International Council for the
Exploration of the Sea

C.M. 1996/S:46
Theme Session S

BATHYMETRIC CONFORMAL VARIOGRAPHY OF THE SPAWNING STOCK OF NORTHERN BLUE WHITING

by

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ABSTRACT

Bathymetric-based conformal isotropic and anisotropic variograms are defined. These are applied to the spawning stock of northern blue whiting (Micromesistius poutassou) along the slope of the continental shelf west of the British Isles. Computations are performed on acoustic survey data collected over a ten-year period.

INTRODUCTION

The spawning stock of northern blue whiting (Micromesistius poutassou) has been acoustically surveyed along the continental slope west of the British Isles in March and April since 1984 and annually since 1986. The surveying methodology has remained essentially unchanged, although both the primary acoustic instruments and postprocessing capability have become increasingly sophisticated due to developments in recent years. The time series is thus unusually long and consistent. Admittedly, the weather has often been so rough that surveying has been difficult, accounting for gaps in the coverage for a number of surveys.

Already during the planning stages for the European Union project "Geostatistics for fish stock assessment", the acoustic survey data on blue whiting have been viewed as candidates for application of geostatistics. In a concession to the project, T. Monstad has adapted his data postprocessing procedures to accommodate a project need for higher-resolution data. In particular, data from the two past surveys (Monstad et al. 1995, 1996) have been stored with the maximal postprocessing resolution of 0.1 nautical miles in sailed distance, with 10-m depth channels. In previous years, the interpreted data were stored with a resolution of five nautical miles in sailed distance and 50 or 100 m in depth.

The data are also interesting for being closely connected with a geographically extensive bathymetric feature, the continental slope west of the British Isles, and associated hydrography including putative shelf-edge current. In characterizing the spatial structure of the blue whiting distribution, therefore, it has become apparent that the ordinary geostatistical tool, the variogram, should be applied conformally with respect to the bottom topography. It is the present aim to introduce a new tool, the conformal variogram, and apply it to survey data.

CONFORMAL VARIOGRAPHY

The ordinary anisotropic variogram for the random variable $Z(\underline{r})$, for all positions $\underline{r}$ over some region or volume, is

$$\gamma(\underline{h}) = \tfrac{1}{2}E\{[Z(\underline{r}+\underline{h}) - Z(\underline{r})]^2\} \quad , \qquad (1)$$

where $\underline{r}$ is defined in ordinary rectangular coordinates (Matheron 1971, Cressie 1991). The expectation operation is performed on the squared difference in values of the random variable at positions separated by the vector distance lag $\underline{h}$. In the absence of directionality, the equation can be simplified by replacing $\underline{h}$ by the simple distance lag h, thus defining the isotropic variogram.

In the general case where some external phenomenon defines the coordinate system, as by isolines and their normals, which are paths of steepest descent, the same equation applies. The vector distance lag $\underline{h}$, however, is defined in this conformal system by a component oriented along the isoline, λ, and a component oriented normally to the isoline, τ. These are referred to respectively as the <u>l</u>ongitudinal and <u>t</u>ransverse components to the isoline as indicated in Fig. 1. The distance vector between points P_1 and P_2 in this coordinate system is thus $\underline{h}_{12}=\underline{r}_1-\underline{r}_2=(\lambda_1,\tau_1)-(\lambda_2,\tau_2)=(\lambda_1-\lambda_2,\tau_1-\tau_2)$. The distance between P_1 and P_2 is

$$h_{12} = [(\lambda_1-\lambda_2)^2 + (\tau_1-\tau_2)^2]^{\frac{1}{2}} \quad .$$

The general conformal variogram is anisotropic, with principal components in the longitudinal and transverse directions $\hat{\lambda}$ and $\hat{\tau}$, namely $\gamma(h\hat{\lambda})$ and $\gamma(h\hat{\tau})$. An isotropic conformal variogram is also defined, but where directionality is absent or ignored, and the vector distance lag $\underline{h}=(\Delta\lambda,\Delta\tau)$ is replaced by the simple distance lag $h=(\Delta\lambda^2 + \Delta\tau^2)^{\frac{1}{2}}$.

MATERIALS AND METHODS

Data collection, postprocessing, and storage

The particular acoustic survey data of greatest interest here are those collected with highest resolution, hence from the echo integration surveys with R/V "Johan Hjort" in 1995 and 1996 (Monstad et al. 1995, 1996). The survey regions, with tracklines and bottom depth contours, are shown in Fig. 2. Acoustic densities of blue whiting are also shown, as described below.

The cited references provide details on the acoustic instrumentation and diverse processing operations including postprocessing. Briefly, the data were collected with the SIMRAD EK500/38-kHz echo sounder (Bodholt et al. 1989), with attached ES38B transducer operating at 38 kHz. Standard instrument

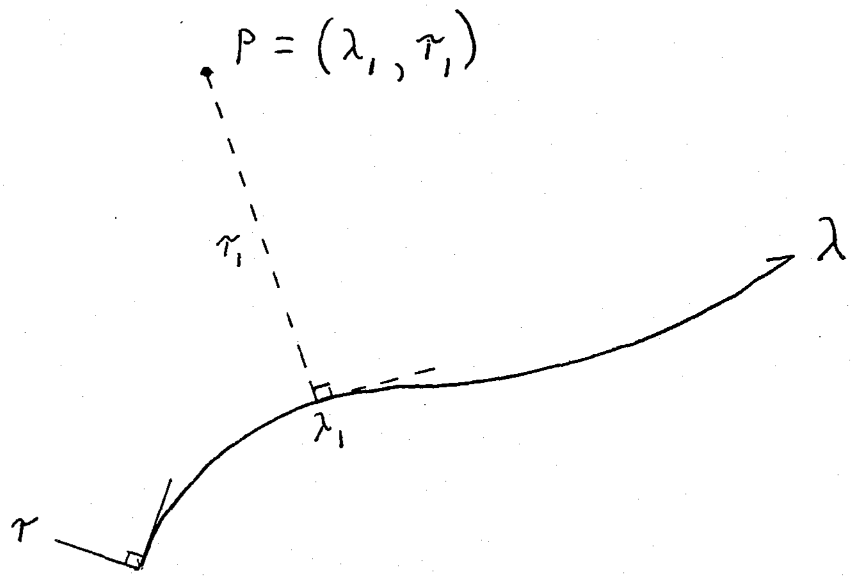


Fig. 1. Conformal coordinate system defined by distance along and transverse to a single curve, for example, a bottom depth isoline. Position is defined by longitudinal and transverse coordinates, λ and τ, respectively. The position of the indicated point is (λ_1, τ_1). Generalization to the case of multiple reference curves or isolines is straightforward.

settings were used, hence the pulse duration was 1 ms and the receiver bandwidth was 10% of the transmit frequency. The system was calibrated in accordance with recommended procedures (Foote et al. 1987).

