ICES COOPERATIVE RESEARCH REPORT

RAPPORT DES RECHERCHES COLLECTIVES

NO. 282

NOVEMBER 2006

INCORPORATION OF PROCESS INFORMATION INTO STOCK–RECRUITMENT MODELS

Carl M. O'Brien and Alyson S. Little

Cefas Lowestoft Laboratory
Pakefield Road
Lowestoft, Suffolk, NR33 0HT, UK
carl.obrien@cefas.co.uk
alyson.little@cefas.co.uk

International Council for the Exploration of the Sea
Conseil International pour l'Exploration de la Mer

International Council for the Exploration of the Sea
Conseil International pour l'Exploration de la Mer
H. C. Andersens Boulevard 44–46
DK-1553 Copenhagen V
Denmark
Telephone (+45) 33 38 67 00
Telefax (+45) 33 93 42 15
www.ices.dk
info@ices.dk

Recommended format for purposes of citation:

ICES. 2006. Incorporation of process information into stock–recruitment models. ICES Cooperative Research Report No. 282. 152 pp.

This document is a report of an Expert Group under the auspices of the International Council for the Exploration of the Sea and does not necessarily represent the view of the Council.

ISBN 87-7482-052-4

ISSN 1017-6195

Contents

Key points

The relationship between spawning stock and recruitment is fundamental to the scientific approach to fisheries management. Environmental factors can influence how one might manage a stock. However, there continues to be a real concern within ICES regarding the low rate of uptake of potential environmental indicators in stock assessment. It is unclear what variety of environmental information should be used and whether it would leave advice open to criticism for using speculative information. However, a debate is necessary, and it is hoped that this report will motivate such further discussion.

The key findings of this report are summarized in the following points:

- Although it is not possible to directly control factors such as sea temperature and wind, changes in the environment clearly influence recruitment and the future size of fish stocks. A better understanding of the relationships between environment, parental stock and recruitment should contribute to the design of robust management for commercial fisheries.
- Convincing incorporation of environmental factors involves a great deal of work, particularly in terms of fieldwork where mechanisms are being explored and in terms of long-term observations. Long-term studies are crucial to the success of this type of work. Progress should be viewed as an iterative process of improvements, and most benefits from such studies are likely to accrue after several years rather than a single year or less.
- There is benefit in long-term studies of the environment and underlying processes so that one is prepared if something unexpected happens.
- Marine systems are complex and care is needed not to focus too narrowly on a single aspect or species. Too narrow a focus could mean that crucial links or factors are missed. Mechanisms may also be flexible and change, depending on a whole suite of parameters.
- Considerations of environmental factors can make a difference in how one might manage a stock. Simulation models can play an important role in identifying whether and where benefits to management are most likely to accrue and where it would be best to focus attention in terms of other (e.g. process) studies.
- Correlative studies on their own are not enough. First, because interactions may be non-linear and, second, because correlations can be spurious. Correlative studies, however, can be used as pointers to where interactions could be expected.
- Short-term focused studies aimed at identifying likely mechanisms are crucial, but results from such studies can only be put to full use with information from longer-term observations.
- ICES' stock assessment working groups should consider reference points in light of apparent changes in environment. However, technical details, particularly regarding implementation (e.g. how to decide *when* to change from one set of reference points to another) have not been resolved yet and are unlikely to be so in the short term.

Finally, when reading this report, remember that its contents summarize work undertaken by an ICES expert group mainly during the years 1999 to 2002. One might criticize the material for being a little dated, but there remains a low rate of uptake of potential environmental indicators in stock assessment. In particular, the pioneering work done by ICES SGPRISM more than four years ago deserves wider exposure, and so the need for this report.

1 Introduction

1.1 The history of SGPRISM

In 1999, the ICES Oceanography Committee (OCC) supported the creation of an ICES expert group to investigate the separation of environmental influences from underlying stock–recruitment relationships. The ICES Study Group on the Incorporation of Process Information into Stock–Recruitment Models (SGPRISM) was formed and so 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 and techniques.

This *ICES Cooperative Research Report* represents a synthesis of the work from the three SGPRISM meetings, held in 1999, 2001, and 2002 (ICES, 2000, 2001, and 2002). The list of participants and their attendance appears in Section 12. The group's terms of reference (ToRs) appear in Annex 1.

The study group's first meeting (ICES, 2000) concentrated on such environmental issues as drivers of recruitment variability. The second meeting considered both possible environmental and biological causes of recruitment fluctuations (ICES, 2001). The third meeting (ICES, 2002) focused on developing modelling and stock assessment tools.

1.2 Scientific justification for the study group

The relationship between spawning stock and recruitment is fundamental to the scientific approach to fisheries management. Environmental factors can influence how a stock might be managed. Simulation models can play an important role in helping identify whether and where benefits to management are most likely to accrue and, therefore, which other studies (e.g. process) to focus on. The results of simulation studies should be used to guide future biological studies. Short-term focused studies aimed at identifying likely mechanisms are crucial, but results from such studies can only be put to full use with information from longer-term observations. Long-term studies of the environment and underlying processes also help in prepare for the unexpected. For example, if a process study revealed a strong relationship with some environmental variable, it would be possible to incorporate this immediately, if historical data are already available.

1.3 Structure of the report

For a given level of spawning-stock biomass, there is often considerable variation in recruitment. Frequently, this variation is attributed to environmental effects on survival. However, evidence is increasing that the age, size, and spatial structure of the spawning stock and the physiological condition of spawners can influence the number of surviving recruits (ICES, 2001).

Section 2 provides details on definitions of recruitment and identifies physical processes that are necessary to better understand and predict recruitment.

In Section 3, examples are presented of recruitment that has been placed in the context of specific stocks, their biological processes, relevant physical processes, and environmental drivers.

Section 4 reviews issues that might well be incorporated into medium-term recruitment forecasts, as well as approaches to quantifying the reproductive potential of individuals and stocks, building on the work of the NAFO Scientific Council Working Group on Reproductive Potential. Results from modelling the effects of environmental variability on North Sea cod are also presented here, with the investigation of model diagnostics and a temperature-induced characterization of the weight-at-age relationship. Data for North Sea plaice are examined in parallel in order to investigate systematic changes in condition factor. Section 4 also provides details on a number of area-based case studies that illustrate a sequential introduction of biological processes into estimates of stock biomass.

The potential impact of incorporating process studies and information about reference points for fishery management are reviewed and discussed in the context of the precautionary approach (PA) in Section 5.

In Section 6, numerical approaches to quantifying uncertainty in stock forecasts and results from the short-term population and fishery projections of anchovy in the Bay of Biscay are presented with a short-term prediction of recruitment in North Sea cod. Section 6 also gives details of the WGMTERM projection programme, which is used for medium-term projections within the ICES stock assessment framework. Results and discussion concerning medium-term projections of North Sea cod and projections incorporating STEREO output are examined here. Finally, population forecasting is discussed, and time-series characterizations of historical weights-at-age are presented for a selection of North Sea stocks. A model of spawning-stock structure in northeast Arctic cod is presented to investigate those components of the spawning population that have had the greatest influence on subsequent recruitment. The model was applied during the meetings of SGPRISM to North Sea cod and herring to ascertain its general applicability and the benefits of using it more widely.

Section 7 comprises a discussion about fisheries management, particularly, the significance, benefits, and disadvantages of incorporating environmental variables into management procedures.

Section 8 discusses the effect on North Sea cod of incorporating environmental variability (sea surface temperature) into Ricker stock–recruitment medium-term projections.

Section 9 consists of a general discussion about all three study group meetings.

Subsequent research, as well as the study group's relevance to similar activities within ICES and NAFO, are discussed briefly in Section 10. This is by no means exhaustive.

Finally, there continues to be a real concern within ICES regarding the low rate of uptake of potential environmental indicators in stock assessment, as highlighted by ICES WGRED (Rice and Rogers, 2006). It is unclear what kind of environmental information should be used and whether it would leave advice open to the criticism of using speculative information. However, a debate is necessary, and it is hoped that this report will motivate such further discussion.

1.4 Acknowledgements

The completion of this report was made possible by the scientific investigations undertaken by the participants who attended the three meetings of SGPRISM. There are too many to acknowledge individually, but a list of participants and their attendance appears in Section 12.

The writing of this report was only possible with financial funding from the UK's Department for Environment, Food, and Rural Affairs (Defra) through contract MF0427 (Population dynamics models of European cod stocks).

2 Background

This section provides details on definitions of recruitment and identifies the physical processes necessary to better understand and predict recruitment.

2.1 Definitions

2.1.1 Environmental factors

In the context of this study group, environmental factors were identified as those biotic and abiotic factors, other than fisheries, that have an impact on the fish population.

2.1.2 Recruitment from a biological perspective

In a biological–ecological context, the term recruitment must always be defined as a number of individuals in relation to the life stage being considered and the origin of the data. Examples might be:

- Numbers at age 1 derived from catch-at-age analysis;
- Numbers of settling larvae derived from time-series of surveys;
- Numbers entering the fishery derived from catch per unit of effort data;
- Numbers entering the spawning population derived from catch-at-age analysis and maturity data.

The term recruitment is usually used in the context of replacing reproductive potential of a nominal population.

Fisheries biologists frequently rely on recruitment data from assessments of stocks, based on management units. However, populations may occur across or within management units, and often, assessment estimates can only be used as proxies for actual population and recruitment levels.

2.1.3 Recruitment from a stock assessment perspective

In an assessment context, the term recruitment is defined as the number of fish estimated at the first age (or the youngest age class for which an index of abundance is available) in the exploitable population. As a result of selection effects by gear types and spatial coverage, the exploitable population may be a subset of the biological population with respect to age and/or spatial structure.

2.1.4 Spawning-stock biomass

Spawning-stock biomass (SSB) is not a biologically meaningful term *per se*. However, in a fisheries context, it is defined as the biomass (typically in tonnes) of mature females. It is usually derived by multiplying the age structure of the stock (derived from catch-at-age data) by a maturity ogive (derived from sampling programmes) and assuming a 1:1 sex ratio between males and females. As a rule, fisheries management attempts to maintain SSB above some predefined level, with the underlying biological assumption that SSB is a valid proxy for the realized reproductive output of a population in any year. This approach, however, may be flawed for several reasons, especially because: maturity ogives are not revised routinely; a 1:1 sex ratio may be inappropriate; spatial structure in the male and female populations may differ; eggs produced by younger fish may be less viable than eggs produced by older fish; and no account is taken of either atresia or interannual changes in condition that might affect reproductive output.

2.2 Oceanographic processes and their application to recruitment studies

The underlying and dominant mechanisms through which recruitment processes are influenced by fluctuations in the physical environment include both direct and indirect impacts. Heating or cooling or changes in the structure of the water column are known to alter physiological processes (e.g. growth, development, and other metabolic processes); turbulence is believed to influence the probability of encountering food particles; variations in circulation can transport larvae into environments of different suitability; changes in upwelling intensity can influence the dynamics of lower trophic levels by altering nutrient inputs. The underlying forcing of these fluctuations derives either from winds or from water density. As a result, the impact or change of one factor may well be correlated with that of others. How they interact must be understood when exploring relationships between recruitment and oceanographic conditions. It is essential to differentiate between exploratory analyses that generate hypotheses and those that develop understanding of the underlying processes within a region of interest.

Oceanographic information can consist of indices that reveal and integrate multiple processes that often reflect the influence of remote forcing over a broad geographic area, direct measurements that reflect measured variables on a local scale (i.e. the region of interest), or predicted elements (e.g. flux) generated from detailed models (e.g. circulation) of the area. Often indices are used instead of local observations or predictions because monitoring or knowledge at the local level is limited. However, it is essential to understand the uncertainty of indices in relation to local conditions because, under different settings, uncorrelated local environmental processes may overwhelm the influence of remote forcing on the physical dynamics of a system. The lack of knowledge of the level of uncertainty (large vs. local scale) is a likely contributor to the frequent breakdown in predictive ability of simple hindcasting models of environmental influence on recruitment fluctuations. When the basic processes operating on a local scale are not understood, the use of summary indices in predicting patterns of recruitment may lead, in fact, to greater inaccuracy in stock predictions.

Our ability to use environmental indices or variables in the stock assessment process depends on understanding and predictability. Environmental forecasting still uses shorter time scales than medium- and long-term stock forecasting. The issue is not necessarily to forecast the environment precisely, but rather to specify how the environment is likely to change in the medium term. In characterizing oceanographic variations, these basic questions must be addressed: whether variables or indices exhibit underlying periodicities (or levels of autocorrelation in both long and short terms); whether variations measured at single or multiple sites provide adequate representation of variations over a larger region.

Such an analysis was performed by Planque and Frédou (1999), who found anomalies in SST for areas corresponding to the population range of nine different cod stocks. This particular variable exhibited little significant autocorrelation beyond six months (Figures 2.2.1 and 2.2.2) suggesting that, for interannual projections, the pattern of variation in this oceanographic variable could be modelled as white noise. On the other hand, Sutton and Allen (1997) found significant decadal predictability of North Atlantic SST arising from advective propagation of anomalies and the existence of a regular period of 12–14 years in the propagating signals. This suggests that the forecasting horizon for SST might be much longer and therefore, that recruitment predictions may be carried out several years in advance. If this becomes possible, the benefits of including environment signals in assessment may extend from short-term to medium- or long-term projections. The behaviour of other variables must be addressed as well.

The analysis of oceanographic time-series, however, should consider issues dealing with the underlying latency (memory), which a variable should exhibit, as well as the uncertainty (error) in any local measurements as they relate to larger areas.

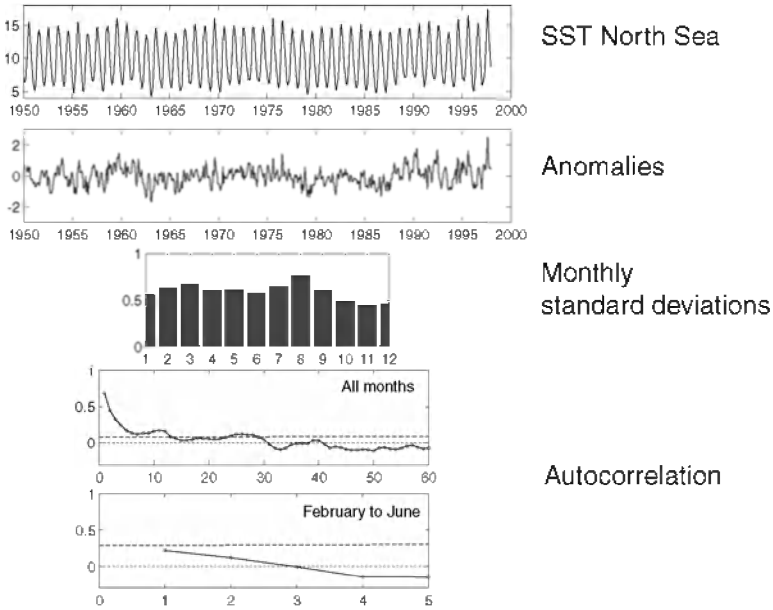


Figure 2.2.1. Analysis of North Sea SST derived from COADS. From top to bottom: time-series of monthly SST; time-series of monthly SST anomalies (departure from monthly mean); standard deviation of monthly temperature anomalies; autocorrelation function of the monthly anomalies time-series; autocorrelation function of the annual anomalies in temperature for the period February to June (used in the correlation with cod recruitment).

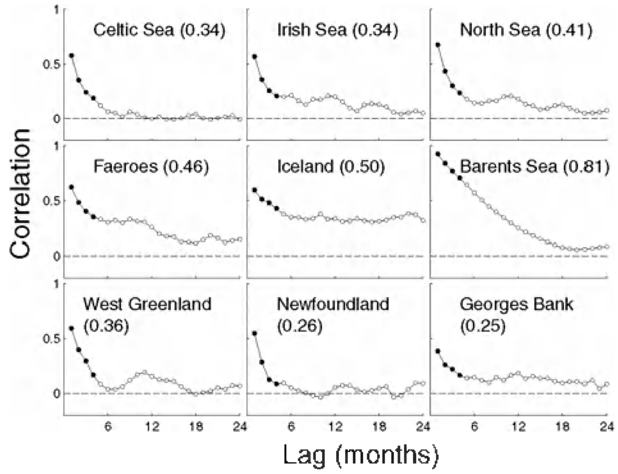


Figure 2.2.2. Autocorrelation function for monthly SST anomalies in nine areas of the North Atlantic margin. Values in brackets indicate the mean correlation values for lags 1–4 (closed circles).

There are methodological issues dealing with the estimation of environmental variables and indices (how it is applied to generate the measure of impact), as well as identifying the methods used to apply environmental data to stock projections. It is not uncommon to estimate the average oceanographic condition over a block of time or space as a significant measure of the environmental state. Inherent in the development of such a simple representation of regional condition is the level of uncertainty that will be included because of the spatial or temporal oversimplification associated with block averaging of oceanographic state. In addition, it is critical to assess the decision process detailing how the breadth of the window was established, as well as determining whether the mechanism through which the variable is acting represents a linear or a non-linear process. The response of currents or water column structure to variations in environmental forcing is generally not instantaneous. Because it is essential that environmental inputs to the assessment process reflect an understanding of the system dynamics, their estimation (and averaging) must also reflect the processes that they represent. These inputs can be based on simple representations of the influence of physical processes on population dynamics, or they can be based on more complex numerical simulations. In the second case, improving the quality of projections through more effective methods of data assimilation (or more realistic models of physical dynamics) must be pursued because such numerical tools, and their response to environmental forcing, are still in an early state of development.

The input of oceanographic data into stock projections (if there is an environmental link) should also reflect the structure of the time-series of oceanographic conditions. The simplest incorporation could restrict future environmental conditions using previously measured uncorrelated variability. This is only valid in instances when oceanographic conditions show no temporal structure. However, some physical processes exhibit a certain degree of system memory or long-term responses to large-scale forcing, as well as shorter-term responses to local conditions. When there is evidence of autocorrelation, various approaches (e.g. moving averages, ARIMA models, scenarios based on the Fourier series) should be developed to provide the range of stock projections.

Representation of oceanographic conditions must be developed with the same level of scrutiny as the biological data with which they are to be contrasted. It is essential to guard against misrepresenting some of the variability that may form part of the signal that influences biological processes.

2.3 Fishery management considerations

Changes in the environment—physical, physiological, and ecological factors—have major effects on fish population dynamics. Fishery managers by and large cannot control the physical environment; however, they can influence the nature and intensity of fishing practices. The challenge for fishery management is to devise and test strategies for controlling fishing that meet conservation and socio-economic objectives as far as possible.

A management strategy has scientific as well as political aspects; the scientific aspects include the assessment strategy. Some aspects, such as technical measures, are not particularly affected by environmental factors. However, choosing an assessment strategy within the current ICES framework entails decisions on a number of issues to which the environment is potentially relevant:

- Appropriate stock structure;
- Assessment technique;
- Fitting of stock–recruitment relationship;
- Single-species reference point calculations;
- Medium-term projection;
- Method for advising on TACs (linked to reference points).

What are the scientific criteria for deciding how to deal with the above? A good management/assessment strategy must cope with the possible effect of the environment on fish populations and the inherent uncertainty about these effects. This does not mean that successful strategies always have to be complicated. For some stocks, it will be worth using a more complex model; for others; it won’t. Although *optimal* strategies are nice, it is more important to be robust. A good robust management strategy should not perform disastrously (or disastrously worse than any other single strategy) under a range of plausible environmental relationships, population dynamics, and future conditions.

In order to decide whether and how to include environmental information, we need a way to check robustness and general performance of different assessment strategies, under a range of plausible future scenarios. Even a simple strategy needs to be tested under realistically complex simulation models to guarantee its robustness. In such simulations, it is neither necessary nor even desirable to have a unique and definite idea about how the environment affects recruitment; it is more important to be realistic about the range of possible effects that might occur. Of course, as more becomes known about environmental links to recruitment and about the likely future state of the environment conditions, it becomes possible to exclude certain scenarios. In principle, this allows tuning of a management strategy to deliver higher yields, more stable catches, etc., while keeping conservation risks low. Strategy testing is a key area where scientists and managers should try to consider all available information about environmental effects on recruitment.

3 Applications and investigations

The task of relating recruitment to the environment is difficult. However, there is a long history of trying to identify links, many without a precise understanding of underlying processes.

3.1 The difficult task of relating recruitment to environment

Analysis of historical data is one way of connecting environmental fluctuations to changes in recruitment. This has been done, mostly in the form of correlations, for a number of stocks and a number of environmental indices. However, when performing such analysis, there are difficulties that can be categorized in three groups:

1) **Type II errors: A link does exist, but the statistical analyses are not conclusive.**

   This arises from the characteristics of recruitment and environmental time-series. The series are often too short for the analysis to be statistically powerful (even 30 years of data is little by statistical standards), and the level of uncertainty on both types of data is high, which further reduces the power of the analysis. This type of error is rarely considered explicitly.

2) **Type I errors: The link detected is spurious.**

   Exploratory analyses and autocorrelation are the two main sources of type I errors. Exploratory analyses, by increasing the number of potential links explored, also increase the number of spurious links detected. For example, when comparing ten environmental indices with ten recruitment series, there is a risk of identifying five spurious correlations at the $\alpha = 5\%$ level. These comparisons, if not done in a single exercise, will inevitably be carried out because different researchers will look for different links. Because non-significant relationships are rarely reported in the literature, the exploratory analysis error will rarely be detected. Autocorrelated time-series are by definition non-random, and the true number of degrees-of-freedom (df) is lower than the usual assumption of n-2. Ignoring the autocorrelation leads to bias in estimates of α and a higher risk in detecting spurious correlation. Accounting for autocorrelation usually reduces the power of the analysis (Type II error).

3) **Causality errors.**

   Even when Type I and II errors are accounted for, the link detected remains only a statistical link until a mechanistic understanding can be suggested and tested. There are a number of situations in which strong correlations can be driven by non-causal links (e.g. if the environmental index is correlated with the *true* environmental forcing).

Sometimes Type I and II errors can be accounted for by increasing time-series length, by performing meta-analysis, by increasing the accuracy of the variables measured, by correcting for autocorrelation, or by testing *a priori* hypotheses rather than performing exploratory analysis. Causality errors can only be accounted for if experimental investigations and/or fieldwork are carried out.

3.2 Stock–recruitment relationships of Baltic cod, incorporating environmental variability and spatial heterogeneity

Stock–recruitment relationships of central Baltic cod are constructed for different ICES subdivisions containing spawning areas with distinct hydrographic regimes, recruitment success, and stock development trends (Köster *et al.*, 1999). In the central Baltic, which can be considered as a semi-closed system, there is evidence of a relationship between spawning-stock biomass and recruitment of cod (Plikshs *et al.*, 1993; Sparholt, 1996). However, this relationship is sensitive to environmental conditions and trophic interactions (Jarre-Teichmann *et al.*, 2000). Low oxygen concentrations at cod spawning sites (Nissling, 1994; Wieland *et al.*, 1994), cannibalism on juvenile cod (Sparholt, 1994), as well as clupeid predation on cod eggs (Köster and Schnack, 1994) are important determinants of recruitment.

Using a statistical analysis based upon a forward selection of covariates in a multiple regression, variables identified as having significant influence on reproductive success are incorporated into modified stock–recruitment models for single subareas and utilized to establish a combined model for the entire central Baltic.

The statistical model obtained for predicting recruitment-at-age 0 in Subdivision 25, based on the potential egg production by the spawning stock, explained 69% of the variance. Besides the egg production, corrected for egg predation by clupeids, the oxygen content in the reproductive water volume was introduced as a statistically significant variable, as well as the larval transport index (Hinrichsen *et al.*, 2001) as being statistically nearly significant. In the more eastern spawning areas (Subdivisions 26 and 28), the hydrographic regime in general did not allow successful egg development in the period 1981–92. Thus, only relatively simple models, based on the egg production by the spawning stock and the reproductive volume, are required to achieve a reasonable explanation of recruitment variability. The predation mortality of 0-group cod resulting from cannibalism, as determined by MSVPA, is positively linear related to the spawning-stock biomass. This significant relationship was used to predict the recruitment-at-age 1 from the number of recruits surviving until age 0. Combining the area-specific recruitment estimates observed against predicted recruitment revealed an overall good agreement (Figure 3.2.1, reproduced from Figure 15 in Köster *et al.*, 1999).

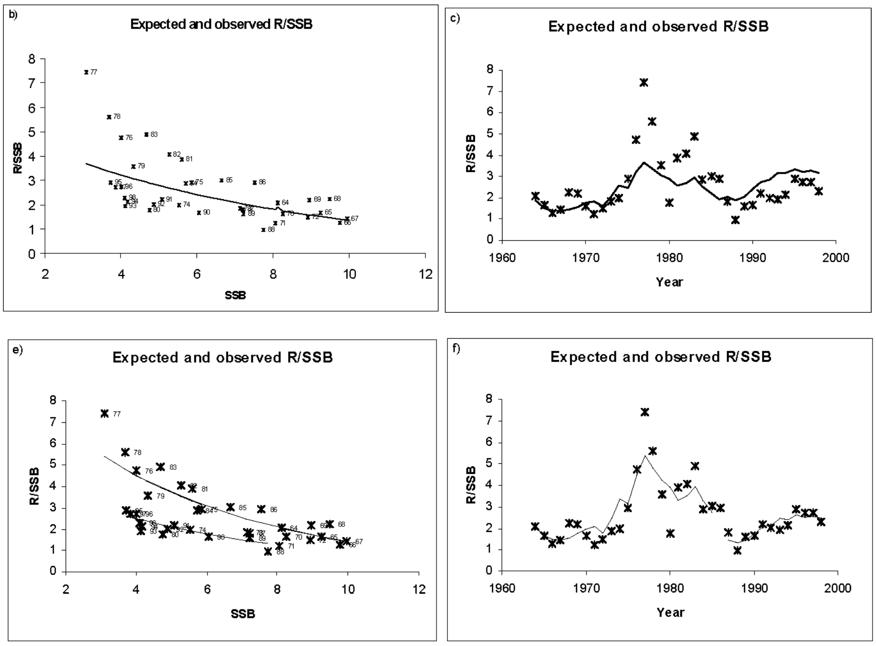


Figure 3.2.1. Observed vs. predicted recruitment of eastern Baltic cod at age 0 (upper graphs) and age 1 (lower graphs) in the combined Subdivisions 25, 26, and 28, based on egg production by SSB, environmental factors (reproductive volume, larval transport index), and species interaction (egg predation by clupeids and cannibalism on 0-group).

To obtain an indication of the sensitivity of the parameter estimates and the predictive power of the established statistical models, refitting of the models over different shorter periods utilizing subsets of the data series was conducted. The exercise demonstrated that the models derived for the different subdivisions are able to capture the trend of decreasing recruitment success during the 1980s and the increase in the early 1990s, though they overestimated recruitment in most recent years and regularly underestimated recruitment in early years to a certain extent. If, however, all years with maximum observed recruitment were excluded from the model fitting, the deviations between observed and predicted recruitment were considerably higher.

The statistical stock–recruitment models explain a considerable part of the variability encountered in recruitment at age 0 and age 1. However, this does not mean that the models are able to predict recruitment in a given year very precisely. The model approach is still preliminary because input data series are currently in the process of being validated. Furthermore, processes potentially affecting reproductive success have not been included in the analyses, e.g. fertilization in relation to salinity (Westin and Nissling, 1991), egg and larval viability in relation to parental conditions and stock structure (Nissling *et al.*, 1998), contamination by toxic substances (Petersen *et al.*, 1997), and a potential starvation of larvae owing to a shortage in suitable food supply (Grønkjær *et al.*, 1995) or limited capture success in relation to turbulence conditions (MacKenzie and Kiørboe, 1995).

3.3 Case studies of the departure of stock and recruitment observations from standard two-dimensional functional models

Three case studies were presented in which observed recruitment showed systematic departures from the predictions resulting from a parametric stock and recruitment model. The studies highlight areas of research that could improve understanding of environmental effects on recruitment to fish stocks. In turn, such studies should reduce the influence of noise or bias introduced into the management procedure through the use of reference points derived from inappropriate stock and recruitment models and predictions made from them.

In each case study, environmentally induced variations in the productivity of a stock were examined by following the development of the number of recruits (R) to the fishery produced by a unit weight of SSB. In the standard stock and recruitment models such as Ricker or Beverton and Holt, the number of recruits per unit of spawning-stock size (R/SSB) is a continuously decreasing function with increasing stock size. Plots of R/SSB against SSB are compared with predictions from the standard stock and recruitment models to find departures from this relationship. As a further diagnostic, time-series of the observed values of R/SSB were examined to establish the degree of correlation between the departures from the expected model estimates and environmental variables.

3.3.1 Annual variation in the environment

Planque and Frédou (1999) used meta-analysis of the North Sea, Irish Sea, and Celtic Sea cod stocks to show that, for cod, there is a decreased probability of good recruitment associated with warm sea temperatures. Their models did not include the conditioning response of the level of spawning-stock biomass. This can be investigated by examining the correlation between sea temperature and the residuals from observed and expected R/SSB, or by fitting a modified form of the Ricker curve.

Two example cases of Irish Sea cod and plaice were presented. The former is discussed next, and the latter will be discussed in Section 3.3.2.

Irish Sea cod

The stock and recruitment data pairs and the diagnostic plots of R/SSB calculated for the Irish Sea cod (ICES, 1999) assessment estimates are presented in Figure 3.3.1.1a–d. The time-series of modelled R/SSB residuals are plotted against the mean sea surface temperature, recorded during the first half of the year in Figure 3.3.1.1e. The correlation is significant at the 5% level. When a temperature effect is fitted within a modified Ricker model as a generalized linear model, the temperature effect is significant at the 1% level of probability. The predicted recruitments are given in Figure 3.3.1.1f. Although the mechanism linking temperature to the productivity as measured by R/SSB remains unclear, there is a change in reproductive success in response to temperature at all levels of spawning stock abundance. For Irish Sea cod, the level of recruitment is influenced by environment, conditional on the level of SSB.

3.3.2 Longer-term level changes

Irish Sea plaice

Figure 3.3.2.1 illustrates a change in the estimated productivity of the Irish Sea plaice stock. The recruitments observed in recent years are lower than would be predicted from a stock and recruitment relationship fitted to complete the time-series (Figure 3.3.2.1a). When plotted against the values expected from the Ricker curve (Figure 3.3.2.1b and c), the temporal changes in the level of recruitment at a given stock size show that, after 1987, there has been a decrease in the estimated rate of production of recruits. This can be illustrated by fitting two Ricker models to the data for the periods 1964–1986 and 1987–1998, as shown in Figure 3.3.2.1d–f.

The change in the level of the stock's productivity could result from changes in environmental conditions or could be induced by changes in the level of hidden mortality (such as misreporting or discarding). The latter could only induce changes in the R/SSB ratio if the mortality rate varied with age, e.g. discarding rates on juveniles but not adults.

If changes in the productivity of the stock are environmentally driven, the consequences for management using reference points derived from models of the stock and recruitment should also be reviewed. The slope at the origin, used to calculate fishing mortality reference points such as F_{crash}, is overestimated using models fitted to the early data period or the complete time-series.

3.3.3 Stock–recruitment models that do not capture the stock dynamics

Figures 3.3.3.1a, b, and c present the stock and recruitment plots for the cod assessment in the NAFO region 3NO. This stock has shown a severe reduction in the estimated stock size and recruitment over time, with only one period that would be adequately modelled by a standard parametric stock–recruitment curve. Even at the high biomass estimated for 1983, recruitment showed a sudden and severe decline with no subsequent recovery, an observation that would not be predicted by a simple recruitment model.

The stock is part of a complex of cod stocks that have been subject to a melange of high fishing mortality rates and possible increases in predation, changes in food distribution and abundance, and strong environmental perturbations. The linkage of recruitment to SSB is weaker than that discussed in the previous examples. The system presents an example of a stock in which production may be controlled by environmental forcing and for which alternative models of recruitment processes are required.

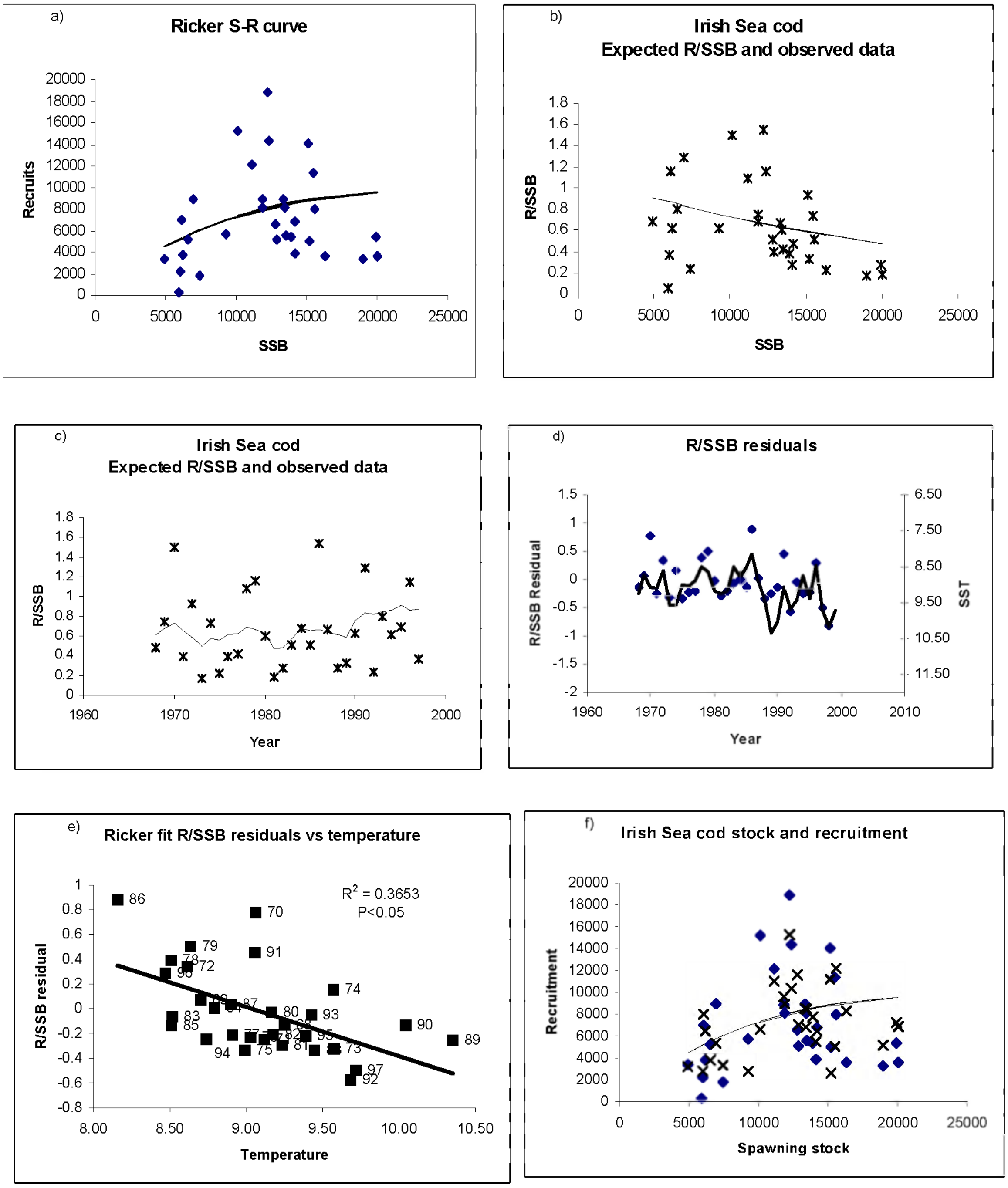


Figure 3.3.3.1. The relationship between the recruits produced per tonne of Irish Sea cod spawning-stock biomass and sea surface temperature.

(a) A Ricker stock and recruitment curve fitted to the data pairs resulting from an assessment.

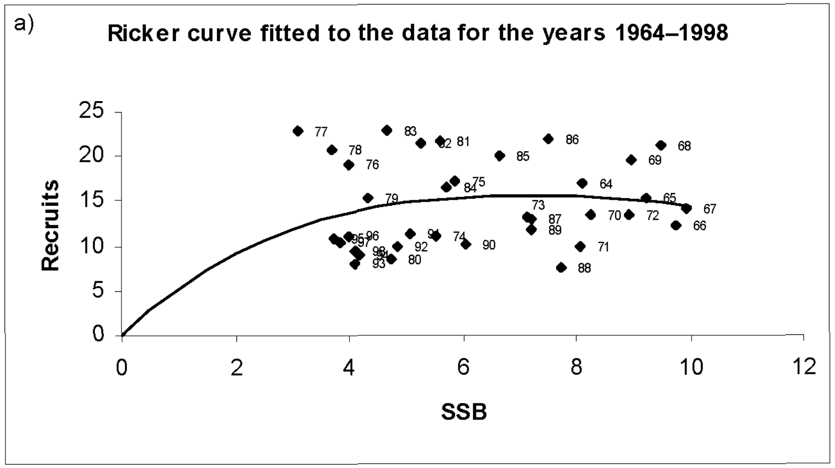
(b) The expected and observed relationship between R/SSB and SSB.

(c) Changes in the R/SSB during the time-series of the assessment.

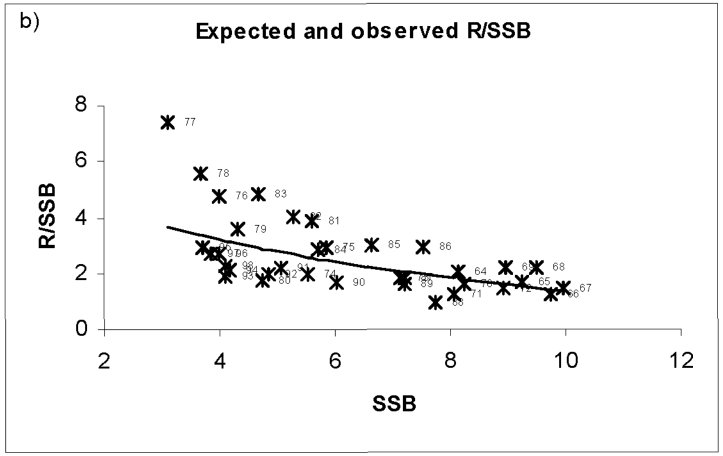
(d) The time-series of residuals of R/SSB; namely, observed values minus the values expected from the fitted Ricker model.

(e) A plot of the residuals of R/SSB against average sea surface temperature recorded in the first half of the year.

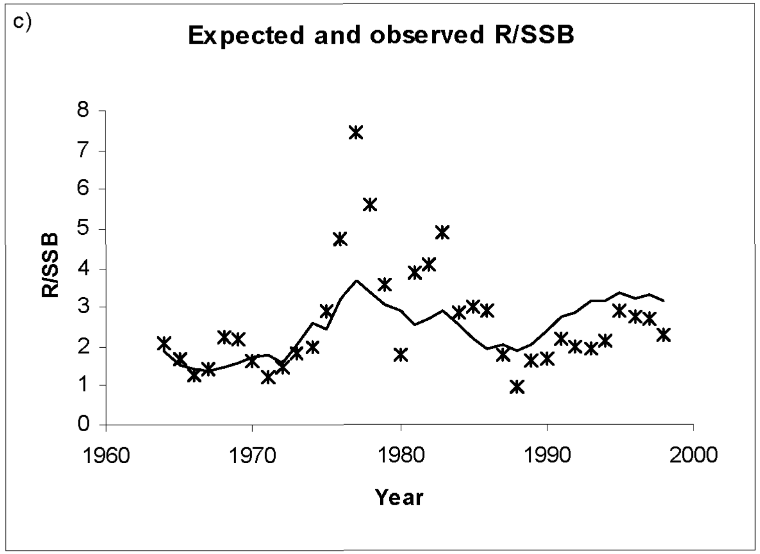
(f) The estimates of recruitment generated by fitting Ricker stock and recruitment with (crosses) and without (solid line) a temperature effect.


a)

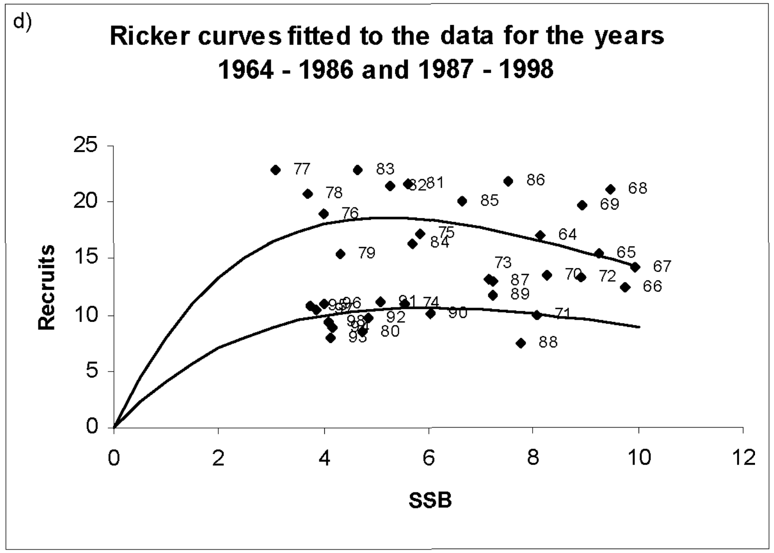
Ricker curve fitted to the data for the years 1964–1998


b)

Expected and observed R/SSB


c)

Expected and observed R/SSB


d)

Ricker curves fitted to the data for the years 1964 - 1986 and 1987 - 1998

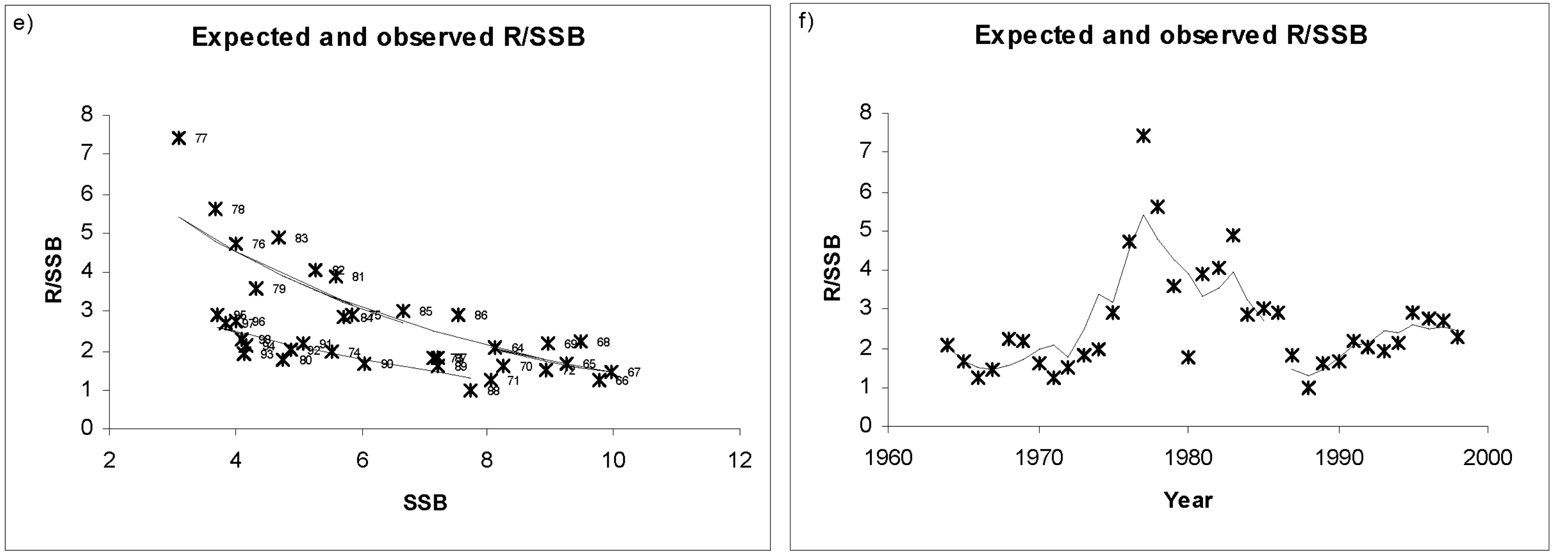


Figure 3.3.2.1. Diagnostic plots of the stock and recruitment time-series for Irish Sea plaice.

(a) The stock and recruit data pairs with a Ricker model fitted to all the data points.

(b) The expected and observed relationship between R/SSB and SSB.

(c) The time-series of R/SSB for the single Ricker curve.

(d) Ricker models fitted to the data points for 1964–1986 and 1987–1998.

(e) R/SSB plotted against SSB with the predictions from two Ricker curves.

(f) The time-series of R/SSB for the two Ricker curves.

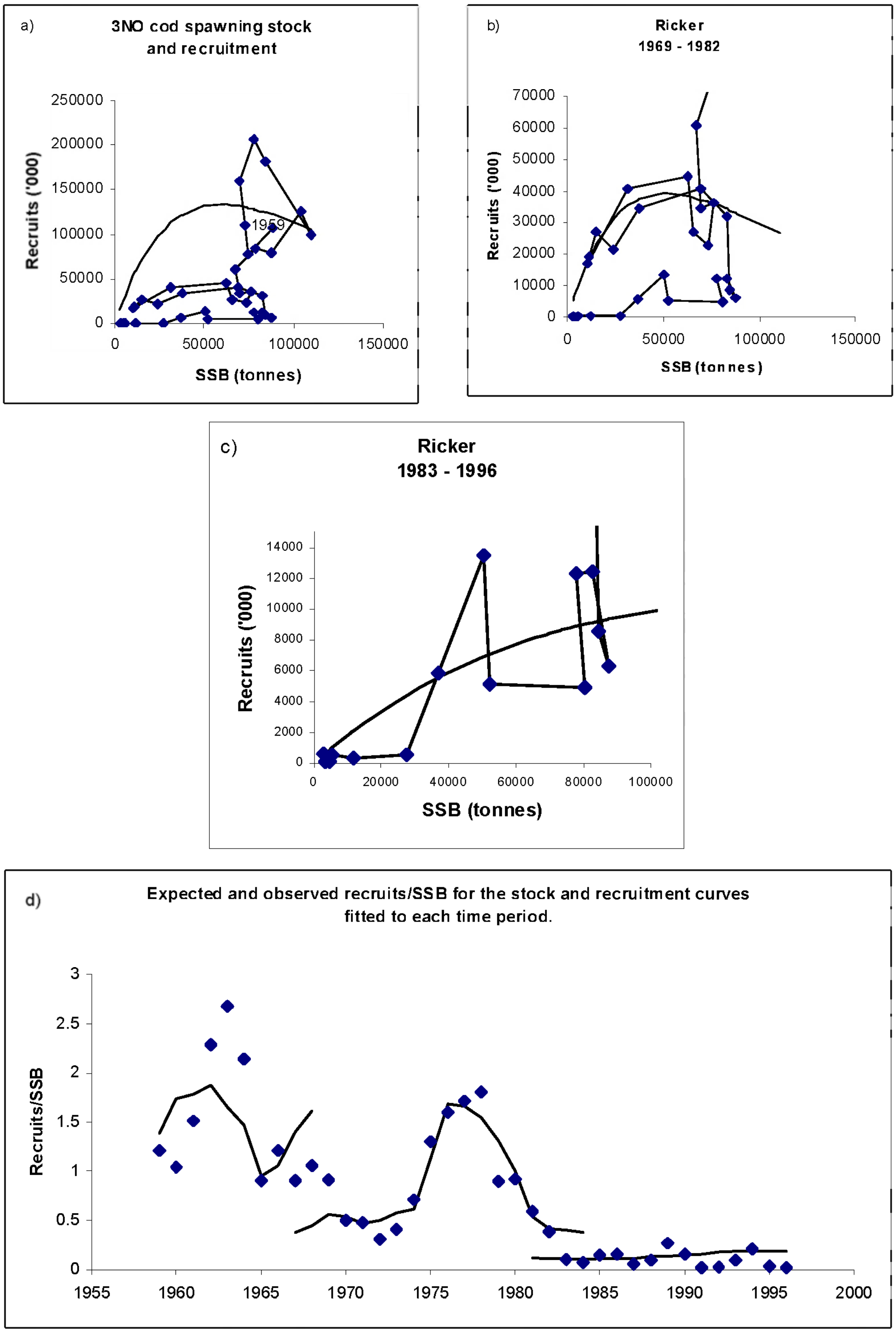


Figure 3.3.3.1. NAFO region 3NO cod trajectories of spawning stock and recruitment.

(a, b, c) The stock and recruitment pairs and fitted Ricker models.

(d) The reconstructed time-series of R/SSB and the expected values from the Ricker models.

3.4 Recruitment and physical processes in Irish Sea herring

The assessment of Irish Sea herring is imprecise compared with many other herring stocks (ICES, 1999a). The series of tuning indices are short, and there is uncertainty about the level of misreporting of catches. Indices of recruitment have been collected since 1992; however, there are problems in discerning the origin of pre-recruits in the Irish Sea because it is a nursery ground for Irish Sea, Celtic Sea, and some Clyde herring (ICES, 1994). The stock of herring in the Irish Sea is smaller than that in the Celtic Sea, and both exhibited similar trends in recruitment during the 1970s and 1980s (Figure 3.4.1). The spawning season for Irish Sea herring runs from mid-September to late October, although in recent years, Celtic Sea herring spawn in January and February.

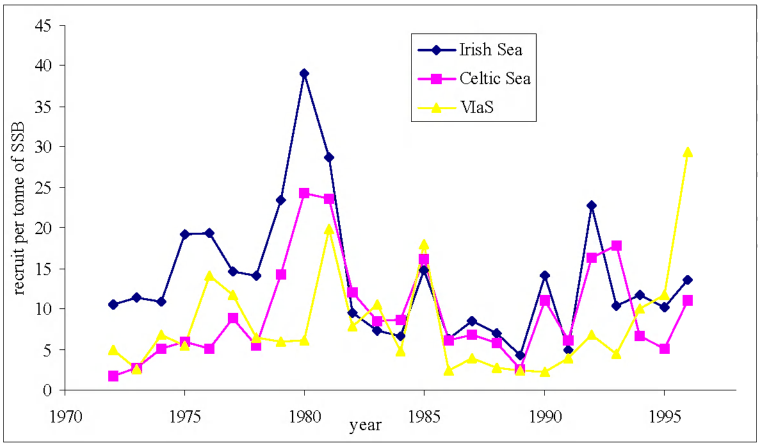


Figure 3.4.1. Trends in recruitment of Irish Sea, Celtic Sea, and VIaS herring stocks from 1972 to 1997.

The interannual differences in lengths of 0-group herring in the Irish Sea were investigated using a time-series of groundfish surveys from autumn 1992 to autumn 1999. It is thought that 0-group herring in the eastern Irish Sea are primarily from Irish Sea spawning sites, while fish in the west are from a mixture of Irish Sea and Celtic Sea sites (Bowers, 1980; Dickey-Collas, 1999). It was hoped that the differing spawning times might result in detectable differences in the modes of length of the juvenile herring. The herring in certain years (e.g. 1993 and 1997) showed similar length distributions in the eastern and western Irish Sea. However, in other years (e.g. 1992 and 1996), the herring were of different lengths. Apart from 1994 and 1995, the eastern herring had a mean length of approximately 112 mm, while the mean length of herring in the western Irish Sea varied greatly (Figure 3.4.2).

The difference in the size of herring between years in the western Irish Sea could indicate years with more Celtic Sea herring in the region. It may be possible to use the difference in mean length between the eastern and western Irish Sea as an index of the abundance of Celtic Sea fish in the region. This hypothesis needs testing, and work continues on the origin of juveniles, using primary increment analysis and the chemical composition of otoliths (Brophy, University College Dublin, pers. com.). An annual estimate of the abundance of 0-group Celtic Sea herring in the Irish Sea would be used by the ICES Herring Assessment Working Group to improve the recruitment indices of Irish Sea herring.

The difference in length may be caused by differing temperatures in the eastern and western Irish Sea. The temperature differences required to create populations with lengths that differ by 25% after nine months of growth are likely to be large and are unlikely to vary so greatly between years and areas. There are few data available on the temperature differences across the Irish Sea, and this needs further investigation.

What would cause a greater abundance of Celtic Sea juveniles in the western Irish Sea in some years? Initial investigations with *real wind*-driven particle-tracking models suggest that, in certain years, large wind events in February may force particles from the Celtic Sea to the west of the Irish Sea within 30 days. It is likely that this physical forcing depends on individual wind events, which may not be detected by models using mean winds. Work is being proposed to investigate the interannual variability in wind-driven transport between the two seas.

It is clear that these initial hypotheses require much testing. The current assumption is that the differences in length between juveniles in the eastern and western Irish Sea represent differences in their origin. That is, smaller fish are spawned in the Celtic Sea and larger fish in the Irish Sea. The length of fish in October varies between years and between regions (e.g. eastern and western Irish Sea, Figure 3.4.3), suggesting that the origins of the fish vary between years. This may depend on transport events between the Seas during the first three months of every year. The difference in size of juvenile (mean length in east minus mean length in west) appears to correlate with the assessment-derived recruitment strengths for Irish Sea herring (age 1). This suggests that, in years with more Celtic Sea herring, i.e. with greater transport and smaller juveniles in the west, the recruitment of Irish Sea herring is lower (Figure 3.4.3). It further suggests that there is a physical component to the determination of year-class strength in Irish Sea herring.

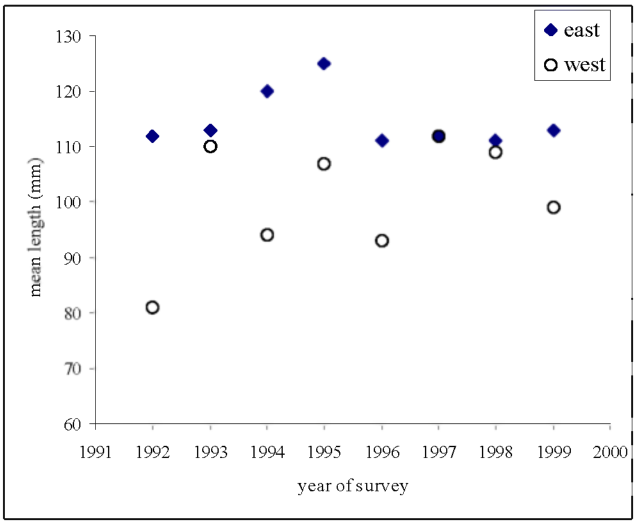


Figure 3.4.2. Mean length of 0-group herring from surveys in autumn 1992 to 1999 in the eastern and western Irish Sea.

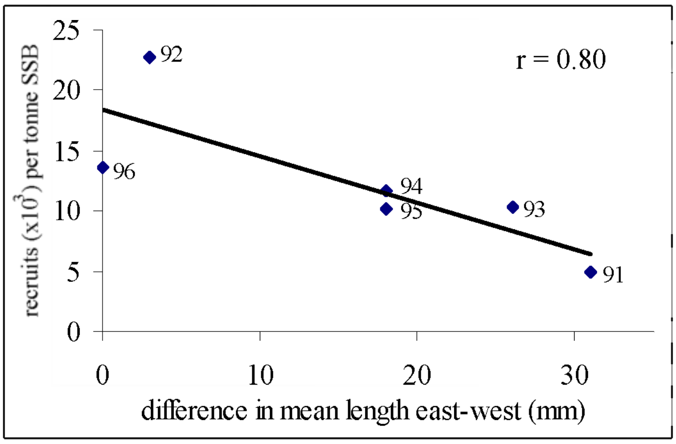


Figure 3.4.3. The number of recruits per tonne of SSB over the difference in length of juvenile herring in the eastern and western Irish Sea for year classes 1991–1996. The difference in length is assumed to represent an index of the abundance of Celtic Sea fish in the Irish Sea relative to Irish Sea spawned fish. The numbers next to each point denote the year class of herring.

3.5 Oceanographic processes

Often for management purposes, simplistic circulation maps of the shelf seas are used to explain contaminant dynamics and factors determining fisheries recruitment. These representations were synthesized from the observational and modelling work of the last century and suggest an apparently weak yet coherent circulation pattern. Such a view runs counter to a significant body of work revealing shelf seas circulation to be dominated by tides and short-term (wind) events. More recent work demonstrates that seasonal stratification plays a crucial role in determining the transport pathways.

The physics of the European shelf seas is dominated by tides and wind. Most evident is the diurnal (twice-daily) movement of water with typical maximum velocities of between 30 and 150 cm s^{-1}, depending on location. However, except for local tidal residuals near headlands, for example, tidal residual transport is weak.

