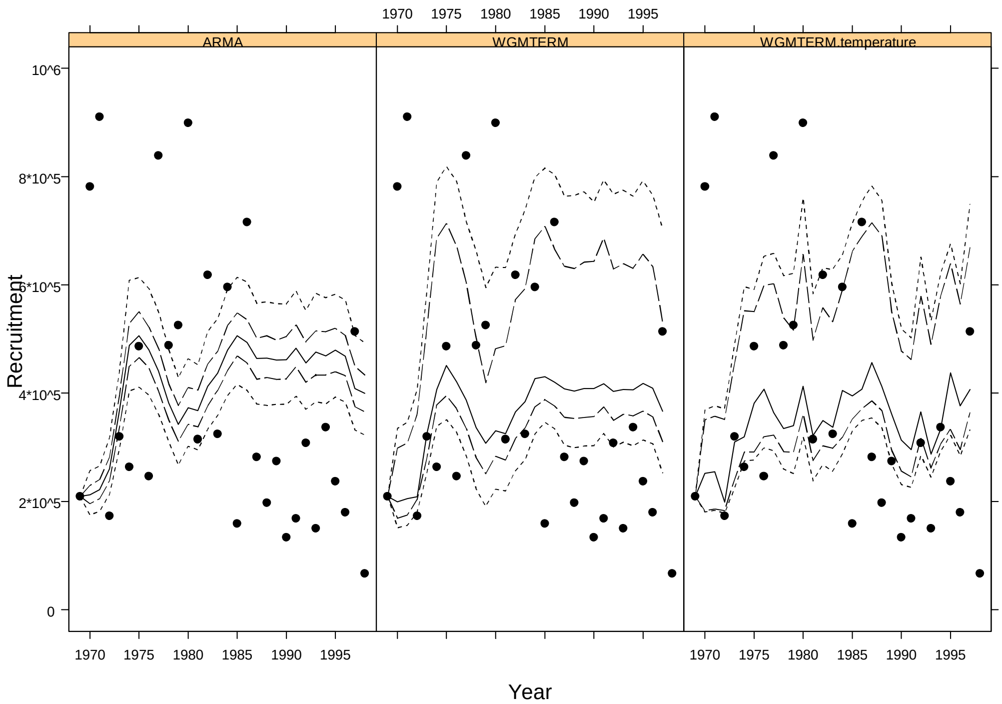


Figure 3.2.2.4. Diagnostic plots for the three models presented in the text, giving deterministic and median SSB projections from five different starting dates. Note that scales vary between plots.