Data were logged with the Bergen Echo Integrator (BEI) (Foote et al. 1991). Postprocessing consisted mainly in allocation of the echo record to the target fish species in the following way: by assignment of values of area backscattering coefficient s_A (Knudsen 1990) for specific, identified features of the echo record to blue whiting. This was done in 1995 and 1996 at the highest resolution ordinarily available in BEI, namely 0.1 nautical miles in sailed distance and 10 m in depth given the extended depth range of interest. The results were stored in an on-board data base. These were subsequently transferred to the institute data base ashore.

Historical acoustic survey data on blue whiting were also examined. These cover the years 1984 and 1986-1994. The resolution in sailed distance is five nautical miles.

Data preparation: quality control

Upon retrieval of the data from the shore-based data base, a number of quality-control procedures were applied. These have been designed to guard against corruption of data in data base operations, a constant worry for some

(a) 1995

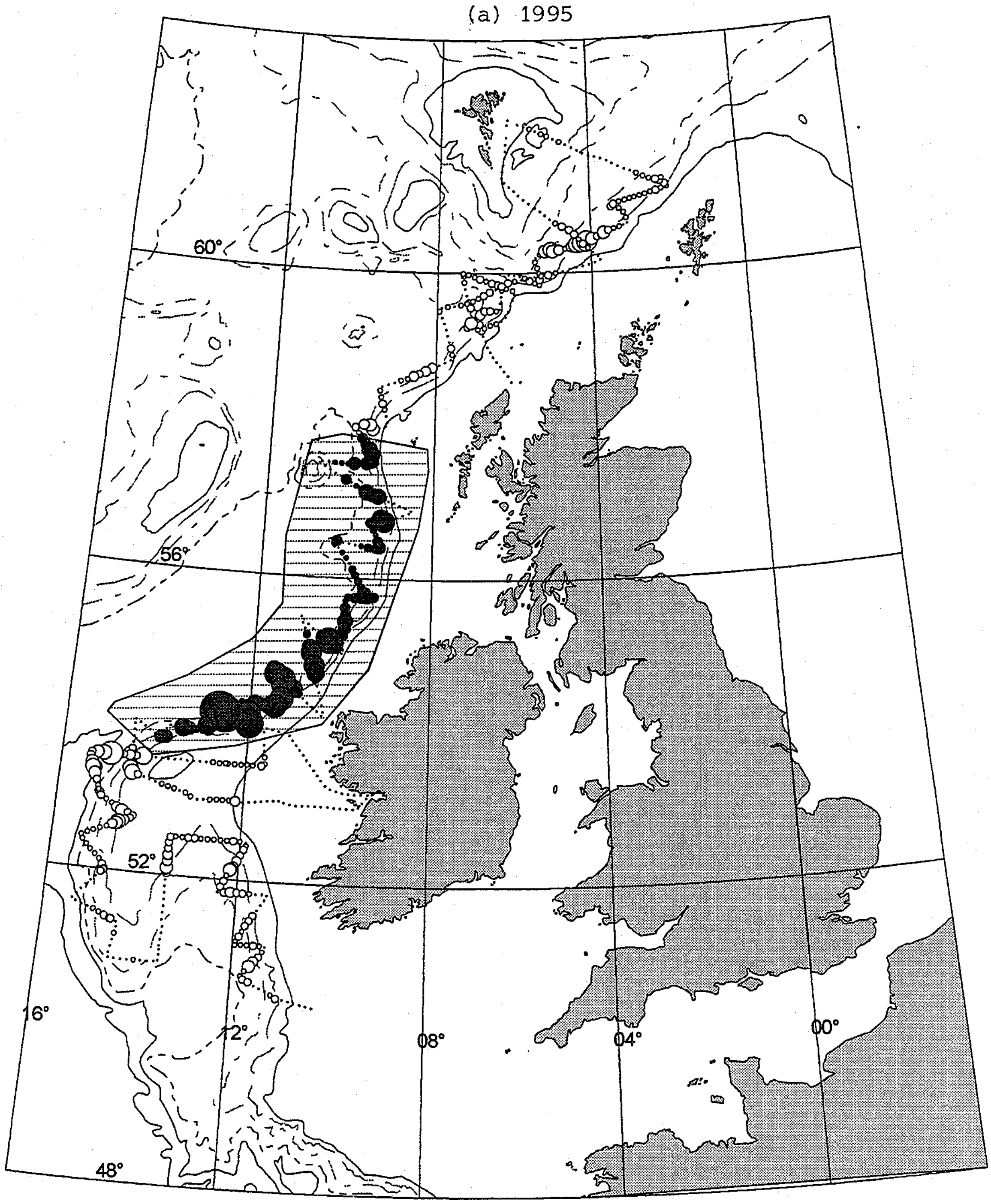


Fig. 2. Tracklines for two surveys of northern blue whiting. The closed polygons indicate regions for which two-dimensional conformal variograms have been computed. Acoustic densities are indicated by circles whose diameters are proportional to the square root of the area backscattering coefficient s_A after averaging over the respective five-nautical-mile interval. Part a: 1995.

