Using commercial landings data to identify environmental correlates with distributions of fish stocks

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ABSTRACT

We examined the efficacy of using commercial landings data to identify potential environmental correlates with fish distributions. Historical landings data for two commercially important species, Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*), were used along with historical conductivity, temperature, and depth (CTD) data to infer monthly mean spatial distributions of catch per unit effort (CPUE), temperature, salinity, density, and stratification over Georges Bank. Relationships between CPUE and these environmental variables plus bottom sediment type and bottom depth were examined on seasonal, annual, and interannual time scales. Empirical analysis suggests that both cod and haddock are found preferentially in water temperatures of approximately 5°C in winter/spring, and as high as 10–11°C during late fall. Both species are also found preferentially over coarse sand and gravel as opposed to fine sand, and in water depths between 60 and 70 m. These preferences appear to vary seasonally. The above results are consistent with findings of previous investigators using semi-annual research trawl survey data, and suggest that commercial landings data, despite their known errors and biases, can be used effectively to infer associations between fish and their environment.

Key words: Atlantic cod, commercial landings, depth, environmental correlates, *Gadus morhua*, haddock, *Melanogrammus aeglefinus*, sediment type, temperature

INTRODUCTION

Numerous investigators have shown that changes in the distributions of a variety of commercial fish stocks can be linked to changes in certain environmental variables (e.g. Smith *et al.*, 1991; Mountain and Murawski, 1992; O'Brien and Rago, 1996; O'Brien, 1997). A number of attempts have been made to use such relationships to predict the distributions of fish stocks over various space and time scales (e.g. Stefansson and Palsson, 1997, 1998; Bertignac *et al.*, 1998). However, a major difficulty of making such predictions is that the models are often 'data poor.' This is because such studies typically rely on research trawl survey data which, while rich with precision, frequently lack wide coverage either spatially or temporally because of the large amount of time and effort required to collect and process the data.

Since the late 1960s, the US National Marine Fisheries Service (NMFS) has been conducting semi-annual stock assessment surveys each winter/spring and fall, off the northeast coast of the United States. These surveys are spatially well resolved and provide valuable information on long-term trends in the fisheries. However, they are still only semi-annual snapshots in time. To predict changes in fish stocks on shorter time scales (e.g. seasonal, monthly or even weekly), spatially and temporally explicit models require more continuous short-term coverage. In this paper, we investigate whether such coverage can be obtained from commercial landings or weigh-out data which, although not as accurate or precise as research trawl survey data, have the advantage of having higher temporal resolution during certain times of the year.

From a modeling as well as a statistical standpoint, commercial landings data complement research trawl data in that they provide additional information, albeit at the expense of accuracy and precision, i.e. commercial landings data represent a well-populated but broad distribution as opposed to a sparsely populated narrow distribution. Both types of data may be equally useful under different circumstances. In the case of commercial landings, a large amount of data can help reduce the overall uncertainty, which can in part compensate for the greater variance in these data.

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Furthermore, with regard to temporal resolution, frequent but noisy information about a system can sometimes be more useful than knowing the system's state precisely but lacking information about its short-term tendencies, depending on the questions being considered.

In this paper, we examine whether commercial landings data can be used to detect associations between fish stocks and certain environmental variables in a manner similar to previous studies that used fishery-independent research trawl data. Our goal is to determine to what extent commercial landings data can be exploited to provide the spatial and temporal coverage needed by predictive fish distribution models. In other words, can predictive models benefit by having more data, albeit of greater variance, without the precision requirements of traditional research surveys?

Background and scope

Canadian and US research trawl survey data have been used by numerous investigators to study relationships between the distributions of commercial fish stocks and certain environmental variables in the northwest Atlantic. For example, Smith *et al.* (1991) argued that the catchability of Atlantic cod over the Scotian Shelf increases with higher incidence of Scotian Shelf Intermediate Water along the bottom because of higher relative abundances of cod near the bottom. Perry and Smith (1994) used cumulative distribution functions to show that haddock maintained particular temperature ranges through the winter/spring and summer by changing their seasonal depth distributions, while cod were associated with particular depth, temperature, and salinity only during summer. Mountain and Murawski (1992) used winter and spring trawl surveys in the Gulf of Maine and the Mid-Atlantic Bight to show that the distributions of a variety of fishes may be associated with particular ranges of bottom temperature. They concluded that in winter and spring, cod and haddock tend preferentially towards bottom temperatures of approximately 5.2–5.4°C. Furthermore, they found that these temperature preferences may also be related to changes in depth and/or latitude. Temperature associations of cod and haddock were also found in fall survey data over the same geographic regions by O'Brien and Rago (1996) and O'Brien (1997) using a generalized additive model. In contrast to Mountain and Murawski's (1992) winter and spring results, however, they found that during fall surveys the distributions of these species were negatively correlated with depth and temperature, with preferred depths generally less than approximately 100 m, and preferred bottom temperatures varying between 8 and 12°C.

Such associations can be used to predict distributions of commercial fish stocks over a variety of time and space scales, provided the associations are 'stable' over the relevant scales. For example, Bertignac *et al.* (1998) used the idea of a habitat index to predict the distributions of tuna in the equatorial Pacific over seasonal time scales. Similarly, a large effort by the Marine Research Institute, Iceland, is underway to develop a multi-species model for boreal systems in an attempt to model the marine ecosystem around Iceland (e.g. Stefansson and Palsson, 1997, 1998).

In the present study, we extend such approaches through an analysis of environmental indicators. We use commercial landings data to complement the findings of previous regional studies, which were based principally on fishery-independent research trawl survey data. In particular, we examine whether commercial landings data, despite their additional sources of error and bias (e.g. Holland and Sutinen, 2000), can complement the survey data by incorporating different time and space scales. Most notably, the commercial data from Georges Bank are available throughout the year and hence provide information about the periods between winter/spring and fall NMFS surveys. The present work focuses on two questions: (1) How do we describe the spatial and temporal variability observed in the distributions of commercial fish stocks in the ocean? (2) What is the efficacy of using commercial landings data for this purpose?

MATERIALS AND METHODS

We examined historical commercial landings of Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) from Georges Bank data compiled by the NMFS, and a number of scientific environmental data sets including historical conductivity, temperature, depth (CTD) records, bottom sediment type distributions, and bathymetry.

Commercial landings data

Catch distributions of commercial fish stocks were obtained from historical commercial landings data compiled by the US NMFS. The data used in this study spanned the 11-yr period (1982–1992) and were in the form of pounds of fish landed and total fishing time per sub-trip (i.e. region fished), from which we computed catch per unit of fishing effort (CPUE) in units of kg day^{-1}. All landings data included the year, month, nominal day, and latitude and longitude (to the nearest 10 min) at which the fish were caught. In addition, the depth zone at which the fish were caught was provided in the following ranges: 0–30 fathoms (0–55 m), 31–60 fathoms (56–110 m), 61–100 fathoms (111–184 m), 101–150 fathoms (185–275 m), 151–200 fathoms (276–366 m), 201–300 fathoms (367–549 m), >300 fathoms (549 m), or mixed depths (three or more depth zones).

To minimize variability within the data, and to avoid the problem of standardizing catch rates across different vessel sizes and gear types (e.g. Gavaris, 1980; Ortega-Garcia and Gomez-Munoz, 1992), we restricted our analysis to data collected by vessels 70–79 ft (21.3–24.1 m) in length, and which fished along the bottom using otter trawls (i.e. from the raw data, length code = 07 and gear code = 050). As the present analysis focuses on near-bottom dwelling species, we further selected data whose reported depth zone encompassed the bottom. The resulting database consisted of a total of 3591 and 2904 CPUE records for cod and haddock, respectively, within the region bounded by 69.5°W, 65.0°W, and 39.5°N, 43.0°N. Of these, 2062 cod and 1558 haddock records were located over the crest of Georges Bank within the 110-m isobath. Resulting spatial distributions of CPUE for cod and haddock are shown by month in Figs 1 and 2 respectively.

In addition to the above 'raw' format, the data were used to create smoothed monthly maps of CPUE across the Bank, averaging over all years. These smoothed maps were used as a baseline for computing CPUE anomalies, which could then be compared with research survey data from previous studies. Smoothing was carried out by the method of optimal interpolation (OI) described by Bretherton *et al.* (1976). As part of this analysis, isotropic spatial correlation functions of both cod and haddock CPUE were first computed for each month. The correlation functions indicated decorrelation scales ranging from 50 to 150 km for both species. To balance the trade-off between retaining small-scale spatial variations versus smoothing over sparse data in both space and time, we thus used an isotropic Gaussian correlation function with a decorrelation scale of 60 km in our OI.

