Patterns in the Annual Weight Increment for Div. 2J+3KL Cod and Possible Prediction for Stock Projection

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Abstract

Sample body weight-at-age data for NAFO Divisions 2J+3KL cod (*Gadus morhua*) from research vessel surveys were examined. Considerable variability in annual weight increment was found. A general linear model containing division and age effects explained 36% of the variance in the logarithm of annual weight increment. The residuals from this model showed a temporal pattern which appears to correspond to changes in the area of the cold intermediate layer ($<0°C$), an indicator of the amount of cold water on the shelf. Including the area of the CIL resulted in a model which explained 41% of the variability in weight increments. This model predicted weight increment data not included in the fitting reasonably well. Consideration is given to whether a predictive model based on this relationship could be useful in stock projections.

Key words: cod, cold intermediate layer, prediction, stock projection, weight increment

Introduction

Predictive relationships between the environment and biological processes associated with fish production (birth rate, body growth rate and mortality rate) have the potential to reduce the uncertainty in stock assessments. This is particularly the case where management measures such as TACs are imposed in year $t+1$ based on an assessment of the stock in year t using data collected in t-1 and earlier years. However most correlations between the environment and biological processes have had little utility in stock assessments, and in fact have often been shown to be spurious (Walters and Collie, 1988) and to fail as more data are added to the analysis (Bradford, 1992, Koslow *et al.*, 1987; Walters and Collie, 1988, see for example Myers *et al.*, 1993; and Shelton and Atkinson, MS 1994).

Analysis of relationships between the environment and fish body growth may hold more promise than relationships between environment and recruitment. Much of the difference in Atlantic cod (*Gadus morhua*) growth among stocks is thought to be attributable to variability in ambient temperature (May *et al.*, 1965, Brander, 1995). Millar and Myers (MS 1990), Campana *et al.* (1995), Cárdenas (1996) and Krohn *et al.* (1997) have reported relationships

between cod growth and temperature for various stocks off the east coast of Canada. Cárdenas (1996) and Krohn *et al.* (1997) analysed annual weight increments for NAFO Div. 2J+3KL cod (Fig. 1) from tables of annual mean weights at age found in Bishop *et al.* (MS 1993) and Bishop *et al.* (MS 1995). In this paper we compute mean weights at age in each division for each year from the raw data, weighting by the survey swept area estimates of population size at age in each division. We develop a general linear model with division and area effects and show that the residuals from this model are correlated with a measure of the annual amount of cold water within the area. The model is expanded to include this effect and used to predict recent weight increment data not included in the fitting. Finally, some consideration is given to whether a predictive model of cod weight increments could be developed for improving the precision of total allowable catch (TAC) projections.

Methods

Bottom trawl research vessel surveys have been conducted routinely in the autumn in NAFO Div. 2J, 3K since 1978 and in Div. 3L since 1981. Lengths and weights were determined for a sample

of these fish in each year and annual rings in the otolith were enumerated to determine age. The number of fish sampled in each NAFO Division in each year is given in Table 1. During the early years of the surveys, otoliths for aging were obtained from a sample of 25 cod per 3-cm length-group per division. An additional sample of 5 cod per 3-cm length-group was frozen at sea and thawed in the laboratory, where otoliths were extracted and body weight (both whole and gutted, head-on) was recorded. All fish were measured (fork length, cm) at sea. Additional samples of frozen fish were collected in Div. 2J in 1984 and 1985. The number of frozen fish increased in 1988 and subsequent years, when Div. 2J and 3K were both subdivided into 2 areas, and a sample of 5 cod per 3-cm length-group was obtained from each area. The number of cod for which weights were available increased dramatically when weighing at sea was initiated (in 1989 in Div. 2J and 3K and in 1990 in Div. 3L, Table 1). It is suspected that there may be a systematic difference between weights obtained at sea and weights obtained after thawing in the laboratory, but in the present study any difference has been ignored. The data set for 1978 to 1995 comprises close to 15 000 aged and weighed fish.

