

On the prediction of short term changes in the recruitment of North Sea cod (*Gadus morhua*) using statistical temperature forecasts*

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SUMMARY: Empirical evidence supports the hypothesis of a general relationship between sea temperature and recruitment of cod stocks across the North Atlantic, as well as between recruitment and the size of the spawning population. In the North Sea, cod year-class strength is inversely related to sea surface temperature during the first half of the year. This stock is currently at a low level, and the future trajectory of the stock biomass will be strongly influenced by recruitment levels. In the present study we investigate the possible use of observed and modelled sea surface temperature (SST) to increase the accuracy and/or time horizon of recruitment forecasts for this stock. We show that the statistical model developed for forecasting spring temperature has good skill (35% skill, with a standard error of 0.36°C) when predictions are made in late January. Within the frame of the current fish stock assessment working group we incorporate SST observations and January forecasts and simulate short-term recruitment projections. The resulting model accounts for a greater fraction of the variance in recruitment (42%) than that obtained without temperature (17%). In operational mode, the model allows forecasting 1.5 years in advance but the accuracy of predicted recruitment remains low. This example indicates that we have not yet reached a point where environmental information can be used with great benefit for the management of North Sea cod. However, a similar strategy may yield greater benefits if developed for other stocks for which environmental effects are better understood and/or account for a larger fraction of the variability in recruitment, for species with a shorter generation time and species for which recruitment forecast is critical to management (e.g. anchovy), and in areas where environmental prediction capabilities may be greater either in accuracy or in lead time.

Key words: North Sea, cod recruitment, sea surface temperature, statistical forecasting.

INTRODUCTION

Most fish stocks in the NE Atlantic are managed through the setting of annual catch quotas. Stock assessments are undertaken using sequential population analyses (SPA) which are used to reconstruct historical changes in the population. Projections about the future trajectory of the stock are based

upon analyses of the reconstructed relationship between recruitment and spawning stock biomass and upon recent trends in recruitment. For management, both short (1-2 years ahead) and medium-term (5-10 years ahead) projections are required. Short-term projections are based upon fitted stock-recruit relationships, recent recruitment trends and survey based estimates of recruitment. Medium-term projections are based upon fitted stock-recruit relationships and recent trends in recruitment. Stock-recruit relationships such as those of Ricker (Ricker, 1958)

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or Beverton-Holt (Beverton and Holt, 1957) are typically fitted to SPA-based population reconstructions using a variety of regression approaches (Quinn and Deriso, 1999). For many stocks, these relationships only explain a small fraction of the variance. In order to improve model fit, attempts have been made to incorporate environmental variables (see e.g. Svendsen *et al.*, 1995). This approach has been strongly criticised for several reasons. The main problems are failure to apply rigorous statistical methods in selecting suitable environmental covariates, failure to account for autocorrelation in the time-series, overfitting and the identification of spurious correlations which break down unexpectedly (Hilborn and Walters, 1992). A number of statistical techniques are available to deal with autocorrelation although they tend to reduce the test power (Drinkwater and Myers, 1987). The risks of overfitting can be reduced by care with exploratory correlation analyses and applying corrections to threshold probabilities for multiple comparisons, whilst the identification of spurious correlations can be tackled by re-analysis as additional data becomes available (Carscadden *et al.*, 2000). For most North Sea stocks, it is only recently that sufficient additional years of data have become available to allow re-analysis of previously identified relationships (see for example van der Veer, 1999).

Based upon such re-analyses, a consensus appears to be emerging that environment-recruitment links for stocks at the peripheries of their geographical range tend to be more stable than those for mid-range (Myers, 1998). This makes ecological sense since stocks at the geographical limits will be more likely to encounter environmental conditions outside their optimum range (Frank, 1991). The argument for including environment in assessments is clearly strengthened if the mechanistic links are understood. Such understanding improves confidence in the underlying relationship and may allow the identification of circumstances in which the correlation could break down. However, uncovering the ecological mechanisms underlying environment-recruitment correlations has proven extremely difficult. It may therefore be worth evaluating the potential benefits of incorporating environmental data into assessments even if the exact mechanistic links are not fully understood.

