Oceanography Committee **ICES CM 2000/C:01**

REPORT OF THE

STUDY GROUP ON INCORPORATION OF PROCESS INFORMATION INTO STOCK-RECRUITMENT MODELS

Lowestoft, UK
23 – 26 November 1999

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1 INTRODUCTION

1.1 Participants

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1.2 Terms of reference

It was decided by Council (**C.Res. 1999/2C01**) at the 1999 Annual Science Conference (87th Statutory Meeting) that:

A **Study Group on Incorporation of Process Information into Stock-Recruitment Models** [SGPRISM] (Chair: Dr C. O'Brien, UK) will be established and will meet in Lowestoft, UK from 23-26 November, 1999 to:

a) determine the potential use of environmental information in increasing our knowledge (in terms of accuracy) of the underlying stock-recruitment relationship, as it is used in population assessments; and

b) determine how accurate knowledge of the impact of environmental variations on recruitment or survival can be used to constrain moderate-term (5-10 year) projections of stock abundance, as they are currently applied in population assessments.

SGPRISM will report to the Oceanography and Resource Management Committees at the 2000 Annual Science Conference.

1.3 Structure of the report

The relationship between spawning stock and recruitment is fundamental to the scientific approach to fisheries management. However, the basic analytical models which are most commonly applied (e.g. Ricker, Beverton-Holt, Cushing, Shepherd) have evolved little in the last 30 years, even though knowledge of the physical and biological processes determining the production and survival of early life stages of fish has advanced dramatically in this time. It is now apposite to consider whether and how this wealth of knowledge can be incorporated into stock-recruitment models which will be of genuine practical value in stock assessment procedures, capitalising on the extensive world-wide investment in research on fisheries recruitment issues.

The terms of reference are addressed within the four main sections of the report.

Section 2 provides details on definitions of recruitment and identifies those physical processes that it might be necessary to consider for the better understanding and prediction of recruitment. Fishery management is briefly discussed but is considered more fully in section 5. In section 3, examples are presented where recruitment has been considered in the context of specific stocks, their biological processes, relevant physical processes and environmental drivers.

In section 4, background details are given of the WGMTERM projection program that is used for medium-term projections within the ICES stock assessment framework. The effect of incorporating environmental variability (sea surface temperature) into the Ricker stock-recruitment model for North Sea cod and plaice is discussed and the results of a number of projections using WGMTERM presented. Results from the short-term population and fishery projections of anchovy in the Bay of Biscay are also presented. The medium-term projection models currently used in the ICES advisory framework, while parsimonious are limited and inflexible but modifications are proposed by the Study Group. The section 5 consists mainly of a general discussion.

The future of the study group, including case studies identified for investigation, is discussed in section 6.

2 BACKGROUND

2.1 Definitions

2.1.1 Environmental factors

For the context of this study group, environmental factors are considered to be those biotic and abiotic factors, other than fisheries, that impact upon 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 effort data; and
- 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 derived from assessments of stocks based on management units. However, populations may occur across or within management units and assessment estimates can often 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 to be 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. Due to 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 *per se* a biologically meaningful term. However, in a fisheries context it is defined as the biomass (usually in tonnes) of mature, female fish. This 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. Fisheries management usually attempts to maintain SSB above some pre-defined level with the underlying biological assumption that SSB is a valid proxy for the realised reproductive output of a population in any year. It is known that this approach may be flawed for several reasons. In particular, 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 inter-annual changes in condition which 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 is 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 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 considered and understood in exploring relationships between recruitment and oceanographic conditions. It is essential to differentiate between exploratory analyses that serve to generate hypotheses and the development of understanding of the underlying processes within a region of interest.

Oceanographic information can consist of indices that reflect 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 area. The use of indices instead of local observations or predictions is often the result of limited monitoring or knowledge at the local scale.

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. Without understanding of the fundamental processes operating on a local scale, the use of summary indices in predicting patterns of recruitment may in fact lead to greater inaccuracy in stock predictions.

Our ability to use environmental indices or variables in the stock assessment process depends both on understanding and predictability. Environmental forecasting is still on shorter time scales than that of medium and long term stock forecasts. However, the Study Group knows of few attempts to describe and characterize the underlying variability of environmental conditions (discussed below). The issue is not necessarily to precisely forecast the environment but rather to confine how the environment is likely to change over the medium-term. Fundamental questions that must be addressed in characterizing oceanographic variations include: whether variables or indices exhibit underlying periodicities (or levels of autocorrelation on both long and short terms); and whether variations measured at single or multiple sites provides an adequate representation of variations over a larger region.

One example of such an analysis was performed by Planque and Frédou (1999) who found that anomalies in sea surface temperature (SST) for areas corresponding to the population range of nine different cod stocks. This particular variable exhibited little significant autocorrelation beyond 6 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 that recruitment predictions may, therefore, 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. How other variables behave must be addressed!

The analysis of oceanographic time series should, however, 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.

There are methodological issues dealing both with the estimation of environmental variables and indices (how it is applied to generate the measure of impact) as well as what methods are 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 over-simplification 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 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. Since it is essential that environmental inputs to the assessment process must reflect an understanding of the system dynamics, then their estimation (and averaging) must also reflect the processes which 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 case of the latter, 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 confine 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, then various approaches (e.g. moving averages, ARIMA models, scenarios based on 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.

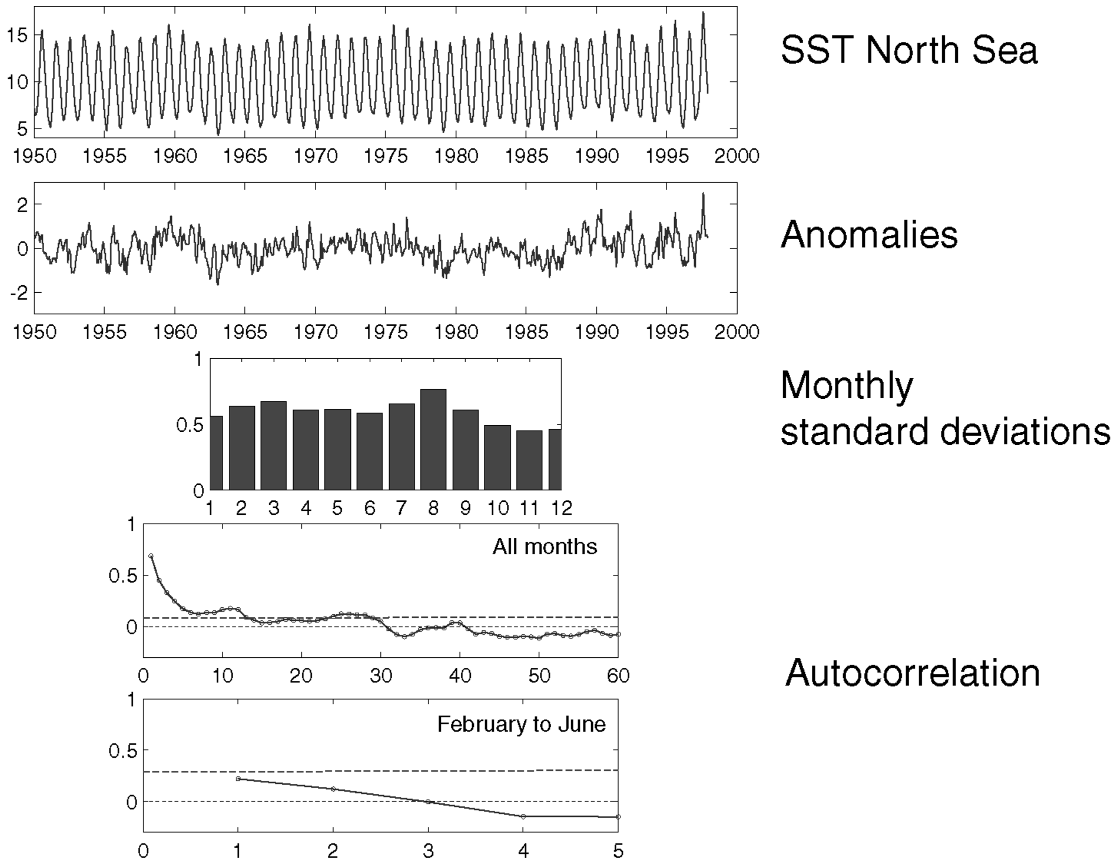


Figure 2.2.1: Analysis of North Sea SST derived from COADS. From top to bottom: time-series of monthly SST; time-series of monthly SST anomalies (departure from monthly mean); standard deviation of monthly temperature anomalies; autocorrelation function of the monthly anomalies time-series; autocorrelation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

