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Environmental indicators and the predictability of commercial fish stocks

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Commercial landings data for Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*), were examined along with historical conductivity, temperature, and depth (CTD) data to demonstrate an approach for assessing seasonal, annual, and interannual relationships between fish stocks and their environment, and to develop predictive models for the distributions of stocks over Georges Bank. A spatially explicit analytical/numerical model was used to demonstrate the predictive capability of such relationships. Results show that bottom temperature alone accounts for up to 40% of the spatial variance within the smoothed monthly catch distributions. Less than 20%, is explained by bottom sediment type and bottom depth. The same model accounts for a much smaller percent of the observed catch variance in individual years.

Keywords: cod, environmental indicators, Georges Bank, haddock, numerical model

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Introduction

Several studies have related environmental variables to fish distributions and abundances in the Northwest Atlantic (Smith et al., 1991; Mountain and Murawski, 1992; O'Brien and Rago, 1996). Others have examined how such relationships can be used to predict distributions and abundances of commercial fish stocks over a variety of time and space scales (Bertignac et al., 1998; Stefánsson and Pálsson, 1997). The present study is an analysis of environmental indicators of commercial fish stocks in the Northwest Atlantic, specifically, Georges Bank. We build on previous results in two ways. First, we use commercial landings data to extend results of previous regional studies based on seasonal bottom trawl surveys. Second, we use a spatially explicit analytical/numerical model to test the predictive skill of empirically based correlations.

Materials and methods

Historical data sets

Cod and haddock commercial landings data for 1982-1992 were obtained from the U.S. National Marine Fisheries Service. The data included the landed weight and total fishing time per fishing subtrip, from which we compute catch per unit fishing effort (c.p.u.e.). Historical CTD data were obtained from a variety of sources including the National Oceanographic Data Center; the Atlantic Fisheries Adjustment Program; the Marine Resources Monitoring, Assessment and Prediction Program; the Global Ocean Ecosystems program; and numerous smaller field programs. Bottom sediment grain size over Georges Bank was obtained from published data by Twichell et al. (1987; republished from Schlee, 1973).

A spatially explicit numerical model

An analytical/numerical model was used to demonstrate the predictive capability of empirically derived correlations. The model represents the concentration of fish by a continuous tracer, and uses an advection/diffusion parameterization to describe tactic searching behavior of fish towards preferred environmental variables (e.g., Grunbaum, 1999).

The model solves the advection/diffusion:

$$\partial C/\partial t \;-\; \partial/\partial x(f_x C) - \partial/\partial y(f_y C) = \kappa\, \partial^2 C/\partial x^2 + \kappa\, \partial^2 C/\partial y^2, \qquad (1)$$

where C represents the fish concentration,

$$f_x(x,y,t)=S\,\partial/\partial x(\theta^2/2), \qquad (2)$$

$$f_y(x,y,t)=S\,\partial/\partial y(\theta^2/2), \qquad (3)$$

$$\theta^2 = (T - T_c)^2, \qquad (4)$$

T represents bottom temperature, T_c is the preferred temperature, and κ is an effective horizontal diffusivity.

Advection terms in (1) represent fish's swimming tendency towards a preferred value of bottom temperature, or any variable for which they have an affinity. Here f_x and f_y can be thought of fish swimming velocities such that the further the fish are from their preferred temperature, the faster they swim towards it, and the larger the temperature gradient, the faster they swim. The scalar parameter, S, sets the overall strength of this affinity; a larger S implies a greater swimming speed. The horizontal diffusion term in (1) can be thought of as a parameterization of random searching behavior, and of the tendency of the fish to avoid aggregating to arbitrarily high concentrations at any given location.

Equations (1)–(4) formally represent the vertically integrated abundance of cod or haddock, i.e., number of fish per unit area; or alternatively the number of individuals per unit volume near the bottom. While the precise relationship between c.p.u.e. and abundance is a widely debated topic, for the purpose of the present study we assume that c.p.u.e. is proportional to abundance, and use c.p.u.e. as a proxy for fish abundance (to within a constant of proportionality) both in (1)–(4) and in our discussion.

