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Analysis of spatial variability of Georges Bank haddock (*Melanogrammus aeglefinus*) from trawl survey data using a linear regression model with spatial interaction.

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ABSTRACT

A regression model with spatially autocorrelated errors is used to test if there is systematic spatial variation across the study area in haddock catch per tow data from the NEFC annual fall survey from 1963 - 1987. A maximum likelihood estimation procedure is used, and the likelihood-ratio method is used for testing the significance of the model. The results suggest that for many of the years analyzed information on the depth and location of sampling stations can be used to explain part of the spatial variability of the trawl catches. If model-based inferences are made from the survey data, the depth related trend and the autocorrelation for the errors of the model should be taken into account. The potential use of a spatial prediction method for geographic mapping of density is discussed.

Key words: model-based inference; distribution of haddock; spatial autocorrelation; groundfish surveys.

Introduction

Knowledge of the spatial distribution of commercial fish stocks is important for understanding their population dynamics and, hence, for fisheries management. Bottom trawl surveys are conducted throughout the world to monitor changes in abundance of many important finfish species, and the data collected are also useful for exploring spatial distribution patterns. If the location of the trawl stations are selected at random in the study area, the observations may be taken as independent and inferences from the data based on standard statistical methods are valid. However, randomly located observations tell us very little about spatial pattern unless sampling units of different sizes are used (Cliff and Ord 1981). The negative binomial distribution frequently provides a good description of the sampling distribution of many marine populations (Taylor 1953, Roessler 1965, Lenarz and Adams 1980, Murawski and Finn 1988), indicating a patchy distribution of individuals.

During recent years there has been a great deal of interest in spatial data analysis (often referred to as geostatistics) in marine science and its application to stock assessment (Anon. 1989). Cliff and Ord (1981), Ripley (1981) and Upton and Fingleton (1985) present various methods for dealing with spatial processes. Examples of the use of methods which have taken sample locations into account in the analysis of marine data are presented in Conan (MS 1985), Jumars (1978), Jumars et al. (1977), Mackas (1984), Stolyarenko (MS 1986) and Vølstad and West (MS 1989). A parametric correlation function may be used to measure the (second-order) spatial dependence exhibited by the data. If data from neighboring samples exhibit dependence, a spatial interpolation method may be useful for predicting densities at locations which have not been sampled. In kriging, a widely used linear interpolation method, a large-scale trend is fitted to the data and the small-scale variation is incorporated by fitting a function to the correlogram for the residuals, either by using a cross-validation procedure or simply by eye (see, e.g., Cressie 1989, Ripley 1981, Upton and Fingleton 1985). A correlogram is a graph showing how autocorrelation in sample values changes with the distance between sample locations. The correlogram can be used to define coefficients in an optimal linear predictor (see Cressie 1989).

The typical behavior of many spatial phenomena produces a correlogram that displays values which diminish rapidly as the inter-point distance increases (Upton and Fingleton 1985). Sokal (1979) and Sokal and Oden (1979) discuss the interpretation of correlograms in biology, and give some suggestions about probable patterns and processes inferable from observed correlograms. Positive autocorrelation, which is often the case for natural populations (Cochran 1977), indicates that values at adjacent localities tend to be similar. If no spatial autocorrelation is present in the survey data, the catch at one location is not predictable from observations at neighboring localities. Thus, before using prediction methods such as kriging, it is essential to evaluate if spatial autocorrelation is present in the data.

Maximum likelihood estimation of regression models with spatially autocorrelated errors provides an objective method for simultaneously fitting a trend and an autocorrelation function to spatial data. In this procedure, an autocorrelation function can be fitted as part of the general maximum likelihood process (Upton and Fingleton 1985, Vølstad and West MS 1989), and the significance of the model can be evaluated by the likelihood-ratio test (see Rao 1973). In this paper we fit a linear regression model with allowance for spatially correlated errors in order to test for the presence of spatial autocorrelation, and to explore possible mechanisms underlying the spatial distribution of haddock on Georges Bank. The potential use of the model for mapping geographic density distribution of trawl caught fish is discussed.