To address the question of how the commercial landings data portrayed changes in abundance of cod and haddock over the Bank, we computed time series of cod and haddock CPUE anomalies over the Bank. Anomalies at individual stations were calculated as the difference between the observed CPUE for a given month and the monthly averaged value at the same location based on OI maps. The mean difference between these values was then taken as the mean anomaly for that month. Note that while this approach removes the seasonal cycle from the monthly anomalies, it does not remove interannual variability.

Hydrographic data

Historical CTD data were compiled from a variety of US and Canadian sources including the National Oceanographic Data Center (NODC); the Marine Resources Monitoring, Assessment and Prediction Program (MARMAP); the Global Ocean Ecosystems Dynamics program (GLOBEC); the Atlantic Fisheries Adjustment Program (AFAP); and a number of other smaller field programs. Only those casts that extended over the full water column (i.e. from within 5 m of the surface to more than 85% of the total water depth) were used. A total of 15 632 CTD profiles were retained for the region bounded by 69.5°W, 65.0°W, and 39.5°N, 43.0°N, and spanning the period from July 11, 1913 to October 6, 1999. Of these, 10 063 profiles were within the region bounded by the 110-m isobath. To coincide with the time span of the historical commercial landings data, only CTD data from 1982 to 1992 were used to assess associations between CPUE and environmental variables. The full CTD data set was used as a reference for computing monthly anomalies.

Profiles that did not extend to the surface or bottom were extrapolated to these levels. Specifically, casts that extended to within 5 m of the surface were extrapolated to the surface using the next shallowest observation as the surface value, while casts that extended deeper than 85% of the overall water depth were extrapolated to the bottom by using the next deepest observation as the bottom value. The extrapolated data set was then used to determine surface and bottom values of temperature, salinity, potential density, and spiciness (the latter a measure of temperature and salinity variability along isopycnal surfaces; Flament and Huyer, 1991). The differences between surface and bottom values, divided by the water depth, h, of these variables were also computed as a measure of their respective contributions to the vertical stratification.

The CTD data were binned by month and used to create smoothed maps of surface and bottom temperature, salinity, potential density, and spiciness, again using the method of OI. As with CPUE, these smoothed maps were used as a baseline for computing anomalies that could be compared with previous studies. Isotropic spatial correlation functions were computed for each month for each of the variables of interest, again revealing decorrelation scales of 50–150 km. In light of this, and to balance the trade-off between retaining synoptic features (such as the

Figure 1. Monthly distributions of commercial CPUE (kg day^{-1}) for Atlantic cod (*Gadus morhua*) over Georges Bank for the period 1982–1992. The 50, 110, and 500-m isobaths are also shown.

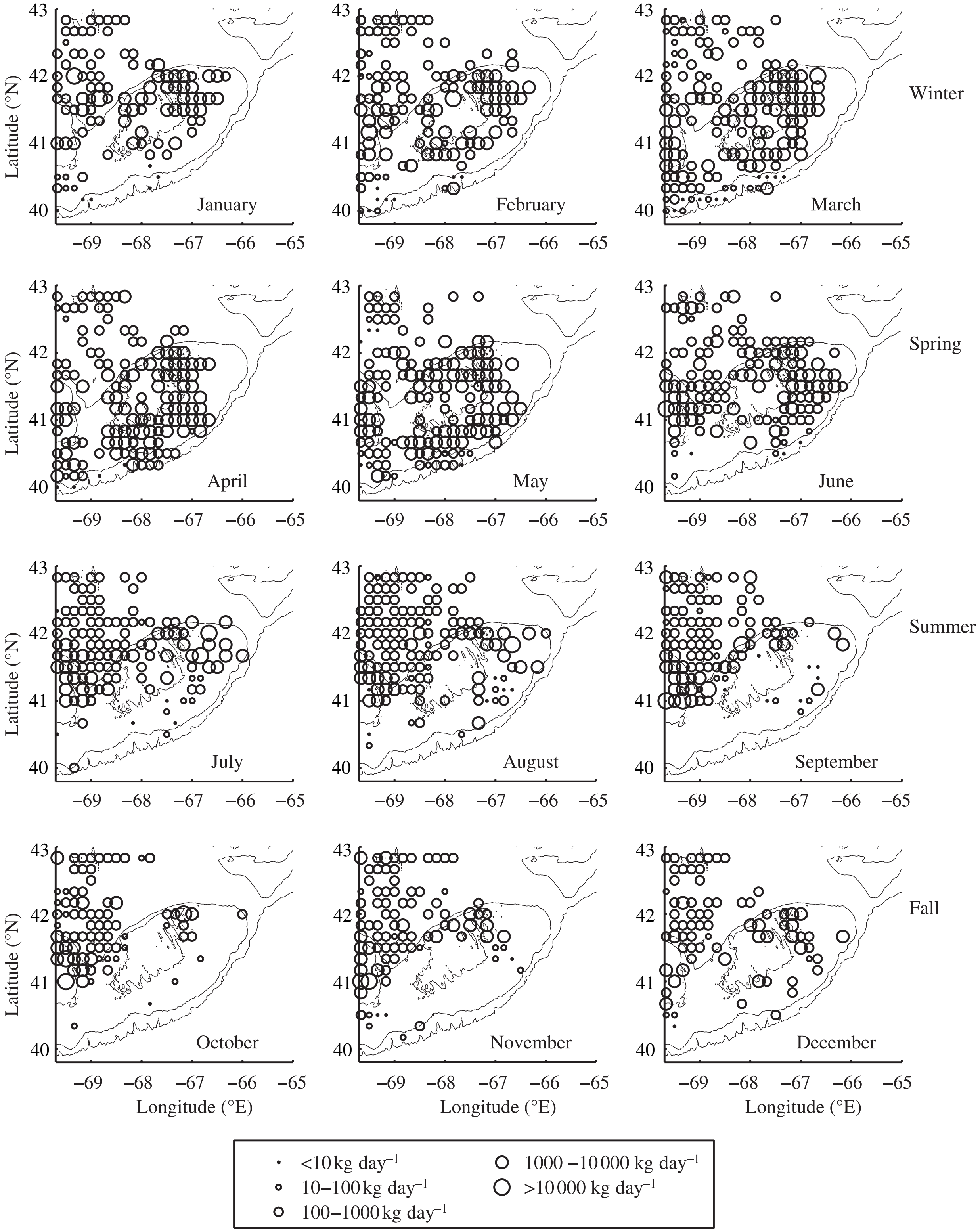
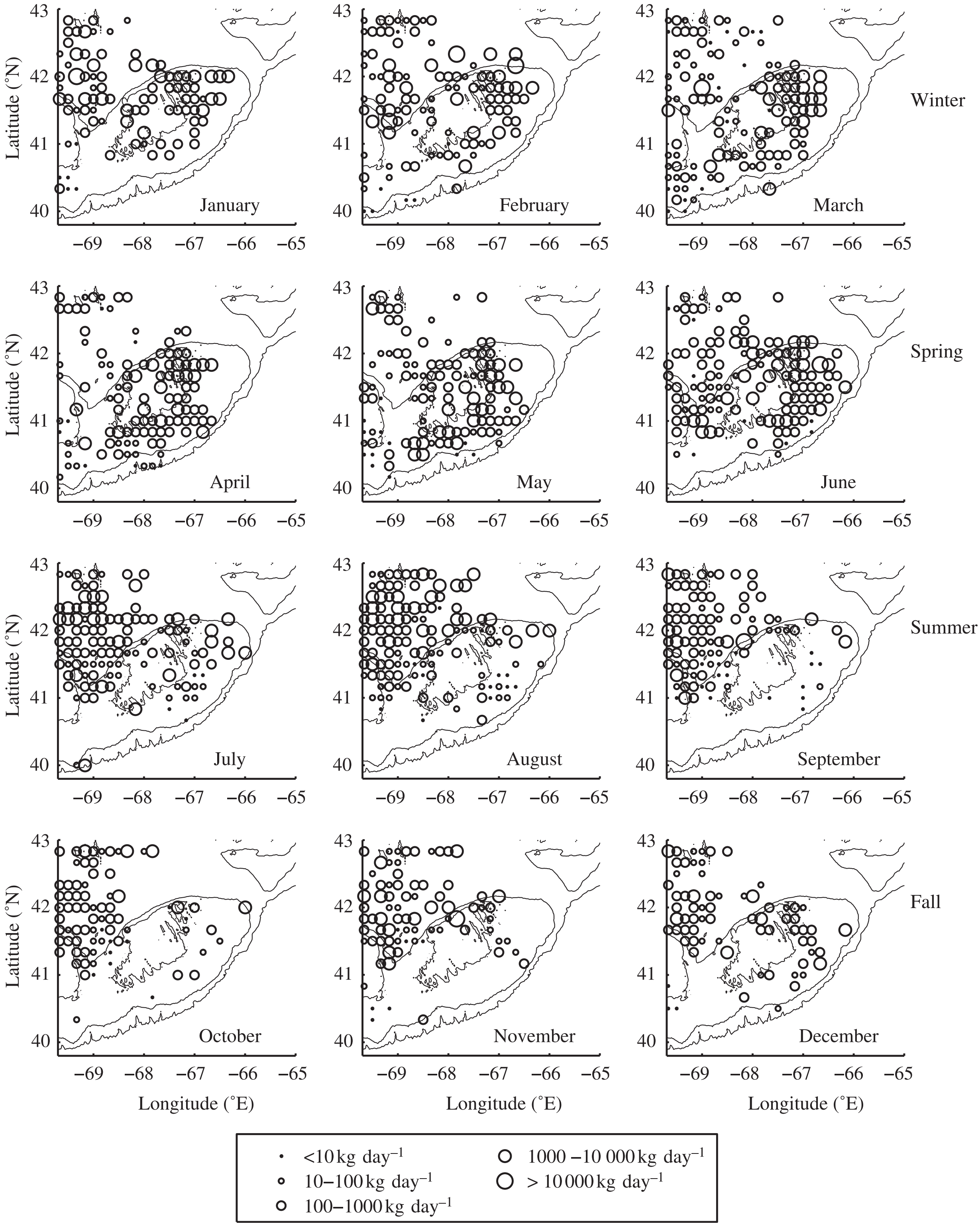


