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Implications of climate change for the management of North Sea cod (*Gadus morhua*)

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Robustness of both short-term stock biomass recovery and longer-term sustainable management strategies to different plausible climatic change scenarios were evaluated for North Sea cod (*Gadus morhua*), where climate was assumed to impact growth and recruitment. In the short term, climate change had little effect on stock recovery, which depends instead upon reducing fishing effort to allow existing year classes to survive to maturity. In the longer term, climate change has greater effects on stock status, but higher yields and biomass can be expected if fishing mortality is reduced. Incorporating environmental covariates in stock assessment predictions will not achieve sustainable resource use. The implications of climate change for biological reference points depend upon the mechanism through which temperature acts on recruitment, i.e. on juvenile survival or carrying capacity. It is not possible to distinguish between these processes with stock assessment data sets alone. However, this study indicates that reference points based on fishing mortality appear more robust to uncertainty than those based on biomass. Ideally, simpler management procedures are required that meet pre-agreed management objectives and are robust to uncertainty about the true dynamics.

Keywords: climate change, cod, evaluation, *Gadus morhua*, harvest control rules, management, recovery plans, simulation.

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Introduction

Mean annual sea surface temperature in the North Sea is projected to increase by more than 1 °C by 2040 (HadCM3 model – see acknowledgements; Gordon *et al.*, 2000; Pope *et al.*, 2000), and poikilotherms such as cod (*Gadus morhua*) are likely to be affected through their metabolic rates and life history processes (Brett, 1979). For example, Brander (2000) found that weight-at-age of North Sea cod in the first year of life was strongly influenced by temperature, a statement confirmed by Björnsson and Steinarsson (2002), who examined the food-unlimited growth rate of Atlantic cod under laboratory conditions. Climate change may also affect juvenile recruitment, and various hypotheses for the processes have been put forward. The most commonly proposed scenario is that temperature affects juvenile survival (Stocker *et al.*, 1985; Planque and Frédou, 1999; Clark *et al.*, 2003) through a Ricker stock-recruitment relationship, with temperature affecting the α parameter. A less commonly considered alternative, however, is that temperature may limit the available habitat (Fromentin *et al.*, 2001) and hence the carrying capacity. Within the Ricker stock-recruitment relationship, this is determined by β.

The International Council for the Exploration of the Sea (ICES) provides scientific advice to ensure that spawning-stock biomass (SSB) remains above a threshold where recruitment may be impaired and fishing mortality remains below a threshold level that would drive the stock below the biomass threshold (i.e. B_{lim} and F_{lim} for the biomass limits and fishing mortality, respectively). In recognition of the uncertainties in stock estimates and in an attempt to apply the precautionary approach, precautionary reference points (i.e. pa-values, F_{pa} and B_{pa}) have also been defined, which trigger management action before the thresholds are reached. The two hypothesized mechanisms for the response of North Sea cod to climate change would be expected to have different consequences for the productivity of the stock and hence have implications for safe biological limits to exploitation and management advice.

In order to take account of the effects of climate change, some have attempted to add increased complexity to the assessment process by incorporating environmental data within stock projections (e.g. Planque *et al.*, 2003), an exercise whose results are driven mainly by the recruitment assumption. However, improving estimates of North Sea cod recruitment for use within short-term projections is unlikely to have much benefit in conserving the North Sea cod stock or for setting quotas since 1-year olds contribute very little to landings. Moreover, North Sea cod fully mature at age 6, so management should be based upon conserving recruiting age classes rather than estimating their contribution to the quota. Kell *et al.* (2005) demonstrated that the simplistic assumptions used within medium-term projections should not be used for setting precautionary biological reference points because they do not estimate the actual risk level.

This study develops and extends the cod population dynamics study described in Clark *et al.* (2003) by evaluating the consequences for stock assessment and management. Rather than trying to incorporate additional complexity into the assessment process, the robustness of both stock recovery and sustainable management strategies to different plausible climatic change scenarios are evaluated using a simulation framework. Short-term management is based upon rebuilding the stock to the precautionary biomass reference point (B_{pa}). Long-term management strategies are based upon setting total allowable catches (TACs) corresponding to a given level of fishing mortality or a simple Harvest Control Rule (HCR). Evaluation is based upon the performance of each management approach in the face of uncertainty due to climate change, measured through their ability to maintain levels of SSB and yield.