At time scales of several days, meteorologically induced flow resulting from depressions, for example, may have a dramatic effect on the transport of material. However, such events are inherently unpredictable and incoherent, although the long-term mean circulation is often said to be driven by the cumulative effects of such events. Largely based on tracer budgets, the net long-term circulation has been characterized as weak at speeds of typically 1–2 cm s^{-1}.

Direct measurement of the water column's response to wind is expensive, and there are problems in maintaining an array of equipment. However, data used in conjunction with realistic models provides valuable insight into processes determining the movement of particles. For example (Young *et al.*, 2000), periodic strong wind events may cause significant flushing of regions such as the Irish Sea. An event lasting two days in February 1994 removed 8% of the volume of the Irish Sea through the North Channel. Combined with the series of depressions in that month, approximately 25% of the volume of the Irish Sea was removed, roughly 4–5 times the typical long-term mean. Such big events would appear to have the potential to import/export significant quantities of eggs, larvae, and juveniles.

In such simulations, models must be rigorously tested against observations, be of sufficient resolution, and must include proper dynamic windfields, adequate bathymetry, and correct physics.

Not surprisingly, large or persistent (in direction) wind events provide the most notable anomalies in terms of movement of eggs, larvae, and juveniles from spawning and settlement sites. Demonstrating that average conditions play a significant role in determining recruitment is likely to be difficult. As with temperature effects, anomalously cold winters may play a significant role in determining recruitment or mortality in many stocks, but detecting a discernible correlation with minor or localized temperature changes is difficult. Consequently, it is the consideration of extreme events that are most likely to play a role in guiding the estimates of recruitment.

Stratification

During summer (May to October), large areas of the shelf seas stratify where tidal currents are too weak to provide sufficient energy to maintain a mixed water column against solar heat input. In other generally shallow areas, the water column remains mixed. At the boundaries between the mixed and stratified water, there exist strong (>20 cm s^{-1}), persistent jet-like flows (e.g. Dickey-Collas *et al.*, 1997; Horsburgh *et al.*, 1998; Brown *et al.*, 1999; Hill *et al.*, 1996). The systems play a strong role in the rapid advection of material, but in some cases may act as retention mechanisms or barriers to exchange between water masses. Generally, the formation of stratification begins in April/May when there are significant concentrations of larvae and juveniles in the water column. The timing is governed by the degree of freshwater input and levels of wind mixing. Delayed or early stratification relative to spawning may play an important role in larval–juvenile survival in terms of transport to nursery grounds or by advancing/delaying primary production. Given that such features have probably existed since the last ice age, it would be surprising if they did not play some role in the life histories of at least some species.

Currently, models of the European shelf seas do not accurately replicate such features. Additionally, the influence of salinity is difficult to include. It will be some time, at least 5–10 years, before a truly convincing operational model exists.

In terms of oceanographic influences on fisheries production, it is likely that the more unusual events will be detectable. The prediction of the influence of global warming on physical forcing remains speculative, particularly given the noise inherent in the weather.

3.6 Anchovy recruitment and environment in the Bay of Biscay

The Bay of Biscay anchovy is a short-living species (typically, three years), in which recruitment plays a major role in determining year-to-year changes in the level of the stock. Its spawning in the Bay of Biscay occurs during the spring/summer, mainly from April to July. The population spawns in areas where increased biological production can occur (Motos *et al.*, 1996)—in river plumes, at shelf break fronts, and in oceanic gyres. In general, spawning is limited to the French and Spanish coasts (south of 46°30'N and east of 05°00'W). Anchovy eggs and larvae develop from April to August. After metamorphosis, anchovy juveniles occur 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 northeasterly 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. These authors identified the major oceanographic events originating in northeasterly winds that probably cause enhancement of the surviving of larvae and early juveniles 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 increases subsurface chlorophyll and general productivity in the area. The joint effect is a weak upwelling, stability, and shallow but pronounced stratification, all of which match well with the ideas of Lasker (1978), Bakun and Parrish (1982), and Roy (1993), among 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 because of the enrichment associated with the areas. The expansion of these areas supposes an expansion of the natural spawning habitats and of the enrichment influence of the rivers. In addition, eggs and larvae will gradually disperse in that rich environment and be less subject to massive predation.

On the contrary, the northwesterly 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 during spawning periods or for the whole year was initially found to be significant by Borja *et al.* (1996), but was finally rejected as statistically significant in their most recent revision (Borja *et al.*, 1998). The explanatory power of that variable has always been placed at the boundary between significance and insignificance.

The northeasterly wind conditions in the Bay of Biscay are summarized in an upwelling index calculated from March to July of every year (Borja *et al.*, 1998). Figure 3.6.1 summarizes the relationship between upwelling index and recruitment estimates from direct DEPM surveys and the assessment performed in 1999 (ICES, 2000a). The upwelling index explains about 60% of the interannual variability of recruitment, without considering any stock–recruitment relationship.

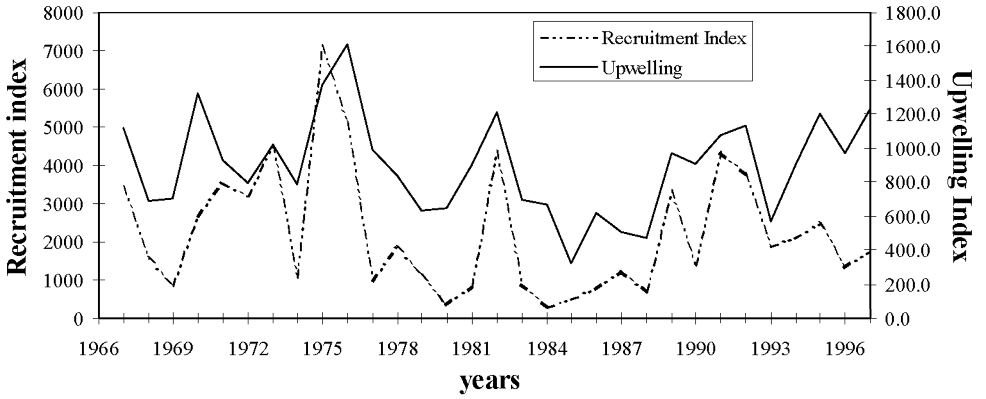


Figure 3.6.1. A summary of the relationship between the upwelling index and recruitment estimates from direct DEPM surveys (ICES, 2000a).

Allain *et al.* (1999) improved the previous estimate on the relationship between wind and recruitment for the period 1987–1996 by simulating the oceanographic processes that are expected to be directly linked to the life history of larvae. This was made by a three-dimensional hydrodynamic physical model (IFREMER, Brest) that simulates processes occurring over the Biscay French continental shelf. Two of these variables were retained by the authors and seem to explain about 75–80% of the recruitment interannual variability between 1987 and 1996. These variables in order of importance are:

- An upwelling index that corresponds to the sum of mean weekly vertical currents from bottom to surface during the period March–July along the Landes coast (southwest of France). These upwelling events are caused by the moderate and intermittent northeasterly winds.
- Destratification or high turbulence index. This is a binary variable describing stratification breakdown events in June–July concerning the waters above the whole continental shelf. This phenomenon links to strong westerly winds (>15 m s^{-1}) that can cause important larvae mortality just after peak spawning.

These modelled environmental variables are not yet operative in real time to predict next year's recruitment, although for the next year they could be obtained in a real-time operative fashion. The Working Group on the Assessment of Mackerel, Horse Mackerel, Sardine and Anchovy (ICES, 2000a) implemented the upwelling index of Borja *et al.* (1996, 1998), attempting to improve the next year's forecast of the fishery and population.

3.6.1 SPACC/IOC study groups

Currently, the low accuracy of environmental indices as recruitment predictors makes it impossible to estimate population abundance one year in advance (ICES, 2000a, 2001, 2002b). Therefore, these indices will not be used to provide forecast advice to managers until better predictive power of the environmental stock–recruitment models is achieved. At a meeting of the SPACC/IOC Study Group on the Use of Environmental Indices in the Management of Pelagic Populations (Cape Town, South Africa, 3–5 September 2001), it was proposed that a simulation analysis be conducted to evaluate the benefits of using environmentally linked recruitment predictors in the management of anchovy stocks. This work was conducted in 2002, and the results are pertinent to ICES.

3.7 Temperature and cod recruitment

The following paragraph summarizes of the paper by Planque and Frédou (1999), where the interested reader can find further details.

The relationship between interannual changes in temperature and variation in recruitment for nine cod stocks in the North Atlantic was examined. This study attempted to reduce the statistical errors of Types I and II (Section 3.1) by performing non-exploratory meta-analysis and correcting for autocorrelation bias. For stocks taken individually, the relationship often appears weak and statistically insignificant, but the meta-analysis demonstrates that recruitment of Atlantic cod is linked to interannual fluctuations in temperature in such a way that, for stocks located in warm water, the relationship is negative, for stocks located in cold water, the relationship is positive, and there is no relationship for stocks located in the middle of the temperature range. In this analysis, the northern cod stock (2J3KL) appears as an outlier, probably because the assumptions underlying the analysis (e.g. coherent and persistent patterns in temperature) are not met within the area of distribution of the stock. The North Sea, Irish Sea, and Celtic Sea cod stocks, situated at the warmer end of the species temperature range, show negative relationships with temperature, so that an increase in 1°C is associated with an average twofold decrease in the recruitment level.

3.8 Synchrony in the recruitment time-series of plaice (*Pleuronectes platessa* L.) around the UK and the influence of sea temperature

Historical time-series of recruitment to plaice stocks around the United Kingdom were examined for evidence of synchrony. Our results reject the null hypothesis (no synchrony) for most stock pairs. Levels of significance are highest for recruit series derived from adjacent pairs of management areas (e.g. North Sea and Eastern Channel), but are also significant between widely separated areas (e.g. North Sea and Irish Sea). Tests of synchrony are highly significant using a meta-analysis test applied over all the stocks. Synchrony between stocks might arise through population exchange or because of a large-scale forcing operating over the whole region. Population exchange between adjacent plaice stocks is known to occur; tagging returns have indicated that 38–53% of the Channel plaice stock is derived from fish spawned in the North Sea (ICES, 1992). There is, however, no evidence that more widely separated stocks (such as North Sea and Irish Sea) are linked in this manner. Evidence of synchrony between population dynamics of isolated stocks, therefore, suggests environmental forcing operating over a similar geographical scale. An obvious candidate for an environmental variable is sea temperature, which displays a high level of spatial autocorrelation on the scale of the western European shelf.

Although the average sea surface temperature for areas corresponding to the different plaice stocks varies, the pattern in interannual temperature fluctuations is similar. Temperature anomalies, therefore, may affect a region considerably larger than the southern North Sea. When we examined the correlation between sea surface temperature and plaice recruitment, we found statistically significant negative relationships for all areas. Based primarily upon data for the North Sea plaice stock, several authors have suggested that an inverse relationship might exist between sea temperature (during the time of early life) and subsequent year-class strength (Bannister *et al.*, 1974; van der Veer *et al.*, 1990). However, such correlations between recruitment and environmental variables have often broken down over time. Myers (1998) states that it is necessary to retest such relationships using independent data. Such an exercise has recently been undertaken for the North Sea plaice stock, verifying the relationship (van der Veer and Witte, 1999). Our results confirm this finding and extend the geographical range of this relationship to include other plaice stocks around the United Kingdom.

Establishing a mechanistic basis for observed correlations between environmental variables and recruitment strengthens the reliability that can be assumed in that relationship. We further examined how the correlation between temperature and recruitment varied when we restricted the source of the temperature data to individual months of the year. For all the stocks considered, correlations are strongest for the period February through April. Excepting the earliest spawning, this period covers the planktonic stages (eggs and larvae). In general, immigration to the nursery grounds is completed by July. Based upon 11 years of plaice egg survey data from the Southern Bight of the North Sea, Bannister *et al.* (1974) observed that egg mortality rates were lowest in the coldest years of sampling. Using the same data source, Brander and Houghton (1982) found that year-class strength in North Sea plaice was detectable by the end of the egg stage (Spearman rank correlation between numbers of eggs and recruits at age 2, $p = 0.0002$). This leads to the conjectural hypothesis that the underlying mechanism linking sea temperature and plaice recruitment may be reduced predation pressure on the egg stages of plaice in cold years. Such a reduction might be the result of lower predator abundance and/or reduced consumption rates. The results from our analyses are consistent with this hypothesis. This suggests that future field studies must consider the interactions between environment and predators upon fish eggs and larvae as well as more direct effects of environment upon growth and development of fish eggs and larvae.

Because the fisheries on plaice stocks are not as dependent on the incoming year class as some other stocks, incorporation of sea temperature data into plaice stock models will probably not have a large impact on short-term projections. This observation is deduced from the conclusions derived from incorporating temperature into a simulation study for cod (Basson, 1999). However, incorporating temperature effects may allow risk analyses to be undertaken for medium- to long-term projections under varying environmental scenarios. In addition, there is evidence of a recent shift in recruitment levels for plaice, at least within the Irish Sea (Section 3.3.2). This concurs with the increasing frequency of warmer than average sea temperatures observed in this region in the past decade and may indicate a temperature-induced effect on stock population dynamics.

3.9 Multispecies recruitment issues

Recruitment of any fish species depends in large part on mortality during the pelagic phase of its early life. Mortality will be determined not just by the physical environment, but also potentially by the abundance of other creatures. The principal mechanism is likely to be predation pressure from older larvae, juveniles, or adults of various species, including commercially important fish; other possibilities include changes in prey availability and competition. If environmental conditions change in the future, the abundance or distribution of predators and prey may change too. It is not obvious that future levels of predation will maintain historical levels, so it is not obvious that historically derived relationships between environment and recruitment will persist. Therefore, it is important to remember possible multispecies effects when considering environmental influences.

Barents Sea cod is a well-known example. Good recruitment requires warm temperatures, so a warming trend might suggest increased recruitment in the future. But good recruitment also demands a low abundance of herring, so if the warming trend were also to lead to increased herring abundance, the overall effect might be to decrease cod recruitment.

Predation among larvae is has not been studied as thoroughly, but is also potentially important. In the North Sea, stock–recruitment fits can be greatly improved by including other species' SSBs as covariates (via the exponent of a Ricker model); this can represent either adult predation or intralarval predation. Unfortunately, there are many models for possible interaction, and results from multispecies forecasts depend critically on which model is selected. Unless the range of likely interactions can be narrowed, there will be little benefit in using complex multispecies models for projection. The same may apply to projections incorporating environmental links to single-species recruitment.

To narrow the range of likely interaction, we need information on processes. There are many potential sources of biological/physical information that could be useful: diet, spawning times and places, stock sizes, etc. One approach is to use hydrographic models to predict likely overlaps—or to eliminate unlikely overlaps—in larval/adult distribution, at sizes when predation is likely. Note that it is not necessary to understand in detail every stage of the population dynamics; once a plausible set of interactions has been established, empirical data analysis (multispecies stock–recruitment relationships) can be used to parametrize the relationship. However, information on which interactions are plausible and how strong they might be is critical.

3.10 The importance of environmental factors in the design of management procedures

One of the background papers (Basson, 1999) discussed by SGPRISM was originally presented at the ICES Symposium "Confronting Uncertainty in the Evaluation and Implementation of Fisheries–Management Systems", Cape Town, 16–19 November 1999.

The main questions considered in the study are: what are the likely gains of incorporating an environmental factor into the model of stock and recruitment, and under which circumstances are the gains likely to be highest? The incorporation of environmental factors into a model of stock and recruitment could improve the prediction of recruitment and/or the definition of reference points, but may also require costly underpinning science. The study uses simulations to explore the implications of including or excluding environmental factors when predicting recruitment. A gadoid-like example with three levels of strength of interaction between the environmental factor and recruitment is considered. The characteristics of the environmental series are highly relevant and important for prediction purposes. Two hypothetical temperature series are considered: a first-order autocorrelated (AC = 0.5) series and a sine wave series with random error. Although the sine wave series is a rather pathological example, it serves to illustrate a best-case scenario, where one can assume that the underlying mechanism of the environmental driver is known, but realized with error.

In the examples considered in this study, there is no gain (in terms of either conservation or average yield) when an environmental factor is incorporated in the short-term prediction of recruitment. This is mainly because:

a) For a long-lived stock that is not totally depleted/overfished, predicted recruitment forms a relatively small proportion of the two-year ahead predicted catch in weight, which is the basis for TACs;

b) Similarly, predicted recruitment forms a relatively small proportion of the two-year ahead predictions of SSB;

c) ICES advice currently focuses on these two-year ahead predictions, and TACs are only set for a single year at a time.

Adaptive management, via changes in fishing mortality reference points as the temperature series changes, only leads to gains when the environmental factor can be well predicted (e.g. the sine wave example). In these examples, the main gains were in $P(SSB < B_{pa})$ rather than in the mean yield. The variability in yield was higher when management was adaptive, and this is more likely to be considered a disadvantage than a gain.

Results suggest that the main factors that influence the likelihood of achieving certain types of gains (e.g. increased long-term mean yield) by incorporating environmental factors into stock and recruitment models used for prediction are:

- The predictability of the environmental series;
- The strength of the effect of the environment on recruitment;
- The contribution of predicted recruitment to predicted catch and SSB.

The importance of doing simulation studies to explore the likely benefits and feasibility of incorporating environmental factors in management procedures is emphasized.

4 Processes and biological issues

4.1 Assessing the effects of incorporating process information in assessments and projections

Routine stock assessments are sometimes criticized for failing to include biological information, particularly about reproductive parameters (e.g. Trippel, 1999). There are undoubtedly many cases where this is a valid criticism. However, although 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.

First to take a hypothetical example, a fishery might be closed, based on 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 simple SSB, then it is possible that the decision to close the fishery may have been reached at a different time. However, it is likely that, for subsequent management of the fishery, the two approaches could give different pictures of the stock. If the stock were rebuilt to some threshold SSB, it is likely that this would still represent a rather low reproductive potential, owing to the relatively high contribution of recently recruited year classes. Hence, decisions based on reproductive potential would tend to be more conservative and as a result, to delay the reopening of the fishery until the actual reproductive potential had improved substantially (Scott *et al.*, 1999; BD17).

While using a reproductive index rather than SSB in a management context as in the example above has a clear advantage, 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 horizontal 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 that needs to be assessed to determine the contribution made by the additional biological information.

A stock–recruitment model within a routine stock assessment is used primarily to predict recruitment in stock projections. Generally, these are used to estimate the uncertainty associated with 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 this context. The approach developed by Patterson *et al.* (2000) to test medium-term projection methods may be useful here.

An analogous problem occurs when several different 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-Teichmann *et al.* (2000), and Köster *et al.* (1999) have developed stock–recruitment models with varying degrees of complexity and that reflect environmental influence to differing extents. The stock–recruitment model used during stock assessments is different from all these (ICES, 2000b). Clearly in this case, it is desirable to have some criteria by which the "best" model can be selected from among these competing candidates. Again, thorough testing as performed by Patterson *et al.* (2000) may be appropriate.

4.2 Natural mortality

Tretyak (BD12) estimates natural mortality in northeast 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 means of reducing the number of parameters to be estimated for use in stock projections. However, for northeast Arctic cod, growth and mortality appear closely linked to capelin abundance, so a multispecies approach might be more appropriate in this case.

4.3 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 Kiseleva (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.

4.4 Reproductive potential

The stock–recruitment (S–R) relationship assumes that spawner biomass (SB) is directly proportional to the reproductive potential of the stock, i.e. that the relative fecundity (number of eggs produced per unit weight) of the stock is constant both temporally and spatially. This assumption has long been recognized as invalid (Oosthuizen and Daan, 1974; Ware, 1980); however, until recently there has been no concerted effort to replace SB with more sensitive measures of reproductive potential.

In the case of Atlantic cod, processes such as skipped spawning and/or atresia (Kjesbu *et al.*, 1991; Witthames and Greer Walker, 1995; Ma *et al.*, 1998; Marshall *et al.*, 1998; Bromley *et al.*, 2000; Rideout *et al.*, 2000) contribute to the lack of proportionality between total egg production and SB over time. As both responses are observed in fish in poor condition, a high degree of interannual variability in food abundance and condition are likely to increase the divergence between reproductive potential and SB. Reproductive potential is also affected by shifts in size composition because large/old spawners have higher relative fecundities than small/young spawners (Marshall *et al.*, 1998; Marteinsdottir *et al.*, 2000). Therefore, the progressive loss of large spawners in stocks experiencing sustained high fishing mortalities (Trippel, 1999) can reduce the total egg production disproportionately to the reduction in spawner biomass.

As a result of increased knowledge of variability in relative fecundity of individuals and stocks, the S–R relationships for several stocks are being re-evaluated using alternative indices of reproductive potential. The approach taken to re-estimating reproductive potential varies according to the type of data available. A limited number of stocks have fecundity data that is being used to hindcast potential total egg production by the stock (Köster *et al.*, 2003; Marshall *et al.*, WD11). Bioenergetic approaches to quantifying the reproductive potential of stocks have also been developed (Painting *et al.*, 1998; Henderson *et al.*, 2000; Marshall *et al.*, 1999, 2000). These take advantage of historical databases derived from industrial sources (e.g. liver condition, oil:meal ratios). Long time-series describing spawner condition have also been used as proxies for the reproductive potential of individual spawners (Marshall and Frank, 1999; Blanchard, 2000). Basic demographic data (e.g. numbers-at-age) have been used to construct age diversity indices that can potentially be used as simple proxies for reproductive potential (Lambert, 1990; Marteinsdottir and Thorarinsson, 1998; Secor, 2000).

Stocks span an information gradient in the sense of having variable quantities of biological data that are relevant to estimating stock reproductive potential (Figure 4.4.1). In the worst case, reproductive potential is quantified by using time-invariant maturity- and weight-at-age values to estimate spawner biomass. These estimates are driven solely by variation in spawner quantity. Incorporating year-specific values for maturity- and weight-at-age increases the sensitivity of spawner biomass to the effect of interannual variation in growth and condition on reproductive potential. Incorporating year-specific fecundity information into estimates of reproductive potential (e.g. total egg production) can also increase the sensitivity of estimates

(Armstrong *et al.*, WD9). Continuing research aims to incorporate interannual differences in egg quality, egg mortality (e.g. predation), or spatial/temporal origin of eggs.

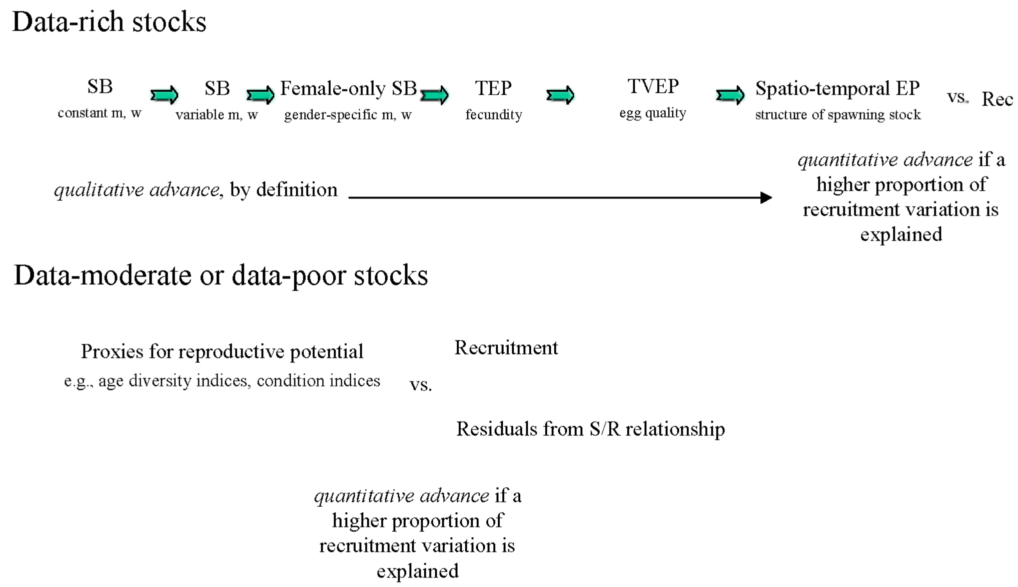


Figure 4.4.1. Schematic illustrating the differences between qualitative and quantitative advances in quantifying reproductive potential. For data-rich stocks, qualitative advances are achieved by replacing spawner biomass (SB) to total egg production (TEP), total viable egg production (TVEP), and spatio-temporally disaggregated egg production (EP) through the addition of more highly resolved information on maturity (m), weight (w), sex ratio, fecundity (f), egg quality, and spatio-temporal distribution of spawners. Quantitative advances result if a higher proportion of recruitment variability is explained by the new index. Data-moderate or date-poor stocks are limited to comparing proxies of reproductive potential with either recruitment or residuals from the stock–recruitment relationship.

The NAFO Working Group on Reproductive Potential designed tables to summarize the available data and their data sources for selected stocks in NAFO and ICES jurisdictions for estimating reproductive potential and stock–recruitment relationships. Information in the tables includes population parameters such as stock size and composition, fish age, weight, maturity, sex ratios, fecundity and condition, as well as existing studies on e.g. potential and realized egg production, critical life stages, and environmental influences on stock–recruitment relationships. The data are of great interest to the ICES community, and these tables have been published in the NAFO Scientific Council Studies (Morgan *et al.*, 2003). Data for estimating reproductive potential have been placed on the NAFO website and should be maintained as recommended by ICES SGGROMAT (ICES, 2004) for use in stock assessments.

In the case of data-poor stocks, alternative indices of reproductive potential are necessarily restricted to proxies that could be derived directly from the analytical assessment (e.g. age diversity indices) or limited time-series. The approach taken at the final meeting of SGPRISM (ICES, 2002) was to contrast northeast Arctic cod and North Sea cod in terms of the available data resources, types of indices of reproductive potential that can be estimated, and how the indices can potentially be used in stock management. Given the lack of knowledge, SGPRISM undertook an exploratory exercise for the North Sea cod.

4.4.1 Estimating reproductive potential

Northeast Arctic cod is an example of a stock having several historical databases that are relevant to estimating reproductive potential. A simulation analysis suggested that the dynamic range of SB is less than the range in total egg production (Marshall *et al.*, 1999). Consequently, several alternative measures of reproductive potential, including total egg production (Marshall *et al.*, WD11) and total lipid energy (Marshall *et al.*, 2000), are being estimated for the assessment period (1946–present) and being compared with both SB and recruitment.

4.4.1.1 North Arctic cod

Until recently, values of SB for northeast Arctic cod were estimated using knife-edge maturity ogives (1946–1981) and constant weight-at-age values (1946–1982). Therefore, the resulting S–R relationship (Figure 4.4.1.1.1a) was insensitive to the effect of growth variation on reproductive potential. In 2001, the ICES Arctic Fisheries Working Group (AFWG) compiled historical data from Russian and Norwegian sources and developed new time-series for maturity- and weight-at-age (ICES, 2001a). Replacing the constant values led to a substantial downward revision of SB, such that the long-term mean decreased from 577 425 t (1946–1999) to 372 934 t (1946–2000; ICES, 2001a). Despite this major change in the SB time-series, the major change to the S–R relationship was a shift of outlying post-war values towards lower SB values (Figure 4.4.1.1.1b).

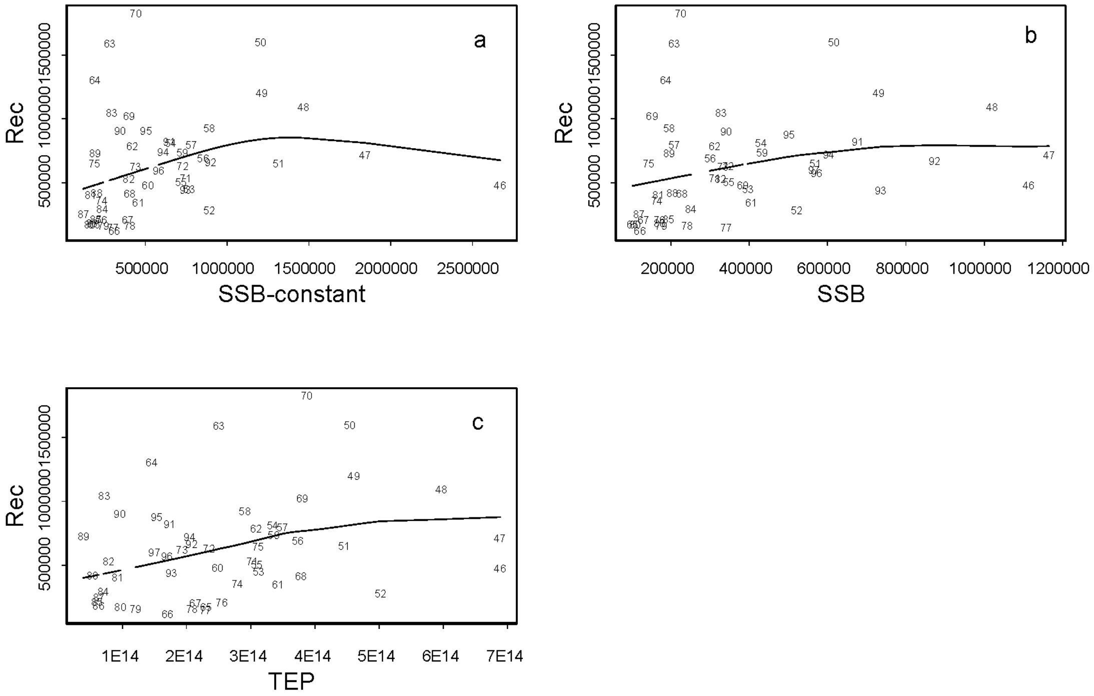


Figure 4.4.1.1.1. The stock–recruitment relationship for northeast Arctic cod using different indices for reproductive potential.

(a) Spawner biomass calculated with constant values of proportion mature and weight-at-age for the pre-survey period (ICES, 2001b).

(b) Spawner biomass calculated with year-specific values of proportion mature and weight-at-age obtained from Russian and Norwegian historical sources (ICES, 2001a).

(c) Total egg production. The recruitment index used is the abundance at age 3. Observations are labelled by year. The Loess curve (degree = 1, span = 1.5) is shown in each panel (a)–(c).

Concurrent with the revision of the SB time-series, preliminary estimates of total egg production were made (Marshall *et al.*, WD11). These estimates were calculated using a general fecundity model developed from field observations made during a period when the condition of Barents Sea cod decreased rapidly as a result of the collapse of the Barents Sea capelin stock (Kjesbu *et al.*, 1998). In the general model, the year effect on the fecundity/length relationships was represented using the condition factor. The relationship between total egg production and recruitment shows that the high recruitment values for 1963, 1964, and 1970 are more consistent with the level of egg production (Figure 4.4.1.1.1c) compared with levels of SB (Figure 4.4.1.1.1b). The SB and total egg production time-series show major differences with total egg production being higher in the 1970s than in the 1990s, while the opposite holds true for SB estimates (Figure 4.4.1.1.2).

Identifying the factors causing discrepancies between SB and total egg production is a high priority for future research. There are several refinements planned for estimates of total egg production that, it is hoped, will increase their sensitivity to true variation in reproductive potential. These include:

- Improvements to the year-specific age/length keys used to convert VPA numbers-at-age to numbers-at-length;
- Improvements to the general fecundity model to better utilize environmental information, e.g. capelin stock biomass or liver condition index;
- Checks on the consistency between time-series of growth parameters (maturity, weight, and fecundity) used in estimates of SB and total egg production;
- Corrections for size- or condition-dependent effects on egg quality.

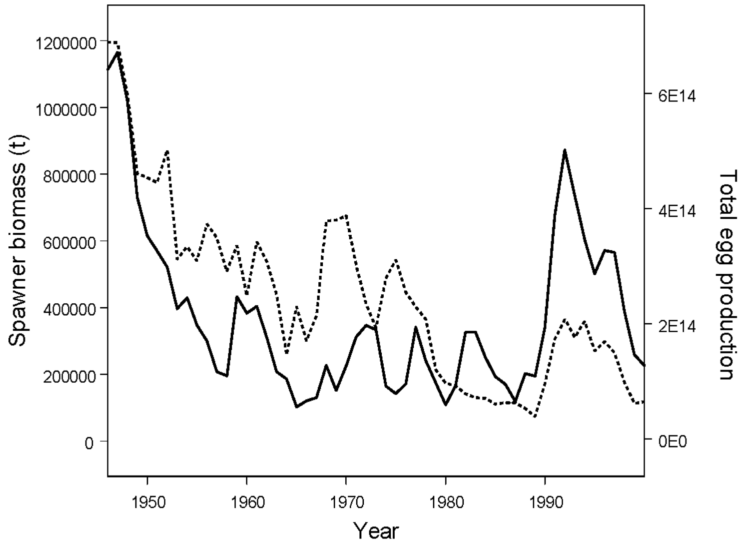


Figure 4.4.1.1.2. Time-series of spawner biomass (solid line; from ICES, 2001a) and total egg production (dashed line).

4.4.1.2 North Sea cod

Initially it was thought that the data available to construct more sensitive measures of reproductive potential for North Sea cod on time scales that are comparable with the assessment were limited, particularly when compared with a data-rich stock such as northeast Arctic cod. Closer investigation revealed limited quantities of relevant data. Cod maturity data from the IBTS for 1980–1995 are given in Cook *et al.* (1999). Maturity ogives separated by sex are reported in Rijnsdorp *et al.* (1991) for 1985–1989. An historical comparison of the changes of length–maturity ogives is given in Oosthuizen and Daan (1974), extending from the 1890s to the 1970s. It shows a shift in L_{50} from approximately 75 cm to just above 50 cm in length-at-maturity over this long-term period (Figure 4.4.1.2.1). Condition data are available for 11 years from English groundfish surveys. Fecundity data exist for 1970–1972 (Oosthuizen and Daan, 1974) and for 1987–1988 (Heessen, unpublished, reported in Rijnsdorp *et al.*, 1991). Mean dry weights of eggs are available from eggs collected from ripe and running females in 1969, 1971, 1972, and 1987 (Rijnsdorp *et al.*, 1991). Estimates of egg production have also been made according to egg surveys carried out in the southern Bight during 1970–1974 (Daan, 1981).

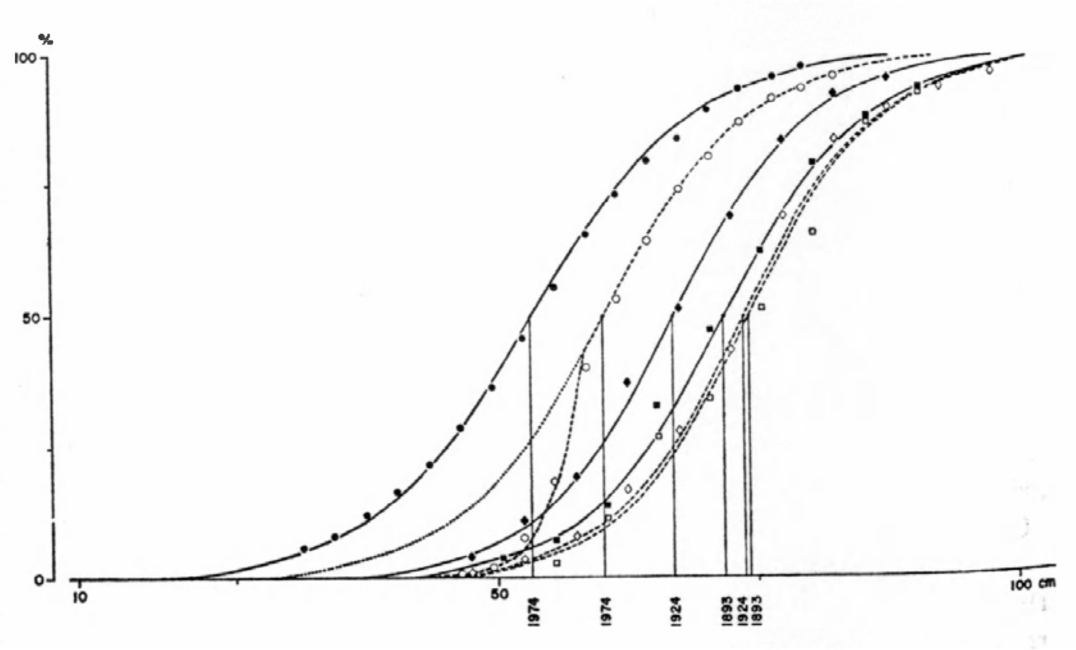


Figure 4.4.1.2.1. Length–maturity ogives (estimated from logit transformations) of North Sea cod for males (solid symbols) and females (open symbols), according to data by Holt (1893; squares), Graham (1924; diamonds), and Oosthuizen and Daan (1974; circles). L_{50} values are indicated by the date.

4.4.2 Collection of survey data

Any reproductive index requires biological information. Ideally, even for a simple measure of SSB, the estimates of maturity and weight-at-age should be updated annually. Research vessel surveys are the key source of this information; hence the scope for incorporating biological realism within reproductive indices is limited by the information available from these surveys. Although it would be desirable to collect all of this information on all surveys, typically this is not the case. SGPRISM was aware that the existing sampling protocols for some surveys do not specify the collection of all these data. As an example, the study group reviewed the protocol for one major survey within the ICES area.

The International Bottom Trawl Survey (IBTS) is a major international 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 are 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, often they are not available within the IBTS database.

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

4.4.3 Estimating alternative reproductive potential indices

During the final meeting of SGPRISM (ICES, 2002), three alternative indices of reproductive potential (age diversity, female-only biomass, and condition) for North Sea cod were estimated.

4.4.3.1 Age diversity

Stocks experiencing sustained high fishing mortalities typically exhibit a truncated age structure (Trippel, 1999). Age diversity indices have been used as an index of reproductive potential for Icelandic cod (Marteinsdottir and Thorarinsson, 1998) and striped bass in Chesapeake Bay (Secor, 2000). As it is easily estimated from basic demographic data, the utility of this index was examined for North Sea cod. The numbers of mature fish at each age, obtained using the proportion mature as used in the assessments (Table 4.4.3.1.1a), were taken from the 2001 XSA assessment (ICES, 2002a). A Shannon diversity index (H) was then estimated to the numbers of mature fish as follows:

$$H = 1/n(\log(n) - \sum_{i=1}^{k} f_i \log(f_i)) \qquad \text{Equation 1}$$

where k is the number of age groups, n is the total number of mature fish in all age groups and f_i is the number of mature fish in each age group (Shannon, 1948). The assessment for North Sea cod used fixed values of proportion mature to estimate spawner biomass. Values of H were estimated using fixed proportions mature and annual estimates of the proportion mature derived from annual surveys (Cook *et al.*, 1999; Armstrong *et al.*, WD9; Table 4.4.3.1.1b).

The age diversity of North Sea cod has shown a long-term decline since 1963 (Figure 4.4.3.1.1). Since 1993, age diversity has been below the long-term mean value. Using values of H estimated with variable annual proportions mature suggests a steeper decline, although the data series is shorter. In the 1990s, fishing pressure was very high on the North Sea cod stocks, and there has been an accompanying decline in the SSBs. So it is not surprising that the age diversity has declined in recent years.

Age diversity indices estimated using time invariant proportions mature show no relationship with recruitment (Figure 4.4.3.1.1). However, the use of year-specific proportions mature suggests a relationship between age diversity and recruitment (Figure 4.4.3.1.2, $r^2 = 0.31$). The relationship is stronger than that observed for Icelandic cod ($r^2 = 0.15$; Marteinsdottir and Thorarinsson, 1998). A multiple linear regression of recruitment (R) on age diversity (H) and $\log_e$ SSB gives a weak positive relationship ($r^2 = 0.44$, $p = 0.06$):

$$R = 25.06\times10^6 - 37.60\times10^6\, H - 2.23\times10^6 \log_e SSB + 3.38\times10^6 (H^*\log_e SSB) \qquad \text{Equation 2}$$

In terms of assessing reproductive potential, age diversity appears to be useful in describing major changes in the population age structure that will have an impact on reproduction (Marteinsdottir and Thorarinsson, 1998; Secor, 2000). For North Sea cod, the correlation between age diversity and recruitment was only significant when the variable proportion mature in the stock were used to estimate H. Time invariant maturity ogives give an incorrect perception of age diversity as well as other aspects of the stock dynamics.

Table 4.4.3.1.1. (a) Proportion of fish mature time invariant used in the 2001 XSA stock assessments of North Sea cod. (b) Survey-derived estimates of proportion mature of North Sea cod, both sexes combined (Cook *et al.*, 1999).

a)

Age	Proportion mature
1	0.01
2	0.05
3	0.23
4	0.62
5	0.86
6	1.00
7	1.00
8	1.00
9	1.00
10	1.00
+ grp	1.00

b)

	Age										
Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**+grp**
1980	0.01	0.1	0.08	0.56	1	0.88	1	1	1	1	1
1981	0.01	0.04	0.16	0.52	0.85	0.87	1	1	1	1	1
1982	0	0.03	0.17	0.64	0.93	1	1	1	1	1	1
1983	0	0.03	0.2	0.5	0.96	0.99	1	1	1	1	1
1984	0	0.06	0.25	0.42	0.81	0.98	1	1	1	1	1
1985	0	0.04	0.1	0.45	0.56	0.91	1	1	1	1	1
1986	0	0.09	0.18	0.35	0.63	0.9	1	1	1	1	1
1987	0	0.02	0.15	0.6	0.76	0.98	1	1	1	1	1
1988	0	0.05	0.27	0.53	0.9	0.95	1	1	1	1	1
1989	0	0.13	0.24	0.59	0.77	0.97	1	1	1	1	1

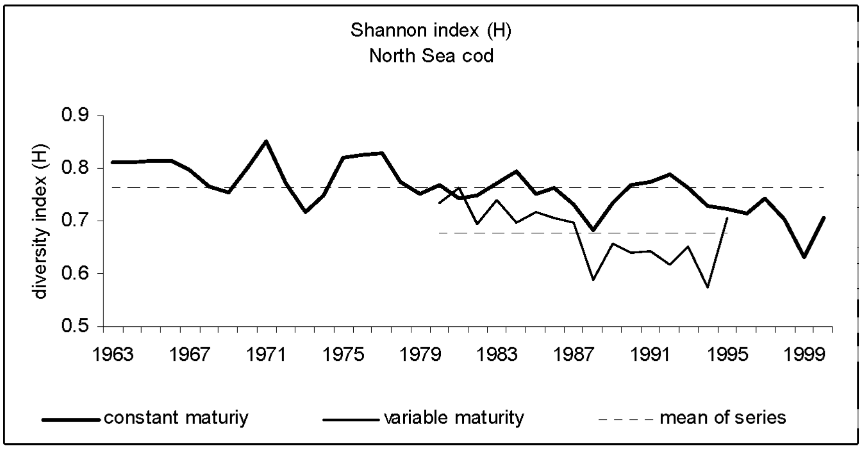


Figure 4.4.3.1.1. Interannual variation of age diversity of North Sea cod based on the Shannon diversity index. Dotted lines denote long-term means.

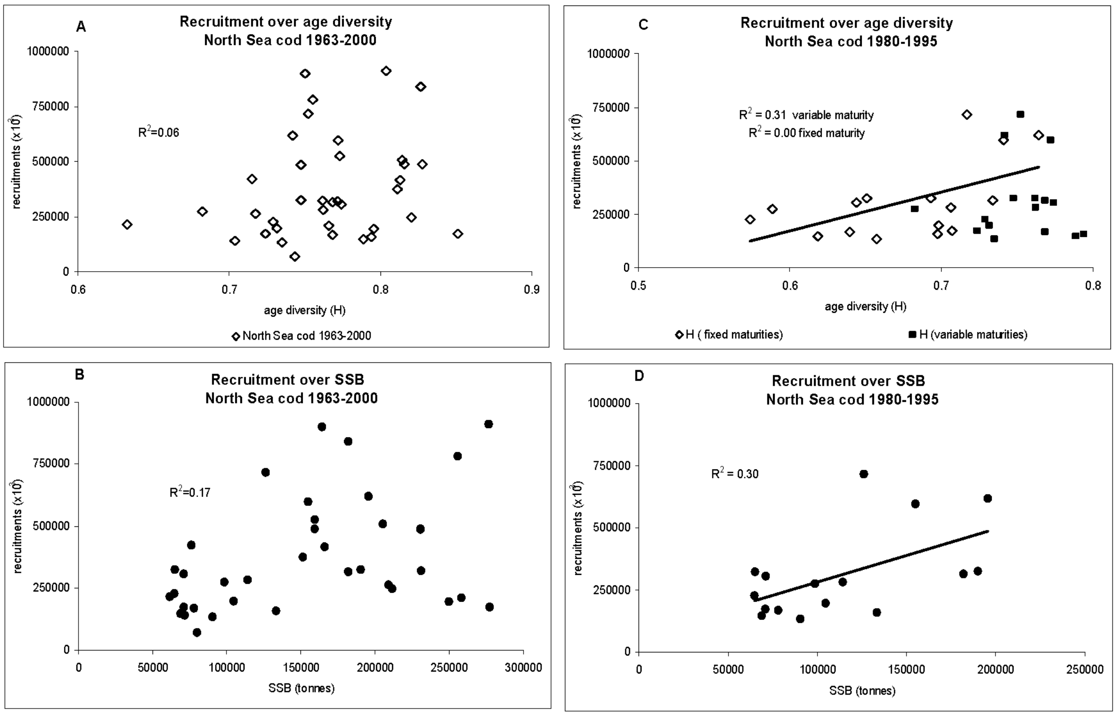


Figure 4.4.3.1.2. Recruitment in North Sea cod (age 1).

(a) Against age diversity H (time invariant proportion mature).

(b) Against SB in tonnes (1963–2000).

(c) Against age diversity H, with variable proportion mature (open diamonds) and fixed proportion mature (closed squares; 1980–1995; Cook *et al.*, 1999; ICES, 2002a).

(d) Against SB in tonnes (1980–1995). Linear relationships are shown where applicable.

4.4.3.2 Condition

Condition indices reflect the amount of available energy reserves of the fish (Kjesbu *et al.*, 1991). Adult female condition affects the quantity (number of eggs produced by individuals) and possibly the quality and survival of offspring (Kjesbu *et al.*, 1991; Marteinsdottir and Steinarsson, 1998). Fluctuations in temperature and food can contribute to interannual variability in condition. For example, in northeast Arctic cod, condition is positively correlated with mean annual bottom temperature and with capelin stock biomass in particular (Kjesbu *et al.*, 1998; Yaragina and Marshall, 2000).

Condition can be measured using a bioenergetic approach (e.g. lipid analyses, liver condition index) or can be based more simply on the relationship between weight and length (Lambert and Dutil, 1997). There is a high degree of seasonal variation in condition (Yaragina and Marshall, 2000). The timing of research surveys may not always be optimal for establishing a representative annual condition measure. Traditionally, weight information has not been collected on the IBTS. Consequently, the data available to describe interannual variation in condition are very limited. Figure 4.4.3.2.1 shows a reconstruction of relative condition factor (Fulton's K = weight/(length)^3) for North Sea cod ages 1–6. The period 1996–2001 suggests a rapid fluctuation that is not synchronous across age classes. For cod ages 4 and 6, there is some suggestion of condition values being lower in 2001 compared with values for 1979–1981. Owing to the short, incomplete nature of the time-series, it is not possible to determine whether there is a correlation between recruitment trends. However, it should be noted that other gadoid stocks show positive associations between condition and recruitment (Blanchard, 2000; Marshall *et al.*, 1999).

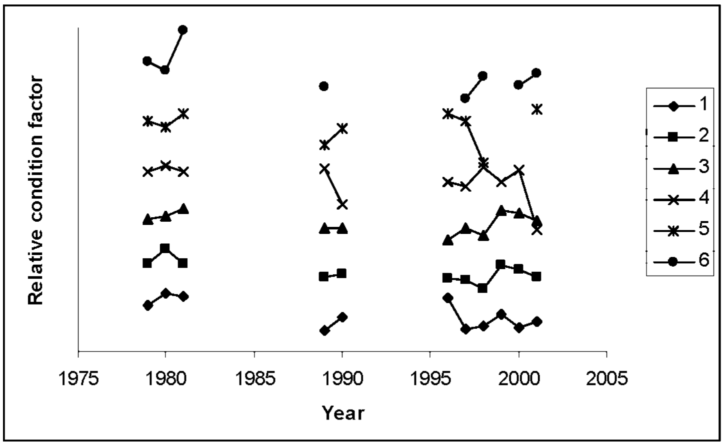


Figure 4.4.3.2.1. The time-series of relative condition factor at ages 1–6 for the North Sea cod (combined sexes) calculated from the English groundfish survey data sets. The values are scaled to separate the time-series so that the year effects can be distinguished.

4.4.3.3 Female-only biomass

As a result of dimorphism in growth, mortality, and behaviour, sex ratios shift toward a higher proportion of females with increasing size. The loss of large/old spawners affects the number of mature females disproportionately. This could result in losses of reproductive potential that are disproportionate to the loss of spawner biomass. For example, more of the variation in recruitment of Baltic cod can be explained using female-only biomass compared with the biomass of males and females combined. Female-only biomass for North Sea cod was calculated as the product of numbers-at-age, sex ratio-at-age, female maturity-at-age, and weight-at-age. Numbers-at-age of cod were available from the North Sea Demersal Working Group report (ICES, 2002a). Female maturity-at-age, sex ratio, and weight-at-age were obtained from the English groundfish surveys carried out in the North Sea during the third quarter. Only ten surveys had sufficiently resolved data. Therefore, estimates of female-only biomass were restricted to the years shown in Table 4.4.3.3.1.

Table 4.4.3.3.1. Results of model fitting for North Sea cod.

YEAR	FEMALE-ONLY SB (METRIC T)	VPA SB	RECRUITMENT-AT-AGE 1	RICKER FITTED RECRUITMENT	RESIDUALS
1979	56 962	164 268	899 522	363 008	536 514
1980	87 145	181 869	314 766	380 027	−65 261
1981	101 074	195 732	618 498	391 356	227 142
1989	47 887	90 611	133 940	253 088	−119 148
1990	25 889	78 040	168 570	226 865	−58 295
1996	27 339	76 358	421 717	223 165	198 552
1997	31 428	80 187	69 536	231 519	−161 983
1998	11 500	71 553	139 369	212 343	−72 974
1999	27 497	61 467	215 023	188 356	26 667

Within this period, there was a weak but insignificant ($r^2 = 0.28$, $p = 0.14$, $n = 9$) linear relationship between female-only SB and recruitment (Figure 4.4.3.3.1b); however, the overall pattern of variation was similar to that observed in the conventional stock–recruitment relationship (Figure 4.4.3.3.1a). It should be noted that the maturity assessment in the third quarter underestimates the SB of the younger first-time spawners. There was no significant ($r^2 = 0.09$, $p = 0.14$, $n = 9$) relationship between female-only SB and the residuals from the S–R relationship.

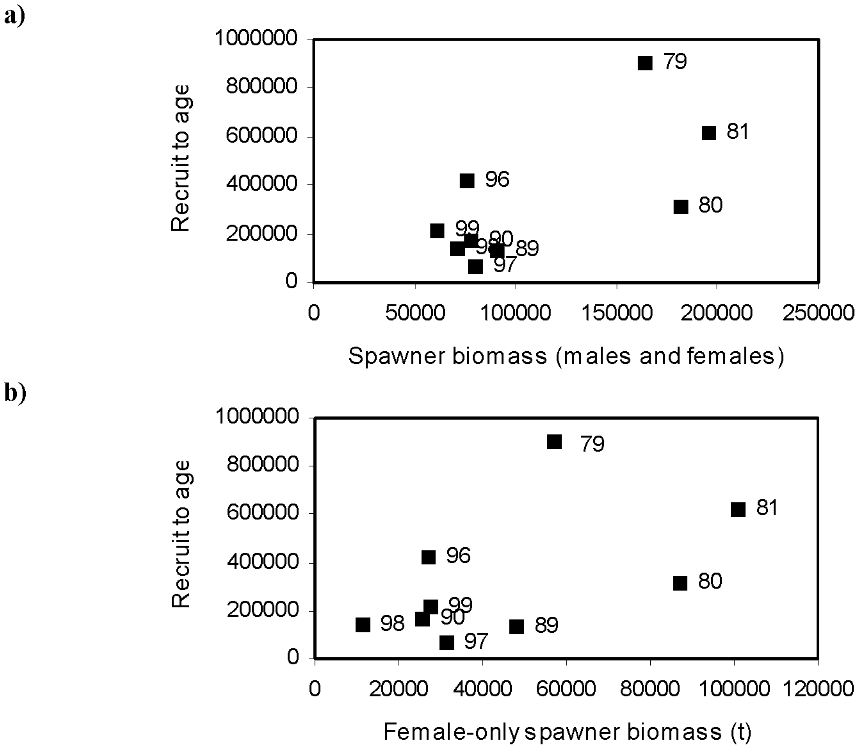


Figure 4.4.3.3.1.

(a) The relationship between SB of North Sea cod and recruitment-at-age 1. Labels denote year.

(b) The relationship between female-only SB and recruitment-at-age 1. Labels denote year.

4.4.4 Incorporating reproductive potential into stock management

4.4.4.1 Northeast Arctic cod

The AFWG is investigating the appropriateness of the biomass reference points in light of the revised maturity- and weight-at-age time-series (Figure 4.4.1.1.1b). However, it should also be recognized that reference points for SB will have a degree of uncertainty resulting from any divergence between SB and total egg production (Figure 4.4.1.1.2). Reference points that are explicit for reproductive potential (e.g. limit and threshold total egg production) will be further developed in future research. Classifications of stock status using these reference points will be compared with the classifications made using B_{pa}. Medium-term stock projections would need modification to take into account reference points for reproductive potential, and the resulting stock projections would need to be compared with projections of SB.

4.4.4.2 North Sea cod

The North Sea cod stock was initially considered data-poor in terms of analysis of reproductive potential. However, the analyses undertaken during the third meeting of SGPRISM (ICES, 2002) revealed that there were data resources that could be utilized. The perception that there are no data is not justified! However, existing data often are discontinuous in time or subject to sampling biases. More definitive databases are required to describe the relationship between SB and reproductive potential, and between reproductive potential and recruitment conclusively.

Considerations when reconstructing historical trends in reproductive potential or collecting new data include:

- When reconstructing historical trends in reproductive potential for data-poor stocks, missing data are often extrapolated from another stock despite evidence of large interstock differences in the fecundity/length relationship (Oosthuizen and Daan, 1974). Until more is known about the stock-specific nature of reproductive parameters and the degree of spatial and temporal variation in sex ratio, maturity, fecundity, and condition, it is inappropriate to extrapolate this information between stocks.

- It is essential to collect time-series of reproductive data if reproductive potential is to be incorporated successfully into stock assessment and projections. Emphasis must be placed on the quality of surveys and appropriate survey design. Surveys must take place at times relevant to the reproductive process under consideration, e.g. maturity should be assessed approaching the spawning period and condition before vitellogenesis. Surveys should also account for biases caused by spatial patterns, fish behaviour, and sampling strategies such as stratified length sampling.
- In the case of North Sea cod, data obtained from market sampling has limited value because gutted fish are landed (e.g. no condition or fecundity information). Consequently, data obtained from surveys are critical to characterizing the dynamics of growth and reproduction.
- Maturity data should be collected and reported by sex and be of suitable resolution for the correct interpretation of diverse spawning strategies.
- In the absence of data, simulation approaches may be advantageous to examine the effect of variation of weights and maturities on medium-term stock projections.
- New data on fecundity and egg quality of North Sea cod may become available in the near future (Witthames *et al.*, WD4).

4.5 Modelling variation in North Sea cod condition factors

Weight- and length-at-age data for individual fish are available from the English third quarter groundfish survey for the years 1979–1981, 1989, 1990, and 1996–2001. In addition, for each observation, the position at which it was caught (latitude, longitude) and the sex and age of the fish were available. Owing to the scarcity of data for older ages and age 0, only data for ages 1–5 were used in fitting the linear models.

To examine the variation in Fulton's condition factor (weight/(length)^3), taken to be a proxy for the quality of the spawning potential of the fish, a log weight–log length linear model was fitted to the data and the effects of explanatory variables on the variability about this relationship examined. The form of the fitted model was:

$$\log(\text{weight}) = \alpha + \beta \log(\text{length}) + \delta A + \varepsilon B + \gamma C \qquad \text{Equation 3}$$

where β, δ, ε, and γ are the regression coefficients for explanatory variables A, B, and C. In addition to the main explanatory variables effects, and where the sampling design permitted, the interactions between explanatory variables were examined. The parameter α equates to Fulton's condition factor.