Several studies have suggested links between sea temperature and recruitment for various marine species (Dickson *et al.*, 1974; Ottersen and Sundby, 1995; Rutherford and Houde, 1995; Henderson and

Corps, 1997; Planque and Fox, 1998; Quinn and Deriso, 1999; van der Veer and Witte, 1999; Fox *et al.*, 2000). Considering cod in the North Atlantic, Planque and Frédou (1999) showed that recruitment success was associated with warmer conditions for stocks at the northern edge of the range and with colder conditions for those at the southern edge of their range. The North Sea cod belongs to the latter category and an inverse relationship between sea surface temperature and recruitment is evident for this stock (Planque and Frédou, 1999). A number of mechanisms have been postulated, although none have been thoroughly investigated (Ponomarenko, 1973; Ottersen and Sundby, 1995; Anderson and Gregory, 2000; Ottersen and Loeng, 2000; Sundby, 2000). Although it is not known whether temperature is acting directly or as a proxy for other drivers, the impact of sea temperature on cod recruitment appears to be a robust statistical observation. Since sea temperature data are readily obtainable, this relationship might be incorporated into assessment procedures. However, to be useful for projections, data on the environmental variable itself must be available at the time the stock assessment is undertaken or it must be possible to forecast it (Walters and Collie, 1988). In this paper we examine whether it is possible to forecast cod recruitment in the North Sea based upon spawning stock biomass and sea temperature and how such forecasting could be incorporated into assessment working group practice. By doing so our objective is to address the second of the two objectives of the SAP concerted action: increasing the time horizon of stock prediction.

DATA

Sea surface temperature (SST) data for the North Sea came from the NCEP/NCAR re-analysis project (Kalnay *et al.*, 1996). SST data are provided globally at monthly intervals with a spatial resolution of 2.5° latitude by 2.5° longitude and have been utilised from 1950 up to the present. The North Sea was defined as the region bounded by the limits 2.5°W-10°E, 50.0°N-62.5°N. Biological data were obtained from ICES (International Council for the Exploration of the Sea) working group documents covering the period 1985 to 2000 (Anonymous, 1985, 1986, 1987, 1988, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001). The recruitment time series derived from the latest

assessment (Anonymous, 2001) was used as the reference against which recruitment predictions were compared. Spawning stock biomass was also taken from the ICES Working Group reports. We also used recruitment estimates based upon young fish surveys (0-group and 1-group), as reported in the working group documents. This information started to be utilised after 1988, when the international young fish surveys (IYFS) database became fully operational (Anonymous, 1988). Since then, the working group has provided IYFS-derived recruitment indices each year. Each index is derived by combining survey results and weighting to the average recruitment through a procedure named RCRTINX2 (and later termed RCT2 and RCT3). In this procedure, survey-based indices reported in the working group documents are constrained by historical recruitment estimates available at the time and are not fully independent from the fisheries data, i.e. they are relative recruitment indices rather than absolute ones.

METHODS

SST forecast

There are two major approaches to forecasting sea temperatures. The first is based on hydrodynamic models and the second on statistical models. Although hydrodynamic models should in theory provide more accurate predictions (because they incorporate representations of the physical processes generating variability in SST), statistical models have up to now performed better in terms of prediction accuracy (Saunders *et al.*, submitted). This is particularly true when the prediction horizon exceeds a few weeks. The model used in the present study is termed UCL1 (University College London 1) and belongs to the statistical category. UCL1 builds on features of the ENSO-CLIPER statistical prediction scheme (Knaff and Landsea, 1997), which has been successfully applied in forecasting the state of the ENSO (El Niño Southern Oscillation) phenomenon in the Pacific Ocean. UCL1 is a linear multiple regression model which uses a robust search procedure to identify statistically significant and stable SST predictors from around the globe. These predictors may be either 1-, 3-, or 5-month mean initial conditions or trends, and the 1-, 3-, or 5-month mean persistence of the predictand. The firm separation of training and forecast periods is funda-