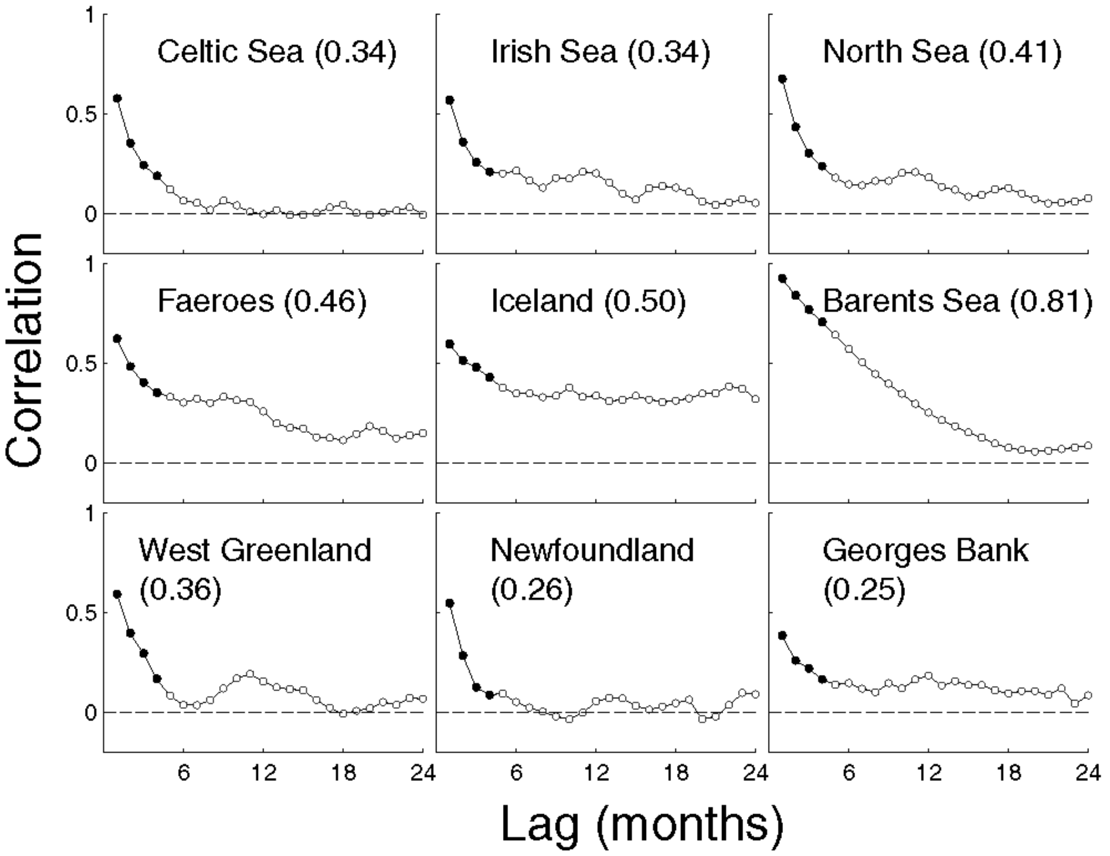


Figure 2.2.2: Autocorrelation function for monthly SST anomalies in nine areas of the North Atlantic margin. Values in brackets indicate the mean correlation values for lags 1-4 (closed circles).

2.3 Fishery management considerations

Changes in the environment - comprising 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 socioeconomic 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; and
- 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 much 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.

To decide whether and how to include environmental information, we need a way of checking 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 in order 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, or whatever, while keeping conservation risks low. Strategy testing is a key area where scientists and managers should try to take account of all available information about environmental effects on recruitment.

3 APPLICATIONS AND INVESTIGATIONS

3.1 The difficult task of relating recruitment to environment

The task of relating recruitment to the environment is difficult. However, there is a long history of attempts to identify links; many in the absence of a precise understanding of underlying processes.

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 several difficulties which can be categorised 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 10 environmental indices with 10 recruitment series there is a risk of identifying 5 spurious correlations at the α=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 n-2 which is generally considered. Not taking account of the autocorrelation results in bias in the estimation of α and a higher risk to detect spurious correlation than expected. Accounting for autocorrelation usually reduces the power of the analysis (Type II error).

3) Causality errors

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

Type I and II errors can sometimes 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 and/or field work 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 Subdivisons 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., 1999). 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) have been shown to be important determinants of recruitment.

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

The statistical model obtained for prediction of 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 significant variable as well as the larval transport index (Hinrichsen et al., 1999) as being nearly significant. In the more eastern spawning areas (Subdivisions 26 and 28) the hydrographic regime did in general 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).

To obtain an indication about the sensivity of the parameter estimates and the predictive power of the established statistical models re-fitting of the models over different shorter time periods utilizing sub-sets 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 as input data series are presently in the process of being validated. Furthermore, processes potentially affecting the reproductive success, 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 due to shortage in suitable food supply (Grønkjær et al., 1995) or limited capture success in relation to turbulence conditions (MacKenzie and Kiørboe, 1995) have not been included in the analyses.

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 lead to improved understanding of environmental effects on recruitment to fish stock. In turn, such studies should reduce the influence of noise or bias introduced to 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 to the fishery (R) produced by a unit weight of spawning stock biomass (SSB). In the standard stock and recruit 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 in order 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 (c.f. section 4.4).

The two example cases of Irish Sea cod and plaice were presented. The former is discussed next, whilst the latter will be discussed in the following 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 (ACFM, 1999) assessment estimates are presented in Figures 3.3.1.1(a to 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 3.3.1.1(e). 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(f). 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
Figures 3.3.2.1 illustrate 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 3.3.2.1(a)). When plotted against the values expected from the Ricker curve (Figures 3.3.2.1(b and c), the temporal changes in the level of recruitment at a given stock size show that subsequent to 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 Figures 3.3.2.1(d to f).

The change in the level of the productivity of the stock could result from changes in environmental conditions or could be induced by changes in the level of hidden mortality (mis-reporting or discarding). The latter could only induce changes in the R/SSB ratio if the mortality rate varies with age e.g. discarding rates on juveniles but not adults.

If the 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 over-estimated 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 3.3.3.1(a to 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 in time 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 the 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 in this section 3.3. 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.

3.4 Recruitment and physical processes in Irish Sea herring

The assessment of Irish Sea herring is imprecise in comparison to many other herring stocks (ICES, 1999). The series of tuning indices are short and there is uncertainty with regards to the level of mis-reporting 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 as 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 whilst in recent years Celtic Sea herring spawn in January and February.

The inter-annual differences in lengths of 0-group herring in the Irish Sea were investigated using a time series of ground fish 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 whilst 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 112mm whilst 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 is ongoing into 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 east and western Irish Sea. The temperature differences required to create populations with lengths that differ by 25% after 9 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 (Brown pers. com., see section 3.5). It is likely that this physical forcing is dependent on individual wind events which models that use mean winds may fail to detect. Work is being proposed to investigate the inter-annual variability in wind driven transport between the two seas.

It is clear that these initial hypotheses require much testing. The assumption at present 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 be dependent 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). Suggesting 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). This would suggest that there is a physical component to the determination of year-class strength in Irish Sea herring.