TABLE 1. Number of individual fish sampled in Div. 2J+3KL autumn surveys in each year in each division for which both body weight was measured and age determined from the otolith.

Year	2J	3K	3L	Total
1978	132	120	0	252
1979	113	120	0	233
1980	140	156	0	296
1981	145	141	138	424
1982	135	160	51	346
1983	173	156	152	481
1984	532	167	0	699
1985	506	143	147	796
1986	119	130	142	391
1987	104	132	161	397
1988	200	249	156	605
1989	890	1 055	144	2 089
1990	852	970	706	2 528
1991	546	764	576	1 886
1992	263	538	494	1 295
1993	95	355	377	827
1994	62	92	126	280
1995	401	468	236	1105
Total	5 408	5 916	3 606	14 930

In addition to the sample of fish for which length, weight and age are determined, the length frequency of the entire catch for each set, or a random portion of the catch if it was too large to process, was also determined. The sample length frequency was transformed into a population length frequency in each division by areal expansion of the stratified mean catch at length per tow (Smith and Somerton, 1981). In this study population mean weight-at-age by division was obtained by weighting the individual measurements in the biological sample by the ratio of the estimated number in the population in each 3 cm length class to the number of fish sampled in the 3 cm length class. Because of the low number of samples of older fish, particularly in more recent years, cod greater than age 10 were omitted from the analysis.

Average annual weight increments by cohorts within divisions were calculated as follows:

$$\Delta W_{i,j,k} = W_{i,j,k} - W_{i,j-1,k-1},$$

where $\Delta W_{i,j,k}$ is the weight increment for a cohort in division i at age j in year k. Because the data are for autumn surveys it is assumed that the weight increment took place in year k.

The variation in annual growth increments caused by NAFO Division effects and age effects were examined by calculating the average of the log-transformed weight increment values for each division across all ages and years and for each age across all divisions and years. Based on these plots we decided to remove variation due to division and age effects from the weight increment data by applying a general linear model of the form

$$Ln\,(\Delta W_{i,j,k}) = \tau + \alpha_i + \beta_j + \varepsilon$$

where τ is the intercept, α_i is the division effect, β_j is the age effect and ε is normally distributed error (Model 1).