mental to the UCL1 scheme. This distinction ensures that hindcasts are always applied to independent data, thus making the model skill the true forecast skill (a ‘hindcast’ is a retrospective forecast issued by a model based on information available at a prior time). There is a degree of persistence in the SST signal in the North Sea (Planque and Frédo, 1999) and recent studies have demonstrated the existence of teleconnections between the North Sea and remote regions of the world ocean (Dong *et al.*, 2000), so a global search persistence model is appropriate for the North Sea. A detailed description of the UCL1 model methodology is given in Saunders *et al.* (submitted). We have used the model to examine the predictability of North Sea SST anomalies averaged over the period February-June out to several months in advance. The mean anomaly for the 5-month period is used and is calculated with reference to the climatology period 1961-90. We employed an initial training period of 1950-1985, leaving 1986-2000 (15 years) for model forecast assessment. The training period increases one year at a time as each forecast is made. The UCL1 model skill is quantified using the RMSE_{CL} skill (%) metric defined as the percentage reduction in root-mean-square-error over what one would obtain from climatology forecasts (Wilks, 1995). This is a robust skill score which is immune to the bias problems associated with the Percentage of Variance Explained and other skill measures. A positive RMSE_{CL} skill (%) indicates that the forecasts are out-performing climatology, while a negative RMSE_{CL} skill (%) indicates that the forecasts are worse than climatology.

Recruitment nowcast/forecast

To predict recruitment using observed or forecast SST, we have used the derived version of the Ricker equation, proposed in Stocker *et al.* (1985):

$$\hat{R}(t+1) = SSB(t) \cdot e^{(\alpha - \beta \cdot SSB(t))} \cdot e^{(\psi \cdot SST(t))} \quad (1)$$

where \hat{R} , SSB and T are respectively recruitment estimate, spawning stock biomass and temperature and α , β , and ψ are the associated coefficients. For cod, recruitment is measured as the number of fish of age 1 and is notated as $R(t+1)$, whereas SSB and SST are given for year t , i.e. the year of birth of the recruits. The model was initially fitted to the longest series of data available to assess its ability to reproduce historical changes in recruitment.

To undertake a nowcast or forecast of recruitment for a given year, we fitted the same model using only the information available to the working group at that time, that is from 1963 to two years prior to the WG meeting date (as recruitment estimates for the last years are considered potentially unstable by the WG). However, to undertake a nowcast or forecast of recruitment, an estimate of current *SSB* is required. For the year of WG meeting, this is not available. Instead, we used *SSB* at $t-2$. This value is considered as a good proxy for *SSB* at t or $t+1$, since the autocorrelation at lag 1 and 2 in the time-series of *SSB* is high (> 0.8).

Integration into the WG procedure

At present, the ICES WG on the assessment of demersal stocks in the North Sea and Skagerrak meets every year in October. The working group, which reports on the state of North Sea cod evaluates the state of stock using fisheries statistics (mainly catch-at-age) and independent survey data (International Bottom Trawl Surveys and International Young Fish Surveys). From the latter data, the group derives estimates of recruitment for the current year (based on 1-group surveys) and one year in advance (based on 0-group surveys). We have simulated the procedure by which the working group could derive additional estimates of recruitment for coming years, using observed and forecast SST and *SSB*. Observed sea temperature for the period February-June in the year of the meeting was used to produce estimates of numbers of recruits at age 1 which will appear the following year. We have termed this estimation 'nowcast', as it is contemporary to the estimate presently produced by the working group from the 0-group surveys. By October of the year of the WG meeting, an SST forecast for the following February-June is not available (see result section below). The earliest the forecast can be produced is late January (lag-0) or late December (lag-1). Here, we have selected lag-0 which produces the best available forecast to produce a recruitment forecast 1.5 years in advance. We termed this recruitment estimate 'forecast', since at the time of its calculation there is no other index of recruitment available that far in advance. Up to 1989, the WG did not meet in autumn but in the springtime. As a result, the nowcasting could not be done for the year of the meeting (since at that time the SST for February-June was still unknown) but only for the previous year. This resulted in one year with no nowcasting estimate at the