Data

Since 1963, the Northeast Fisheries Center (NEFC) has conducted intensive bottom trawl surveys off the northeast coast of the United States. Annual fall surveys have been conducted since 1963 and annual spring surveys since 1968. Survey design, sampling procedures and data processing are described in Anon. (1988), Azarowitz (1981), Grosslein (1969), Clark (1979) and Almeida et al. (1986). The trawl stations are allocated within strata which have been defined according to depth, latitude, and historic fishing patterns. This stratified random design ensures that stations are located in each depth zone in all geographic subdivisions. A map of the survey area and stratification scheme is presented in Figure 1. At each sampling location, a 30-minutes tow is conducted, at a towing speed of approximately 3.5 knots. The position, average depth and catch in number and weight by species is recorded for each trawl haul. Previous to 1983, bottom water temperature was also routinely measured. Since 1983, temperature has only been measured at about 1/3 of the stations.

The spring survey from 1973 to 1981 employed a larger trawl than was used in the other surveys. This difference in trawl size confounds, to some extent, the continuity of the spring time series and its comparability with the fall series. Because of this problem, the analyses were only performed on data from the fall time series. We also have restricted our analysis to Georges Bank haddock of length > 20cm (corresponding to age 1+) since the catchability of 0-group haddock is low relative to other age-classes. Data from 1963 to 1987 were analyzed for strata 13 to 25 and strata 29 to 30 (see Figure 1). Assessment of Georges Bank haddock has traditionally encompassed these strata (Clark et al. 1982). Some basic characteristics of the trawl survey data are presented in Table 1, and abundance indices of age 1+ haddock from the fall surveys are presented in Figure 2.

Methods

A regression model which included both linear terms and spatial autocorrelation among the residuals was used to analyses the spatial distribution of haddock on Georges Bank. The maximum likelihood method which was used for the estimation of the parameters allowed for simultaneously estimating and testing linear trends and spatial autocorrelation.

Depth was used as the co-variate for the linear trend portion of the model. The density of haddock on Georges Bank is known to vary with depth and temperature (Murawski and Finn 1988). For the Georges Bank survey data, depth and temperature are highly correlated within a year (Murawski and Finn 1988). We have explored models involving both depth and temperature. We have omitted temperature in our model because depth generally accounted for more of the variation than temperature. Moreover, the inclusion of temperature in addition to depth did not significantly reduce the overall variance. The following linear regression model

$$Z = \theta_0 + \theta_1 D + \theta_2 D^2 + \epsilon \qquad (1)$$

was employed, where Z is the square-root of the catch per tow in numbers, D is depth, θ_0, θ_1 and θ_2 are parameters to be fitted and ϵ is a normally distributed error term. The square root transformation was applied to the counts to stabilize the variance and normalize the distribution of the errors.

Standard linear models assume that the errors are independent and identically normally distributed. For data with a geographic ordering this requirement implies that the errors are not spatially autocorrelated (Cliff and Ord 1981). In model (1) we do not assume independence, but allow the errors to be spatially autocorrelated. For many natural populations the spatial autocorrelation diminish exponentially as the distance r between sampling stations increase (Cochran 1977). We assumed positive auto-correlation, and employed a simple parametric function to describe the error structure in model (1):

$$q(r) = \begin{cases} \exp\{-r/\alpha\} & \alpha > 0 \\ 0 & \alpha = 0 \end{cases} \qquad (2)$$

The above correlation function is isotropic, i.e. it is stationary and direction invariant (Cliff and Ord 1981). The function $\exp\{-r^2/\alpha\}$ for the correlation structure was also tested, but function (2) generally gave the best fit to the data.

The linear trend parameters in model (1) were estimated simultaneously with the parameter α in the correlation function $q(r)$ using the maximum likelihood method as described by Vølstad and West (MS 1989). The parameters in the linear trend were fitted in a stepwise procedure for each of the years 1963 - 1987. Starting with step 1, θ_1 and θ_2 are set to zero leaving only the mean, θ_0. In step 2 depth is inserted and in step 3 both depth and depth square are inserted (i.e. the full model (1) is fitted). This stepwise procedure was applied for both correlated errors as modeled by $q(r)$, and for independent errors. The significance of either individual parameter or sets of parameter estimates are evaluated by the likelihood-ratio test using a significance level of 0.05.