3.5 Oceanographic processes and their application to recruitment

Often, for management purposes simplistic circulation maps of the shelf seas are relied on to explain contaminant dynamics and factors determining fisheries recruitment. These representations were synthesised from the observational and modelling work of this century and suggest an apparently weak yet coherent circulation pattern. Such a view runs counter to a significant body of work showing shelf seas circulation to be dominated by tides and short-term (wind) events. More recent work is demonstrating 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}, dependant on location. However, with the exception of local tidal residuals in the vicinity of 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 on the basis of tracer budgets, the net long-term circulation has been characterised as weak at speeds of typically 1-2 cm s^{-1}.

Direct measurement of the response of the water column 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.*, 1999), periodic strong wind events may cause significant flushing of regions such as the Irish Sea. An event of two days duration 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/juveniles (section 3.4).

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

Not surprisingly, large or persistent (in direction) wind events provide the most notable anomalies in terms of movement of eggs/larvae/juveniles from spawning and settlement sites. Demonstrating that *average* conditions play a significant role in determining recruitment is likely to be difficult. Similarly, 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 localised temperature changes is difficult. Consequently, it is the consideration of extreme events which are most likely to play a role in *guiding* the estimates of recruitment.

Stratification

During summer (May through 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. 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 concentration 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 advancing/delaying primary production. Given that such features have probably existed since essentially 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 to be the more unusual events that 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, 3 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 potentially occurs (Motos *et al.*, 1996): this being in river plumes, at shelf break fronts and in oceanic gyres. In general, spawning is limited to the French and Spanish coasts (south of 46º 30' N and east of 05º 00' W). Anchovy eggs and larvae develop from April 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 for the period 1967-1996, that oceanographic conditions caused by northerly-easterly winds of medium and low intensity in spring/summer in the Bay of Biscay are related to good levels of recruitment to the anchovy population. The major oceanographic events originating from north-easterly winds that probably cause enhancement of the surviving of larvae and early juveniles are identified by these authors as:

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

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

The north-easterly wind conditions in the Bay of Biscay are summarised in an upwelling index calculated from March to July of every year (Borja et al. op.cit). Figure 3.6.1 summarises the relationship between upwelling index and recruitment estimates from direct DEPM surveys and the assessment performed in 1999 (ICES, 2000). The Upwelling index turns out to explain about 60% of the inter-annual variability of recruitment, without considering any stock-recruitment relationship.

Recently the Allain *et al.* (1999) have improved the previous relationship between wind and recruitment for the period 1987-96 by simulating the oceanographic processes that are expected to be directly linked to the life history of larvae. This was made by a 3-D hydrodynamic physical model (IFREMER, Brest) that simulates processes occurring over the Biscay French continental shelf. Two of these variables were retained by the authors and seem to explain about 75-80% of the recruitment interanual variability between 1987-96. These two variables are by order of importance:

- An upwelling index which correspond to the sum of mean weekly vertical currents from bottom to surface over the period March-July along the Landes coast (SW of France). These upwelling events are caused by the moderate and intermittent North-eastern winds.
- 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 are phenomena links to strong westerly winds (>15 m/s) that can cause important larvae mortality just after peak spawning.

These modelled environmental variables are not yet operative in real time as to predict next year recruitment, although for the next year they could be obtained in a real time operative fashion. Therefore the Working Group on the Assessment of Mackerel, Horse-mackerel, Sardine and Anchovy (ICES, 2000) is by now using the upwelling index of Borja *et al.* to improve the forecast of the fishery and the population for the year ahead (as explained in section 4.3).

3.7 Temperature and cod recruitment

The relationship between interannual changes in temperature and variation in recruitment for nine cod stocks in the North Atlantic was examined. In this study, an attempt is made to reduce the statistical errors (see section 3.1) of type I and II, by performing non-exploratory meta-analysis and correcting for autocorrelation bias. For stocks taken individually, the relationship often appears weak and statistically not significant, 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 (c.f. section 3.5). 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 two-fold decrease in the recruitment level.

The above paragraph is a summary of the paper by Planque and Frédou (1999) where the interested reader may find further details.

3.8 Synchrony in the recruitment time-series of plaice (*Pleuronectes platessa* L.) around the United Kingdom 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 be due to 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 is therefore suggestive of environmental forcing operating over a similar geographical scale. An obvious candidate 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 inter-annual temperature fluctuations is similar. Temperature anomalies may therefore 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 re-test such relationships using independent data. Such an exercise has recently been undertaken for North Sea plaice stock and the relationship shown to be holding (van der Veer and Witte, 1999). Our results confirm this finding and extend the geographical range of this relationship to other plaice stocks around the United Kingdom.

If a mechanistic basis for observed correlations between environmental variables and recruitment can be established, the confidence one may place in that relationship will be strengthened. 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, the 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 upon the egg stages of plaice in cold years. Such a reduction might be due to lower predator abundance and/or to reduced consumption rates. The results from our analyses are consistent with this hypothesis. This suggests that future field studies must consider the inter-actions 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 in-coming 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 seems some evidence of a recent shift in recruitment levels for plaice, at least within the Irish Sea (see section 3.3.2). This seems coincident with the increasing frequency of warmer than average sea temperatures observed in this region in the last decade and may be indicative of a temperature induced effect on stock population dynamics.

3.9 Multi-species recruitment issues

Recruitment of any fish species X 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, juvenile 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, then the abundance or distribution of predators and prey may change too. It is not obvious that levels of predation in future will be the same as they have been historically, so it is not obvious that historically-derived relationships between environment and recruitment will persist. It is therefore important not to forget about possible multi-species 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 future. But good recruitment also demands a low abundance of herring, so if the warming trend were also to lead to increased herring abundance, then the overall effect might be to decrease cod recruitment.

Predation amongst larvae is less well-studied, 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 intra-larval predation. Unfortunately, there are a great many models for possible interactions, and results from multi-species 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 multi-species models for projection. The same may apply to projections incorporating environmental links to single-species recruitment.

To narrow down the range of likely interactions, we need information on processes. There are potentially many sources of biological/physical information that could be useful: diet, spawning times and places, stock sizes, etc. One way to start would be 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 population dynamics; once a plausible set of interactions has been established, empirical data analysis (multi-species 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) was originally presented at the ICES Symposium on *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 potentially 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 realised 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, and
(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 which influence whether 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 and
- 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 emphasised.

4 STOCK-RECRUITMENT MODELS, SIMULATION AND MEDIUM-TERM PROJECTION

Stock-recruitment (S-R) theory generally considers recruitment as parametrically dependent upon stock. S-R analysis consists of looking 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 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 2-dimensions as the level of recruitment versus 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 2-dimensional functional S-R model (c.f. ICES, 1998). This difference might result from not taking due account of temporal effects (O'Brien, 1999b).

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

$$R = f(S; \alpha)$$

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

4.1 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 in an attempt 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 scatter-plot 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, whilst recent work (O'Brien, 1999a) has developed the application of generalized linear models (GLMs).

The RECRUIT program, which is part of the *Aberdeen Suite* (see Section 4.2.2.) and which 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 construct. 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 (c.f. 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 since 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 4.1.1) then a Ricker curve is sensible but if average recruitment stays approximately constant over a wide range of SSB then 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 4.1.2).

Model fitting of a parametric S-R curve must be undertaken with care so as to avoid inappropriate inferences being made and biassed estimation. A flexible and reliable way to fit parametric models is to re-write the S-R model as a generalized linear model (GLM), as intimated 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 (1999a).

The effect that an inappropriate distribution assumption can have on parametric-based estimates of recruitment is best illustrated graphically as in Figures 4.1.1 and 4.1.2. 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 upon the standard assumption of log-normality (both without and with bias correction) and an assumed Gamma distribution which 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 biassed downwards (c.f. McCullagh and Nelder, 1983) so is not to be recommended. Adequacy of the distribution assumption can be diagnosed from a plot of the $\sqrt{|\text{Pearson residual}|}$ against the corresponding fitted value and if an error assumption is appropriate then 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 at this Study Group (see Figures 4.1.1 and 4.1.2).