Material and methods

The simulation framework used within this study (Kell *et al.*, 2005) models both the "real" and "perceived" systems. It implicitly acknowledges the presence of a variety of sources of uncertainty, as categorized by Rosenberg and Restrepo (1994). The "real" stock and fishery dynamics are represented as the *operating model*, from which simulated data are sampled. These data are used within a *management procedure* to assess the status of the stock and, depending on perception of its status, management controls are applied to the fishery and fed back into the "real" system (Figure 1).

Operating model

Biological parameters were set equal to those used in the ICES assessment (ICES, 2003) and both growth and recruitment were modelled as a function of sea surface temperature.

Stock-recruitment relationships as a function of temperature

Two alternative stock-recruitment relationships (SRR) were hypothesized based upon the Ricker form (Ricker, 1954), where α and β are the standard Ricker parameters and δ is the temperature effect.

SRR I: α affected by temperature (T) is given by

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

Survival of recruits is related to temperature, and the expected recruitment at any biomass level is scaled by the same amount for a given temperature.

SRR II: β affected by temperature (T) is given by

$$R = \alpha \times SSB \times e^{-\beta(1-\delta \times T)SSB}$$

Density-dependent processes are acting so that recruitment is limited by available habitat, which in turn is related to temperature. For example, if temperature increases, the available habitat and hence virgin biomass declines.

All parameters (initially α and β, then δ) were estimated via a Bayesian analysis using WinBUGS (Thomas *et al.*, 1992; Spiegelhalter *et al.*, 1999). Prior probability distributions for α, β, and δ were chosen to be as non-informative as possible (α a normal distribution with a mean 0 and a variance of 1000 $\sim N(0, 1000)$, $\beta \sim LN(2.26e^{-6}, 0.1)$, $\delta \sim N(0, 1000)$). Stock and recruit data came from the ICES North Sea cod stock assessment database (ICES, 2003), and sea surface temperature data for February–June, corresponding to the spawning period, came from the Comprehensive Ocean Atmosphere Dataset (COADS – see acknowledgements; Woodruff *et al.*, 1998). The final values for the parameters α and β were fixed at 4.232 and $2.901e^{-6}$, respectively, to ensure comparability between runs. δ was then estimated for each proposed SRR (Table 1).

Modelling growth as a function of temperature

Using the parameterization derived by Björnsson and Steinarsson (2002), the proportional annual growth increment between one age class and the next for each cohort was modelled as:

$$W_{i+1} = W_i \left(1 + \frac{(\delta_1 \times SST)W_i^{\beta_i}}{100}\right)^{365}$$

where $\beta_i = \gamma_2 + \delta_2 T$, W = weight of the fish (g), T = temperature (°C), and δ_1 is an age-specific multiplier. The increment is raised to the power of 365, because the output of Björnsson and Steinarsson's model is a daily growth multiplier. This model was based upon a laboratory study, where food was unlimited but exercise restricted. In turn, their model was not tested on fish >5 kg. Thus, while β_i was taken from Björnsson and Steinarsson (2002) ($\gamma_2 = -0.1934$, $\delta_2 = -0.02001$), an age-specific δ_1 was