Results

Empirical Correlations

Mean bottom temperatures and weighted mean catch temperatures over Georges Bank were computed by month by multiplying the temperature at each catch location by the natural log (ln) of c.p.u.e. for that location. Results show a seasonal cycle in mean bottom temperature and weighted mean catch temperature, as well as a tendency for ln(c.p.u.e.)-weighted temperature to be consistently less than mean bottom temperature for large bottom temperature (Figure 1A). To assess variations in

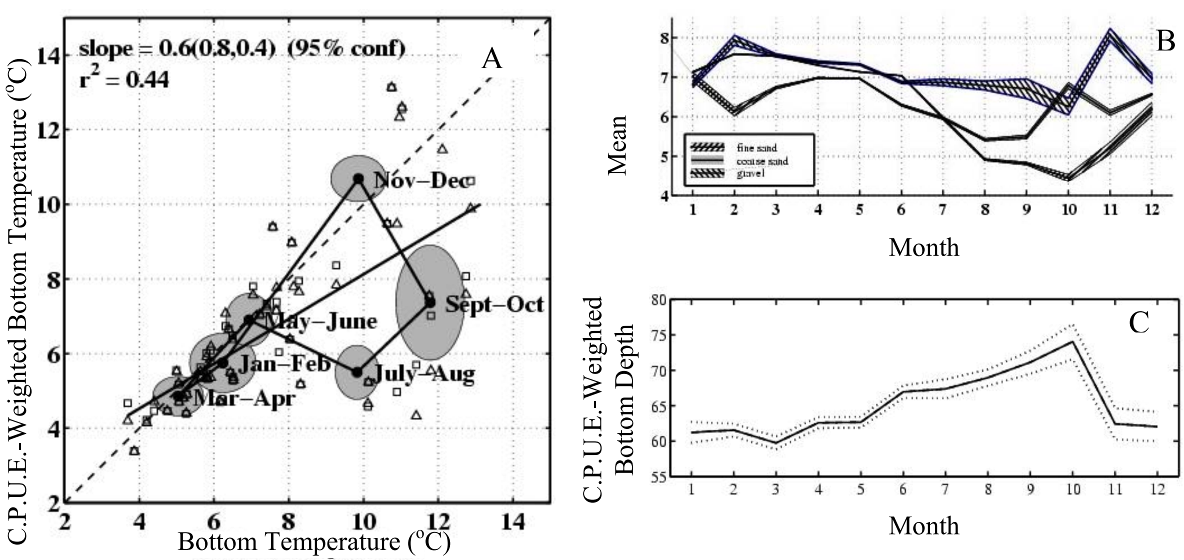

Figure 1. (A) Cod (squares) and haddock (triangles) ln(c.p.u.e.)-weighted bottom temperature versus mean bottom temperature, and bi-monthly average values of the same for cod (shaded ellipses). Regression statistics for a straight line fit through the cod data are cited in the figure. Time-series of (B) monthly averaged cod ln(c.p.u.e.) over each sediment type and (C) cod ln(c.p.u.e)-weighted bottom depth over Georges Bank from 1982-1992. Error estimates for the curves in panels (B) and (C) are shown by shading and dashed lines, respectively.

c.p.u.e. over different sediment types, we further computed the average ln(c.p.u.e.) over each of three sediment grain size classes as defined by Twitchell et al. (1987): 1/16 – 1/4 mm (fine sand), 1/4 – 1 mm (medium-to-coarse sand), and > 1 mm (gravel). Time series of monthly averaged ln(c.p.u.e.) over Georges Bank showed that for all three sediment classes, cod and haddock follow an annual cycle of higher values in winter/spring and lower values in summer/fall. Furthermore, throughout the year both species tend to yield significantly higher c.p.u.e. over coarse sand and gravel compared to fine sand (Figure 1B). Finally, we computed ln(c.p.u.e.)-weighted monthly average depth. This showed a tendency by both species towards shallower waters during winter/spring and deeper waters in summer/fall.