4.2 Medium-term projection

4.2.1 ICES stock assessments

In order to be an effective and appropriate input to the current regulatory management structure, fishery scientists must be able to characterise, 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 pre-defined biomass reference points.

4.2.2 The WGMTERM projection program

The most widely used method for simulating medium-term projections in the ICES assessment framework is the WGMTERM software and its descendants. This forms part of the *Aberdeen Suite* of programs, developed over a number of years at the FRS Marine Laboratory in Aberdeen to facilitate those aspects of assessments that fall out with the standard historical-reconstruction phase. Full descriptions of these programs are given in Reeves and Cook (1994).

WGMTERM is a simple program to explore the likely response of an assessed population to fixed rates of fishing and natural mortality, given initial population-at-age estimates and an assumed stock-recruitment parametric model. It requires three inputs: an F-multiplier, which is fixed for each simulation run; a sensitivity analysis file (the .SEN file), which is derived from the output of an age-based assessment (e.g. the Lowestoft XSA assessment run) and which contains initial population estimates and their estimated variances, along with such parameters as natural mortality and weights-at-age; and a file of residuals from a stock-recruitment model fit. The latter are obtained from the output of the RECRUIT program, which fits to the historical stock-recruitment scatter-plot a Ricker, Beverton-Holt or Shepherd curve (with log-normal errors assumed and an optional moving average term), or a simple autocorrelation model of lag 1.

Each WGMTERM analysis consists of a number of simulation runs (up to 1000), each projecting the development of the stock over a number of years (up to 10). At the start of each run the vector of initial population sizes is drawn from the distribution of possible sizes determined by the standard deviations given in the .SEN file. The underlying model governing stock size is a standard Baranov age-structured model, in which exponential population decay is determined by the fixed fishing and natural mortality rates. A deterministic value of recruitment for each year in each simulation run is given by the model fitted in the RECRUIT program: to this is added a residual drawn at random from the set of residuals used as an input to WGMTERM. The output from WGMTERM consists of percentiles (generally 10%, 25%, 50%, 75% and 90%) of the obtained distributions of yield, recruitment and SSB from the simulation runs.

As currently implemented, WGMTERM is extremely parsimonious and as a result lacks some of the functionality that such a tool might ideally possess. The *F*-multiplier imposed on the stock is fixed for each analysis, so the program is not suitable for investigating the uncertainty in the application of management actions. Weights-at-age, maturity, natural mortality and selectivity are all assumed fixed and without error, as are the parameters in the fitted stock-recruitment model. In the current version, there is no facility to incorporate any environmental factor that might be considered to be influential. RECRUIT estimates parameters on a log-log scale, the back-transformation to the arithmetic scale introduces a bias of $\exp\{\sigma^2/2\}$, where $\sigma^2 = \text{var}\{\ln R\}$, and this is not corrected for. There is ready scope for improvement in the way that medium-term projections are performed within the context of ICES stock assessment.

4.3 Short-term population and fishery projections for the management of anchovy in the Bay of Biscay

The anchovy spawning population heavily depends upon the strength of the recruitment at age 1 produced every year. This means that the dynamics of the population directly follow those of the recruitment with very small buffer. The fishery mainly exploits the 1 and in a much lesser extent, the 2 year-old anchovies (see Table 4.3.1). Therefore the forecast of the fishery and the population depends on the provision of an estimate of the current year recruitment at age 0 (the year when the assessment is made) which will be the anchovies at age 1 comprising the bulk of the population the next year. The assessment is made with the Integrated Catch at Age (ICA) analysis package (Patterson and Melvin, 1996) which fits a separable model of fishing mortality. That assessment provides an estimate of the recruitment at the last year with catches at age but none information about the current year recruitment other than the geometric mean recruitment. Given the absence of quantitative recruitment surveys, the only information available for the year of the assessment is therefore the one arising from the relationship between the environment and the recruitment of anchovy. 1999 is the first year for which the index of Upwelling in the Bay of Biscay has been used to improve the accuracy of the fishery and population short-term projections. In this year the index has been used for the first time to define the inputs for the projections. The way the index was used can be summarised as follows:

- The upwelling index was not included in the assessment: The index is not an observation of recruitment abundance (as a survey would be) but a calculated environmental index and its reliability as a predictor was re-evaluated after the assessment according from its fitting to the new series of recruitment estimates. The *a priori* basis for a relationship between the upwelling index and anchovy recruitment is not well understood and the form of that relationship is unknown. The form or intensity of a relationships between a certain environmental index and recruitment may change according to different oceanographic regimes. Therefore the *a priori* inclusion of such an index to tune an assessment can mask or artificially increase its relationship with the recruitment. If we admit that any form of the relationship can be subject to process errors, it seems judicious to evaluate the form and the performance of the relationship after an independent assessment of past recruitments has been produced. For these reasons the upwelling index was not included as a tuning index for recruitment in the assessment.

- A model was selected and fitted for the relationship between the Upwelling index and the recruitment estimates from the assessment with standard statistical software. A log-linear model was selected (Figure 3.6.1) among other possible simple linear models.

- The fitted model was used to obtain environmental predicted estimates of recruitment for the year classes that were born in 1998 and 1999, the two most recent and relevant year classes for the population in year 2000. For 1999 no other source of information was available about the strength of that year class, so the model predicted recruitment with its variance was retained. For the year class from 1998 the estimate of recruitment produced by the assessment according to the last year catches at age 0 was as well available. A synthetic estimate from both sources of information was obtained making a weighted average to the inverse of the variance of the assessment and environmental prediction estimates of recruitment. The synthetic estimate of recruitment in 1998 with its variance was then corrected for the fishing and natural mortality experienced during 1998 so as to produce the numbers at age 1 at the beginning of year 1999, which serve as input for the population and fishery projections. The log-variance of these numbers at age 1 was set equal to that of the synthetic estimate at age 0 under the assumption of no error in fishing and natural mortality (fishing mortality is negligible for age 0 and natural mortality is a fixed assumption of the whole assessment). Thus the derivations were as follows:

ESTIMATES of RECRUITMENT (age 0) FOR PROJECTIONS in 1998 and 1999

Year	Source	Non-Log Values	Log Values	Log Standard Error	Log Variance
1998	Assessment ICA output	2963	7.9939	0.9767	0.9540
1998	Upwelling prediction	5394	8.5930	0.4956	0.2457
				Sum of Variance	1.1996
1998	Age0_Synthesis	4774	8.4710	0.4418	0.1954
1999	Age1 in 1999	1434	7.2684	0.4418	0.1954
1999	Age0_Upwelling prediction	4394	8.3880	0.5206	0.2710

No correction was applied for the bias arising from the log-transformation of the original values of recruitment and Upwelling index. The influence of this bias is discussed later on.

- The projections of the anchovy population for 1999 (the year when the assessment is made) and year 2000 (the year for which the advice on management is to be provided) were done the using the IFAP software for deterministic prediction with management catch options and a probabilistic short term forecast provided by the WGFRANS program of Cook (1993). The inputs were the population at age 2 and older calculated by the assessment at the beginning of 1999 along with the estimates for ages 1 and 2 obtained with the aid of the environmental index as explained above.

For comparative purposes during this study group the projections for year 2000 were repeated in two different ways: The first one applying correcting factors for the bias arising from anti-log transformation of the log-recruitment predicted values from the upwelling index by a factor equal to $\exp(\sigma^2/2)$, where σ^2 is the variance of regression of the log-linear model. The second alternative procedure is based on a projection ignoring any auxiliary information from the upwelling index: this is based therefore on the estimates of survivors at first of January 1999 given by the assessment for ages 1 to 5 and setting the recruitment at age 0 in 1999 equal to geometric mean of past years. Table 4.3.2 summarises the different inputs for these alternative projections of the population and table 4.3.3 presents the deterministic forecasts obtained from each procedure. Figure 4.3.1 presents the probabilistic spawning stock biomass projections for 2000 deduced for each set of inputs.