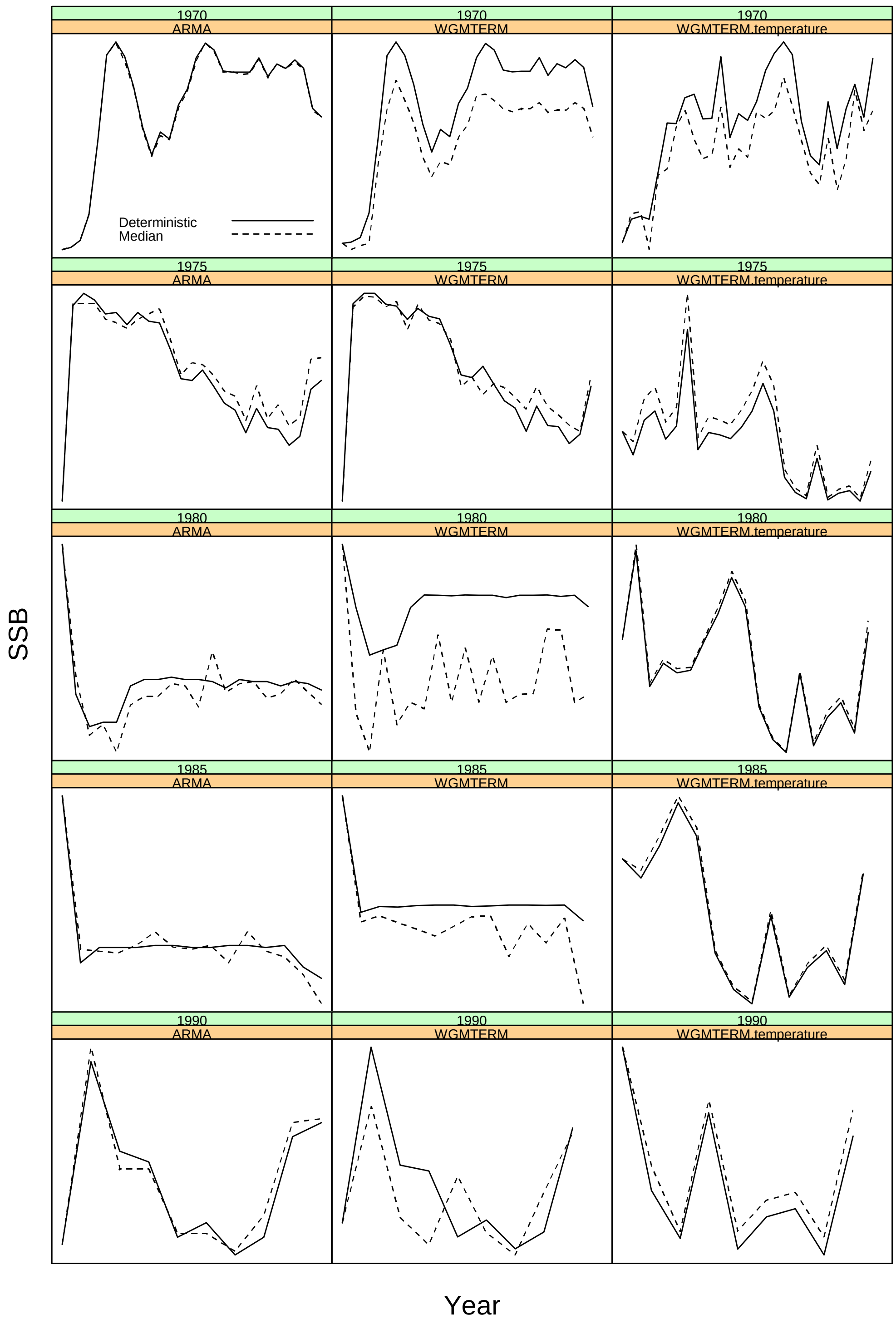
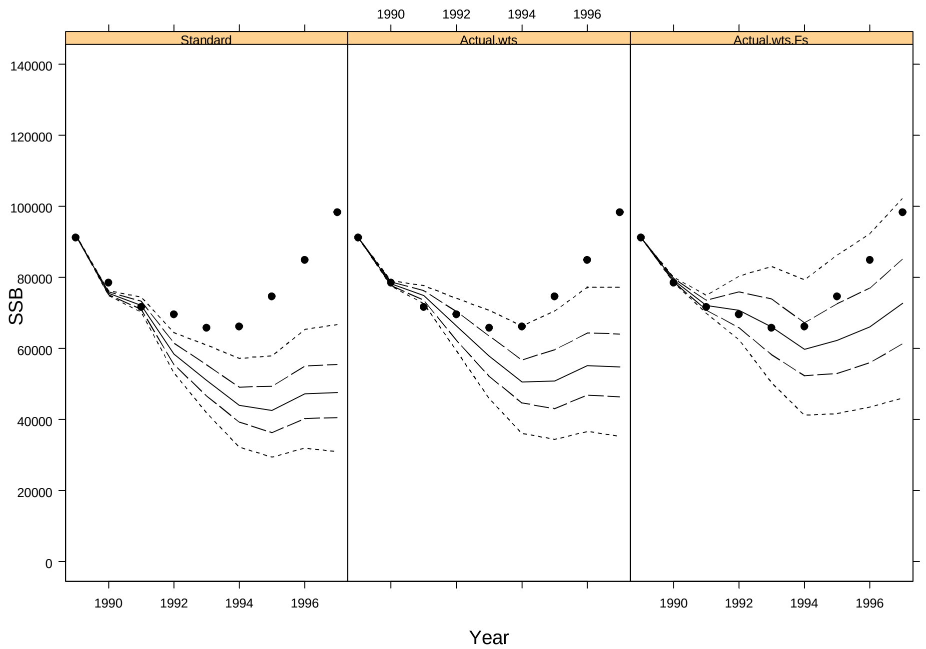