Figure 2. Monthly distributions of commercial CPUE (kg day^{-1}) for haddock (*Melanogrammus aeglefinus*) over Georges Bank for the period 1982–1992. The 50, 110, and 500-m isobaths are also shown.



shelf-slope front and the tidal mixing front), and smoothing over sparse data in both space and time (which could lead to artificially large spatial gradients in the property fields), we again used an isotropic Gaussian correlation function with a decorrelation scale of 60 km.

As with CPUE, anomalies of hydrographic variables were computed as the average difference between observed temperature and the corresponding mean monthly value for the same location using the OI maps. For direct comparison with Mountain and Murawski (1992), where appropriate we have restricted our mean temperature calculation to the region within the 110-m isobath (approximately 60 fathoms), and limited our temperature anomaly analysis to winter/spring months. Note that throughout this paper we equate the four seasons with the following monthly periods 'winter', January to March; 'spring', April to June; 'summer', July to September; 'fall', October to December.

Bottom type and depth

Information about bottom type (i.e. sediment grain size) over Georges Bank was obtained from published data by Twichell *et al.* 1987; republished from Schlee, 1973). They classified sediments in terms of four categories of grain sizes: <1/16 mm (silt and clay), 1/16–1/4 mm (fine sand), 1/4–1 mm (medium-to-coarse sand), and >1 mm (gravel). This classification scheme coarsely follows Wentworth (1922). The distribution of sediment sizes over Georges Bank and surrounding areas is shown in Fig. 3.

The discretely classified sediment sizes were further interpolated to form a continuous distribution of sediment types over a regular grid. This was carried out in order to assess whether our analysis is significantly affected by the discretization of continuous sediment size. The interpolation was performed by assigning an integer value to the contours of each of the sediment classes listed above (i.e. silt and clay = 1, fine sand = 2, medium-to-coarse sand = 3, and gravel = 4). The values of the sediment type were then interpolated between contours using simple quadratic interpolation. Both the discrete and continuous versions of these bottom types were used in the analysis.

Bathymetry data used in the present study were obtained from the US Geological Survey. The 15-s resolution data used here are a subset of a larger database that covers the Gulf of Maine, Georges Bank, and the New England continental shelf. Contours of the bathymetry are overplotted on the sediment type distributions in Fig. 3.

Mean and catch-weighted mean environmental variables

Following the approach of Mountain and Murawski (1992), we computed mean and catch-weighted mean values of select hydrographic variables, bottom sediment type, and bottom depth over Georges Bank. In contrast to their analysis, which used simultaneous observations of CPUE and environmental variables, however, here we used independent (i.e., non-colocated) data sets for CPUE and hydrographic variables.

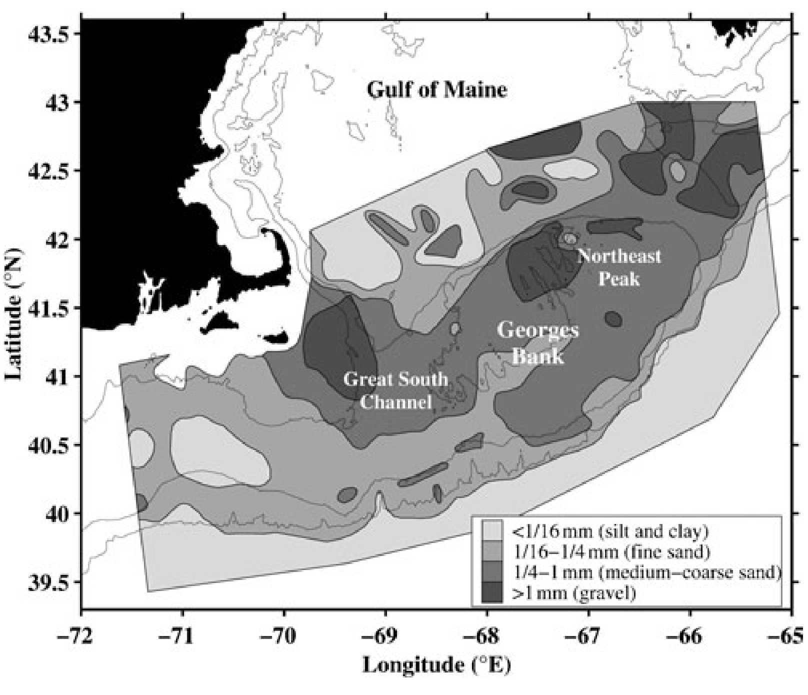


Figure 3. Bottom sediment grain size over Georges Bank showing distributions of silt and clay, fine sand, medium-to-coarse sand, and gravel (after Twichell *et al.*, 1987; republished from Schlee, 1973). The 50, 110, and 500-m isobaths are also shown.

This was necessary because the latter were not available as part of the commercial landings data set.

To address the problem of non-co-located fish and hydrographic data, hydrographic variables were estimated at the locations of the CPUE records via two methods. In the first method, we defined co-located data as those CPUE records for which there were CTD data collected within 5 days and 60 km. These values were chosen subjectively to allow co-location of a significant number of CPUE and hydrographic data records without excessively smoothing the hydrographic data. Tests in which we increased/decreased the values of the interpolation time and space scales by 50% suggested that our results were not extremely sensitive to their precise values. For CPUE records where multiple hydrographic data were available within the specified radius, hydrographic variables at the catch locations were computed using nearest-neighbor interpolation. Catch-weighted means of each hydrographic variable were then computed for each month of the time series by multiplying the hydrographic variable at each location by the natural log of CPUE for that location, and dividing by the sum of the weights. The natural log of CPUE was used because both species exhibited an approximately log-normal distribution (e.g. Mountain and Murawski, 1992; see also Results section). The total number of CPUE records that could be co-located with hydrographic data via this method was approximately 20% of the total number available over the Bank, i.e. 464 (of 2062) records for cod, and 269 (of 1558) records for haddock.

Given the high percentage of the CPUE data that could not be co-located with hydrographic data via the above method, a second method of co-locating data was also used. In the second method, hydrographic variables at the locations of the CPUE records were inferred from the monthly OI analysis described above, and adjusted by the corresponding monthly anomaly for the appropriate year. For example, if the observed temperature anomaly for January of a given year was −1°C, the temperature corresponding to a CPUE record from January of that year was estimated as the January OI temperature at the location of that CPUE record minus 1°C. While this approach leads to a greater amount of smoothing of the data (both temporal and spatial), a major advantage over the first co-location method is that it provides an estimate of the hydrographic variables at nearly all of the CPUE data locations.