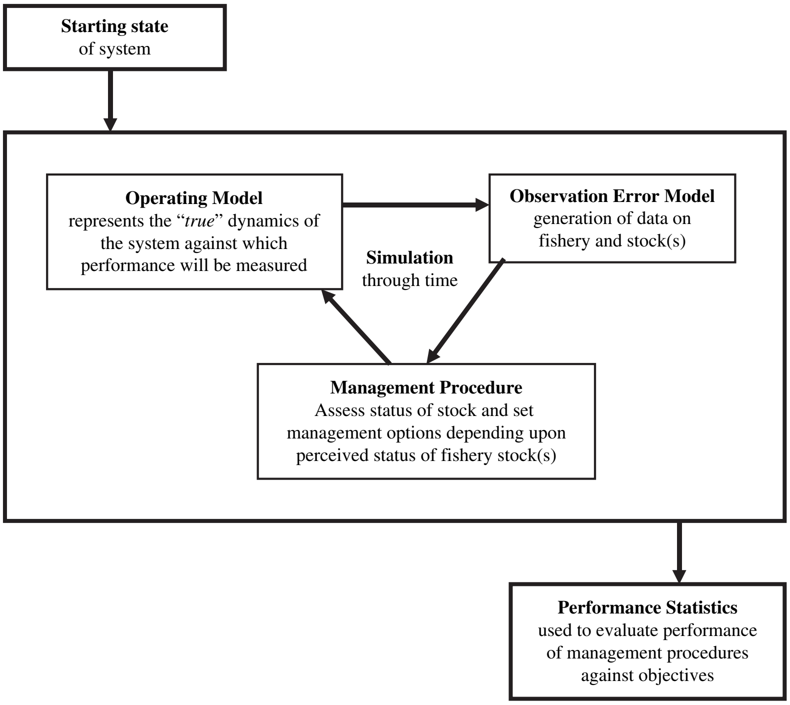

Figure 1. Conceptual framework.

estimated using ICES assessment Working Group weights-at-age (ICES, 2003) and the mean sea surface temperature between February and June from COADS sea surface temperature data (so maintaining compatibility with the recruitment model; Table 2).

Fishing fleets

There was one fishery, corresponding to a single human consumption fleet, which included discards (all fish below minimum size being discarded). The historical fishing mortality level was taken from the ICES assessment. The selection pattern was modelled as a random variable, where expected selectivity at age was equal to the expected values estimated by a lowess smoother (Cleveland, 1979) with a span of 0.75, and those in the future to the expected values from the last year (2001) in the ICES assessment. Variability was modelled by bootstrapping the residuals to the smoothed fit.

Table 1. Mean estimates of the temperature parameter δ, and corresponding standard deviation (s.d.), for the two stock-recruitment relationships.

	SRR I	SRR II
Mean δ	−0.439	−0.934
s.d. δ	0.114	0.224

In addition, fishing mortality was constrained to ensure that the operating model only generated realistic values, where the probability was given by:

$$P(F) = \begin{cases} 0 & \text{for } F < a \\ \frac{1}{b-a} & \text{for } a < F < b \\ 0 & \text{for } F > b \end{cases}$$

where for the minimum F: a = target F − 0.05, b = target F − 0.2; where for the maximum F: a = target F + 0.05, b = target F + 0.3.

Management procedure

The Management Procedure is the specific combination of sampling regime, stock assessment method, choice of biological reference points, and harvest control rules. The sampling regime corresponded to the commercial catch data and research vessel surveys used to generate time-series of abundance estimates. It was modelled by the

Table 2. δ_1 Values for cohort growth by weight estimated using ICES North Sea cod Working Group and COADS SST data.

Age_i	1	2	3	4	5	6	7	8	9	10
Age_{i+1}	2	3	4	5	6	7	8	9	10	11
δ_1	0.15	0.32	0.33	0.29	0.22	0.15	0.09	0.11	0.09	0.08

Observation Error Model, which generated data from the Operating Model for use in the Management Procedure (see Figure 1).

Biomass-at-age and catch-at-age were sampled with error from the Operating Model based upon the estimates of measurement error in commercial catch data (Kell *et al.*, 2003). Natural mortality-at-age and maturity-at-age did not vary between years, and corresponded to the values used by ICES.

EXtended Survivors Analysis (XSA; Shepherd, 1999) was the assessment method used to estimate historical stock size. XSA was calibrated using a single catch per unit effort (cpue) series that covered ages 1–6, constructed so that cpue was proportional to population size, with a CV of 30%.

Allowable Biological Catch (ABC) was calculated using a "short-term projection", and the TAC was set equal to the ABC. Numbers-at-age were projected through the "current year" (for which total catch data were not yet available), assuming a fishing mortality in the current year was equal to the value in the previous year. Exploitation pattern and biomass-at-age were set to the mean in the last 3 years.

Management strategies

Short- and long-term management strategies were evaluated. In the short-term management strategy, which corresponded to a recovery plan, catches were set each year so that SSB increased by 30% annually until the stock recovered to 150 000 t (B_{pa}). Long-term catches were set so that the projected fishing mortality was equal to either 0.65 (the precautionary fishing mortality level F_{pa}) or 0.45 (a 50% reduction in current levels).