Residuals from this model were plotted against the area of the cold intermediate layer (CIL) to look for possible temperature effects. CIL was derived from oceanographic transects across the Hamilton Bank (Seal Island) in Div. 2J, off Bonavista Bay across the Div. 3K/Div. 3L boundary, and in Div. 3L shorewards from the Flemish Cap along the 47°N latitude (Fig. 1). These transects have been surveyed regularly in summer since the 1950s
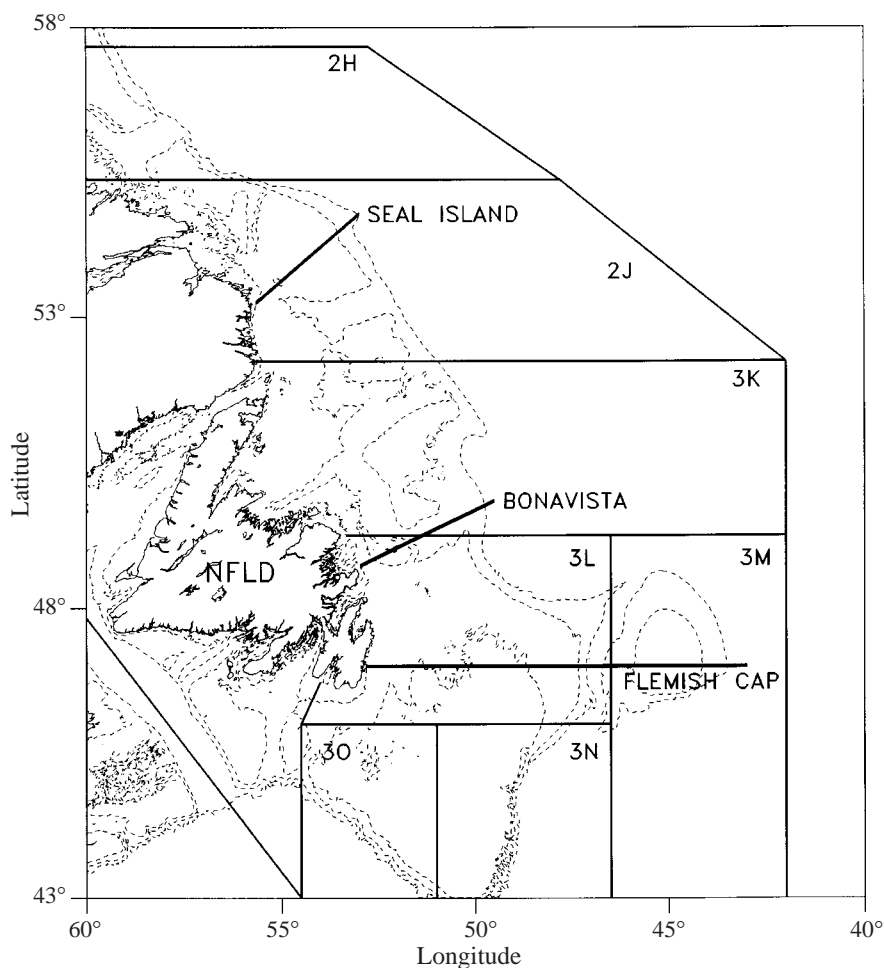
Fig. 1. Map of the study area showing NAFO Divisions 2J, 3K and 3L, and the location of the three oceanographic sections along which the area of the CIL is monitored.

(Colbourne, MS 1995). Annual estimates of area of the CIL, defined as <0°C, are considered to provide an index of thermal conditions within the northern cod habitat. The time series for the three transects appeared quite similar (Fig. 2) and in order to derive a single series to related to cod growth, we computed the annual mean area of the CIL.

Based on the plot of the residuals from the fitted model against the area of the CIL, the model was expanded to include this as an additional term (Model 2),

$$Ln\,(\Delta W_{i,j,k}) = \tau + \alpha_i + \beta_j + \gamma\,CIL_k + \varepsilon.$$

CIL and weight increment data for 1996 and 1997 were not used in the fitting of the model. The ability of the model to predict weight increments at age for these two years, given the CIL, values was examined.

Stock assessment projections carried out in year t-1 require weight predictions for years t and t+1. It would therefore be necessary to predict CIL in years t and t+1. The predictability of CIL was examined by computing the lag correlation in the data for the Bonavista transect for the period 1948 to 1995 and comparing the observed values with those predicted by a first order autoregressive process. Predictions were obtained by subtracting the mean from the data, setting the initial value, Y_t, to the 1948 value and modelling the remainder of the series by recursively calculating Y_{t+1} applying