time of transition between the spring and autumn working group meetings (1989). Because of the limited number of years in which it was possible to compare the nowcast and forecast recruitment estimates with those from the groundfish surveys, it was not possible to perform a formal objective evaluation of the skill of the recruitment model.

RESULTS

SST forecast model

The hindcast predictability of the February-June North Sea SST anomaly for the period 1986-2000 was examined for different monthly lead times ranging from zero months (the prediction is given at the beginning of the period February-June) up to 12 months (the prediction is given a year in advance). We found the model has skill at 0-month lead and at 1-month lead but possesses no skill at longer leads.

The $RMSE_{CL}$ skill at 0-month lead is 35% and at 1-month lead it is 9%, these skills being relative to the 1961-90 climatology. For comparison the skill based on variance explained is 59% at 0-month lead and 16% at 1-month lead. The stable predictor used at 0-month lead is the 1-month mean initial condition of the predictand region itself. The skill from predictor persistence at 0-month lead is 31%. Stable initial condition and trend predictors are not found elsewhere in either the North Atlantic or global SST fields. The results for zero lag are presented in Figure 1. This shows that the model reproduces adequately the year-to-year variations in SST as well as the overall amplitude in the SST signal. The forecast

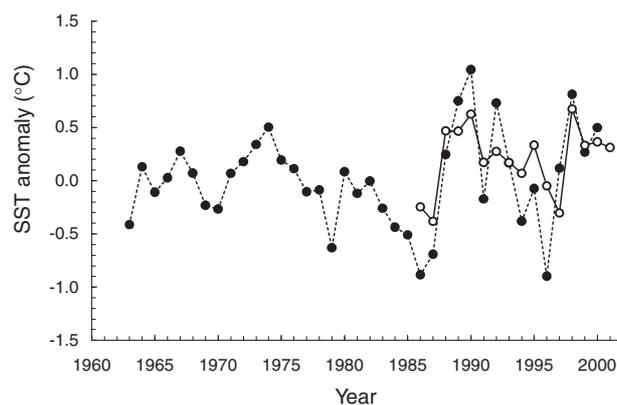


FIG. 1. – Comparison of observed (dotted line) and forecast (plain line) sea surface temperature anomalies for the North Sea. The geographic area covered is 2.5°W-10°E and 50.0°N-62.5°N. The observed anomalies are from the NCEP/NCAR re-analysis dataset and are averaged over the period February to June. Forecasts are given with 0-month lead (at the end of January).