The correction of the bias introduced by the log-transformation of the original scale and its reverse for projections produce an increase of the projected catches and SSB in 2000 of about 8-9%. The omission of the environmental auxiliary information (the upwelling index) strongly modifies the forecast of the population and the fishery in 2000: the population increases by about 70% and the catches would increase in about 45%, depending on the exact amount of the level of fishing mortality. If the inclusion of the environmental variable put the expected SSB in year 2000 below B_{pa} (= 36000 t) for every option, its omission has led the SSB above the B_{pa} in all cases. This is a good example of strong change in the perception of the population due to the inclusion of an environmental auxiliary variable to predict recruitment. This extreme situation arises from the fact that the upwelling index for 2000 was the lowest of the series and so it is predicted the Recruitment at age 0 by it. Thus the contrast with a *normal* projection based on a geometric mean recruitment conditions without making use of the environment is largely increased in comparison with any other situation or scenario. Figure 4.3.1 shows the probabilistic SSB profiles at status quo fishing mortality for year 2000, where the effects of the bias correction factor and of the omission of the environmental information can be readily seen.

In summary, the inclusion of the log-bias correction factor has a moderate effect on the perception of the expected level of the projections (although it should be taken into account in future); whereas the inclusion of the environment has a more potentially deep impact for the short-term projections of this short living species.

4.4 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 (c.f. 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 (c.f. section 4.2.2) but was further modified to enable the inclusion of temperature effects in the stock-recruitment model.

4.4.1 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); namely,

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

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 re-sampling residuals from a fitted model and re-applying them to the predicted value.
3) Where applicable the temperature regime was modelled by randomly re-selecting an annual temperature signal from a portion of the time series.

Temperature was modelled according to the Ricker stock-recruitment relationship (SRR) with the parameterisation:

$$R = \alpha SSB e^{-\beta SSB} e^{\phi T}$$

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

4.4.2 Simulation experiments

Simulations were run during the meeting 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.

Subsequently, a subset of the original simulations were re-run 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; and
- not including a bias correction on the starting population numbers.

Table 4.4.2.1 presents the list of the simulations undertaken.

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

4.4.3 Results

North Sea cod

Figure 4.4.3.1 shows the log-normal bias corrected Ricker stock-recruitment models fitted for North Sea cod, obtained excluding and including a temperature effect.

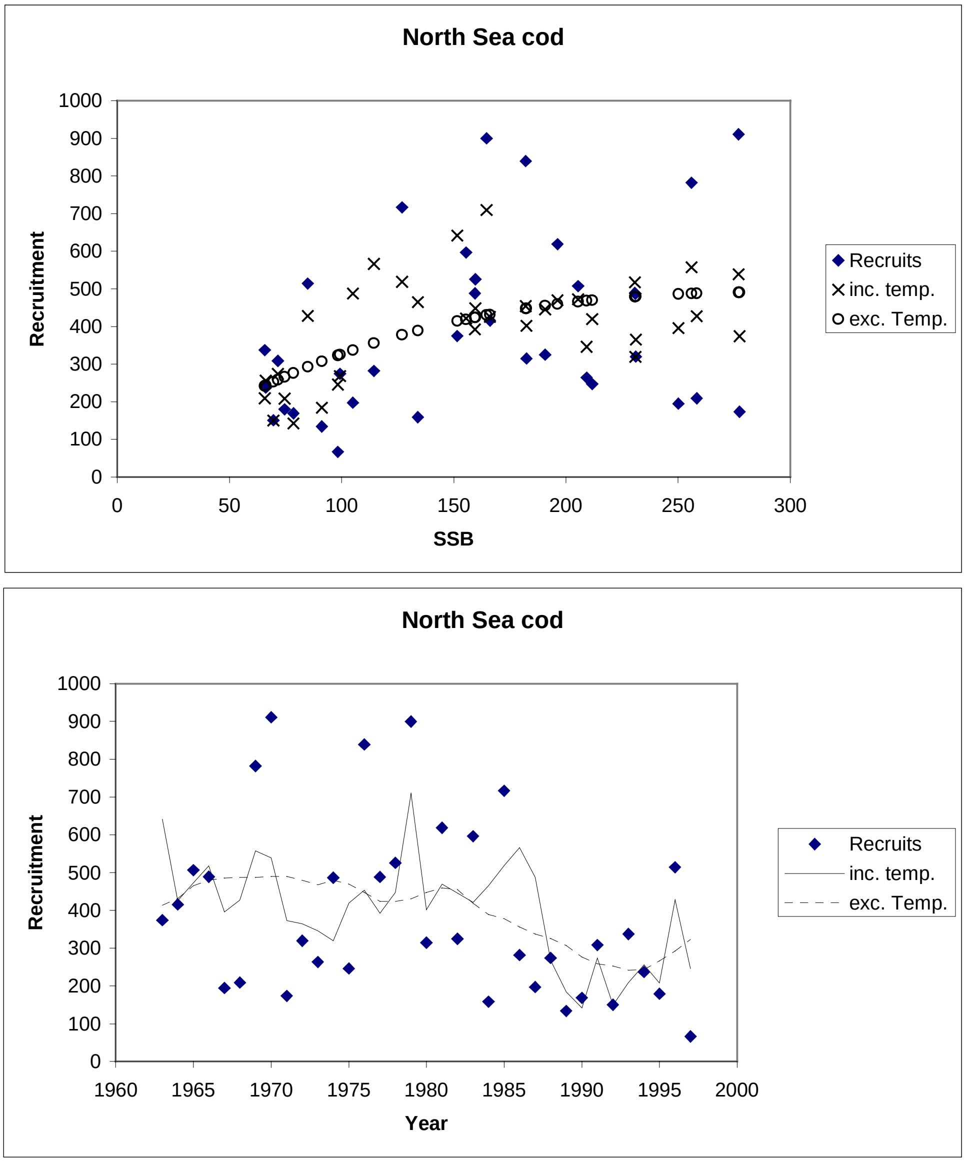


Figure 4.4.3.1: North Sea cod stock-recruitment. In the upper plot, recruitment is plotted against SSB; whilst in the lower plot the recruitment trajectory through time is shown.

The temperatures used for the predicted recruitment values shown in figure 4.4.3.1 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 (see Figure 4.4.3.2).