(b) 1996

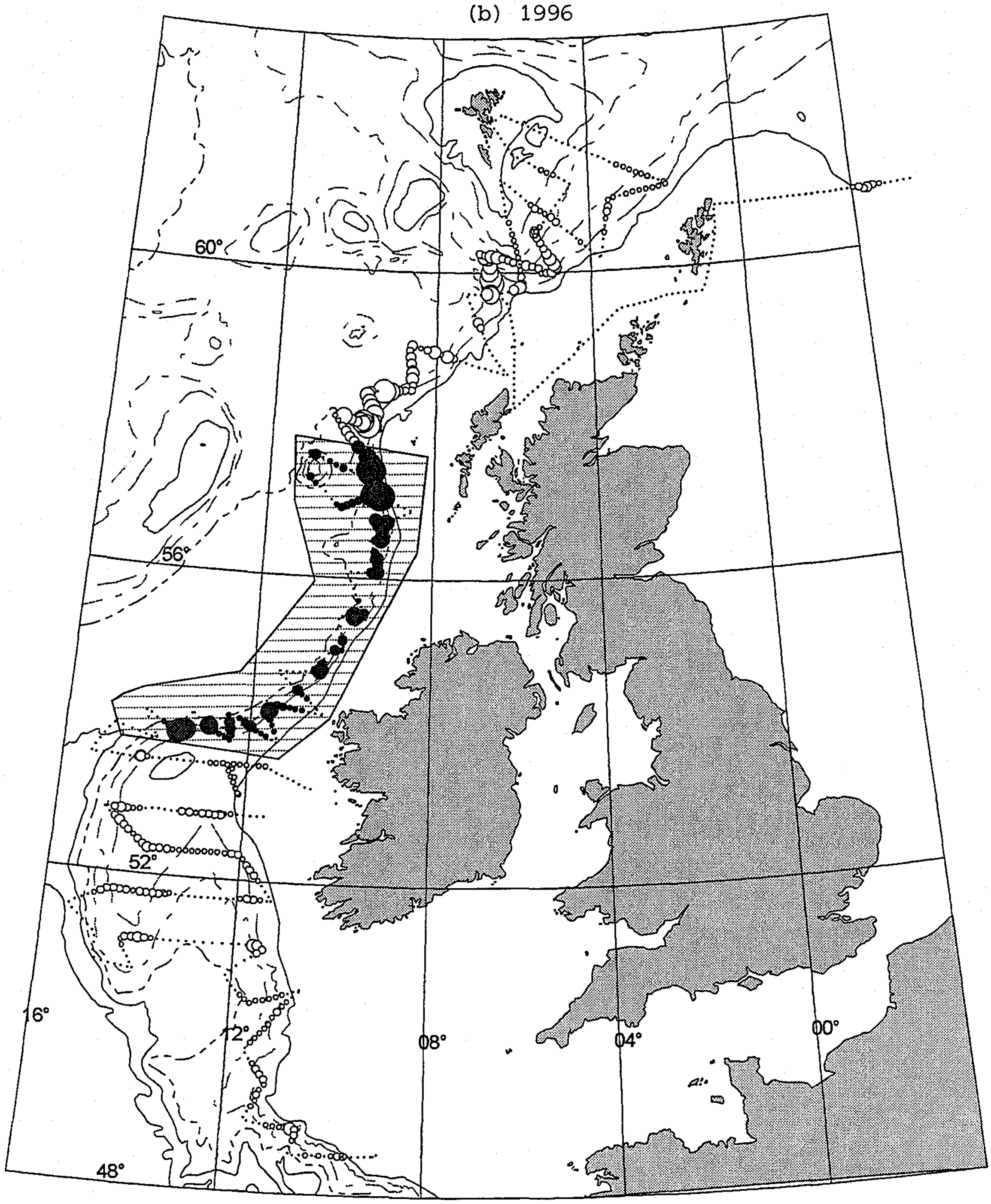


Fig. 2. (Continued) Part b: 1996.

data base users. These procedures included summing the echo integrator values s_A over all depth channels and comparing the result with the tabulated total value. This is a simple but often surprisingly revealing test.

Visualization of the data has also been performed, another most effective quality-control procedure. In Fig. 2, the blue whiting concentrations along the tracklines are indicated by circles with diameters proportional to $\bar{s}_A^{\frac{1}{2}}$, after averaging of s_A over the particular five-nautical-mile interval.

Data preparation: selection of areas and individual transects

The geographical extent of the survey regions and evident differences in coverage for the two years shown in Fig. 2 argue for selection of more homogeneous subsets. This has been done first for application of the two-dimensional conformal variogram. The respective selected regions are indicated by the closed polygons in Fig. 2.

For more detailed comparisons, individual transects were also selected. This was done on the basis of four criteria: (1) that the north-south range of the overlapping portions of the surveys be spanned more or less, (2) that some transects be selected from similar regions to examine possible year-to-year similarities or differences, (3) that each analyzed transect or transect segment be continuously sampled, hence without interruption for trawling stations or changes in sailing direction, and (4) that transects cross at least a major part of the continental slope. The result of the transect selection is shown in Fig. 3.

Numerical computations

Two-dimensional anisotropic and isotropic conformal variograms have been computed for each of the indicated central regions of the surveys in Fig. 2. The basis data are the values of s_A for blue whiting when integrated throughout the water column and averaged over intervals of 0.1-nautical mile. These values were subsequently averaged over statistical squares of side length 0.2-nautical miles. The resultant averaged s_A-values were combined according to a discrete version of equation (1), in which the 500-m bottom-depth contour and associated normals defined the conformal coordinate system. Paired averaged values of s_A were accepted for the transverse variogram if $\sin^{-1}(|\lambda_1-\lambda_2|/h_{12})<0.1$. Similarly, paired values were accepted for the longitudinal variogram if $\sin^{-1}(|\tau_1-\tau_2|/h_{12})<0.1$. The several coordinates are those of the data centroid for the respective statistical square, computed from the actual tabulated positions. All paired differences were used in computing the isotropic variogram, for this depends only on the distance lag h_{12}. The distance lag in the anisotropic transverse variogram and isotropic variogram was quantized by the step size $\Delta h=0.2$ nautical miles. That for the anisotropic longitudinal variogram was the step size $\Delta h=5$ nautical miles.

Two-dimensional conformal variograms were also computed for the mentioned historical data from the years 1984 and 1986-1994. The step size here was necessarily five nautical miles.