$$Y_{t+1} = rY_t + \varepsilon$$

where r is the lag-1 regression coefficient and ε is normally distributed random noise with standard error equal to the standard error of the data, having first subtracted the mean. Y_{t+1} was then added to the mean to obtain the realization.
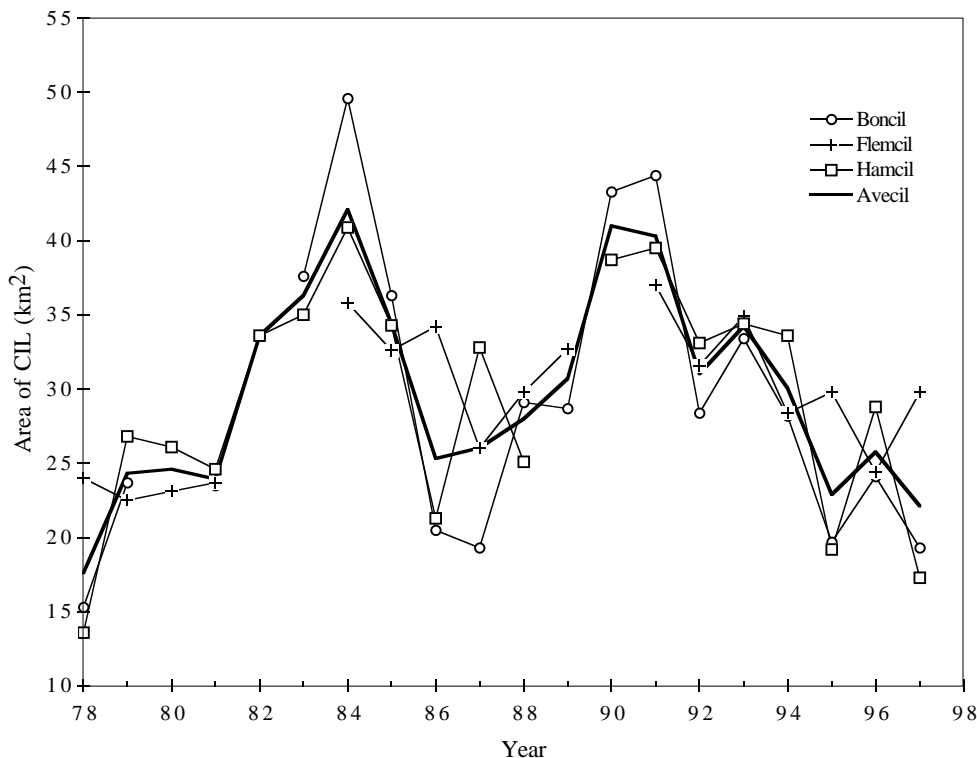
Fig. 2. Annual area of the CIL in summer on the Hamilton Bank, Bonavista and Flemish
Cap sections, together with the annual mean for all three sections.

Results

Annual weight increments across year and ages show a lot of variation in each division (Fig. 3 and 4). This is a consequence of age-dependent growth and annual variation in weight increments. Weight increment increased from Div. 2J through Div. 3K to 3L. Weight increments at age across years and divisions increased with age up to age 3, then leveled off before increasing again for fish older than age 6 (Fig. 4). The variation in weight increment increased substantially beyond age 5.

Model 1, which included division and age effects, explained 36% of the variance in the logarithm of the annual mean weight increment (Table 2). A plot of the residuals from this model against year suggest a non-random pattern (Fig. 5). A scatter plot of the residuals against average area of the CIL and a plot of the residuals together with CIL against year (Fig. 6), suggested a negative relationship – negative residuals tended to be associated with high CIL values and positive residuals with low CIL values. Model 2, which included division,

age and CIL effects, explained 41% of the logarithm of the annual weight increment (Table 2).

CIL and survey weight data for 1996 and 1997 were not used in the model fitting. Sample sizes were very small for fish over age 6. Observed versus predicted weight increments from Model 2 for ages less than 6 for 1996 and 1997 are plotted in Fig. 7. Observed weight increments were higher than predicted for fish aged 4 in Div. 3K and 3L in 1997 and fish age 5 in Div. 3K and 3L in 1996, as indicated by the cluster of 4 points for weight increments between 0.8 and 1 kg in Fig. 7. The value for Div. 3L in 1995 is not shown – the observed weight increment was more that 1.5 kg. Values for other ages are reasonably close to the line. The addition of the CIL term in Model 2 resulted in a 33% reduction over Model 1 in the sums of squares for the predicted weight increments in 1996 and 1997.