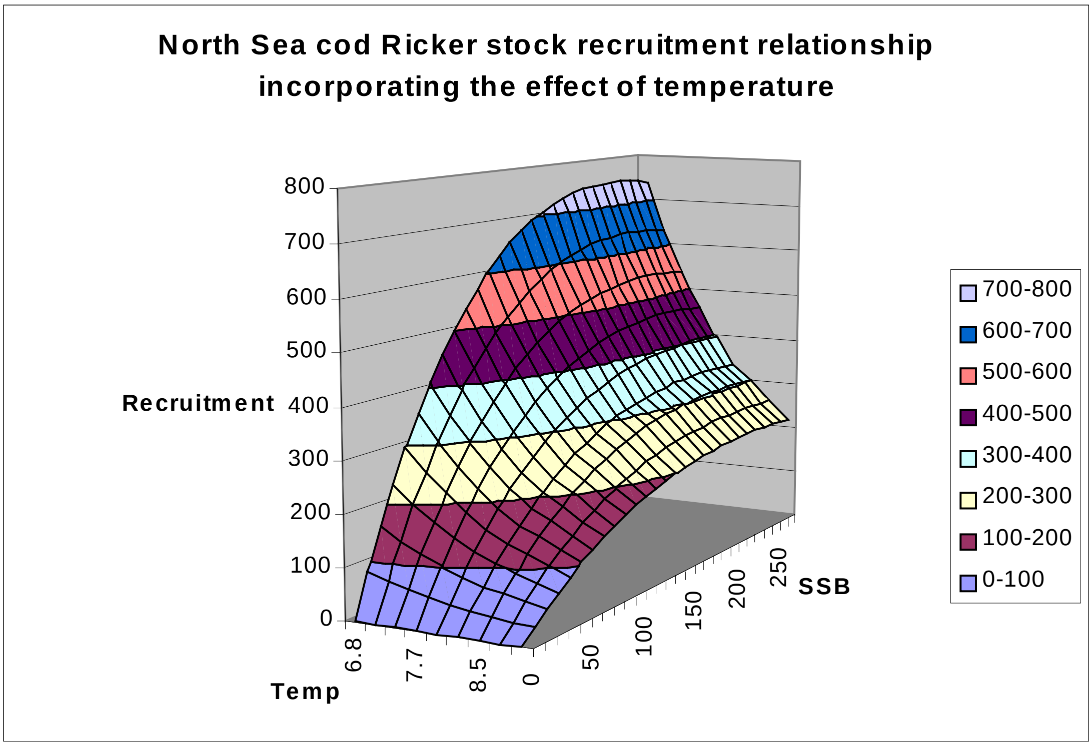


Figure 4.4.3.2: North Sea cod. Ricker stock-recruitment model incorporating the effect of temperature.

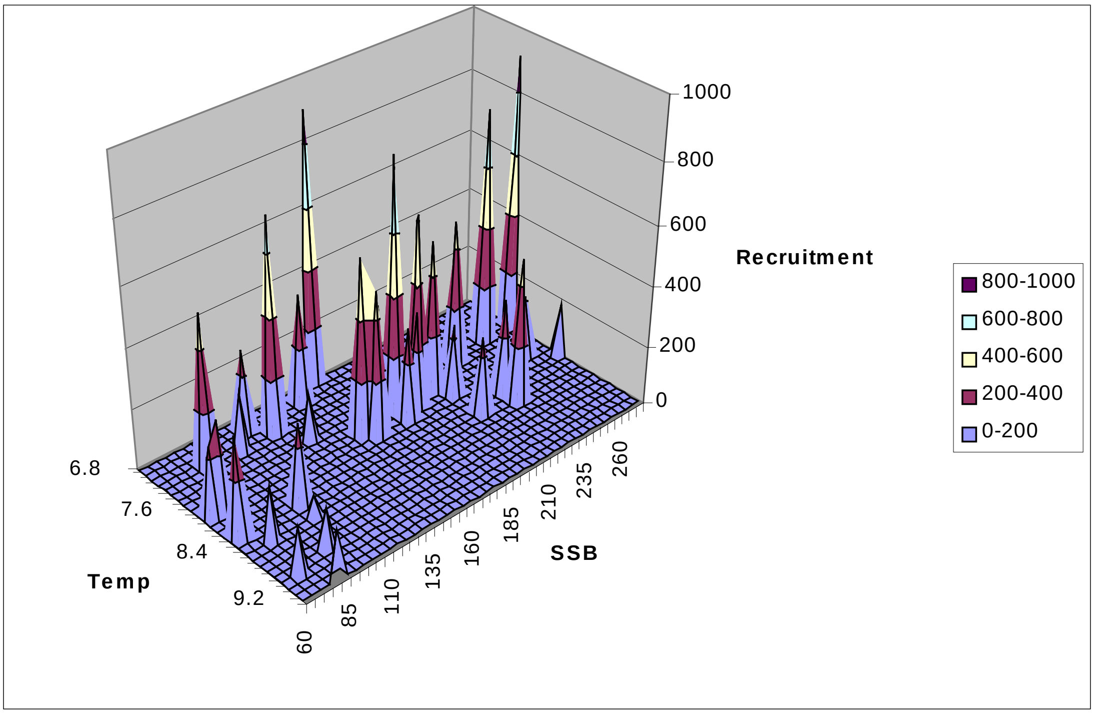


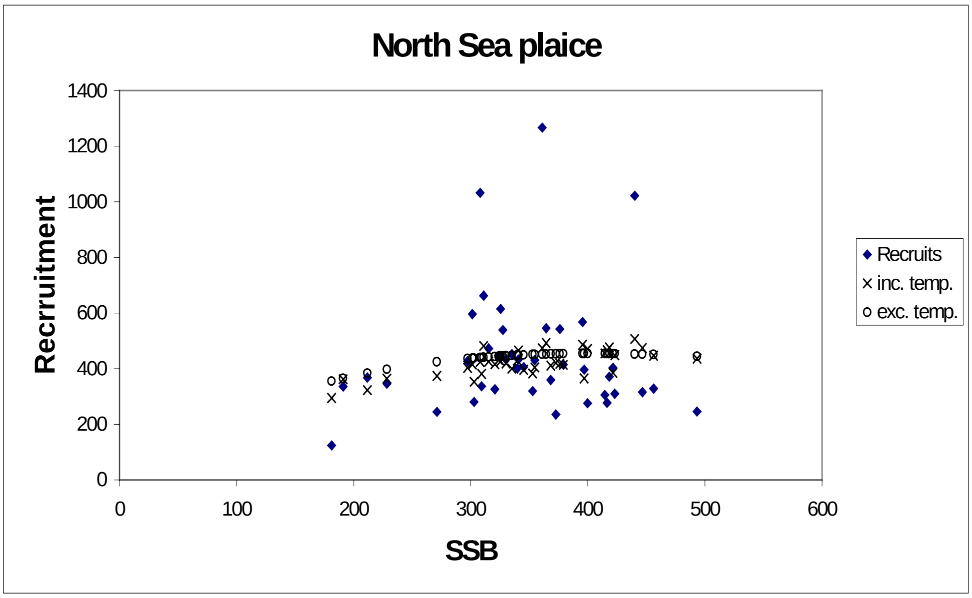
Figure 4.4.3.3: North Sea cod stock-recruitment and temperature data.

The effect of temperature on cod recruitment appears dramatic from the figures 4.4.3.2 and 4.4.3.3. It should be remembered, however, that stock-recruitment data are generally sparse and noisy which poses problems when fitting multi-dimensional 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 4.4.3.3. It can be seen that while 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

Analogous plots to those produced for North Sea cod were produced for North Sea plaice.

Figure 4.4.3.4 shows the log-normal bias corrected Ricker stock-recruitment models fitted for North Sea plaice, obtained excluding and including a temperature effect.



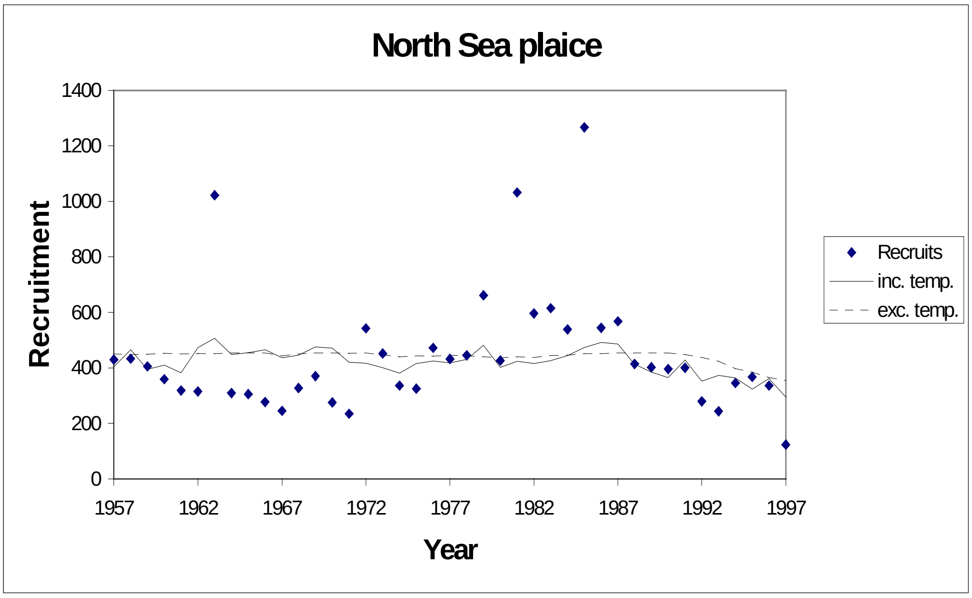


Figure 4.4.3.4: North Sea plaice stock-recruitment. In the upper plot, recruitment is plotted against SSB; whilst in the lower plot the recruitment trajectory through time is shown.