Bottom type and bottom depth data sets were well resolved across the Bank, and hence did not have the same issue of non-co-location as the hydrographic data. Instead, bottom type and bottom depth at each catch location were inferred directly by OI. CPUE-weighted sediment type was calculated in two ways. First, we computed time series of monthly averaged CPUE of cod and haddock over each discrete sediment class over Georges Bank. Second, using the 'continuous' sediment type, we computed monthly averaged ln(CPUE)-weighted sediment type in the same manner described above for hydrographic variables. Monthly averaged ln(CPUE)-weighted bottom depth was also computed in this manner.

The above catch-weighted means were used to determine environmental associations in two ways. First, in the case of the hydrographic variables, linear regression was used to determine whether scatter plots of weighted versus unweighted monthly means differed significantly from a random distribution. Specifically, if fish were randomly distributed with respect to the environmental variables in question, regardless of the value of that variable, the regression would be expected to yield a slope of 1. Conversely, a slope significantly different from 1 would imply a non-random distribution, i.e. a tendency toward a particular value (or values) of that variable. Second, in the case of bottom type and bottom depth, CPUE-weighted monthly means were again compared with the unweighted mean values over the same region. Again, any differences between the weighted and un-weighted means would indicate a non-random distribution, i.e. a tendency toward a particular value of the environmental variable in question.

RESULTS

Spatial distributions

The data over Georges Bank provided between 30 and 50% spatial coverage during winter and spring, and somewhat less coverage during late summer and fall (see Figs 1 and 2). In general, spatial distributions inferred from the commercial landings data showed good agreement of aggregations of cod and haddock with published results from NMFS winter/spring and fall bottom trawl surveys (e.g. Begg, 1998; Fogarty and Murawski, 1998). Both cod and haddock indicated a general tendency of relatively high CPUE (CPUE approximately 1000–10 000 kg day^{-1}) over the crest of the Bank during winter and spring, which decreased toward late summer/early fall. Cod CPUE tended to remain high over the crest of the Bank during winter and spring (December to May), while haddock CPUE peaked for a limited period during late spring (April to June). Double maxima, one over the northeast peak of the Bank and one just northwest of the Great South Channel, were also evident in the CPUE distributions of both species. These local maxima appeared between June and December in the cod data, and between February and March in the haddock data (e.g. Brown and Munroe, 2000; O'Brien and Munroe, 2000).

Anomaly time series of cod and haddock CPUE over the Bank indicate a general trend of declining CPUE for both cod and haddock over the 11-year period examined (Fig. 4). These trends are consistent with results of previous investigators who showed declining stocks of both species over Georges Bank (e.g. Brown and Munroe, 2000; O'Brien and Munroe, 2000; see also Fig. 4). For example, a regression analysis (not shown) applied to cod landings per unit effort versus catch per tow from spring and fall survey data reported by O'Brien and Munroe (2000) for the period 1978–1999 gives slopes of 6.6 (9.2 and 4.0) (at 95% confidence) and 4.9 (7.1 and 2.7) for winter/spring and fall, respectively, with r^2 values of 0.58 and 0.53, and P-values of 3.6×10^{-5} and 1.3×10^{-4}. These results suggest that CPUE data derived from commercial landings data can be used as an approximate indicator of abundance (see also Discussion).

Monthly histograms of the landings data showed that CPUE distributions for both species were very nearly log-normal throughout much of the year (Fig. 5). Specifically, at the 99% confidence level a Kolmogorov–Smirnov test showed that six of 12 cod, and four of 12 haddock distributions were consistent with a log-normal distribution, while a Lilliefors test indicated that five of 12 cod, and eight of 12 haddock distributions were consistent with a log-normal distribution. Months when CPUE distributions were not lognormal occurred in spring/early summer when distributions for both species were somewhat skewed toward lower CPUE.

The distributions shown in Fig. 5 further showed a general trend toward higher mean CPUE in winter/spring for both cod and haddock. This seasonality is consistent with the findings of Lough (1984) and Smith and Morse (1985), who suggested that peak spawning times for cod and haddock over Georges Bank occur in late February to early March, and early April, respectively. A trend from fairly narrow CPUE distributions (low variance) in winter/spring to much broader distributions (higher variance) in summer/fall was also apparent for both species.

Hydrography

Hydrographic data, particularly bottom temperature, were similarly compared with analogous data sets by previous investigators. Figure 6 shows the annual temperature cycle over the crest of Georges Bank (i.e. within the 110-m isobath) computed from the temperature OI fields. Both surface and bottom temperature time series are shown. Also shown are monthly mean temperatures over the Bank based on trawl surveys from the period 1977 to 1987 by Manning and Holzwarth (1990). The latter were averaged over two depth ranges, 0–30 m and 30–100 m. The two data sets agree to within the uncertainty of the measurements, suggesting that the two data sets are of comparable quality.

Surface and bottom temperature anomaly time series averaged for the months of February through April of each year are shown in Fig. 7 along with anomalies estimated from winter/spring trawl surveys

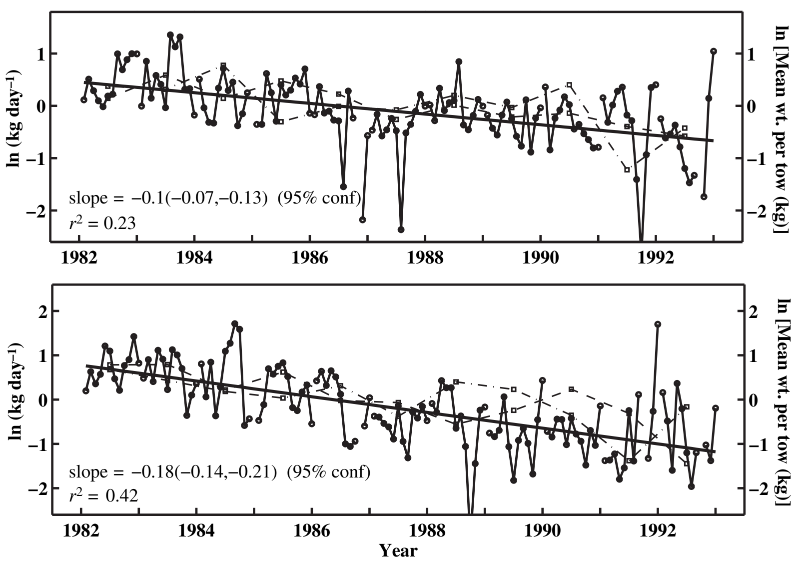


Figure 4. Time series of monthly ln(CPUE) anomaly for (a) Atlantic cod and (b) haddock over Georges Bank for the period 1982–1992. Circles connected by a line show monthly anomalies, while thick lines indicate a linear least squares fit to the data. The respective slopes, 95% confidence limits, and r^2 values for the fitted lines are also given in each subplot. Time series of catch per tow (kg) from spring (dashed line) and fall (dot-dashed) NMFS bottom trawl surveys reported by O'Brien and Munroe (2000) and Brown and Munroe (2000), respectively, for the same period are also shown.