The analysis of variance tables for the linear models is presented in Table 4.5.1. In each case, an analysis of variance was used to compare model structures. Latitude and sex were non-significant effects within all models in which they were fitted. Year effects had a significant influence on model fit, both as a main effect and within interaction terms with the coefficient of log length. This indicates variation in the power relationship between length and weight within years. When age and year-class effects were fitted within the model, they had significant effects only if the interaction between the coefficient of log length and the year of sampling was omitted from the model.

The final fitted model is listed in Table 4.5.1 as Model 13. It included main effects for longitude log length and a year effect with and interaction between year and log length. Plots of the residual from the fitted model, model predictions, and observed values are presented in Table 4.5.1. Longitude has a strongly significant effect, with fish collected in the western North Sea having higher condition factors (Figure 4.5.2). The year effects in condition show that weight-at-length has been declining throughout the period for which data are available (Figure 4.5.3). Recent values appear to have been more stable.

Excluding 2001, annual average bottom temperature data were available for each year in which the samples were taken. In order to examine the correlation between the temperature signal and condition factor, a model was included that included only log length and the temperature time-series as a linear term. The model diagnostics show that temperature has a significant effect on the fit of the model to the observations (Table 4.5.2). The coefficient is negative, indicating a decrease in weight per unit length with increasing temperature (Figure 4.5.4). However, the reduction in the variance of the model fit was not as great as that achieved when fitting individual year effects to the condition factor time-series. If year effects are fitted within the model, the temperature effect is not significant. Table 4.5.2 also shows a significant effect of an interaction between temperature and age on the fit of a length–weight model. This suggests that there is a different effect of temperature at each age.

The results of this analysis are preliminary, no causal mechanism has been suggested, and the fit is to average annual temperature. It would be expected that a temperature series recorded before the capture of the fish and from the location in which the fish was captured would have a dominant effect on an individual's condition.

Table 4.5.1. Analysis of variance table used to fit the log weight–log length generalized linear and additive models to the English groundfish survey data for North Sea cod.

Terms	Resid. Df	RSS	Test	Df	Sum of Sq	F Value	Pr(F)	Model
log(len)	7 712	90.59865						
log(len) + lat	7 711	90.59803	+ lat	1	0.000619	0.0527	0.81840	1
log(len) + lon	7 711	90.56313	+ lon	1	0.035518	3.0242	0.08207	2
log(len) + factor(sex)	7 710	90.58079	+ factor(sex)	2	0.017863	0.7602	0.46759	3
log(len) + factor(yr)	7 702	83.75453	+ factor(yr)	10	6.844125	62.938	0	4
log(len) + factor(yc)	7 690	84.19453	+ factor(yc)	22	6.404122	26.588	0	5
log(len) + factor(age)	7 708	90.39423	+ factor(age)	4	0.204425	4.3579	0.00161	6
log(len) + factor(yr)	7 702	83.75453						
log(len) × factor(yr)	7 692	82.21828	+ log(len):factor(yr)	10	1.536242	14.372	0	7
log(len) × factor(yr)	7 692	82.21828						
log(len) × factor(yr) + factor(sex)	7 690	82.20466	+ factor(sex)	2	0.013627	0.6374	0.5287	8
log(len) × factor(yr) + lat	7 691	82.21718	+ lat	1	0.001108	0.1037	0.7472	9
log(len) × factor(yr) + lon	7 691	82.08083	+ lon	1	0.137456	12.880	0.0003	10
log(len) × factor(yr) + factor(age)	7 688	82.16372	+ factor(age)	4	0.054566	1.2764	0.2767	11
log(len) × factor(yr)	7 692	82.21828						
log(len) × factor(yc)	7 668	82.72291	1 vs. 2	24	–0.50462	1.9490	0.0036	12
log(len) × factor(yr) + lon	7 691	82.08083						
log(len) × factor(yr) + s(lon, 4)	7 687	81.31790 1	vs. 2	3.0	0.762924	24.037	1.776357e-015	13

Table 4.5.2. Analysis of variance table used to examine the effect of temperature on the fit of the log weight–log length for the English groundfish survey data for North Sea cod.

Terms	Resid. Df	RSS	Test	Df	Sum of Sq	F Value	Pr(F)	Model
log(len)	7 295	87.41872						
log(len) + temp	7 294	86.73512	+ temp	1	0.6835991	57.48734	3.819167e-014	14
log(len) + temp	7 294	86.73512	+ temp	1	0.6835991	57.48734	3.819167e-014	
log(len) + temp + factor(age):temp	7 290	86.52371	+ factor(age):temp	4	0.2114185	4.453234	0.001354111	15

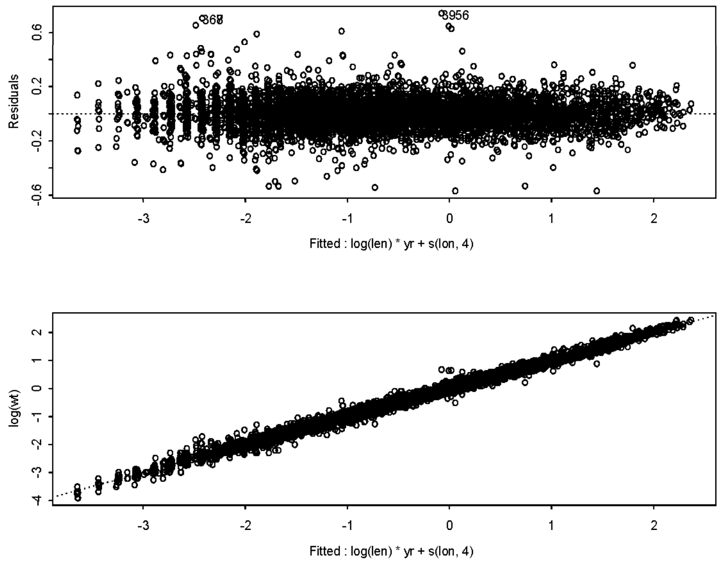


Figure 4.5.1. The residual vs. model prediction and observed value vs. model prediction plots for a linear model of log weight against log length with covariates for the North Sea cod.

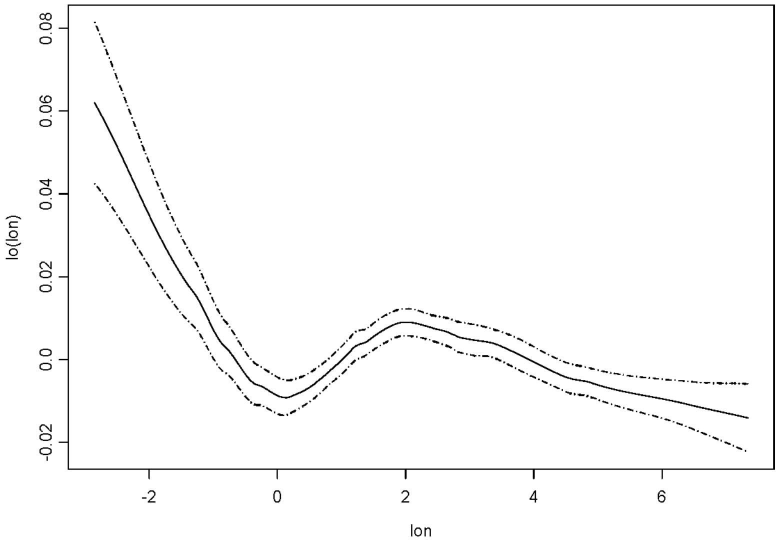


Figure 4.5.2. The response effect for the weight of North Sea cod to the position from which the English groundfish survey samples were taken. Lon = longitude. Negative values represent degrees west of the Meridian.

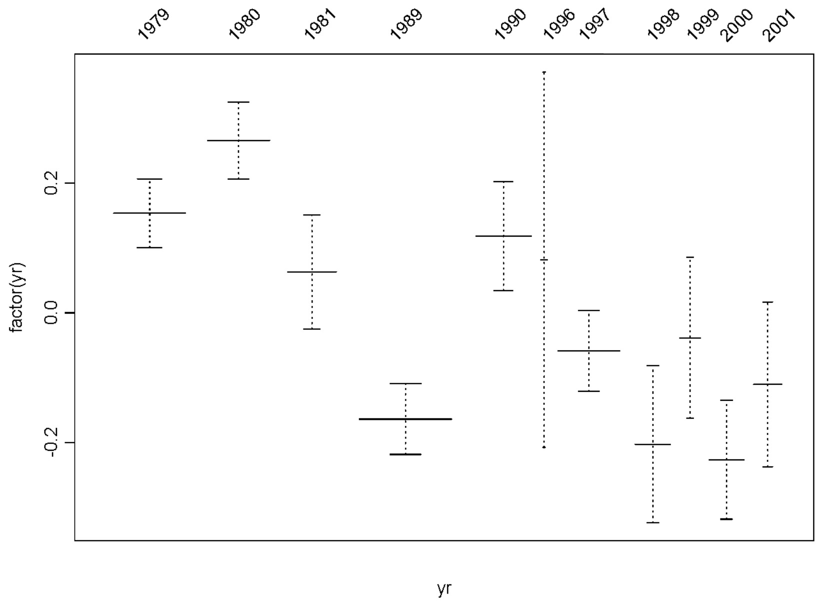


Figure 4.5.3. The response effect for the weight of North Sea cod to the year in which the English groundfish survey samples were taken.

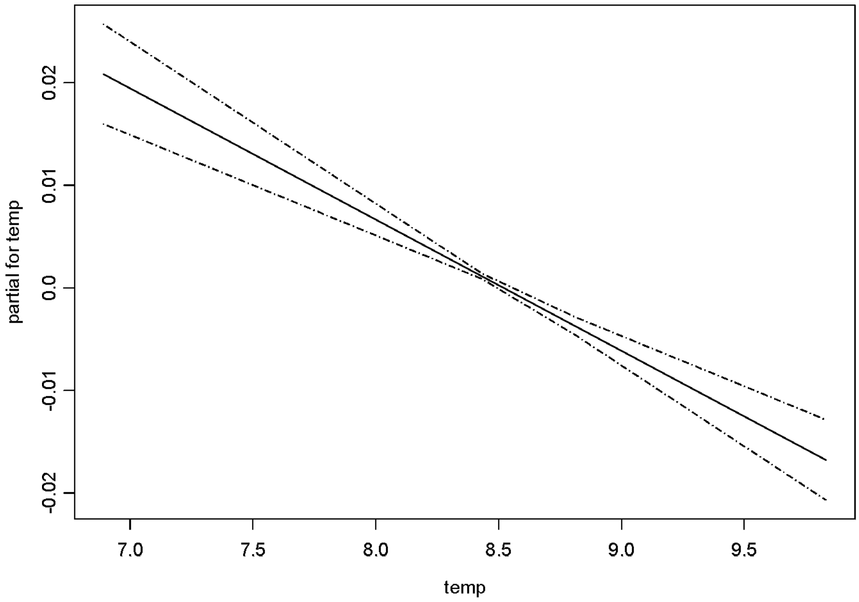


Figure 4.5.4. The response effect for the weight of North Sea cod to the average annual temperature of the year in which the English groundfish survey samples were taken.

4.6 Changes in North Sea plaice condition

4.6.1 Methods and results

Data for this analysis were available both from research surveys and from market sampling, principally from the port of Lowestoft during the period 1983–1999. The data were extracted from the biological sampling database held at Cefas, Lowestoft. A breakdown is given in Table 4.6.1.1. The complete data set contains 50 000 records from market sampling and 11 654 from groundfish surveys. Survey-derived data were not considered in further analyses because the fishing gear used in the North Sea is not designed to sample plaice. For most years from 1983 onward, the market sampling consists of between 100 and 300 records per month. The origin of the fish is described in Bromley (2000) and are principally from the central North Sea. In general, individual parameters of age (from otolith analyses), length, gutted weight, sex, and maturity stage have been recorded (note that plaice caught during the groundfish survey are weighed complete). The data have been analysed by Bromley (2000). Plaice sexual maturation was shown to be affected by body weight, age, and geographical location and was subject to annual and seasonal variation. A clear annual cycle of changes in weight-at-age for mature fish was demonstrated with weight increasing in the months before the onset of spawning (June–December), followed by a rapid decrease. Males showed a similar though less extreme cyclical pattern. Of interest to the present working group is whether there are identifiable patterns in change of weight-at-length (condition) in the data set. This was not analysed by Bromley (2000). Condition was computed as:

$$\text{Condition} = (\text{weight} \div (\text{length})^3) \times 100 \qquad \text{Equation 4}$$

Table 4.6.1.1. Summary of southern North Sea plaice data available from surveys and market sampling.

	From groundfish survey	From market sampling
1977 Female	404	0
1977 Male	296	0
1978 F	458	0
1978 M	354	0
1979 F	463	0
1979 M	367	0
1980 F	390	0
1980 M	259	0
1981 F	411	0
1981 M	300	0
1982 F	221	0
1982 M	170	0
1983 F	211	2 326
1983 M	177	1 117
1984 F	270	2 285
1984 M	207	1 051
1985 F	266	2 263
1985 M	187	1 128
1986 F	331	2 221
1986 M	252	993
1987 F	276	2 357
1987 M	225	1 021
1988 F	419	2 274
1988 M	316	800
1989 F	395	2 379
1989 M	314	841
1990 F	464	1 833
1990 M	353	1 036
1991 F	567	1 719
1991 M	434	973
1992 F	210	1 746
1992 M	157	986
1993 F	152	1 614
1993 M	107	953
1994 F	0	1 484
1994 M	0	902
1995 F	0	1 505
1995 M	0	938
1996 F	247	1 753
1996 M	144	982
1997 F	374	1 922
1997 M	264	966
1998 F	56	1 851
1998 M	53	1 031
1999 F	72	1 772
1999 M	61	978
Total number of observations	11 654	50 000

Figure 4.6.1.1 shows the cycles in median condition with age averaged. A clear difference between males and females is apparent, with the males reaching a peak in condition a month or two before the females.

Figures 4.6.1.2 and 4.6.1.3 show annual cycles in median condition for all males and females. There are indications of periods when peak condition appeared to be lower than average (e.g. 1991–1994 for females).

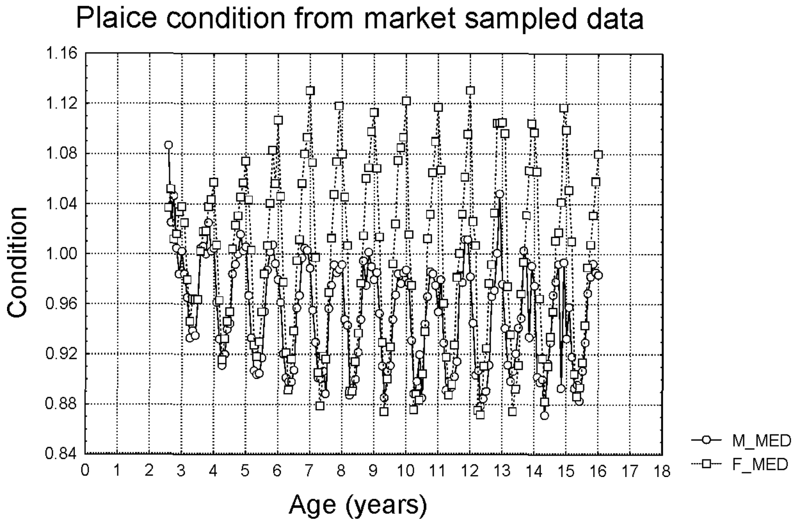


Figure 4.6.1.1. Changes in condition of males and females with age averaged over all years.

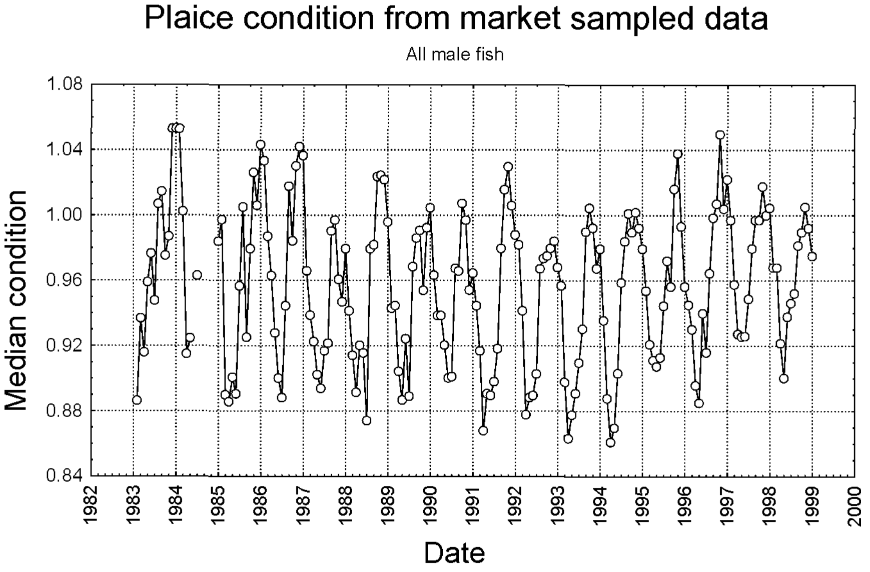


Figure 4.6.1.2. Annual cycles in median condition for male plaice.

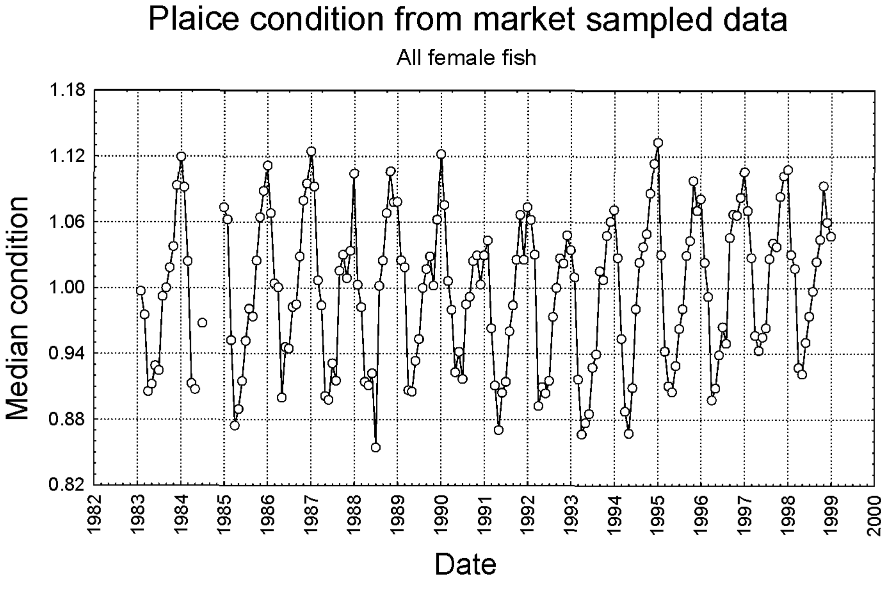


Figure 4.6.1.3. Annual cycles in median condition for female plaice.

Exploratory plots were made to evaluate whether any connection existed between peak female condition and peak North Sea bottom temperatures. Figure 4.6.1.4 shows that there does not appear to be any obvious relationship, but it must be emphasized that this is a very preliminary and crude analysis; for example, the bottom temperature data are averaged for the whole southern North Sea and not targeted by region where plaice feed during the summer. Condition is likely affected by many other factors than temperature, and this requires further exploration.

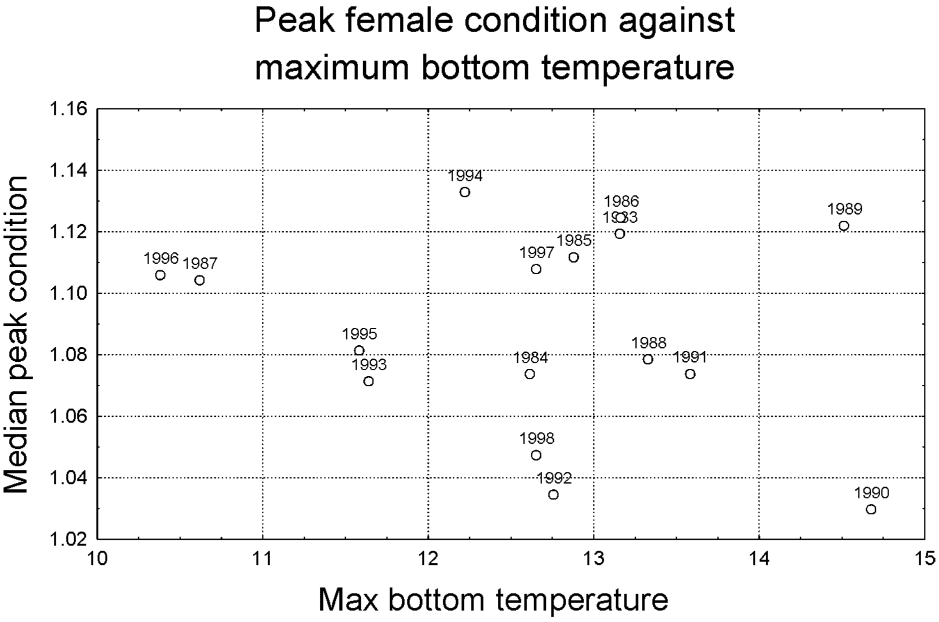


Figure 4.6.1.4. Peak female condition against peak monthly mean bottom-water temperature for the whole North Sea.

A preliminary exploratory analysis was undertaken to investigate the relationship between the condition factor and sexual maturity of female North Sea plaice. The maturity data were derived from the Lowestoft fish market during the period 1983–1999 and the English summer groundfish surveys of the North Sea from 1977–1998. Data from the market sampling for the months August to December (6500 fish) and from the surveys for the same months (3100 fish) were analysed. Market sampled fish are gutted at sea, but the gonads were left *in situ*. The stage of sexual maturity was determined for length-stratified samples of up to 200 fish (mixed sexes) per month, based on visual inspection of the exposed anterior region of the gonad. For this analysis, ovaries were classed as immature or maturing/mature. Plaice maturity was also sampled on the annual English summer (August/September) North Sea groundfish surveys from 1977–1998, which covered the whole North Sea. The fish were caught in a Granton trawl with a 20-mm stretched-mesh liner in the codend to retain smaller plaice than are landed commercially. Sampling was length-stratified on a regional basis, with the fish measured and weighed at sea.

Regression analysis was used to summarize the data to ascertain the general trends in maturity in relation to year, age, and condition factor. The form of the model was:

$$\text{Logit}\,(\,E[y]\,) = I + \beta_1 Y_i + \beta_2 A_i + \beta_3 C_i$$

In the model, the maturity of each individual fish was input in binary form, taking the value 0 if the gonad was immature and 1 if the gonad was maturing. The estimated maturity level (E[y]) predicted by the model was the number of maturing and mature fish expressed as a proportion of the total number of fish, where I = intercept, Y= year, A = age in years, and C = Condition factor (100 × weight ÷ length^3). The exploratory analysis was undertaken for females only.

The results from market sampling (Table 4.6.1.2 and Figure 4.6.1.2) show the proportion of maturing/mature fish increased markedly with the age of the fish as expected. However, there also appears to be an effect of condition with young fish needing to reach a higher condition factor before starting to mature. Within year classes, there is variability in maturity that appears related to year effects and the month of sampling. It is clear that, when the condition factor is high, a greater proportion of fish are likely to mature, thereby increasing the spawning-stock biomass estimates. Similar results are apparent in the analysis of groundfish survey data (Table 4.6.1.3 and Figure 4.6.1.6). The shape of the relationship is slightly different, probably reflecting the more restricted time over which the fish are sampled (August–September as opposed to August–December). The conclusions from the groundfish survey data are in accord with those reached based upon market sampled data.

Table 4.6.1.2. Logistic modelling of plaice maturity data derived from English market sampling.

Logit(MATURITY) = −72.11 + 0.031 YEAR + 1.22 AGE + 6.21 CONDITION

Analysis of Deviance					
Source	DF	Deviance	Deviance / DF	Scaled Dev	Pr>
Model	3	2 298.8963	766.2988	2 298.8963	<0.0001
Error	6 556	3 243.5765	0.4947	3 243.5765	
C Total	6 559	5 542.4728			

Type III (Wald) Tests			
			Pr >
Source	DF	ChiSq	ChiSq
Year	1	9.0273	0.0027
Age	1	686.5551	<0.0001
Cond	1	219.2528	<0.0001

Parameter Estimates					
					Pr >
Variable	DF	Estimate	Std Error	ChiSq	ChiSq
Intercept	1	−72.1103	20.7523	12.0743	0.0005
Year	1	0.0313	0.0104	9.0273	0.0027
Age	1	1.1791	0.0450	686.5551	<0.0001
Cond	1	6.2050	0.4191	219.2528	<0.0001

Table 4.6.1.3. Logistic modelling of plaice maturity data derived from English groundfish survey.

Logit(MATURITY) = −26.17 + 0.010 YEAR + 1.04 AGE + 2.22 CONDITION

Analysis of Deviance					
Source	DF	Deviance	Deviance / DF	Scaled Dev	Pr>
Model	3	1 164.4013	388.1338	1 164.4013	<0.0001
Error	3 139	2 839.9536	0.9047	2 839.9536	
C Total	3 142	4 004.3550			

Type III (Wald) Tests			
			Pr >
Source	DF	ChiSq	ChiSq
Year	1	2.0946	0.1478
Age	1	516.5365	<0.0001
Cond	1	39.6058	<0.0001

Parameter Estimates					
					Pr >
Variable	DF	Estimate	Std Error	ChiSq	ChiSq
Intercept	1	−26.1746	14.4988	3.2591	0.0710
Year	1	0.0105	0.0072	2.0946	0.1478
Age	1	1.0457	0.0460	516.5365	<0.0001
Cond	1	2.2233	0.3533	39.6058	<0.0001

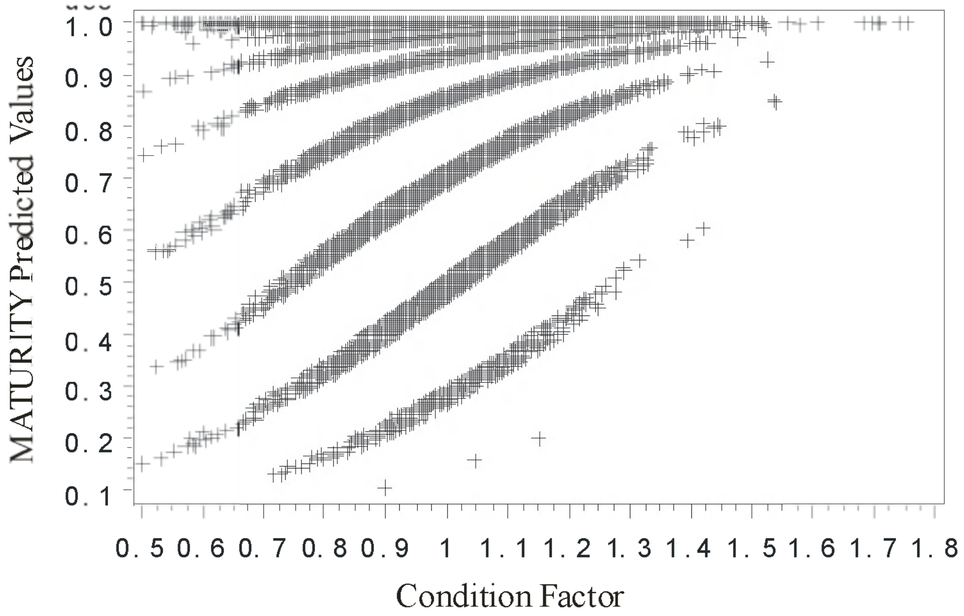


Figure 4.6.1.5. English market sampling of North Sea plaice.

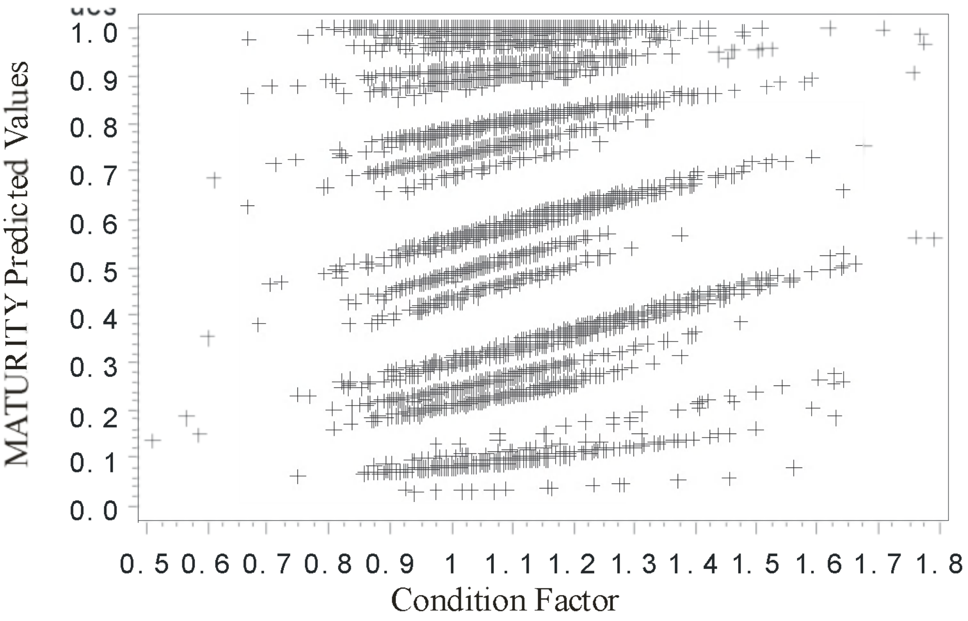


Figure 4.6.1.6. English groundfish sampling of North Sea plaice.

4.6.2 Conclusions

The allometric weight–length relationship expressed as a simple condition index for plaice in the central North Sea shows clear annual cycles related to maturation and spawning. The peak of condition is reached in December for females and in October or November for males. In addition to the month of sampling, condition is influenced by the sex and age of the fish as indicated by Bromley (2000). Statistical modelling also indicates that there is a significant year effect, and there is some preliminary indication that periods of lower than average or higher than average peak condition may persist for several years. For any age group, higher condition during August–December is linked to an increased probability of ovaries maturing. The data suggest that maturity ogives used in the assessment could be tuned using fish condition data. The level of condition reached in any year is presumably related to the overall feeding success of the maturing fish, balanced with metabolic demands. Because temperature might be expected to affect growth and possibly the levels of prey availability, we undertook a crude analysis using North Sea bottom temperature data. However, this variable alone does not appear to explain interannual changes in peak female condition. It must be cautioned that the analysis was extremely crude and could be extended to include more direct measures of potential growth-regulating factors on the feeding grounds such as prey availability or temperature data selected from the known summer feeding areas of plaice in the North Sea. Excepting temperature, the likely limit on these analyses will be the availability of time-series data for variables such as prey availability for non-coastal regions of the North Sea. The data described were derived from the English plaice fishery, which takes place in the central North Sea. Similar market sampling data have also been collected from the Dutch fishery, and the two data sets are currently being analysed jointly (P. Bromley, pers. comm.). This analysis has been complicated by differences in the maturity scales used by the two countries. Future joint studies would be greatly facilitated by the adoption of common protocols and scales for assessing maturity within ICES member countries.

4.6.3 Recommendations

Further work on developing the cod growth and recruitment model shall focus on reconstructing the weight-at-age component. It is believed that the higher variation in observed weights in the older age classes may be driven partly by more uncertainty in their estimation and also by additional factors influencing the weight-at-age. As such, the way that temperature influences the weight-at-age will be reassessed. In addition, comparing modelled and observed lengths-at-age will show whether differences in observed and modelled weight result from lack of fit in the growth model or varying condition factors. A possible development in the model is to allow variable condition factors, because these may be able to capture some of the year-to-year variation in weight-at-age.

The model will be used in the near future in conjunction with sea temperature projections derived from the Hadley3 coupled atmosphere–ocean model to assess possible impacts of climate change on North Sea cod over the next 50 years. This work falls within the context of longer-term scenario simulations. Currently, the results cannot be passed directly into medium-term projections for this stock because of the relative uncertainty in the underlying relationships included in the model. See Section 8 for further discussion and details.

Finally, such models could be reparametrized for cod stocks in contrasting regions such as the Barents Sea. A comparison of stocks at the northern and southern limits of the species range could be informative.

The rationale for considering maternal effects (age, condition, and whether fish are first-time or repeat spawners) is that these factors are very probably linked to egg quality and size, and thus survivability of early life history stages. Much of the understanding of maternal factors has come from aquaculture studies. Recent mesocosm studies in Norway have attempted to extend this understanding by rearing larvae from known parental stocks in mixed populations. Genetic identification was used to identify the parentage of surviving larvae. Published results from this study indicated that differences in environmental conditions between replicate mesocosms appeared to have a stronger effect on survival than parentage. We recommend support for further experimental studies on larval growth and survival in relation to maternal factors and also suggest that the ICES Working Group on Recruitment Processes (WGRP) might review current understanding on this subject.

Market sampling and fisheries survey observations that include measurements of condition (in whichever form is appropriate to each species) along with assessments of maturity can provide valuable insight into changes in fisheries population reproductive potential. But such analyses must be based on rigorously collected data. For market sampled observations, in particular, care must be taken to understand possible changes in selectivity of the commercial fishery. For both sources of data, there needs to be unified protocols and scales for the assessment of maturity to ensure that data sets from differing countries can be combined for analysis. There is a temptation to merge maturity stages to achieve this, but maturity scales need to be sufficiently detailed so that patterns in maturity and spawning can still be resolved. Coordination of maturity assessment on national market sampling needs to be considered within ICES.

4.7 The STEREO project (Stock Effects on Recruitment Relationships, EU FAIR-CT98-4122, December 1998–November 2001)

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 methods of stock assessment and projections. The study group felt that STEREO should also be considered within the larger management context, and so it investigated what of the project's additional information could be useful to managers.

4.7.1 Overview of the STEREO project

The STEREO project has been described and summarized in several ICES documents (Mackenzie *et al.*, 1999; ICES, 2000c, 2000e). Briefly, on one hand, the project involves field, laboratory, and modelling investigations of 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 project involves the dispersal, growth, mortality, and settlement of eggs, larvae, and juveniles, including density-dependent processes. The project has developed a biophysical modelling approach that integrates knowledge of demersal fish reproductive biology and early life history ecology. The basic philosophy of the project 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 can predict the spatial distributions of surviving juveniles from an initial space-age-length-abundance distribution of spawning stock, and its success with respect to measured trawl survey data is the major test of its performance. The project's case studies include Icelandic cod, North Sea and west of Scotland cod, and haddock.

4.7.2 Applications of STEREO project outputs

From the project's inception, it was never envisaged that the STEREO model system would ever be applied as a method in stock assessment and prediction. The system is too complex for that and is fundamentally a research tool for integrating understanding of the processes that 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 basic shape of stock–recruitment relationships, given the various biophysical 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 believed that this would be a valuable contribution to assessment methods 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, BD15).

The project's emphasis 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 therefore, that are 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 also larger eggs per unit of 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 could 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, BD17). 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.

4.8 Area-based case studies

This section provides a brief summary of process studies in selected areas, touching on the potential for using the results from these studies in management advice. The areas covered here represent the interests of members of this meeting of SGPRISM. They are also notable for the differing extents to which the areas have been covered by process studies, ranging from highly detailed and systematic coverage (Baltic Sea) to much sparser coverage (North Sea).

4.8.1 Baltic Sea

The processes affecting recruitment to stocks in the Baltic Sea have been studied extensively under the EU CORE and STORE programmes. A general introduction to these programmes is given by MacKenzie and Köster (2001), and the following summary of progress in the STORE project, with particular reference to cod recruitment, is adapted from Schnack and Köster (2001).

The objectives of the STORE project are:

1) Determine stock–recruitment relationships for Baltic cod and sprat in relation to key environmental factors influencing the production of viable spawn and the survival of early life history stages.
2) Improve short-term predictions of stock development by integrating recruitment estimates, based on the present status of the stock and its biotic and abiotic environment.
3) Develop predictive recruitment models for medium- to long-term forecasts of stock development under different environmental and fishery scenarios.
4) Estimate biological management reference points, critical stock limits, and target spawning stock sizes based on stock–recruitment relationships and stock development simulation models, and considering the precautionary approach for fisheries management.

Based on extensive retrospective data compilation and verification, simple correlation analysis have been made first between SSB and stage I egg production derived from ichthyoplankton surveys, and then between four successive developmental stages of cod and sprat (Table 4.8.1.1). When concentrating on these subareas, which were best sampled for the respective species, there is a significant correlation for cod between the abundance of larvae and 0-group stage, but not between any of the earlier stages. This indicates that variations in spawning stock structure and in environmental conditions during egg-to-larval development are critical for recruitment success of Baltic cod, whereas larval-to-juvenile development appears more stable. In sprat, the main regulation seems to take place in the larval-to-juvenile phase. In the following, only cod is considered further, with a focus on the critical early stages.

Table 4.8.1.1. Correlation coefficients for successive early life stages of cod in Subdivision 25 and sprat in Subdivision 26.

Variable 1	Variable 2	Cod SD 25	Sprat SD 26
SSB[1]	Egg production stage 1	019	**066***
Egg production stage 1	Egg production stage 3	051	**082***
Egg production stage 3	Laval abundance	036	**081***
Laval abundance	0-group abundance	**080***	032

***correlation coefficients significant at p<0.01.**

[1]based on maturity ogives invariate over time.

In Table 4.8.1.1, SSB is based on constant maturity ogives as used previously in standard stock assessment. When including the actual fluctuation in maturity ogives and using only the mature female stock component, this is already significantly correlated with stage I egg production. Moreover, relative fecundity changes over the years, with an obvious general trend to higher values in more recent years (Kraus *et al.*, 2000). At the population level, this fecundity appears clearly related to the food supply (Kraus *et al.*, 2002), expressed as suitable clupeid (sprat age-groups 1+ and herring 1–2) biomass per predator weight. Temperature had an additional but very minor effect. Because SSB appears too coarse a measure of the potential egg production, information on maturity and fecundity must also be considered.

Calculating the potential seasonal egg production, based on area-specific mature female stock components and relative fecundity values predicted from food availability, leads to a significant relationship with the observed daily egg production as obtained from egg surveys during peak spawning time. A corresponding relationship is also obtained with the observed total seasonal egg production, but can be based only on a rather limited data set.

Turning now to the second phase in the correlation scheme, which addresses the variability in egg mortality, this phase for cod is assumed to depend largely on the oxygen conditions in the deepwater layers. To consider this factor, the recruitment volume (RV) has been defined by Plikshs *et al.* (1993), which identifies the pelagic habitat volume in the depth range with sufficient salinity for fertilization success and floating of cod eggs, and with an oxygen level above the minimum required for egg development. This RV has frequently been utilized in stock–recruitment considerations, but unfortunately it explains only a limited part of the variation in egg mortality (Köster *et al.*, 2005). This can be related to the problem that, when using the total RV in the Baltic combined for the different spawning areas as a measure of oxygen-related survival, a large and varying amount of the total egg production is placed in areas with no RV. Further, large and varying portions of the total RV may be available in areas with no egg production. Thus, individual spawning areas must be considered separately. In addition, the proportion of the total egg production placed within the vertical range of the RV varies according to the shifting salinity profile, and the survival of these *well placed* eggs depends largely on the widely varying oxygen profile within the limits of the RV. So this vertical information must be utilized as well.

From experimental work, the relative viable hatch has been related to oxygen, and this relationship has been utilized to define an improved oxygen-related survival index (OES). This index is based on the observed oxygen profile and the predicted vertical egg distribution, derived from the salinity profile (Köster *et al.*, 2001). This new survival index follows the variation in RV only in the very general trend; for specific years or periods, there are substantial differences. Predicted egg survival, based on the OES, is significantly related to observed daily egg survival, as derived from successive egg surveys during peak spawning. Further, when applying OES to the estimated potential egg production, the predicted surviving seasonal egg production explains a significant part of the variation in the observed seasonal production of stage III eggs. This could not be achieved with the RV. The remaining variance is still high, but this is not surprising because the variance between potential and realized egg production is still included, and other factors, especially predation, are effective in addition to oxygen.

Quantitative estimates of predation on early life stages are difficult to obtain (Bailey and Houde, 1989). The predation by sprat is rather high in the early years of this time-series, but is much reduced in recent years, whereas predation by herring has increased, and in total, the relative importance of predation has decreased. This shift in the importance of the two clupeid species can be explained by the shift in the peak spawning time of Baltic cod from spring to summer. Sprat leave the central parts of the basins after spawning and feed in shallower waters, and herring, having spawned in the coastal areas, return to the central parts.

In addition to these changes in the horizontal overlap of predator and prey, variation is also observed in the vertical overlap, depending on the salinity and oxygen profiles. When combining predator abundance and vertical overlap of predator and prey, the results indicate an especially high predation on cod eggs in the second half of the 1980s and much lower levels in the years before that and in recent years.

In the early larval phase, predation appears much less important (Köster and Möllmann, 2000), but during this stage, the food supply may be more relevant, especially when considering changes in the zooplankton composition, described by Möllmann *et al.* (2000, 2001). Based on light conditions, visual performance, and vertical distribution of the larvae, the food supply in the depth range of 25–50 m should be most critical, as described by Grønkjær and Wieland (1997). The seasonal distribution of abundance of nauplii has been modelled for the Bornholm basin (Hinrichsen *et al.*, 2002) and presented as average concentration in dependence of the total water depth. When all species are considered, the concentration of nauplii is not substantially different between deep and shallow areas, and a marked seasonal maximum appears in May–June. Excluding *Pseudocalanus elongates*, a species that has reduced in abundance in recent years (e.g. Möllmann *et al.*, 2000), the seasonal maximum of nauplii is shifted to autumn, and concentrations are much lower in the deeper parts of the basin, where the early larvae are mainly placed, as compared with the shallower areas. This result shows the potential relevance of the observed changes in species composition of zooplankton in recent years for cod larvae survival.

For the larval to juvenile phase, mortality was not as variable as for eggs (Table 4.8.1.1). Nevertheless, two factors are important: the drift of the pelagic stages and the mortality resulting from cannibalism.

In the drift pattern of larvae, yearly differences may be quite striking as derived from hydrodynamic modelling (Hinrichsen *et al.*, 2001). The drift into shallow areas appears essential to the settlement of the early juvenile stages and successful further development. Therefore, a larval transport index has been developed, based on the wind conditions, to be included in the cod recruitment model.

MSVPA indicates that the second factor, cannibalism, is indicated by to be a major potential source of pre-recruit mortality (e.g. Neuenfeldt and Köster, 2000). However, large differences were obtained in the suitability coefficients of 0-group cod as prey obtained from MSVPA runs based on subsets of stomach content data covering different periods. These differences were obvious only for predators above age 4, related obviously to a decline in spatial overlap with the juvenile stages at decreasing adult stock size (Uzars and Plikshs, 2000). Thus, a substantial variability in pre-recruit mortality resulting from cannibalism is to be expected only if substantial amounts of older age classes are present in the stock.

Those factors identified as significant in the different spawning areas have been included in statistical stock–recruitment models, built up individually for the three major spawning areas. Then the effects were combined for the central Baltic in total. Factors being considered are: potential egg production, clupeid egg predation, oxygen content in the reproductive volume, and larval transport index (the last in Subdivision 25 only).

The combined model fairly well describes at least the general trends in recruitment variability as obtained from MSVPA. However, differences may still be substantial for individual years, e.g. 1979. To test its predictive power, the model was refitted again to the time-series of data, excluding alternatively the first or the last four years. The models derived this way could predict the recruitment success reasonably well in these excluded years, again with exception of 1979. Also for the most recent years after 1995, not included in any of the fitting procedures, the predictions compare well with the VPA estimates. This, however, is a less rigid test, because only minor changes occurred in stock size and recruitment during this last period.

In conclusion, the basis for prediction of Baltic cod recruitment has obviously been improved, but the model still utilizes a conventional statistical approach. The improvements have been achieved by using more of the available information and including newly provided results, which, for instance, allow estimates of the potential egg production more reliably than only using SSB, a too-coarse proxy. To a large extent improvements are related to a better spatial resolution of information: i.e. individual spawning areas have been handled separately, and predator–prey overlap, larval transport, and the distribution of eggs within the oxygen profile—including consequences for survival—have been considered. The remaining variance in the recruitment model may be mainly attributed to the result of parental effects on early life stages (Vallin and Nissling, 2000) and to the prey availability for larvae (Hinrichsen *et al.*, 2002). Neither factor has been considered in the model, but both are being studied in the STORE project.

In addition to the spatial aspects, further improvement of resolution in time will be essential. So far, average environmental conditions in the main spawning times and areas have been considered. However, these may not always be the most relevant ones. Backtracking of actual survivors to their birth dates and places, based on age analysis and drift modelling, shows that they might, to a large and varying extent, originate outside the spatial and temporal centres of egg production (St John *et al.*, 2000).

Thus, a main focus of the project is describing characteristics of survivors and identifying the environmental conditions relevant to growth and survival on adequate scales. On the modelling side, purely statistical models, assuming linear though multifactorial relationships, do not seem to be satisfactory for predicting purposes. Thus, the construction of individual-based models (IBM) is attempted to follow the developmental success, based on a number of functional relationships and non-linear responses to environmental conditions. This is done in combination with hydrodynamic and some foodweb modelling to provide the relevant environmental input data to the IBM. This approach introduces a better resolution in time and allows the study of sequential effects for changing conditions, which may be different from effects of constant average conditions. Also, it allows the inclusion of variance in the performance of individuals within a cohort and its relation to characteristics of the parental stock.

Potential use of process information in assessments for Baltic cod

As the above summary notes, the STORE project intends to incorporate information obtained on recruitment processes into medium-term projections and reference points for cod and sprat. WD14 summarized some preliminary investigations for Baltic cod. It noted that most of the existing studies on stock and recruitment used multiple regression models, which were not suitable for direct use in stock projections. This was partly because regression models are not appropriate for use with values outside the range of observations, and partly because the studies summarized above have used multispecies assessments, which differ in age range and area coverage from the stock units used in the routine assessments. However, these studies emphasize that potential egg production and reproductive volume are important determinants of recruitment, and future work will focus on the incorporation of these effects into stock projections.

4.8.2 Barents Sea

It is believed that, to a large extent, the state of the Barents Sea ecosystem will be revealed through the state of the stocks of northeast Arctic cod, Barents Sea capelin, and Norwegian spring-spawning herring (Hamre, 1994). Both total fish production in the Norwegian–Barents

Sea area (including Norwegian coastal waters) and other aspects of the total ecosystem are believed to be closely linked to the development of these stocks. Cod prey on capelin, herring, and young cod (Bogstad and Mehl, 1997), while herring is an important predator of capelin larvae (Huse and Toresen, 2000). Cod growth is also affected by prey (especially capelin) abundance (Mehl and Sunnanå, 1991). All three stocks show large variations in recruitment.

In the present case study on including process information in stock–recruitment models for fish species in the Barents Sea, we only consider these three species. Appropriate modelling of other processes (growth, maturation, predation–species interactions) are also important, both for short-term and medium- and long-term stock prognosis for these three stocks. However, in this context, we will focus on how to incorporate process information in stock–recruitment models for these three species.

Cod

The recruitment of northeast Arctic cod is quite variable, and several processes and variables have been suggested as explanation: spawning-stock biomass, egg production, temperature in the spawning–larvae period, NAO, cod cannibalism, prey abundance, wind and currents, etc. (see e.g. Marshall *et al.*, 2001, WD 11; Ottersen and Sundby, 1995; Ottersen and Stenseth, 2001; Bogstad *et al.*, 1994). The issue of replacing spawning-stock biomass with other measures (e.g. total egg production) of reproductive potential was considered in Section 4.4.

To improve short-term predictions for this stock, there is a need for predicting year classes that have been spawned but have not yet entered the fishery. Also, there is a need for incorporating process information to improve medium- and long-term predictions. These two issues will be addressed separately below.

Northeast Arctic cod enters the fishery at age 3. Since 1987, the ICES Arctic Fisheries Working Group has used the ICES computer program RCT3 (formerly RCRTINX2; Shepherd, 1997) to predict the strength of recruiting year classes at age 3. This is a simple calibration and regression method, which combines multiple time-series of recruitment indices and VPA estimates of year-class strength at the age of recruitment to the fishery. It does not consider at which life stage an index is measured. Also, RCT3 does not include information on environmental conditions, cod cannibalism, and other processes, which are important in determining recruitment of this cod stock. A model that predicts the abundance of NEA cod of a cohort of age 3, based on available information about the abundance at earlier life stages, as well as process information, should be constructed. Tretyak (1999) constructed this type of a model that included the mortality from ages 0–3, but a model is required that incorporates both Norwegian and Russian data sources and recent knowledge of process information (see WD 7 for a summary of some recent studies).

For medium- and long-term predictions, a population model for cod, where the recruitment is modelled accounting for fecundity information and cannibalism, could be a reasonable first step. Thereafter, the biological realism of the predictions could be improved more easily by using a cod–capelin–herring model rather than by including more process information in the stock–recruitment model for cod. Cod cannibalism is inversely related to capelin abundance (ICES, 2001a), which could be accounted for using a multispecies model.

For this stock, it is also important to model the length of the age 3 recruits, as this can vary from 28 to 41 cm, according to Norwegian survey data (ICES, 2001a).

Herring

Norwegian spring-spawning herring spawn along the Norwegian coast, but abundant year classes are generally found in the Barents Sea approximately from age 6 months until age 3. Year-class strength seems to be determined in the first half year of life; the larval survey in April is a good indicator of spawning stock size, but is useless for predicting recruitment, while the 0-group survey in August–September is a reasonable predictor of recruitment. Temperature variations are also an important factor affecting recruitment, but according to

Toresen and Østvedt (2000), it was mainly heavy fishing pressure and not environmental variability that caused the stock to collapse in the late 1960s.

The recruitment model used by WGNPBW (ICES, 2001d) is a traditional Beverton–Holt recruitment model, where the parameters are estimated on a log scale. However, the recruitment is highly dynamic with a few outstanding year classes. To better adapt the model to this stock, 10% of the highest recruitments are excluded from the regression. When a draw from the recruitment model is made, these year classes are selected with a 10% probability, and a draw with equal probability is made. If the highest recruitments are not selected, the recruitment is given as the exponentiation of the logarithm of the Beverton–Holt model with a random draw from the residuals added. This relationship does not contain any process information.

As for cod, process information should be included in predicting herring year classes that already have been spawned (from age 0 to age 3, at which the fishery starts). However, much less survey information is available for age 0–3 herring than for cod.

Capelin

Predation by juvenile herring on capelin larvae seems to have a strong impact on the recruitment to the Barents Sea capelin stock. Hamre (1985) was the first to suggest that the decline in the capelin stock could possibly be associated with the presence of young herring in the nursery area of the capelin larvae. In years with high abundance of juvenile herring in the Barents Sea, capelin recruitment is severely hampered (Gjøsæter and Bogstad, 1998).

Capelin spawn approximately 1 April. In “herring” years, the abundance of capelin larvae, as measured during a larval survey in June, seems to be adequate for securing recruitment. However, in these years, nearly all 0-group capelin disappear between this June survey and the 0-group survey (Anon., 1997) in August–September (WD 3). Predation by herring on capelin larvae has also been observed (Huse and Toresen, 2000). The effect of herring on capelin recruitment also appears to be linked to the overlap of juvenile herring and 0-group capelin (Gjøsæter and Bogstad, 1998).

Gjøsæter and Bogstad (1998) fitted the following curve to the stock–recruitment data for capelin abundance data for young herring:

$$R = \frac{758SSB}{SSB + 74 + 2797H_{1+}}$$

where H_{1+} is the biomass (million tonnes) of 1-year and older herring in the Barents Sea from the acoustic young herring surveys in the Barents Sea during May/June. This model explains 87% of the variation in recruitment at age 1. The relationship should be revised, based on new data on herring abundance and capelin spawning-stock biomass, but is formulated so that it can be used for short- and medium-term predictions of the capelin stock. The abundance of young (1+) herring in the Barents Sea can be predicted reasonably well one year ahead, based on survey data.

Barents Sea capelin has almost total spawning mortality and is managed by a target escapement strategy (Gjøsæter *et al.*, 2002). The management is based on an acoustic survey in September, which is believed to give an absolute estimate of the abundance of 1+ capelin. A length-dependent maturation model is then used to determine the maturing stock, which is predicted half a year ahead, based on a multispecies model where predation by cod is taken into account. The fishery is conducted in January–April, mainly on the spawning stock. It has been discussed in the Northern Pelagic and Blue Whiting Fisheries Working Group (ICES, 2001d; Anon., 2001) how the target escapement strategy could be made dependent on the expected abundance of young herring in the Barents Sea in the year of spawning, but no method to do this has been found.

Prediction models that could be used

The multispecies model Bifrost (Anon., 2001) could be used for making predictions for the cod–capelin–herring system in the Barents Sea. This model is an age-structured multispecies model where predation, growth, recruitment, and fishery are modelled. It is currently used to investigate harvest control rules for Barents Sea capelin.

One way to include the process information on reproductive potential (Section 4.4) is to use a population model with an age and length structure. For northeast Arctic cod, such a tool is available: Fleksibest (Frøysa *et al.*, 2002). Fleksibest is a single-species application to northeast Arctic cod of the multi-area, multifleet, multispecies, age-length structured model framework Gadget (formerly BORMICON; Anon., 2001a). Here the population dynamics processes—growth, maturation, predation, and fishing—are modelled as length-dependent processes. A stock can be divided into a mature and an immature part, as is done in Fleksibest. It is easy to include information on sex ratio and on fecundity, as well as letting the condition factor influence the processes besides the length. Gadget currently lacks a stock–recruitment module (recruitment is estimated or read from file), but there are plans to include it. Using such a flexible framework allows studies of the effect of changes in growth, exploitation rate, and selection pattern on stock development.

4.8.3 North Sea

The only North Sea species examined by the study group was herring (*Clupea harengus*; WD8). The work was based on an interest in exploring life history trajectories to understand the factors that determine year-class strength in fish populations. In general, there are very few species for which there is sufficient information to undertake relatively detailed analyses of the different life history stages.

One exception is the long series of survey indices for North Sea herring. Fishery-independent data are available on the age, length, mean weight, fecundity, and abundance of the adults, larvae, 0-ringer pelagic stage, 1-ringers, and 2-ringers, thus providing information on the estimated number of eggs and abundance at spawning, 0–3 months, 3–6 months, 1 year, and 2 years within the life of a cohort. The data used in this study are generated from survey data and are assumed to be linearly related to the abundance of the life stage measured. Because there are no estimates of absolute abundance, the relationships between life stages can only be considered as relative.

The age structure of the adult population affects the numbers of eggs produced. There are relationships between egg production and the numbers of larvae, but there is a suggestion that the relationship has shifted over time (a regime shift in the North Sea during the late 1980s (Reid *et al.*, 2001)). In general, the numbers of early juveniles are positively correlated with the numbers of larvae, although there are some notable exceptions. In a series of three years (1988–90) plus 1997 there was poor survival from larvae to early juveniles and one year (1986) when survival appeared particularly good. In the next transition from early juveniles to 1-ringers, there was a good correlation between years, with one exception (1995). This was a particularly strong year class. Again, in the transition from 1- to 2-ringers, there were correlations between successive years, although there appeared to be a shift in survivorship for the periods pre- and post-1990. These data are visualized in the form of Paulik diagrams (Paulik, 1973), four panel graphs that highlight where in the life history changes occur in correlations between years in each year class (Figure 4.8.3.1, note that neither the estimated egg production nor 2-ring abundance are shown in this figure).