Results

Maximum likelihood values from a stepwise fitting of the model, with and without allowance for spatially correlated errors, are presented in Table 2. A summary of the results is presented in Table 3. For 8 out of 25 years the full model (step 3) with allowance for spatially correlated errors gave the best fit. Step 1 with allowance for spatially correlated errors gave the best fit for 6 of the years. For one year, step 2 with allowance for spatially correlated errors gave the best fit. Thus, the maximum likelihood model involved spatial autocorrelation in 15 out of 25 years. The mean value of the parameter α in the correlation function for these years was 9.53, ranging from 2.45 to 18.47 (Table 4). An α equal to 9.53 corresponds to a correlation of 0.40 between the residuals for trawl stations that are 8.6 miles a part. The average distance between tows in the surveys ranged from 6.1 to 10.3 miles (Table 1).

Within a given year the estimates of α remained reasonably stable as additional variables were inserted in the model (Table 5). For a simple model involving only the mean (step 1) and with spatial correlation, α is significant in 18 out of the 25 years (Table 2). For four years the estimates of α were zero, suggesting that for these years no spatial autocorrelation exists among the errors in the model.

The inclusion of depth and/or depth square in the regression model gave a significantly better fit in 14 out of the 25 years. Across different years the estimates of the parameters for depth and depth square, θ_1 and θ_2 vary by up to a factor of 20 (Table 6). Also when identical models are fitted for each year, the absolute values of these parameter estimates between years varies by an order of magnitude. Note that the signs of estimated depth, θ_1, and depth squared, θ_2 parameters are always opposite; and that from 1963-1967 θ_1 is negative, while from 1968-1987 θ_1 is almost always positive (Table 7).

For the years prior to 1968, when the percentage of tows with zero catches were low (< 25%) the frequency distributions of the errors for the fitted models were approximately normal. For the years 1968 - 1987 the errors display a skew frequency distribution, in large part due to the high proportions of zero catches (Figure 3).

Discussion

The regression analyses suggest that for many of the years analyzed, depth or depth related effects and spatial autocorrelation between the residuals are important for describing the density distribution of haddock on Georges Bank. For the maximum likelihood model there is a significant spatial autocorrelation in the errors for 15 out of 25 years of survey data. For these years, prediction of abundance of haddock at a particular location where no sample is taken may be based on observations from neighboring locations. Kriging is one approach that could be used for mapping the abundance which would take into account the autocorrelation structure of the spatial process. Kriging is particularly useful for the estimation of local abundance. For a global estimate of abundance, an estimator based on the delta distribution is efficient (Pennington 1983).

The lack of spatial autocorrelation in 10 of the years for the maximum likelihood model does not necessarily imply that the errors are independent. The number of tows may be too low for detecting significance given the average distance between trawl stations and the magnitude of α found in this study. Perhaps even more importantly, individual trawl hauls do not consistently sample a constant fraction of the population due to changes in catchability. Changes in catchability from tow to tow may result from a large number of factors (e.g. sea state, bottom type, currents, gear performance, time of day, etc.) and such sampling errors tend to obscure any true, underlying relationship. Moreover, it is possible to envision more complicated correlograms than employed here (see Upton and Fingleton 1985). In such cases, function (2) may fail to detect autocorrelation.

Within each year, the estimates of α are relatively stable across different steps in model (1). The significance of α only changed in 3 of the 25 years when parameters for depth were added to the trend and the magnitude of the estimated α was relatively constant with the addition of parameters for depth and depth squared. Short distance positive autocorrelation can arise if the distance between adjacent sample-locations is less than the diameter of patches of fish and is also less than inter-patch gaps (Sokal 1979, Upton and Fingleton 1985). Significant autocorrelation suggests that the aggregation of haddock is not simply a response to the depth topography or other physical environmental factors, but may be biologically driven (e.g. in response to patchy distributions of prey). Results in Polacheck and Vølstad (MS 1990) using alternate, non-parametric methods provide further evidence for spatial autocorrelation. They found that the spatial distributions of adult haddock in these trawl survey data were highly patchy and that catches from nearest neighbor tows were correlated for all years from 1963-1987.