Experimental treatment

Climatic change scenarios were conditioned on projected sea surface temperature (SST) for 2000–2050 (Special Report on Emission Scenarios (SRES)-driven HadCM3 climate change experiments; see Gordon *et al.*, 2000; Clark *et al.*, 2003). Three future temperature scenarios (Figure 2)

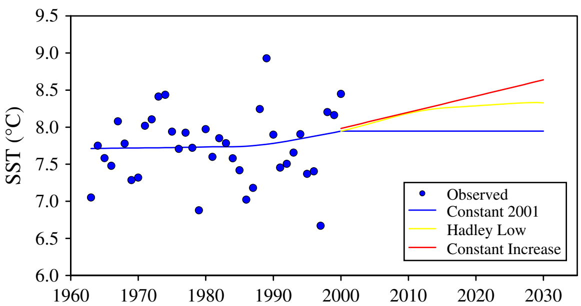

Figure 2. Historical sea surface temperatures in the North Sea, the average historical level, and the patterns assumed for the three future temperature scenarios examined.

were chosen to bracket the most plausible range of future conditions.

(i) 2001: Future temperature equal to that in 2001. A "best-case" scenario.
(ii) HadCM3 (specifically HadCM3B1): This resulted in around a 0.2°C temperature increase by 2040 (see also Clark *et al.*, 2003). This is the most "ecologically friendly" projection.
(iii) Constant increase: A 0.026°C increase each year, representing a continuation of the average projected increase during the period 2000–2010. This results in an approximately 1°C temperature increase by 2040. A "worst-case" scenario.

For each treatment, 1000 Monte Carlo simulations were performed with random variables as stated above (e.g. recruitment, growth, selection, and initial population numbers). Results were compared for their performance in the short- and long-term (recovery and maintenance periods).

Implementation error

There were two recovery strategy treatments:

(i) The quota was respected and total catch was available to the management procedure.
(ii) The misreporting scenario was defined when the total catch was greater than reported catch (i.e. the quota) owing to a bycatch in non-target fisheries, and the bycatch component was not included in the management procedure.

Results

To investigate short-term consequences for stock recovery (i.e. achieving B_{pa}) of the three climate change scenarios, the probability of recovery (i.e. SSB > B_{pa}) with respect to time was examined (Figure 3). The climate change scenario had very little impact on the time to recovery, so only one regime is presented in Figure 3.

Where perfect information was available, the time to recovery was about 6 years, which incidentally coincides with the first age at which all cod are mature. Importantly, recovery is only perceived by the Working Group 2 years after it has occurred. When misreporting was included, time to recovery was much longer; the expected time was >15 years. Furthermore, recovery was not perceived to have occurred within 20 years.

The expected productivity of the stock attributable to changes in recruitment, growth, and discarding was explored through the use of an equilibrium age-structured model. This model combines SSB per recruit, yield per

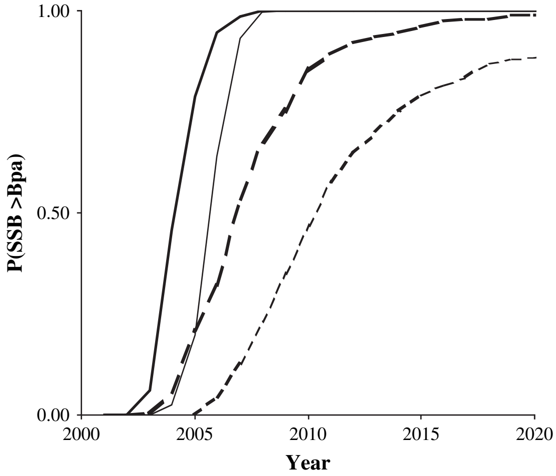

Figure 3. The probability of recovery where temperature followed the HadCM3 projection and affected α in the Ricker SRR. Patterns were identical for all temperature regimes and SRR. The thick solid line shows the "true" recovery (actual stock status) where there is no misreporting, the thin solid line the corresponding perception of the Working Group, the thick broken line the "true" recovery where misreporting occurred, and the thin broken line the corresponding perception of the Working Group.

recruit, and stock-recruitment analyses (Kell and Bromley, 2004). Figure 4 shows the productivity of the stock, presented in the form of yield−SSB curves, for the expected temperature in 2030 under the three climate change scenarios, and for the two effects on the stock-recruitment relationship. The maximum of these curves represents the maximum sustainable yield (MSY), and the corresponding value of SSB is designated B_{MSY}. The value of fishing mortality corresponding to the point where SSB declines to zero on the right of the biomass per recruit curve is defined as F_{crash}, the level of fishing mortality which if maintained indefinitely would drive the stock to extinction.