One-dimensional variograms were computed for each of the selected transects in Fig. 3. Because of imprecise specification of the position of each integration interval and relative shortness of the transects, the data

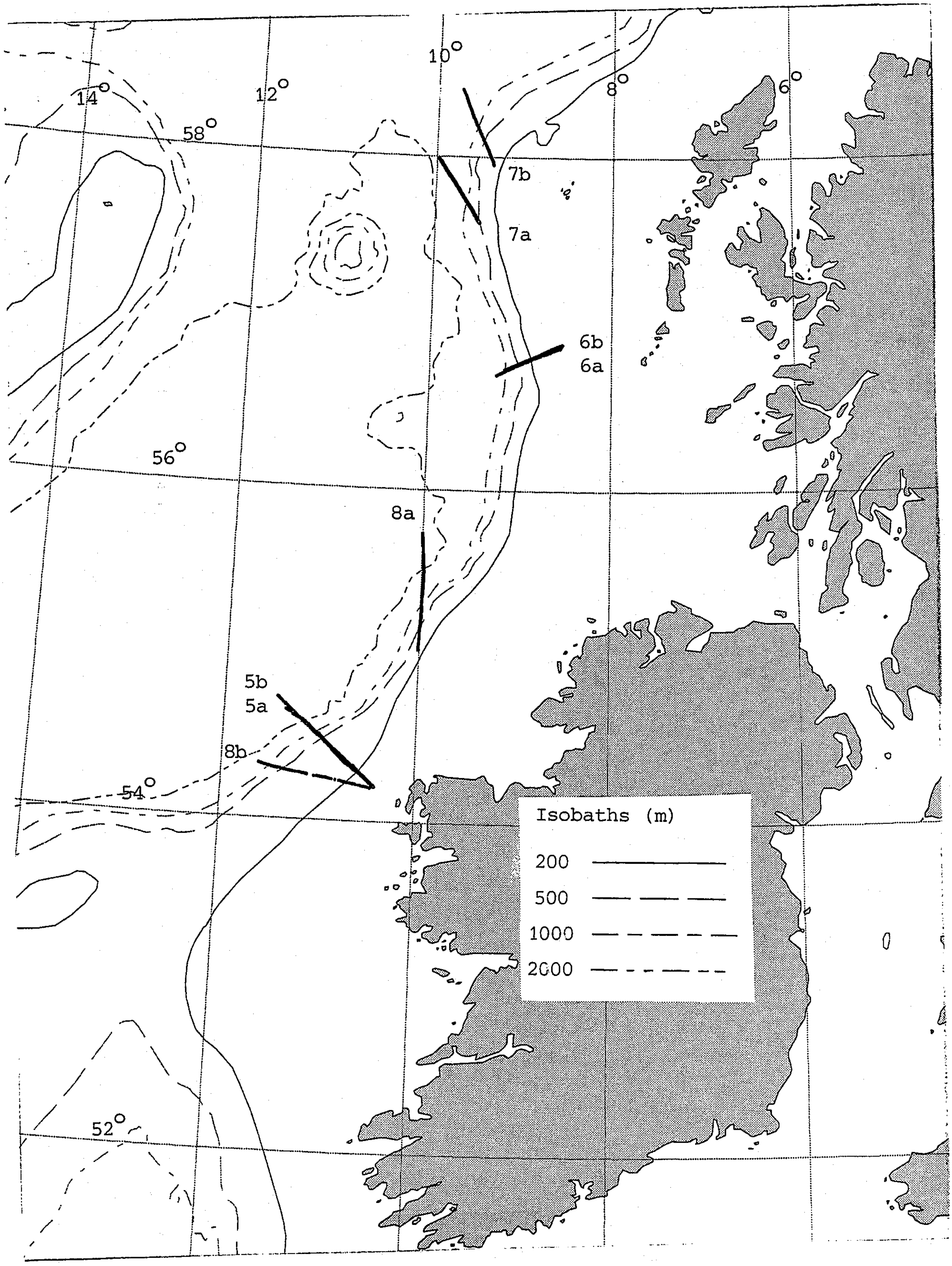


Fig. 3. Selected transects from the two surveys, identified by the number of the figure where the corresponding vertical section is displayed and by the survey year, designated as 'a' for 1995 and 'b' for 1996.

were assumed to lie on a straight line with even spacing between successive integration intervals of 0.1 nautical mile. Reference was not made to any bottom contour. The quantization interval for computation of the one-dimensional variogram in its numerically discrete form was 0.1 nautical miles.

No attempt was made to compute one-dimensional variograms for the historical data for want of a sufficient number of integration intervals along single transects. The resolution in sailed distance, five nautical miles, was simply too coarse.

RESULTS AND DISCUSSION

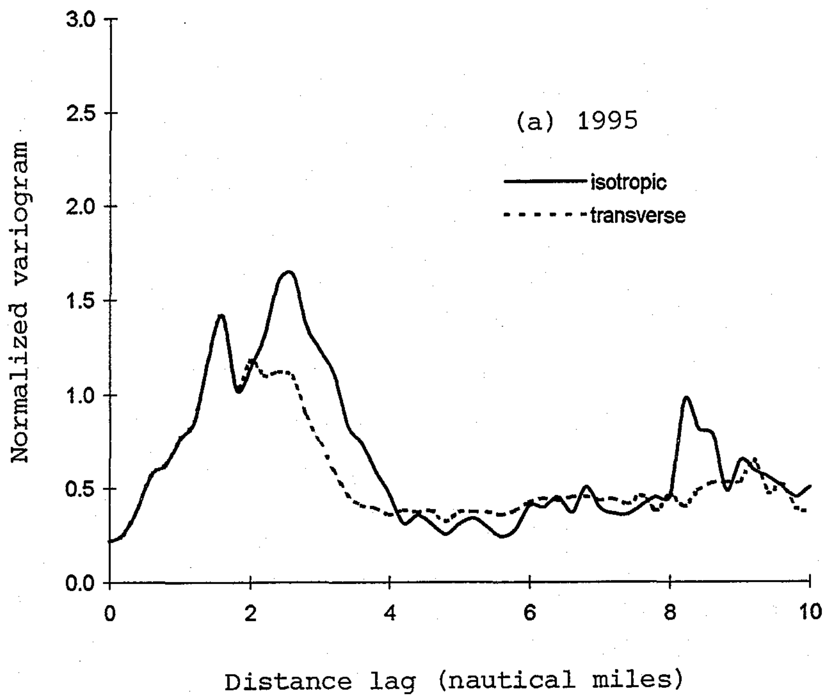
Conformal variogram

Conformal variograms have been computed for the s_A-values in the indicated regions of Fig. 2 following the described averaging over statistical squares of side length 0.2 nautical miles. Results for 1995, presented in Fig. 4a, indicate a high degree of short-range structure. In geostatistical terms (Petitgas 1993), the normalized variogram might be modelled by the sum of a nugget of amplitude 0.22 and spherical or other, smoother function with range of about 1.5 nautical miles. Differences in the isotropic and transverse anisotropic variograms become apparent at about 2 nautical miles; these undoubtedly reflect a greater degree of homogeneity in data that are aligned with gradients as compared to those of more oblique orientation. Interestingly, the variogram decreases to near the nugget level at a range of about four nautical miles and remains quite low to a range of eight nautical miles. This may very well reflect a characteristic scale size of aggregation or patchiness, which is more apparent in the vertical sections presented below.