Polacheck and Vølstad (MS 1990) also observed that the distribution of haddock on Georges Bank shifted in 1968 with the population becoming more contracted, possibly in response to a decline in abundance. The shift in sign for the estimated parameters noted above for depth and depth squared when the full model is fitted to each year's data (Table 7) is consistent with this observed change. These results suggest that the regression model successfully reflected a major component of the underlying spatial process in spite of the high variability of the parameter estimates.

The trend function for the maximum likelihood model involved depth in 14 out of the 25 years analyzed. This result suggest that if kriging is to be used for spatial prediction of abundance, the usual assumption about a constant mean over the study area does not hold for these years. The years with no significant depth effects, with the exception of 1963, 1976 and 1977, were years in which the abundance of haddock was low (mean catch per tow < 10). The relationship between depth and the density distribution of haddock may be difficult to detect in years of low abundance due to the many zero observations for these years. The linear trend in model (1) is a poor predictor of zero's for the dependent variable. In the years 1968-1987 the proportion of zero tows was always greater than 50 %. For these years the zero observations have a major influence on the estimation of the trend function. If kriging is used for the prediction of density of haddock at some unsampled location, the impact of the zero observation on the results should be carefully examined. The performance of the kriging method for years with many zero observations is important to investigate, since large numbers of zero catches frequently occur in groundfish surveys and other marine abundance surveys.

The departure from normality for the errors in model (1) in low abundance years raises questions about the validity of the likelihood-ratio tests of significance. While maximum likelihood estimates of the parameters in regression models are considered to be robust to departures from normality, the skewness in the distribution of errors suggest that possibly a different transformation might be used for the dependent variable. For a limited number of years, a log transformation was applied to the dependent variable. However, no real improvement was observed compared to the square-root transformation with respect to reducing the skewness in the distribution of the residuals. Since the lack of normality in the errors for a large part is due to the zero tows, any standard transformation is not likely to remove the observed skewness. The robustness of the likelihood ratio test to departures from normality when data contain high percentages of zeros needs to be further explored. While recognizing this limitation, the maximum likelihood approach to fitting a correlogram seems preferable to fitting a correlogram by eye (with or without the use of cross validation procedures). Some form of statistical test is needed to evaluate whether the model for the spatial process represents a significant departure from a random model.

While our analyses indicate that depth or depth related effects and spatial autocorrelation are important, it is not clear how the results should be used to produce either a time series of abundance indices or for describing the spatial distributions over time. A possible approach would be to take the parameter estimates from the best significant fit for each year and produce high density grid surfaces using kriging. The problem with this approach is the lack of consistency in the results, in particular years in which the results imply that the distribution was random. This lack of consistency is not unexpected and stems from at least three causes:

1) The actual factors determining the distribution of fish in space are not constant in time and would also be expected to vary with the abundance and size/age structure of the population (i.e. the spatial process is not constant in time).

2) The regression model with spatially autocorrelated errors is a simplification of the underlying process. While depth and spatial autocorrelation in general appear to be useful for detecting systematic spatial variation for catch per tow of haddock, these factors only explain a small portion of the overall variation in the trawl catches. Development of a more sophisticated model is limited by the availability of data on other factors potentially determining abundance and by sample size. In particular, violation of the assumption of stationarity in the covariance structure for the errors may be more serious in some years when depth and depth square do not adequately account for underlying trends.

3) Catchability is likely to vary both within and between years (Pennington 1986). In this regard, it would be worth determining whether survey conditions were in anyway anomalous during those years in which the best fit model was a random process.

In order to use the results from the maximum likelihood fitting of model (1) with a linear spatial prediction method to compare spatial process across years, the first of these factors must be the dominant source of the variability in the results between years. Unfortunately, all three factors are highly confounded and we suspect that the latter two factors may be the dominant source, at least in those years in which a "random model" provides the best fit to the data. Analyses in Polacheck and Vølstad (MS 1990) indicate that the spatial distribution was non-random in all years, including those years in which the fit of model (1) does not detect significant autocorrelation among the errors. Spatial prediction methods, such as kriging, assume that the spatial process can be estimated with a high degree of resolution. The observed variability among years suggests that the information content from trawl surveys, at least for Georges Bank haddock, is limited with respect to providing reliable estimates for a linear trend and the correlogram.