Analysis of the autocorrelation in the CIL data, for example data from Bonavista transect for the period 1948 to 1995, showed that only the lag-1
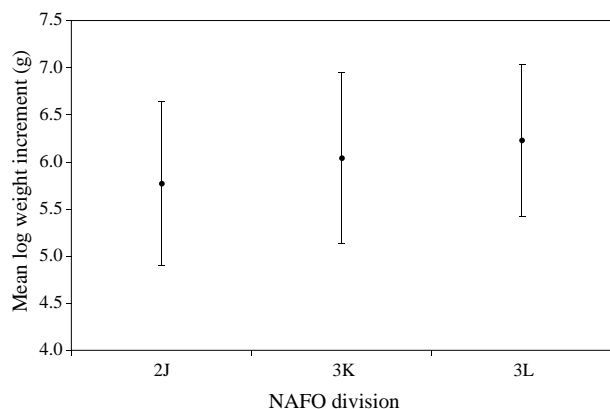
Fig. 3. Mean log-transformed weight increments by NAFO Division. Error bars indicate plus and minus one standard deviation.
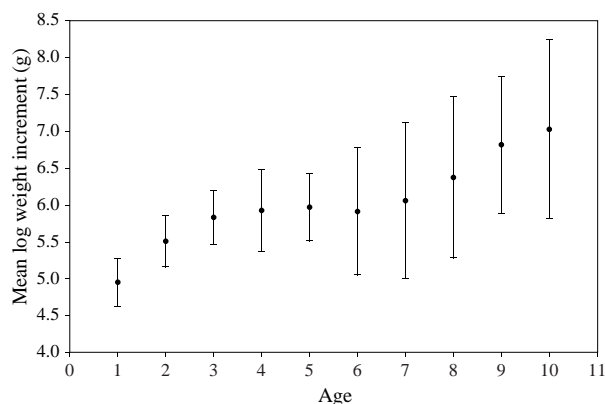

Fig. 4. Mean log-transformed weight increment plotted against age. Error bars indicate plus and minus one standard deviation.

TABLE 2. Results of the general linear models in which variability resulting from age and NAFO division effects were removed from the log-transformed weight increment data for Div. 2J+3KL cod (Model 1) and for which age, NAFO division and area of the cold intermediate layer (CIL) effects were removed (Model 2). DF = degrees for freedom, SS = sums of squares, MSE = means square error, F = value for the F statistic, Pr>F is the significance probability value associated with the F value. For a Type III test the result does not depend on the order in which the effects enter the model.

Model 1

Number of observations	366				
R-square	0.364				
Residual sums of squares	182.738				

Type III Sums of Squares

Effect	DF	SS	MSE	F	Pr>F
Age	9	92.346	10.261	19.88	0.0001
NAFO	2	14.659	7.330	14.20	0.0001

Model 2

Number of observations	366				
R-square	0.414				
Residual sums of squares	168.164				

Type III Sums of Squares

Effect	DF	SS	MSE	F	Pr>F
Age	9	89.562	9.951	20.89	0.0001
NAFO	2	14.952	7.476	15.69	0.0001
AVECIL	1	14.575	14.575	30.59	0.0001