Figure 3.2.3.4.3. Projections of spawning stock biomass (a) and recruitment (b) for the WGMTERM-type model with a temperature covariate, starting from 1990, for three different parameter assumptions: *F*-multipliers from the assessment, with fixed weights-at-age and selectivity ogives (**Standard**); *F*-multipliers and weights-at-age from the assessment, with a fixed selectivity ogive (**Actual.wts**); and weights-at-age and selectivity ogives from the assessment (**Actual.wts.Fs**). Lines give percentiles (5th, 25th, 50th, 75th and 95th) of stochastic projection distributions, and points show the estimated spawning stock biomass (a) and recruitment (b) from the 1999 ICES assessment.

a.



b.

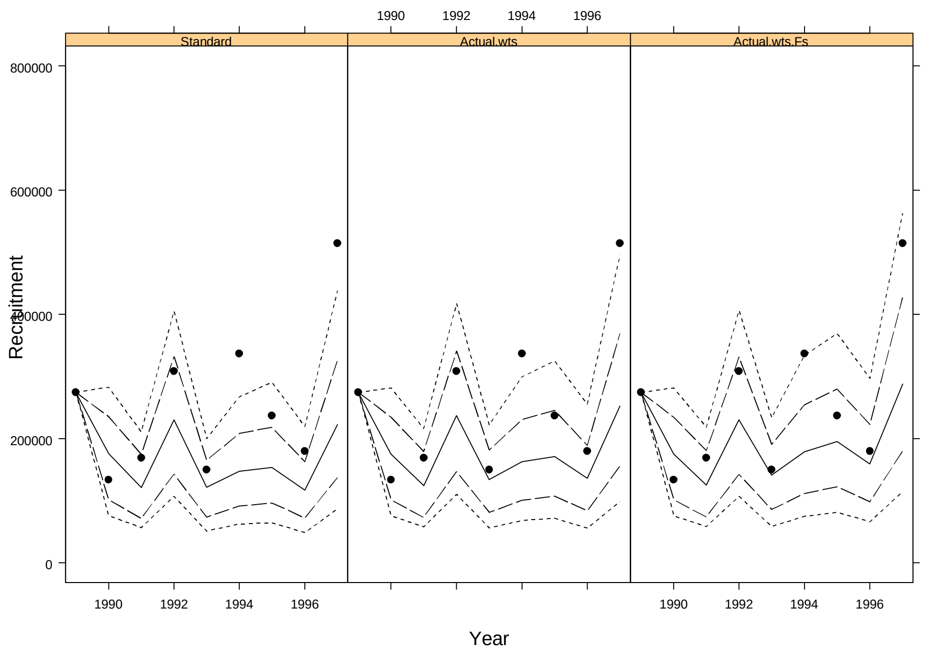
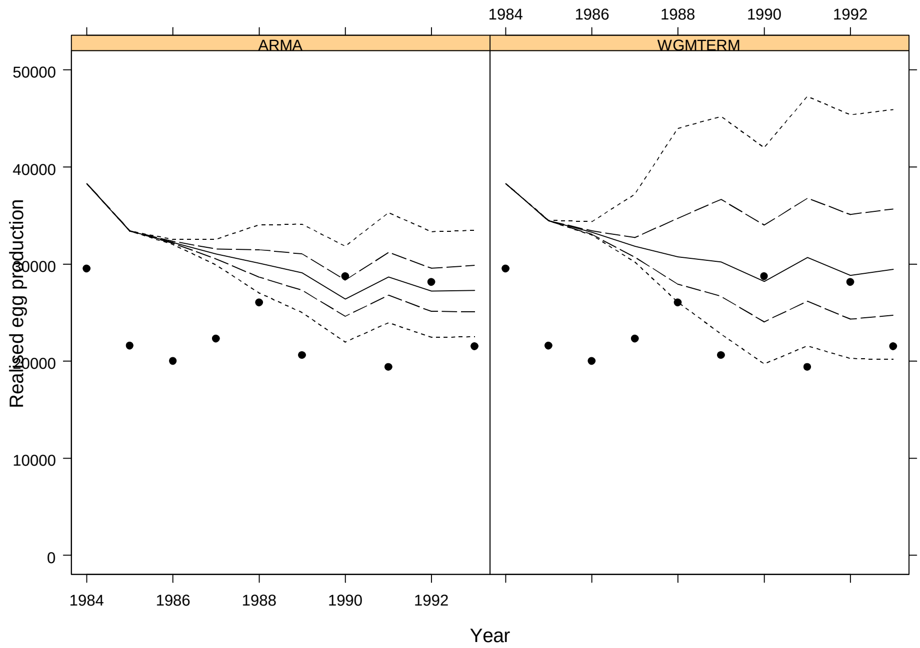
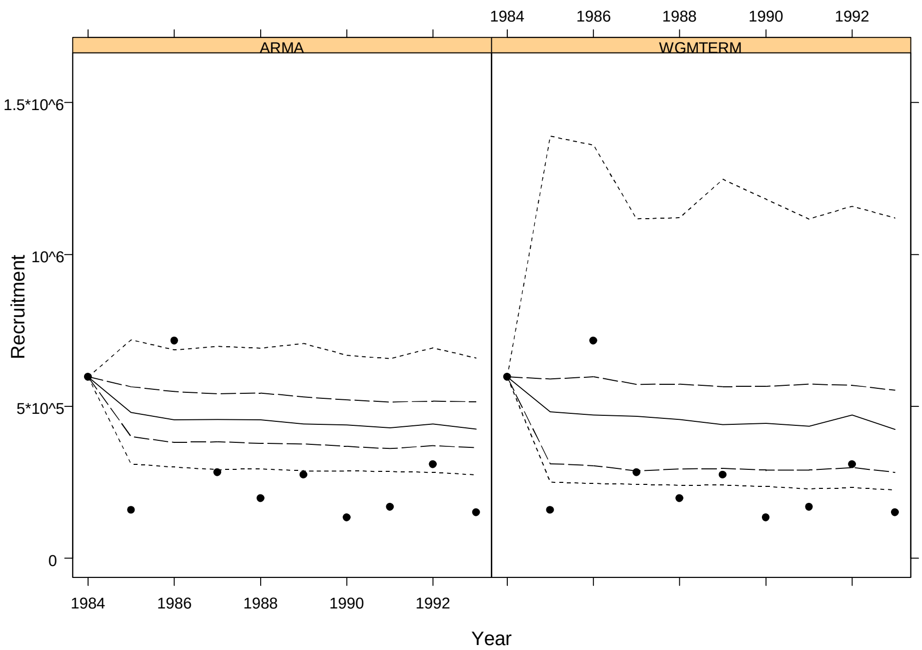


Figure 3.3.3.1. Projections of realised egg production (REP) and recruitment for two different models (ARMA and WGMTERM-type), starting from 1985. Lines give percentiles (5th, 25th, 50th, 75th and 95th) of stochastic projection distributions, and points show the estimated REP (a) and recruitment (b) as derived from the 1999 ICES assessment. Projections use *F*-multipliers from the assessment, with fixed weights-at-age and selectivity ogives. REP data are derived as outputs from the STEREO project (EU FAIR CT98-4122).



a.



b.