The conformal variograms for 1996, presented in Fig. 4b, are dominated by a nugget of amplitude 0.75 in the usual normalized units of the sample variance. Differences in the isotropic and transverse anisotropic variograms become apparent at about two nautical miles. The fact that the experimental variograms do not reach or cross the sill, a level equivalent to the sample variance, before about four nautical miles indicates some structure. Modelling could be somewhat complicated, possibly requiring the use of exponential and cosine functions, for example, to allow for the apparent hole-effect at the mid-range of two nautical miles.

Comparison of the conformal variograms for the two years clearly indicates a higher degree of structure in the 1995 data. The qualitative observations of biologists participating in the surveys would be very interesting in this context.

So-called conformal longitudinal anisotropic varigrams were computed but are not presented. In order to collect a sufficient number of data pairs to achieve a degree of significance in the experimental variogram, a quantization distance of five nautical miles was applied. Short-range structure is thus lost, and larger-scale structure is not evident, if present at all. The blue whiting distribution has been undersampled with respect to this dimension.



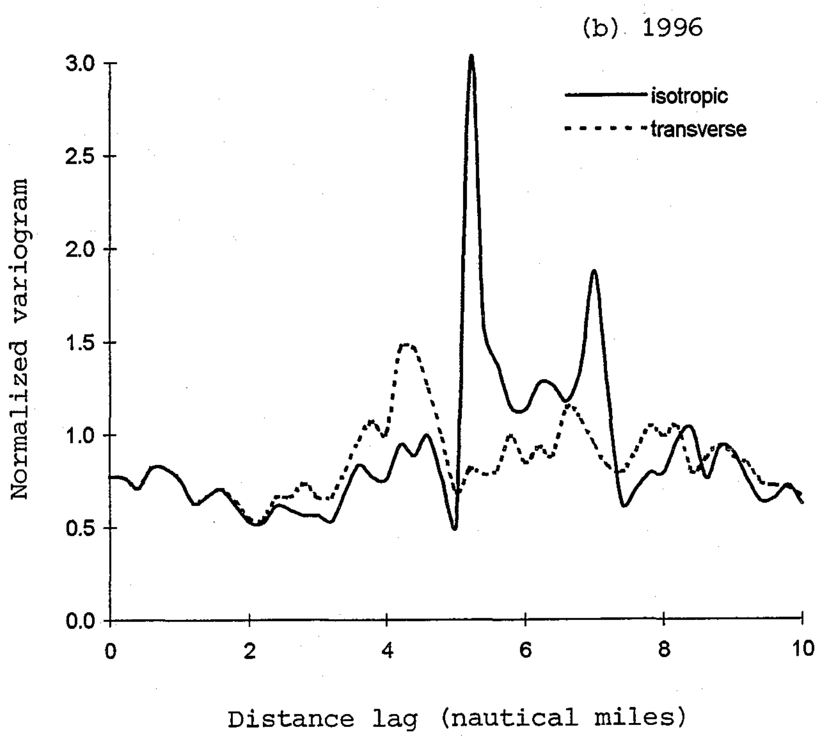


Fig. 4. Conformal variograms based on the s_A-values from the indicated regions in Fig. 2, normalized to the respective sample variance. Both isotropic and transverse anisotropic variograms are shown for each year: (a)1995, (b) 1996.

Conformal variograms were also computed for the historical data from the years 1984 and 1986-1994. The basic resolution of five nautical miles in sailed distance for the integration interval is so coarse that the variograms have the character of noise, hence are not presented.

In the reported computations, only the 500-m bottom depth isoline was used. Given the general similarity in isolines in the depth range 200-1000 m for the selected regions in Fig. 2, or at least where data were actually collected in these regions, this seems entirely adequate. Computations with data collected on Porcupine Bank itself or near seamounts, for instance, would require treatment of multiple isolines in measuring the distance between pairs of acoustic samples.

Vertical sections and one-dimensional variograms

To supplement the present study, vertical sections are displayed, and corresponding one-dimensional variograms are computed for individual transects, as selected according to the listed criteria and identified in Fig. 3. These are paired for year-to-year comparison.

In Fig. 5, distributions of blue whiting north of Porcupine Bank are shown. The two distributions are quite different, with that for 1995 extending off the slope, while that for 1996 remaining immediately above it. The variograms are determined by the particular form of the concentration, which showed less structure for the 1996 data because of the presence of an extreme density value.

Further north, on a steep part of the continental slope, the same transect was executed in both years. Indeed, the distributions in Fig. 6 are very similar. Apparent differences indicated by the respective variograms may be artificial, for the 1995 transect was truncated at a trawling station, consistent with the selection criterion of continuity in sampling.

Still further north, transects are selected from oblique crossings of the continental slope. The vertical sections are displayed in Fig. 7. The full extent of the respective distribution has apparently been covered. Visual similarities are confirmed by the variograms. These could be modelled by a spherical function of approximate range three nautical miles and, especially for 1995, additional cosine term to reflect the nature of patchiness in horizontal distribution.

In a final example, vertical sections are presented in Fig. 8 for different localities which show similar tendencies to those observed throughout the southern and central parts of the survey region. As in the vertical sections in Fig. 5, the distribution in 1995 extends off the slope, while that in 1996 remains immediately above it. The particular values of acoustic density, namely s_A, determine the variogram; extreme values for 1995 dominate the variogram, lending this the character of a noise process. In 1996, less extreme values were encountered, and short-range structure is evident, with a characteristic range of two nautical miles.