The consequence of a change in temperature depends upon whether the effect is on juvenile survival (α) or carrying capacity (β). Where α is a function of temperature, the slope at the origin of the stock-recruit curve changes. F_{crash} is therefore expected to change. However, MSY and B_{MSY} only change if β is a function of temperature.

Table 3 summarizes the effect of temperature on F_{crash} and F_{MSY} in the current simulations, and compares them with the average fishing mortality (from 2000 to 2002) and with F_{lim}. Fishing mortality reference points are not affected by changes in carrying capacity (β), but do seem to be affected slightly by changes in juvenile survival (α). These changes are, however, unlikely to be detectable in practice with stock assessment data.

In Table 4, a similar comparison is performed for the biomass reference points B_{MSY}, B_{pa}, and B_{lim}. Under the climate change scenarios, values of B_{pa} and B_{lim} are reported for the equivalent point on the productivity curve (e.g. $B_{pa} \times B_{MSY}'/B_{MSY}$, where B_{MSY}' is the value under the climate change hypothesis). Only if climate change acts upon carrying capacity (β) do the values of B_{pa} and B_{lim} change.

The expected biomass as a percentage of B_{pa} at current fishing mortality ($B_{F2000-2002}$), at F_{pa} (B_{Fpa}), and at a fishing mortality of 0.45 ($B_{F=0.45}$) is summarized in Table 5. The current level of fishing mortality is not sustainable if climate change acts on juvenile recruitment (α), but it is sustainable (albeit for a low stock level) if it acts on carrying capacity (β). At F_{pa}, B_{pa} will only be achieved under the more conservative temperature increase hypothesis (Hadley HadCM3), and this is independent of the process through which climate change acts on the stock-recruit relationship. If fishing mortality is reduced to half of the current level (0.45), however, B_{pa} can be achieved under all scenarios.

The expected long-term yields are given in Table 6 as a percentage of MSY in 2001. In all cases yield decreases, markedly at current exploitation levels. The decrease in yield is greater if carrying capacity rather than juvenile recruitment is affected by temperature, although the greatest impact is due to the climate change scenario. However, if fishing mortality is reduced, then yields at the level of the 1980s could still be achieved.

Our ability to detect changes in biological reference points attributable to climate change in the long term was also investigated using the stochastic simulation model with

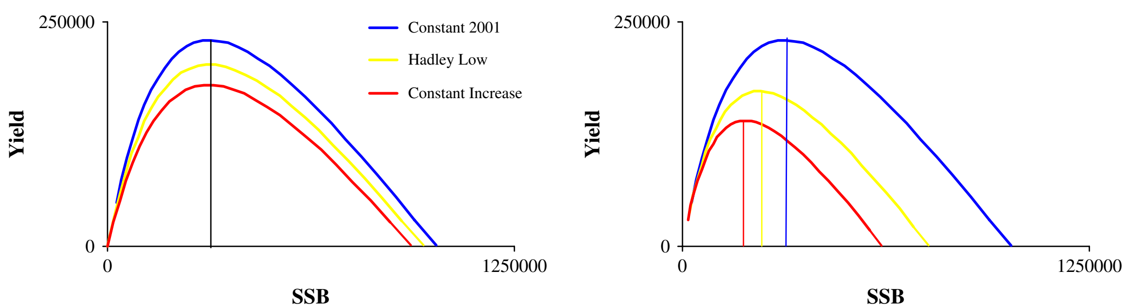

Figure 4. Stock production curves under the three climate change scenarios. The left panel shows the relationship where α is a function of temperature (SRR I) and the right panel where β is a function of temperature (SRR II). Vertical lines indicate the biomass at maximum sustainable yield (see Table 4 for numerical values).

Table 3. Summary of long-term fishing mortality reference points in 2001. For reference, $F_{2000-2002} = 0.96$, $F_{lim} = 0.86$.

		α		β	
	2001	HadCM3	Constant increase	HadCM3	Constant increase
F_{crash}	0.98	0.91	0.84	0.98	0.98
F_{MSY}	0.51	0.47	0.43	0.51	0.51

Table 5. Summary of relative long-term biomass, given as a percentage of B_{pa} in 2001.