APPENDIX B – RETROSPECTIVE ANALYSES FOR BAY OF BISCAY ANCHOVY

Table 4.1.4.1: Inputs to short term retrospective analysis for the Bay of Biscay anchvovy

												1000									
		Cuantitative		Seminquantita		Cuantitative		Seminquantita		Cuantitative		Seminquantita		Cuantitative		Seminquantita		Cuantitative		Seminquantitat	
	CASE Y	1996		1996		1997		1997		1998		1998		1999		1999		2000		2000	
PARAMETERS	**Code**	**Inputs**	**CV**	**Inputs**	**CV**	**Inputs**	**CV**	**Inputs**	**CV**	**Inputs**	**CV**	**Inputs**	**CV**	**Inputs**	**CV**	**Inputs**	**CV**	**Inputs**	**CV**	**Inputs**	**CV**
Population at age 0 in Y (millions)	'N0'	18089	0.41	20671	0.3	28070	0.40	19943	0.32	13820	0.32	13179	0.69	5903	0.52	6505	0.33	11531	0.39	12174	0.67
Population at age 1 in Y (millions)	'N1'	4495	0.53	4495	0.53	5096	0.48	5096	0.48	9282	0.39	9282	0.39	1434	0.52	1434	0.52	3770	0.28	3770	0.28
Population at age 2 in Y (from ICA ouput)	'N2'	976.6	0.25	976.6	0.25	842.2	0.33	842.2	0.33	1537	0.21	1537	0.21	2710	0.21	2710	0.21	511.6	0.26	511.6	0.26
Population at age 3 in Y (from ICA ouput)	'N3'	136.6	0.22	136.6	0.22	66.1	0.31	66.1	0.31	113.6	0.2	113.6	0.2	285.4	0.18	285.4	0.18	266.9	0.17	266.9	0.17
Population at age 4 in Y (from ICA ouput)	'N4'	31.3	0.27	31.3	0.27	12	0.38	12	0.38	6.4	0.28	6.4	0.28	20.8	0.22	20.8	0.22	34.7	0.2	34.7	0.2
Population at age 5 in Y (from ICA ouput)	'N5'	3.3	0.35	3.3	0.35	2.9	0.46	2.9	0.46	1.7	0.38	1.7	0.38	2.2	0.33	2.2	0.33	3.7	0.24	3.7	0.24
Fishing Mortality mean 1995-99 at age 0	'sH0'	0.006	0.44	0.006	0.44	0.006	0.44	0.006	0.44	0.006	0.44	0.006	0.44	0.006	0.44	0.006	0.44	0.006	0.44	0.006	0.44
Fishing Mortality mean 1995-99 at age 1	'sH1'	0.399	0.44	0.399	0.44	0.399	0.44	0.399	0.44	0.399	0.44	0.399	0.44	0.399	0.44	0.399	0.44	0.399	0.44	0.399	0.44
Fishing Mortality mean 1995-99 at age 2	'sH2'	0.918	0.44	0.918	0.44	0.918	0.44	0.918	0.44	0.918	0.44	0.918	0.44	0.918	0.44	0.918	0.44	0.918	0.44	0.918	0.44
Fishing Mortality mean 1995-99at age 3	'sH3'	0.807	0.44	0.807	0.44	0.807	0.44	0.807	0.44	0.807	0.44	0.807	0.44	0.807	0.44	0.807	0.44	0.807	0.44	0.807	0.44
Fishing Mortality mean 1995-99 at age 4	'sH4'	0.727	0.44	0.727	0.44	0.727	0.44	0.727	0.44	0.727	0.44	0.727	0.44	0.727	0.44	0.727	0.44	0.727	0.44	0.727	0.44
Fishing Mortality mean 1995-99 at age 5	'sH5'	0.918	0.44	0.918	0.44	0.918	0.44	0.918	0.44	0.918	0.44	0.918	0.44	0.918	0.44	0.918	0.44	0.918	0.44	0.918	0.44
Weight in the catch at age 0	'WH0'	0.012	0.28	0.012	0.28	0.012	0.28	0.012	0.28	0.012	0.28	0.012	0.28	0.012	0.28	0.012	0.28	0.012	0.28	0.012	0.28
Weight in the catch at age 1 (mean 87-99)	'WH1'	0.021	0.09	0.021	0.09	0.021	0.09	0.021	0.09	0.021	0.09	0.021	0.09	0.021	0.09	0.021	0.09	0.021	0.09	0.021	0.09
Weight in the catch at age 2 (mean 87-99)	'WH2'	0.029	0.09	0.029	0.09	0.029	0.09	0.029	0.09	0.029	0.09	0.029	0.09	0.029	0.09	0.029	0.09	0.029	0.09	0.029	0.09
Weight in the catch at age 3 (mean 87-99)	'WH3'	0.035	0.13	0.035	0.13	0.035	0.13	0.035	0.13	0.035	0.13	0.035	0.13	0.035	0.13	0.035	0.13	0.035	0.13	0.035	0.13
Weight in the catch at age 4 (mean 87-99)	'WH4'	0.040	0.17	0.040	0.17	0.040	0.17	0.040	0.17	0.040	0.17	0.040	0.17	0.040	0.17	0.040	0.17	0.040	0.17	0.040	0.17