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Table 1. Sampling intensity, percentage of tows with zero catch of haddock, and mean distance between nearest tows during NEFC fall bottom trawl surveys on Georges Bank in strata 13-25 and 29-30.

Year	Number of Stations	Percentage of Zero Tows	Mean Distance between nearest tow (Nautical miles)
1963	73	25	10.3
1964	73	18	9.8
1965	76	13	8.7
1966	74	28	8.9
1967	78	24	9.6
1968	80	58	9.3
1969	84	62	8.7
1970	81	51	9.8
1971	84	69	8.7
1972	85	52	8.4
1973	84	68	8.0
1974	85	71	7.9
1975	84	60	9.5
1976	78	56	8.8
1977	112	51	7.5
1978	175	54	6.1
1979	171	53	6.3
1980	102	55	7.4
1981	82	52	8.1
1982	79	65	8.4
1983	81	68	8.7
1984	80	70	9.2
1985	77	57	9.1
1986	79	72	9.3
1987	77	78	9.1

Table 2. Maximum log-likelihood values from Stepwise fitting of model 1 with and without allowance for spatially correlated errors. Step 1 equals overall mean, Step 2 adds the effect of depth and Step 3 adds the effect of depth and depth squared.

	Step 1		Step 2		Step 3	
Year	No Corr.	Corr. Errors	No Corr.	Corr. Errors	No Corr.	Corr. Errors
1963	-362.00*	-362.00	-360.12	-360.12	-358.26	-358.26
1964	-406.79	-400.83	-392.64	-391.86	-390.46*	-390.46
1965	-393.40	-380.04	-376.58	-369.89	-370.77	-367.47*
1966	-342.98	-340.67	-339.16*	338.43	-338.42	-337.81
1967	-351.23	-351.23	-348.34*	-348.34	-347.92	-347.92
1968	-340.44	-333.98*	-339.67	-333.51	-339.66	-333.49
1969	-309.73	-306.64*	-309.58	-306.60	-309.09	-306.56
1970	-349.05*	-347.77	-349.01	-347.77	-347.11	-345.45
1971	-309.95*	-309.95	-309.92	-309.32	-309.63	-309.63
1972	-338.59	-335.32	-338.45	-334.69	-334.06	-330.71*
1973	-382.60	-368.19*	-382.25	-367.94	-381.67	-367.06
1974	-335.28*	-333.54	-335.28	-333.53	-333.40	-332.49
1975	-371.22	-363.85	-361.73*	-360.41	-359.99	-359.42
1976	-409.91*	-408.57	-409.80	-408.17	-409.69	-408.16
1977	-584.05	-562.24*	-584.02	-560.91	-582.31	-560.40
1978	-898.58	-894.25	-887.71	-884.92	-884.24	-882.10*
1979	-931.33	-929.78	-921.56	-921.56	-916.37*	-916.37
1980	-514.58	-489.16	-505.15	-486.04	-497.27	-479.15*
1981	-378.43	-365.36	-377.01	-365.36	-371.21	-353.85*
1982	-323.75	-320.38	-321.92	-319.09	-318.28	-316.59*
1983	-333.26	-321.03	-331.59	-320.46	-328.47	-318.92*
1984	-350.87	-340.49	-350.39	-340.48	-347.33	-337.73
1985	-343.26	-339.26*	-342.54	-339.42	-342.04	-339.02
1986	-363.16	-334.25	-362.60	-331.10*	-359.49	-330.81
1987	-302.72	-294.39	-298.03	-294.39	-296.85	-287.29*

* = significant, best fit model

Table 3. Summary of results for stepwise fitting of model (1), with and without allowance for spatially autocorrelated errors. Step 1 equals the overall mean, in step 2 depth is added and in step 3 the full model (1) is fitted. Number of years where the models provided maximum likelihood are given.