It can be seen in figure 4.4.3.4 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 4.4.3.5) and data (Figure 4.4.3.6) 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 (see Figure 4.4.3.4) and it may be that the Ricker stock-recruiment relationship is not appropriate over some or all of the temperature range. This requires further investigation but has not been considered further due to the shortness of the Study Group.

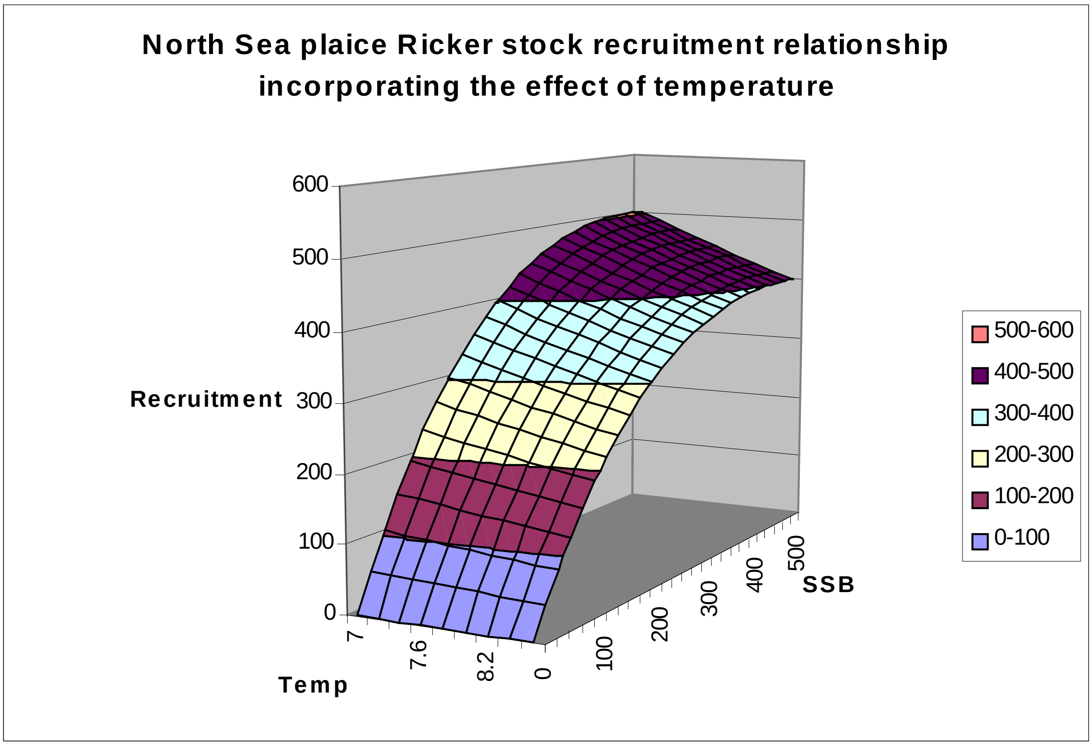


Figure 4.4.3.5: North Sea plaice. Ricker stock-recruitment model including the effect of temperature.

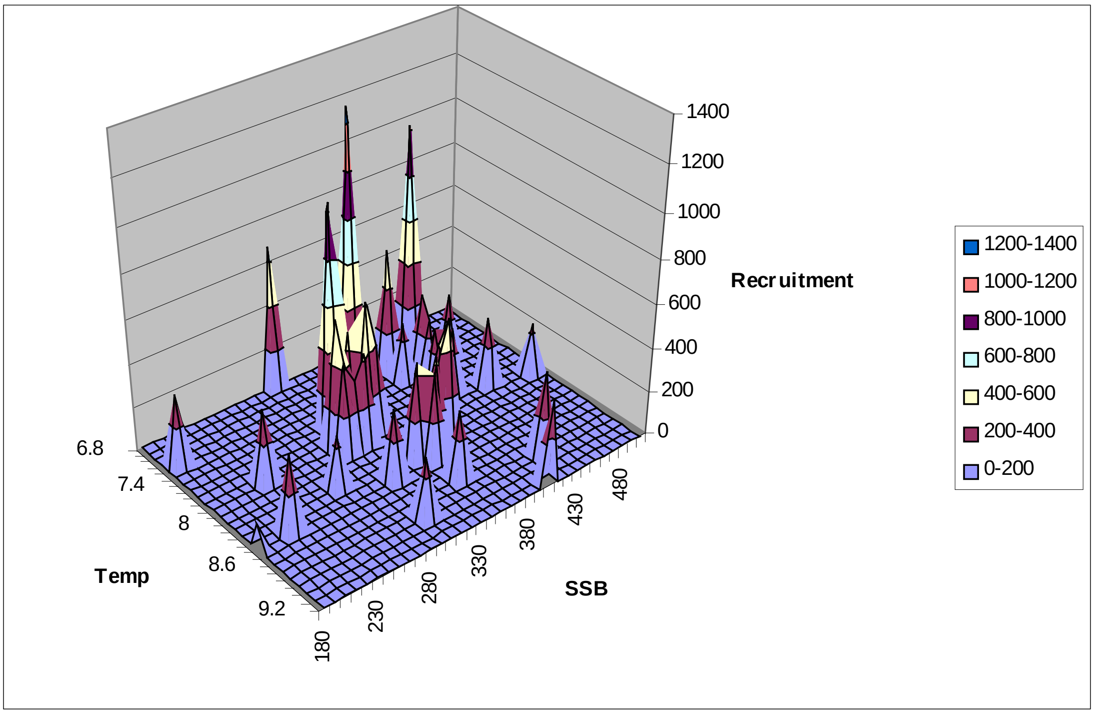


Figure 4.4.3.6: North Sea plaice stock-recruitment and temperature data.

North Sea cod and plaice
Results from the simulations have been summarised in a number of ways:

- A page of four plots, the first showing the observed recruitment and stock recruitment relationship and the other three showing time trajectories of recruitment, yield and SSB expressed as 5th, 10th, 20th, 50th and 95th percentiles. These plots are contained in appendix A for North Sea cod and in appendix B for North Sea plaice.

- A sheet of two plots showing 5th, 10th, 20th, 50th and 95th percentiles of SSB against fishing mortality in the short-term (year 3 - 2001) and the medium-term (year 10 - 2008). The upper (short-term) plot expresses fishing mortality as an F multiplier; whilst the lower plot uses the reference F (Fbar). These plots are contained in appendix C for North Sea cod and in appendix D for North Sea plaice.

- Summary tables 4.4.3.1 and 4.4.3.2 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).

4.4.4 Discussion

The log-normal bias correction to the Ricker stock-recruitment relationship produces expected values of recruitment which are, not surprisingly, higher than the uncorrected values. This correction is additive on the log-scale, multiplicative on the untransformed scale, and amounts to an increase in recruitments of around 15% for North Sea cod and an increase in recruitments of around 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 versus 3 and 11 versus 12 (Tables 4.4.3.1 and 4.4.3.2) 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 mis-estimating 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 4.4.3.1, 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.280kt) 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 stabilise. For plaice, the 5th and 95th percentiles of SSB remain within historical levels throughout all simulations, due 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 mis-estimation of recruitment, whilst 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 to 1.1 for North Sea cod and 0.7 to 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 last 10 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% then environmental effects may have a significant impact.