Weight in the catch at age 5 (mean 87-99)	'WH5'	0.042	0.17	0.042	0.17	0.042	0.17	0.042	0.17	0.042	0.17	0.042	0.17	0.042	0.17	0.042	0.17	0.042	0.17	0.042	0.17
Weight in the stock at age 0 (mean 90-98)	'WS0'	0.012	0.28	0.012	0.28	0.012	0.28	0.012	0.28	0.012	0.28	0.012	0.28	0.012	0.28	0.012	0.28	0.012	0.28	0.012	0.28
Weight in the stock at age 1 (mean 90-98)	'WS1'	0.016	0.14	0.016	0.14	0.016	0.14	0.016	0.14	0.016	0.14	0.016	0.14	0.016	0.14	0.016	0.14	0.016	0.14	0.016	0.14
Weight in the stock at age 2 (mean 90-98)	'WS2'	0.029	0.08	0.029	0.08	0.029	0.08	0.029	0.08	0.029	0.08	0.029	0.08	0.029	0.08	0.029	0.08	0.029	0.08	0.029	0.08
Weight in the stock at age 3 (mean 90-98)	'WS3'	0.034	0.06	0.034	0.06	0.034	0.06	0.034	0.06	0.034	0.06	0.034	0.06	0.034	0.06	0.034	0.06	0.034	0.06	0.034	0.06
Weight in the stock at age 4 (mean 90-98)	'WS4'	0.041	0.15	0.041	0.15	0.041	0.15	0.041	0.15	0.041	0.15	0.041	0.15	0.041	0.15	0.041	0.15	0.041	0.15	0.041	0.15
Weight in the stock at age 5 (mean 90-98)	'WS5'	0.042	0.15	0.042	0.15	0.042	0.15	0.042	0.15	0.042	0.15	0.042	0.15	0.042	0.15	0.042	0.15	0.042	0.15	0.042	0.15
Natural Mortality at age 0	'M0'	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1
Natural Mortality at age 1	'M1'	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1
Natural Mortality at age 2	'M2'	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1
Natural Mortality at age 3	'M3'	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1
Natural Mortality at age 4	'M4'	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1
Natural Mortality at age 5	'M5'	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1	1.2	0.1
Maturity at age 0	'MT0'	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Maturity at age 1	'MT1'	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0
Maturity at age 2	'MT2'	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0
Maturity at age 3	'MT3'	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0
Maturity at age 4	'MT4'	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0
Maturity at age 5	'MT5'	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0
Recruitment at age 0 in Y+1 (millions)	'RY+1'	12174	0.67	12174	0.67	12174	0.67	12174	0.67	12174	0.67	12174	0.67	12174	0.67	12174	0.67	12174	0.67	12174	0.67
Recruitment at age 0 in Y+2 (millions)	'RY+2'	12174	0.67	12174	0.67	12174	0.67	12174	0.67	12174	0.67	12174	0.67	12174	0.67	12174	0.67	12174	0.67	12174	0.67
Fishing mortality multiplier for Y	'HFY'	1.200	0.12	1.200	0.12	0.700	0.12	0.710	0.12	0.530	0.12	0.53	0.12	0.650	0.12	0.640	0.12	1.400	0.12	1.400	0.12
Fishing mortality multiplier for Y+1	'HFY+1'	0.7	0.12	0.62	0.12	0.67	0.12	0.81	0.12	0.56	0.12	0.58	0.12	2.3	0.12	2.02	0.12	1	0.12	1	0.12
Fishing mortality multiplier for Y+2	'HFY+2'	0.7	0.12	0.62	0.12	0.67	0.12	0.81	0.12	0.56	0.12	0.58	0.12	1	0.12	1	0.12	1	0.12	1	0.12
Natural mortality multiplier for Y	'KY'	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1
Natural mortality multiplier for Y+1	'KY+1'	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1
Natural mortality multiplier for Y+2	'KY+2'	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1