	No spatial correlation	Spatial correlation
Step 1	5	6
Step 2	3	1
Step 3	2	8

Table 4. The estimated α for the maximum likelihood model. Only those 15 years in which α was significant at the 0.05 level are included.

Year	$\hat{\alpha}$
1965	6.67
1968	9.00
1969	8.59
1972	5.44
1973	11.33
1977	9.09
1978	2.45
1980	11.02
1981	6.09
1982	3.58
1983	11.24
1984	15.34
1985	7.76
1986	16.85
1987	18.47

Table 5. Estimates of α in different steps of the regression model (1). Only those years in which α was significant at the 0.05 level are included. Step 1 involves only the overall mean, in step 2 depth is inserted and in step 3 the full model (1) is fitted.

Year	Step 1	Step 2	Step 3
1965	11.27	9.05	6.67
1968	9.00	-	-
1969	8.59	-	-
1972	4.99	5.34	5.44
1973	11.33	-	-
1977	9.09	-	-
1978	3.53	2.69	2.45
1980	11.02	11.01	11.02
1981	12.89	12.76	6.09
1982	4.82	4.50	3.58
1983	12.49	11.96	11.24
1984	15.34	-	-
1985	7.76	-	-
1986	16.85	16.85	-
1987	13.41	13.35	18.4

Table 6. Parameter estimates for effect of depth and depth square for those years in which the best fit included these terms. The variances of the depth parameters (θ_1) are < 5.0×10^{-5}, and the variances of parameters for depth squared (θ_2) are < 5.0×10^{-10}.

Year	Depth	Depth square
1964	-0.141×10^{0}	$0.26[illegible]\times10^{-3}$
1965	-0.962×10^{-1}	0.191×10^{-3}
1966	0.139×10^{-1}	-
1967	-0.866×10^{-2}	-
1972	0.251×10^{-1}	-0.706×10^{-4}
1975	0.124×10^{-1}	-
1978	0.443×10^{-1}	-0.968×10^{-4}
1979	0.740×10^{-1}	-0.185×10^{-3}
1980	0.807×10^{-1}	-0.214×10^{-3}
1981	0.631×10^{-1}	0.168×10^{-4}
1982	0.240×10^{-1}	-0.637×10^{-3}
1983	0.283×10^{-1}	-0.808×10^{-4}
1986	-0.726×10^{-2}	-
1987	0.288×10^{-1}	-0.899×10^{-4}

Table 7: The sign of the depth and depth square parameters when the full model (step 3) is fitted to each year's data.

Year	Θ_1	Θ_2
1963	-	+
1964	-	+
1965	-	+
1966	-	+
1967	-	+
1968	+	-
1969	+	-
1970	+	-
1971	+	-
1972	+	-
1973	+	-
1974	+	-
1975	-	+
1976	+	-
1977	+	-
1978	+	-
1979	+	-
1980	+	-
1981	+	-
1982	+	-
1983	+	-
1984	+	-
1985	+	-
1986	-	+
1987	+	-