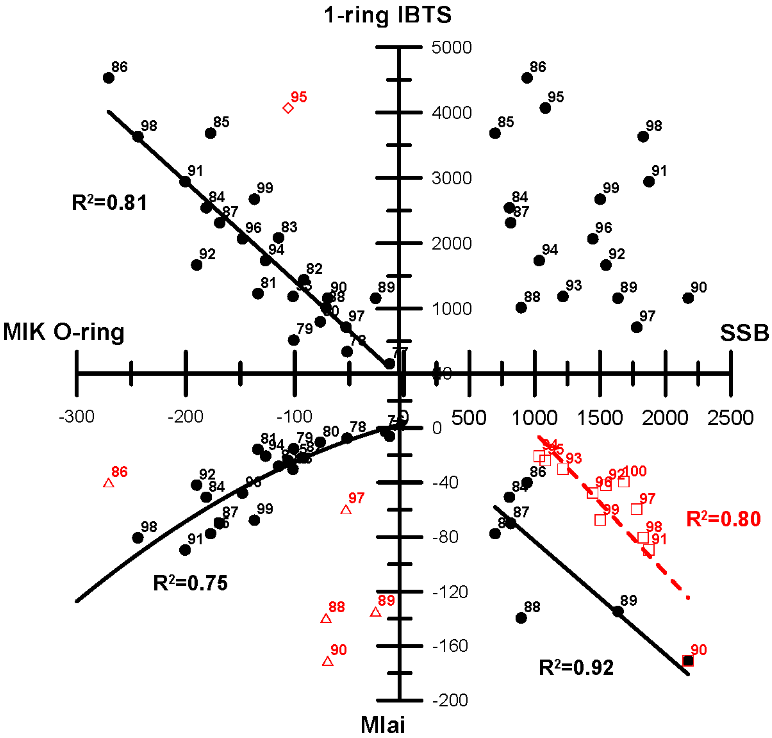


Figure 4.8.3.1. Paulik diagram for North Sea herring using survey data. Axes show the units for each index and are not absolute values. SSB estimated from acoustic surveys, Mlai (Multiplicative Larvae abundance Index), MIK 0-ring (Methot–Isaacs–Kidd 0-ring index), and 1-ring IBTS (1-ring index from the International Bottom Trawl Surveys). The SSB/Mlai panel has data divided into pre- and post-North Sea "regime shift" (see Reid *et al.*, 2001). In the Mlai/MIK panel, the years shown as triangles have been removed from the regression. In the MIK/1-ring panel, the 1995 data point (open diamond) has been removed from the regression.

It is apparent that good or bad year classes are formulated at different periods within life history. Variation in abundance of potential predators and/or competitors were examined in conjunction with the abundance of herring at the different life history stages, but these shed no light on the apparent shifts in survivorship. Without detailed studies on the predator–prey relationships for herring, it is not possible to determine the processes that determine year-class strength.

In reviewing stocks in the North Sea, it became apparent that no other stocks have sufficient information through the life history to allow such studies. In the same vein, there was not sufficient information on North Sea cod to undertake studies similar to those made on Baltic cod and sprat or Barents Sea cod and capelin. This may stem partly from the more complicated species interactions in the North Sea compared with either the Baltic or Barents Seas.

5 Fisheries and biology: process studies in assessment and advice

5.1 The management context for process information

Typically, management advice for an ICES stock uses an age-based assessment that estimates the current state of the stock, which is then compared with predetermined reference points. A short-term catch forecast will be used to present catch options for the coming year for a range of possible levels of fishing mortality; medium-term projections will be used to make a statement about the probability of a given management objective being achieved as a result of the various management options that are presented. In the absence of explicit management objectives for most stocks, these statements usually frame the probability of returning or maintaining the stock above specified biomass reference points.

This system presents two areas where process information might be incorporated: in the determination of reference points and in the projections used to estimate the probability that the management targets are achieved in the medium term.

5.1.1 Precautionary approach reference points

The precautionary approach to fishery management provides the framework for the fishery management advice provided by the ICES Advisory Committee on Fishery Management (ACFM; ICES, 2001c). This states that reference points will be given in terms of biomass and fishing mortality rate. The first of these two indicators describes an attribute of the resource (biomass) and the second one describes an attribute of the fishing fleet (fishing mortality). Although the two indicators are related, it is clear that process information is most relevant to the resource indicator. The use of the two indicator scales is summarized in the following extract from the ACFM advice:

> In order for stocks and fisheries exploiting them to be within safe biological limits, there should be a high probability that (1) the spawning-stock biomass is above the threshold where recruitment is impaired, and (2) the fishing mortality is below that which will drive the spawning stock to the biomass threshold, which must be avoided. The biomass threshold is defined as B_{lim} ($_{lim}$ stands for limit) and the fishing mortality threshold as F_{lim}.

This extract implies that ICES implementation of the precautionary approach centres on a rather simple model of stock dynamics, i.e. that there is a specific value of spawning biomass below which recruitment is impaired, and that fishing mortality is the only external factor that influences the size of the spawning stock. Such a simple approach is open to criticism, particularly in view of the information becoming available from process studies. Before elaborating on these criticisms however, we should point out that the simplicity of this conceptual model has a number of advantages from a management perspective. First, the two indicators, SSB and mean fishing mortality, are readily available from age-based stock assessments, so their estimation does not require data or modelling beyond what is already routine. Second, the simplicity also implies a correspondingly simple control rule for management action, e.g. "If $B < B_{lim}$, then take action". Third, the implication that SSB is influenced only by fishing mortality is often not far from the truth for heavily exploited stocks, with the added justification that fishing mortality is usually the only factor influencing SSB that fishery managers can seek to manage.

As noted above, the results from various process studies imply a number of criticisms of the conceptual model underlying the ICES implementation of the precautionary approach. First, there is the implicit assumption that SSB is an adequate measure of the stock's reproductive potential, when increasing evidence indicates that this is not the case (see Section 4.4). Second is the assumption that there is a fixed level of SSB (or reproductive potential) below which recruitment is impaired. This in turn implies that recruitment is determined only by reproductive potential—another point that is not consistent with the results of process studies.

These points also have implications for the effectiveness of fleet reference points, as in cases where stock size is not the only important influence on recruitment; a greater reduction in fishing mortality may be required to ensure a given probability of stock recovery. This in turn implies that process studies have implications for both resource (biomass) reference points, and fleet (fishing mortality) reference points.

Within the context of the current ICES implementation of the precautionary approach, a number of approaches based on the use of process information may be possible, for example:

- Use resource reference points that incorporate more biological complexity than SSB. At its simplest this could be no more than specifying a higher minimum SSB in cases where a large proportion of the spawning stock consisted of first-time spawners. More complex measures, perhaps even incorporating environmental information, might also be possible.
- Set reference points more conservatively in cases where effects other than fishing have a strong influence on the stock to account for the additional uncertainty caused by these other components.

Although they do not incorporate process information, it is useful to note that the segmented regression models used by O'Brien and Maxwell (WD5 and WD6) are an objective means of fitting a model that corresponds to the conceptual model behind the ICES precautionary approach.

5.1.2 Medium-term projections

A key feature of current medium-term projections is the use of a stock–recruitment model to estimate future recruitment. Fitting a stock–recruitment model in this way treats the other factors contributing to recruitment variation (apart from SSB) as residual variation, which is assumed to be random; using such a model in a projection implicitly assumes that this variation will continue to be purely random. A process study, by its very nature, will try to identify other components of this variation. Hence, a process study may increase the proportion of variance allocated to modelled effects in medium-term projections, and so reduce the residual variance. This will not reduce the variance around the projected recruitment estimates, unless the additional factors are readily predictable. This applies whether the additional factors are biological (e.g. fecundity) or environmental (e.g. temperature). The uncertainty around projections may actually be increased by explicitly accounting for the variation of these additional parameters, but this may be more realistic because current medium-term projection methods have been shown to underestimate the uncertainty around stock projections (Patterson *et al.*, 2000).

The reallocation of variance through the incorporation of process information represents a potential improvement to the procedure because it makes the assumptions about future variation of the additional factors explicit rather than implicit. This would allow presentation of medium-term projections for a number of scenarios—for example, environmental change, improved estimates of uncertainty, as well as in the quality of probabilistic statements that are based on the medium-term projections. This point was addressed in the report of this study group's the first meeting (ICES, 2000), and since then, some progress in these areas has been made.

5.1.3 Practical implications of incorporating process information in assessment and advice

Process studies can help us understand why a stock produces a certain level of recruitment for a given number of individuals in that stock and how the stock will behave in space and time. The implication is that more realistic population models and stock projection models can be formulated.

In the context of stock and recruitment, the process studies provide information and relationships, often relatively complex, on the factors that influence production and survival. Essentially, it is possible to provide new relationships between stock and recruitment with a basis in biological processes.

The general problem is that, currently, very few process studies have been undertaken with the direct intention of input to the assessment and management process. By their very nature, process studies try to understand what has happened in the past, and so, the models they use are detailed and descriptive, and are often based on multiple-regression approaches. Usually, these models are not suitable for use in projections, partly because of the need to forecast a large number of variables and partly because of undesirable properties, such as the possibility of generating negative recruitment or of generating a finite recruitment at zero stock size. Other drawbacks of these approaches are discussed in ICES (2000).

The fact that process studies tend not to produce recruitment models that can be used directly within projections means that additional work is required to develop recruitment models for projections using the results from process studies. How this is done depends on the nature and results of the process study, but in general such work might involve identifying a small number of major factors, and considering how these might be incorporated in a recruitment model of an appropriate functional form, and how they might be projected forward. Similar considerations also apply to how external factors might influence such processes as growth and fecundity.

5.1.4 The consequences of incorporating process information in management advice

The current ICES implementation of the precautionary approach assumes that SSB is an adequate measure of the reproductive potential of a stock and that fishing mortality is the major factor influencing SSB. Under this model, stock recovery is assured if managers can reduce fishing mortality and so allow SSB to return to above the biomass reference point. The simplicity of this conceptual model has advantages because it is readily understood by other stakeholders in the fishery. Introducing additional biological realism to the management advice would remove this advantage but, it is hoped, would improve the quality and credibility of the advice by more explicit acknowledgement of the influences of effects other than fishing.

6 Stock–recruitment models and simulation

Stock–recruitment (S–R) theory generally considers recruitment as parametrically dependent on stock. S–R analysis looks at the empirical relationship between the spawning stock size and the subsequent recruitment of the year class produced by that spawning. Analyses of S–R relationships are performed by fits of various curves to the S–R pairs. There is usually considerable deviation of S–R pairs from the best-fitting parametric curve(s). The deviations might arise because the assumptions leading to the derivation of the parametric S–R relation are not valid; the parameters in the S–R model equation(s) are not constant, but are functions of time; and errors in estimating stock size or recruitment are sufficiently large to obscure the underlying theoretical relationship.

The investigation of S–R relationships can result in functional models that are appealing when depicted in two dimensions as the level of recruitment vs. SSB. Translation of a fitted functional S–R model to the third dimension of time may produce an estimated sequence of recruitment that bears little resemblance to the time-series of recruitment used to estimate the two-dimensional functional S–R model (ICES, 1998). This difference might result from a failure to consider temporal effects (O'Brien, 1999a).

Attempts to quantify the relationship between stock and recruitment have their roots in the work of Ricker (1954) and Beverton and Holt (1957). Their approaches assume a functional relationship

$$R = \mathrm{fn}(S; \alpha)$$

between stock (S) and recruitment (R), dependent on a vector (α) of parameters. The approaches differ only in the particular choices of fn and α.

6.1 Parametric estimation

Much current analysis of the relationship between spawning-stock biomass (SSB) and recruitment (R) in a given stock is based on two- or three-parameter analytic models, developed to encapsulate biological processes in a way that can be used tractably in fisheries management. The initial task in such analyses is to estimate the parameters of the chosen model—that is, to fit the stock–recruitment curve to the scatterplot of stock–recruitment pairs via statistical estimation. There are several ways to do this: traditional approaches have used non-linear least-squares regression or maximum likelihood, while recent work (O'Brien, 1999) has developed the application of generalized linear models (GLMs).

The RECRUIT program, which is part of the Aberdeen Suite (Section 6.4.2) and is used to generate recruitment estimates for medium-term projections in WGMTERM, encapsulates the formulations for the Ricker, Beverton–Holt, and Shepherd models in one five-parameter construction. The particular model required is selected by fixing the values of certain of these parameters, while estimation of the remaining parameters (two for Ricker and Beverton–Holt, three for Shepherd) is achieved via non-linear least-squares regression.

The usual assumption for S–R modelling is that the pattern of variability in the level of recruitment follows a log-normal distribution (Peterman, 1981), although particular data sets may show different patterns and other distributions may be preferred for specific stocks (Power, 1996). A variety of distributional shapes can be expected to be descriptive of recruitment for different stocks, and the most appropriate function to describe the shape should be selected on a stock-by-stock basis (Shelton, 1992). This distribution assumption can be relaxed and replaced by a statement merely about the mean-variance relationship given that, in general, a particular choice of error distribution might be difficult to justify.

The first step is to decide which parametric S–R model(s) to fit. With some data sets, the choice may be made easily by visual inspection. If there is clear evidence of a decline in recruitment at high SSB (e.g. Figure 6.1.1), then a Ricker curve is sensible. But if average recruitment stays approximately constant over a wide range of SSB, a Beverton–Holt curve is more reasonable. Many data sets, however, do not have enough S–R pairs at high enough SSBs to allow a clear choice, and other S–R pairs may exhibit characteristics reminiscent of more than one parametric S–R model (e.g. Figure 6.1.2).

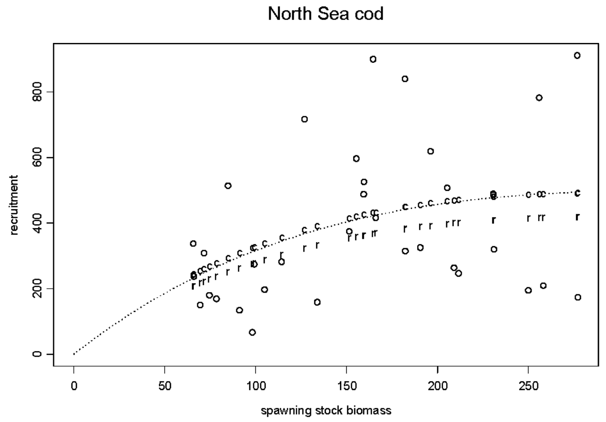


Figure 6.1.1. North Sea cod stock–recruitment. Recruitment is plotted against SSB, the log-normal Ricker stock–recruitment model is shown by the symbol r, the log-normal bias corrected Ricker stock–recruitment fit is shown by the symbol c, and the expected curve from a Gamma fit of the Ricker stock–recruitment model is shown by the dotted curve.

Model fitting of a parametric S–R curve must be undertaken with care to avoid inappropriate inferences and biased estimation. A flexible and reliable way to fit parametric models is to rewrite the S–R model as a generalized linear model (GLM), as suggested earlier. Software for fitting GLMs is available as part of standard statistical packages (e.g. GLIM: Francis *et al.*, 1993; S-PLUS: MathSoft, 1998); all that is required is the specification of a link function and the identification of an appropriate error distribution for recruitment. The details are presented in O'Brien (1999).

The effect that an inappropriate distribution assumption can have on parametric-based estimates of recruitment is best illustrated graphically as in Figures 6.1.1 and 6.1.2. In these plots, a Ricker stock–recruitment function has been fitted to S–R pairs for North Sea cod and North Sea plaice, respectively, based on the standard assumption of log-normality (both without and with bias correction) and an assumed Gamma distribution that does not require bias correction. Fitting the Ricker curve by the approach of least-squares regression with *ln* R as the dependent variable, under a constant CV assumption, however, leads to fitted values of recruitment at particular values of SSB that are biased downwards (McCullagh and Nelder, 1983), so this approach is not to be recommended. Adequacy of the distribution assumption can be diagnosed from a plot of the √|Pearson residual| against the corresponding fitted value, and if an error assumption is appropriate, there should be little systematic trend in the plot. This is the case for the assumed Gamma distribution, but not for the log-normal distribution.

Ideally, GLMs should be routinely fitted, but the log-normal bias-corrected Ricker stock–recruitment function yields similar fitted values for the two North Sea stocks considered by this study group (Figures 6.1.1 and 6.1.2).

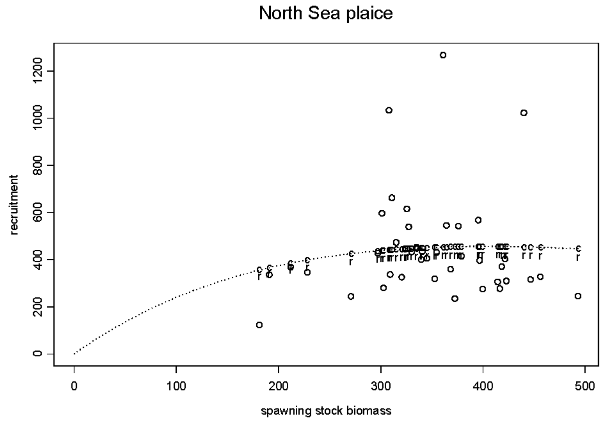


Figure 6.1.2. North Sea plaice stock–recruitment. Recruitment is plotted against SSB, the log-normal Ricker stock–recruitment fit is shown by the symbol r, the log-normal bias corrected Ricker stock–recruitment fit is shown by the symbol c, and the expected curve from a Gamma fit of the Ricker stock–recruitment model is shown by the dotted curve.

6.2 Numerical approaches to quantifying uncertainty in stock forecasts

6.2.1 Anchovy recruitment and environment in the Bay of Biscay

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 fluctuations. Spawning takes place in the Bay of Biscay between April and July. The population spawns in areas with 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 46°30'N and east of 05°00'W). Anchovy eggs and larvae develop from April until 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 anchovy 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 northeasterly 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 northeasterly winds, which 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 increasing subsurface chlorophyll, and to 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), among 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 as a result of the enrichment associated with 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 gradually disperse in that rich environment and be less subject to massive predation.

On the contrary, the northwestern winds are stronger, provoking downwelling and turbulence in the area, pushing the areas of influence of rivers toward the coasts and reducing the production and suitable spawning habitat for the spawning anchovy.

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

The northeasterly wind conditions in the Bay of Biscay are summarized in an upwelling index calculated from March to July each year (Borja *et al.*, 1996, 1998). Figure 6.2.1.1a summarizes the relationship between the upwelling index and recruitment estimates from the assessment performed in 2000 by ICES (2001e). Previously, the upwelling index explained about 55–60% of the interannual variability of the recruitment from 1987–1998. However, the addition of the most recent recruitment estimates (1999/2000) lowered that value to about 45%, without considering any stock–recruitment relationship.

Figure 6.2.1.1. Relationship between the upwelling indices 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 1987–1998 by simulating the oceanographic processes that are expected to be directly linked to the life history of larvae. This was made by a three-dimensional 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 interannual variability between 1987–1998. These two variables are by order of importance:

- An upwelling index that corresponds to the sum of mean weekly vertical currents from bottom to surface during the period March–July, along the Landes coast (southwest of France). These upwelling events are caused by the moderate and intermittent northeastern winds. This variable, as AZTI's upwelling index, has a positive effect in determining anchovy recruitment (Figure 6.2.1.1b).
- Stratification breakdown 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^{-1}) 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) in the IFREMER model drops to about 65% (and to 59% when adjusted for df).

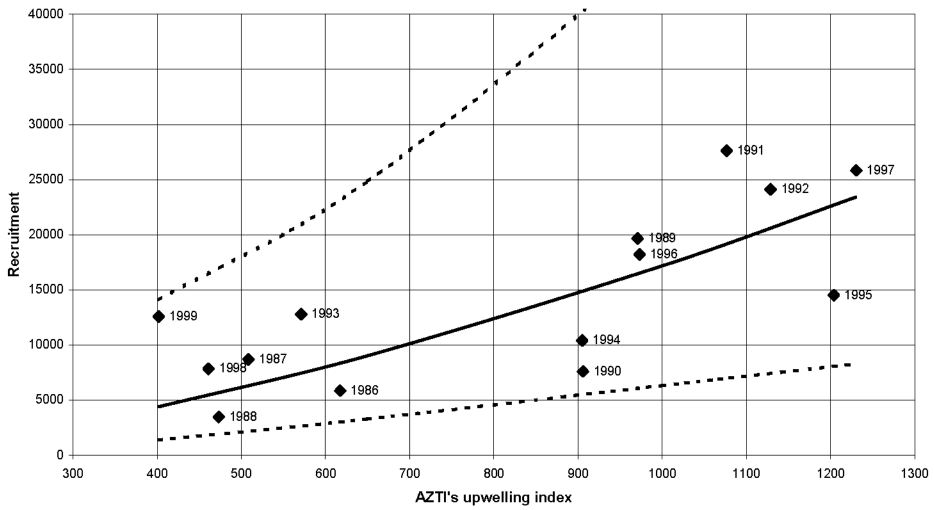


Figure 6.2.1.2. Predictive model applied in 1999 and recruitment estimates obtained in 2000 (ICES, 2001e).

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, 2000). Two bad recruitments were expected to occur in 1998 and 1999, and so the average spawning biomass predicted for 2000 (about 25 000 t) was below B_{pa} (= 36 000 t). However, the SSB estimate obtained during 2000 was actually about 47 000 t, resulting from better-than-expected recruitment in 1999. Given the low predicted SSB, the management measures adopted in 1999 to protect the stock turned out to be unnecessary, causing friction between the management bodies and 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 6.2.1.2), but the deviations in 1998 and 1999 had a common trend, leading to a SSB projection with only about 2–3% probability of upwelling occurring at random. That focused attention on the uncertainties associated with the predictions and on finding ways to enhance their predictive capability. Although the IFREMER model seems to have better predictive power, ICES (2001e) decided in 2000 not to make use of the environmental indices when recommending a catch level for 2001. Further investigation to improve the reliability and predictive power was endorsed.

6.2.2 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 (SSB) are the ones estimated by the most recent assessment performed (ICES, 2001e) 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 present 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 deviation in upwelling for each year compared with the average value since 1967 (= 869). The results from fitting the Ricker model with and without an environmental index are shown in Figure 6.2.2.1. 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.

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.

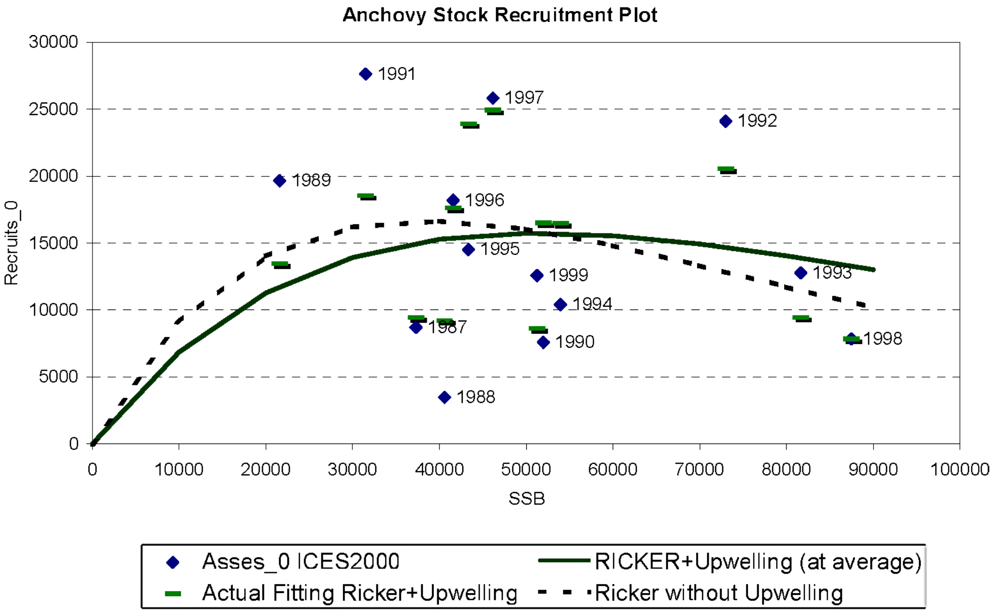


Figure 6.2.2.1. Ricker model fits, with and without an environmental index.

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. For simplicity, the relationships between the environmental indices 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 6.2.2.1. In all cases, the dependent variable R is the log-transformed number of recruits. The time-series of fitting values are presented in Figure 6.2.2.2.

Table 6.2.2.1. Comparison in terms of coefficient of determination of the fitting of S–R models and of direct environment–recruitment (log) models. R^2 is at Original Scale.

	ENVIRONMENT INCLUSION	
	WITHOUT	WITH
Ricker	1%	44%
AZTI index of upwelling		56%
IFREMER environmental index		65%
Synthesis of AZTI and IFREMER indices		75%

These results indicate that including an environmental index leads to 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 a horizontal line crossing the S–R points at 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 provides better results than the alternative methods which 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.

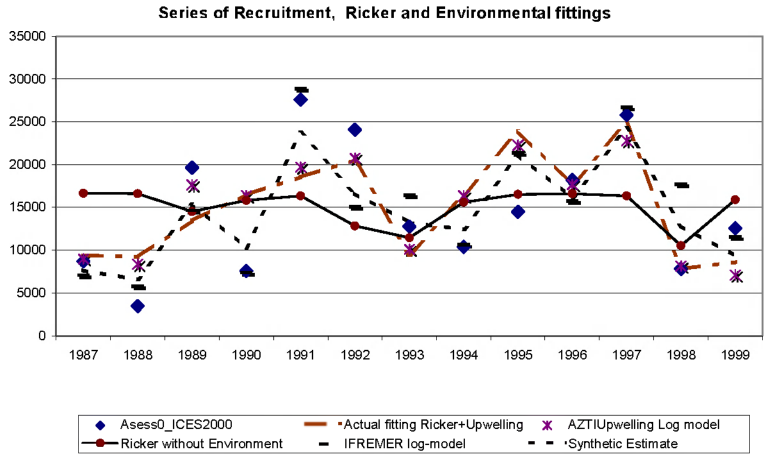


Figure 6.2.2.2. Time-series of recruitment values.

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 forecast a year ahead. In fact, once the average is removed from the time-series of upwelling, what is left is essentially white noise. Figure 6.2.2.3 presents the autocorrelation plot of the AZTI's upwelling index since 1967, which demonstrates no significant autocorrelation of the index in time.

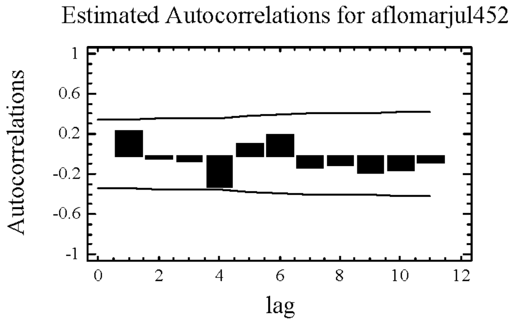


Figure 6.2.2.3. Autocorrelation analysis of the AZTI's upwelling estimate since 1967 (n = 34).

6.2.3 Procedures for forecasting

In this section, because 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 destratification), 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 of each other.

Two procedures to forecast anchovy recruitment for short-term predictions (one 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 one available, was performed in 1999 (ICES, 2000). 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 difference in the forecasted and the 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. The definition of the two approaches followed by the study group is:

a) Quantitative estimate: recruitment is forecast 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, so the weighted average would not be strongly dominated by any particular index. The variance of such an estimate is taken as the variance of a weighted sum of correlated variables.

b) Semi-quantitative estimate: the quantitative forecast based on the upwelling indices as in a) is then classified as above average, average, or below average, depending on 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 working group in 2000 and the corresponding percentiles of reference are shown in Table 6.2.3.1.

Table 6.2.3.1. 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%

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

In summary:

If R ≥66% (9269) then $\hat{R}$ = Avg [R ≥50%]

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

If 66% >R ≥33% then $\hat{R}$ = Avg [R]

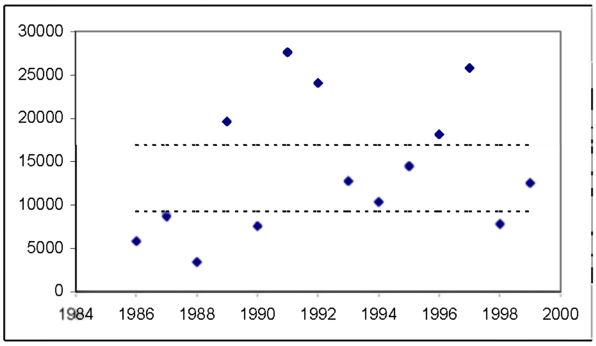


Figure 6.2.3.1. Time-series of number of recruits as estimated by the working group in 2000, and 33% and 66% percentiles.

The average adopted was the geometric mean of series of data within the range selected, leading to the following estimates of recruitment:

Qualitative Estimates of Recruitment			
Log estimates	Below	Average	Above
Counts	7	14	7
W mean	8.93	9.41	9.89
W variance	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%

6.2.4 Retrospective analyses

6.2.4.1 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 working group 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).

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, 2000). In the retrospective analysis that follows (period 1996 to 1999), only the 0-year-olds in the year of the assessment are forecast and, for the biomass projection for 2000, the same input used by the working group in 1999 concerning the 1998 year class was used.*

6.2.4.2 Results

Figure 6.2.4.2.1 shows the time-series of the quantitative estimates of recruitment compared with the most recent recruitment estimates obtained in the assessment performed in 2000 (ICES, 2001e). This synthetic environmental index fits these recruitment estimates better than each index alone (reaching an r^2 of 75%; Table 6.2.2.1). The quantitative retrospective forecast of the recruitments since 1996 is shown in Figure 6.2.4.2.2 (including ±1 CV). In the previous two years, the predictions performed better than in later years. The semi-quantitative retrospective forecast is shown in Figure 6.2.4.2.3 with confidence intervals corresponding to the CVs of the recruitment estimates used to compute the forecast. The performance during the first three years seems to be good, although in 1999, there is still an underestimation of the actual recruitment. For both methods, the most recent estimates were never outside the 95% confidence limits.

The retrospective analysis shows that, in the first three years, SSB biomasses fall within the confidence limits of the predictions, but for 2000, the probability of getting the actual estimate of SSB is very low (about 1%). The probability of observing the actual biomass in 2000 is very low, even when F retains the *status quo* (about 6%). The performances of the quantitative and semi-quantitative approaches are rather similar. The failure in predicting 2000 would have been the same with either method.

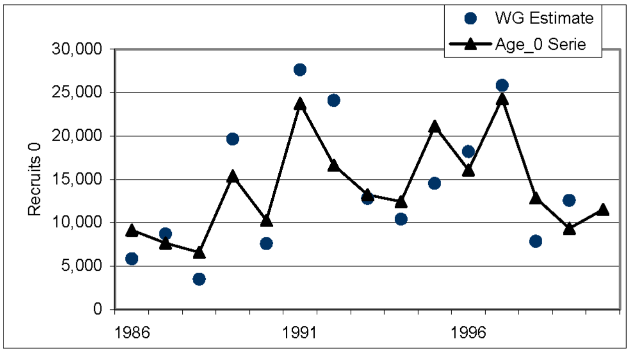


Figure 6.2.4.2.1. Time-series of recruitment synthetic and working group 2000 estimates.

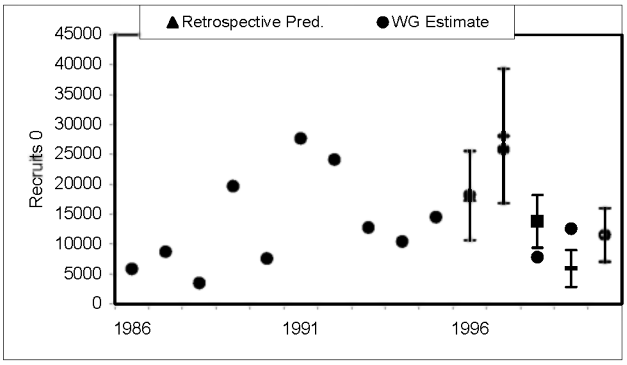


Figure 6.2.4.2.2. Time-series of working group 2000 recruitment estimates and retrospective quantitative predictions with corresponding CVs.

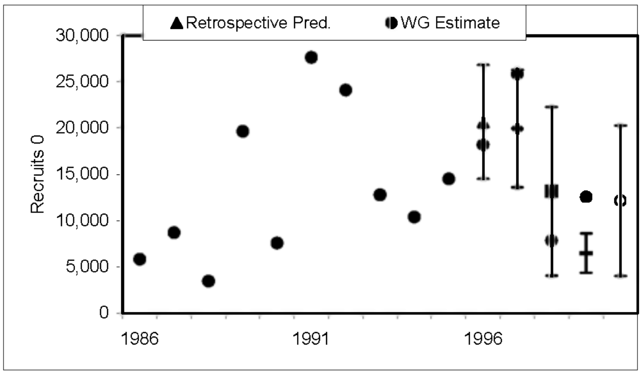


Figure 6.2.4.2.3. Time-series of working group 2000 recruitment estimates and retrospective semi-quantitative predictions with corresponding CVs.

6.2.5 Discussion

The current indices 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 benefit the short-term anchovy fishery forecast. Now that both indices are available by September each year, a synthesis of both indices seems to perform better than each index alone over the range of recruitment estimates available. The role of the parental stock is not yet evident in the short series of data available and so, direct recruitment–environment models perform as well or better than stock–environment–recruitment models. 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; Table 6.2.2.1). This suggests that a semi-quantitative use of these indices can perform as well as a purely 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 indices and methods, the current retrospective exercise shows that in three out of four years the probability of falling below B_{pa} (= 36 000 t) was low. In this sense, the current methods can be used to split safe years from risky years concerning the probability of falling below threshold limits. This use of the models fits well with the requirements set for ICES by the STECF in 2000 as triggers to switch between a constant annual TAC and a two-step TAC procedure (in-season update of a preliminary TAC).

Although the current analysis is far from 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, to better evaluate the relative performance of the two forecast methods outlined above. Other semi-quantitative approaches can also be devised and checked over a similar range of years. Improvements can be made by analysing residuals to the models outlined above (ARMA and time-series models) or by further exploring non-linear relationships of the environmental indices with recruitment (Cury and Roy, 1989; Roy, 1993).

In future, it is also advisable to use a synthetic environmental index rather than two independent ones, found through 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 to larvae survival than upwelling, or better indices of reproductive biomass rather than current SSB estimates, etc. This line of research should be promoted because it may greatly improve our current ability to predict recruitment.

6.3 Short-term predictions 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. It might be possible to use this link in short-term projections and, thus, 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. Therefore, for a stock assessment working group meeting in October, a forecast is available for SST in the following spring. 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.*, 2003, BD11).

When compared with the observed recruitment patterns over the past ten years, the predictions were poorly related to the observations. It is believed that problems are caused by difficulties in forecasting SST with this length of lead time.

Actual observations on the SST in 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 on 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 interannual 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 current 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 utilized in fisheries management.

6.4 Medium-term projections

6.4.1 ICES stock assessments

In order to offer effective and appropriate input to the current regulatory management structure, fishery scientists must be able to characterize, at least to some degree, the future development of a given stock over the so-called medium-term, which for moderately long-lived stocks will be five to ten years. To do this, projections of stock dynamics must be able to encapsulate uncertainty in the potential drivers of population change (principally recruitment variation) and the imposition of different levels of fishing mortality, and are typically used to determine the probability of falling below predefined biomass reference points.

6.4.2 The WGMTERM projection programme

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 (ten years) 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, 2001) proposed several modifications to WGMTERM to address concerns about autoregressive time-series structures in the recruitment model residuals used to drive projections, and attempted to implement in projection procedures stock–recruitment models mediated by hypothesized environmental and stock-structure influences. Intersessional work by study group members (Needle *et al.*, 2000, 2000a) using ARMA time-series models and recruitment models with environmental covariates represented a first step toward meeting these requirements, and the analyses carried out therein were extended and augmented during the current meeting. Results are presented in Section 6.5. Work was also initiated on the use of indices of potential egg production (as derived from outputs of the STEREO project) in stock–recruitment-driven projections rather than SSB.

WGMTERM’s methods and their extension to include temperature as a covariate in the Ricker stock–recruitment relationship were summarized in the previous SGPRISM report (ICES, 2001). 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. To conform to requirements for stationarity, 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:

$$x_i - \Phi_1 x_{i-1} - \Phi_2 x_{i-2} - \ldots - \Phi_p x_{i-p} = a_t - \Theta_1 a_{i-1} - \Theta_2 a_{i-2} - \ldots - \Theta_q a_{i-q}, \qquad \text{Equation 5}$$

where p and q are the order of the AR and MA components of the model respectively, Φ_i (i = 1, 2, ..., p) and Θ_i (i = 1, 2, ..., q) are AR and MA parameters to be estimated, and $a_i \sim N(0, \sigma^2_{\text{ARMA}})$ 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 current meeting, only first-order autoregressive models were fitted during the meeting, although ideally, a full investigation of the correct model choice would be performed (Needle *et al.*, 2000, 2000a). Thus, Equation 5 reduces to:

$$x_t = \phi x_{t-1} + a_t. \qquad \text{Equation 6}$$

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 $a_i \sim \mathrm{N}(0, \sigma^2_{\text{ARMA}})$. 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(10) model with parameter ϕ_1, the *i*th projection value is:

$$x_i = \phi_1 x_{i-1} + a_i, \qquad \text{Equation 7}$$

The required projected Ricker recruitment is then:

$$R_i = \alpha S_{i-1}\,\mathrm{e}^{-\beta S_{i-1} + x_i}. \qquad \text{Equation 8}$$

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

6.4.3 Proposed modifications to WGMTERM

The medium-term projection models currently used in the ICES advisory framework, while parsimonious, are somewhat limited and inflexible, and would benefit from a timely revision. The potential modifications to WGMTERM proposed by the study group were itemized at the first meeting as follows:

- Incorporating a correction term to account for the bias generated by back transformation from the logarithmic scale. This would be a simple way of tailoring the currently generated non-linear least-squares stock–recruitment fit to mimic the more statistically appropriate GLM solution. However, the GLM solution is the preferred approach.
- Modelling time-series of residuals to parametric recruitment model fits, and subsequently using simulated time-series in projections, instead of random draws from historical residuals. This would serve to characterize any autocorrelation structure in the historical series, as well as any overall trend in level or variability.
- Implement stock–recruitment models mediated by hypothesized environmental influences. Projections of residuals to these models would be accompanied by projections of the environmental time-series. Using this approach, care would have to be taken in management, as a clear linkage between recruitment and the chosen

environmental factor *and* a strong time-series signal in the latter would be required (see Section 7.4.4).

- Allowing for the possibility of a change in the imposed F-multiplier in mid-simulation run, thus facilitating empirical explorations of harvest control laws and recovery plans.

6.5 Medium-term projection of North Sea cod

6.5.1 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,…,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, 2001f). 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. For each combination of starting year and method, 1000 stochastic simulations were performed, 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 that compared the median of projected R with a deterministic projected R—that is, the R that would result if there were 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.*, 2000, 2000a).

6.5.2 Results

Figure 6.5.2.1 and Table 6.5.2.1 compare the parameters of the Ricker model for each starting year, 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 on recruitment.

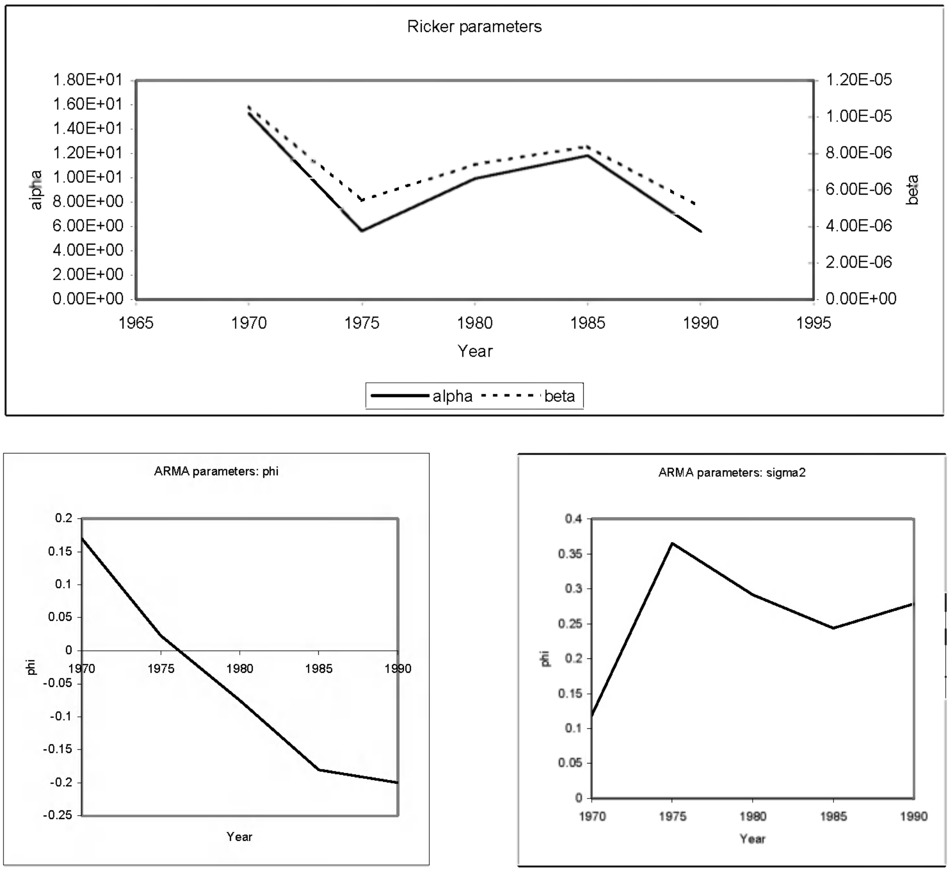


Figure 6.5.2.1. Parameters of the Ricker model of reach of the distinct starting years, together with time-series model parameters.

Table 6.5.2.1. Tabulated parameter values for the models investigated.

Projection year	Ricker		ARMA		Ricker and temperature		
	A	ß	Φ	Σ	A	ß	Γ
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

6.5.3 Discussion

6.5.3.1 Projected recruitment

Table 6.5.3.1.1 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.

Table 6.5.3.1.1. Summary of projected recruitment under each of the three models.

PROJECTION YEAR	WG	TEMPERATURE	ARMA
1970	Wide simulation envelope, but the 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 points, although the trend is similar to the observed.	Tighter simulation envelope fails to capture some of the high and low recruitment points. 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 points.
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 early series.	Tight simulation envelope fails to capture the trend, and most of the later low recruitment points.
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 points and the short-term trends.

The working group type of 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 and follows the median more closely. Observed trends in recruitment are captured by this model, except the 1970 projection in which the SRR model is fitted to data from 1963–1968, and the 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 working group model fails to capture the low recruitments in recent time in the projections started from 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 time in the projections started from 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.

6.5.3.2 Projected spawning-stock biomass

Table 6.5.3.2.1 compares projected SSB with that found by the 1999 assessment.

The working group type of model tends to be overly optimistic regarding 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 overestimates recent SSB; 1975 and 1990 projections underestimate the most recent SSB, whereas the 1980 and 1985 projections are roughly in accord with recent SSB. The ARMA model tends to be overly optimistic in the recent past, except for the 1990 projection and is generally similar in trend to the standard working group type of model, but with much tighter simulation envelopes.

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

Table 6.5.3.2.1. Summary of project SSB using the three models.

PROJECTION YEAR	WG	TEMPERATURE	ARMA
1970	The projection underestimates SSB over the first five years, loosely matches the level but not the trend in the next eight years, and overestimates for the most recent ten years. The overall trend is down on initial level and stable or rising in recent time.	The projection underestimates SSB over the first five years, loosely matches the level in the next eight years, and overestimates for the most recent ten years. The overall trend is down on initial level and stable or rising in recent time.	The projection underestimates SSB over the first five years, loosely matches the level in the next eight years, and overestimates for the most recent ten years. The overall trend is down on initial level and stable or rising in recent time.
1975	The simulation interval encapsulates the historical trend, but is smoother, and SSB tends to be overestimated in recent time. The overall trend is well down on initial level and rising after the series, low in recent time.	The projection simulation interval, 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 interval encapsulates the historical trend, but is smoother and SSB tends to be overestimated in recent time. The overall trend is well down on initial level and rising after the series, low in recent time.
1980	The projection tracks SSB for five years, but is overly optimistic in the recent period. The overall trend is a recent recovery after a slight decline.	The projection is overly optimistic for most of the series, but declines sharply in the early 1990s and matches the historical series in recent time. The overall trend is a decline followed by ten years stability, then a further decline and slight recovery.	The projection tracks SSB for five years, but is overly optimistic in the recent period. The overall trend is a recent recovery after a slight decline.
1985	The projection overestimates SSB, and the historical series is outside the simulation interval in recent time. The trend is stable with a slight increase in recent time.	SSB is overestimated initially, declines dramatically in the early 1990s, and is in accord with the late part of the historical series. The trend is stable and rising, followed by a sharp decline and recent slight recovery.	The projection overestimates SSB, and the historical series is outside the simulation interval 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 interval fails to capture the historical series and underestimates 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.

The relative levels of SSB from projection start to finish for the working group model decline in SSB for the 1970 and 1975 projections, remain level for the 1980 and 1985 projections, and increase for the 1990 projection. The first two and last projections agree 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 the perceived SSB apart from 1990. Relative SSB levels for the ARMA model decline in SSB for the 1970 and 1975 projections, remain level for the 1980 projection, and increase for the 1985 and 1990 projections. The first two and last projections agree with the perceived trend in SSB.

6.5.3.3 Diagnostic plots and bias

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, though on occasion, 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 (−ve) in the median resulted. In the other runs, more positive residuals were present, and a positive bias (+ve) was noted.

Table 6.5.3.3.1. Summary of stochastic simulations.

	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

For the working group type of 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 and no systematic bias.

Thus, interpretation of bias over time in the projection is not straightforward owing to feedback occurring through the SRR and also considerations regarding the distribution of residuals about the expected value.

6.5.3.4 Confounding of results caused by 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, established that the resulting trajectories were extremely sensitive to the choice of model. The figures below illustrate this, using a prediction from the year 1990.

Figure 6.5.3.4.1 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, 2001f). 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 overestimated in each year; the medians lie above the observed value. The trajectory of simulated SSB shows a good fit to the observed values.

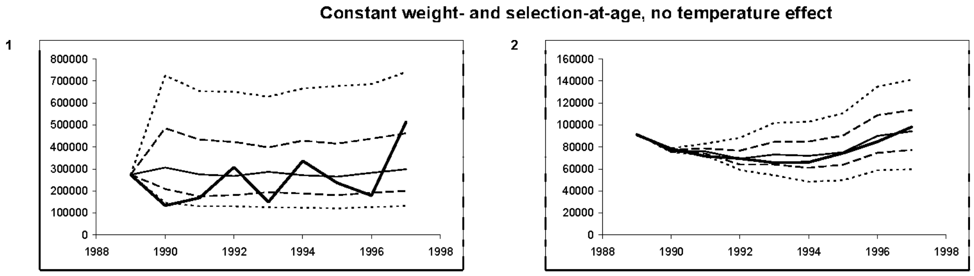


Figure 6.5.3.4.1. Recruitment (left) and SSB (right) predicted by the stock and recruitment model without temperature effects.

Figure 6.5.3.4.2 shows the trajectories for the projections using the stock and recruitment model with temperature effects. Recruitment is generally underestimated, and after the first few years, SSB is underestimated 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.

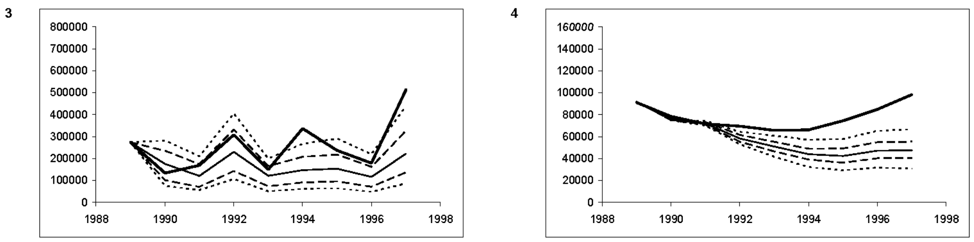

Constant weight- and selection-at-age, temperature effect included

Figure 6.5.3.4.2. Recruitment (left) and SSB (right) predicted by the stock and recruitment model with temperature effects and assuming constant weight- and selection-at-age.

To investigate the underestimation 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 6.5.3.4.3 and 6.5.3.4.4. The results show that the underestimation of recruitment by the model with temperature effects is still present and results in an increasing but gradual underestimation of SSB as the starting population year classes decrease in their contribution to SSB with increasing exploitation. The degree of underestimation is reduced by including the weights observed for each year and also by the use of the assessment estimates of fishing mortality-at-age.

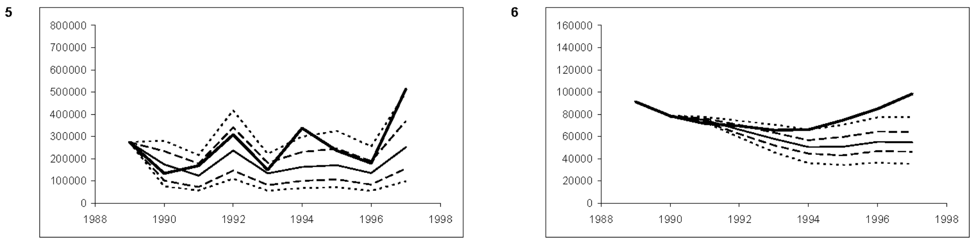

"Real" weight-at-age, constant selection-at-age

Figure 6.5.3.4.3. Recruitment (left) and SSB (right) predicted by the stock and recruitment model with temperature effects, constant selection-at-age, and observed weights-at-age.

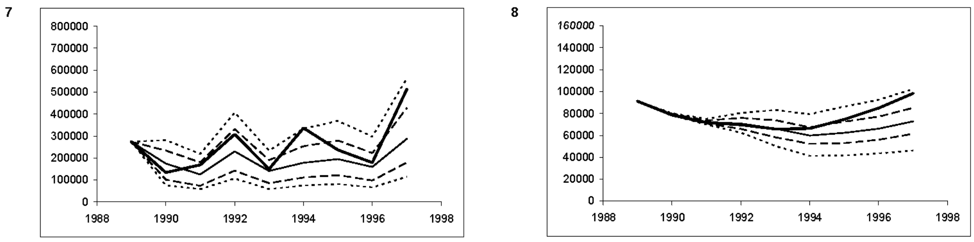

"Real" fishing mortality-at-age and weight-at-age

Figure 6.5.3.4.4. Recruitment (left) and SSB (right) predicted by the stock and recruitment model with temperature effects, estimated fishing mortality-at-age, and observed weights-at-age.

An examination of the relative weight-at-age for the period 1986–1997 (Figure 6.5.3.4.5) shows that the weight-at-age of the 1987 and subsequent year classes was heavier at the youngest ages than the previous year classes. This could be the result of 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.

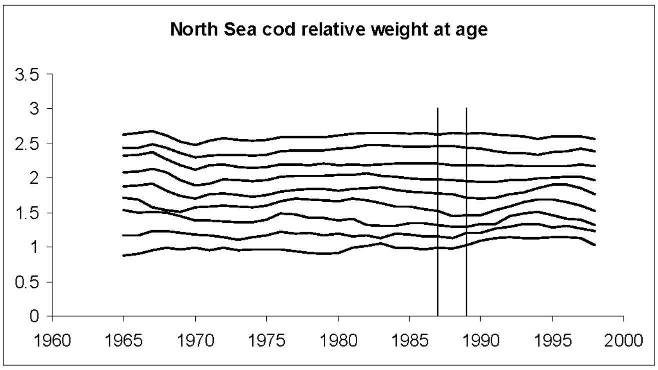


Figure 6.5.3.4.5. Relative weights-at-age observed for North Sea cod (ages 1–9) in the years 1965–1999. The vertical lines indicate the years used for the calculation of the average weight-at-age in the simulations.

The results of the exploratory simulations have established that the overestimation of recruitment by the model without temperature (i.e. WGMTERM-type) has compensated for the use of an average weight-at-age that 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 underestimated recruitment, and when combined with the low weight-at-age, resulted in the simulated SSB being severely underestimated.

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 by 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.

6.6 Medium-term projections of North Sea cod (*Gadus morhua* L.) incorporating STEREO output

6.6.1 Background

The changes in age structure that have occurred in the North Sea cod stock since the 1960s 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 oocytes may be resorbed (a process referred to as atresia) for a variety of reasons. Hence, the realized 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 interannual variations in potential fecundity to body weight and potential fecundity to body length relationships are small compared with 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 interannual variability linked to changes in fish condition. Hence, estimation of realized population fecundity from standard stock assessment outputs is not possible unless accompanying data on year-specific weight–length relationships are available.

6.6.2 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 assumes 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, the estimate of maturity for years outside the period presented by Poulding (1997) was 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.

Table 6.6.2.1. The observed proportion of cod mature-at-age (combined sexes, total North Sea; Poulding, 1997).

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 6.6.2.2. Smoothed proportion of cod mature-at-age (combined sexes, total North Sea; 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

The STEREO project has not studied cod fecundity in the North Sea, and few recent data are available in the literature. During the study group meeting therefore, we 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 = $-1\,396\,801 + 1\,044\,446 \times$ 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, therefore, was fitted-by-eye to the data (fecundity = $5.2 \times 10^5 \times (\text{weight})^{1.25}$). 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 because North Sea data were lacking during the study group. However, it is expected that fecundity–weight should be less variable between stocks and regions than fecundity–age, which will also depend on weight-at-age. Therefore, the error introduced should be limited and the results adequate for the demonstration of the study group's methods.

6.6.3 Results

A ten-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, so allowing for comparison with observed *E* for the years 1986–1995.

6.6.4 Discussion

Many of the relevant data sources are already sampled at sea or on the commercial fish markets, and the 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 allow improved SRR fitting, but given existing methods, would not necessarily result in improved projections (see confounding caused by 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.

6.7 Population forecasting

6.7.1 Medium-term projections

During the first two meetings of SGPRISM (ICES, 2000, 2001), work was initiated on improving the prevailing ICES medium-term projection methods, currently available as WGMTERM (Reeves and Cook, 1994) or ICP (Patterson, pers. comm.). These methods differ somewhat, but share the underlying theme of using bootstrapped recruitment residuals to drive stochastic population forecasts, with such variables as weights-at-age and proportion mature-at-age being held constant over time. The improvements proposed under the remit of SGPRISM related to the statistical appropriateness or otherwise of the bootstrap resampling approach, and the possibility of incorporating aspects of biological process modelling.

Studies have continued intersessionally and are now pursued under the aegis of SGPRISM, the Methods Working Group (ICES, 2002c), and the UK CFRD Working Group on Recruitment Processes. Development of the method is recorded in Needle *et al.* (2000, 2001, 2003). Attention has focused on time-series characterizations of recruitment, weights-at-age, and proportion mature-at-age because of problems caused by the way these variables are modelled in WGMTERM and its kind. For example, the assumption of constant weights-at-age in short- and medium-term catch forecasts can result in significant estimation bias. Darby (BD21, BD22; see also ICES, 2002c) has shown that for most North Sea stocks, trends in catch weights-at-age through time could have resulted in estimation bias in the total catch of up to 50%. During the past five years, North Sea cod landings could have been overestimated by 5–25%, a bias that is consistent with the deficit between the total catch landed by the fishery and the final agreed TAC. If the recent landings information is "reliable", the magnitude of the bias is such that it could have removed the pressure of TAC regulation from the fishery. Darby

(BD21, BD22) showed further that there appear to be systematic changes in weights-at-age that could be modelled using time-series and/or cohort effect models. Removal of the bias from the short- and medium-term forecasts will require modelling of such temporal changes in weight-at-age. At the second meeting of SGPRISM in 2001, two presentations were made relating to this topic (in addition to Darby, BD21, BD22).

Projection development work plan

- Recruitment residuals will be modelled using ARMA time-series (where a significant ARMA fit is found). However, the efficacy of using only a subsample of the historical stock–recruitment pairs for each projection will be investigated. Under this scheme, several different model formulations would be fitted to these data, and the one that fit best would be used to generate projections. Thus, uncertainty about the form of the recruitment model would be modelled, as well as variation about it.
- The VARMA method, presented in Needle (BD23) for characterizing weights-at-age models, incorporated cohort effects in weights, but not in year effects. For stocks such as cod, cohort effects appear to be more important (Darby, BD21, BD22), and in this context, the VARMA model is likely to be sufficient. However, for other stocks, year effects may be more important. To account for this, an alternative has been proposed in which weights at age 1 would still be projected as residuals to a function of stock density, but subsequent ages would be modelled in terms of increments down cohorts. This would have the additional benefit of avoiding the problem in the VARMA method of ignoring data from incomplete cohorts.
- Maturity could be modelled in several ways. A single ogive could be fitted with weights as the independent variable (thus ignoring age), or use could be made of empirical non-parametric kernel distributions. Examples of these two approaches are given in Figure 6.7.1.1. Ultimately, deriving maturity as a function of weight will always be an approximation, and it is intended that alternative methods involving length-driven fecundity estimates will be pursued. Indeed, for many stocks, spawning-stock biomass is an unsuitable proxy for egg production. The new method would base stock–recruitment modelling on potential egg production rather than spawning-stock biomass, and thus, will be more cognisant of the deleterious effect of a compressed age structure, among other influential factors.
- Natural mortality M is currently fixed throughout projections. However, annual values of M are available from MSVPA and, if possible, these would be used in the new approach (after accounting for any time-series structure).
- The key justification for work on medium-term projections is to allow managers to determine the likely responses of the stock in question to specified management actions. To this end, the methodology could allow for future imposed changes in fishing effort, gear selectivity, and catch constraints, and would permit the modelling of formal harvest control rules. WGMTERM does not currently allow for the modelling of management actions, although ICP does.
- The proposed new model will include the facility to accept a different realization of starting values for each projection iteration, as would be produced by a bootstrapped assessment model. If such a model is not available, starting values for each projection could be drawn from a multivariate distribution about assessment results with standard errors stipulated by the assessment model (this facility is available in both TSA and ICA).