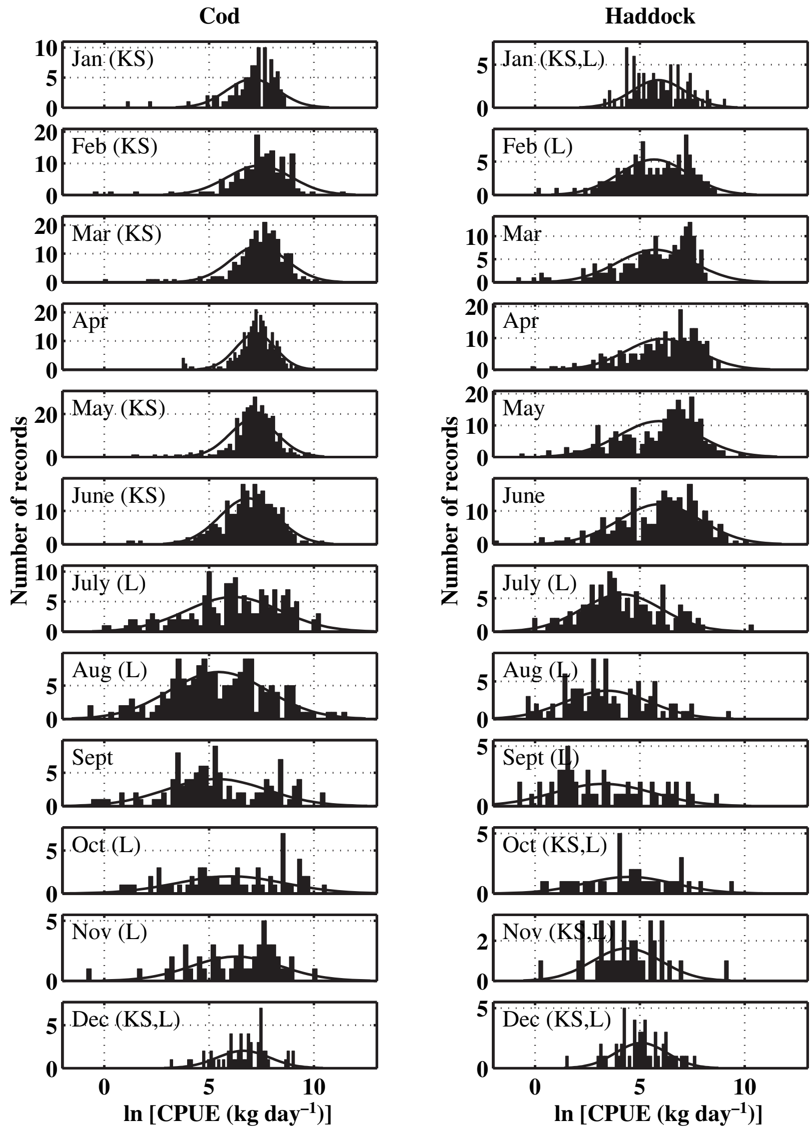


Figure 5. Monthly histograms of ln(CPUE (kg day^{-1})) for the period 1982–1992 for Atlantic cod and haddock for the region of Georges Bank inside the 110-m isobath showing approximately log-normal distributions throughout the year. Distributions that were indistinguishable from a log-normal distribution at the 99% confidence level using either a Kolmogorov–Smirnov or Lilliefors test are annotated by (KS) or (L), respectively. Note that both species show a trend of higher mean CPUE but lower variance in winter/spring months compared with summer/fall. Also note the different vertical scales.

by Mountain and Murawski (1992). Again we found reasonable agreement between the two data sets. A notable exception was 1988, a year when our data set had relatively poor coverage. Also note that 1991 and 1992 were years not studied by Mountain and Murawski (1992).

Mean and catch-weighted mean environmental variables

The CPUE-weighted bottom temperatures for cod computed using the first co-location method described in the previous section, and corresponding mean bottom temperatures, are shown as scatter plots in Fig. 8a. For larger values of mean bottom temperature, the majority of points fall below the 1 : 1 line. A linear fit to the data yields an r^2 of 0.44 and a slope of 0.6 (0.8 and 0.4), where upper and lower bounds on the slope represent 95% confidence intervals. The fact that this slope is <1 indicates that while mean bottom temperatures over the Bank generally increased toward summer, CPUE-weighted temperatures did so to a lesser degree. In other words, as bottom temperatures on Georges Bank increased, cod tended toward cooler regions of the Bank. The same analysis using the second co-location method (not shown) yielded comparable results, except that in that case the r^2 value and slope were slightly greater, i.e. an r^2 of 0.79 and a slope of 0.74 (0.84 and 0.65).

Similar results were found for haddock (not shown). Namely, for larger values of mean bottom temperature, again the majority of points fell below the 1 : 1 line. A linear fit to the data yielded an r^2 of 0.65 and a slope of 0.77 (0.93 and 0.61), where upper and lower bounds

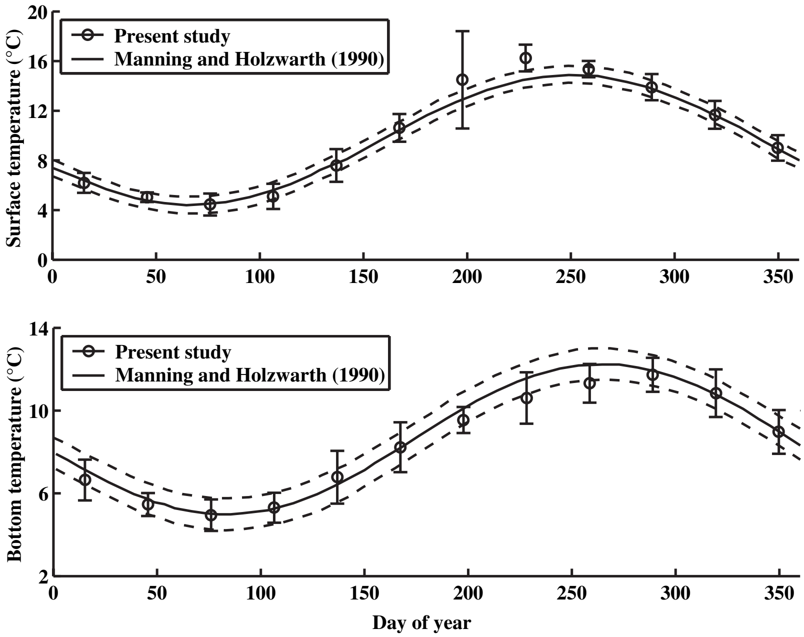


Figure 6. Annual cycle of monthly mean Georges Bank (a) surface temperature and (b) bottom temperature. Open circles (with error bars representing 1 SD) are averages for the present data set based on OI fields using only data within the 110-m isobath. Solid lines (with dashed lines representing uncertainty) are after Manning and Holzwarth (1990), and represent averages over 0–30 m and 30–100 m depth ranges, respectively.

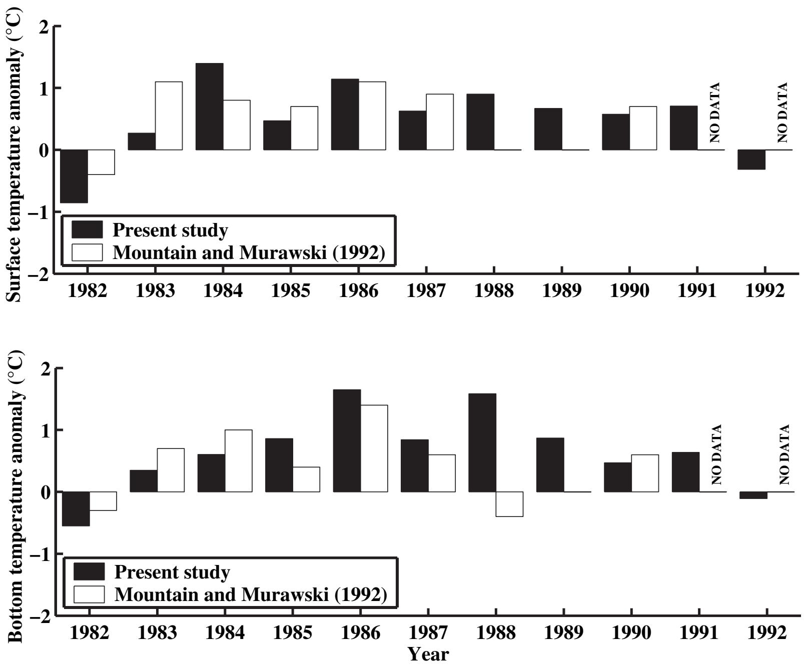
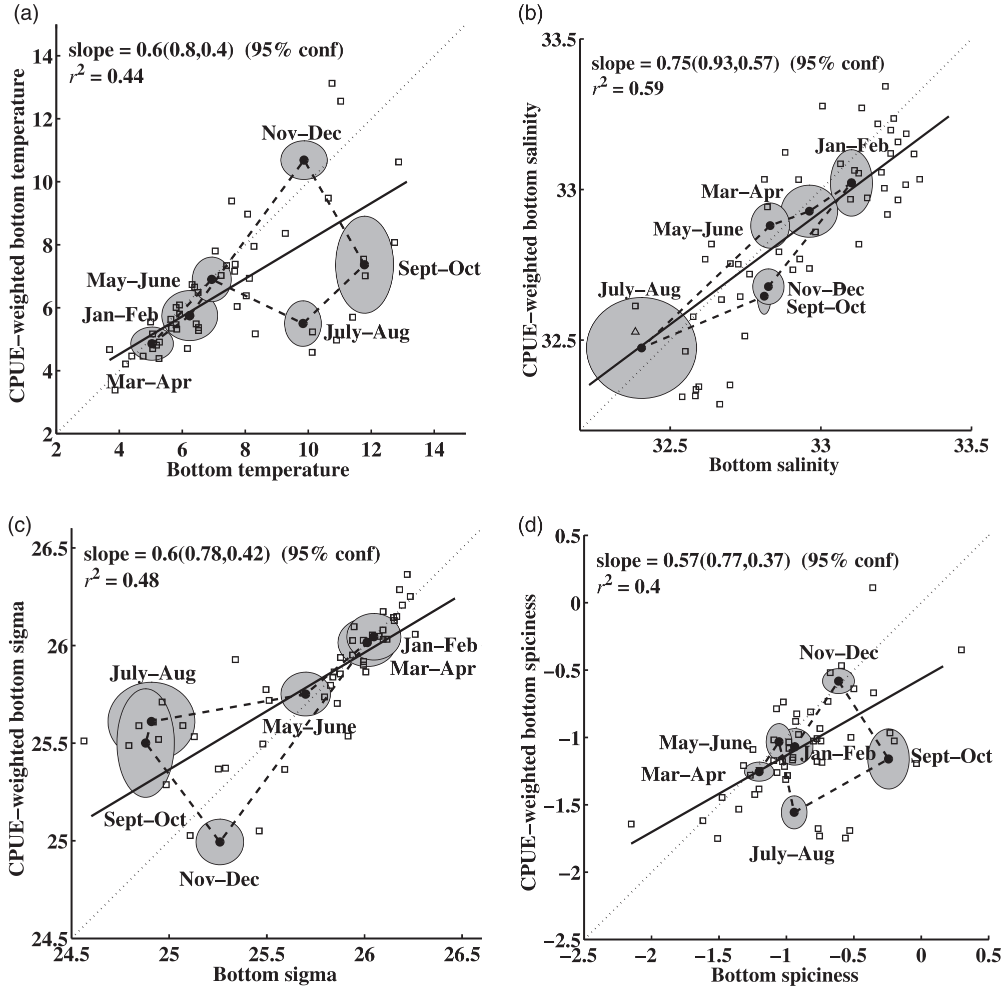