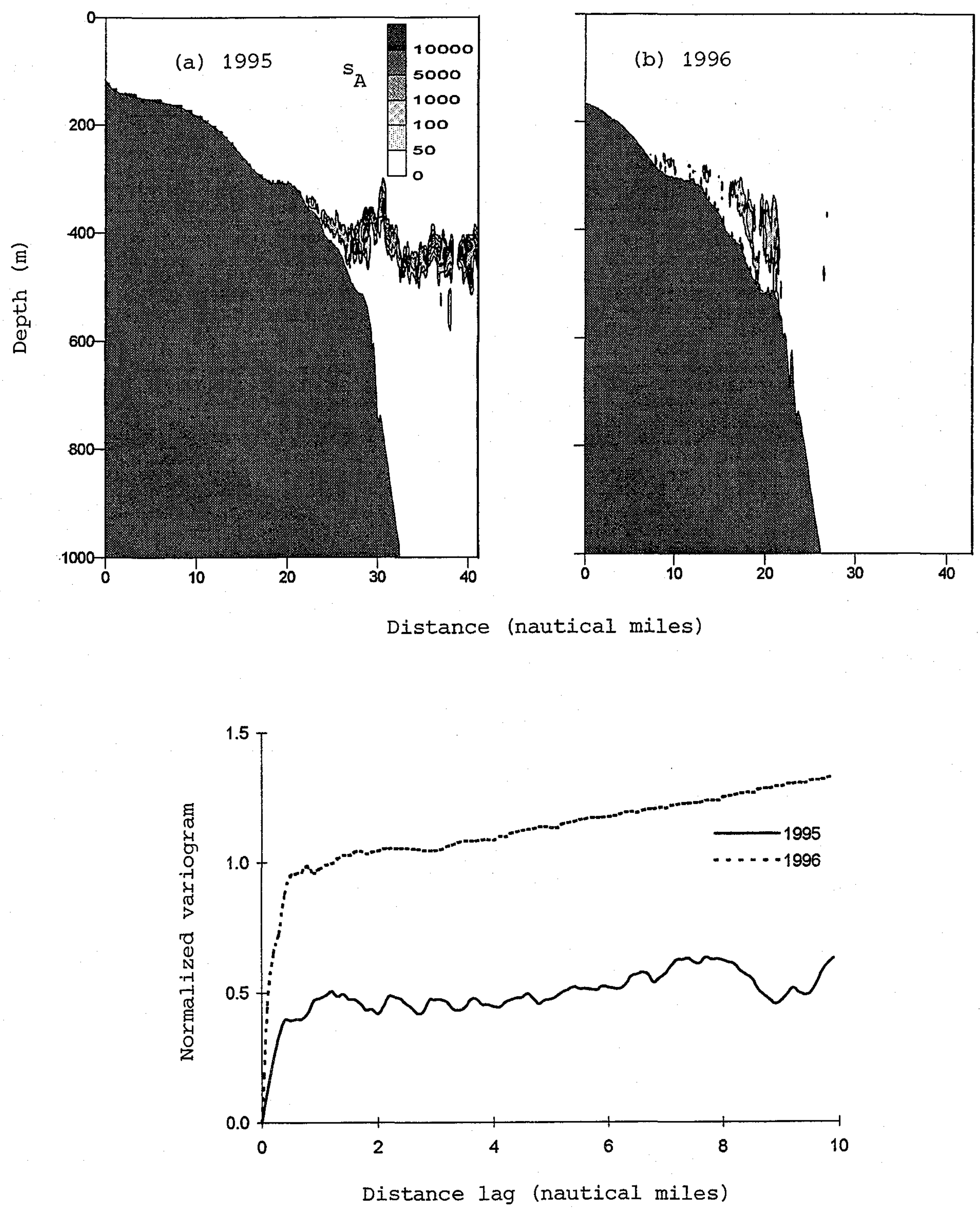
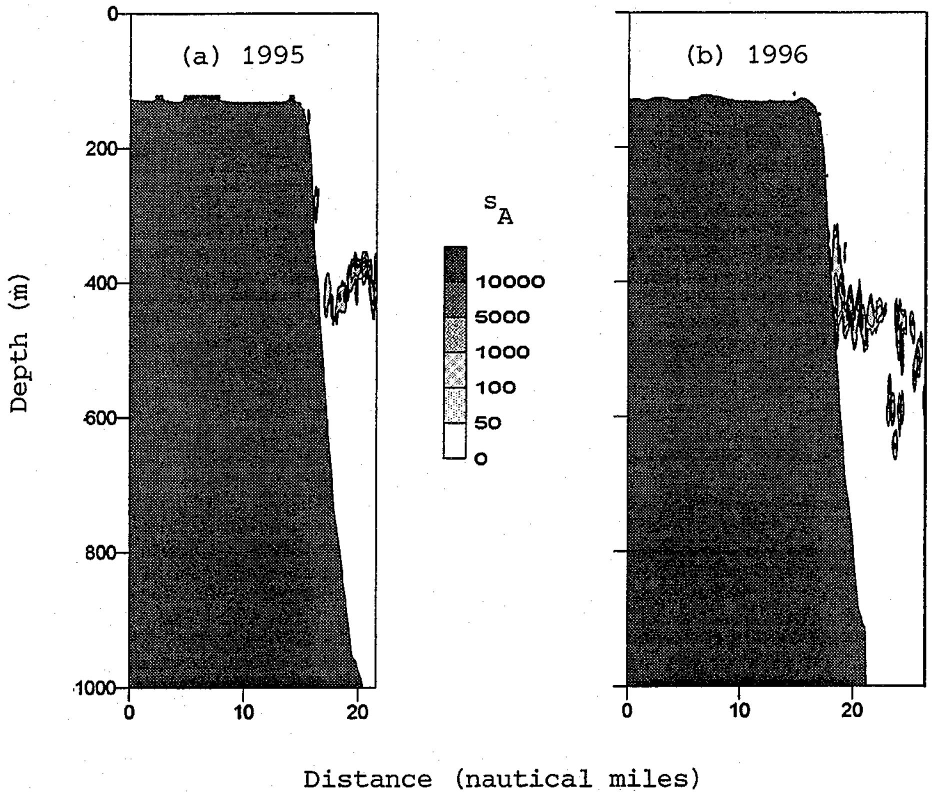


Fig. 5. Vertical sections of northern blue whiting distribution from the same transect north of Porcupine Bank, crossing the continental slope obliquely, together with corresponding one-dimensional variograms of s_A-values derived by integrating over the entire water column and normalized to the respective sample variance.