The method would be implemented to be as general as possible, while allowing for additional model structure if data are available.

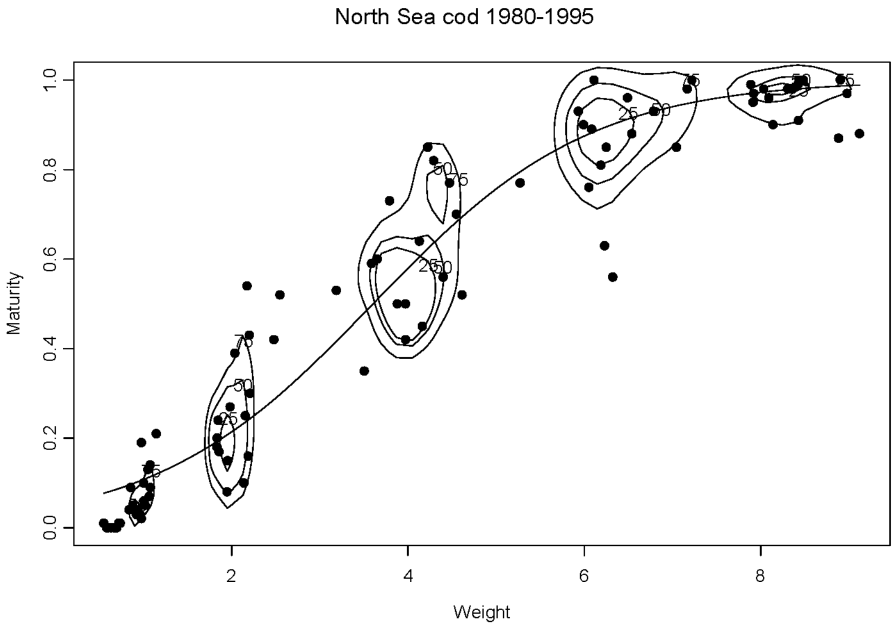


Figure 6.7.1.1. Scatterplot of maturity-at-age against weights-at-age for North Sea cod, ages 1–6, years 1980–1995. Maturity-at-age data are taken from Cook *et al.* (1999), and weights-at-age data from the appropriate ICES working group report (ICES, 2002a). The logistic curve is a maturity ogive fitted to all data (so ignoring age structure). The contours are empirical kernel-smoothed distributions by age; labels indicate percentile probability.

Weights-increments modelling

The second presentation (Needle, WD10) looked at some first steps taken in pursuit of this work plan, namely the modelling of weights as increments down cohorts. WD10 applied the approach to North Sea cod, while further work during the current SGPRISM meeting extended the analyses to North Sea haddock, whiting, and plaice. Results for these stocks are summarized below.

Three different methods of generating increments were used:

1. First differences: $\Delta_{a,y} = W_{a+1,y+1} - W_{a,y}$
2. Log ratios: $\Delta_{a,y} = \ln\left(\frac{W_{a+1,y+1}}{W_{a,y}}\right)$
3. Age N to age 1 ratios: $\Delta_{a,y} = \frac{W_{a,1}}{W_{a+y,y+1}}$

For each method, time-series along age classes were formed (with the mean subtracted in each case) and a number of ARMA(p,q) models fitted with the autoregressive order p and the moving-average order q, both varying between 0 and 3. The significance of the fitted model parameters was evaluated using a t-test

$$t = \frac{\text{parameter}}{\text{s.d.(parameter)}},$$

and the model was accepted if $|t| > 1.96$ for all fitted parameters. Where more than one model was accepted, the best was chosen, based on the lowest estimated value of the AIC test criterion (conditioned on the highest allowed value of p, in other words, 3).

Results of these analyses appear in Figures 6.7.1.2, 6.7.1.3, 6.7.1.4, and 6.7.1.5, and Table 6.7.1.1. ARMA model fits are distributed as follows:

ARMA Model Order	Number of Fits	
No Significant Fit	**45**	**37.5%**
01	32	26.6%
11	14	11.7%
22	9	7.5%
02	6	5.0%
10	4	3.3%
12	4	3.3%
13	4	3.3%
23	1	0.8%

A large percentage of weights–increments time-series do not have a significant ARMA model fit. On the other hand, there is time-series information in many of the weights–increments data sets, and in general, it would seem unwise to ignore time-series structure in these data if it is present. Where no significant ARMA model could be found, simple bootstrapping is probably adequate.

Table 6.7.1.1. Orders of those best-fitting ARMA model fits to weights–increments time-series for which all fitted parameters are significant. Parameter significance was determined using a *t*-test, while the AIC statistic was used to select the best-fitting model. Dashes indicate no significant ARMA fit.

(a) North Sea cod (1963–2000).

	First differences		Log ratios		Age N to age 1 ratios	
Age	AR	MA	AR	MA	AR	MA
1–2	–	–	–	–	–	–
2–3	1	0	2	2	0	1
3–4	0	3	2	3	0	3
4–5	–	–	2	2	0	2
5–6	1	1	1	1	1	2
6–7	1	1	1	3	0	1
7–8	1	1	1	1	1	1
8–9	–	–	–	–	0	3
9–10	1	1	1	1	0	3
10–11+	0	1	–	–	1	2

(b) North Sea haddock (1963–2000).

	First differences		Log ratios		Age N to age 1 ratios	
Age	AR	MA	AR	MA	AR	MA
0–1	0	1	–	–	0	1
1–2	0	2	0	2	0	1
2–3	0	1	2	2	0	1
3–4	0	1	–	–	0	1
4–5	0	2	0	2	0	1
5–6	2	2	2	2	0	1
6–7	–	–	0	1	0	1
7–8	–	–	1	3	0	1
8–9	–	–	3	2	0	1
9–10+	–	–	–	–	0	1

Table 6.7.1.1 continued on next page.

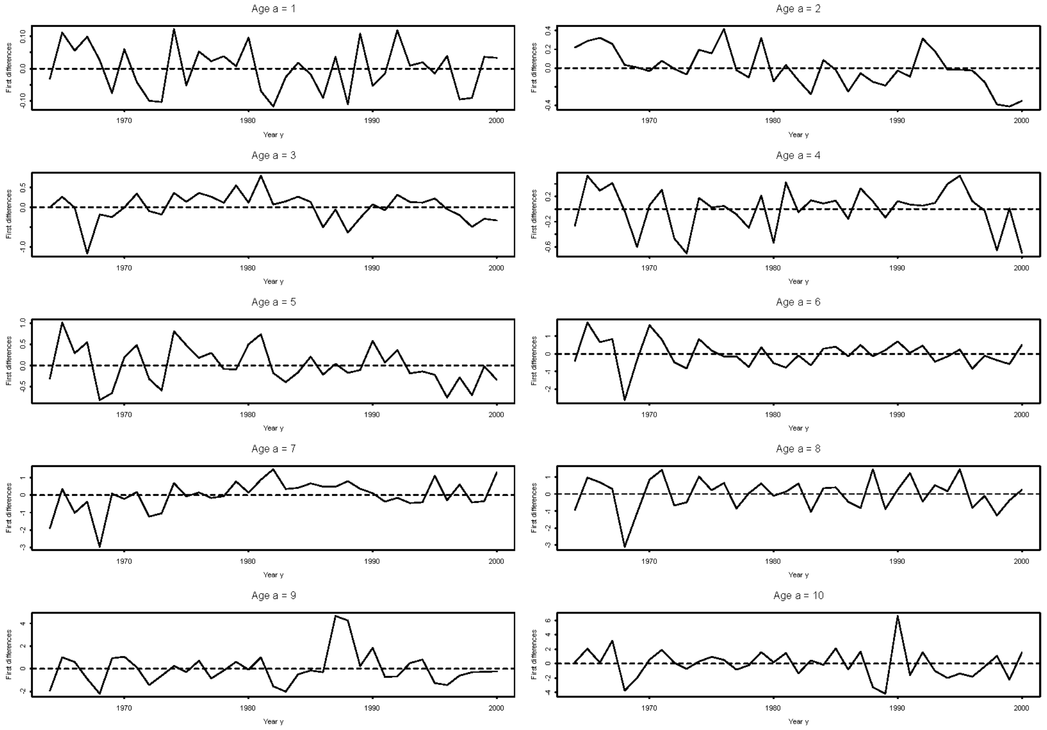
(c) North Sea whiting (1960–2000).

	First differences		Log ratios		Age N to age 1 ratios	
Ages	AR	MA	AR	MA	AR	MA
1–2	–	–	–	–	–	–
2–3	2	2	–	–	0	1
3–4	–	–	–	–	1	0
4–5	1	1	1	1	0	1
5–6	–	–	–	–	–	–
6–7	1	0	0	1	–	–
7–8+	–	–	–	–	0	3

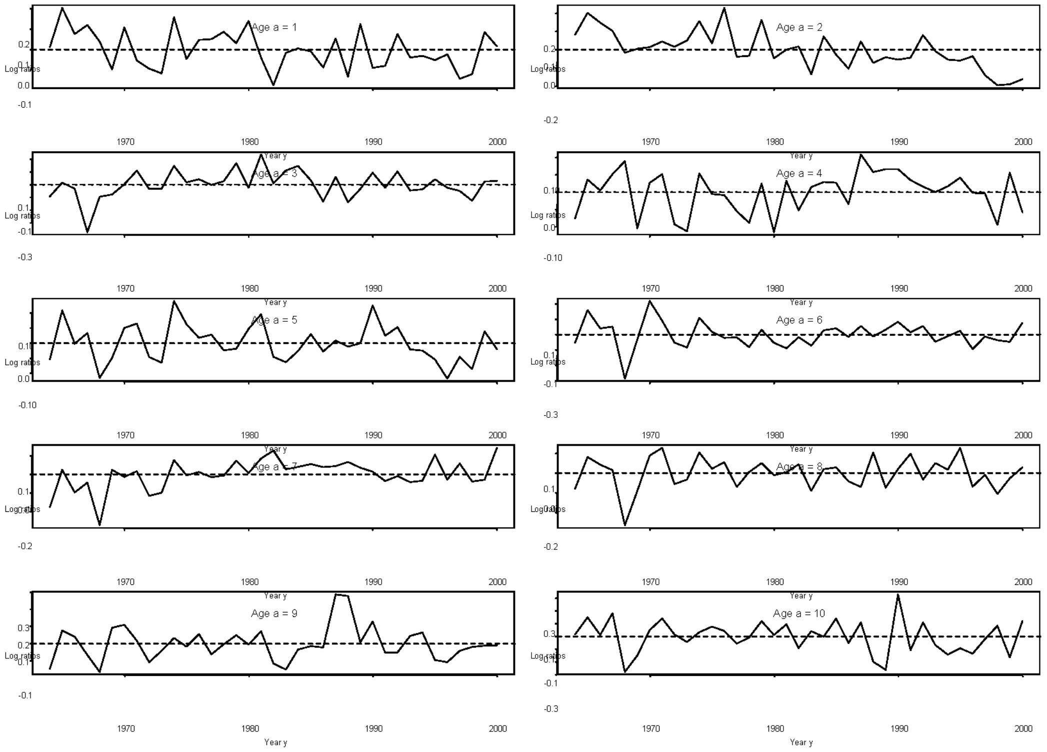
(d) North Sea plaice (1969–2000).

	First differences		Log ratios		Age N to age 1 ratios	
Ages	AR	MA	AR	MA	AR	MA
1–2	–	–	–	–	–	–
2–3	–	–	–	–	2	2
3–4	0	1	0	1	2	2
4–5	1	0	2	2	–	–
5–6	0	2	–	–	–	–
6–7	–	–	–	–	–	–
7–8	–	–	–	–	–	–
8–9	0	1	1	1	–	–
9–10	1	3	1	3	–	–
10–11	0	1	0	1	1	1
11–12	0	1	0	1	–	–
12–13	1	2	1	2	1	1
13–14	0	1	0	1	1	1
14–15+	–	–	–	–	0	1

(a) Using first differences to generate weights data $\left(\Delta_{a,y} = W_{a+1,y+1} - W_{a,y}\right)$:



(b) Using log ratios to generate weights data $\left(\Delta_{a,y} = \ln\left(\frac{W_{a+1,y+1}}{W_{a,y}}\right)\right)$:



(c) Using ratio of age *N* to age 1 to generate weights data $\left(\Delta_{a,y} = \frac{W_{a,1}}{W_{a+y,y+1}}\right)$:

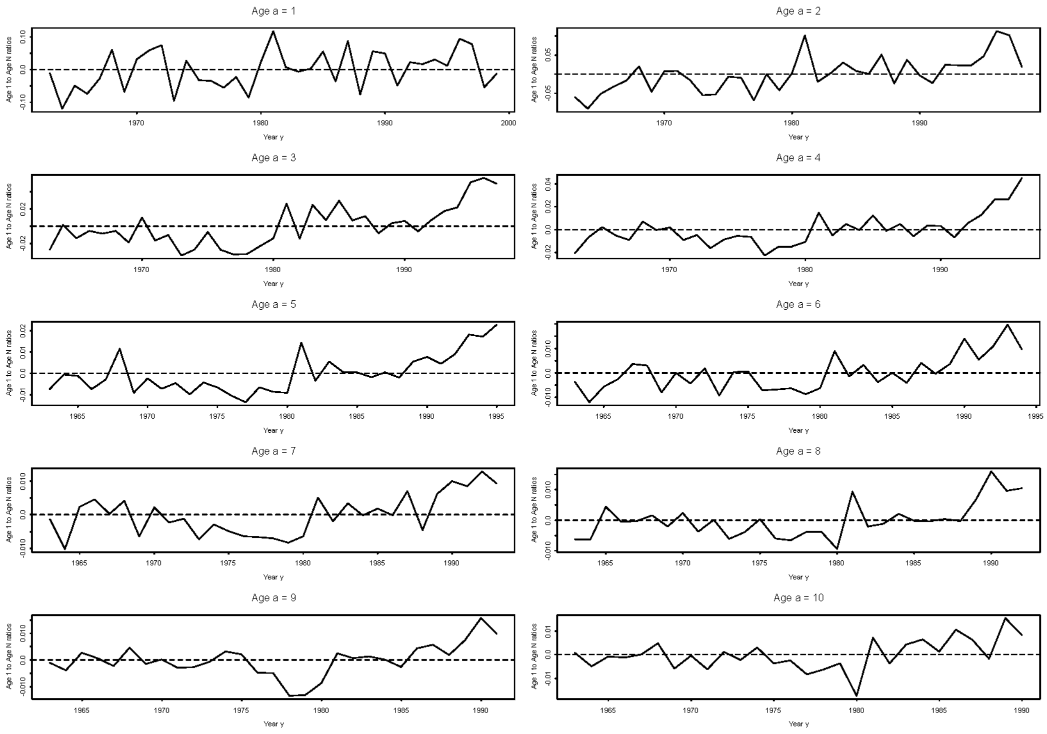
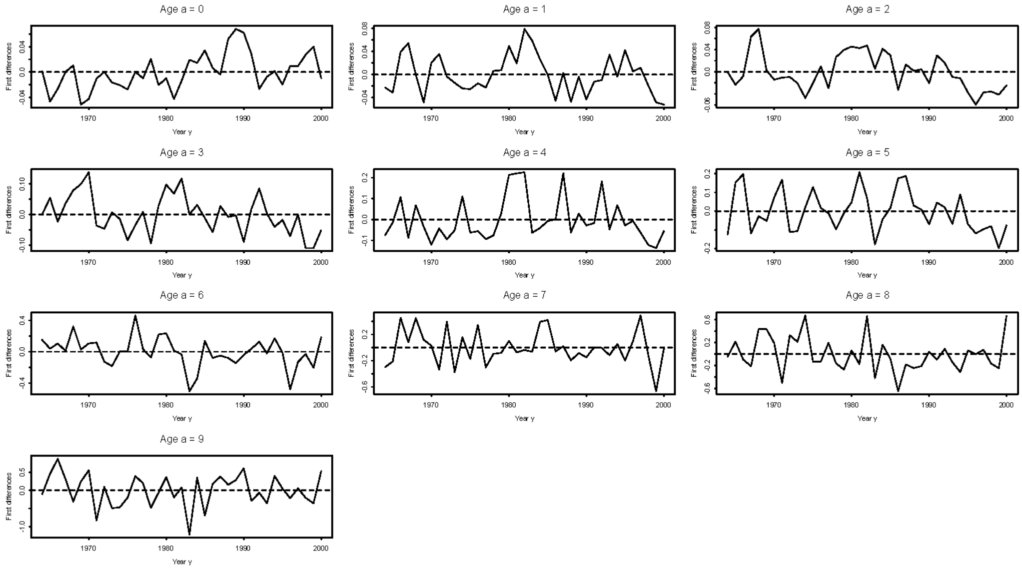
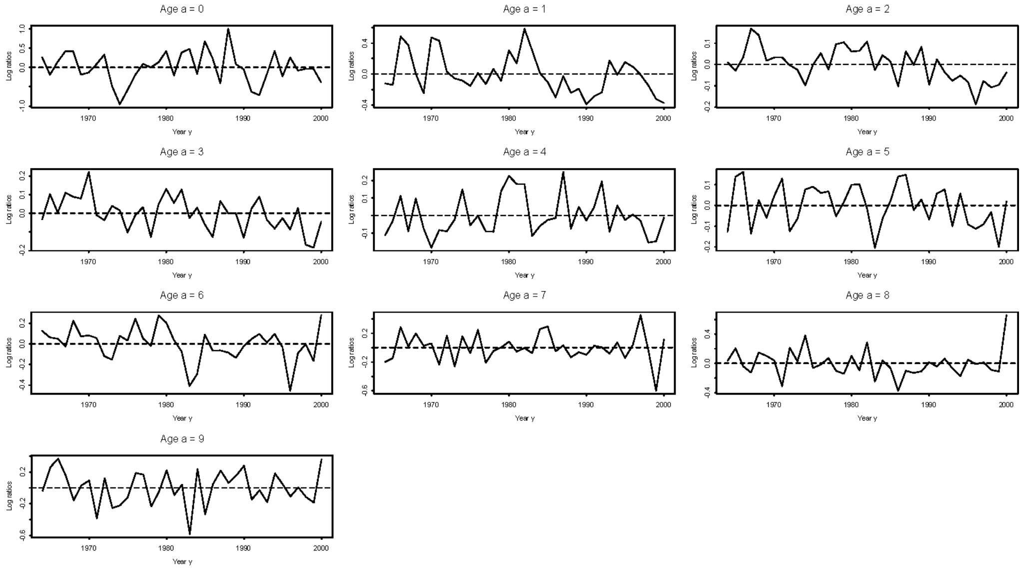


Figure 6.7.1.2. Time-series of weight-at-age increments by year classes for North Sea cod.

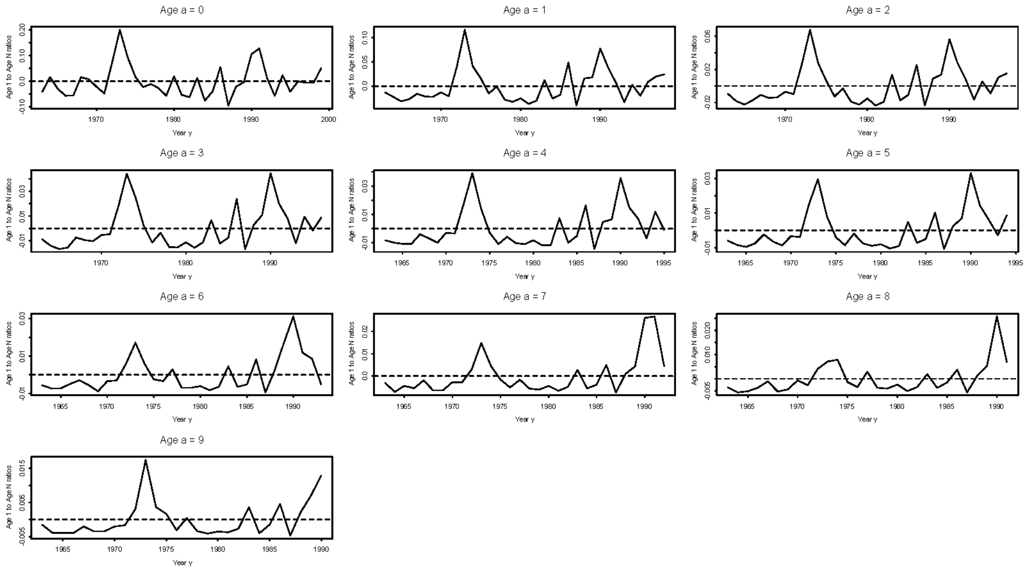
(a) Using first differences to generate weights data $\left(\Delta_{a,y} = W_{a+1,y+1} - W_{a,y}\right)$:



(b) Using log ratios to generate weights data $\left(\Delta_{a,y} = \ln\left(\frac{W_{a+1,y+1}}{W_{a,y}}\right)\right)$:



(c) Using ratio of age *N* to age 1 to generate weights data $\left(\Delta_{a,y} = \frac{W_{a,1}}{W_{a+y,y+1}}\right)$:



Age a = 0

Age a = 1

Age a = 2

Age a = 3

Age a = 4

Age a = 5

Age a = 6

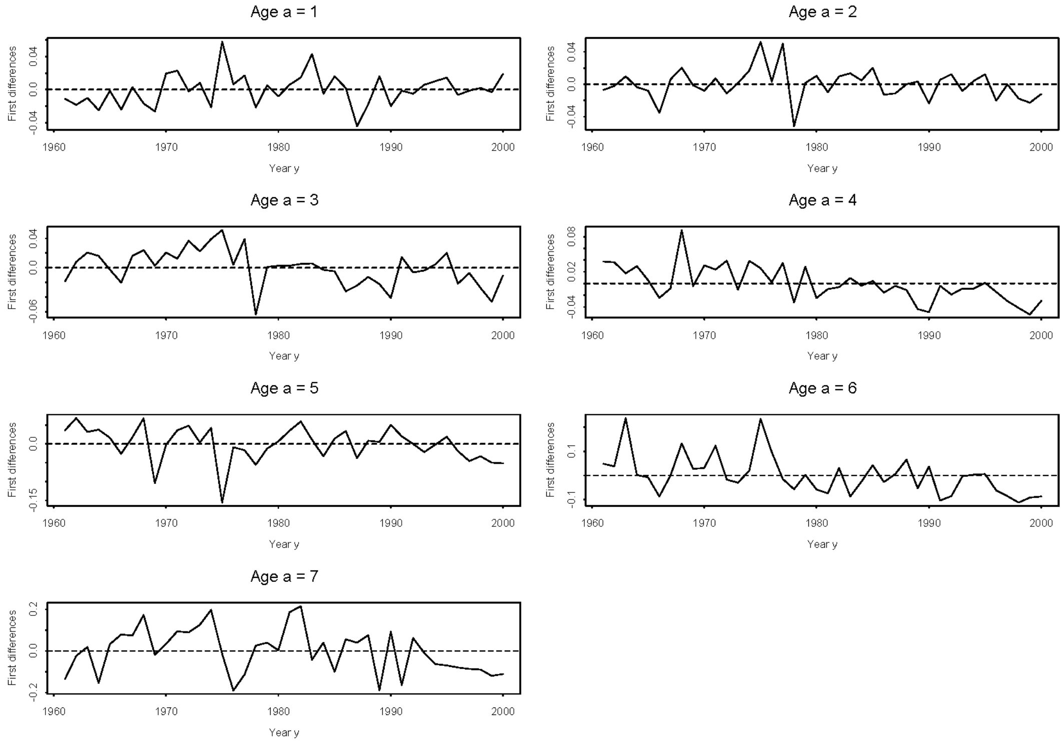
Age a = 7

Age a = 8

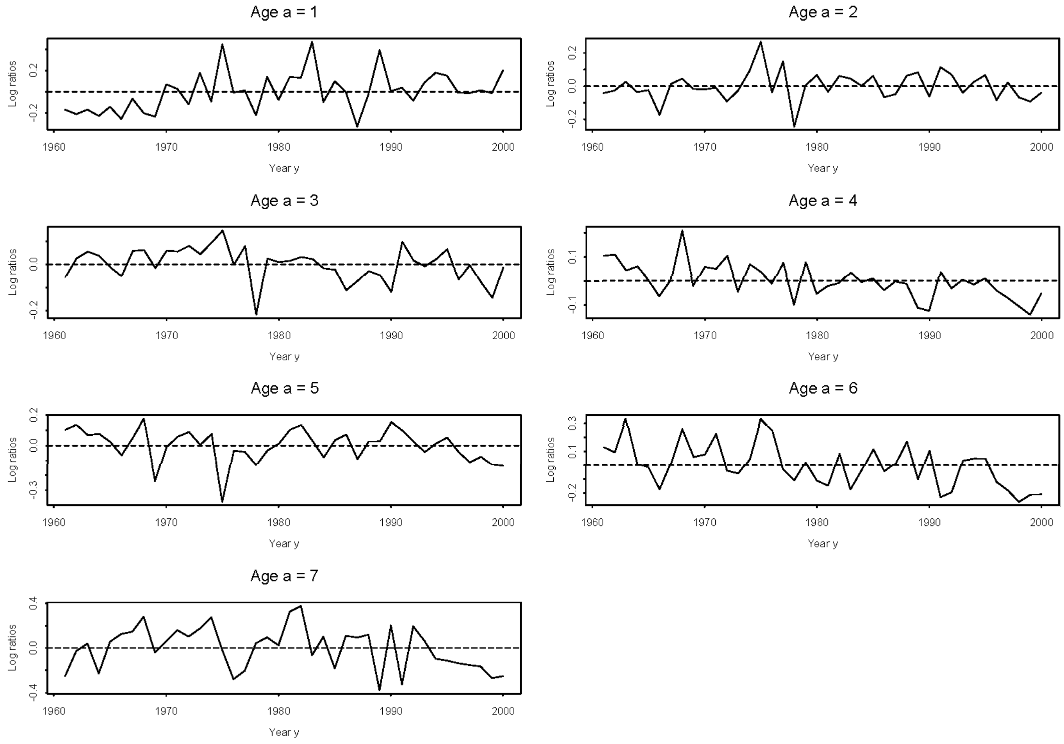
Age a = 9

Figure 6.7.1.3. Time-series of weight-at-age increments by year classes for North Sea haddock.

(a) Using first differences to generate weights data $\left(\Delta_{a,y} = W_{a+1,y+1} - W_{a,y}\right)$:



(b) Using log ratios to generate weights data $\left(\Delta_{a,y} = \ln\left(\frac{W_{a+1,y+1}}{W_{a,y}}\right)\right)$:



(c) Using ratio of age *N* to age 1 to generate weights data $\left(\Delta_{a,y} = \frac{W_{a,1}}{W_{a+y,y+1}}\right)$:

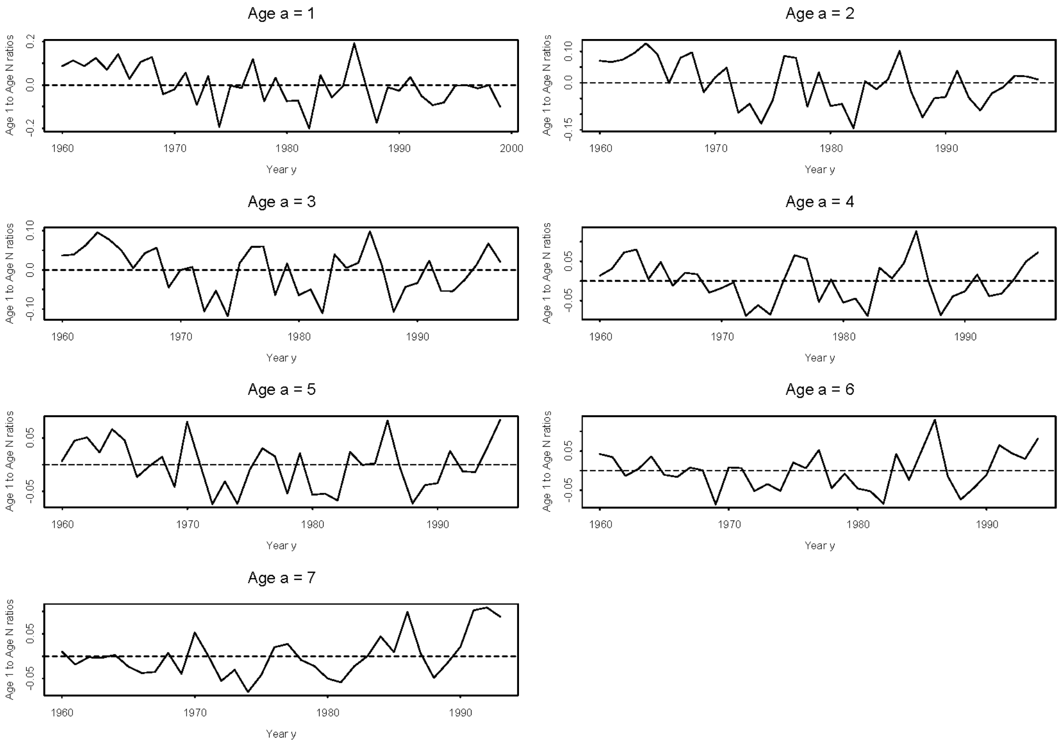
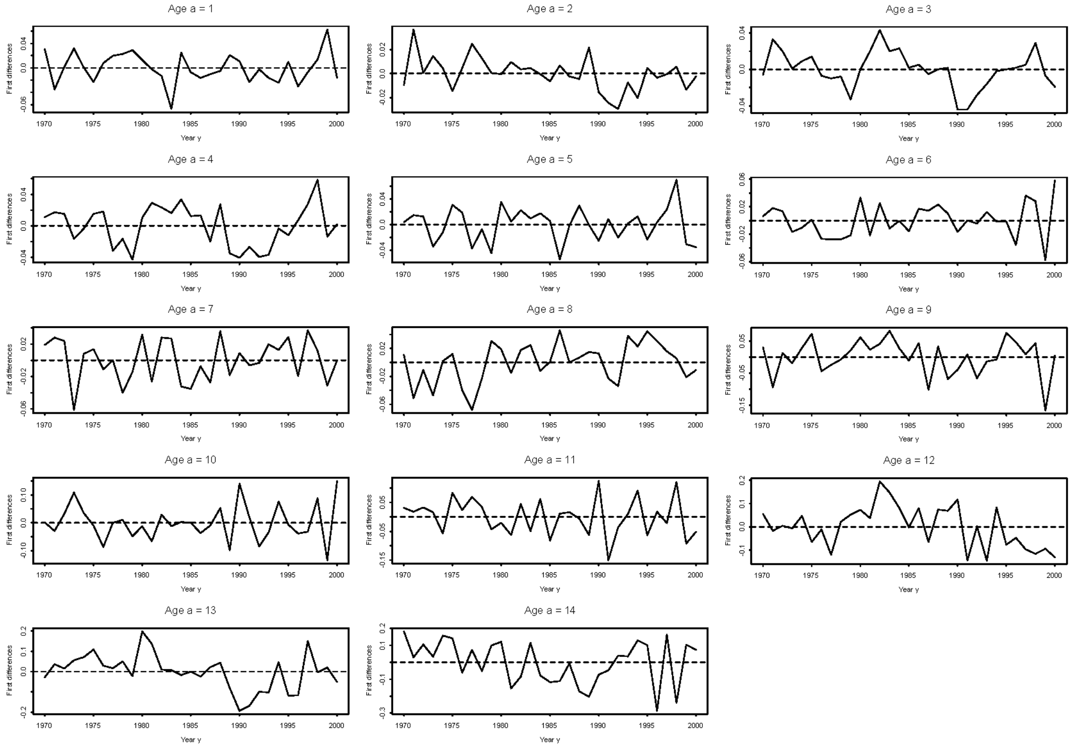
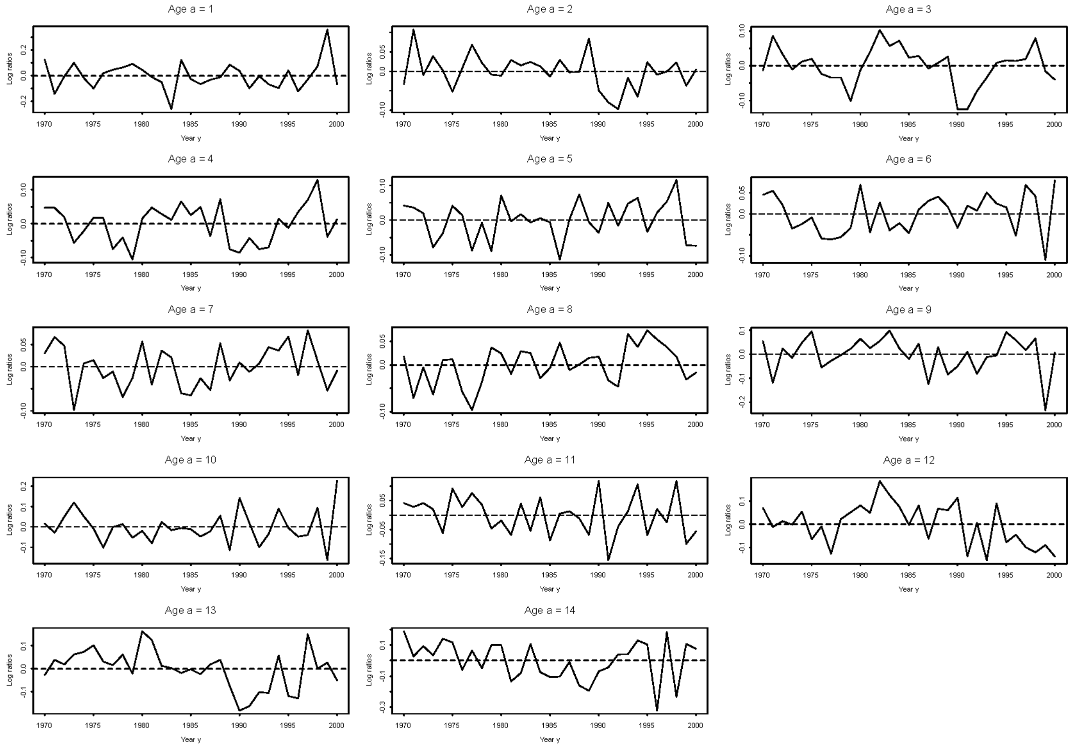


Figure 6.7.1.4. Time-series of weight-at-age increments by year classes for North Sea whiting.

(a) Using first differences to generate weights data $\left(\Delta_{a,y} = W_{a+1,y+1} - W_{a,y}\right)$:



(b) Using log ratios to generate weights data $\left(\Delta_{a,y} = \ln\left(\frac{W_{a+1,y+1}}{W_{a,y}}\right)\right)$:



(c) Using ratio of age *N* to age 1 to generate weights data $\left(\Delta_{a,y} = \frac{W_{a,1}}{W_{a+y,y+1}}\right)$:

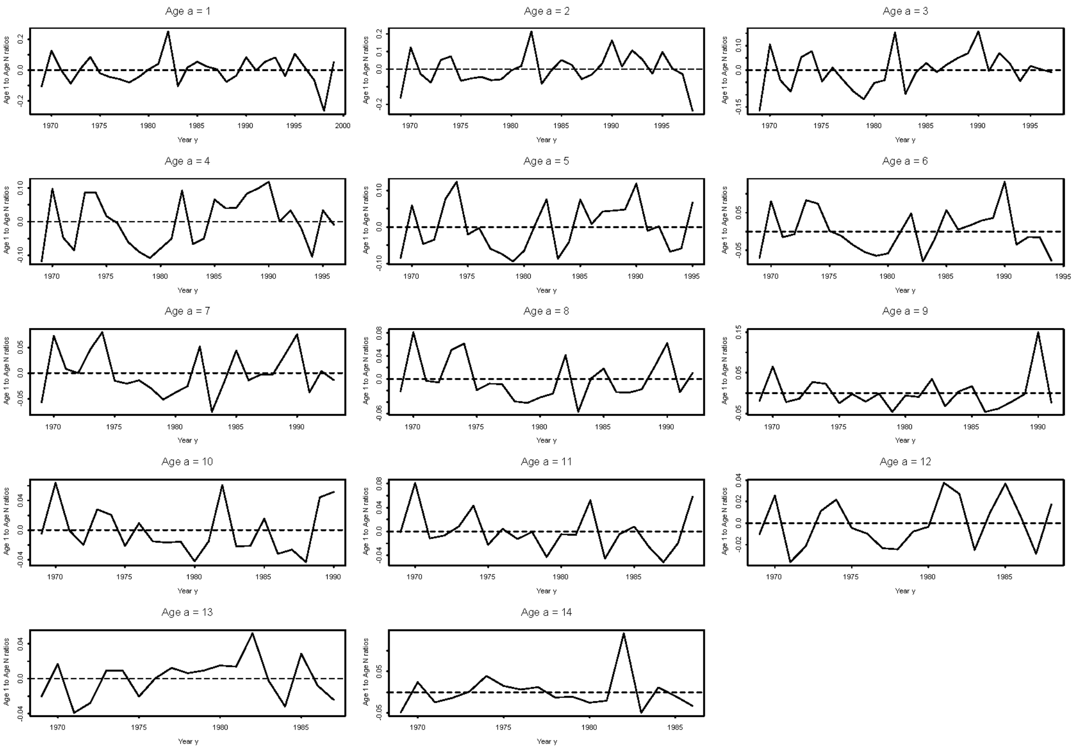


Figure 6.7.1.5. Time-series of weight-at-age increments by year classes for North Sea plaice.

6.7.2 Spawning-stock structure

Northeast Arctic cod

Tretyak (WD12) presented a model of spawning-stock structure in northeast Arctic cod, which he used to indicate which components of the spawning population have had the greatest influence on subsequent recruitment. The following is a brief summary of the method and conclusions from the working document.

Spawning-stock biomass (SSB) is a simple summary of the biomass of mature cod from different age groups. It takes into account only the age structure and mean weight of spawners at each age, and does not recognize sex ratio, differences between the weights of males and females, absolute individual fecundity, and the proportion of fish that skip spawning. It also suggests that all spawners are of the same quality and, as a result, that all eggs have a similar quality, viability, distribution, and survival. WD12 proposes a hypothesis about inter- and intra-annual dissimilarity of spawners, according to which a simple summation of the biomass of mature cod from different age groups does not reveal the actual relationship between recruitment and spawners' abundance. An algorithm for defining the abundance of first-time and repeat spawners is presented.

The abundance of *k*th-time spawners at age *t* in year *y* can be estimated using:

$$N^{p}_{t,k,y} = N_{t,y}\left(\delta_{t-k+1,y-k+1} - \delta_{t-k,y-k}\right),$$

where $\delta_{t,y}$ and $N_{t,y}$ are the maturity-at-age and abundance-at-age for age *t* in year *y*, respectively. Coefficients of correlation between recruitment and the abundance of cod of different age spawning a different number of times indicate a weak, but stable and statistically significant positive linear relationship between recruitment and the abundance of late-maturing cod spawning for the first time at age 9 and older, as well as between recruitment and the abundance of fish at the plus-group age spawning for the sixth time or more. This permits the classification of all spawners into late-maturing (first-time spawners at age 9 and older) and early-maturing fish (all others). The first group exhibited a well-pronounced decreasing trend throughout the entire time-series (Figure 6.7.2.1). Until the early 1960s, its abundance was close to that of the second group. Variations in these two components of the spawning stock were highly synchronous. However, at that time a change occurred in the structure of the spawning stock. The trend toward decrease in the abundance of late-maturing fish remained, while the abundance of early-maturing cod started to grow steadily.

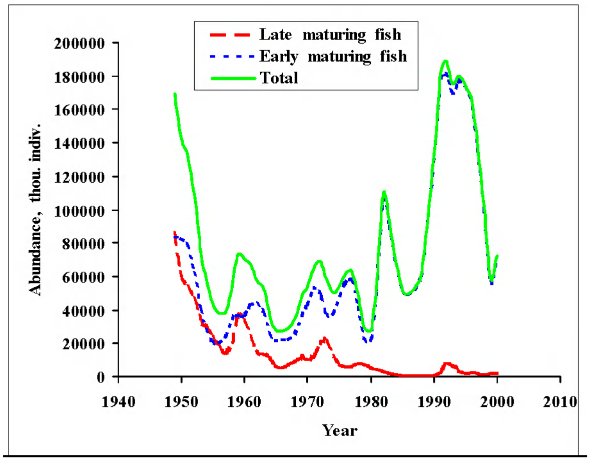


Figure 6.7.2.1. Abundance of late- and early-maturing cod and total abundance of mature cod in different years.

Approximation of variations in cod recruitment by Ricker stock–recruitment models, with the abundance of both spawning stock components and total spawning stock as independent variables, gives the results shown in Figure 6.7.2.2. As expected, over the entire history of observation, a statistically significant relationship exists only between recruitment and the abundance of late-maturing fish (Figure 6.7.2.2a). Their contribution to recruitment variance is ca. 20%. The contribution of early-maturing fish to the recruitment variance is below 1%, which is rather counter-intuitive because that component has dominated the spawning stock after the 1960s and constituted more than 93% after the mid-1970s (Figure 6.7.2.2b). This may be the result of the interannual dissimilarity of early-maturing spawners that creates noise, suppressing the actual dependence of recruitment, not only on the abundance of early-maturing fish, but also on the total abundance of the spawning stock (Figure 6.7.2.2c).

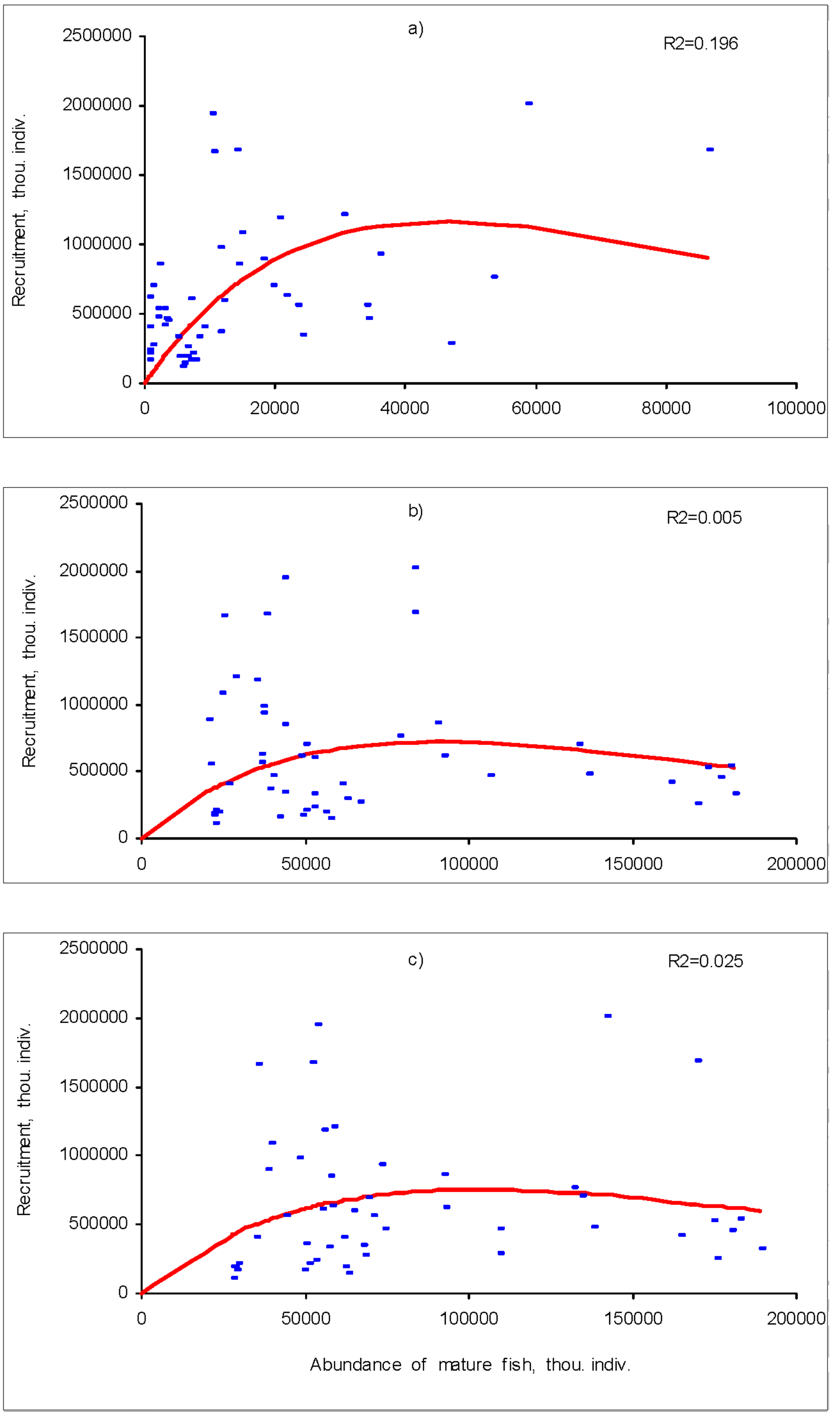


Figure 6.7.2.2. Ricker stock–recruitment model fits for northeast Arctic cod (1949–1997), using the abundance of (a) late-maturing and (b) early-maturing fish, as well as (c) total abundance.

Assuming that interannual dissimilarity of the spawning stock is caused primarily by earlier maturation, we divided the time-series of spawners' abundance (1949–1997) into four intervals. Each was related to a 25% interval of the logistic curve showing the age of 50% maturity (Figure 6.7.2.3). The 1949–1964 year classes were assigned to the first interval, the 1965–70 year classes to the second interval, the 1971–75 year classes to the third interval, and the 1976–1997 year classes to the fourth interval. We assumed that the age of 50% maturity approached the threshold of 6.65 years (Tretyak, 2000). This led to a marked smoothing of interannual differences in the quality of early-maturing spawners in the fourth interval. A decline in the abundance of older fish also reduced the dissimilarity of late-maturing cod. Therefore, it can be stated that interannual dissimilarity of all spawners in this interval is the lowest.

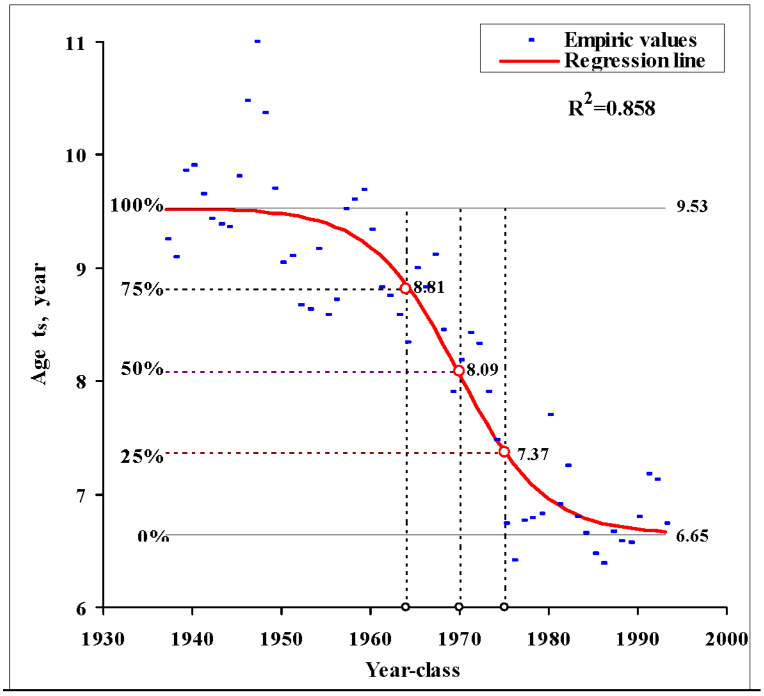


Figure 6.7.2.3. Age of 50% maturity (t_s) in different year classes of northeast Arctic cod.

Although the abundance of late-maturing fish in the fourth interval is the lowest on the record—less than 7% of the total spawning stock—the recruitment–abundance correlation for these fish has not weakened but even become closer (Figure 6.7.2.4a). For early-maturing fish, this relationship acquired statistical significance when the data set was restricted to the fourth quarter (Figure 6.7.2.4b). The contribution of a large number of these fish to recruitment variance equalled that of late-maturing cod, which is only a very small fraction of the spawning stock. The addition of late-maturing to early-maturing cod does not notably change the total abundance of the spawning stock; therefore, the dependence of recruitment on the total abundance became statistically significant when the data set was restricted to the fourth quarter. However, the total contribution of all spawners to recruitment variance did not exceed the contribution of each component of the spawning stock (Figure 6.7.2.4c).

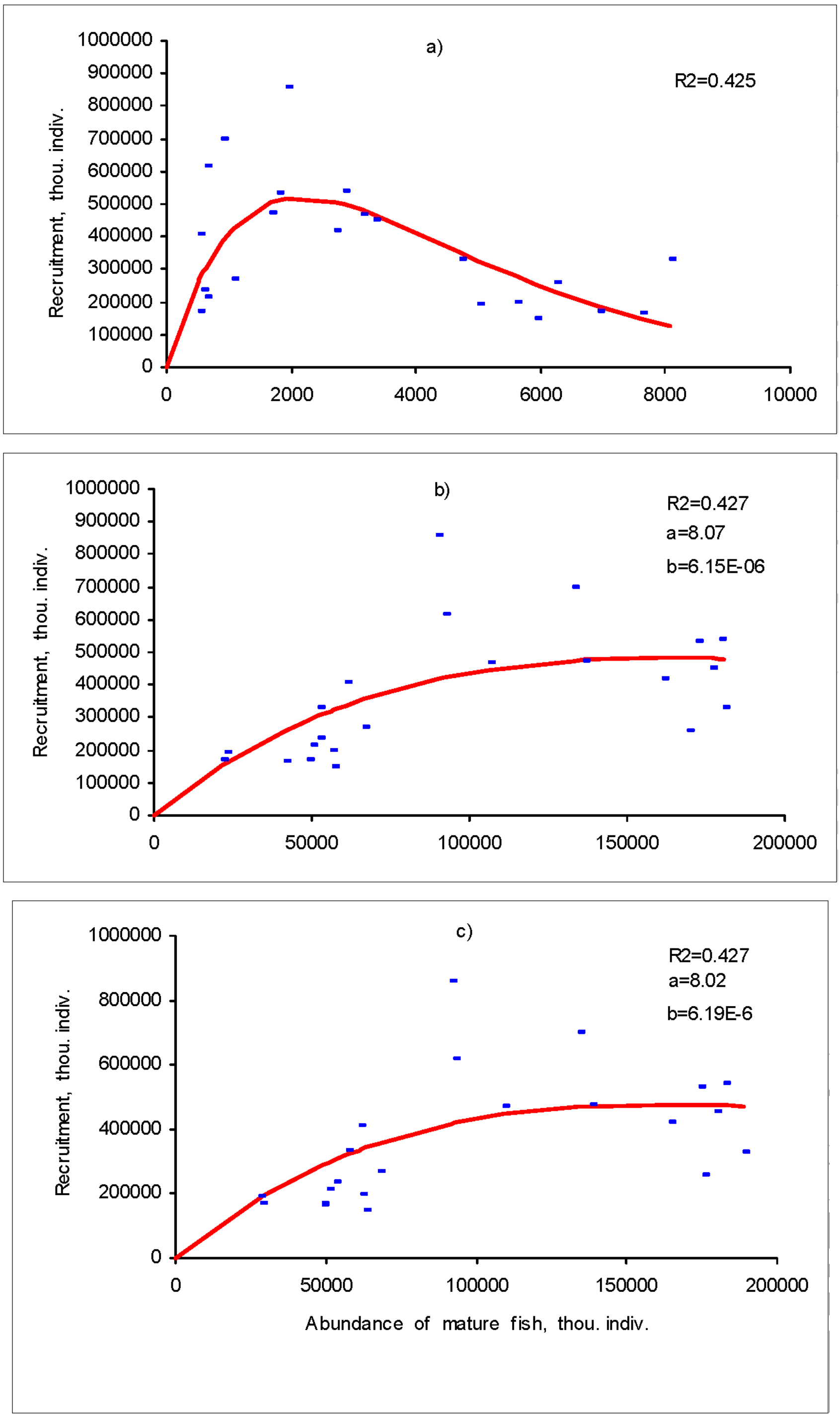


Figure 6.7.2.4. Ricker stock–recruitment model fits for northeast Arctic cod (1976–1997), using the abundance of:

(a) Late-maturing fish.

(b) Early-maturing fish.

(c) Total abundance.

The actual contribution of early- and late-maturing fish to recruitment variations is apparently somewhat greater. A determination coefficient was calculated between actual recruitment and recruitment calculated by the linear regression equation with two independent variables at the third step of recruitment approximation, and is given by:

$$\sum_j \left(R_{3,j} - \hat{R}^{(3)}_{3,j}\right)^2 \Rightarrow \min$$

where

$$\hat{R}^{(3)}_{3,j} = a_1 \cdot \left(\alpha_1 \cdot NL_j \cdot \exp\left(-\beta_1 \cdot NL_j\right)\right) + a_2 \cdot \left(\alpha_2 \cdot NE_j \cdot \exp\left(-\beta_2 \cdot NE_j\right)\right) + a_3 .$$

Here, NL_j is the abundance of late-maturing fish in year j, NE_j is the abundance of early-maturing fish in year j, and a_1, a_2, and a_3 are equation parameters calculated by the integrated gradients method. For northeast Arctic cod, this coefficient was 0.563 (Figure 6.7.2.5). The first independent variable in the above equation is the result of the first step of approximation, that is, the approximation of recruitment by the Ricker model for late-maturing fish only. The second variable is the result of the second step, that is, approximation by the Ricker model for early-maturing fish only.

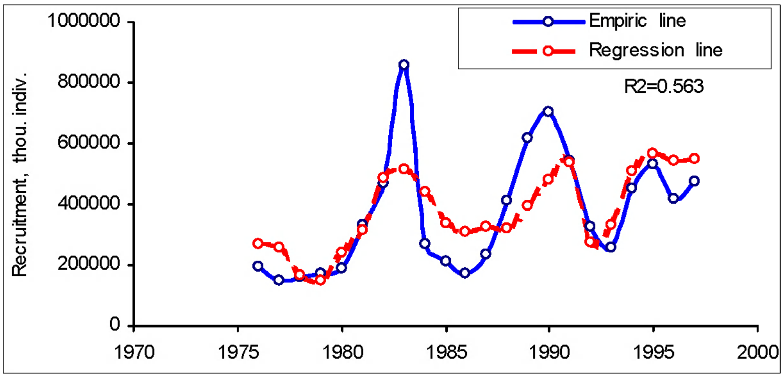


Figure 6.7.2.5. Sequential approximation of recruitment to northeast Arctic cod by linear regression equations with two independent variables.

North Sea cod and herring

Tretyak's model was applied during SGPRISM to North Sea cod and herring to ascertain its general applicability and whether it would be beneficial to use it more widely.

North Sea cod abundance and recruitment estimates were taken from ICES (2002a). Maturity estimates for 1980–1995 were taken from Cook *et al.* (1999); however, these were rather noisy and were smoothed down cohorts using the logistic ogive $W_{a,y} = 1/(1+\exp(\alpha - \beta a))$ to prevent negative spawning abundances.

Figures 6.7.2.6 and 6.7.2.7 give the abundances of kth-time spawners for North Sea cod and herring, respectively. The relative proportions of these decline with increasing k in a straightforward manner for cod; for herring, the importance of second-, third-, fourth-, and fifth-time spawners fluctuates more unpredictably. This is likely a result of the contrasting shapes of maturity ogives for the two stocks, being quite shallow for cod and very steep for herring.