Figure 7. (a) Surface and (b) bottom temperature anomalies over Georges Bank showing annual variations in winter/spring conditions. Solid bars represent data from the present study, while open bars are after Mountain and Murawski (1992). Temperature anomalies computed for the present study represent 3-month averages from February to April of each year. Mountain and Murawski (1992) values were based on winter and spring bottom trawl survey data.

on the slope again represent 95% confidence intervals. The same analysis using the second co-location method yielded an r^2 of 0.88 and a slope of 0.79 (0.86 and 0.71), i.e. again a slightly greater slope than the first co-location method.

The above tendency is consistent with that found by Mountain and Murawski (1992). Specifically, using winter/spring survey data (bottom temperatures between 4 and 7°C) they found that during anomalously warm winter/spring periods, cod and haddock were caught predominantly in the cooler regions of the Bank, while during anomalously cooler winter/spring periods they were caught predominantly in the warmer regions. That our results show a somewhat tighter relationship between catch temperature and mean bottom temperature during winter/spring periods than

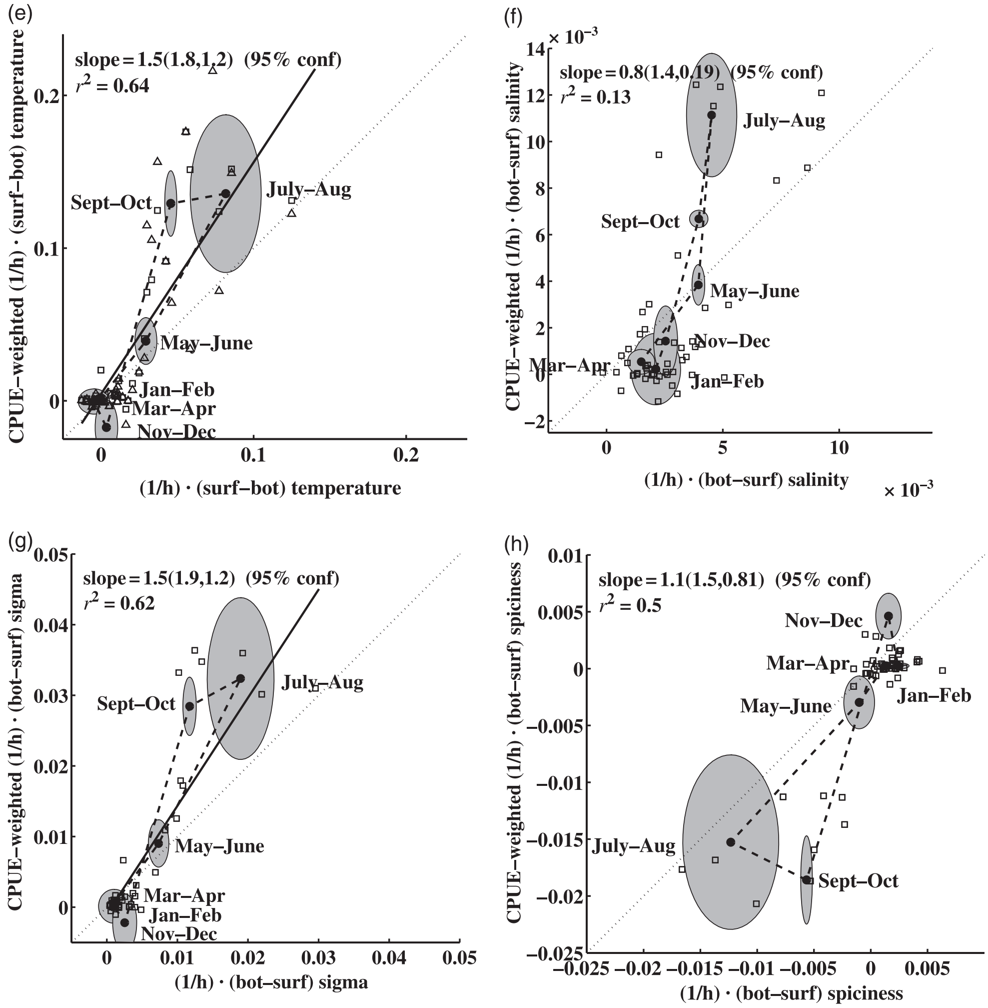
Figure 8. (a) CPUE-weighted bottom temperature for Atlantic cod versus mean bottom temperature over Georges Bank for the period spanning 1982–1992 (reprinted from Sundermeyer *et al.*, 2003), and analogous plots for (b) bottom salinity, (c) bottom density, (d) bottom spiciness, (e) (1/*h*)·(surface-bottom) temperature, (f) (1/*h*)·(bottom-surface) salinity, (g) (1/*h*)·(bottom-surface) density, and (h) (1/*h*)·(bottom-surface) spiciness, where *h* is the water depth. Monthly means are indicated by squares. Ellipses within each panel indicate bimonthly averages, with the ellipse centers indicating the averages and the sizes indicating the standard error (computed as the standard deviation divided $\sqrt{N}$). Regression statistics for a linear fit to the monthly mean values are also shown. Regression lines are only plotted for cases where the slope was significantly different from 1 : 1 at the 95% confidence level. All calculations were for the area of the Bank within the 110-m isobath (60 fathoms).



did Mountain and Murawski (1992) (i.e. data in Fig. 8a lie closer to the 1 : 1 line; they obtained a slope of 0.34 (0.09 and 0.58) with an $r^2 = 0.29$) we believe is because of the interpolation and hence averaging of the temperature fields in the present study. The effect of the latter would cause our estimates of catch temperature to be closer to the mean bottom temperature. This conclusion is also consistent with our finding that regression slopes using the second co-location method were greater than the first; this is because the second method incorporates additional smoothing into the analysis.

The larger deviation from the 1 : 1 line in Fig. 8a for the summer/fall seasons can be interpreted in one of two ways. First, it may be that cod and haddock prefer temperatures of 5°C throughout the year, and the fact that they are found in 10–11°C water in late fall is simply because that is the coolest temperature available to them on the Bank at that time. Alternatively, it may be that during fall months, cod and haddock over the Bank prefer higher temperatures between 10 and 11°C rather than the cooler 5°C of winter/spring. The latter interpretation is more consistent with that of O'Brien and Rago (1996) and

Figure 8. Continued.



O'Brien (1997) based on analysis of fall trawl survey data using a generalized additive model.

Similar analyses were performed between other CPUE-weighted hydrographic variables and their Bank-wide averages (Fig. 8b–h). The surface to bottom property differences divided by water depth can be thought of as a bulk measure of the stratification associated with each of these variables. In all cases, environmental variables were again examined against both cod and haddock data. Results for cod, including regression statistics for each variable are given in the respective subplots of Fig. 8. Again, results for haddock (not shown) were similar.