correlation, explaining about 64% of the variation, was significant (Fig. 8). The implication is that the CIL data can be adequately modelled by a first order autoregressive process. This was demonstrated by generating a random realization from a first order autoregressive process with $r = 0.8$ and comparing this to the observed CIL for Cape Bonavista (Fig. 9). The two series are quite similar.
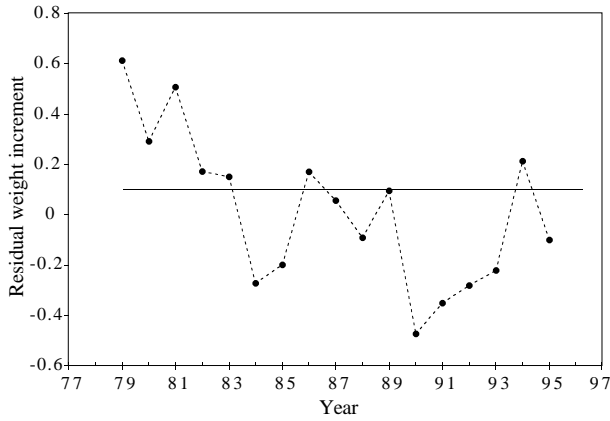
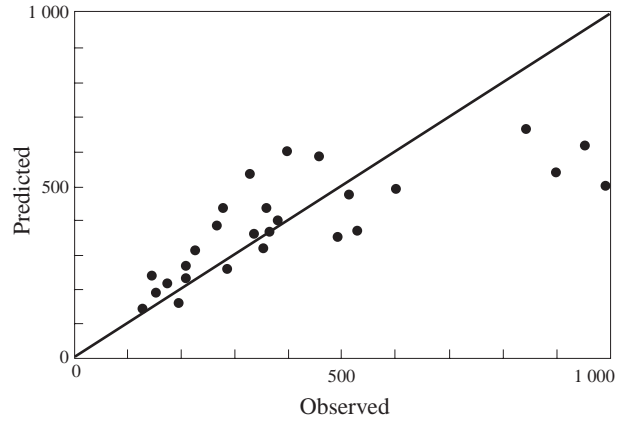Fig. 5. Residuals in log-transformed weight increment after removing age and division effects, plotted against year.

Fig. 7. Observed weight increments (g) in 1996 and 1997 for ages 1 to 5 *versus* predicted weight increments based on age, division and CIL effects.
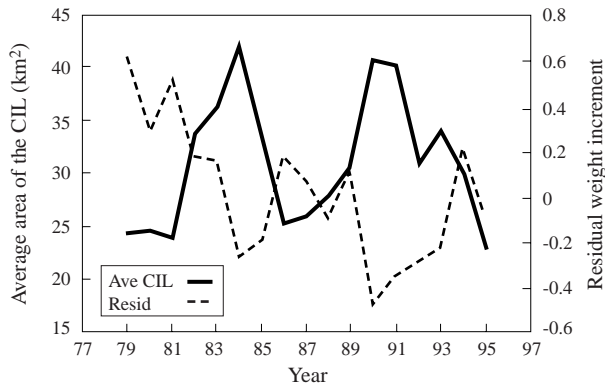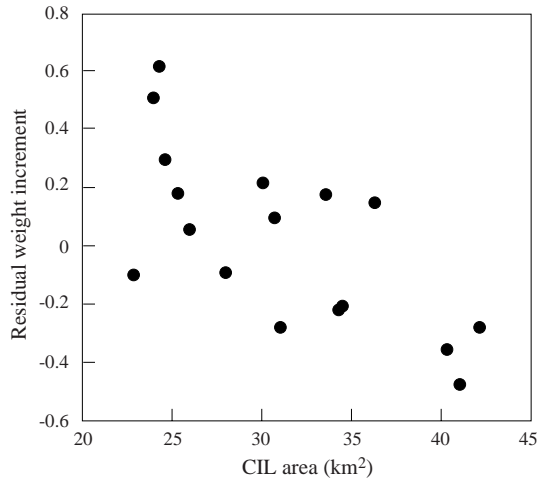

Fig. 6. Plot of the residuals in log-transformed weight increment against area of the CIL, and a plot of the log-transformed weight increment and CIL against year.
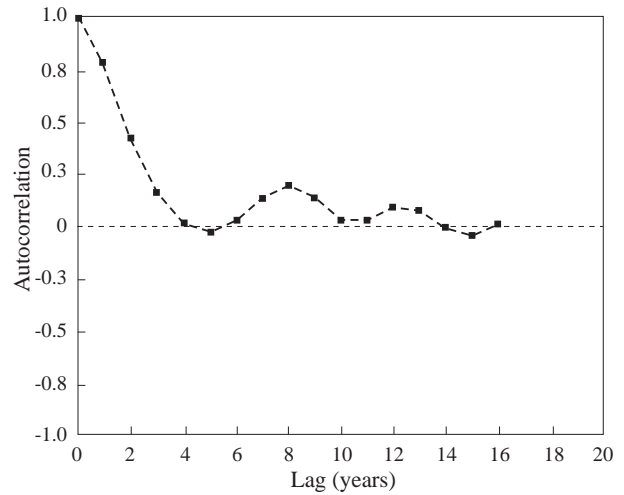

Fig. 8. Autocorrelation in the Bonavista CIL data shown for a range of lags. Only the lag-1 autocorrelation is significant.