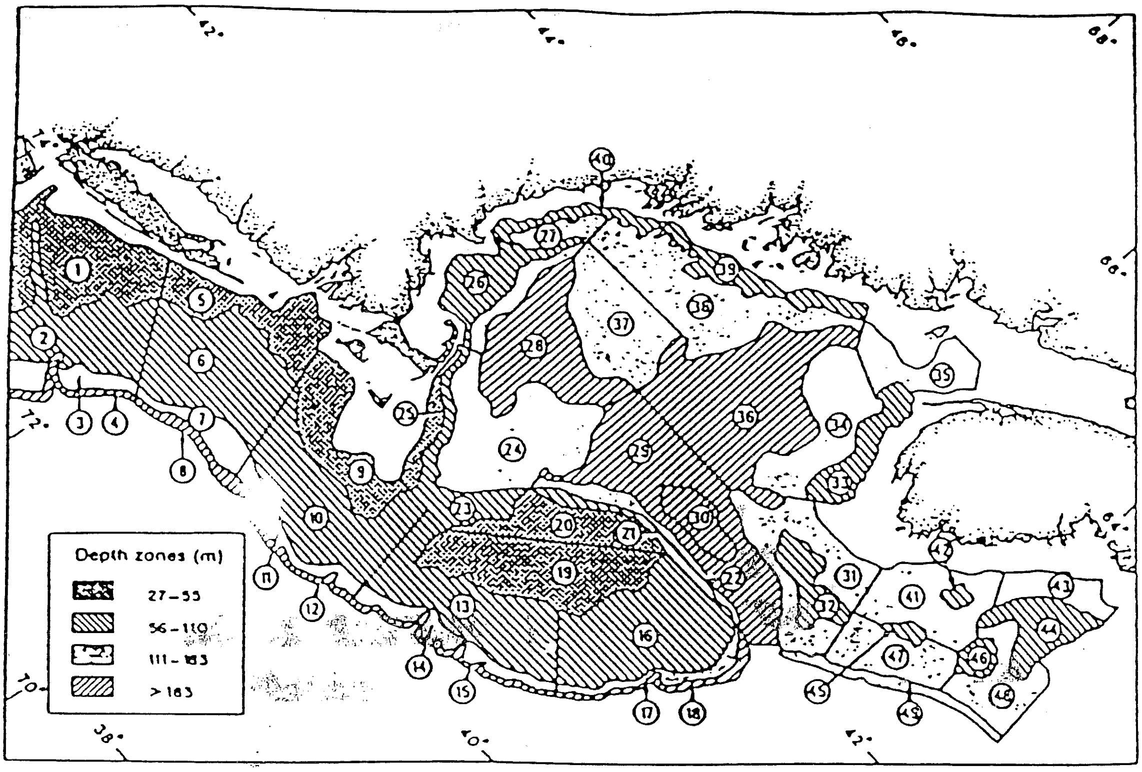

Figure 1. Stratification scheme used for USA spring and autumn bottom-trawl surveys of Georges Bank and Gulf of maine areas (from Clark. et al. 1982).

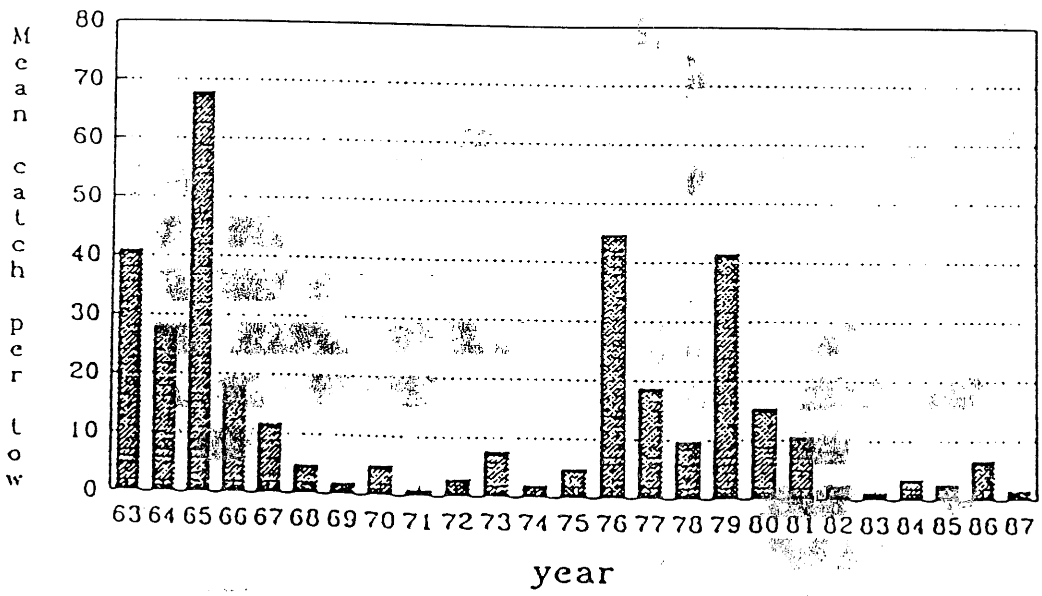

Figure 2. Haddock of age 1+ caught per tow in autumn bottom-trawl survey on Georges Bank 1963-87