Figure 4.1.4.4 Retrospective projections of SSB in year y+1 Constrained to the catches known for years y and y+1

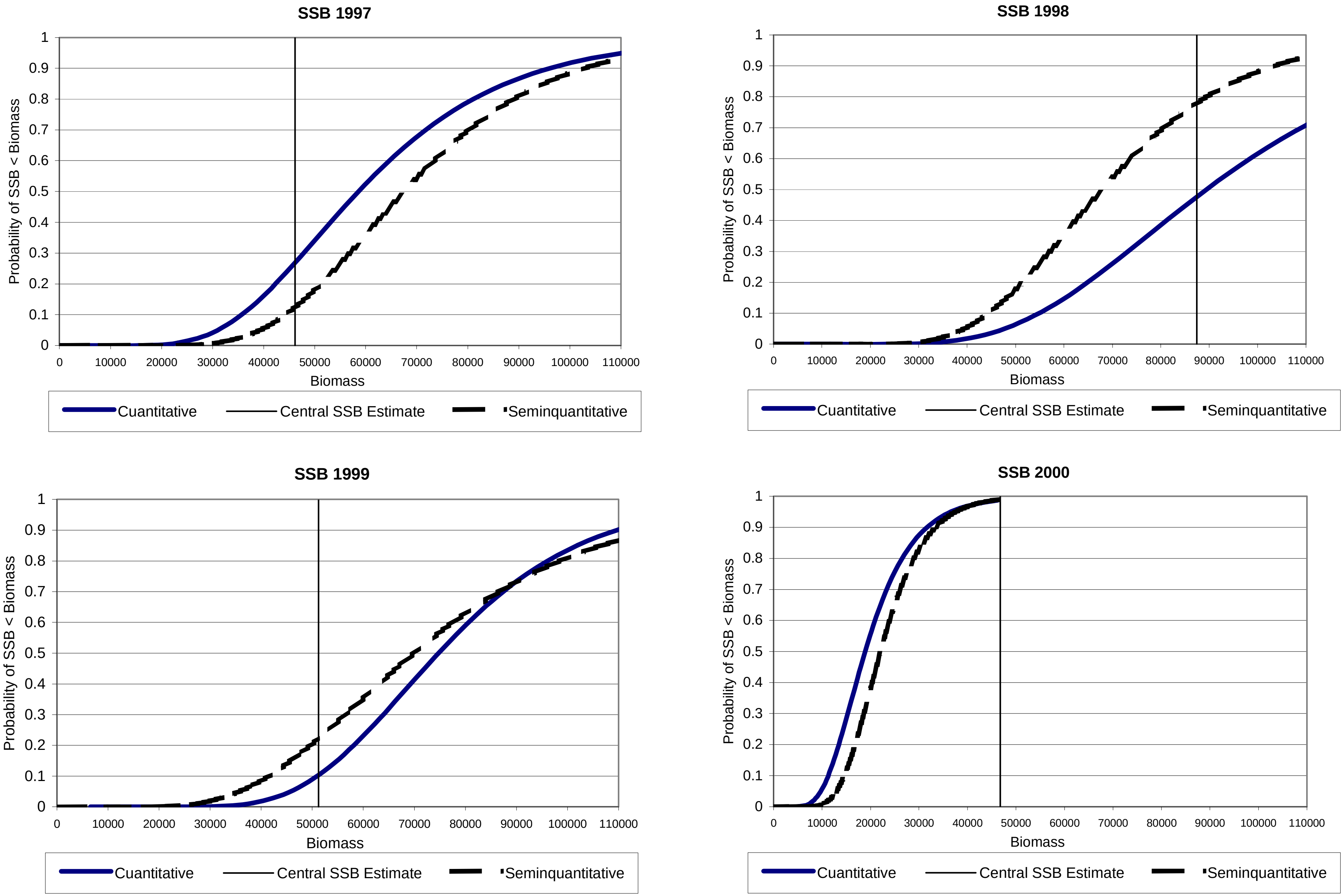
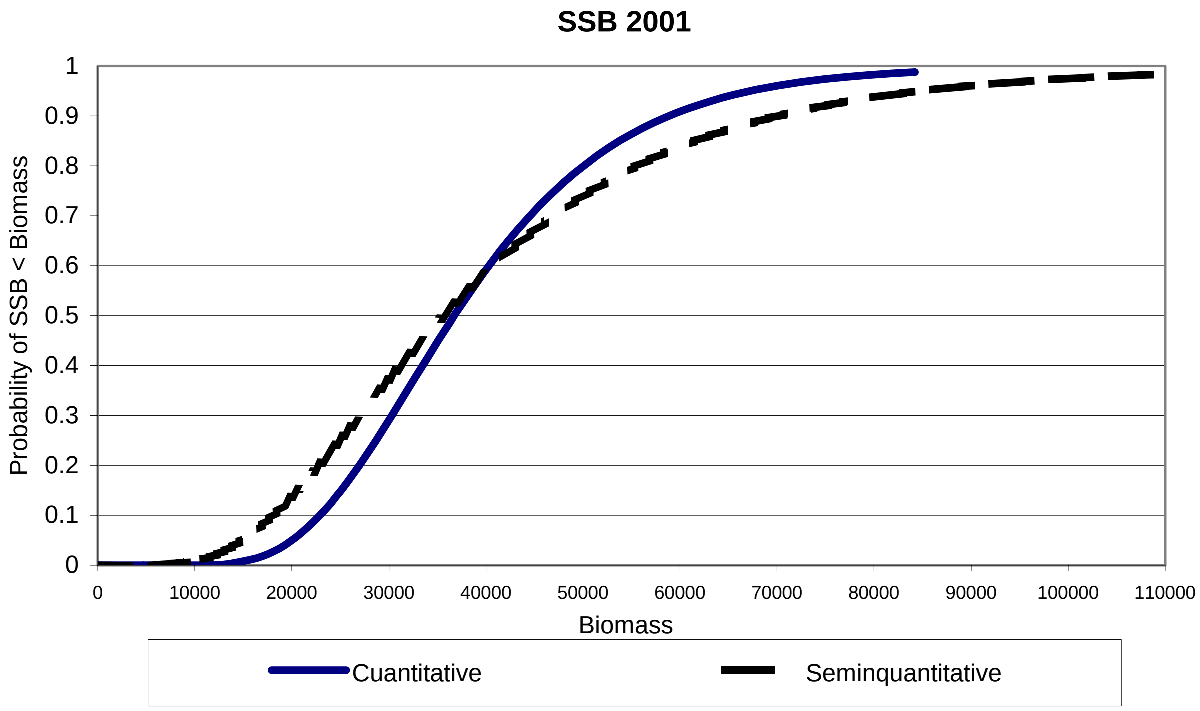


Figure 4.1.4.5


SSB 2001
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Probability of SSB < Biomass
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
110000
Biomass
Cuantitative
Seminquantitative