Discussion

The literature on the effect of environment on Atlantic cod growth can be divided into two main categories – those papers that examine the effect of geographical differences in average ambient temperature and those that examine temporal changes in ambient temperature within a specific geographic area. With respect to geographic differences in
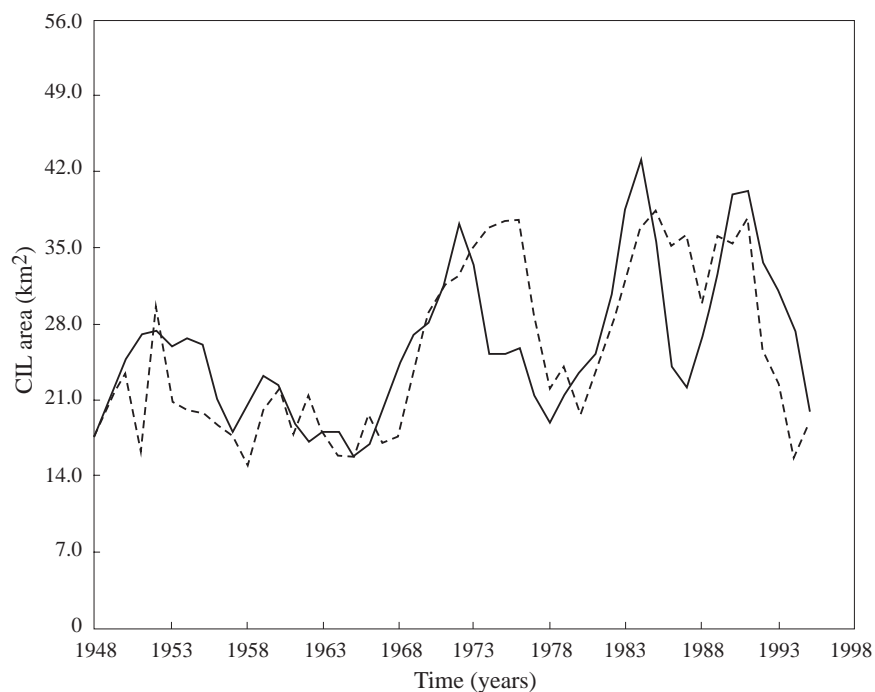
Fig. 9.   A sample CIL time series generated using the observed lag-1 autocorrelation in the Bonavista CIL data, together with a random noise component (broken line) compared to the observed CIL time series for this transect (solid line).

ambient temperature, Brander (1995) examined the growth of Atlantic cod (derived mainly from commercial catch data) in 17 stocks, and concluded that 92% of the variance among stocks in the logarithm of mean weight-at-age for ages 2 to 4 fish could be explained by a model with age and temperature effects. Brander (1995) considered that the temperature effect was big enough to have significant consequences for assessments with respect to catch forecasts. Brander's research was preceded by that of Sager *et al.* (1988) and two ICES studies of cod growth in four Arcto/Boreal systems (Barents Sea, Greenland, Iceland and Newfoundland (Anon., MS 1991), later extended to three other cod systems (Gulf of Maine, Georges Bank and North Sea (Anon., MS 1992). Although the primary aim of the ICES studies was to examine the impact of food consumption on growth, ecosystem differences were attributed in part to ambient temperature. Campana *et al.* (1995) showed that growth differences in cod on Georges Bank, eastern Scotian Shelf and southern Gulf of St. Lawrence could be explained in part by ambient temperature. Shackell *et al.* (MS 1995) suggested that differences in cod growth among the Scotian shelf and adjacent areas were due to differences in the hydrographic regime.