The final column of tables 4.4.3.1 and 4.4.3.2 indicates the absolute F required for a 10% probability of SSB being at B_{pa} in the final year of the projection. It is noticeable that for North Sea plaice the differences between scenarios are very slight (c. 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 $P(SSB_{10}<B_{pa}) = 0.1$ (c. 0.075 at the extreme) which equates to about 10% of F, but this is still at the limit of assessment and management precision.

4.4.5 Conclusions

The log-normal bias correction significantly increases estimates of recruitment, not surprisingly. Mis-estimation of recruitment has cumulative effects over time in medium-term simulations. Simplistic inclusion of temperature effects into stock-recruitment relationships affected the outcome of medium-term projections, particularly for North Sea cod but rather less so 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, which was robust to the environmental changes simulated.

4.5 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 can be itemised as follows:

- Incorporation of 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 of time-series of residuals to parametric recruitment model fits, and subsequent use of simulated time-series in projections instead of random draws from historical residuals. This would serve to characterise any autocorrelation structure in the historical series, as well as any overall trend in level or variability.

- Implementation of stock-recruitment models mediated by hypothesised environmental influences. Projections of residuals to these models would be accompanied by projections of the environmental time-series. Care would have to be taken before the use of this approach in management, as both a clear linkage between recruitment and the chosen environmental factor *and* a strong time-series signal in the latter would be required (see also section 3.10).

- Allowance 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.

5 GENERAL DISCUSSION PERTINENT TO FISHERY MANAGEMENT

5.1 Potential benefits and drawbacks

There are several ways in which the incorporation of 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 historic 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 over-exploited) stocks that are managed by TAC, since in such cases recruitment may contribute a large proportion to predicted catches. If TACs were to be set for more than one year ahead, then further benefits are likely. For example, if the catch is dominated by three-year olds, then a good prediction of recruits (at age 0) in the current year would have an effect on the catch prediction three years hence.

If multi-annual TACs were to be contemplated, advice would have to be provided for a longer time period based on predictions further into 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 (see section 4.4).

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 essentially be identical (see Section 4.4). 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, and this could lead to a tendency to *sail closer to the wind* (e.g. harvesting at higher Fs), implying more risky 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, see Section 4.4.2). One can evaluate what would happen if the environment returns to historic patterns or persists at recent levels, and base management advice on this information. This type of *what if* or scenario modelling can, of course, 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 hydrographical 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 be due to hydrographical conditions. This is an example where the effect of E may be more like an *on-off* switch rather 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.

There is also the possibility of making Type I or Type II errors (see section 3.1), and this would have implications for management if E is included.

5.2 When to incorporate environmental factors

Evidence of a clear relationship between E and population dynamics may point to 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, come 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 since anchovies are 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 which could in turn 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 (say, recruitment) is not enough on its own to justify inclusion into assessment. At the least, plausible hypotheses for mechanisms are required, and at best some evidence for the hypotheses. There is also a need for some confidence that the detected relationship will persist. These issues are best addressed by studies aimed at identifying one or more likely mechanism. 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 (see section 2.2).

5.3 Ways of incorporating environmental factors

The potential benefits to management (or improved assessment/prediction) are closely related to the way in which environmental factors are incorporated. An E-series can, in principle, 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, then 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, which still need to be resolved.

An index of some environmental condition 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. There are again technical details which need to 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 (see the applications and investigations presented in section 3 for examples) as covariates. If the mechanism is not known, tractable formulations of S-R models with E-terms will tend to be fitted. Different formulations may, however, have different implications, and it may not be possible to distinguish between models on the basis of goodness-of-fit. The recruitment dynamics at low SSB, which is usually outside the range of the data, could be strongly affected.

Improvements in a stock-recruitment model fit when 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, say) 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 E into the future, 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 of this report), there may also be a need to re-evaluate current reference points to ensure that they are compatible with the current and assumed near future environmental conditions. The key here is the assumption about future environmental conditions.

Section 4.4 illustrates how assumptions about the future environmental dynamics can be incorporated in medium-term projections. It is clearly not essential to predict E exactly into the medium-term 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, e.g. in terms of stock conservation or yield, from incorporating E into assessment. One can also explore the implications of:

(a) incorporating E into assessment when there really is NO persistent link, or
(b) ignoring E when there really IS a link between E and, say recruitment.

5.4 Conclusions

Considerations of environmental factors can make quite a big difference to how one might manage a stock. Simulation models can play an important role in helping identify whether and where benefits to management are most likely to accrue and therefore where it would be best to focus attention in terms of other (e.g. process) studies. Results from simulation studies should be used to guide biological studies.

Short-term focused studies aimed at identifying likely mechanisms are also crucial, but results from such studies can only be put to full use with information from longer term observations.

There is also benefit in long-term studies of the environment and underlying processes so that one is prepared if something unexpected happens. For example, if a process study reveals a strong relationship with some environmental variable, then it would be possible to incorporate this immediately if historic data are already available.

The systems we are studying are complex and we therefore need to be careful not to focus too narrowly on a single aspect or species, for example. 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. Firstly, because interactions may be non-linear, and secondly because correlations can be spurious. Correlative studies can, however, 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 are, however, 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.

ICES Stock AssessmentWorking Groups should note the possibly large effects of incorporating the bias correction to 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 (preferred approach).

The ICES Stock Assessment Working Groups should consider reference points in the light of apparent changes in environment. Technical details, particularly regarding implementation (e.g. how to decide WHEN to change from one set of reference points to another) have, however, not yet been resolved.

6 RECOMMENDATIONS

6.1 Possible case studies

Our current perception of the potential benefits of including environment in fish stock assessment is conditioned by our ability to relate environment to population parameters (such as recruitment) but also by the prediction horizon of climate forecasts. The benefits of including environmental signals in stock assessment may extend from short-term to medium-term projections but need to be evaluated in the context of specific stocks reflecting the interests of the whole ICES Area.

Many of the suggested stocks for consideration are based partly on the preliminary results of the FAIR-project CT 97-3805 (*Concerted Action*): Sustainable fisheries – how can the scientific basis for fish stock assessments and predictions be improved? (SAP), funded by the European Commission. The emphasis should be placed on species where there are multiple stocks in order to provide a basis for contrast and provide an opportunity to conduct comparative analyses of the mechanisms of environmental relationships.

The Study Group suggests that the stocks identified are:

Cod	Barents Sea Iceland North Sea Baltic Irish Sea Celtic Sea
Capelin	Barents Sea Iceland
Herring	North Sea Atlanto-Scandian Baltic
Sprat	Baltic
Anchovy	(Biscay) Iberian Peninsula Western Mediterranean Adriatic (Central Mediterranean)
Sardine	Iberian Peninsula Adriatic (Central Mediterranean)
Hake	Western Mediterranean Iberian Peninsula
Plaice	North Sea Irish Sea Celtic Sea Channel (East, West)
Sole	North Sea Irish Sea Celtic Sea

6.2 Future work and terms of reference

The Study Group meet for 4 days in late January 2001 (Chair: Dr C. O’Brien, UK) in Lowestoft, UK to:

1. Investigate and evaluate medium-term projection methodology for use in fishery assessment, taking account of characterisations (in space/time) of historical patterns in recruitment and the environment for specific case studies (cod and anchovy).

2. Incorporate realistic variability in the parameters of management simulation models and evaluate more fully the potential of environmental studies to impact on management procedures.

3. To investigate the variability and predictability of environmental conditions known or supposed to affect the dynamics of fish populations.

7 BACKGROUND MATERIAL PRESENTED TO THE STUDY GROUP

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9 FIGURES

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10 TABLES

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APPENDIX A: Output of medium-term projection simulation experiments for North Sea cod

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APPENDIX B: Medium-term SSB probability profiles for North Sea cod

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APPENDIX C: Output of medium-term projection simulation experiments for North Sea plaice

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APPENDIX D: Medium-term SSB probability profiles for North Sea plaice

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