Numerical Model Results

A spatially explicit model was used to evaluate the predictive skill of these correlations. For each month (1)-(4) were integrated until a steady state was reached. Per equation (1), this is equivalent to the assumption that fish are in equilibrium with their preferred environment. Integration was repeated for each environmental variable by replacing T and T_c in (4) by their appropriate counterparts, and for all three environmental variables combined by adding respective terms of the form (2)-(3) to (1). Integration was on a 3 km x 3 km grid spanning Georges Bank.

Comparison between model predictions and observed monthly c.p.u.e. indicates that temperature alone accounts for between 0%-40%, and 0%-15%, of the total variance in the observed monthly ln (c.p.u.e.) fields of cod and haddock, respectively. Sediment type and bottom depth account for between 0%-15%, and 0%-20% of the variance, respectively. The three environmental variables combined account for approximately the same or slightly greater variance than any one individually (Figure 2A,B).

To assess model performance on interannual time scales, the procedure was repeated for monthly distributions of the full 11-year time series. Rather than using monthly mean spatial distributions of bottom temperature, each month's temperature was adjusted by an amount equal to the mean temperature anomaly of that month of that year. This time, the percent variance accounted for by the model in either species ranged from less than zero (the model overpredicted the observed variance) to as much as 60% (Figure 2C,D). (Note that the percent variance explained is computed as the [(observed variance) – (variance of the (predicted – observed fields))] / (observed variance). Hence the percent variance explained is negative if the variance of the predicted-observed fields exceeds the observed variance.)

Discussion

In the context of the model (1)-(4), bottom temperature can account for up to 40% of the spatial variance in the observed monthly ln(c.p.u.e.) fields of either cod or haddock over Georges Bank. Bottom sediment type and bottom depth account for up to15% of the observed variance in either species. This suggests that bottom temperature, bottom sediment type, and bottom depth are all significant

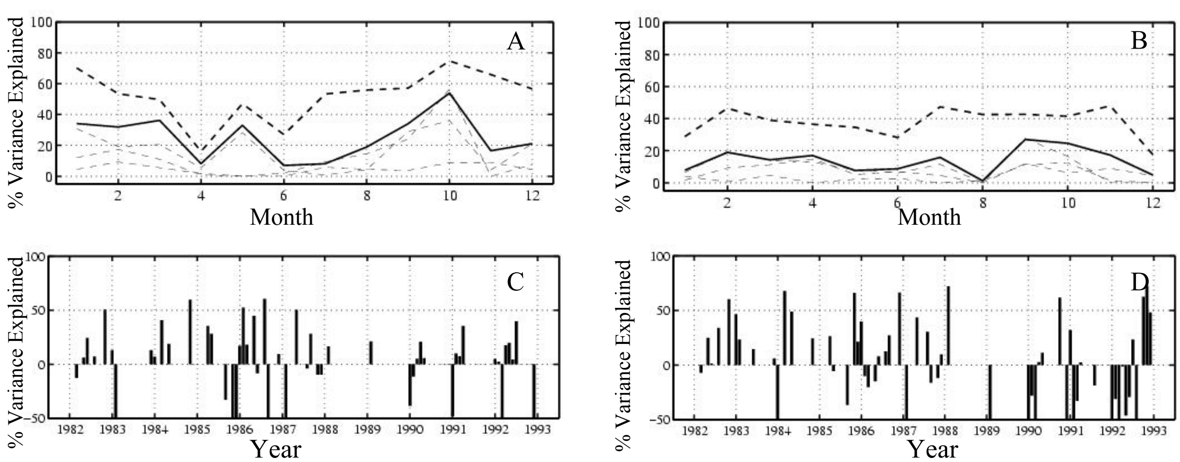

Figure 2. Monthly time series of percent variance accounted for in (A) cod and (B) haddock distributions over Georges Bank by (1)-(4) using bottom temperature, sediment type, and bottom depth combined (solid) and optimal interpolation of the data (dashed); percent variance accounted for in 11-year time series of (C) cod and (D) haddock by bottom temperature, sediment type and depth combined.

indicators for distributions of cod and haddock on Georges Bank. That bottom temperature preference accounts for more of the observed variance than do bottom type and bottom depth may indicate that temperature has a greater effect on the distributions of these species over the Bank. However, variations in the variance accounted for by each of these variables also suggests that the dominance of temperature as an indicator may vary seasonally.

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