Studies of geographic variability within cod stocks have been carried out in Iceland (Jónsson, 1965), off Labrador and eastern Newfoundland (Flemming, 1960; May *et al.*, 1965), between Norwegian fjordic systems (Berg *et al.*, 1993) and in post-larval cod off southwestern Nova Scotia (Suthers *et al.*, 1989). These studies suggest that substantial changes in cod growth can take place with respect to geographic location within ecosystems. In the present study, NAFO Division accounted for a significant portion of the variability in the logarithm of annual weight increment when included in a model with age effects (Table 2). Weight increments increased from north to south in Div. 2J+3KL.

Annual variability in growth has been reported for many cod stocks. Studies of factors responsible for this variability have generally emphasized temperature as the main causative factor. Some of the stocks for which temperature effects on growth rate have been suggested include cod on the Scotian shelf (Campana *et al.*, 1995; Shackell *et al.*, MS 1995), Div. 2J+3KL cod (Millar and Myers, MS 1990; Warren, MS 1993; Cárdenas, 1996, Shelton and Lilly, MS 1995; Krohn *et al.*, 1997) southern

Gulf of St Lawrence cod (Beacham, 1983), Icelandic cod (Jónsson, 1965; Steinarsson and Stefánsson, MS 1991; Cárdenas, 1996), North-east Arctic cod (Loeng, 1986; Loeng and Gjøesaeter, MS 1990; Jørgensen, 1992; Nakken, 1994; Nakken and Raknes, 1987; Ohzigin *et al.*, MS 1994; Cárdenas, 1996) and West Greenland cod (Hermann and Hansen 1965). In the analysis of interannual variation in cod growth in Barents Sea, Greenland, Iceland and Newfoundland (Div. 2J+3KL) cod stocks, Anon. (1991) concluded that the overwhelming presence of year effects in the data indicates the existence of a strong environmentally influenced component to cod growth. Significant temperature effects in the Barents Sea, Iceland and Newfoundland stocks were apparent over a variety of analyses in Anon. (MS 1991).

The present study adds to the evidence that cod growth is influenced by the environment. A general linear model with division, age and CIL effects fit to the weight increment data for Div. 2J+3KL cod explained 41% of the variance compared to 36% of the variance explained by a model with only division and age effects. The model which included CIL predicted the weight increments for 1996 and 1997 much more accurately, when provided with the observed CIL values for each of the two years, than the model with only division and age effects (a decrease of 33% in the sums of squares for the predicted values).

Factors which could account for the large amount of residual unexplained variability in the weight increments of Div. 2J+3KL cod include, amongst others, density dependence. Millar and Myers (MS 1990) found significant density dependent effects in the Div. 2J+3KL cod stock in an analysis of the data up to 1989. However, Cárdenas (1996) found little evidence of any relationship in the data between 1979 and 1991. The pattern of residuals from the fitting of Model 1 (Fig. 6) did not visually suggest any relationship with overall stock biomass. However, there is evidence that the stock became spatially more aggregated just prior to the collapse (see for example Lilly *et al.*, MS 1998), so that the very low weight increment residuals in the early-1990s could possibly be explained by more detailed analysis of cod density.

The use of environmentally-based models to predict weight increments for stock projections for Div. 2J+3KL cod does not look promising. Because of the time elapsed between fitting the model to data

(up to and including year *t*-1) and the projection (year *t*+1), the model has to be able to make 2-year predictions. To do this, CIL has to be predicted in year t and year *t*+1, however only a significant lag-1 autocorrelation (explaining 64% of the variance) has been found in the CIL data. Clearly the model including CIL will have limited value in improving current stock assessment projections. Further analyses using stochastic models incorporating autocorrelation in the environmental variable could be carried out to determine how much autocorrelation would be required to improve on the predictions made by non-environmental weight increment models.

Acknowledgements

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