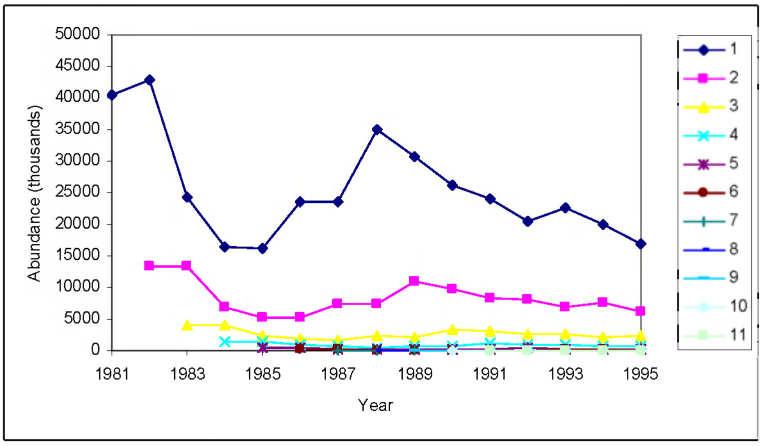


Figure 6.7.2.6. Abundance of North Sea cod spawning for the kth time. The legend gives values of k.

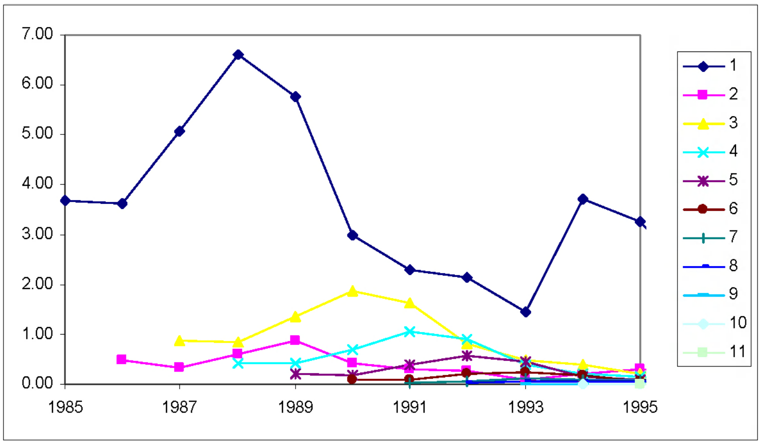


Figure 6.7.2.7. Abundance of North Sea herring spawning for the *k*th time. The legend gives values of *k*.

Table 6.7.2.1 gives linear correlation coefficients between the *k*th-time spawning abundance-at-age, and the full-stock–recruitment for North Sea cod. This is not the ideal diagnostic and in future, should be augmented by (for example) an analysis of Ricker model fits to each relationship, but it can be seen that very young and very old spawners apparently have less influence on recruitment than those of moderate age (that is, between ~5 and ~7 years old). However, very few of these correlations are statistically significant.

Table 6.7.2.1. North Sea cod: linear correlation coefficients between *k*th-time spawner abundance-at-age, and recruitment. Significant correlations (single-tailed test, 5% level) are highlighted.

	NUMBER OF SPAWNINGS										
AGE	1	2	3	4	5	6	7	8	9	10	11
1	−0.1232										
2	0.3160	0.0658									
3	−0.1022	−0.3008	−0.3086								
4	0.3284	0.0121	0.2012	0.4149							
5	0.3097	0.1814	−0.0020	−0.1509	−0.0317						
6	0.3066	**0.5939**	**0.4770**	0.3506	0.4445	0.4707					
7	0.4247	0.1515	0.3286	0.3410	0.3791	0.1054	0.0775				
8	**−0.4963**	−0.1123	−0.2921	**0.5053**	**0.7225**	0.3393	−0.1337	−0.3156			
9	−0.2654	−0.1172	**0.5748**	**0.6154**	**0.5519**	0.2558	−0.0095	−0.0134	−0.4344		
10	−0.3385	−0.3566	−0.4070	−0.3174	−0.4742	−0.1758	−0.2009	−0.3156	−0.6240	−0.4854	
11	−0.1640	−0.1444	−0.1665	−0.1132	**0.9224**	**0.5503**	0.5161	0.2165	−0.1325	−0.2678	−0.2476

North Sea herring abundance, recruitment, and maturity estimates were all taken from ICES (2001g). Table 6.7.2.2 gives linear correlation coefficients (equivalent to Table 6.7.2.1 for herring). Correlation coefficients are smaller for herring than for cod (indeed, none of them are statistically significant), and there is no obvious pattern to them. This may be a consequence of the very steep maturity ogive for herring.

The study group concluded that Tretyak's approach to the determination of the components of the spawning population that may drive recruitment is cogent and parsimonious, and would recommend that further analysis be conducted in the future into the model and its implications. An example would be the determination of the influence of first-time spawners on recruitment, with further implications for management regarding stock rebuilding strategies.

Table 6.7.2.2. North Sea herring: linear correlation coefficients between *k*th-time spawner abundance-at-age and recruitment. There are no statistically significant correlations.

	NUMBER OF SPAWNINGS							
AGE	1	2	3	4	5	6	7	8
1								
2	0.1398							
3	−0.0395	0.0303						
4	−0.2479	−0.1294	−0.1099					
5			0.1993	0.2035				
6			0.2449	0.2465	0.2138			
7				−0.0634	−0.0475	−0.1321		
8					0.1694	−0.2870	−0.2823	
9						0.0020	−0.1823	−0.3103

7 Fishery management

7.1 Reference points and management

7.1.1 Life history and reproduction dynamics

The working 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 corresponding reference points must also be reviewed. Reference points for SSB may prove to be inefficient at stock conservation when SSB does not indicate the reproductive potential of the stock, or when there are decadal changes in productivity. Although the study group recognized the practical need for biomass-based reference points in formulating management advice, it was felt that assessment working groups should consider new approaches. For example, additional reference points specific to reproductive potential could be developed.

Therefore, to keep a stock in biological perspective, it is necessary develop additional reference points specific to reproductive potential. Several such measures are currently being evaluated by the NAFO Scientific Council Working Group on Reproductive Potential (BD9). 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, BD17; Marshall, WD1). An age–diversity index (Marteinsdottir and Thorarinsson, 1998) is one possible index of reproductive potential that is easily calculated using numbers-at-age. The measure of the viable number of eggs per kilogramme of SSB, a measure utilized by Scott *et al.* (1999), is another example of an easily computed index of stock reproductive potential. Maximizing the viable egg production per unit spawning-stock biomass would seem to be a highly desirable objective for stock management because 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, particularly because they relate to selection, life history strategies, and natural mortality. The long-term consequences of sustained high rates of mortality may be underappreciated given that the link between fishing mortality and reproductive potential has not been accurately specified. 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). During the study (1946–1996), the total lipid energy exhibited ca. 20-fold variation (Figure 7.1.1.1a). 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. 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.

From 1946 to 1996, the PRR varied from 0.22 to 0.58, indicating that 20–60% of the reproductive potential was being removed annually through fishing. The PRR was significantly positively correlated ($r^2 = 0.91$, $n = 51$; Figure 7.1.1.2) with fishing mortality averaged across age classes 5 to 10 (F5–10). Values of F5–10 higher than 0.79 result in the removal of more than 50% of the reproductive potential. The precautionary value of F ($F_{pa} = 0.42$) will remove 34% of the reproductive potential annually. During the past five years, 46–61% 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.

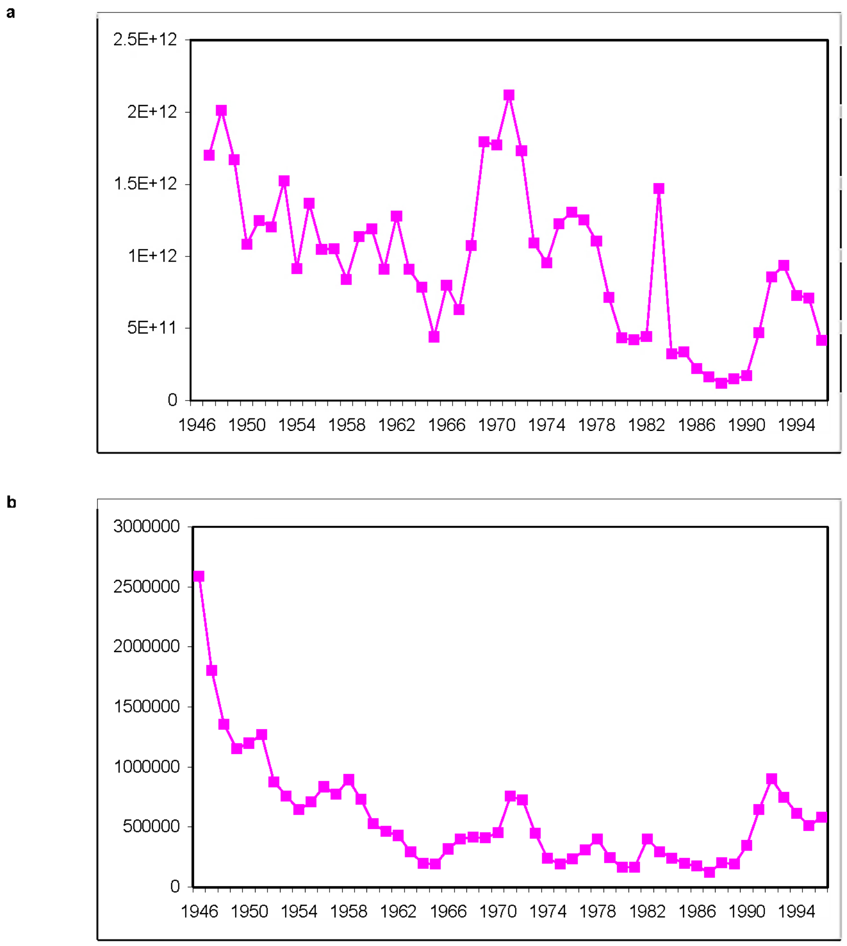


Figure 7.1.1.1. (a) Time-series of total lipid energy of northeast Arctic cod. (b) Time-series of spawner biomass for northeast Arctic cod.

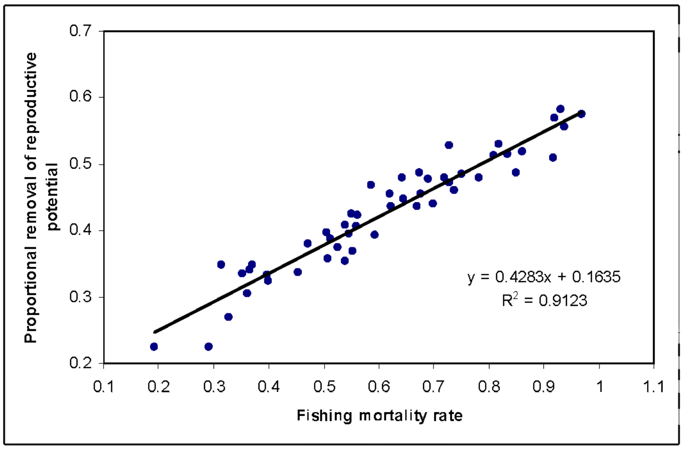


Figure 7.1.1.2. The relationship between fishing mortality rates (average values for cod age 5–10) and the proportional removal of reproductive potential by the fishery (1946–1996). A fishing mortality of 0.78 corresponds to the removal of 50% of the reproductive potential annually.

7.1.2 Spatial and fishery concerns

The role of spatial and fishery considerations, while 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, 2000d). This was in light of an apparent regime shift in recruitment between 1968 and 1978. The issue had been raised and discussed by HAWG and ACFM for a number of years. Previously, HAWG had noted that tagging investigations in the 1960s, recent acoustic surveys, and groundfish 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; 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, 2000d). Previously, HAWG had considered 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 about 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 had an impact 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 do, 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.

7.2 Should reference points and environmental factors be linked?

One question regarding management in the context of productivity that exhibits cycles or regime shifts is whether to (and how to) change biological reference points. This question is considered in Basson (1999, BD16). 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). Therefore, it is 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 B_{msy}-based threshold because 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, 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. Therefore, it is neither a reflection of the existing ICES *modus operandi* for advising on TACs, for example, nor 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 (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;
- 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 that reduces F linearly between F_{msy} and 0 for 0.5 B_{msy}<SSB<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 F_{msy};
- Performance is good if recruitment is not affected by SST.

One of the main reasons that the harvest control rule performs well under these scenarios is because it maintains SSB at a higher level than the strategies that adjust the reference points (to lower B_{msy}) as SST increases. The harvest control rule and the adjusted reference point strategies all lead to increased variability in catches compared with a fixed F_{msy} strategy (as one might expect). The average catches, however, are 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 strategies may not even incorporate a factor such as SST directly, but it is crucial that robustness tests be performed for a wide range of hypotheses about, or scenarios for, the environmental driver.

Many details and issues are not considered in the simulation study and need to be explored in a case-specific context. Issues such as assessment error and bias and management inaccuracies (e.g. catches not being equal to the TAC) have already been mentioned. Another issue is testing with a wide range of environmental scenarios; for example, not only should regime shifts that lead to reduced recruitment be considered, but also ones that lead to increased recruitment.

7.3 Discussion

During discussion, it was noted that, although knowledge and understanding of the underlying process and mechanisms are necessary for the construction of an operating model that 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 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, bias, etc.); smoothness to minimize 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 interannual variability in catches, a strategy could be designed with a limit on the percentage change in catch from one year to the next. However, it was pointed out that, in some cases (heavily or overexploited stocks), it may be difficult to achieve a sustainable fishery with a harvest strategy that limits year-to-year changes in catches.

The potentially large differences between a system that is at or close to its target exploitation level (as modelled in the simulations) and a system that is overexploited (outside safe biological limits) was also noted. For most of the ICES stocks that 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 be usefully investigated within a simulation context.

7.4 Discussion pertinent to fishery management

7.4.1 Potential benefits and drawbacks

There are several ways in which incorporating environmental factors (E) into stock assessment can inform or improve management. Although environmental factors can affect the population in many different ways (e.g. growth, spatial distribution, etc.), the main focus here is on recruitment (R), which is a major influence on the population dynamics of most fish stocks.

In terms of historical data, the incorporation of E into a stock–recruitment model could lead to improved estimates of stock–recruitment parameters, which should provide a better basis for setting biological reference points. If E is predictable, the stock–recruitment model could be used with predictions of E to obtain better short-term predictions of recruitment. This is likely to be particularly valuable for short-lived (or overexploited) stocks that are managed by TAC because, in such cases, recruitment may contribute a large proportion to predicted catches. If TACs were set for more than one year ahead, further benefits are likely. For example, if the catch is dominated by 3-year-olds, then a good prediction of recruits (at age 0) in the current year would affect the catch prediction three years ahead.

If multi-annual TACs were to be considered, advice would have to be provided for a longer period, based on predictions further in the future than is currently the case. In such a situation, the incorporation of an environmental factor could lead to predictions that are wrong by far more than predictions based on mean recruitment values. This is partly because both E and R need to be predicted, but also because the incorporation of E gives predictions of R further away from the mean. This could have a severe effect on the stock, particularly since effects are cumulative (Section 8.3).

Medium- to long-term predictions of E are clearly difficult. Nonetheless, if we assume that the basic characteristics of the E-series would persist, then this can be used in medium-term projections. If the E-series is simply random, results from runs including and excluding E would be essentially identical (Section 8.3). However, if there is a great deal of structure (e.g. cycles, autocorrelation, etc.) in the E-series, then the variance of, say, projected SSB could be different if E is included in projections.

The incorporation of E may lead to an impression of increased certainty, which could lead to a tendency to sail closer to the wind (e.g. harvesting at higher Fs), implying riskier harvesting strategies. This could have serious implications for the stock if predictions turn out to be poor or if the relationship with E breaks down.

One of the main benefits for medium-term projections, or management strategy evaluations, is likely to occur in situations where there appears to be a distinct change in the environment (e.g. warmer temperatures in the most recent decade in the North Sea). One can evaluate what would happen if the environment returns to historical patterns or persists at recent levels, and base management advice on this information. Of course, this type of what-if or scenario modelling can be done even if we do not know what is causing the observed changes in recruitment.

There are also potential benefits if hydrographic models can inform us about spatial aspects of recruitment. For example, if larvae from a spawning area (A) drift to another area (B) to settle, this process may be highly dependent on certain hydrographic conditions at the right time of year. If recruitment fails in area B in a given year, this may have nothing to do with harvesting at area B, but could simply stem from hydrographic conditions. This is an example where the effect of E may be more like an on/off switch than a continuous positive or negative influence. This type of information can be particularly useful when considering issues such as closed areas or stock structure/distribution.

It is also possible to make a Type I or Type II errors (Section 3.1), and this would have implications for management if E is included.

7.4.2 When to incorporate environmental factors

Evidence of a clear relationship between E and population dynamics may point to the inclusion of E, though the strength of the effect and potential benefits to management should also be explored. In some cases, evidence may be relatively indirect, coming from a range of studies in different geographical areas, and contain a high level of common sense plausibility. The effects of upwelling on anchovy recruitment may be such an example. Particularly because anchovies are a short-lived species and recruitment, therefore, dominates stock and catch dynamics, it seems sensible to incorporate E, even if the exact mechanism is not fully known. Once such a likely candidate has been identified, further studies may reveal more about the mechanism that, in turn, could lead to improved environmental indices with greater explanatory—and predictive—power (see, for example, Allain *et al.*, 1999). This spiral of iterative improvement is crucial to the process.

Progress in the inclusion of E-series in recruitment prediction has been hampered by purely correlative studies that easily generate spurious correlations. A good correlation between some E-series and a biological variable (recruitment, for example) is not enough on its own to justify inclusion into assessment. Having plausible hypotheses for mechanisms is the least requirement, while the ideal situation is having some evidence for the hypotheses. It is also necessary to have confidence that the detected relationship will persist. These issues are best addressed by studies aimed at identifying one or more likely mechanisms. An increased understanding of the possible reason for observing a strong correlation will strengthen trust that there really is a link and, therefore, increase confidence to incorporate E. An understanding of the mechanism also provides information on how/where in a functional relationship the E-term should enter as a covariate.

In addition to the strength and nature of a possible link between E and a biological process, the nature and characteristics of the environmental factor is very important.

7.4.3 Ways to incorporate environmental factors

The potential benefits to management (or improved assessment/prediction) are closely related to the way in which environmental factors are incorporated. In principle, an E-series can be used as a tuning index in an assessment, although possible non-linearities may be a problem. If a direct index of the variable being estimated is available, for example larval abundance index to estimate recruitment, this may be preferred. Although both direct and indirect indices (e.g. an upwelling index) can be used together, there may be technical details, such as relative weighting of the indices, that still need to be resolved.

An index of some environmental conditions can also be used in a two-step approach. Here the idea is to run an assessment (e.g. XSA, ICA) without the environmental index (Step 1). In Step 2, results (e.g. estimates of recruitment) and the environmental index are calibrated to allow the index to be used in a predictive way. Such an implementation would be similar to using the RCT3 program to predict current year recruitment using an index that has *not* been used in the XSA tuning. Again, there are technical details that need to be elaborated in further work, and some issues would have to be addressed on a case-by-case basis.

Environmental series can be incorporated into stock–recruitment models as covariates. If the mechanism is not known, tractable formulations of S–R models with E-terms will tend to be fitted. Different formulations, however, may have different implications, and it may not be possible to distinguish between models based on goodness-of-fit. The recruitment dynamics at low SSB, which is usually outside the range of the data, could be strongly affected.

Improvements to a stock–recruitment model fit where E is included may suggest changes in biological reference points (in terms of SSB and/or F). Here, however, a set of reference points (F_{crash} and MBAL, for example) would be associated with a given level of the environmental factor. This is because there is no longer a single S–R curve, but rather a surface, i.e. a different curve for each value of E. Given that reference points should not change from year-to-year and that it may be impossible to predict future E values, exactly how reference points should be adjusted for E still requires careful thought and further work.

In situations where E appears to have changed in level in the recent past (e.g. the Irish Sea and North Sea examples discussed in an earlier section), there may also be a need to re-evaluate current reference points to ensure that they are compatible with the current and the assumed near-future environmental conditions. The key here is the assumption about future environmental conditions.

Assumptions about the future environmental dynamics can be incorporated in medium-term projections. Clearly, it is not essential to predict E exactly into the medium-term projection in order to explore the likely future dynamics of the stock. Instead, a (statistical) distribution of future E is assumed. The projections can be done in a what-if approach to see whether different assumptions about the future distribution of E make a difference to results, or to identify worst-case scenarios.

The incorporation of E into management strategy evaluation can also play an important role. These studies can help identify the likely benefits gained from incorporating E into assessment, e.g. in terms of stock conservation or yield. One can also explore the implications of:

a) Incorporating E into assessment when there really is *no* persistent link;

b) Ignoring E when there really *is* a link between E and recruitment, for example.

7.4.4 The importance of environmental factors in the design of management procedures

One of the background papers (Basson, 1999) was originally presented at the ICES symposium "Confronting Uncertainty in the Evaluation and Implementation of Fisheries-Management Systems", Cape Town, 16–19 November 1999.

The main questions considered in the study are: what are the likely gains of incorporating an environmental factor into the model of stock and recruitment, and under which circumstances are the gains likely to be highest? The incorporation of environmental factors into a model of stock and recruitment could improve the prediction of recruitment and/or the definition of reference points, but may also require costly underpinning science. The study uses simulation to explore the implications of including or excluding environmental factors when predicting recruitment. A gadoid-like example, with three levels of strength of interaction between the environmental factor and recruitment, is considered. The characteristics of the environmental series are highly relevant and important for prediction purposes. Two hypothetical *temperature* series are considered: a first-order autocorrelated (AC = 0.5) series and a sine wave series with random error. Although the sine wave series is a rather pathological example, it serves to illustrate a best-case scenario where one can assume that the underlying mechanism of the environmental driver is known, but realized with error.

In the examples considered in this study, there is no gain (in terms of either conservation or average yield) when an environmental factor is incorporated in the short-term prediction of recruitment. This is mainly because:

a) For a long-lived stock that is not totally depleted/overfished, predicted recruitment forms only a relatively small proportion of the two-year ahead predicted catch in weight, which is the basis for TACs.

b) Similarly, predicted recruitment forms only a relatively small proportion of the two-year ahead predictions of SSB.

c) ICES advice currently focuses on these two-year ahead predictions, and TACs are only set for a single year at a time.

Adaptive management via changes in fishing mortality reference points as the temperature series changes only leads to gains when the environmental factor can be well predicted (e.g.

the sine wave example). In these examples, the main gains were in P(SSB<B_{pa}) rather than in the mean yield. The variability in yield was higher when management was adaptive, and this is more likely to be considered a disadvantage than a gain.

Results suggest that the main factors influencing the likelihood that certain types of gains (e.g. increase in long-term mean yield) are likely to be achieved by incorporating environmental factors into stock and recruitment models used for prediction are:

- The predictability of the environmental series;
- The strength of the effect of the environment on recruitment;
- The contribution of predicted recruitment to predicted catch and SSB.

The importance of doing simulation studies to explore the likely benefits and feasibility of incorporating environmental factors in management procedures is emphasized.

7.4.5 Conclusions

Considerations of environmental factors can make a big difference in how one might manage a stock. Simulation models can play an important role in identifying 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, it would be possible to incorporate this immediately, if historical data are already available.

The systems we are studying are complex, and we need to be careful not to focus too narrowly on a single aspect or species. Too narrow a focus could cause crucial links or factors to be missed. Mechanisms may also be flexible and change, depending on a whole suite of parameters.

Correlative studies on their own are not enough, first, because interactions may be non-linear and, second, because correlations can be spurious. Correlative studies, however, can be used as pointers to where interactions could be expected.

Convincing incorporation of environmental factors involves a great deal of work, particularly in terms of fieldwork where mechanisms are being explored and in terms of long-term observations. Long-term studies, however, are crucial to the success of this type of work. Progress should be viewed as an iterative process of improvement, and most benefits from such studies are likely to accrue after several years rather than a single year or less.

ICES stock assessment working groups should be aware of the possibly large effects of incorporating the bias correction into stock–recruitment models fitted with a log-normal error assumption. A bias correction should be applied, unless stock–recruitment models are fitted using the GLMs in the first place (the preferred approach).

ICES stock assessment working groups should consider reference points in light of apparent changes in environment. However, technical details, particularly regarding implementation (e.g. how to decide *when* to change from one set of reference points to another) have not been resolved yet and are unlikely to be so in the short term.

8 Modelling environmental change on fish stocks

8.1 Introduction

It is now acknowledged that changes in the environment do affect fish population dynamics. This is demonstrated both by the spatial scales over which recruitment appears synchronized for several stocks (Myers *et al.*, 1995; Myers *et al.*, 1997) and by apparent correlations between recruitment and environmental variables (Ottersen and Sundby, 1995; Myers, 1998; Planque and Frédou, 1999; Fox *et al.*, 2000). A significant problem with advancing this work is that variables such as temperature are correlated with many other environmental variables that also affect fish at the individual and, by inference, at the population level. For example, sea surface temperatures in the Northeast Atlantic during the first six months of the year are correlated with atmospheric conditions (NAO) and, thus, with windstress and average direction. Windstress, in turn, can affect primary productivity through water column processes, while varying levels of turbulence have been linked to changes in the feeding success of fish larvae (Alcaraz, 1997; Dower *et al.*, 1997; Fiksen *et al.*, 1998). Environment also affects the growth of adult fish, both directly and through links with prey availability (Brown *et al.*, 1989; Brander, 1995; Dutil *et al.*, 1999; Ottersen and Loeng, 2000; Purchase and Brown, 2001). For mature fish, feeding conditions affect condition and the amount of energy that can be put into reproduction. Combined with the status of the fish as first-time or repeat spawners, this could affect subsequent recruitment success (Marshall and Frank, 1999; Marshall *et al.*, 1998). Changes in environmental variables such as temperature can also affect fish distribution directly and may lead to changes in spatial overlap with prey (Sparholt *et al.*, 1991; deYoung and Rose, 1993; Heessen, 1993; Swain and Wade, 1993; Ottersen *et al.*, 1998).

Models developed to explore such relationships vary from simple statistical approaches (examples above) through single-species population dynamics models to complex coupled hydrodynamic–biological models. To date, the last category has tended to focus on the biology of early life history stages (Hermann *et al.*, 1996; Leising and Franks, 1999). Their complexity and consequent computer resource requirements currently prevent their application over multiple years, which is a requirement for extended time-series population dynamics modelling (Hermann *et al.*, 2001). Similarly, it can prove prohibitive to undertake multiple model runs for sensitivity testing, although application of engineering simulation theory can help in this respect (Megrey and Hinckley, 2001). Thus, extended time-series population dynamics modelling has tended to use simple, single-species population dynamics models, but representations of at least some biological processes can be included. Usually, the problem is knowing how much biological realism to include to generate realistic results. The most useful aspect of such models is that they allow exploration of the sensitivity of the population dynamics to changes in rates and processes at different life history stages over several decades of simulated time (Quinlan and Crowder, 1999). Modern computers allow large numbers of model runs, providing the scope to explore the effects of stochastic variability. The challenge for the future appears to be producing models capable of bridging these extremes.

In the first section, the working group considers results from a simple, single-species population dynamics model for cod. This model is used to explore how North Sea cod population dynamics might be affected by sea temperature. The model is used to assess the relative impact of temperature on stock dynamics through effects on recruitment (early life history stages) and adult growth. The working question was whether increases in adult growth rates can compensate for reduced recruitment linked with increased sea temperatures? One of the model's assumptions is that condition (i.e. the relation between length and weight) is constant. In the second section, we examine survey-based and market sampling data available for North Sea cod and plaice for changes in adult condition factors. We then conduct a simple exploratory analysis to assess whether changes in such factors could be modelled using simple environmental indices as covariates.

8.2 Modelling the effects of environmental change on North Sea cod

8.2.1 Introduction

Interannual changes in North Sea cod recruitment are related to changes in sea surface temperature (SST; Brander, 1996; Planque and Fox, 1998; Planque and Frédou, 1999; O'Brien *et al.*, 2000). The relationship is negative with increased February to June SSTs, resulting in reduced recruitment to the stock. Fluctuations in water temperature also have a secondary continuous effect on cod individuals through their influence of growth rates and hence, weight-at-age. Cod stocks located in regions with low water temperatures (e.g. Labrador) generally have lower growth rates and reach a larger maximum size than fish stocks located in warmer waters (e.g. Celtic Sea; Taylor, 1956; Brander, 1995).

Given this, the expected changes in climate and sea temperatures in future decades will ultimately influence the abundance and biomass of cod stocks. However, although increased temperatures may result in a reduced level of recruitment, this may be offset through higher rates of growth, leading to higher spawning-stock biomass. We present the results of a study that investigates the combined effects of temperature on recruitment and weight-at-age, through the use of a self-generating model of North Sea cod.

8.2.2 Model functioning

Overview

The model is a self-generating cod model (similar to WGMTERM; Reeves and Cook, 1994), but with SSTs influencing the interannual changes in the numbers of recruits each January, and bottom temperature influencing the changes in the mean length and weight of each age class (Figure 8.2.2.1). Abundances of new recruits (at age 1) are calculated using a combined Ricker-temperature stock–recruitment function that incorporates the previous February–May SST and the previous year's SSB. For each year, the abundance of age classes 2–15 are calculated by considering the levels of fishing and natural mortality (which for 1963–2000 were set at ICES 2001 WGNSSK values (ICES, 2002a)). Each month the average increments in length of each year class are computed using a temperature-dependent growth equation. These lengths are then converted into weight using a constant length:weight conversion (currently taken from FISHBASE), multiplied by maturity ogives (currently taken from ICES 2001 WGNSSK), and summed to give SSB of each age class calculated. The main functional relationships in the model are as follows.

Ricker-temperature stock–recruitment function

This is an adaptation of the standard Ricker stock–recruitment function with temperature as an added parameter:

$$R = SSB.e^{(a\text{-}b.SSB)}e^{(c.SST)}$$

where R is the abundance of new recruits, SSB is spawning-stock biomass, SST is sea surface temperature. Constants are statistically fitted parameters calculated using data from the 1963–2000 period (a = 5.27542, b = 0.00000355342, c = –0.560823).

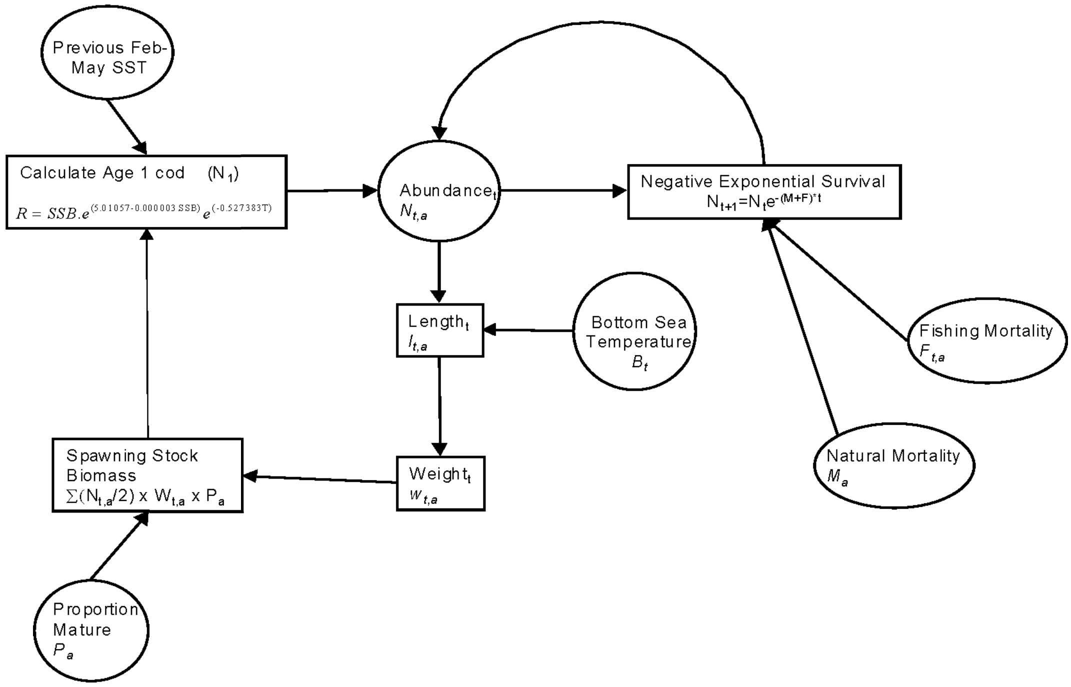


Figure 8.2.2.1. Model interrelationships.

Negative exponential survival

This function calculates the number of survivors relative to the previous month, given the natural as well as the fishing mortality pressure on the stock:

$$N_t = N_{t-1}e^{-(M+F)t}$$

where N_t is abundance of fish during that particular month, N_{t-1} is abundance of fish during the previous month, M is instantaneous natural mortality rate, F is instantaneous fishing mortality rate, t is change in time in years (i.e. as monthly t is 1/12).

Temperature-influenced von Bertalanffy size-at-age function

The mean length of a particular age class may be calculated using the standard von Bertalanffy function:

$$L_a = L_\infty(1 - e^{-K(a-tzero)})$$

where L_a is length-at-age, L_∞ is asymptotic length (set at 119 cm), K is growth parameter, a is age, tzero is age where model registers that length as zero.

In a work by Taylor (1956), examining differences in growth rates of cod stocks across the North Atlantic, it is observed that temperature is related to both the rate of growth (K) and the maximum length (L_∞). Thus, K may be calculated as follows:

$$Log_{10}K = 1.22(Log_{10}T) - 1.72$$

where K is growth parameter, T is bottom temperature.

Taylor (1956) obtained his parameters by relating the growth rates of many North Atlantic cod stocks with the mean water temperatures that these different stocks inhabit (similar models have been formulated by Brander (1995)). However, here we are trying to relate relatively small changes in growth rates to similarly small changes in temperature during 1963–2000. As such, the parameters in the above equation have been tuned *ad hoc* from those given in the Taylor paper, so that the model will produce weights with a similar mean to those observed during 1963–2000. Taylor (1956) also related differences in L_{inf} to water temperature. However, it has been considered that this is not appropriate for this study when we are only dealing with changes in a single stock (hence L_{inf} is set at 119 cm (Gulland, 1977)).

For the calculation of the length of age 1 cod, the von Bertalanffy equation is used, with the mean annual bottom temperature (obtained from ICES) experienced during the first year of growth used to calculate K (Gamito, 1998):

$$\frac{\partial l}{\partial t} = \frac{K}{12}(L_{\infty}.1 - K.L_{t-1})$$

where L_{t-1} is the length at the previous time-step (in this case the previous month).

8.2.3 Evaluation of model performance and diagnostics

Comparison of observed and modelled cod recruitment and SSB

The fit of the model was evaluated by producing output for 1963–2000, both incorporating and omitting the influence of temperature on the calculation of recruitment and SSB according to the following scenarios:

- Ricker. Standard growth
- Ricker + SST. Standard growth
- Ricker. Temperature growth
- Ricker + SST. Temperature growth

The output from each scenario was then compared visually (Figures 8.2.3.1–8.2.3.4) and statistically (Table 8.2.3.1) with those values of recruitment and SSB for 1963–2000 given in the ICES WGNSSK 2001 report (ICES, 2001f).

To identify how well the recruitment and growth calculations perform separately within the model, two additional scenarios replaced modelled recruitment and growth with observed values taken from the ICES WGNSSK 2001 report (ICES, 2001f) as follows:

1) Observed recruitment. Standard growth
2) Observed recruitment. Temperature growth

Table 8.2.3.1. Sum of squares error (× 10^{-8}) between the observed and modelled recruitment and SSB.

Model Run	Recruitment	SSB
Observed recruits, Standard growth	0.00	116.65
Observed recruits, Temperature growth model	0.00	185.07
Ricker, observed weight-at-age	22763.36	1736.60
Ricker, Standard growth model	20295.30	1211.87
Ricker, Temperature growth model	20193.57	799.69
Ricker + SST, observed weight-at-age	10384.32	790.86
Ricker + SST, Standard growth model	10916.53	1266.19
Ricker + SST, Temperature growth model	10309.60	415.64

The inclusion of SST in the calculation of recruit abundance notably improves the model's fit in predicting the abundance of recruits (Figure 8.2.3.1–8.2.3.4, Table 8.2.3.1). However, the additional inclusion of temperature information in the calculation of length (and thus weight) at age produces little additional improvement in the prediction of recruitment (cf. Figure 8.2.3.1 with Figure 8.2.3.3, and Figure 8.2.3.2 with Figure 8.2.3.4), owing to the negligible effect that changes in SSB (over the range of values considered here) are predicted to have on recruitment, i.e. over this range of SSB, the Ricker function is almost flat.

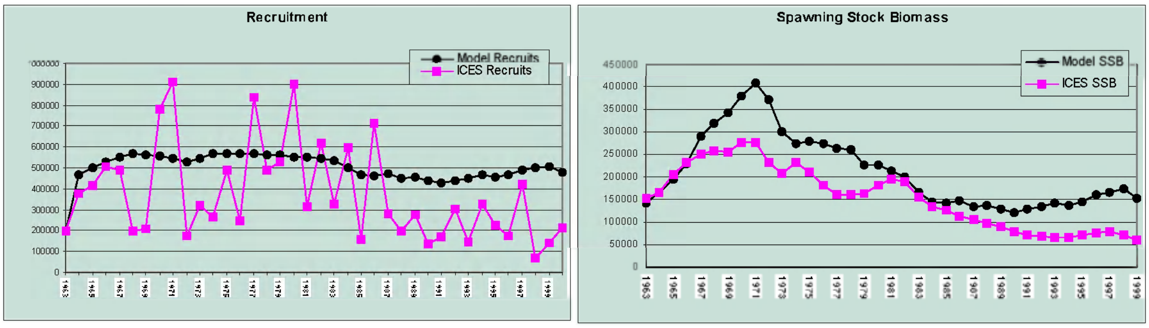


Figure 8.2.3.1. Comparison of model output produced using the standard Ricker function and the standard von Bertalanffy growth curve, with ICES values.

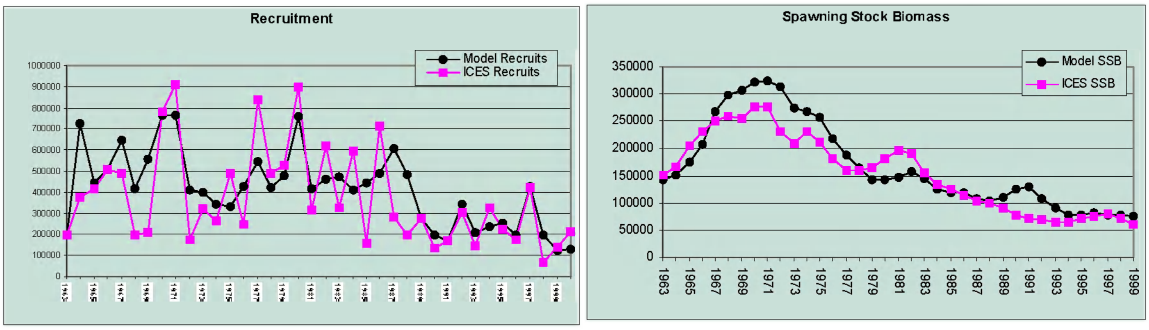


Figure 8.2.3.2. Comparison of model output, produced using the Ricker-temperature function and the standard von Bertalanffy growth curve, with ICES values.

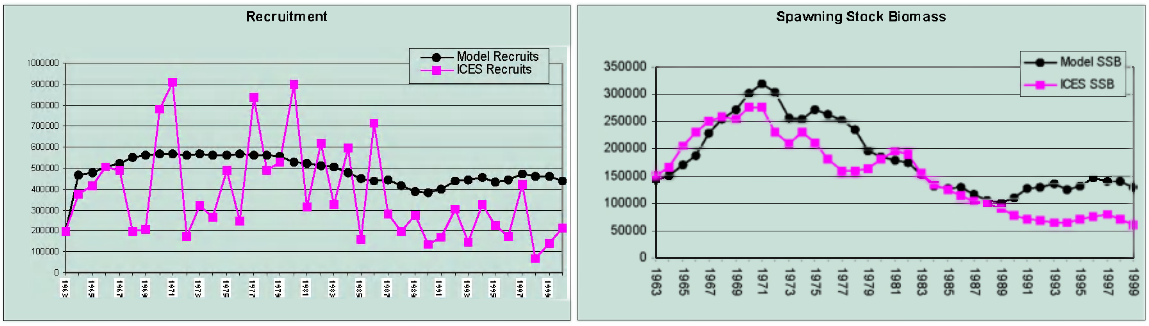


Figure 8.2.3.3. Comparison of model output, produced using the standard Ricker function and the temperature-influenced growth function, with ICES values.

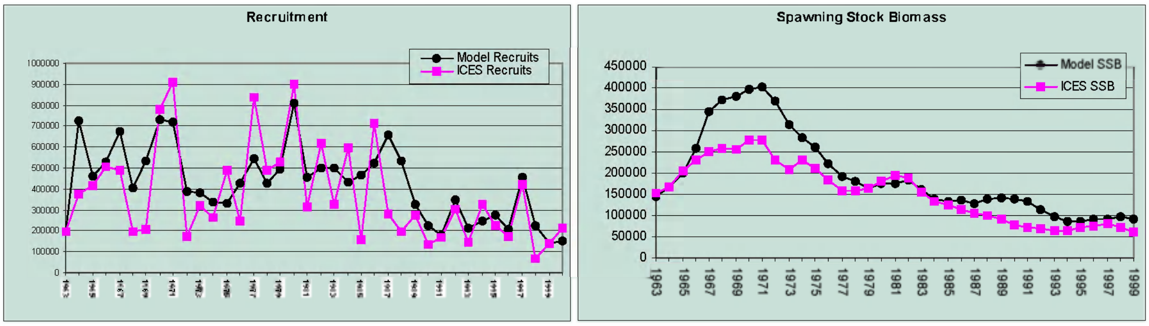


Figure 8.2.3.4. Comparison of model output, produced using the Ricker-temperature function and the temperature-influenced growth function, with ICES values.

A greater improvement is observed when temperature information is incorporated into the prediction of SSB because omitting the temperature information causes the model to overestimate the SSB. However, this might not be entirely reliable because the equation of Taylor (1956) has been tuned to mimic the observed weights-at-age. Unsurprisingly therefore, there is a reasonable similarity between the modelled and the observed mean weights-at-age. Figure 8.2.3.5 shows that the median modelled weight-at-age is too low for age 1, slightly below the observed for ages 2, 5, 6, 7, 9, and similar for ages 3, 4, 8, 10, 11. The variation in weight is reasonably captured by the model for ages 1–5. However, older age classes have increasing interannual variation in weight, which the model does not reproduce.

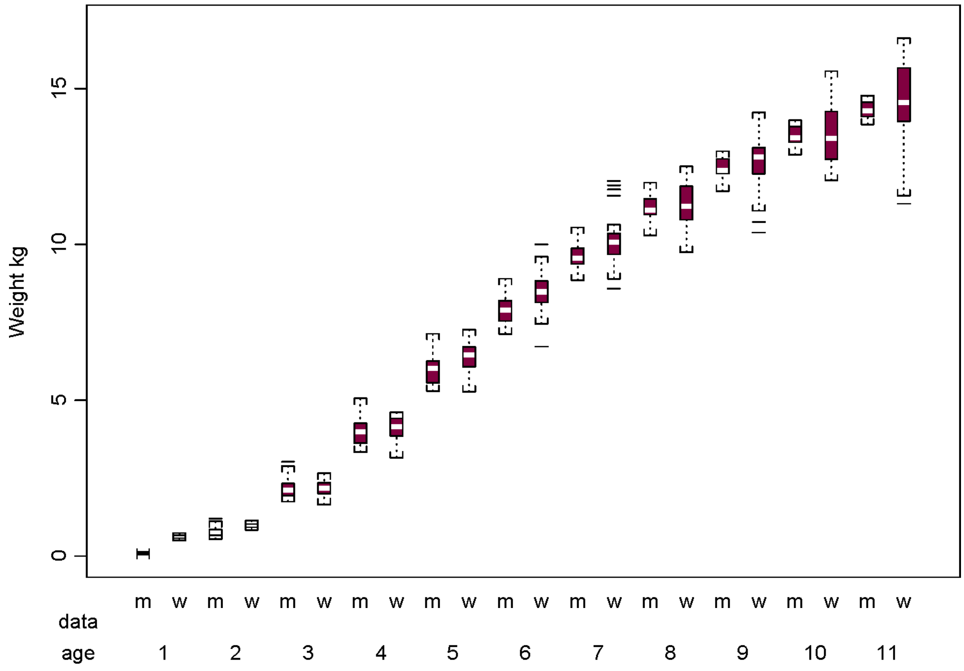
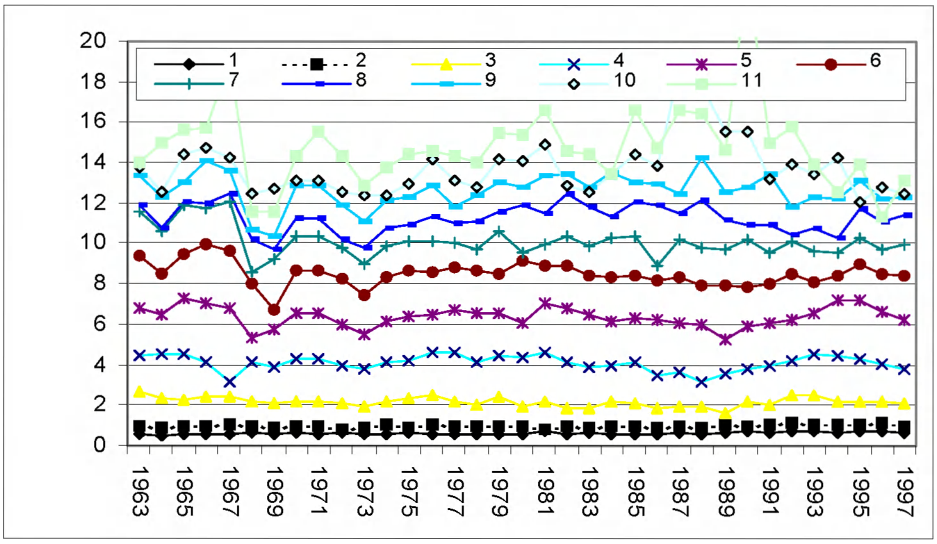


Figure 8.2.3.5. Comparison of modelled (m) weights-at-age with observed values from the working group report (w). Solid block part of bar represents the 25th to 75th percentile, white horizontal bar the median.

The greater variation in observed weight-at-age relative to modelled weight-at-age may be seen in Figure 8.2.3.6 (lower plot). A comparison of the weight-at-age by year using correlation analysis (Table 8.2.3.2) shows similar trends in modelled and observed weight for age classes 1 and 2. However, it is proposed that in the near future, the weight-at-age portion of the model will be more thoroughly reviewed and reparametrized.



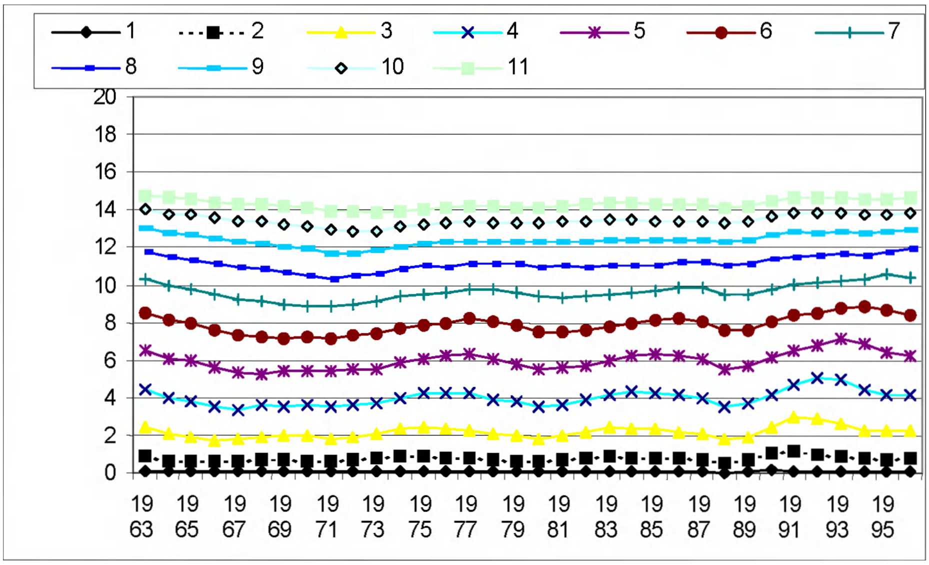


Figure 8.2.3.6. Comparison of observed weight-at-age 1963–1997 (upper plot) with modelled weight-at-age (lower plot) 1963–2000.

Comparison of observed and modelled growth curves (incorporating temperature) for North Sea cod

The distributions of observed and modelled weights-at-age were compared for the 1963–1997 period (Figure 8.2.3.5). A second comparison involved evaluating the observed changes in weight-at-age with time against the modelled weight-at-age with time.

The greater variation in observed weight-at-age relative to modelled weight-at-age may be seen in Figure 8.2.3.6 (upper plot). A comparison of the weight-at-age by year using correlation analysis (Table 8.2.3.2) shows similar trends in modelled and observed weight for age classes 1 and 2.

Table 8.2.3.2. Results of correlation analysis between observed and modelled interannual fluctuations in weight.

AGE CLASS	R	P
1	**0.536**	**0.001**
2	**0.384**	**0.023**
3	0.209	0.228
4	0.326	0.056
5	0.307	0.073
6	0.122	0.484
7	0.086	0.625
8	0.153	0.38
9	0.203	0.241
10	0.037	0.833
11	0.016	0.927

Examination of bias in modelled SSB

An examination of Figures 8.2.3.1–8.2.3.4 shows a bias in the modelled SSB, with the observed SSB being lower than the modelled SSB during the late 1960s/early 1970s. This is despite the model's underestimate of the weights-at-age (see above). To ensure that this bias was not caused by an inherent error in the calculation of recruits, residuals obtained from the modelled and observed recruits and SSB were plotted. In addition, a comparison was made of the stock–recruitment functions fitted to the data used in the ICES WGNSSK report.

The residual plots (Figures 8.2.3.7 and 8.2.3.8), taken together with Figures 8.2.3.1–8.2.3.4, suggest that any bias in the SSB is simply the result of the different abundances obtained in the calculation of the abundances of recruits. For example, the observed overestimation of recruitment in both the standard and temperature models from 1963 to 1970, and the resulting increased cod abundances resulting from this for the next few years, is the cause of the later bias in SSB during the late 1960s/early 1970s.

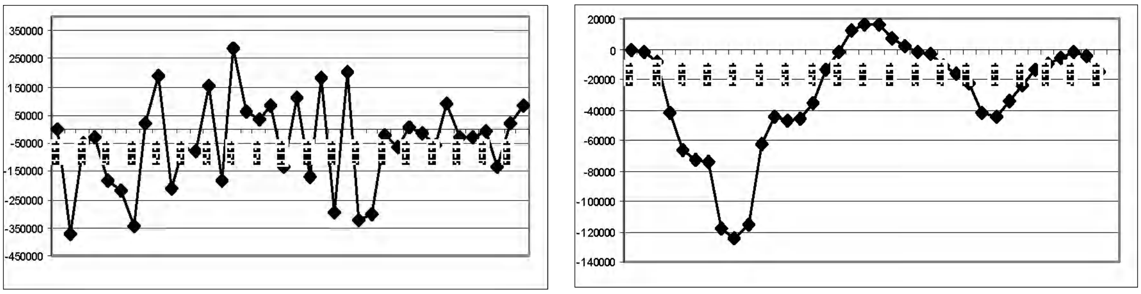


Figure 8.2.3.7. Residuals from modelled recruitment (left), and SSB (right) calculated using the Ricker-temperature function.

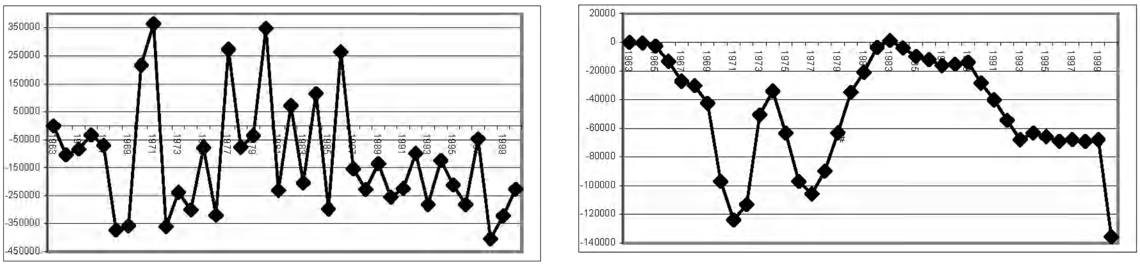


Figure 8.2.3.8. Residuals from modelled recruitment (left), and SSB (right) calculated using the standard Ricker function.

A final examination of the modelled stock–recruitment functions (Figure 8.2.3.9) suggests that there is little difference between the Ricker (no SST) and the WG Shepherd fits, except at the higher values of spawning-stock biomass.

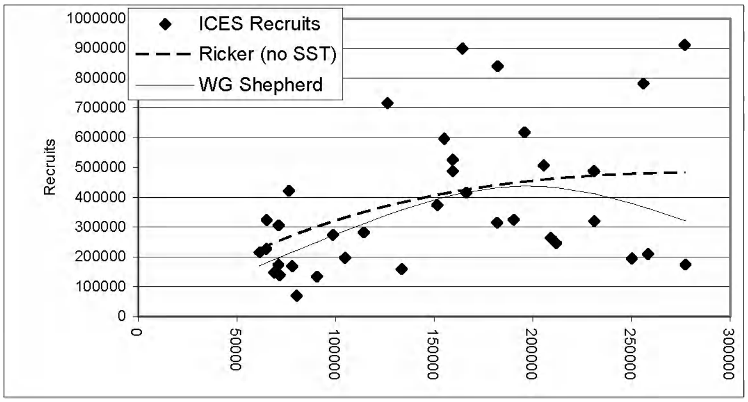


Figure 8.2.3.9. Comparison of fitted stock–recruitment functions from the model (Ricker (no SST) and Ricker + SST with that in the ICES WGNSSK report (WG Shepherd). Note that the functions have not been bias corrected.

8.2.4 Conclusions

Models of this type can be used for examining the relative impact of changes in environmental variables such as temperature on different life history stages of fish population dynamics. The model described above will be used with sea temperature projections from coupled ocean–atmosphere circulation models to examine possible impacts of climate change on cod.

8.3 Investigation into the effect of including environmental data into medium-term projections

In the two applications considered (North Sea cod and North Sea plaice), recruitment and spawning-stock biomass have been estimated from the single-species assessment method XSA, Extended Survivors Analysis (Darby and Flatman, 1994).

Medium-term stochastic projections were run using a modified version of the Visual Basic program MTSP (Medium-Term Stochastic Projection). This program, currently under development at the Cefas Lowestoft Laboratory, is similar to WGMTERM, but was further modified to allow the inclusion of temperature effects in the stock–recruitment model.

8.3.1 Population dynamics

The program takes age-structured steady-state vectors as its input. Initial numbers are carried forward and catch numbers estimated by applying natural and fishing mortality rates according to the catch equations of Baranov (1918):

$$N_{t+1,age+1} = N_{t,age}e^{-Z_{age}}$$

and

$$Catch_{t,age} = N_{t,age}\frac{F_{age}}{Z_{age}}\left(1 - e^{-Z_{age}}\right)$$

with

$$F_{age} = FMult \times Sel_{age}$$

and

$$Z_{age} = F_{age} + M_{age}$$

M denotes natural mortality and $FMult$ is an effort multiplier applied to a selection pattern Sel.

If the maximum age is a plus group, then

$$N_{t+1,PlusGrp} = N_{t,PlusGrp-1}e^{-Z_{PlusGrp-1}} + N_{t,PlusGrp}e^{-Z_{PlusGrp}}.$$

Yield and spawning-stock biomass (SSB) are estimated using

$$Yield \;=\; \sum_{MinAge}^{MaxAge}\left(Catch_{age} \;\; x \;\; CWt_{age}\right)$$

and

$$SSB \;=\; \sum_{MinAge}^{MaxAge}\left(N_{age} \;\; x \;\; SWt_{age} \;\; x \;\; Mat_{age}\right)$$

where *CWt* denotes the average weight (at age) in the catch, *SWt* denotes the average weight (at age) in the stock at spawning time, and *Mat* is the estimated maturity (at age).