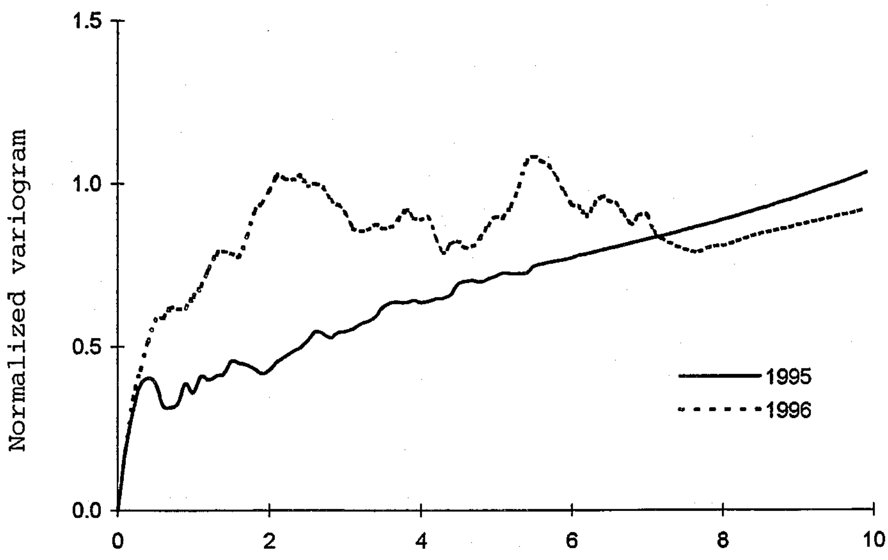


Fig. 6. Vertical sections of blue whiting from the same transect crossing a steep part of the continental slope, together with corresponding one-dimensional variograms of s_A-values normalized by the respective sample variance.

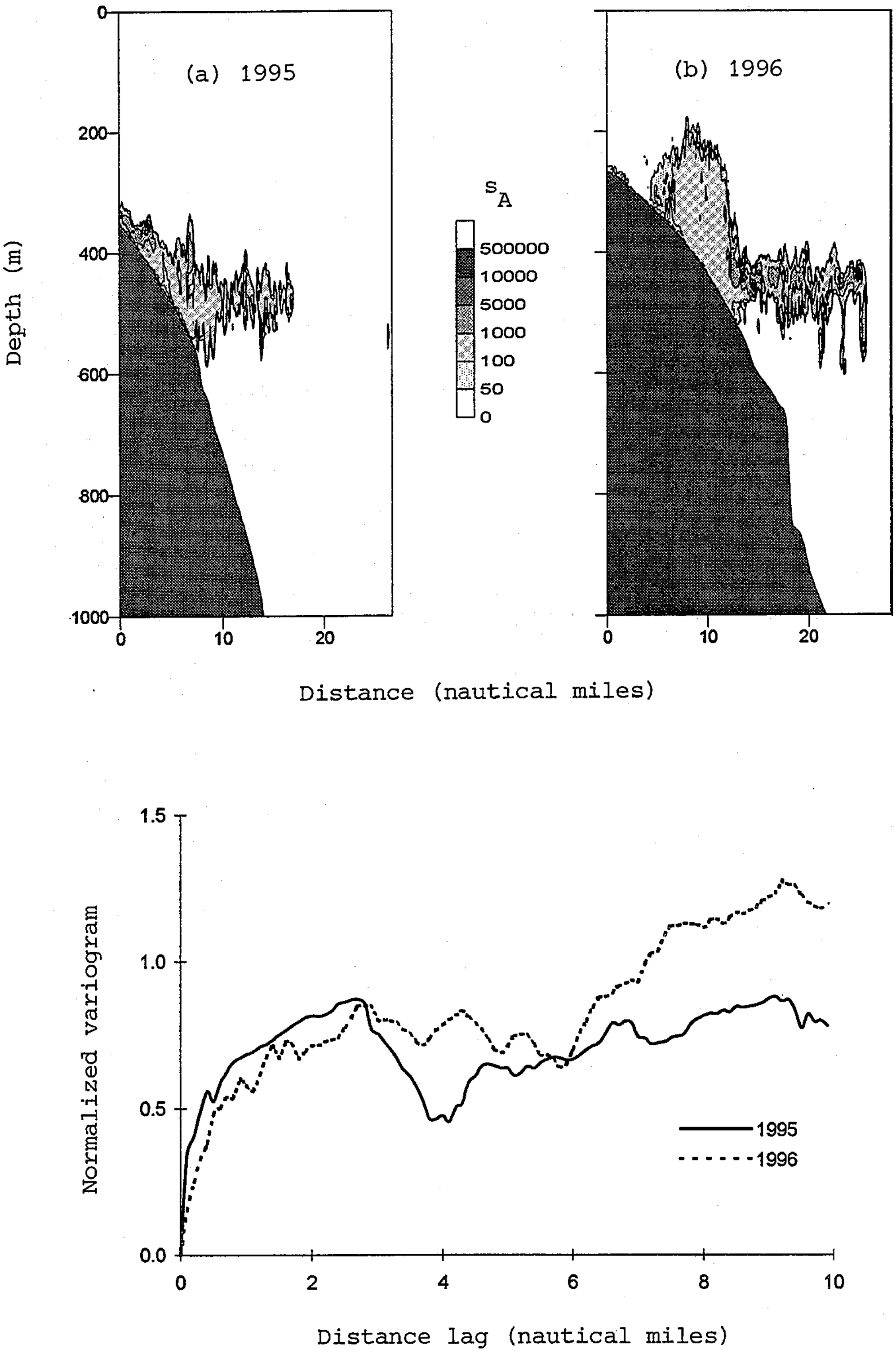
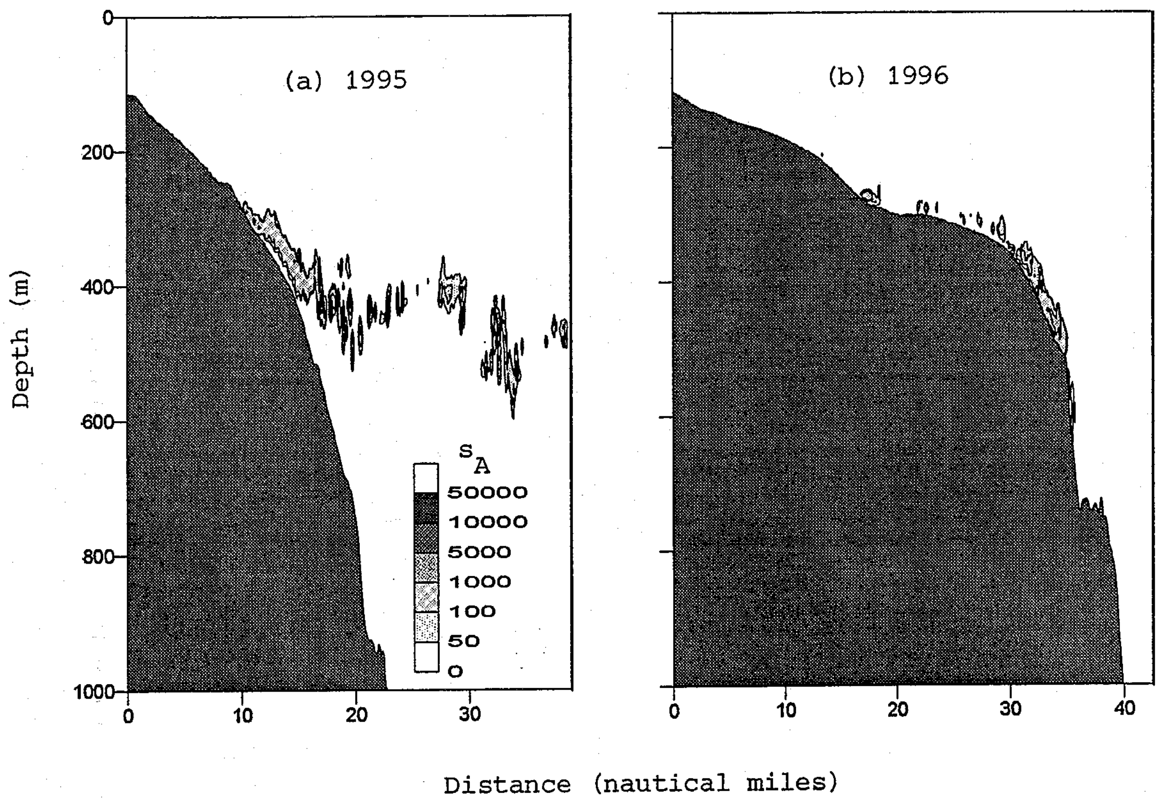