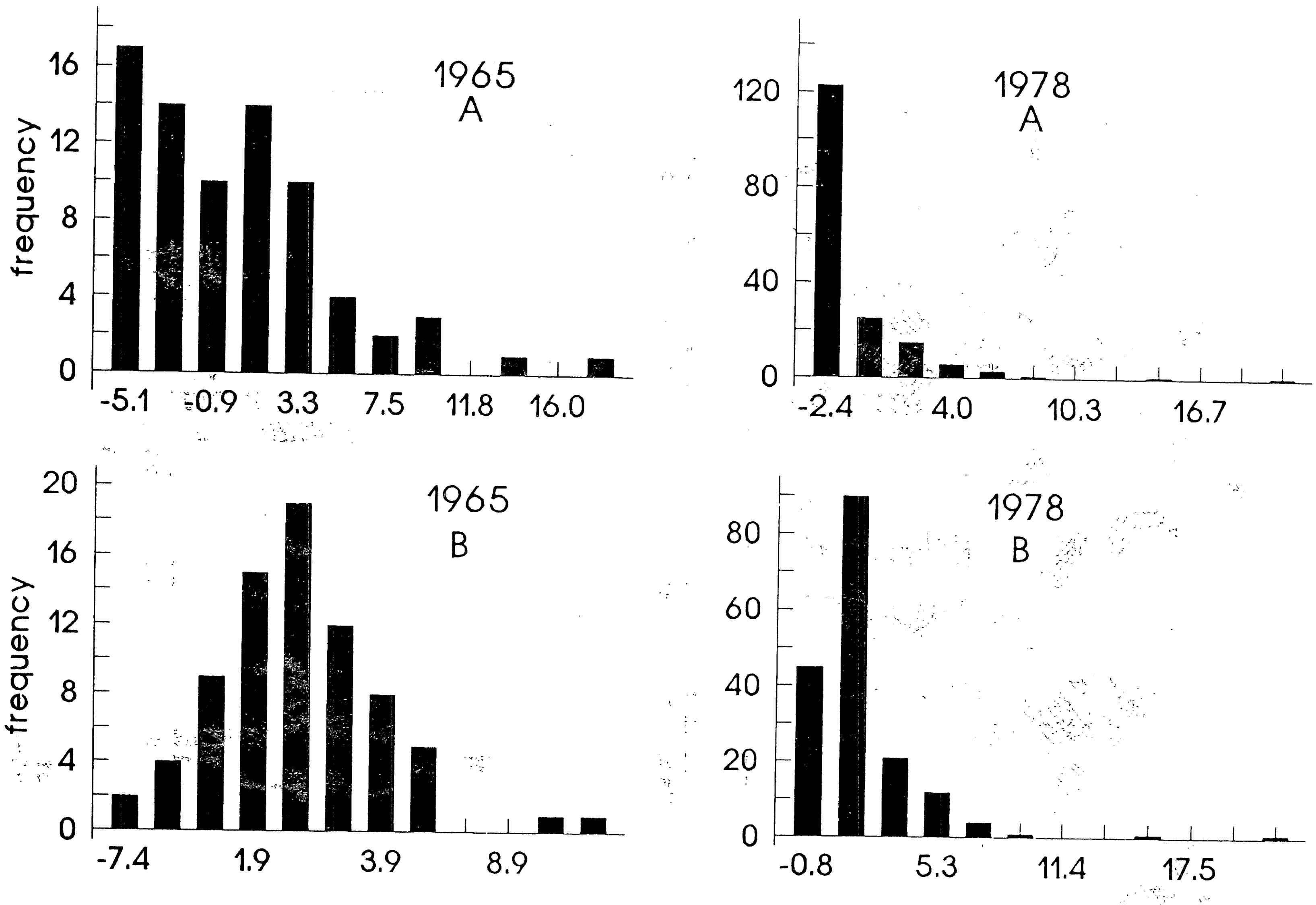

Figure 3. Frequency distribution of residuals from model (1) for 1965 and 1978. **A**: Step 1 with no allowance for autocorrelated errors. **B**: Step 3 (the full model (1) with correlated errors) is the maximum likelihood model.