Stochastic variation was introduced into the simulations in one of three ways:

1) Starting populations were simulated according to a log-normal distribution using coefficients of variation (CVs) from the standard stock assessment.

2) Recruitment was varied by randomly resampling residuals from a fitted model and reapplying them to the predicted value.

3) Where applicable, the temperature regime was modelled by randomly reselecting an annual temperature signal from a portion of the time-series.

Temperature was modelled according to the Ricker stock–recruitment relationship (SRR) with the parameterization:

$$R = \alpha \text{ SSB } e^{-\beta \text{SSB}} \, e^{\varphi \text{T}}$$

Estimates of the recruitment parameters were obtained by non-linear minimization of log-residuals.

8.3.2 Simulation experiments

Simulations were run during the first meeting of SGPRISM to demonstrate the medium-term effects of log-normal bias correction to recruitment estimates and to investigate the possible effects of changes in the temperature regime on the North Sea cod and North Sea plaice stocks. Not all of the simulations offered material relevant to the present exercise; therefore, only scenarios 1–3, 5, 7, 9–12, 14, 16, and 18 are presented and discussed further.

Subsequently, a subset of the original simulations were rerun following minor alterations to the program suggested during the meeting, which included:

- Starting the three independent random number streams with different seeds;
- Extending the number of iterations from 500 to 1000;
- Not including a bias correction on the starting population numbers.

Table 8.3.2.1. Details of simulations undertaken.

SCENARIO	RECRUITMENT MODEL	LOG-NORMAL BIAS CORRECTION APPLIED	TEMPERATURE
1	Recruitment data randomly resampled	N/A	N/A
2	Ricker SRR	no	N/A
3	Ricker SRR	yes	N/A
5	Ricker SRR incorporating temperature	yes	Randomly resampled 1963–1997
7	Ricker SRR incorporating temperature	yes	Randomly resampled 1963–1987
9	Ricker SRR incorporating temperature	yes	Randomly resampled 1988–1997
10	Resample	N/A	N/A
11	Ricker	no	N/A
12	Ricker	yes	N/A
14	Ricker SRR incorporating temperature	yes	Randomly resampled 1957–1997
16	Ricker SRR incorporating temperature	yes	Randomly resampled 1957–1987
18	Ricker SRR incorporating temperature	yes	Randomly resampled 1988–1997

The three temperature regimes investigated consisted of a) the full time-series of temperature, b) all temperatures except the past ten years in the time-series, and c) just the final ten years of temperature. The final ten years represent a warm period, while the first (n-10) years represent a cooler period. The temperature signal used was the mean annual North Sea surface temperature for February to June derived from the Comprehensive Ocean Atmosphere Dataset (COADS) and provided by the National Center for Atmospheric Research (NCAR, Boulder, CO, USA).

8.3.3 Results

North Sea cod

Figure 8.3.3.1 shows the log-normal bias-corrected Ricker stock–recruitment models fitted for North Sea cod, obtained excluding and including a temperature effect.

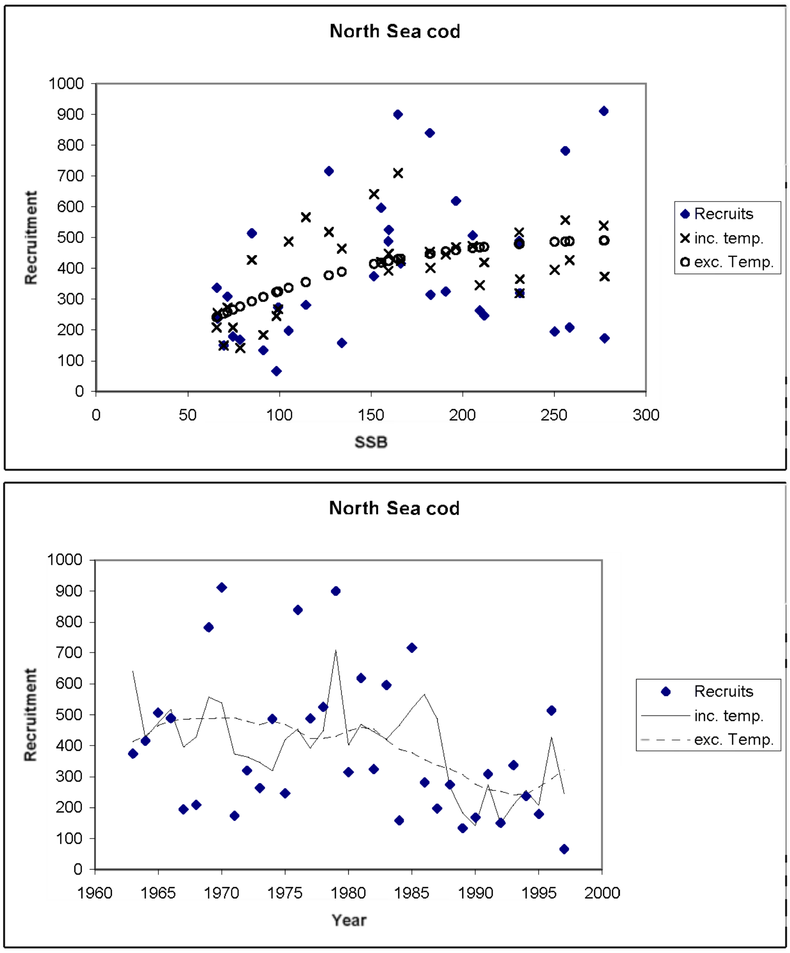


Figure 8.3.3.1. North Sea cod stock–recruitment. In the upper plot, recruitment is plotted against SSB; in the lower plot the recruitment trajectory through time is shown.

The temperatures used for the predicted recruitment values shown in Figure 8.3.3.1 are those actually occurring in the year of spawning, hence these points represent predicted values from many different Ricker stock–recruitment curves, i.e. a family of SRR conditional on temperature (Figure 8.3.3.2).

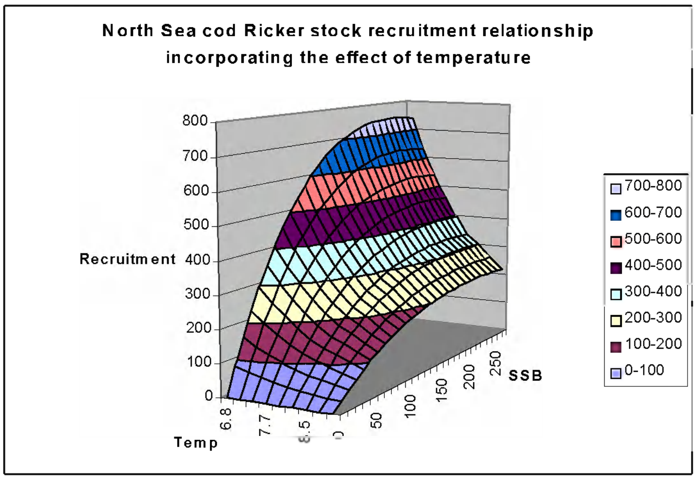


Figure 8.3.3.2. North Sea cod. Ricker stock–recruitment model incorporating the effect of temperature.

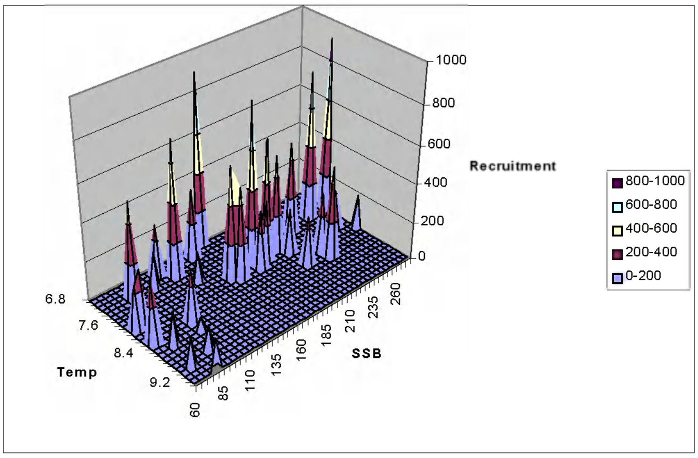


Figure 8.3.3.3. North Sea cod stock–recruitment and temperature data.

The effect of temperature on cod recruitment appears dramatic from the Figures 8.3.3.2 and 8.3.3.3. It should be remembered, however, that stock–recruitment data are generally sparse and noisy, which poses problems when fitting multidimensional curves and interpreting the resulting surfaces. Fitting a surface makes many more assumptions and demands on the data. The observed stock and recruitment data are plotted in Figure 8.3.3.3. It can be seen that, although there is evidence of low recruitment at low SSB and high temperature, data are noticeably absent from the high SSB and high temperature region.

North Sea plaice

Plots analogous to those produced for North Sea cod were produced for North Sea plaice.

Figure 8.3.3.4 shows the log-normal bias-corrected Ricker stock–recruitment models fitted for North Sea plaice, obtained excluding and including a temperature effect.

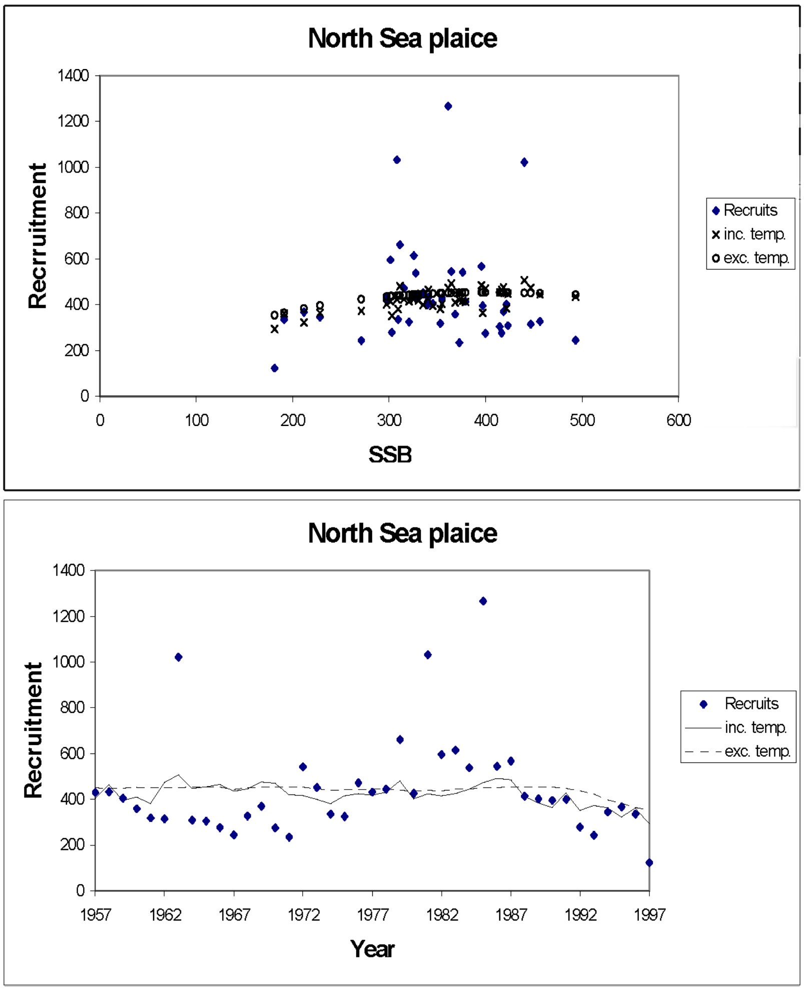


Figure 8.3.3.4. North Sea plaice stock–recruitment. In the upper plot, recruitment is plotted against SSB; in the lower plot the recruitment trajectory through time is shown.

It can be seen in Figure 8.3.3.4 that the curvature of the Ricker stock–recruitment relationship is much less pronounced in the range of observed SSB than that observed for North Sea cod, and that the effect of temperature is much less pronounced. This results in relatively little systematic variability in the range of the data.

Surface plots of the fitted model (Figure 8.3.3.5) and data (Figure 8.3.3.6) are presented.

The data show that low recruitment tends to occur at both low and high SSB and at high temperature. Medium and high recruitment tend to have occurred between medium and high SSB and at low to moderate temperatures. The effect of temperature appears much stronger in the data than in the fitted model (Figure 8.3.3.4), and it may be that the Ricker stock–recruitment relationship is not appropriate over some or all the temperature range. This requires further investigation, but has not been further considered because of the shortness of the study group meeting.

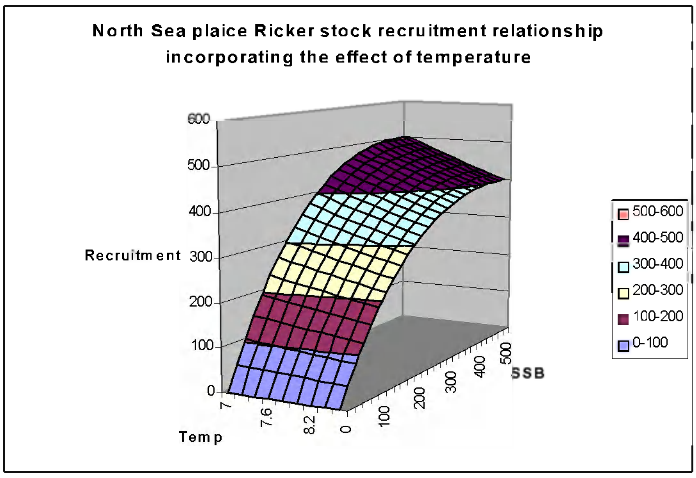


Figure 8.3.3.5. North Sea plaice. Ricker stock–recruitment model including the effect of temperature.

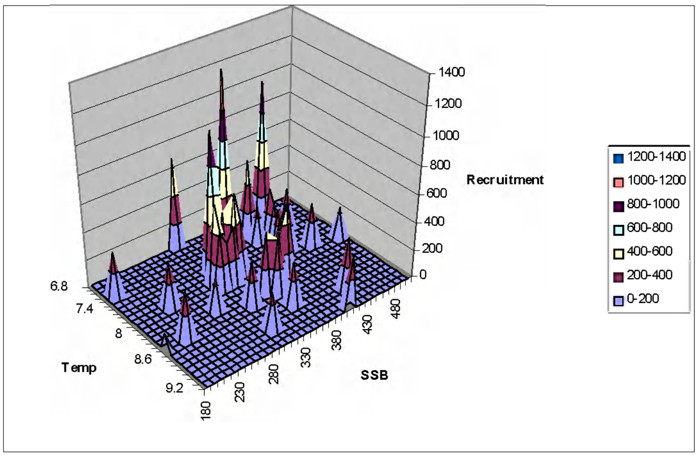


Figure 8.3.3.6. North Sea plaice stock–recruitment and temperature data.

North Sea cod and plaice

Results from the simulations have been summarized in many ways in the annexes to the reports of each SGPRISM meeting.

Summary Tables 8.3.3.1 and 8.3.3.2 give estimates of the probability of SSB falling below B_{pa} in year 5 (2003) and year 10 (2008) over a range of F multipliers. Also shown in this table is the reference F at which the probability of SSB falling below B_{pa} is 10% in year 10 (2008).

8.3.4 Discussion

The log-normal bias correction to the Ricker stock–recruitment relationship produces expected values of recruitment, i.e. values higher than the uncorrected values. This correction is additive on the log-scale, multiplicative on the untransformed scale, and amounts to an increase in recruitment of around 15% for North Sea cod and an increase in recruitment of approximately 8% for North Sea plaice. The residual variances, and hence bias corrections, were slightly lower for the model incorporating a temperature effect, despite the loss of a degree of freedom through the incorporation of an additional parameter in the model fitting.

As expected, comparison of scenarios 2 vs. 3 and 11 vs. 12 (Tables 8.3.3.1 and 8.3.3.2) confirms that the log-normal bias correction has a significant effect on the probabilities of SSB falling below B_{pa}, and that this is more notable in the final year of the simulation. The effects of systematically misestimating recruitment will be cumulative over time in the projection.

In general, the trajectory of SSB for North Sea cod, at *status quo* F, declines slightly during the first 3–4 years of the simulations, then recovers steadily. This can also be seen in Table

8.3.3.1, where P(SSB<B_{pa}) in 2003 (year 5) is higher than in 2008 (year 10). The projected 95th percentile of cod SSB increases to levels outside the maximum seen in the historical SSB series (c. 280 kt) in the later years of the projection, as does the median in scenarios 3, 5, and 7 (bias corrected and not unfavourable environmental conditions).

The trajectory of SSB for North Sea plaice at *status quo* F shows an initial rise followed by a decline, which tends to gradually stabilize. For plaice, the fifth and 95th percentiles of SSB remain within historical levels throughout all simulations, owing to the flat nature and apparent relative insensitivity to environmental conditions of the stock–recruitment relationship. At high fishing mortalities, the stock is highly likely to fall below B_{pa}, irrespective of environmental effects or misestimation of recruitment, while at low fishing mortalities, it will tend to recover above B_{pa}. At fishing mortalities which produce SSB in the region of B_{pa}, the probability P(SSB<B_{pa}) becomes sensitive to changes in recruitment estimation, and the effects of bias correction and temperature become apparent. This is in the range of F multipliers 0.9–1.1 for North Sea cod and 0.7–0.9 for North Sea plaice.

For example, with an F multiplier of 0.8, the probability P(SSB_{10}<B_{pa}) for North Sea plaice varies from 0.41 to 0.61, according to scenario. At this fishing pressure, SSB is about 15% more likely to go below B_{pa} if the temperature regime of the past ten years persists as opposed to a cooler regime. For North Sea cod, the situation is more dramatic. With an F multiplier of 1.1 under the cooler regime of 1963–1987, the probability of SSB in 2008 falling below B_{pa} is 8%, but under the present warm conditions, the probability rises to 60%. Given management aims of P(SSB<B_{pa}) around 5–10%, environmental effects may have a significant impact.

The final columns of Tables 8.3.3.1 and 8.3.3.2 indicate the absolute F required for a 10% probability of SSB being at B_{pa} in the final year of the projection. It is notable that, for North Sea plaice, the differences between scenarios are very slight (ca. 0.02 at the extreme), probably below the precision provided by assessment and certainly below the precision of management actions.

For North Sea cod, there is a slightly greater range of F for P(SSB_{10}<B_{pa}) = 0.1 (ca. 0.075 at the extreme), which equates to about 10% of F, but this is still at the limit of assessment and management precision.

8.3.5 Conclusions

Not surprisingly, the log-normal bias correction significantly increases estimates of recruitment. Misestimation of recruitment has cumulative effects over time in medium-term simulations. Simplistic inclusion of temperature effects in stock–recruitment relationships affected the outcome of medium-term projections, particularly for North Sea cod, but rather less for North Sea plaice. Adverse climatic conditions can increase the probability of falling below biomass reference points in medium-term simulations, at particular levels of F. The range of F between scenarios required to achieve P(SSB_{10} <B_{pa}) = 0.1 was very narrow. Small reductions in F would provide management robust to the environmental changes simulated.

Table 8.3.3.1. Probability of North Sea cod SSB <B_{pa} in years 5 and 10 for a range of F multipliers.

PROBABILITY OF BEING BELOW B_{PA} (150 000 T) IN 2003														
				F MULTIPLIER										
Scenario	Recruitment	Bias correct	Temperature	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
1	Resample	N/A	N/A	0.00	0.00	0.01	0.10	0.33	0.57	0.77	0.90	0.98	1.00	1.00
2	Ricker	no	N/A	0.00	0.00	0.00	0.07	0.30	0.59	0.82	0.96	1.00	1.00	1.00
3	Ricker	yes	N/A	0.00	0.00	0.00	0.04	0.18	0.41	0.67	0.86	0.96	1.00	1.00
5	Ricker	yes	35	0.00	0.00	0.00	0.05	0.18	0.43	0.68	0.86	0.96	0.99	1.00
7	Ricker	yes	First 25	0.00	0.00	0.00	0.03	0.12	0.33	0.59	0.83	0.94	0.99	1.00
9	Ricker	yes	Last 10	0.00	0.00	0.01	0.12	0.39	0.71	0.90	0.97	1.00	1.00	1.00

PROBABILITY OF BEING BELOW B_{PA} IN 2008															
				F MULTIPLIER											
Scenario	Recruitment	Bias correct	Temperature	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	F_{bar} giving P(SSB<B_{pa}) = 10%
1	Resample	N/A	N/A	0.00	0.00	0.00	0.00	0.02	0.12	0.34	0.60	0.84	0.96	0.99	0.68
2	Ricker	no	N/A	0.00	0.00	0.00	0.00	0.01	0.11	0.43	0.81	0.97	1.00	1.00	0.685
3	Ricker	yes	N/A	0.00	0.00	0.00	0.00	0.00	0.03	0.18	0.51	0.84	0.98	1.00	0.735
5	Ricker	yes	35	0.00	0.00	0.00	0.00	0.00	0.03	0.19	0.51	0.84	0.97	1.00	0.735
7	Ricker	yes	First 25	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.35	0.74	0.95	0.99	0.76
9	Ricker	yes	Last 10	0.00	0.00	0.00	0.00	0.02	0.21	0.60	0.91	0.99	1.00	1.00	0.66

Fbar (2–8) = 0.69

Table 8.3.3.2. Probability of North Sea plaice SSB <B_{pa} in years 5 and 10 for a range of F multipliers.

PROBABILITY OF BEING BELOW B_{PA} (300 000 T) IN 2003

				F MULTIPLIER										
Scenario	Recruitment	Bias correct	Temperature	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
10	Resample	N/A	N/A	0.00	0.03	0.30	0.60	0.77	0.86	0.92	0.96	0.99	0.99	0.99
11	Ricker	no	N/A	0.00	0.05	0.34	0.65	0.81	0.89	0.95	0.98	0.99	0.99	1.00
12	Ricker	yes	N/A	0.00	0.02	0.23	0.55	0.74	0.84	0.91	0.96	0.98	0.99	0.99
14	Ricker	yes	41	0.00	0.03	0.25	0.59	0.78	0.89	0.95	0.98	0.99	1.00	1.00
16	Ricker	yes	First 31	0.00	0.02	0.24	0.55	0.77	0.88	0.94	0.98	0.99	0.99	1.00
18	Ricker	yes	Last 10	0.00	0.05	0.35	0.67	0.84	0.92	0.98	0.99	1.00	1.00	1.00

PROBABILITY OF BEING BELOW B_{PA} IN 2008

				F MULTIPLIER											
Scenario	Recruitment	Bias correct	Temperature	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	F_{bar} giving P(SSB<B_{pa}) = 10%
10	Resample	N/A	N/A	0.00	0.02	0.22	0.55	0.73	0.85	0.93	0.96	0.98	0.99	0.99	0.3
11	Ricker	no	N/A	0.00	0.02	0.24	0.58	0.79	0.92	0.97	0.99	1.00	1.00	1.00	0.297
12	Ricker	yes	N/A	0.00	0.00	0.09	0.41	0.68	0.83	0.93	0.97	0.99	1.00	1.00	0.315
14	Ricker	yes	41	0.00	0.01	0.11	0.45	0.74	0.89	0.97	0.99	1.00	1.00	1.00	0.315
16	Ricker	yes	First 31	0.00	0.00	0.10	0.42	0.70	0.87	0.96	0.98	1.00	1.00	1.00	0.316
18	Ricker	yes	Last 10	0.00	0.01	0.23	0.61	0.83	0.94	0.99	1.00	1.00	1.00	1.00	0.297

Fbar (2–10) = 0.45

9 Discussion

9.1 Introduction

The study group worked from the premise that there is often considerable variation in recruitment, for a given level of spawning-stock biomass. This variation is frequently attributed to environmental effects on survival at particular life history stages. 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.

To address the Terms of Reference, which appear in Annex 1, the study group divided their task into four components:

1) **Comprehension of processes and prediction of recruitment**—approaches that aim at understanding the underlying processes that contribute to the recruitment process and, hence, have the potential for a future prediction of recruitment. This necessitated a consideration of biological processes, physical processes, and environmental drivers.

2) **Simulation of recruitment patterns**—approaches that generate ensemble recruitment appropriate for simulation purposes. These may not *per se* be good for predicting recruitment, but may allow evaluation of recruitment uncertainty within fishery assessment and management models.

3) **Fishery management**—incorporation of prediction models and simulation models into short-term predictions and medium-term projections of stock status. Quantification of appropriate levels of uncertainty and risk.

4) **Single species vs. multispecies**—how much is recruitment variability attributable to multispecies effects such as predation/competition rather than to environmental drivers?

The study group provided examples of how accounting for the effect of environmental variability has had an impact on the perception of the status of a stock through assessment (ICES 2000, 2001, 2002). Case studies of North Sea cod and the Bay of Biscay anchovy were central themes of the three meetings.

9.2 Summary

The study group reviewed a number of issues that have considerable potential for incorporation into medium-term recruitment forecasts.

The results may be categorized under three broad headings: environmental parameters, environmental parameters/biological processes, and biological processes.

Environmental parameters (EP)

1) Background details were given of the WGMTERM projection computer 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 were presented, together with a number of modifications (O'Brien *et al.*, 2000; ICES, 2000, 2001, 2002).

2) Two procedures to forecast anchovy recruitment for short-term predictions (one 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 one available, was performed at the first meeting (ICES, 2000). Now that two models are available, a synthesis of the methods is required to obtain the recruitment forecast. Given the large deviance between forecasted and estimated population for 2000, the study group felt that it was convenient to set up a semi-quantitative approach to forecast the level of recruitment from the two aforementioned models.

3) Currently, the low accuracy of the environmental indices as recruitment predictors makes it impossible to estimate the population abundance one year in advance. Therefore, any use of those indices in forecast advice to managers should be postponed in the short term until better predictive power of the environmental stock–recruitment models is achieved.

4) It has been proposed that a simulation study be conducted to evaluate the benefits of using environmentally linked recruitment predictors in the management of anchovy stocks. This work was conducted in 2002, and the results are pertinent to ICES (Uriarte *et al.*, 2002).

5) The study group requested that ICES 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 utilized in fisheries management.

6) The study group had a general discussion based on the results of a simulation study to investigate the potential for environmental studies to impact upon management procedures (e.g. harvest control rules). 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 evidence 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.

Environmental parameters (EP)/Biological processes (BP)

1) Results from a modelling of the effects of environment variability on North Sea cod were presented, together with the investigation of model-diagnostics and a temperature-induced characterization of the weight-at-age relationship. Data for North Sea plaice were also examined in parallel with an investigation of systematic changes in condition factor.

2) Further development of stock assessment software tools, as proposed by the ICES Working Group on Methods on Fish Stock Assessments (WGMG; ICES, 2002c) was discussed in the context of computer software for medium-term projections. Time-series characterizations of historical weight-at-age were presented for a selection of North Sea stocks, including the highly topical North Sea cod. A model of spawning-stock structure in northeast Arctic cod was applied to North Sea cod and herring during the third meeting to ascertain its general applicability and whether it would be beneficial to use it more widely (ICES, 2002).

Biological processes (BP)

1) Routine stock assessments are sometimes criticized for their lack of biological information, particularly in relation to reproductive parameters. In many cases, this is a valid criticism. Although it seems obvious 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.

2) 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 (number of eggs g^{-1}) and integrate across age to give an estimate of total egg production. The data required for this calculation include:

    2.1) Assessment-derived numbers-at-age;
    2.2) Age-specific values of the proportion of females;
    2.3) Age-specific values of the proportion mature;
    2.4) Age-specific weight;
    2.5) 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.

1) In reviewing progress within the EU-funded STEREO Project (STock Effects on REcruitment relatiOnships), the study group considered the project within the

larger management context, and so it investigated what additional information from the project would be of use to managers. Data on the reproductive potential of cod from the STEREO project were made available to stock projections; the results are described in ICES (2001).

2) The changes in age structure that have occurred in the North Sea cod stock since the 1960s 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 were recast in terms of egg production. Many of the relevant data sources are already sampled at sea or on the commercial fish markets, and including maturity-at-age data on an annual basis, with a weight-based fecundity relationship, would not be a major problem for many stocks. This would allow improved stock–recruitment relation (SRR) fitting but, given existing methods, would not necessarily result in improved projections. 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 (Needle *et al.*, 2001; ICES, 2002).

3) The study group prepared a partial list of continuing 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.

4) A limited number of area-based case studies were presented that illustrate a sequential introduction of biological processes into estimates of stock biomass. Recruitment is viewed from both a biological and a stock assessment perspective. Potential impacts of spawning characteristics on reference points for fishery management were reviewed and discussed in the context of the current precautionary approach to fishery management.

9.3 Closing remarks

Although it is not possible to control factors such as sea temperature and wind directly, changes in the environment clearly influence recruitment and the future size of fish stocks. A better understanding of the relationships between environment, parental stock, and recruitment should contribute to the design of robust management for commercial fisheries. Research aimed at addressing these issues continues.

Consideration of environmental factors can make a difference to how one might manage a stock (Basson, 1999). 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 it immediately if historical data are already available.

Marine systems are complex, and care is needed not to focus too narrowly, for example, on a single aspect or species. Too narrow a focus could mean that crucial links or factors are missed. Mechanisms may also be flexible and change depending on a whole suite of parameters.

Correlative studies on their own are not enough, first, because interactions may be non-linear, and second because correlations can be spurious. Correlative studies, however, can be used as pointers to expected interactions.

Convincing incorporation of environmental factors involves a great deal of work, particularly fieldwork—where mechanisms are being explored—and in long-term observations. Long-term studies, however, are crucial to the success of this type of work. Progress should be viewed as an iterative process of improvement, and most benefits from such studies are likely to accrue after several years rather than in a single year or less.

Since the conclusion of SGPRISM, much has been written about global warming and climate change. It would be remiss not to mention this briefly.

9.4 Climate change

Climate change could have serious scientific and economic repercussions for fisheries (Klyashtorin, 2001), but the implications are not clear (Cook and Heath, 2005). During the past decade, fishing pressure coupled with warming has put pressure on North Sea cod, catches of which are mainly made up of young immature fish (O'Brien *et al.*, 2000).

Temperature is frequently used as an environmental variable in recruitment models (Cardinale *et al.*, 2004) because temperature is recognized as affecting fish biology (Brander, 1995). Temperature affects fish directly and indirectly through ecological and physiological mechanisms (Ottersen *et al.*, 2005; Drinkwater, 2005). In Section 8, the study group explained the importance of incorporating temperature into recruitment models.

The marine ecosystem is full of complex interactions that are not fully understood. There is evidence of fish changing their latitude, depth, and boundaries with climate change (Perry *et al.*, 2005). Consequently, there is ambiguity about how these changes will alter predator–prey relationships and habitat availability (Perry *et al.*, 2005). The long-term changes in abundance and distribution of stocks will depend on complex predator–prey interactions, habitat availability, and extent of climate variability (Perry *et al.*, 2005). A greater knowledge of fish biology is required to understand exactly how climate change may act (Kell *et al.*, 2005).

The combination of fishing and climate change are placing pressures on fish stocks (Schiermeier, 2004; McFarlane *et al.*, 2000; Cook and Heath, 2005), and precautionary action needs to be taken to help rebuild stocks (O'Brien *et al.*, 2000). Current rates of fishing mortality are not sustainable and may need to be cut to ensure recovery of depleted stocks (Cook and Heath, 2005). If fishing mortality were reduced to half of the current levels, biomass precautionary reference points could possibly be reached (Kell *et al.*, 2005). Precautionary action needs to be taken by fishery managers as a North Sea fishery of young immature fish has emerged from an amalgamation of changes in North Sea temperature, low spawning-stock biomass, and levels of exploitation (Longhurst, 1998). The collapse of fish stocks may be exacerbated more by warming than by fishing alone (Clark *et al.*, 2003).

General circulation models (GCMs) predict that global sea surface temperatures will increase as a result of climate change. However, the extent of the warming is uncertain (Drinkwater, 2005). The HadCM3, a coupled atmosphere–ocean general circulation model (AOGCM) predicts that by 2040, North Sea surface temperature will have risen by 1°C (Gordon *et al.*, 2000; Pope *et al.*, 2000). The regional climate model HadRM3 predicts that mean annual North Sea surface temperatures will increase by 0.5–1.0°C, 1.0–2.5°C, and 1.5–4.0°C by 2020, 2050, and 2080, respectively, based on different emission scenarios (Hulme *et al.*, 2002).

Much uncertainty surrounds the relationship that temperature shares with fish (Cardinale *et al.*, 2004) because the reaction of individual species to climate change is ambiguous (Perry *et al.*, 2005). Some species may benefit, while others become less productive as a consequence of higher sea temperatures (Cook and Heath, 2005). Species that spawn in shallow, low salinity waters may be more affected than in deeper water, hydrographically stable species (Rose, 2005). Cod may respond unexpectedly to climate change, as we experience temperatures not previously witnessed (Kell *et al.*, 2005). Sustained temperature changes may cause stocks to become distressed, causing them to diminish (Drinkwater, 2005).

Environmental data are built into stock assessments to account for climate change (Planque *et al.*, 2003). When a climate effect is found, temperature is associated with recruitment, suggesting it should be incorporated into modelling (Cardinale *et al.*, 2004). Incorporating climate change into stock–recruitment models helps to improve stock assessment predictions, but is extremely complex with a high degree of uncertainty (Cardinale *et al.*, 2004).

Temperature shares a complex relationship with recruitment (Cook and Heath, 2005). The Ricker stock–recruitment model is frequently used to examine the effect of temperature on recruitment (Cook and Heath, 2005; Kell *et al.*, 2005). Temperature affects recruitment through juvenile survival (Planque and Frédou, 1999; Clark *et al.*, 2003) and habitat availability (Fromentin *et al.*, 2001). The impact of climate change may depend upon whether juvenile survival or carrying capacity are affected by temperature (Kell *et al.*, 2005).

The considerable variation in the strength and sign of the relationship species share with temperature consequently makes it hard for fisheries managers to produce reliable stock predictions (Cook and Heath, 2005). The benefits associated with incorporating environmental parameters into stock–recruitment models will depend on whether they can be predicted well and if a strong relationship exists between the environmental variable and recruitment (Basson, 1999). Stock assessment advice may need to be adjusted frequently to incorporate the uncertainty of climate change. Annual revisions to stock assessment advice are believed to be the most efficient strategy, but are also thought to be the most expensive (Roel *et al.*, 2004). Scientists face a difficult task in making reliable predictions in the face of future climate change because it is challenging to produce accurate stock forecasts in the longer term (Rothschild *et al.*, 2005). Modelling capabilities are increasing rapidly and, with the development of regional climate models (RCMs), scientists will be able to bring more certainty to recruitment predictions, which will be particularly important to fishery managers and policy makers.

10 Research activities after SGPRISM

10.1 Links to other groups and activities

In this section is a partial listing of 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.

10.1.1 ICES Study Group on Growth, Maturity and Condition Indices in Stock Projections

The Study Group on Growth, Maturity and Condition Indices in Stock Projections (SGGROMAT; Co-Chairs: C. L. Needle, UK, and C. T. Marshall, Norway) first met at ICES Headquarters 5–10 December 2002 to review progress summarizing data on weights, maturity, condition, and fecundity for stocks. In addition, the group reviewed the suitability of available process-based models for growth, maturity, condition, and fecundity for use in medium-term projections and proposed modifications where necessary.

Participants at SGGROMAT included process modellers, assessment scientists, and data collectors. The study group decided that other ICES groups should continue some of the work carried out by SGGROMAT. Specifically, WGMG would continue work on software development, while the Study Group on Age–Length Structured Assessment Models (SGASAM) would be responsible for data collation and the length-based modelling aspects of SGGROMAT. The last meeting of the group was in 2004.

10.1.2 NAFO Working Group on Reproductive Potential

A meeting of the NAFO Working Group on Reproductive Potential was held at the Northeast Fisheries Science Centre, National Marine Fisheries Service, Woods Hole 15–18 October 2003 to complete an inventory of available data on reproductive potential for fish stocks of the North Atlantic and Baltic Sea. It explored correlation analyses to estimate the reproductive potential of stocks and model interannual and interstock variability in size-dependent fecundity for multiyear stock estimates. In addition, the group explored how biological reference points and medium-term projections can be used to include new information on reproductive potential, and explored the consequences of fishery-induced changes in the timing and location of spawning to reproductive success. The group also made recommendations on data collection in research surveys, sentinel fisheries, and captive fish experiments to improve the estimates of reproductive potential. It also explored the effects of the environment on the reproductive potential.

Methods for quantifying the reproductive potential of individuals and stocks were reviewed and summarized by the working group. The information compiled by the working group should benefit fisheries management by allowing the development of methods for incorporating information on stock structure into stock assessment.

10.1.3 ICES Working Group on Recruitment Processes

The Working Group on Recruitment Processes (WGRP; Co-Chairs: P. Pepin, Canada, and R. D. M. Nash, UK) met at ICES Headquarters 18–19 April 2002 to review multidisciplinary projects dealing with recruitment research and to consider the results of SGPRISM's examination of the STEREO project. It evaluated simulations of the effects of stock structural factors on the parameters of stock–recruitment relationships, and considered a synthesis of the Theme Session on "Spatial and Temporal Patterns in Recruitment Processes". In addition, it identified areas in the study of recruitment processes where sufficient progress has been achieved, with the objective of developing a workshop dealing with specific case studies. WGRP also reviewed the development of new approaches used in the study of factors and processes that influence the development and survival of fish eggs and larvae in relation to recruitment.

The WGRP did not meet in 2003; it worked by correspondence with limited communication. Some members participated in other working groups and study groups. The group reviewed progress in approaches that have taken place since the publication of *ICES Cooperative Research Report No. 155* (1992), "Models for Recruitment Processes", considered the spatial and temporal variation in the mortality of fish eggs and larvae, reviewed multidisciplinary recruitment research, and planned a joint session with WGZE (Working Group on Zooplankton Ecology) on reconstructing fine-scale spatial patterns in zooplankton distribution and their relevance to larval fish modelling.

In 2004, WGRP met in Copenhagen and continued to review multidisciplinary research in recruitment. The group last met in Barcelona, Spain on 15 July 2005, with the central objective of critically reviewing the group's work and identifying specific contributions that it could make to advice provided by ICES to their clients. Over the longer term, it is the group's intention to approach other issues, namely environmental predictors of recruitment, synchronous and asynchronous recruitment in large marine ecosystems, the influence of recruitment events on community dynamics, and the effects of a changing global environment on recruitment processes.

10.1.4 ICES International Bottom Trawl Survey Working Group

The International Bottom Trawl Working Group (IBTSWG) has its origin in the North Sea; since 1965 coordinated surveys have occurred in the Skagerrak and the Kattegat. Since 1994, the IBTSWG has assumed responsibility for coordinating western and southern division surveys. The working group tasks also include standardization of sampling protocols and strategies.

The ICES International Bottom Trawl Survey Working Group (IBTSWG) last met in Hamburg, Germany 29 March–1 April 2005 to plan the North Sea and northeastern Atlantic surveys for the next year and develop criteria to standardize sampling tools and survey gear. In addition, the group investigated the adequacy of fishing protocols defined in the IBTS manual from ancient studies with respect to recent data from modern monitoring of gear performances. The working group also reviewed the Norwegian survey trawl project, the new DATRAS database, the WKSAD (Survey Design and Data Analysis Workshop) held in 2004, and progress made in defining a stratification scheme for the eastern Atlantic and Skagerrak. In the last three years, the group has made detailed checks of age, length, sex, and maturity data from the ICES roundfish database.

10.1.5 ICES Working Group on Methods of Fish Stock Assessments

The Working Group on Methods of Fish Stock Assessments (WGMG; Chair: C. O'Brien, UK) met at ICES Headquarters 3–7 December 2001 to develop diagnostics and testing procedures for the evaluation of methods used for producing stock assessments, short-term forecasts, and medium-term projections, and apply these testing procedures to methods routinely used by ICES. They identified strengths and weaknesses in the methods and proposed modifications to assessment models, used diagnostics to evaluate the performance of new methodological proposals, and presented the results in a form that could be readily implemented in assessments.

The group met at ICES Headquarters 29 January–5 February 2003 to develop diagnostics for use within stock assessments for data and modelling issues, investigate the sensitivity of catch-at-age stock assessment methods, develop techniques to detect inconsistencies in data currently used in ICES stock assessments, and implement quality control procedures for medium-term projections. In addition, the working group evaluated approaches, methods, and software for investigating management strategies, reviewed developments in TSA, XSA, MedAN, AMCI, and other assessment methods, discussed the choice of model structure for taking account of stock dynamics, biology, and data availability, and also further developed the specification of software to generate stock assessment data, taking into account the spatial, temporal, and multispecies nature of fisheries.

The working group met in February 2004 to develop robust methods and software for investigating management procedures for stock recovery and the evaluation of harvest control rules. WGMG identified estimators of stock conservation limits and reference points relating to longer-term yield, together with a characterization of their statistical properties for a range of stocks currently assessed by ICES for its clients and management agencies (EU, IBSFC, NAFO, NASCO, NEAFC, and ICCAT).

The work of SGPRISM is relevant to the ICES Working Group on Methods on Fish Stock Assessments, specifically with respect to models for weight-at-age, maturity-at-age, and condition factors for both historical stock assessment and medium-term projections.

10.1.6 ICES Study Group on the Further Development of the Precautionary Approach to Fishery Management

The principal international agreements specifying the introduction of the precautionary approach to fisheries are the FAO Code of Conduct for Responsible Fisheries and the UN Agreement on the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks. Their aim is to "apply the precautionary approach to conservation, management, and exploitation of living aquatic resources in order to protect them and preserve the aquatic environment" and to "avoid serious and irreversible harm to fisheries" by ensuring "long-term sustainability of fishery resources at levels that promote the objective of their optimum utilization and maintain their availability for present and future generations". The application of the precautionary approach in ICES was undertaken at two meetings of the ICES Study Group on the Precautionary Approach to Fisheries Management, in 1997 and 1998. ACFM has continued to develop a precautionary approach to fishery management and has developed a practice.

The Study Group on the Further Development of the Precautionary Approach to Fishery Management (SGPA; Co-Chairs: C. Bannister, UK, and M. Azevedo, Portugal) met at ICES Headquarters 2–6 December 2002 to define technical guidelines for the revision of reference point values, specify software to be used in the revision of reference values, and define a format for the presentation of the relevant data and results. In addition, the study group started to develop a framework for specifying and monitoring rebuilding plans that take into account the status and dynamics of stocks, technical interactions, uncertainty, time period, and risk, and the data required.

10.1.7 ICES Planning Group on North Sea Cod and Plaice Egg Surveys

The Planning Group on North Sea Cod and Plaice Egg Surveys in the North Sea (PGEGGS; Chair: C. Fox, UK) was established in 2001 by ICES to plan an internationally coordinated ichthyoplankton sampling programme for the North Sea, focusing on cod and plaice.

The planning group met in IJmuiden 24–26 June 2003 to review the results of a trial cruise carried out in March 2003 in the Irish Sea to test genetic tools, review the progress of current projects on the identification of cod eggs using genetic probes, plan an international survey to map the distribution of cod and plaice spawning in 2004, and develop protocols for evaluating and presenting the data. PGEGGS also met later in the year in Kiel, Germany 11–12 November 2003 to review existing plans for North Sea ichthyoplankton surveys for 2004, agree protocols for sampling and data handling, and examine contingency planning for the surveys to deal with events such as poor weather.

The group last met in Lowestoft, UK 6–10 June 2005 to compile data from the surveys taken in 2004 and produce a survey report for the 2005 Annual Science Conference; it also planned a workshop of detailed spatio-temporal analyses of the data from surveys. A feasibility study of stock biomass assessments of main North Sea commercial stocks using egg production methods will be undertaken in the future.

10.1.8 ICES Working Group for Regional Ecosystem Description

In the process of preparing the ecosystem overviews, the working group identified several specific environmental factors that were suspected of being in anomalous conditions in the recent past (roughly, but not precisely the past one or two years), relative to the more usual long-term conditions. In each case, the anomalous state of the environmental feature was thought to pose a higher than usual risk that the application of routine assessment practices might lead to incorrect assumptions about stock status or dynamics. The incorrect assumptions in the assessment, in turn, could lead to inappropriate advice for the special environmental conditions.

From these anomalous environmental factors, the working group further selected a subset for which it could recommend some practical steps in the 2005 assessment and advisory process, which would address the additional risk posed by the environmental conditions. These were discussed to allow the working group chairs to consider how to implement the recommended steps.

The Working Group on Regional Ecosystem Descriptions (WGRED) first met at ICES Headquarters 14–18 February 2005 to play a central role in including of more ecosystem and environmental information in the short-term advisory tasks for ICES. The group reviewed and revised a report template for ecosystem description in the advisory reports. In addition, it considered ways to develop regional assessments, based on an incremental approach, taking on-board existing knowledge, and incorporating integrated assessments when such become available. The meeting took place concurrently with the Annual Meeting of Assessment Working Group Chairs, so that significant interaction could occur. This joint discussion highlighted the importance of differentiating the treatment of environmental issues in the assessment process from the inclusion of environmental variables in assessment models.

The working group (Chair: Jake Rice, Canada) last met at ICES Headquarters, Copenhagen 30 January–3 February 2006 to consider feedback from ICES expert groups and advisory groups and clients of ICES advice. The group reviewed draft ecosystem overviews that have been prepared by teams of national experts and identified major environmental or anthropogenic events in each ecoregion that should be taken into special account in ICES assessments and advice in 2007. Additionally, the group reviewed work undertaken intersessionally to test the robustness of harvest control strategies to environmental forcing and recommended improvements to practice in the use of HCRs in ICES assessment and advice. Finally, WGRED reviewed the progress made by the ICES Cod and Climate Change initiative in the context of current assessment working groups, with the objective of identifying opportunities to alter assessment practices to operationalize the results of that initiative.

10.1.9 ICES Working Group on Ecosystem Effects of Fishing Activities

The Working Group on Ecosystem Effects of Fishing Activities (WGECO; Chair: S. Rogers, UK) met at ICES Headquarters 12–19 April 2005 to focus on the ecosystem approach to management. WGECO identified the need for fully integrated ecosystem assessments to link manageable human activities with the pressures they cause in the marine ecosystem.

The working group last met 5–12 April 2006 at ICES Headquarters to review and report on the effects of fishing on the North Sea ecosystem, selected human pressures on the marine ecosystem, and identified indicators, metrics, data series, and reference levels for these pressures. In addition, they examined recommendations of the Study Group on Management Strategies in their review of WGECO suggestions for ways in which ecosystem considerations could be incorporated into fisheries management strategies. The group also reviewed the work of WGFE 2006 in its development of the EcoQO on the changes in the proportions of large fish, and hence the average weight and average maximum length of the fish community, and complete the evaluation of size-based indicators in management frameworks. Also, the group reviewed advice on ecosystem effects of fisheries relevant to the Regional Advisory Councils and reviewed the report and results of the North Sea ecosystem assessment undertaken by the Regional Ecosystem Group for the North Sea (REGNS). This year WGECO continued to assist REGNS in its work on an integrated assessment.

10.1.10 Regional Ecosystem Study Group for the North Sea

The Regional Ecosystem Study Group for the North Sea (REGNS) first met to take a strategic view on how ICES, over the medium and long term, should move toward providing ecosystem-based advice supported by sound science, utilizing the existing network of ICES working groups. The group was tasked with looking beyond the North Sea Pilot Project (NORSEPP) and at the future needs to support member countries in the delivery of the ecosystem approach (EA).

REGNS recognizes two types of assessment underpinning the ecosystem approach, general assessments and thematic-based assessments, both of which have different purposes. Thematic assessments embody the adaptive management principle, which requires that management is responsive to the dynamics of the ecosystem. In considering general assessments, a combination of activities and their effects on the ecosystem needs to be assessed. This requires a greater degree of understanding of ecosystem function and the cause–effect pathways that determine state and impact. This distinction clearly has implications for how integrated assessments should be coordinated and delivered by ICES at the working group level.

In both types of assessment, it helps to visualize the ecosystem as a set of biological compartments that are tropically linked and that interact with their environment, including human pressures. It is apparent that ICES working groups map onto the compartments of the ecosystem reasonably well. However, the links between ecosystem compartments are not reflected so well by ICES working group structure, and this represents a gap in capability that should be addressed.

The work of REGNS should have been completed after the third meeting in 2005. However, it was recommended that REGNS be extended for one year to complete its work.

The study group (Chair: A. Kenny, UK) last met at ICES Headquarters 15–19 May 2006 to evaluate and plan the 2006 integrated ecosystem assessment for the North Sea for presentation at the 2006 ASC and, based on the experience of the 2006 North Sea integrated assessment, consider the requirements to be weighed in designing a holistic monitoring of the North Sea ecosystem.

11 References

Alcaraz, M. 1997. Copepods under turbulence: grazing, behaviour and metabolic rates. Scientia Marina, 61: 177–195.

Allain G., Petitgas, P., and Lazure, P. 1999. Environmental and stock effects on the recruitment of anchovy in the Bay of Biscay: A multivariate analysis. ICES Document CM 1999/Y:22.

Anon. 1997. Preliminary Report of the International 0-group survey in the Barents Sea and adjacent waters in 1996. ICES Document CM 1997/G:31.

Anon. 1998. Recruitment processes in cod and haddock: developing new approaches. Final report of EU-FAIR project CT95-0084. 277 pp. + diagrams.

Anon. 2001. Report from the 2001 joint Russian–Norwegian meeting to assess the Barents Sea capelin stock. Vadsø, Norway, October 5–7, 2001. Working Document to the 2001 ACFM meeting.

Anon. 2001a. dst^2. Development of structurally detailed statistically testable models of marine populations. QLK5-CT1999–01609. Progress report for 1 January 2000 to 31 December 2000. Marine Research Institute Technical Report No. 78, Marine Research Institute, Reykjavik, Iceland.

Bagge, O., Thurow, F., Steffensen, E., and Bay, J. 1994. The Baltic cod. Dana, 10: 1–29.

Bailey, K. M., and Houde, E. D. 1989. Predation on eggs and larvae of marine fishes and the recruitment problem. Advances in Marine Biology, 25: 1–83.

Bakun, A., and Parrish, R. H. 1982. Turbulence, transport and pelagic fish in the California and Peru current systems. California Cooperative Oceanic Fisheries Investigations, 23: 99–112.

Bannister, R. C. A., Harding, D., and Lockwood, S. J. 1974. Larval mortality and subsequent year-class strength in the plaice (*Pleuronectes platessa* L.). *In*: The Early Life History of Fish, pp. 21–37. Ed. by J. H. S. Blaxter. Springer-Verlag, Berlin.

Baranov, T. I. 1918. On the question of the biological basis of fisheries. Nauchnyi issledovatelskii ikhtiologicheskii, 1: 81–128.

Basson, M. 1999. The importance of environmental factors in the design of management procedures. ICES Journal of Marine Science, 56: 933–942.

Beverton, R. J. H., and Holt, S. J. 1957. On the dynamics of exploited fish populations. Fisheries Investigations Series 2, No. 19. 533 pp.

Blanchard, J. L. 2000. Maternal contribution to the reproductive potential of a recovering fish stock: variability in the fecundity and condition of haddock (*Melanogrammus aeglefinus* L.) on the Scotian Shelf. M.Sc. thesis, Dalhousie University, Halifax, N. S. 110 pp.

Bogstad, B., Lilly, G. R., Mehl, S., Pálsson, Ó. K., and Stefánsson, G. 1994. Cannibalism and year-class strength in Atlantic cod (*Gadus morhua* L.) in Arcto-boreal ecosystems (Barents Sea, Iceland, and eastern Newfoundland). ICES Marine Science Symposia, 198: 576–599.

Bogstad, B., and Mehl, S. 1997. Interactions between cod (*Gadus morhua* L.) and its prey species in the Barents Sea. Forage Fishes in Marine Ecosystems. Proceedings of the International Symposium on the Role of Forage Fishes in Marine Ecosystems. Alaska Sea Grant College Program Report No. 97–01: 591–615. University of Alaska, Fairbanks.

Borja, A., Uriarte, A., Valencia, V., Motos, L., and Uriarte, Ad. 1996. Relationship between anchovy (*Engraulis encrasicolus* L.) recruitment and the environment in the Bay of Biscay. Scientia Marina, 60(2): 179–192.

Borja, A., Uriarte, A., Egaña, J., Motos L., and Valencia, V. 1998. Relationship between anchovy (*Engraulis encrasicolus* L.) recruitment and environment in the Bay of Biscay. Fisheries Oceanography, 7(3/4): 375–380.

Borja, A., Skreslet, S., Wyatt, T., and Hansen, G. 2002. Environmental and climatic factors affecting recruitment of the Northeast Arctic cod (*Gadus morhua* L.) along the Norwegian coasts. Fisheries Oceanography, 11(2): 116.

Bowers, A. B. 1980. The Manx herring stock, 1948–1976. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 177: 166–174.

Brander, K., and Houghton, R. G. 1982. Predicting the recruitment of North Sea plaice from egg surveys. ICES Document CM 1982/G:5.

Brander, K. M. 1995. The effect of temperature on growth of Atlantic cod (*Gadus morhua* L.). ICES Journal of Marine Science, 52: 1–10.

Brander, K. 1996. Effects of climate change on cod (*Gadus morhua* L.) stocks. *In*: Global Warming: Implications for Freshwater and Marine Fish, pp. 255–278. Ed. by C. M. Wood and D. G. McDonald. Cambridge University Press.

Bromley, P. J. 2000. Growth, sexual maturation and spawning in central North Sea plaice (*Pleuronectes platessa* L.), and the generation of maturity ogives from commercial catch data. Journal of Sea Research, 44: 27–43.

Bromley, P. J., Ravier, C., and Witthames, P. R. 2000. The influence of feeding regime on sexual maturation, fecundity, and atresia in first-time spawning turbot. Journal of Fish Biology, 56: 264–278.

Brown, J. A., Pepin, P., Methven, D. A., and Somerton, D. C. 1989. The feeding, growth and behaviour of juvenile cod, *Gadus morhua* L., in cold environments. Journal of Fish Biology, 35: 373–380.

Brown, J., Hill, A. E., Fernand, L., and Horsburgh, K. J. 1999. Observations of a seasonal jet-like circulation at the Central North Sea cold pool margin. Estuarine, Coastal and Shelf Science, 48: 343–355.

Cardinale, M., Hjelm, J., and Casini, M. 2004. Effect of climate on recruitment success of clupeid stocks in the North Atlantic. ICES Document CM 2004/K:01.

Clark, R. A., Fox, C. J., Viner, D., and Livermore, M. 2003. North sea cod and climate change—modelling the effects of temperature on population dynamics. Global Change Biology, 9: 1669–1680.

Cook, R. M. 1993. The use of sensitivity analysis to quantify uncertainties in stock projections. ICES Document CM 1993/D:66.

Cook, R. M., Kunzlik, P. A., Hislop, J. R. G., Poulding, D. 1999. Models of growth and maturity for North Sea cod. Journal of Northwest Atlantic Fishery Science, 25: 91–99.

Cook, R. M., and Heath, M. R. 2005. The implications of warming climate for the management of North Sea demersal fisheries. ICES Journal of Marine Science, 62: 1322–1326.

Cury, P., and Roy, C. 1989. Optimal environmental window and pelagic fish recruitment success in upwelling areas. Canadian Journal of Fisheries and Aquatic Sciences, 46: 670–680.

Daan, N. 1981. Comparison of estimates of egg production of the southern Bight cod stock from plankton surveys and market statistics. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 178: 242–243.

Darby, C. D., and Flatman, S. 1994. Virtual Population Analysis: Version 3.1 (Windows/DOS) User Guide. Information Technology Series, MAFF Directorate of Fisheries Research, Lowestoft, (1): 85.

deYoung, B., and Rose, G. A. 1993. On recruitment and distribution of Atlantic cod (*Gadus morhua* L.) off Newfoundland. Canadian Journal of Fisheries and Aquatic Sciences, 50: 2729–2741.

Dickey-Collas, M., Brown, J., Fernand, L., Hill, A. E., Horsburgh, K. J., and Garvine, R. W. 1997. Does the western Irish Sea gyre influence the distribution of pelagic juvenile fish? Journal of Fish Biology, 51(A): 206–229.

Dickey-Collas, M. 1999. Results of larval herring surveys in the north Irish Sea (Area VIIaN) in November 1998. Working document to ICES Herring Assessment Working Group for the Area South of 62°N, 1999, Copenhagen, Denmark. 8 pp. (mimeo).