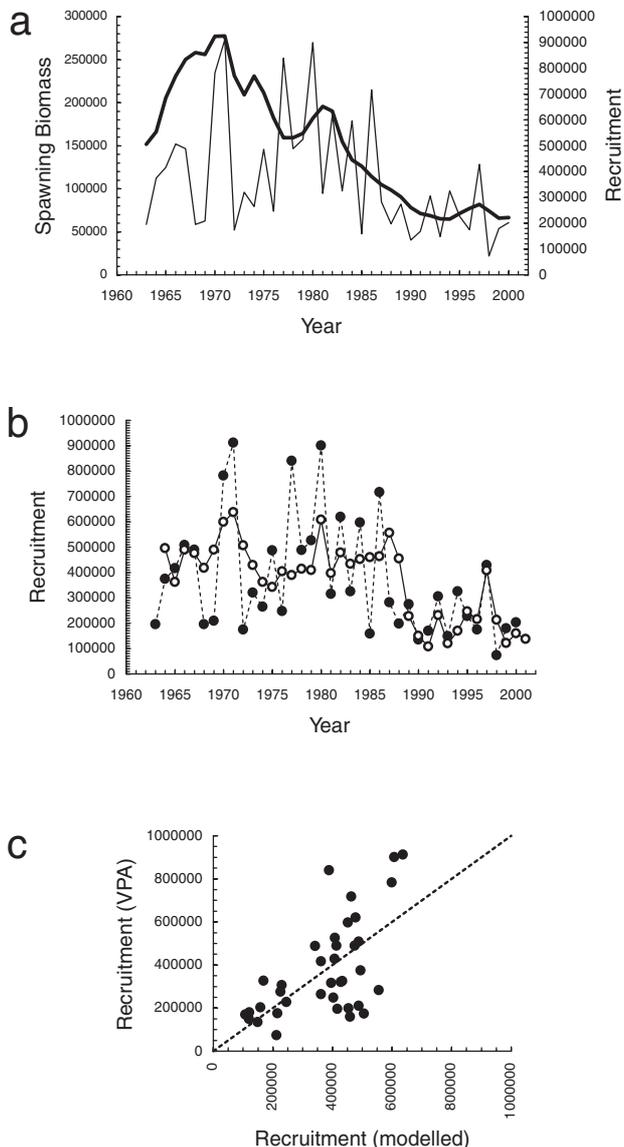


FIG. 2. – **a.** Recruitment (thin line, 1000s of recruits at age 1) and spawning stock biomass (heavy line, in tons) time series for North Sea cod from the latest ICES assessment WG (Anonymous, 2001) **b.** Recruitment (dotted line, closed circles) and the fit of the SSB-SST model (plain line, open circles) based on all data available in year 2000. **c.** VPA derived recruitment values against fitted recruitment values.

standard error at 0-month lead is 0.36°C . This error is 40% less than the standard deviation (0.60°C) of the raw 1986-2000 data.

Fit of the SSB-SST-Recruitment model

The modelled recruitment derived from the Ricker-SST model (eq. 1) fitted to the full time series is shown in Figure 2. The model accounts for 42% of the variance of the recruitment series, which is a significantly larger fraction of the variance than the 17% obtained when SSB alone is used (Standard

Ricker). The recruitment time-series derived from the latest VPA (and used as a reference) shows a marked change in recruitment in the mid-1980s. After 1986, the mean and the variance of recruitment is much lower than had been observed in the earlier period. The general trend in the decline of recruitment in the mid-1980s is reproduced well by the model although the timing of the transition is not. The inter-annual variations in recruitment are better represented towards the end of the series (from the end of the 1980s) when the recruitment levels are low.

Survey derived recruitment indices

The survey of 1-group cod in the North Sea provides a recruitment index for the year in which the assessment working group is meeting. This index is closely related to the subsequent recruitment estimate derived from the VPA (Fig. 3). For recent years this is to be expected, since the VPA estimate is heavily weighted by recent survey estimates. Since fishing pressure on North sea cod is high, the conventional VPA equations converge rapidly and the survey indices have little influence on the time-series of estimates excluding the most recent years (Cook, 1997). Considering the period prior to 1995, the 1-group survey index is still close to the VPA estimate, although a bias appears to be present. The 0-group index shows much greater variability than the 1-group index although in most cases the sign of the change in the number of recruits from year-to-year (i.e. increase or decrease) are indicated accurately. It should be noted that the procedure used to