Fig. 7. Vertical sections of blue whiting from transects crossing a similar northern region of the continental slope, with corresponding one-dimensional variograms of s_A-values normalized by the respective sample variance.



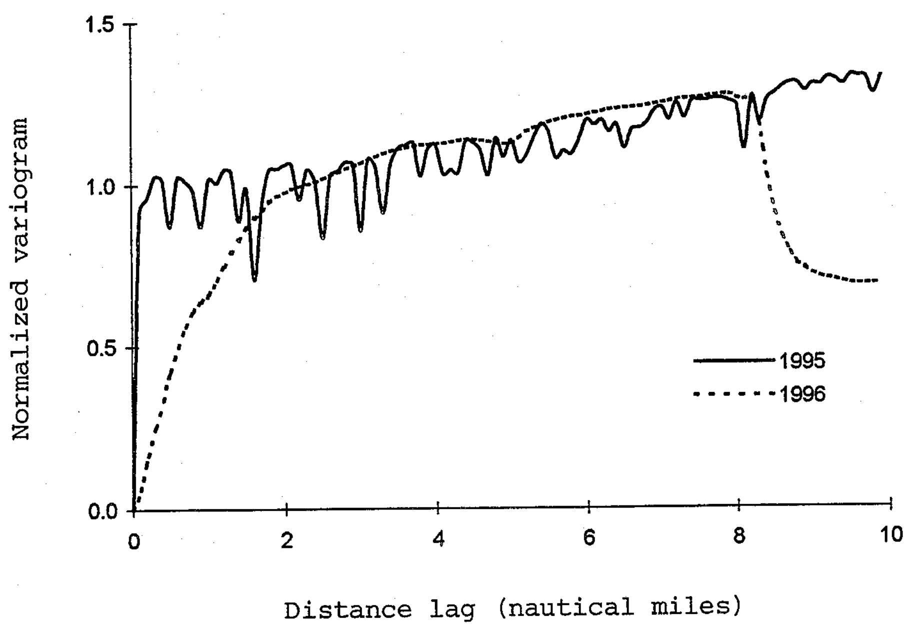


Fig. 8. Vertical sections of blue whiting from different localities but showing fish distributions similar to the respective cases in Fig. 5, together with corresponding one-dimensional variograms of s_A-values normalized by the respective sample variance.

Remarks on characterizing structure

The aim here has been to introduce the conformal variogram and to apply this to distribution data on the spawning stock of northern blue whiting. This has been done for both isotropic and anisotropic variograms. Because of differences in sampling density, the resolving powers of the longitudinal and transverse anisotropic variograms are necessarily different. In fact, the sampling is essentially continuous along transects which have been designed to cross the continental slope and which avoid following bottom depth contours. Comparison of longitudinal and transverse variograms has thus been precluded, especially at distance lags less than five nautical miles, where short-range structure has been observed along normals to the 500-m isoline.

Structure in the blue whiting distribution evidently exists at different scales, as the variograms often show a marked decrease at ranges beyond that where the sill is first reached or approached. In addition, inspection of the vertical sections shows strong differences in aggregation properties with respect to the continental slope itself. In some similar regions in 1995, the distribution extended well beyond the slope, while in 1996 it remained concentrated immediately above the slope. The one-dimensional density distribution along single transects also shows varying degrees of concentration that are undoubtedly related to slope proximity. North-south differences are also evident, although the period of time for surveying such a large area may influence this.

All in all, non-stationarities must be present. At one level, the driving forces may be differences in fish behavior from year to year or with time of surveying in the same year. At a deeper level, the driving force may be the postulated shelf-edge current and temporal and spatial variations in this. Perhaps temporal differences in blue whiting distribution in the same region mark small but significant changes in this current, just as regional differences in blue whiting distribution may indicate differences connected with slope topography, for example.

Thus, while characterizing structure is necessary for such geostatistical applications as estimating fish stock abundance and mapping the distribution based on partial sampling, it may also provide the means of revealing connections to underlying phenomena. In this work, a bathymetric link has been explored.

ACKNOWLEDGEMENTS

T. Monstad is thanked for generously making available acoustic survey data on blue whiting for project use. R. J. Korneliussen is thanked for extracting data from the data base. The assistance of Dr. B. Faras-Ostrowska in verifying data quality is gratefully acknowledged. The partial support of the European Union through RTD contract no. AIR2-CT94-1007 has been essential to the conduct of this work and is gratefully acknowledged.

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