Dower, J. F., Miller, T. J., and Leggett, W. C. 1997. The role of microscale turbulence in the feeding ecology of larval fish. Advances in Marine Biology, 31: 170–220.

Drinkwater, K. F. 2005. The response of Atlantic cod (*Gadus morhua* L.) to future climate change. ICES Journal of Marine Science, 62: 1327–1337.

Dutil, J-D., Castonguay, M., Gilbert, D., and Gascon, D. 1999. Growth, condition, and environmental relationships in Atlantic cod (*Gadus morhua* L.) in the northern Gulf of St Lawrence and implications for management strategies in the Northwest Atlantic. Canadian Journal of Fisheries and Aquatic Sciences, 56: 1818–1831.

Fiksen, Ø., Utne, A. C. W., Aksnes, D. L., Eiane, K., Helvik, J. V., and Sundby, S. 1998. Modelling the influence of light, turbulence and ontogeny on ingestion rates in larval cod and herring. Fisheries Oceanography, 7: 355–363.

Fox, C. J., Planque, B., and Darby, C. D. 2000. Synchrony in the recruitment time-series of plaice (*Pleuronectes platessa* L.) around the United Kingdom and the influence of sea temperature. Journal of Sea Research, 44: 159–168.

Francis, B., Green, M., and Payne, C. 1993. The GLIM System, Release 4 Manual. Oxford University Press, Oxford. xiv+821 pp.

Fromentin, J-M., Myers, R. A., Bjørnstad, O. N., Stenseth, N. C., Gjøsæter, J., and Christie, H. 2001. Effects of density-dependent and stochastic processes on the regulation of cod populations. Ecology, 82(2): 829–836.

Frøysa, K. G., Bogstad, B., and Skagen, D. W. 2002. Fleksibest—an age-length structured fish stock assessment tool with application to Northeast Arctic cod (*Gadus morhua* L.). Fisheries Research, 55: 87–101.

Gamito, S. 1998. Growth models and their use in ecological modelling: an application to a fish population. Ecological Modelling, 113: 83–94.

Gjøsæter, H., and Bogstad, B. 1998. Effects of the presence of herring on the stock–recruitment relationship of Barents Sea capelin (*Mallotus villosus* M.). Fisheries Research, 38: 57–71.

Gjøsæter, H., Bogstad, B., and Tjelmeland, S. 2002. Assessment methodology for Barents Sea capelin (*Mallotus villosus* Müller). ICES Journal of Marine Science, 59: 1086–1095.

Gordon, C., Cooper, C., Senior, C. A., Banks, H., Gregory, J. M., Johns, T. C., Mitchell, J. F. B., and Wood, R. A. 2000. The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. Climate Dynamics, 16: 147–168.

Graham, M. 1924. The annual cycle in the life of the mature cod in the North Sea. Fishery Investigations Lond. Series II 6(6): 1–77.

Grønkjær, P., Möllmann, C., and Voss, R. 1995. Abundance and distribution of larval cod (*Gadus morhua* L.) in the Bornholm Basin. ICES Document CM 1995/J:24.

Grønkjær, P., and Wieland, K. 1997. Ontogenetic and environmental effects on vertical distribution of cod larvae in the Bornholm Basin, Baltic Sea. Marine Ecology Progress Series, 154: 91–105.

Gulland, J. A. 1977. Fisheries Population Dynamics. John Wiley and Sons, London.

Hamre, J. 1985. Assessment and management of Barents Sea capelin. *In*: Proceedings of the Soviet–Norwegian Symposium on the Barents Sea Capelin, Bergen, 14–17 August 1984, pp. 5–24. Ed. by H. Gjøsæter. Institute of Marine Research, Bergen, Norway.

Hamre, J. 1994. Biodiversity and exploitation of the main fish stocks in the Norwegian–Barents Sea ecosystem. Biodiversity and Conservation, 3: 473–492.

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 Document CM 2000/N:11.

Heessen, H. J. L. 1993. The distribution of cod (*Gadus morhua* L) in the North Sea. NAFO Scientific Council Studies, 18: 59–65.

Henderson, B. A., Trivedi, T., and Collins, N. 2000. Annual cycle of energy allocation to growth and reproduction of yellow perch. Journal of Fish Biology, 57: 122–133.

Hermann, A. J., Rugen, W. C., Stabeno, P. J., and Bond, N. A. 1996. Physical transport of young pollock larvae (*Theragra chalcogramma* L.) near Shelikof Strait as inferred from a hydrodynamic model. Fisheries Oceanography, 5: 58–70.

Hermann, A. J., Hinckley, S., Megrey, B. A., and Napp, J. M. 2001. Applied and theoretical considerations for constructing spatially explicit individual-based models of marine larval fish that include multiple trophic levels. ICES Journal of Marine Science, 58: 1030–1041.

Hill, A. E., Brown, J., and Fernand, L. 1996. The western Irish Sea gyre: a retention system for Norway lobster (*Nephrops norvegicus* L.)? Oceanologica Acta, 19: 357–368.

Hinrichsen, H-H., St John, M. A., Aro, E., Grønkjær, P., and Voss, R. 2001. Testing the larval drift hypothesis in the Baltic Sea: Retention vs. dispersion due to the influence of the wind driven circulation. ICES Journal of Marine Science, 58: 973–984.

Hinrichsen, H-H., Möllmann, C., Voss, R., Köster, F. W., and Kornilovs, G. 2002. Biophysical modelling of larval Baltic cod (*Gadus morhua* L.) survival and growth. Canadian Journal of Fisheries and Aquatic Sciences, 59: 1858–1873.

Holt, E. W. L. 1893. North Sea investigations. Journal of Marine Biological Association of the United Kingdom. 3(1): 78–106.

Horsburgh, K. J., Hill, A. E., and Brown, J. 1998. A summer jet in the St George's Channel of the Irish Sea. Estuarine, Coastal and Shelf Science, 47: 285–294.

Hulme, M., Jenkins, G. J., Lu, X., Turnpenny, J. R., Mitchell, T. D., Jones, R. G., Lowe, J., Murphy, J. M., Hassell, D., Boorman, P., McDonald, R., and Hill, S. 2002. Climate change scenarios for the United Kingdom: The UKCIP02 scientific report. Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK. 120 pp.

Huse, G., and Toresen, R. 2000. Juvenile herring prey on Barents Sea capelin larvae. Sarsia, 85: 385–39.

ICES. 1992. Report of the Study Group on Tagging Experiments for Juvenile Plaice, IJmuiden, the Netherlands, 16–22 March 1992. ICES Document CM 1992/G:10.

ICES. 1994. Report of the Study Group on Herring Assessment and Biology in the Irish Sea and Adjacent Waters, Belfast, Northern Ireland, 21–25 February 1994. ICES Document CM 1994/H:05.

ICES. 1998. Report of the Study Group on Stock–recruitment Relationships for North Sea Autumn-Spawning Herring, Lowestoft, UK, 26–28 May 1998. ICES Document CM 1998/D:02.

ICES. 1999. Report of the ICES Advisory Committee on Fishery Management, 1998. Copenhagen, 13–22 May 1998, Copenhagen, 20–29 October 1998. ICES Cooperative Research Report No. 229.

ICES. 1999a. Report of the Working Group on the Assessment of Herring for the Area South of 62°N, Copenhagen, 15–24 March 1999. ICES Document CM 1999/ACFM:12.

ICES. 2000. Report of the Study Group on Incorporation of Process Information into Stock–recruitment Models, Lowestoft, UK, 23–26 January, 1999. ICES Document CM 2000/C:01.

ICES. 2000a. Report of the Working Group on the Assessment of Mackerel, Horse Mackerel, Sardine, and Anchovy, Copenhagen, 14–23 September 1999. ICES Document CM 2000/ACFM:05.

ICES. 2000b. Report of the Baltic Fisheries Assessment Working Group, Copenhagen, 10–19 April 2000. ICES Document CM 2000/ACFM:14.

ICES. 2000c. Report of the Working Group on Recruitment Processes, Bergen, Norway, 8–10 March 2000. ICES Document CM 2000/C:03.

ICES. 2000d. Report of the Herring Assessment Working Group for the Area South of 62°N, Copenhagen, 14–23 March 2000. ICES Document CM 2000/ACFM:10.

ICES. 2000e. Report of the ICES/GLOBEC Working Group on Cod and Climate Change. Dartmouth, Nova Scotia, Canada, 11–12 May 2000. ICES Document CM 2000/C:11.

ICES. 2001. Report of the Study Group on Incorporation of Process Information into Stock–recruitment Models, Lowestoft, UK, 23–26 January 2001. ICES Document CM 2001/C:02.

ICES. 2001a. Report of the Arctic Fisheries Working Group, Bergen, Norway, 24 April–3 May 2001. ICES Document CM 2001/ACFM:19.

ICES. 2001b. Report of the Arctic Fisheries Working Group, Copenhagen, 22–31 August 2001. ICES Document CM 2001/ACFM:02.

ICES. 2001c. Report of the ICES Advisory Committee on Fishery Management, 2000. Copenhagen, 25 May–1 June 2000, Copenhagen 24 October–2 November 2000. ICES Cooperative Research Report No. 242.

ICES 2001d. Report of the Northern Pelagic and Blue Whiting Fisheries Working Group, Reykjavik, 18–27 April 2001. ICES Document CM 2001/ACFM:17.

ICES. 2001e. Report of the Working Group on the Assessment of Mackerel, Horse Mackerel, Sardine, and Anchovy, Copenhagen, 14–23 September 2000. ICES Document CM 2001/ACFM:06.

ICES. 2001f. Report of the Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak, Copenhagen, 3–12 October 2000. ICES Document CM 2000/ACFM:07.

ICES. 2001g. Report of the Herring Assessment Working Group for the Area South of 62°N, Hamburg, Germany, 13–22 March 2001. ICES Document CM 2001/ACFM:12.

ICES. 2002. Report of the Study Group on Incorporation of Process Information into Stock–recruitment Models, Lowestoft, UK, 14–18 January 2002. ICES Document CM 2002/C:01.

ICES. 2002a. Report of the Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak, Hamburg, Germany, 19–28 June 2001. ICES Document CM 2002/ACFM:01.

ICES. 2002b. Report of the Working Group on the Assessment of Mackerel, Horse Mackerel, Sardine, and Anchovy, Copenhagen, 4–13 September 2001. ICES Document CM 2002/ACFM:06.

ICES. 2002c. Report of the Working Group on Methods on Fish Stock Assessments, Copenhagen, 3–7 December 2001. ICES Document CM 2002/D:08.

ICES. 2004. Report of the Study Group on Growth, Maturity, and Condition in Stock Projections, Aberdeen, UK, 19–23 January 2004. ICES Document CM 2004/D:02.

Jarre-Teichmann, A., Wieland, K., MacKenzie, B. R., Hinrichsen, H. H., Plikshs, M., and Aro, E. 2000. Stock–recruitment relationships for cod *(Gadus morhua callarias* L.) in the central Baltic Sea incorporating environmental variability. Archive of Fishery and Marine Research, 48(2): 97–123.

Kell, L. T., Pilling, G. M., and O'Brien, C. 2005. Implications of climate change for the management of North Sea cod (*Gadus morhua* L.). ICES Journal of Marine Science, 62: 1483–1491.

Kiseleva, V. M. 2000. Population fecundity of the Barents Sea cod in the 1990s. Working Document to the Arctic Fisheries Working Group, Bergen, May 2000.

Kjesbu, O. S. 1988. Fecundity and maturity of cod, *Gadus morhua* L., from northern Norway. ICES Document CM 1988/G:28.

Kjesbu, O. S., Klungsyr, J., Kryvi, H., Witthames, P. R., and Greer Walker, M. 1991. Fecundity, atresia, and egg size of captive Atlantic cod (*Gadus morhua*) in relation to proximate body composition. Canadian Journal of Fisheries and Aquatic Sciences, 48: 2333–2343.

Kjesbu, O. S., Witthames, P. R., Solemdal, P., Greer Walker, M. 1998. Temporal variations in the fecundity of Arcto-Norwegian cod (*Gadus morhua*) in response to natural changes in food and temperature. Journal of Sea Research, 40: 303–321.

Klyashtorin, L. B. 2001. Climate change and long-term fluctuations of commercial catches—the possibility of forecasting. Federal Institute for Fisheries and Oceanography, Moscow. FAO Fisheries Technical Paper 410.

Köster, F. W., and Schnack, D. 1994. The role of predation on early life stages of cod in the Baltic. Dana, 10: 179–201.

Köster, F. W., and Möllmann, C. 1997. Predation by sprat and herring on early life stages of cod and sprat in the central Baltic. Proceedings of the Symposium on Forage Fishes in Marine Ecosystems, Alaska. Sea Grant College Program No. 97–01: 41–70.

Köster, F. W., Hinrichsen, H-H., Schnack, D., St John, M. A., MacKenzie, B., Tomkiewicz, J., and Plikshs, M. 1999. Stock–recruitment relationships of Baltic cod incorporating environmental variability and spatial heterogeneity. ICES Document CM 1999/Y:26.

Köster, F. W., and Möllmann, C. 2000. Trophodynamic control by clupeid predators on recruitment success in Baltic cod? ICES Journal of Marine Science, 57: 310–323.

Köster, F. W., Hinrichsen, H-H., Schnack, D., St John, M. A., MacKenzie, B. R., Tomkiewicz, J., and Plikshs, M. 2001. Developing Baltic cod recruitment models II: Incorporation of environmental variability and species interaction. Canadian Journal of Fisheries and Aquatic Sciences, 58: 1535–1557.

Köster, F. W., Hinrichsen, H-H., Schnack, D., St John, M. A., MacKenzie, B. R., Tomkiewicz, J., Möllmann, C., Kraus, G., Plikshs, M., Makarchouk, A., and Aro, E. 2003. Recruitment of Baltic cod and sprat stocks: Identification of critical life stages and incorporation of environmental variability and spatial heterogeneity into stock–recruitment relationships. Scientia Marina, 67(1): 129–154.

Köster, F. W., Möllmann, C., Hinrichsen, H-H., Wieland, K., Tomkiewicz, J., Voss, R., Makarchouk, A., St John, M. A., Schnack, D., Linkowski, T., and Beyer, J. E. 2005. Baltic cod recruitment—the impact of climate variability on key processes. ICES Journal of Marine Science, 62: 1408–1425.

Kraus, G., Müller, A., Trella, K., and Köster, F. 2000. Fecundity of Baltic cod: temporal and spatial variation. Journal of Fish Biology, 56: 1327–1341.

Kraus, G., Tomkiewicz, J., and Köster, F., 2002. Egg production of Baltic cod (*Gadus morhua* L.) in relation to variable sex ratio, maturity, and fecundity. Canadian Journal of Fisheries and Aquatic Sciences, 59: 1908–1920.

Lambert, T. C. 1990. The effect of population structure on recruitment in herring. Journal du Conseil International pour l'Exploration de la Mer, 47: 249–255.

Lambert, Y., and Dutil, J-D. 1997. Condition and energy reserves of Atlantic cod (*Gadus morhua* L.) during the collapse of the northern Gulf of St Lawrence stock. Canadian Journal of Fisheries and Aquatic Sciences, 54: 2388–2400.

Lasker, R. 1978. The relation between oceanographic conditions and larval anchovy food in the California current: identification of factors contributing to recruitment failure. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer , 173: 212–230.

Leising, A. W., and Franks, P. J. S. 1999. Larval Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus* L.) growth on Georges Bank: a model with temperature, prey size, and turbulence forcing. Canadian Journal of Fisheries and Aquatic Sciences, 56: 25–36.

Longhurst, A. 1998. Cod: perhaps if we all stood back a bit? Fisheries Research, 38: 101–108.

Ma, Y., Kjesbu, O. S., and Jørgensen, T. 1998. Effects of ration on the maturation and fecundity in captive Atlantic herring (*Clupea harengus* L.). Canadian Journal of Fisheries and Aquatic Sciences, 55: 900–908.

MacKenzie, B. R., and Kiørboe, T. 1995. Encounter rates and swimming behavior of pause-travel and cruise larval fish predators in calm and turbulent laboratory environments. Limnology and Oceanography, 40: 1278–1289.

Mackenzie, B., Tomkiewicz, J., Köster, F., and Nissling, A. 1998. Quantifying and disaggregating the spawner effect: incorporating stock structure, spatial distribution and female influences into estimates of annual population egg production. ICES Document CM 1998/BB:11.

MacKenzie, B., Heath, M., Ardlandsvik, B., Backhaus, J., Bogstad, B., Gallego, A., Godø, B., Gudmundsdottir, A., Harms, I., Heilemann, J., Jonsson, S., Kjesbu, O., MacKenzie, E., Marteinsdottir, G., Nielsen, E., Scott, B., Strugnell, G., Stefansson, G., Thorsen, A., Visser, A., and Wright, P. 1999. Overview of the EU FAIR project STEREO (STock Effects on REcruitment relatiOnships). ICES Document CM 1999/Y:10.

MacKenzie, B. R., and Köster, F. W. 2001. CORE/STORE Project: a case study with cooperation between countries inside and outside the EU. ICES Document CM 2001/U:00

Marshall, C. T., Kjesbu, O. S., Yaragina, N. A., Solemdal, P., and Ulltang, Ø. 1998. Is spawner biomass a sensitive measure of the reproduction and recruitment potential of Northeast Arctic cod? Canadian Journal of Fisheries and Aquatic Sciences, 55: 1766–1783.

Marshall, C. T., and Frank, K. T. 1999. The effect of interannual variation in growth and condition on haddock recruitment. Canadian Journal of Fisheries and Aquatic Sciences, 56: 347–355.

Marshall, C. T., Yaragina, N. A., Lambert, Y., and Kjesbu, O. S. 1999. Total lipid energy as a proxy for total egg production by fish stocks. *Nature,* 402: 288–290.

Marshall, C. T., Yaragina, N. A., Ådlandsvik, B., and Dolgov, A. V. 2000. Reconstructing the stock/recruit relationship for Northeast Arctic cod using a bioenergetic index of reproductive potential. Canadian Journal of Fisheries and Aquatic Sciences, 57: 2433–2442.

Marshall, C. T., Yaragina, N. A., and Thorsen, A. 2001. Evaluating the effectiveness of biological reference points in conserving reproductive potential. ICES Document CM 2001/V:17.

Marteinsdottir, G., and Steinarsson, A. 1998. Maternal influence on the size and viability of Iceland cod (*Gadus morhua* L.) eggs and larvae. Journal of Fish Biology, 52: 1241–1258.

Marteinsdottir, G., and Thorarinsson, K. 1998. Improving the stock–recruitment relationship in Icelandic cod (*Gadus morhua* L.) by including age diversity of spawners. Canadian Journal of Fisheries and Aquatic Sciences, 55: 1372–1377.

Marteinsdottir, G., Guðmundsdóttir, A., Þorsteinsson, V., and Stefánsson, G. 2000. Spatial variation in abundance, size composition and viable egg production of spawning cod (*Gadus morhua* L.) in Icelandic waters. ICES Journal of Marine Science, 57: 824–830.

MathSoft 1998. S-PLUS for Windows, Version 4.5. MathSoft, Inc., Seattle, WA.

MathSoft 1999. S-PLUS 2000 Programmer's Guide. Mathsoft, Inc., Seattle, WA.

McCullagh, P., and Nelder, J. A. 1983. Generalized Linear Models. Chapman and Hall, London. xiii+261 pp.

McFarlane, G. A., King, J. R., and Beamish, R. J. 2000. Have there been recent changes in climate? Ask the fish. Progress in Oceanography, 47: 147–169.

Megrey, B. A., and Hinckley, S. 2001. Effect of turbulence on feeding of larval fishes: a sensitivity analysis using an individual-based model. Journal of Marine Research, 58: 1015–1029.

Mehl, S., and Sunnanå, K. 1991. Changes in growth of Northeast Arctic cod in relation to food consumption in 1984–1988. ICES Marine Science Symposia, 193: 109–112.

Möllmann, C., Kornilovs, G., and Sidrevics, L. 2000. Long-term dynamics of main mesozooplankton species in the Central Baltic Sea. Journal of Plankton Research, 22: 2015–2038.

Möllmann, C., Kornilovs, G., Sidrevics, L., and Köster, F. W. 2001. Variability in population biology of calanoid copepods in the Central Baltic Sea. ICES Document CM 2001/U:08.

Morgan, M. J., Burnett, J., Tomkiewicz, J., and Saborido-Rey, F. 2003. The availability of data for estimating reproductive potential for selected stocks in the North Atlantic. NAFO Scientific Council Studies, 37: 1–3.

Motos, L., Uriarte, A., and Valencia, V. 1996. The spawning environment of the Bay of Biscay anchovy (*Engraulis encrasicolus* L.). Scientia Marina, 60(2): 117–140.

Myers, R. A., Mertz, G., and Barrowman, N. J. 1995. Spatial scales of variability in cod recruitment in the North Atlantic. Canadian Journal of Fisheries and Aquatic Sciences, 52: 1849–1862.

Myers, R. A., Mertz, G., and Bridson, J. 1997. Spatial scales of interannual recruitment variations of marine, anadromous, and freshwater fish. Canadian Journal of Fisheries and Aquatic Sciences, 54: 1400–1407.

Myers, R. A. 1998. When do environment-recruitment correlations work? Reviews in Fish Biology and Fisheries, 8: 285–305.

Needle, C. L., O'Brien, C. M., Darby, C. D., and Smith, M. 2000. The use of recruitment time-series structure and environmental information in medium-term stock projections. ICES Document CM 2000/V:05.

Needle, C. L., O'Brien, C. M., Darby, C. D., and Smith, M. 2000a. Incorporating time-series structure and environmental information in medium-term stock projections. SAP Symposium, Fish Stock Assessments and Predictions: Integrating Relevant Knowledge, 4–6 December 2000, Bergen.

Needle, C. L., O'Brien, C. M., and Darby, C. D. 2001. Ogive characterizations in medium-term stock projections. ICES Document CM 2001/V:19.

Needle, C. L., O'Brien, C. M., Darby, C. D., and Smith, M. T. 2003. Incorporating time-series structure and environmental information in medium-term stock projections. Scientia Marina, 67 (1): 201–209.

Neuenfeldt, S., and Köster, F. W. 2000. Trophodynamic control on recruitment success in Baltic cod: the influence of cannibalism. ICES Journal of Marine Science, 57: 300–309.

Nissling, A. 1994. Survival of eggs and yolk-sac larvae of Baltic cod (*Gadus morhua* L.) at low oxygen levels in different salinities. ICES Marine Science Symposia, 198: 626–631.

Nissling, A., Larsson, R., Vallin, L., and Frohlund, K. 1998. Assessment of egg and larval viability in cod, *Gadus morhua*—methods and results from an experimental study. Fisheries Research, 38: 169–186.

O'Brien, C. M. 1999. An approach to stock–recruitment modelling based upon GLMs, HGLMs, and DLMs. ICES Document CM 1999/T:01.

O'Brien, C. M. 1999a. Time-series models in fish recruitment—a journey from classical statistics to dynamic models and Bayesian forecasting. ICES Document CM 1999/T:02.

O'Brien, C. M., Fox, C. J., Planque, B., and Casey, J. 2000. Climate variability and North Sea cod. Nature, 404: 142.

Oosthuizen, E., and Daan, N. 1974. Egg fecundity and maturity of North Sea cod, *Gadus morhua* L. Netherlands Journal of Sea Research, 8: 378–397.

Ottersen, G. S., and Sundby, S. 1995. Effects of temperature, wind and spawning-stock biomass on recruitment of Arcto-Norwegian cod. Fisheries Oceanography, 4: 278–292.

Ottersen, G., Michalsen, K., and Nakken, O. 1998. Ambient temperature and distribution of northeast Arctic cod. ICES Journal of Marine Science, 55: 67–85.

Ottersen, G., and Loeng, H. 2000. Covariability in early growth and year-class strength of Barents Sea cod, haddock, and herring: the environmental link. ICES Journal of Marine Science, 57: 339–348.

Ottersen, G., and Stenseth, N. C. 2001. Atlantic climate governs oceanographic and ecological variability in the Barents Sea. Limnology and Oceanography, 46: 1774–1780.

Ottersen, G., Alheit, J., Drinkwater, K., Frieland, K., Hagen, E., and Stenseth, N. C. 2005. The responses of fish populations to ocean climate fluctuations. *In*: Marine Ecosystems and Climate Variation: The North Atlantic: A Comparative Perspective, pp. 73–94. Ed. by N. C. Stenseth, G. Ottersen, J. W. Hurrel, and A. Belgrano. Oxford University Press.

Painting, S. J., Hutchings, L., Huggett, J. A., Korrûbel, J. L., Richardson, A. J., and Verheye, H. M. 1998. Environmental and biological monitoring for forecasting anchovy recruitment in the southern Benguela upwelling region. Fisheries Oceanography, 7: 364–374.

Parma, A. M. 2000. In search of robust harvest rules in the face of uncertain assessments and decadal changes in productivity. Presented at the Symposium on Targets, Reference Points, and the Burden of Proof in Fishery Management, 31 October–2 November 2000, MOTE Marine Laboratory, Sarasota, FL.

Patterson, K. R., and Melvin, G. D. 1996. Integrated Catch at Age Analysis, Version 1.2. Scottish Fisheries Research Report 58. 60 pp.

Patterson, K. R., Cook, R. M., Darby, C. D., Gavaris, S., Mesnil, B., Punt, A. E., Restrepo, V. R., Skagen, D. W., Stefánsson, G., and Smith, M. 2000. Validating three methods for making probability statements in fisheries forecasts. ICES Document CM 2000/V:06.

Paulik, G. J. 1973. Studies of the possible form of the stock–recruitment curve. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 164: 302–315.

Perry, A. L., Low, P. J., Ellis, J. R., and Reynolds, J. D. 2005. Climate change and distribution shifts in marine fishes. Science, 3085730: 1912–1915.

Peterman, R. M. 1981. Form of random variation in salmon smolt-to-adult relations and its influence on production estimates. Canadian Journal of Fisheries and Aquatic Sciences, 38: 1113–1119.

Petersen, G. I., Gerup, J., Nilsson, L., Larsen, J. R., and Schneider, R. 1997. Body burdens of lipophilic xenobiotics and reproductive success in Baltic cod (*Gadus morhua* L.). ICES Document CM 1997/U:10.

Petitgas, P., Allain, G., and Lazure, P. 2000. A recruitment index for anchovy in 2001 in Biscay. Working Document to the ICES Working Group on the Assessment of Mackerel, Horse Mackerel, Sardine, and Anchovy. Copenhagen, 14–23 September 2000.

Planque, B., and Fox, C. J. 1998. Interannual variability in temperature and the recruitment of Irish Sea cod. Marine Ecology Progress Series, 172: 101–105.

Planque, B., and Frédou, T. 1999. Temperature and the recruitment of Atlantic cod (*Gadus morhua* L.). Canadian Journal of Fisheries and Aquatic Sciences, 56: 2069–2077.

Planque, B., Fox, C. L., Saunders, A., and Rockett, P. 2003. On the prediction of short-term changes in the recruitment of North Sea cod (*Gadus morhua* L.) using statistical temperature forecasts. Scientia Marina, 67(Suppl.1): 211–218.

Plikshs, M., Kalejs, M., and Graumann, G. 1993. The influence of environmental conditions and spawning stock size on the year-class strength of the eastern Baltic cod. ICES Document CM 1993/J:22.

Poulding, D. 1997. M.Sc. thesis, University of Aberdeen. 69 pp.

Pope, V. D., Gallani, M. L., Rowntree, P. R., and Stratton, R. A. 2000. The impact of new physical parameterizations in the Hadley Centre climate model: HadAM3. Climate Dynamics, 16: 123–146.

Power, M. 1996. The testing and selection of recruitment distributions for North Atlantic fish stocks. Fisheries Research, 25: 77–95.

Purchase, C. F., and Brown, J. A. 2001. Stock-specific changes in growth rates, food conversion efficiencies, and energy allocation in response to temperature change in juvenile Atlantic cod. Journal of Fish Biology, 58: 36–52.

Quinlan, J. A., and Crowder, L. B. 1999. Searching for sensitivity in the life history of Atlantic menhaden: inferences from a matrix model. Fisheries Oceanography, 8: 124–133.

Reeves, S., and Cook, R. 1994. Demersal assessment programmes, September 1994. Working Document to the 1994 Meeting of the ICES North Sea Demersal Working Group.

Reid, P. C., Borges, M. F., and Svendsen, E. 2001. A regime shift in the North Sea circa 1988 linked to changes in the North Sea horse mackerel fishery. Fisheries Research, 50: 163–171.

Rice, J., and Rogers, S. 2006. ICES advice and the Ecosystem Approach—How Are We Actually Doing? ICES Document CM 2006/R:03.

Ricker, W. E. 1954. Stock and recruitment. Journal of the Fisheries Research Board of Canada, 11: 559–623.

Rideout, R. M., Burton, M. P. M., and Rose, G. A. 2000. Observations on mass atresia and skipped spawning in northern Atlantic cod, from Smith Sound, Newfoundland. Journal of Fish Biology, 57: 1429–1440.

Rijnsdorp, A. D., Daan, N., van Beek, F. A., and Heessen, H. J. L. 1991. Reproductive variability in North Sea plaice, sole, and cod. Journal du Conseil International pour l'Exploration de la Mer, 47: 352–375.

Roel, B. A., O'Brien, C. M., and Basson, M. 2004. Management options for the Blackwater herring, a local spring-spawning stock in the Thames Estuary. ICES Journal of Marine Science, 61: 297–307.

Rose, G. A. 2005. On distributional responses of North Atlantic fish to climate change. ICES Journal of Marine Science, 62: 1360–1374.

Rothschild, B. J., Changsheng Chen, and Greg Lough, R. 2005. Managing fish stocks under climate uncertainty. ICES Journal of Marine Science, 62: 1531–1541.

Roy, C. 1993. The optimal environmental window hypothesis: a non-linear environmental process affecting recruitment success. ICES Document CM 1993/L:76. 13 pp.

Schiermeier, Q. 2004. Climate findings let fishermen off the hook. Nature, 428: 4.

Schnack, D., and Köster, F. W. 2001. Environmental and fisheries influences on fish stock–recruitment in the Baltic Sea (STORE). Summary of results 1999–2000. ICES Document CM 2001/Mini Symp. U:15.

Scott, B., Marteinsdottir, G., and Wright, P. 1999. The potential effects of maternal factors on spawning stock–recruitment relationships under varying fisheries pressure. Canadian Journal of Fisheries and Aquatic Sciences, 56: 1882–1890.

Secor, D. H. 2000. Spawning in the nick of time? Effect of adult demographics on spawning behavior and recruitment of Chesapeake Bay striped bass. ICES Journal of Marine Science, 57: 403–411.

Serebryakov, V. P., Borisov, V. M., and Aldonov, V. K. 1984. Population fecundity and abundance of year classes of the Arcto-Norwegian cod. *In:* Reproduction and recruitment of Arctic cod: Proceedings of the Soviet-Norwegian Symposium, Leningrad, 26–30 September 1983, pp. 139–156. Ed. by O. R. Godø and S. Tilseth. IMR, Norway.

Shannon, C. E. 1948. A mathematical theory of communication. Bell System Technical Journal, 27: 379–423, and 623–656, July and October, 1948.

Shelton, P. 1992. The shape of recruitment distributions. Canadian Journal of Fisheries and Aquatic Sciences, 49: 1754–1761.

Shepherd, J. G. 1997. Prediction of year-class strength by calibration regression analysis of multiple recruit index series. ICES Journal of Marine Science, 54: 741–752.

Sparholt, H. 1994. Fish species interaction in the Baltic Sea. Dana, 10: 131–162.

Sparholt, H. 1996. Causal correlation between recruitment and spawning stock size of central Baltic cod? ICES Journal of Marine Science, 53: 771–779.

Sparholt, H., Aro, E., and Modin, J. 1991. The spatial distribution of cod (*Gadus morhua* L.) in the Baltic Sea. Dana, 9: 45–56.

St John, M. A., Mosegaard, H., Hinrichsen, H-H., Grønkjær, P., Köster, F. W., Hüssy, K., and Nielsen, R. 2000. Baltic Cod: Resolving processes determining spatial and temporal windows of survival. ICES Document CM 2000/N:2.

Sutton, R. T., and Allen, M. R. 1997. Decadal predictability of North Atlantic sea surface temperature and climate. Nature, 388: 563–567.

Swain, D. P., and Wade, E. J. 1993. Density-dependent geographic distribution of Atlantic cod (*Gadus morhua* L.) in the southern Gulf of St Lawrence. Canadian Journal of Fisheries and Aquatic Sciences, 50: 725–733.

Taylor, C. C. 1956. Cod growth and temperature. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 366–370.

Toresen, R., and Østvedt, O. J. 2000. Variation in abundance of Norwegian spring-spawning herring (*Clupea harengus* L., *Clupeidae* L.) throughout the 20th century and the influence of climatic fluctuations. Fish and Fisheries, 1: 231–256.

Tretyak, V. L. 1999. On possibility of the use of the Ricker's model "Stock–recruitment" for estimation of recruitment of northeastern Arctic cod population. ICES Document CM 1999/Y:12.

Tretyak, V. L. 2000. Modelling of age-dependent instantaneous coefficients of natural mortality for northeast Arctic cod. ICES Document CM 2000/V: 09. 23 pp.

Trippel, E. A. 1999. Estimation of stock reproductive potential: history and challenges for Canadian Atlantic gadoid stock assessments. Journal of Northwest Atlantic Fishery Science, 25: 61–81.

Uriarte, A., Roel, B. A., Borja, A., Allain, G., and O'Brien, C. M. 2002. Role of environmental indices in determining the recruitment of the Bay of Biscay anchovy. ICES Document CM 2002/O:25.

Uzars, D., and Plikshs, M. 2000. Cod (*Gadus morhua callarias* L.) cannibalism in the Central Baltic: interannual variability and influence of recruitment, abundance and distribution. ICES Journal of Marine Science, 57: 324–329.

Vallin, L., and Nissling, A. 2000. Maternal effects on egg size and egg buoyancy of Baltic cod, *Gadus morhua*: implications for stock structure effects on recruitment. Fisheries Research, 49: 21–37.

van der Veer, H. W., Pihl, L., and Bergman, M. J. N. 1990. Recruitment mechanisms in North Sea plaice (*Pleuronectes platessa* L.). Marine Ecology Progress Series, 64: 1–12.

van der Veer, H., and Witte, J. I. 1999. Year-class strength of plaice (*Pleuronectes platessa* L.) in the Southern Bight of the North Sea: a validation and analysis of the inverse relationship with winter sea water temperature. Marine Ecology Progress Series, 184: 245–257.

Ware, D. M. 1980. Bioenergetics of stock and recruitment. Canadian Journal of Fisheries and Aquatic Sciences, 37: 1012–1024.

Westin, L., and Nissling, A. 1991. Effects of salinity on spermatozoa mortality, percentage of fertilized eggs and egg development of Baltic cod (*Gadus morhua* L.), and implications for cod stocks fluctuations in the Baltic. Marine Biology, 10: 5–9.

Wieland, K., Waller, U., and Schnack, D. 1994. Development of Baltic cod eggs at different levels of temperature and oxygen content. Dana, 10: 163–177.

Witthames, P. R., and Greer Walker, M. 1995. Determinancy of fecundity and oocyte 7 atresia in sole (*Solea solea* L.) from the Channel, North Sea, and the Irish Sea. Aquatic Living Resources, 8: 91–109.

Yaragina, N. A., and Marshall, C. T. 2000. Trophic influences on interannual and seasonal variation in the liver condition index of Northeast Arctic cod (*Gadus morhua* L.). ICES Journal of Marine Science, 56: 42–55.

Young, E. F., Aldridge, J. N., and Brown, J. 2000. Development and validation of a three-dimensional curvilinear model for the study of fluxes through the North Channel of the Irish Sea. Continental Shelf Research, 20: 997–1035.

12 Participants and attendance

The Study Group on the Incorporation of Process Information into Stock–recruitment Models SGPRISM (Chair: C. M. O'Brien, UK) met in Lowestoft, UK on three occasions: 23–26 November 1999, 23–26 January 2001, and 14–18 January 2002. Participants' contact information and a record of their attendance at the three meetings appear below.

NAME	ADDRESS	1999	2001	2002
Carl O'Brien (Chair)	Cefas Lowestoft Laboratory, Pakefield Road, Lowestoft, Suffolk, NR33 0HT	x	x	x
Marinelle Basson	Cefas Lowestoft Laboratory	x	x	
Ewen Bell	Cefas Lowestoft Laboratory	x	x	x
Julia Blanchard	Cefas Lowestoft Laboratory			x
Bjarte Bogstad	Institute of Marine Research, PO Box 1870 Nordnes, N-5817 Bergen, Norway			x
Mark Bravington	Cefas Lowestoft Laboratory	x		
Peter Bromley	Cefas Lowestoft Laboratory			x
Juan Brown	Cefas Lowestoft Laboratory	x		
Robin Clark	Cefas Lowestoft Laboratory			x
Chris Darby	Cefas Lowestoft Laboratory	x	x	x
Mark Dickey-Collas	Department of Agriculture and Rural Development, AESD, Newforge Lane, Belfast, BT9 5PX, Northern Ireland	x	x	x
Clive Fox	Cefas Lowestoft Laboratory	x	x	x
Hans-Harald Hinrichsen	Institute of Marine Science, Düstenbrooker Weg 20, 24105 Kiel, Germany	x		
Mike Heath	FRS Marine Laboratory, PO Box 101, 375 Victoria Rd, Aberdeen AB11 9DB		x	
Tara Marshall	Institute of Marine Research		x	x
David Maxwell	Cefas Lowestoft Laboratory			x
Richard Nash	University of Liverpool, Port Erin Marine Laboratory, Port Erin, Isle of Man IM9 6JA		x	x
Coby Needle	FRS Marine Laboratory	x	x	x
Pierre Pepin	Fisheries and Ocean, PO Box 5667, St John's Newfoundland, Canada A1C 5X1	x		
Benjamin Planque	Cefas Lowestoft Laboratory	x		
Stuart Reeves	Department of Marine Fisheries, Danish Institute for Fisheries Research, Charlottenlund Slot, DK-2920 Charlottenlund, Denmark		x	x
Beatriz Roel	Cefas Lowestoft Laboratory		x	
Mike Smith	Cefas Lowestoft Laboratory	x	x	
Victor Tretyak	Polar Research Institute of Marine Fisheries and Oceanography (PINRO), 6 Knipovitch Street, 183763 Murmansk, Russia		x	x
Andres Uriarte	AZTI, Herrera Kaia, Portualde z/g, 20110 Pasaia, Euskadi, Spain	x	x	
Dmitri Vasilyev	Russian Federal Research Institute of Fisheries and Oceanography (VNIRO), 17 Krasnoselskaya V., 107140 Moscow, Russia			x
Peter Witthames	Cefas Lowestoft Laboratory			x

Annex 1: Terms of Reference

WGRP initially proposed two terms of reference (ToRs) for the **first meeting** of the Study Group on the Incorporation of Process Information into Stock–Recruitment Models:

a) Determine the potential use of environmental information in increasing the accuracy of the underlying stock–recruitment relationship, as it is used in population assessments;

b) Determine how accurate knowledge of the impact of environmental variations on recruitment or survival can be used to constrain medium-term (5–10 years) projections of stock abundance, as they are currently applied in population assessments.

The details of how the study group addressed these two ToRs are presented in ICES (2000).

Given the progress made at the first meeting on North Sea cod and the Bay of Biscay anchovy, a **second meeting** of the study group was agreed with the following ToRs:

c) Investigate and evaluate medium-term projection methods for use in fishery assessment, taking account of characterizations (in space/time) of historical patterns in recruitment and the environment for specific case studies (cod and anchovy);

d) Incorporate realistic variability in the parameters of management simulation models and evaluate more fully the potential of environmental studies to have an impact on management procedures;

e) Investigate the variability and predictability of environmental conditions known or supposed to affect the dynamics of fish populations;

f) 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 methods of stock assessment and projections.

The details of how the study group addressed these four ToRs are presented in ICES (2001).

Finally, the study group met for a **third time** with the following ToRs:

g) Further consider the two case studies (North Sea cod and Bay of Biscay anchovy);

h) Further develop the modelling and testing of process and recruitment relationships for incorporation into management procedures;

i) Identify the sources of data necessary to determine the reproductive potential of fish stocks and specify a protocol for their collection within existing coordinated surveys.

The details of how the Study Group addressed these four ToRs are presented in ICES (2002).

Annex 2: Working documents and background material presented to the study group

A number of working documents (WD) and background documents (BD) where presented at the three meetings of SGPRISM. They are listed here together with their code for easy reference within this report.

	WORKING DOCUMENTS	1999	2001	2002
WD1	Marshall, C. T. A review of recent research related to quantifying the reproductive potential of marine fish.		x	
WD2	Tretyak, V. L. On the possibility of Northeast Arctic cod recruitment modelling.		x	
WD3	Bogstad, B. Predation by herring on capelin larvae—incorporation in capelin management.			x
WD4	Witthames, P. R. Reproduction and stock evaluation for recovery (RASER).			x
WD5	O'Brien, C. M., and Maxwell, D. L. Stock–recruitment modelling based upon a segmented regression approach—the case of North Sea cod.			x
WD6	O'Brien, C. M., and Maxwell, D. L. Stock–recruitment modelling based upon a segmented regression approach—the case of Bay of Biscay anchovy.			x
WD7	Bogstad, B. Incorporating process information in recruitment predictions for northeast Arctic cod.			x
WD8	Nash, R. D. M., and Dickey-Collas, M. At what point in the life history is year-class strength determined? An examination of North Sea herring (*Clupea harengus* L.).			x
WD9	Armstrong, M., Dickey-Collas, M., and Gerritsen, H. Estimation of reproductive characteristics of Irish Sea cod.			x
WD10	Needle, C. Exploratory analyses: weights-at-age modelling.			x
WD11	Marshall, C. T., Yaragina, N. A., Thorsen, A., and Kjesbu, O. S. Incorporating reproductive potential into stock–recruitment models for Northeast Arctic cod.			x
WD12	Tretyak, V. L. Spawning stock structure of northeast Arctic cod.			x
WD13	Clark, R., and Fox, C. Modelling the effects of climatic change on North Sea cod stocks. Subsequently published as: Clark, R. A., Fox, C. J., Viner, D., and Livermore, M. (2003) North Sea cod and climate change—modelling the effects of temperature on population dynamics. Global Change Biology, 9: 1669–1680.			x
WD14	Reeves, S. A. Possible approaches to using process information in medium-term projections for Eastern Baltic cod.			x

	BACKGROUND DOCUMENTS	1999	2001	2002
BD1	Basson, M. 1999. The importance of environmental factors in the design of management procedures. ICES Journal of Marine Science, 56: 933–942.	x		
BD2	Bell, E., and Bravington, M. Multispecies recruitment: life and death before settlement.	x		
BD3	Cook. Medium-term scenario analysis, WGMTERM. Concerted Action FAIR-PL98–4231, Appendix 8 (Cook).	x		
BD4	Kell, L. T., O'Brien, C. M., Smith, M. T., Stokes, T. K., and Rackham, B. D. 1999. An evaluation of management procedures for implementing a precautionary approach in the ICES context for North Sea plaice (*Pleuronectes platessa* L.). ICES Journal of Marine Science, 56: 834–845.	x		
BD5	Needle, C. Modelling stock–recruitment relationships for assessment purposes.	x		
BD6	O'Brien, C. M. An approach to stock–recruitment modelling based upon GLMs, HGLMs, and DLMs. ICES Document CM 1999/T:01.	x		
BD7	O'Brien, C. M. 1999. Time-series models in fish recruitment—a journey from classical statistics to dynamic models and Bayesian forecasting. ICES Document CM 1999/T:02.	x		

	BACKGROUND DOCUMENTS	1999	2001	2002
BD8	Reeves, S., and Cook, R. Demersal assessment programs. Working Document to 1994 meeting of the North Sea Demersal Working Group.	x		
BD9	Report of the Working Group meeting NAFO Scientific Council Working Group on Reproductive Potential, 10–13 October 2000, AZTI, San Sebastian, Spain.		x	
BD10	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. Subsequently published as: Needle, C. L., O'Brien, C. M., Darby, C. D., and Smith, M. T. 2003. Incorporating time-series structure and environmental information in medium-term projections. Scientia Marina, 67(1): 201–209.		x	
BD11	Planque, B., Fox, C. J., Saunders, M. A., and Rockett, P. 2000. On the prediction of short term changes in the recruitment of North Sea cod (*Gadus morhus* L.) using temperature forecasets. Subsequently published as: Planque, B., Fox, C. J., Hamilton, T., and Saunders, M. A. 2003. On the statistical prediction of short-term changes in the recruitment of North Sea cod (*Gadus morhus* L.) using temperature forecasts. Scientia Marina, 67(1): 211–218.		x	
BD12	Tretyak, V. L. Modelling of age-dependent instantaneous coefficients of natural mortality for northeast Arctic cod. ICES Document CM 2000/V:09.		x	
BD13	Tretyak, V. L. On the possibility of the use of the Ricker's model "stock–recruitment" for estimation of recruitment of northeastern Arctic cod populations. ICES Document CM 1999/Y:12.		x	
BD14	Borja, A., Skreslet, S., Wyatt, T., and Hansen, G. 2002. Environmental and climatic factors affecting recruitment of the northeast Arctic cod (*Gadus morhua* L.) along the Norwegian coasts. Fisheries Oceanography, 11(2): 116–127.		x	
BD15	Heath, M., and Gallego, A. Modelling the spatial and temporal structure of survivorship to settlement in North Sea and West of Scotland haddock. ICES Document CM 2000/N:11.		x	
BD16	Basson, M. 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, FL) and submitted to Bulletin of Marine Science.		x	
BD17	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.		x	
BD18	Report of the 2nd Working Group Meeting, NAFO Scientific Council Working Group on Reproductive Potential, St Petersburg, Russia, 23–26 October 2001.			x
BD19	NAFO Working Group on Reproductive Potential—current and proposed terms of reference.			x
BD20	NAFO Working Group on Reproductive Potential—data on reproductive potential for Atlantic cod in ICES Subareas I and II.			x
BD21	Darby, C. Estimation bias in the North Sea short-term forecasts. Working paper presented to the ICES Working Group on Methods on Fish Stock Assessments, ICES Headquarters, Copenhagen, Denmark, 3–7 December 2001.			x
BD22	Darby, C. Overestimation bias in the North Sea cod short-term forecasts. Working paper presented to the ICES Working Group on Methods on Fish Stock Assessments, ICES Headquarters, Copenhagen, Denmark, 3–7 December 2001.			x
BD23	Needle, C. L. ARMA and VARMA models in medium-term projections. Working paper presented to the ICES Working Group on Methods on Fish Stock Assessments, ICES Headquarters, Copenhagen, Denmark, 3–7 December 2001.			x

Annex 3: Glossary

Institutions, groups, and commissions

ICES – International Council for the Exploration of the Sea	
ACE	Advisory Committee on Ecosystems
ACFM	Advisory Committee on Fishery Management
ACME	Advisory Committee on the Marine Environment
AFWG	Arctic Fisheries Working Group
ASC	Annual Science Conference
CRR	Cooperative Research Report
DATRAS	DAtabase TRawl Survey
EcoQO	Ecological Quality Objective
HAWG	Herring Assessment Working Group
IBTSWG	International Bottom Trawl Survey Working Group
NORSEPP	North Sea Pilot Project
OCC	Oceanography Committee
PGEGGS	Planning Group on North Sea Cod and Plaice Egg Surveys
REGNS	Regional Ecosystem Study Group for the North Sea
SGASAM	Study Group on Age-Length Structured Assessment Models
SGGROMAT	Study Group on Growth, Maturity and Condition in Stock Projections
SGPA	Study Group on the Further Development of the Precautionary Approach to Fishery Management
SGPRISM	Study Group on Incorporation of Process Information into Stock–recruitment Models
WGBTS	Working Group on Bottom Trawl Surveys
WGCCC	ICES/GLOBEC Working Group on Cod and Climate Change
WGECO	Working Group on Ecosystem Effects of Fishing Activities
WGMG	Working Group on Methods of Fish Stock Assessments
WGMHSA	Working Group on the Assessment of Mackerel, Horse Mackerel, Sardine and Anchovy
WGNPBW	Northern Pelagic and Blue Whiting Fisheries Working Group
WGNSSK	Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak
WGRED	Working Group for Regional Ecosystem Description
WGRP	Working Group on Recruitment Processes
WGZE	Working Group on Zooplankton Ecology
WKSAD	Survey design and data analysis Workshop
EU – European Union	
FAIR	Fisheries- and Agro-Industrial Research
SPACC/IOC	IOC is an inter-governmental panel. SPACC/IOC Study Group on the Use of Environmental Indices in the Management of Pelagic Populations.
STEREO	STock Effects on REcruitment relatiOships
Defra – Department for Environment, Food and Rural Affairs	
Cefas	Centre for Environment, Fisheries and Aquaculture Science
SEERAD – Scottish Executive Environment and Rural Affairs Department	
FRS	Fisheries Research Services
DARD – Department of Agriculture and Rural Development	
AESD	Agricultural and Environmental Science Division
IBSFC – International Baltic Sea Fishery Commission	
ICCAT – International Commission for the Conservation of Atlantic Tuna	
IFREMER – Institut Francais de Recherche Pour l'Exploitation de la Mer	
NAFO – Northwest Atlantic Fishery Organisation	
NASCO – North Atlantic Salmon Conservation Organization	
NCAAE – National Center for Atmospheric Research	
NEAFC – Northeast Atlantic Fisheries Commission	
NERC – Natural Environment Research Council	
NGO – Non-Governmental Organization	

Mathematical terms

AOGCM	Atmosphere-Ocean General Circulation Model
AR	Autoregressive
ARMA	Autoregressive moving average
df	Degrees of freedom
GCM	General Circulation Model
GLM	Generalized Linear Model
IBM	Individual-Based Models
MA	Moving average
MSVPA	Multispecies Virtual Population Analysis
MTSP	Medium-Term Stochastic Projection
RCM	Regional Climate Model
VARMA	Vector Autoregressive Moving Average
XSA	Extended Survivors Analysis

Biological terms

B	Biomass
B_{lim}	Biomass limit
B_{msy}	Biomass which results in maxium sustainable yield
B_{pa}	Biomass precautionary level
E	Environmental factors
EA	Ecosystem approach
EP	Egg production
f	Fecundity
F	Fishing mortality
F_{msy}	Fishing mortality which results in maximum sustainable yield
F_{pa}	Fishing mortality precautionary level
H	Shannon Diversity Index
HCR	Harvest control rule
K	Growth parameter
L_a	Length-at-age
L_{∞}	Asymptotic length
m	Maturity
N	Abundance of fish
NAO	North Atlantic Oscillation
PA	Precautionary approach
PRR	Proportional removal of reproductive potential
R	Recruitment
SB	Spawner biomass
S–R	Stock–recruitment
SSB	Spawning-stock biomass
SST	Sea surface temperature
t	Time
TAC	Total Allowable Catch
TEP	Total egg production
TVEP	Total viable egg production
w	Weight

Titles Published in the ICES Cooperative Research Report Series

No.	Title	Price (Danish Kroner)
282	Incorporation of process information into stock–recruitment models. 152 pp.	90
281	Zooplankton Monitoring Results in the ICES Area: Summary Status Report 2004/2005. 43 pp.	90
280	ICES Report on Ocean Climate. 47 pp.	70
279	Protocol for the Use of an Objective Mesh Gauge for Scientific Purposes. 8 pp.	40
278	Description of the ICES HAC Standard Data Exchange Format, Version 1.60. 86 pp.	60
277	The intentional introduction of the marine red king crab Paralithodes camtschaticus into the Southern Barents Sea. 18 pp.	60
276	Zooplankton Monitoring Results in the ICES Area: Summary Status Report 2003/2004. 34 pp.	80
275	The Annual ICES Ocean Climate Status Summary 2004/2005. 2005. 37 pp.	80
274	Spawning and life history information for North Atlantic cod stocks. 152 pp.	90
273	Guidance on the Application of the Ecosystem Approach to Management of Human Activities in the European Marine Environment. 22 pp.	40
272	Ecosystem Effects of Fishing: Impacts, Metrics and Management Strategies. 177 pp.	70
271	Vector Pathways and the Spread of Exotic Species in the Sea. 25 pp.	60
270	The *Nephrops* fisheries of the Northeast Atlantic and Mediterranean – A review and assessment of fishing gear design. 38 pp.	50
269	The Annual ICES Ocean Climate Status Summary 2003/2004. 32 pp.	60
268	The DEPM Estimation of Spawning-Stock Biomass for Sardine and Anchovy. 87 pp.	90
267	Report of the Thirteenth ICES Dialogue Meeting: Advancing scientific advice for an ecosystem approach to management: collaboration among managers, scientists, and other stakeholders. 59 pp.	50
266	Mesh Size Measurement Revisited. 56 pp.	80
265	Trends in important diseases affecting the culture of fish and molluscs in the ICES area 1998–2002. 26 pp.	40
264	Alien Species Alert: Rapana venosa (veined whelk). 14 pp.	50
263	Report of the ICES Advisory Committee on the Marine Environment, 2003. 227 pp.	150
262	Report of the ICES Advisory Committee on Ecosystems, 2003. 229 pp.	170
261	Report of the ICES Advisory Committee on Fishery Management, 2004 (Parts 1–3). 975 pp.	430
260	Stockholm 1999 Centenary Lectures. 48 pp.	170
259	The 2002/2003 ICES Annual Ocean Climate Status Summary. 29 pp.	150
258	Seabirds as Monitors of the Marine Environment. 73 pp.	200
257	Proceedings of the Baltic Marine Science Conference. 334 pp.	420
256	Report of the ICES Advisory Committee on the Marine Environment, 2002. 155 pp.	270
255	Report of the ICES Advisory Committee on Fishery Management, 2002. (Parts 1–3). 948 pp.	1200
254	Report of the ICES Advisory Committee on Ecosystems, 2002. 129 pp.	250
253	ICES Science 1979–1999: The View from a Younger Generation. 39 pp.	170
252	Report of the ICES/GLOBEC Workshop on the Dynamics of Growth in Cod. 97 pp. (includes a CD-ROM from ICES ASC 2001)	220
251	The Annual ICES Ocean Climate Status Summary 2001/2002. 27 pp.	180
250	ICES/GLOBEC Sea-going Workshop for Intercalibration of Plankton Samplers. A compilation of data, metadata and visual material, 2002. 34 pp.	190
249	Report of the ICES Advisory Committee on Ecosystems, 2001. 75 pp.	200
248	Report of the ICES Advisory Committee on the Marine Environment, 2001. 203 pp.	310
247	Effects of Extraction of Marine Sediments on the Marine Ecosystem. 80 pp.	200
246	Report of the ICES Advisory Committee on Fishery Management, 2001. (Parts 1–3). 895 pp.	1170
245	The Annual ICES Ocean Climate Status Summary 2000/2001. 21 pp.	150

No.	Title	Price (Danish Kroner)
244	Workshop on Gadoid Stocks in the North Sea during the 1960s and 1970s. The Fourth ICES/GLOBEC Backward-Facing Workshop. 55 pp.	160
243	Report of the 12 th ICES Dialogue Meeting (First Environmental Dialogue Meeting). 28 pp.	130
242	Report of the ICES Advisory Committee on Fishery Management, 2000. (Parts 1–3). 940 pp.	1100
241	Report of the ICES Advisory Committee on the Marine Environment, 2000. 263 pp.	370
240	Report of the Young Scientists Conference on Marine Ecosystem Perspectives. 73 pp.	170
239	Report of the ICES Advisory Committee on the Marine Environment, 1999. 277 pp.	350
238	Report on Echo Trace Classification. 107 pp.	200
237	Seventh Intercomparison Exercise on Trace Metals in Sea Water. 95 pp.	190
236	Report of the ICES Advisory Committee on Fishery Management, 1999. (Part 1 and Part 2). 821 pp.	920

These publications can be ordered from: ICES Secretariat, H. C. Andersens Boulevard 44–46, DK-1553 Copenhagen V, Denmark, fax: +45 33 93 42 15, e-mail: info@ices.dk. An invoice including the cost of postage and handling will be sent. Publications are usually dispatched within one week of receipt of payment. Further information about ICES publications, including ordering and payment by credit card, cheques, and bank transfer, can be found at http://www.ices.dk under “Products”.