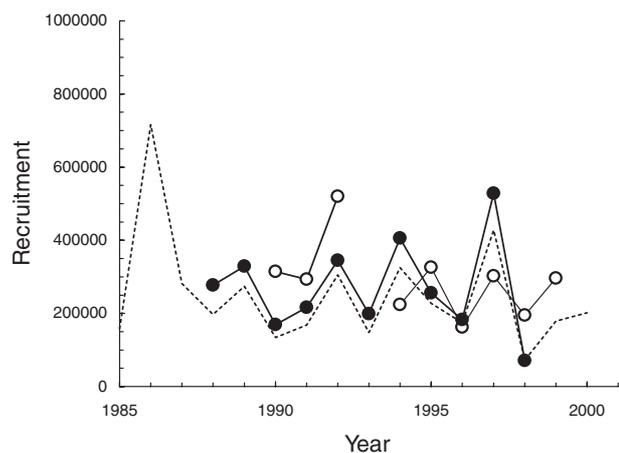


FIG. 3. – Time series of recruitment of North Sea cod reconstructed from the most recent VPA (dotted line) and time series of recruitment indices derived from the International Young Fish Surveys (IYFS) for 0-group (plain line, open circles) and 1-group (plain line, closed circles).

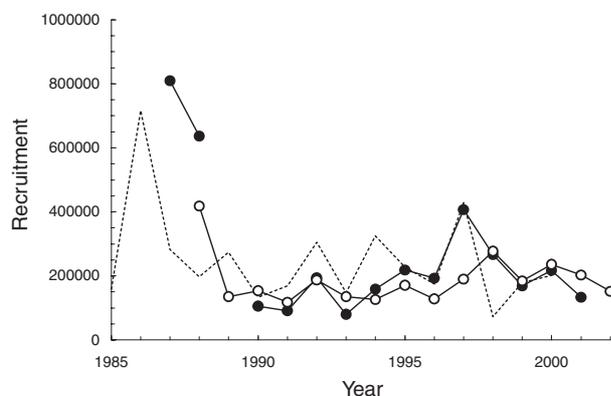


FIG. 4. – Comparison of the time series of recruitment of North Sea cod taken from the most recent VPA (dotted line), recruitment ‘nowcasting’ based on the Ricker SSB-SST model using SST observations (plain line, closed circles) and recruitment ‘forecasting’ using zero month lead SST forecasts (plain, open circles). Nowcasts and forecasts are produced respectively in October and January of the year preceding recruitment at age 1. For each year, the model was fitted and recruitment predictions generated using only the information available to the assessment working group at that time.

derive recruitment indices from the young-fish surveys includes a shrinkage step so that the variability of the raw survey-derived indices is reduced in the index reported in the Working Group reports.

SST derived recruitment indices

We have generated SST-SSB based recruitment estimates for 1987 onwards, with a gap in 1989 (nowcast) due to the change in the date of the working group meeting in that year (Fig. 4). After 1990, the two series provide recruitment indices within the range of the recruitment derived from the latest VPA. From 1987 to 1990, the recruitment estimates are distinct from those derived from the VPA. In these early years, the parameters of the model were estimated based upon observations from previous years when recruitment and SSB were systematically greater (see Fig 2). The period 1987-1990 appears as a transition period and is not well captured by the model. The relative changes in the number of recruits from year to year (i.e. increase or decrease) are well captured by the nowcast estimates (the sign of the change is correct 8/11 times) but not by the forecast estimates (the sign of the change is correct 5/12 times).

DISCUSSION

Cook (1997) compared groundfish survey results with VPA reconstruction for North sea cod and concluded that the 1-group survey was a reliable predic-

tor of trends in recruitment. Despite the noise present in the survey data, they appear to provide the most reliable estimate of future recruitment (Anderson and Gregory, 2000). Estimates of 0-group abundance from the North Sea surveys appear less informative. This is related to problems of gear selectivity and possibly sampling of juvenile fish utilising habitat refuges (Gregory and Anderson, 1997). Indices of recruitment derived from environmental signals are highly unlikely to provide more accurate estimates than surveys. On the other hand, they can be generated up to 1.5 years in advance of survey results becoming available and therefore constitute an improvement in the lead time with which recruitment predictions can be obtained.