As with bottom temperature, significant relationships were found between bottom spiciness and CPUE-weighted bottom spiciness, and between bottom density and CPUE-weighted bottom density, except that in the latter case the large deviations from the 1 : 1 line occurred at low values of density (Fig. 8c). With respect to the latter finding, note that temperature and spiciness are positively correlated, whereas temperature and density are negatively correlated. Thus we believe the deviations from the 1 : 1 line found in bottom density simply reflect the deviations found for bottom temperature. This conclusion is supported by the fact that both species showed only modest deviations from 1 : 1 for mean bottom salinity versus CPUE-weighted bottom salinity (Fig. 8b).

The CPUE-weighted surface-bottom temperature difference normalized by depth generally increased more rapidly than corresponding mean values over the Bank (i.e. slope significantly greater than 1 : 1 line), with largest values occurring during summer/fall (Fig. 8e). A similar trend was found for the bottom-surface density difference normalized by depth (Fig. 8g). The same tendency could be seen in bi-monthly mean ellipses for bottom-surface salinity difference normalized by depth, and inversely in bottom-surface spiciness difference normalized by depth, although regression statistics in these cases were not significantly different from 1 : 1 (Fig. 8f and h). These results suggest that during the (warmer) summer/fall well-stratified periods, cod and haddock tended towards the more strongly stratified regions of the Bank and hence, by inference away from the well-mixed crest of the Bank. This tendency may be related to the bottom temperature and density relationships noted above, because regions of stronger stratification tend to coincide with cooler bottom waters during the summer and fall.

Finally, the above analysis was repeated for surface values of the same hydrographic variables. Based on linear regression, no significant deviations from a 1 : 1 relationship were found for surface temperature or surface salinity for either cod or haddock, and only marginal deviations were found for surface density and spiciness.

Bottom type and depth

The above results suggest that variations in certain water properties, specifically bottom temperature, may affect local fish distributions. However, it is also possible that fish distributions are affected by other physical environmental variables not directly related to hydrography. Studies by Lough *et al.* (1989), Mountain and Murawski (1992), and Scott (1982) have suggested that bottom sediment type and bottom depth may be two such variables.

Time series of monthly averaged CPUE of cod and haddock computed for each sediment type over Georges Bank are shown in Fig. 9. The data show two predominant signals. First, for all sediment types, cod and haddock had an annual cycle of higher CPUE in winter/spring and lower CPUE in summer/fall. Secondly, and more relevant here, is that throughout the year both species showed significantly higher CPUE over coarse sand and gravel compared with fine sand. This parallels the findings of Lough *et al.* (1989), who showed with video surveys that juvenile cod and haddock on eastern Georges Bank tended to aggregate predominantly over pebble/gravel bottom sediments, rather than over sand or clay.

Time series of CPUE-weighted sediment class computed for cod and haddock are shown in Fig. 10. The curves indicated a preferred sediment type between 3.2 and 3.8, i.e. coarse sand to gravel, for both cod and haddock throughout the year. For both species, the weighted means were significantly different from the mean sediment type (3.4 on our scale) over the entire Bank, indicating a preference toward certain bottom types. As in Fig. 9, both species tended slightly toward coarser sediment types during winter/spring compared with summer/fall. Note that two curves are plotted in each subpanel, one representing the calculation carried out using discrete sediment classes and the other using continuous sediment distributions. That the respective curves for each species showed the same tendencies with only a small offset in magnitude between them indicates that the results of this calculation were not highly sensitive to our definition of individual sediment classes. The constant offset between the respective curves occurs because the continuous model assigns a higher value of sediment size between contour lines (because of interpolation) than does the discrete model.

Lastly, Fig. 11 shows monthly averaged CPUE-weighted bottom depth time series for both cod and haddock. The curves show a general tendency of both species toward shallower waters in winter/spring, progressing toward deeper waters in summer/fall. Again the weighted means were significantly different from the mean depth (67 m) over the region of interest. This is consistent with the results of Mountain and Murawski (1992) and with the analysis of the previous section, which indicated that on seasonal as well as interannual time scales both of these species tended toward deeper cooler waters. As discussed by Mountain and Murawski (1992) with respect to inter-annual variations in mean bottom temperature, migration from deeper/cooler to shallower/warmer waters may be one way in which fish compensate for temporal variations in temperature over the Bank. Similarly, on seasonal times scales we might then expect that as the crest of Georges Bank warms toward summer, cod and haddock tend toward relatively cooler deeper waters to compensate. In winter/spring, as cooler water temperatures return to the Bank, so do the fish.

DISCUSSION

This analysis provides a framework for evaluating environmental indicators of commercial fish stock distributions using commercial landings data. However, there are also some caveats. First, the fact that the commercial landings data did not include co-located environmental data affected our analysis in two ways: (1) the number of useable landings data was limited to those data that were approximately co-located with independent hydrographic data (applies to co-location method 1 only), and (2) as the landings data and the CTD data were not exactly co-located, our estimates of catch-weighted variables were more uncertain (applied to both co-location methods).

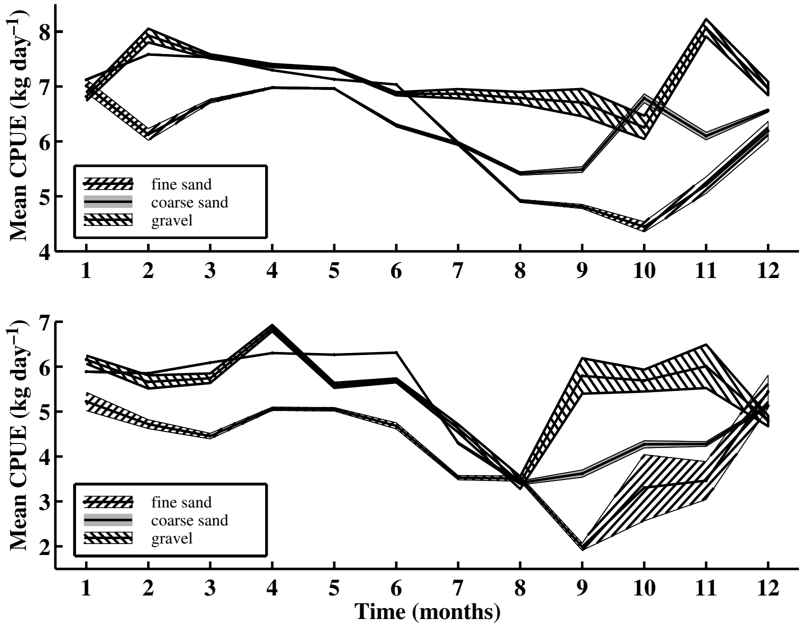
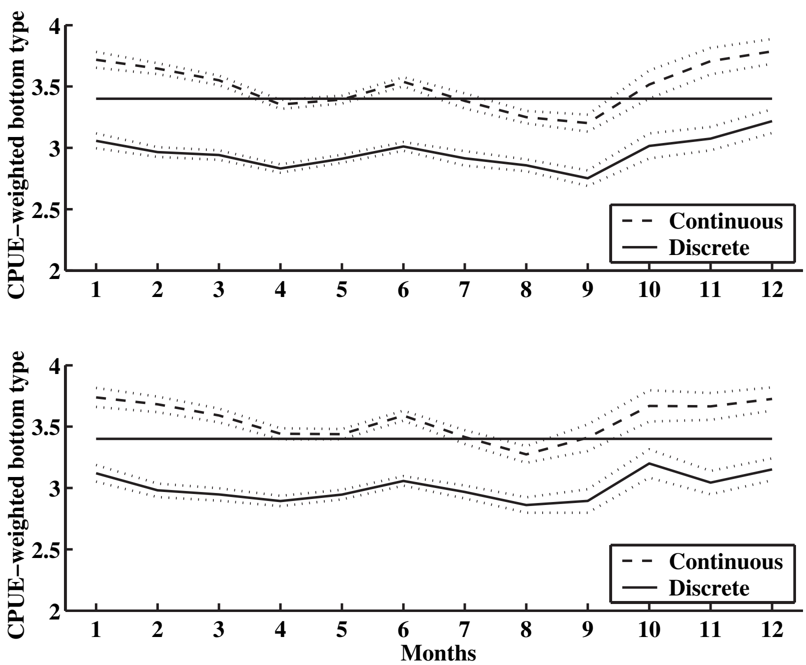


Figure 9. Time series of monthly averaged CPUE for (upper) Atlantic cod (reprinted from Sundermeyer *et al.* 2003) and (lower) haddock found over each sediment type over Georges Bank. Individual curves represent averages over the period 1982–1992 for a given sediment type, and show generally higher CPUE over coarse sand and gravel. Uncertainties of the means for each curve (computed as the standard deviation divided by the number of data) are indicated by the shaded region. Units are ln(CPUE (kg day^{-1})).