		α		β	
	2001	HadCM3	Constant increase	HadCM3	Constant increase
$B_{F2000-2002}$ (%)	32	6	0	24	20
B_{Fpa} (%)	141	114	90	106	86
$B_{F=0.45}$ (%)	255	228	203	192	155

full feedback, although the details are not reported fully here. Kell *et al.* (2005) showed that important biases exist in our ability to monitor, assess, and control stocks. These biases are difficult to predict unless the quantification and control processes are simulated within the modelling process. Conclusions about expected yield and biomass were similar to those of the equilibrium analysis. However, the analysis showed that it was extremely difficult to detect changes in population parameters and hence biological reference points.

Figure 5 shows a single realization from the operating model used in this study for the constant increase in temperature scenario, where climate acts through reducing recruitment (i.e. α). Fishing effort was controlled without any implementation error, so expected fishing mortality was 0.65. The solid line in Figure 5 indicates the actual fishing mortality and SSB, and the dotted line the perception from the management procedure in the year of assessment. Initially, when fishing mortality was reduced, the perception was that fishing mortality was overestimated, and correspondingly SSB was underestimated, the trend in SSB would then be better captured by the management procedure than the trend in fishing mortality. Following recovery, bias in the estimate of fishing mortality is reduced, while that in SSB increases. Although fishing mortality is constant, SSB still varies because of stochasticity. This makes it difficult to detect a signal attributable to climate changes of the magnitude investigated. In addition, bias exists in the perceived SSB because of estimation error, which means that it can be difficult to detect a signal in the recent period. Figure 6 shows SSB as a function of the relative change in SSB $(SSB_t - SSB_{t-1})/SSB_{t-1}$. The magnitude of bias in SSB depends upon the change in SSB. Figure 6 also shows that this is not the case for fishing mortality.

Discussion and conclusions

Crucially, the results of this study are predicated upon the assumptions used in the simulation experiments, which are extrapolations of historical observations. If climate change is a reality, then we may be moving into temperature scenarios that we have not seen within our historical data sets. Cod may then respond in an unforeseen manner, for example by shifting their distribution northwards. Changes in the species composition and feeding ecology of the North Sea may result, leading to very different consequences. In turn, climate may impact both carrying capacity and juvenile survival, which was not studied within the simulations. It is stressed that the results of the current study are not predictions of what will happen, but rather an investigation of the relative importance of the various processes and the interactions between them. To really understand the effects of climate change, improved knowledge of the underlying biology is also ultimately required.

Climate change seemingly has little effect on North Sea cod stock recovery in the short term. The increase in temperature is relatively small during the period analysed, and most of the spawning-stock biomass will be year classes recruited prior to the start of the recovery period. Recovery is therefore dependent upon conserving these year classes and not on incoming recruitment. Reduction in fishing effort coupled with the use of technical

Table 4. Summary of long-term biomass reference points in 2001.

		α		β	
	2001	HadCM3	Constant increase	HadCM3	Constant increase
B_{MSY}	314 847	313 546	311 398	237 036	192 098
$B_{pa} \times B_{MSY}'/B_{MSY}$	150 000	149 380	148 357	112 929	91 520
$B_{lim} \times B_{MSY}'/B_{MSY}$	70 000	69 711	69 233	52 700	42 709

Table 6. Summary of relative long-term yields as a percentage of MSY in 2001.

		α		β	
	2001	HadCM3	Constant increase	HadCM3	Constant increase
MSY (%)	100	88	78	75	61
$Yield_{F2003}$ (%)	36	7	0	27	22
$Yield_{F=0.65}$ (%)	93	76	59	70	57
$Yield_{F=0.45}$ (%)	98	88	78	74	60

measures to allow cod to survive to maturity and reproduce is of primary importance in the short term. Technical measures are particularly important, because cod are taken by a range of gears and by boats fishing for a variety of target species in the North Sea.

The perception of stock recovery can be very different from the actual situation, especially if implementation error is present. The accuracy of stock assessment estimates is also affected by changes in fishing mortality and stock size. This can mean that assessment procedures tend to underestimate changes in biomass. In addition, data used within assessments only become available some time after the event. As a result, the perception of the stock is worse than the actual case, and more draconian management controls tend to be implemented (lower quotas than are actually necessary). This results in faster recovery than would occur if perfect information were available. The delay in identifying recovery also results from these factors.