In the present recruitment model (Eq. 1) the year-to-year variability in recruitment is mostly driven by the fluctuations in the environment whilst the long-term decline in the number of recruits is related to the decrease in SSB. In addition, this model implicitly assumes that SSB is a reasonable proxy for the spawning potential of North Sea cod, but this may not be the case as suggested for other stocks (Marshall *et al.*, 1998). The model also implicitly assumes that SSB is measured exactly, which may also be incorrect. This, combined with the fact that SSB two years prior is used as a proxy for current SSB in the recruitment model, may explain the failure of the model to reproduce the transition in recruitment which occurred around 1990. Alternatively, the fall in recruitment during this period may have been triggered by other factors not taken into account here.

Temperature affects most aspects of biology at the individual level, e.g. metabolic rates, growth rates, swimming rates, oxygen consumption and spawning (Brown *et al.*, 1989; Blaxter, 1992; Hutchings and Myers, 1994; Brander, 1995; Rideout *et al.*, 2000), and at the community level, e.g. geographical distributions and predation rates (Heessen and Daan, 1994; Ottersen *et al.*, 1998; van der Veer and Witte, 1999). Given the multiple influences of temperature on biological processes, it may prove difficult to demonstrate clear underlying mechanisms, so one might need to be prepared to use such relationships for management purposes, even if there is not a full understanding of the underpinning mechanisms. Environmental information may be included in both medium and short-term predictions. The incorporation of environmental scenarios into medium-term projections is considered in papers presented elsewhere in this symposium (e.g. Needle *et al.*, 2003).

In the present paper we have dealt with the short-term projection based on environmental forecasts rather than scenarios. This approach allows for prediction of recruitment up to 1.5 years in the future. However, forecasts of recruitment did not appear to be very reliable when compared with recruitment subsequently reconstructed from VPA although there is only sufficient data at present to allow comparison over a limited number of years. Unreliability is related to the fact that the SST forecast skill at zero month lead is only 35% (RMSE_{CL} skill measure) or 59% of the variance. In addition, the underlying SST-SSB-recruitment model still only captures <50% of the variance in recruitment. Improvements in forecasting recruitment of North Sea cod will require improved forecasting of SST, improved understanding of the links between recruitment and spawning potential and improved understanding of the links between recruitment and environment. Results from nowcasting appeared to be more reliable and could be implemented in current assessments relatively cheaply. Such examples of environmentally based operational management advice already exist for other stocks (e.g. walleye pollack, see <http://www.pmel.noaa.gov/foci/forecast/index.html>).

Considering impacts upon short-term management decisions, Basson (1999) considered that this approach would not provide substantial gain in terms of yield or conservation, since weak predictions based upon environmental correlations would be subsequently overwhelmed by more up-to-date fisheries survey data. This is clearly a correct conclusion based upon current management practices, which is concerned with short-term yield prediction. However, our results show that the use of forecasting and nowcasting techniques can be used to extend the time horizon of recruitment prediction potentially allowing an increased time horizon for implementing management action. The example presented here clearly indicates that we have not yet reached a point where environmental information, in the form of SST, can be used with great benefit to the management of North Sea cod. This does not preclude developing the approach suggested here to other stocks for which environmental effects are better understood and/or account for a larger fraction of the variability in recruitment, to species with shorter generation time for which recruitment forecast is critical to management (e.g. anchovy) and to areas where environmental prediction capabilities may be greater either in accuracy or in lead time. We believe

it would be worthwhile to extend the approach suggested herein to examine the benefits to fish stock recruitment in other North Atlantic regions where interannual SST variability is correlated with stocks and where SST predictability may be higher than in the North Sea. These regions might include West Greenland, the Celtic Sea and the Barents Sea. It would also be beneficial to examine the SST prediction skill using a range of models.

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