Figure 10. Time series of CPUE-weighted bottom sediment type for (upper) Atlantic cod and (lower) haddock over Georges Bank. The two curves in each subpanel are derived from the same calculation except that one uses a discrete and the other a continuous representation of sediment type across the Bank. The following convention was used to identify each of the four sediment classes: class 1 = <1/16 mm (silt and clay), class 2 = 1/16–1/4 mm (fine sand), class 3 = 1/4–1 mm (medium-to-coarse sand), and class 4 = >1 mm (gravel). In all cases weighted averages were computed for the period 1982–1992. The unweighted mean sediment type averaged over the entire bank is plotted as a solid straight line in each panel. Note that fractional classes are an artifact of the analysis, and may represent either mixtures of integer classes, or the next larger or smaller whole integer class.



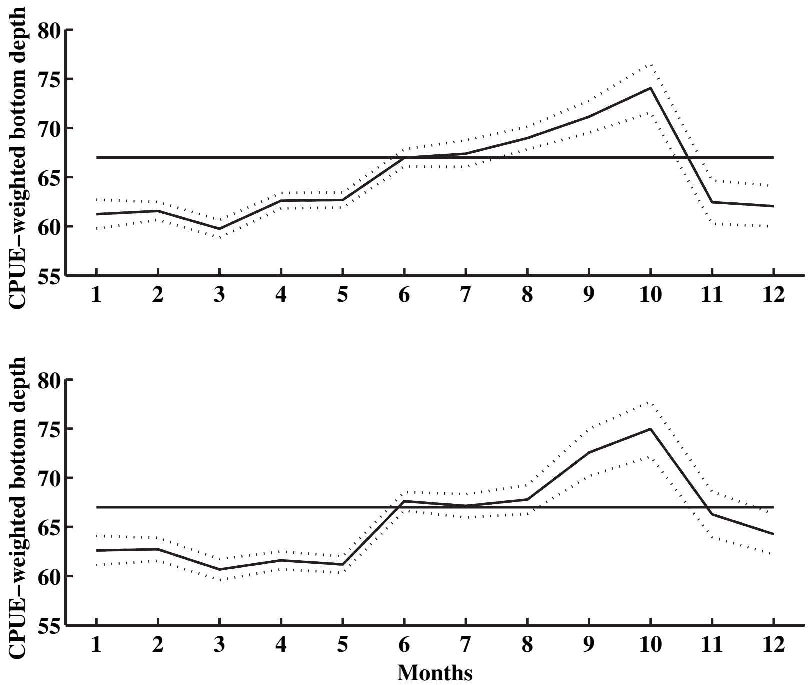


Figure 11. Time series of CPUE-weighted bottom depth for (upper) Atlantic cod (reprinted from Sundermeyer *et al.* 2003) and (lower) haddock over Georges Bank showing a tendency of both species towards shallower water depths in the winter/spring, and greater depths in summer/fall. All averages were computed for the period 1982–1992. The unweighted mean bottom depth averaged over the entire bank is plotted as a solid straight line.

Second, regional fisheries management regulations such as the seasonal closures of portions of Georges Bank from 1982 to 1985 and the designation of the 200-mile limit (the Hague line) in 1984 (e.g. Fogarty and Murawski, 1998) may have contributed to bias in our data. We have attempted to limit the effect of such bias at least in part by using monthly mean spatial distributions that average over all years. However, we have made no other attempt to compensate for the possible impacts of these regulations and closures.

A third caveat is that neither the fish CPUE nor the CTD data were synoptic during the period studied. There were also periods (most notably during late summer and fall) that commercial catch data were relatively sparse. As a result, derived variables such as CPUE-weighted bottom temperature were incomplete in their temporal and spatial coverage, and thus for any given year were not always representative of the study region as a whole. If the distribution of fishing effort reflects the distribution of the fish themselves, as suggested by Gillis *et al.* (1993) (see also Fretwell and Lucas, 1970; Fretwell, 1972), then sparse data coverage would not be an issue because regions with little or no data would presumably represent regions of low CPUE and hence low weighting in our catch-weighted calculations. However, if effort does not reflect distribution, then, for example, our estimates of CPUE-weighted temperature may be biased low during summer/fall when there is only minimal data coverage over the relatively warm crest of the Bank (see Fig. 8). Some of this bias would have been taken into account insofar as we used monthly mean spatial distributions as a basis for our anomaly time series analysis. Nevertheless, an inevitable result of non-synopticity is that because the two data sets were not co-located, our comparison of environmental variables with fish CPUE is only approximate.

Another major caveat is that CPUE derived from commercial landings data may be biased by other factors, including the fishermen's choice of fishing locations (e.g. Holland and Sutinen, 1999, 2000), and possible effects of competition within the fishery (e.g. Gillis *et al.*, 1993). The impact of competition would presumably be diminished during periods when fishing effort is low, i.e. during months of sparse data coverage. However, during periods of high fishing effort the effects of competition may be significant. Such effects are difficult to quantify, because attempts to do so may themselves be biased by other unquantified covariants (e.g. Gillis, 1999). One possible solution, suggested by Gillis *et al.* (1993), is that for an ideal free distribution (IDF; Fretwell and Lucas, 1970; Fretwell, 1972) effort may 'map' fish density better than CPUE. However, this has its own problems; one of the predictions for an IDF is that CPUE should be equalized among different areas fished, which was clearly not the case in our data (see Figs. 1 and 2). In short, although the relationships between catch and fishing effort are known to be complex and not simply governed by fish abundance, in lieu of better information CPUE is still commonly used as an index of abundance (e.g. Gillis *et al.*, 1993, and references therein) as we have performed here. The favorable comparisons between the present analysis and those of previous investigators suggest that this is at least somewhat justified.

An important point regarding the results of the present study compared with those of previous investigators using research trawl data is that the major conclusions are similar. Namely, the commercial landings data indicate that cod and haddock are distributed non-randomly with respect to certain environmental variables over Georges Bank, most notably bottom temperature, sediment type, and bottom depth. The fact that these relationships can be obtained from the commercial landings data suggests that the landings data, despite their biases and uncertainties, may be useful in future studies of environmental indicators and/or numerical modeling studies. We reiterate, however, that in this study we have made no attempt to quantify these biases and uncertainties; such an analysis is beyond the scope of the present study and is left as a subject for future investigations. The important point is that one can draw similar statistical inferences from the commercial data as from the survey data.

Having established a set of empirical relationships between fish distributions and environmental variables, the next logical step is to evaluate the predictive skill of such relationships. As discussed in the Results section, one measure of predictive skill is an r^2 statistic applied to, for example, the relationship between CPUE-weighted bottom temperature and mean bottom temperature across the Bank. Here the r^2 value represented the percent of the seasonal and interannual variance in the monthly averaged data explained by a fitted (linear) curve. While this statistic is useful, however, it is limited in that it represents the temporal variance of spatially averaged quantities, and says nothing about the spatial variance itself. Instead, the question of spatial variance must be addressed using a spatially explicit model. The latter is extremely important to the problem of fisheries management, and is the subject of ongoing investigation.

CONCLUSIONS

A major goal of this study was to develop a framework for using commercial landings data to examine environmental indicators of the distributions of commercial fish stocks, using Georges Bank as a pilot study. The foregoing analysis suggests that commercial landings data, although noisy, reveal statistically significant associations with environmental variables. Both temporal and spatial variability in the commercial data were consistent with results of previous investigators based on standardized NMFS survey data. Furthermore, when compared with historical CTD and other environmental data, the commercial landings data indicated a number of significant associations with environmental variables. Significant associations were found between bottom temperature and cod and haddock distributions over Georges Bank. Both species exhibited a tendency towards preferred temperatures which may vary seasonally from approximately 5°C in winter/spring to as high as 10–11°C in late fall. Associations were also found between cod and haddock distributions and bottom sediment type and bottom depth over Georges Bank. Both cod and haddock preferred coarse sand or gravel bottom sediments throughout the year, and water depths ranging from approximately 60 m in winter/spring to 75 m in summer/fall.

These results show that commercial landings data yield results that are consistent with those obtained from NMFS survey data as discussed by previous investigators. While the present study has focused on particular species and environmental data sets, we note that the methodology described here is readily extended to other species and other environmental variables, including physical, biological and/or chemical variables.

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