In the longer term, once recovery has been achieved, climate change has the potential to impact fisheries significantly. Compared with the case where climate remained at 2001 levels, increasing temperatures resulted in slower increases in SSB and reduced yields. This was particularly notable where temperature affected β in the stock-recruitment relationship. The management regime implemented had little impact on this reduction in yield, but it did influence the probability of SSB being above B_{pa} in the face of climate change. The lowest target F resulted in high probability, regardless of the mechanism of temperature on stock recruitment. Indeed, for the majority of measures examined, the lower target F performed better than, or at least comparable with, the higher F target and HCR approaches. For example, if temperature affected α, yields comparable with those achieved during the 1980s could be obtained following reduction in fishing mortality to a target of $F = 0.45$ if bycatch could be reduced. This implies a move towards management regimes based upon lower fishing mortalities than seen in the recent past.

The effect of temperature on growth was swamped by the much larger year-to-year variability in growth of North Sea cod. The effect of temperature change on the stock-recruitment relationship produced a much stronger effect. It must be recognized that reference points such as B_{MSY} or B_{lim} are proxies for biological processes that show time-dependent variation. This study has shown that, to understand the consequences for productivity, it is important to understand the biological mechanism through which climate change acts in order to quantify the magnitude of potential change. It is unlikely that this can be determined solely through stock assessment or analyses based upon VPA.

Management, rather than improved assessment, is required to achieve stock recovery and sustainable resource use. Stock assessment models should not be made more complex by including environmental covariates with the aim of improving predictions (e.g. Brander, 2003; Köster *et al.*, 2003). The requirement is for simpler management procedures that meet management objectives and are robust to uncertainty about the true dynamics (Walters and Collie, 1988; Basson, 1999). Although reference points based on both biomass and fishing mortality are required by international agreement, it appears from this study that those based on fishing mortality are more robust to uncertainty about dynamic processes and future conditions than those based on biomass. Therefore, management procedures that minimize the reliance on biomass reference

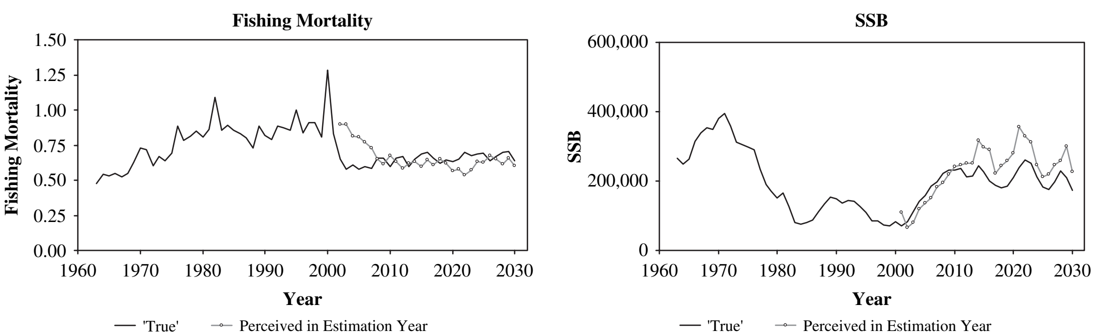

Figure 5. A single realization from the stochastic simulation model for an expected fishing mortality of 0.65.

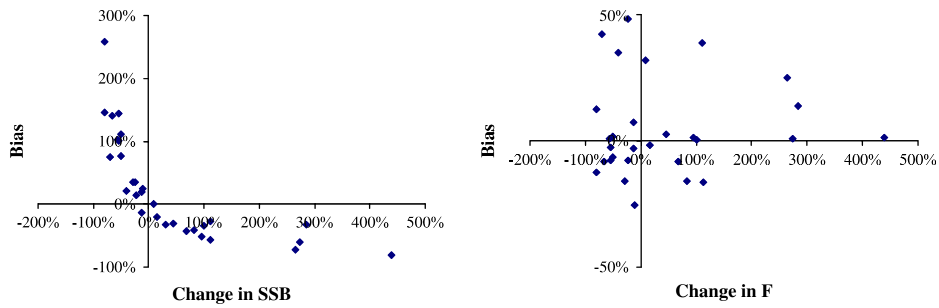

Figure 6. Bias in estimates of SSB and fishing mortality related to relative changes in SSB (i.e. $(SSB_t - SSB_{t-1})/SSB_t$) and fishing mortality.

points should be explored, and candidate strategies evaluated against plausible hypotheses represented by the operating model, using the style of framework employed in the current study.

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