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ACOUSTIC PORTRAIT OF HERRING IN VESTFJORD, JANUARY 1996, WITH GEOSTATISTICAL ANALYSIS

by

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ABSTRACT

In January 1996 the stock of Norwegian spring-spawning herring (Clupea harengus) was acoustically surveyed in the wintering area. Both immature and mature fish were present. Because of the comparative lateness of the survey, the spawning migration had already begun, and the total survey area extended from the inner reaches of Ofotfjord and Tysfjord to the sea area southwest of Vestfjord, well over 200 nautical miles from end to end. Coverage of the Vestfjord area alone occupied three days, thus also including diurnal vertical migration. The evident complex of dynamics is described in two ways: (1) by acoustic images of herring distribution in vertical sections of Vestfjord, and (2) through variograms computed for strata identified by the visual presentation. Speculation is offered on the use of such an analysis in stratification.

INTRODUCTION

The migration habits of Norwegian spring-spawning herring (Clupea harengus) changed dramatically in autumn 1987 when the fish began wintering in the fjords of northern Norway (Røttingen 1992). Beginning in autumn 1991, the herring has wintered primarily if not exclusively in the Ofotfjord-Tysfjord-Vestfjord system. This circumstance of annual concentration has been exploited in the performance of acoustic surveys in the fjord system in autumn and winter to estimate stock abundance (Foote 1993, Røttingen et al. 1994, Foote and Røttingen 1995, Foote et al. 1996). At the same time, the opportunity to perform collateral or supporting studies has been seized. Some examples include in situ observation of herring by a stereo-camera system and high-frequency scanning sonar (Huse et al. 1994), determination of the prevalence of Ichthyophonus hoferi, trials of a new multiple-codend pelagic trawl (Engås et al. 1996) to improve stratification, application of geostatistics to specify the variance of the abundance estimate (Foote 1993), and development of visualization tools (Ostrowski 1996) to aid in data-quality control and the search for diurnal or other patterns of behavior (Huse and Korneliussen 1995).

The last-mentioned technique of visualization requires no additional sampling effort beyond that of the primary acoustic data collection, yet it can reveal striking patterns, such as those of diurnal vertical migration as elaborated by Huse and Korneliussen (1995). This has been an inspiration for the present study, which incorporates geostatistics with visualization tools to begin quantifying observed distribution patterns in space and time, and to facilitate interpolation for the purpose of mapping the distribution over a surface.

MATERIALS AND METHODS

General techniques of data collection and postprocessing

The primary data are the ordinary acoustic survey data. The particular materials and methods used in the collection and preparation of such data have been described many times (Foote 1993, Røttingen et al. 1994, Foote and Røttingen 1995, Foote et al. 1996). They are summarized here for completeness.

The principal instrument of data collection is the SIMRAD EK500/38-kHz echo sounder (Bodholt et al. 1989), with attached ES38B transducer. The beam pattern is approximately circular, with opening angle between opposite half-power points of 7 deg. The echo sounder is typically operated at the maximum pulse repetition frequency (PRF) as determined by the bottom depth and signal processing requirements. For typical bottom depths in the surveyed fjord system and multiple-frequency operation, the effective PRF is very roughly 50 pings per minute. The average sailing speed is about 8 knots.

The echo sounder configures echo data in the form of digital streams of absolute values of the volume backscattering strength S_v throughout the designated depth range, typically 0-500 m, with a vertical resolution of 1 m for herring in the described fjord system. An additional 150 S_v-values are also attached to describe the near-bottom region with generally high vertical resolution, for example, 0.1 m.

Echo sounder data are broadcast over a local-area network (LAN), where they are received by a postprocessing system, the Bergen Echo Integrator (BEI) (Foote et al. 1991). This system enables the data to be displayed on the electronic screen of a workstation. Through software, an operator may allocate the echo recordings to arbitrary scatterer classes. What is then assigned to designated scatterers is a matrix of values of the area backscattering coefficient s_A, with absolute physical units of square meters of backscattering cross section per square nautical mile (Knudsen 1990, Foote and Knudsen 1994). The resolution defines the size of a matrix element. For surveys on wintering herring in fjords, this is 10 m in depth and 0.1 nautical mile in sailed distance.

Following allocation, which is generically called "interpretation", the so-interpreted data are stored in an on-board database. The original echo sounder-processed data are stored in files deposited on a long-term storage medium.

Data used for abundance estimation among other purposes are extracted from the database by a standard series of routines. These data are subjected to a series of quality-control routines by the user to ensure their integrity, especially to guard against corruption of the data by operations connected with the database. They are subsequently adjusted for the attenuating effect of acoustic extinction according to the algorithm documented in Foote (1990), using the extinction parameter specified in Foote (1994), namely $\sigma_e=2.41\sigma_b$, where σ_e and σ_b are the respective extinction and backscattering cross sections. Since the present study concerns visualization and not the absolute estimation of biological density, it is sufficient to perform the extinction compensation in a relative sense using the ratio $\sigma_e/\sigma_b=2.41$.

The extinction-corrected data are then averaged over statistical squares of side length 0.2 nautical mile. The aim in averaging is to avoid effects due to uncertainty in positioning, including use of the position at the start of each 0.1-nautical-mile integration interval, as well as intrinsic uncertainties in position.

Particular data of interest

The particular data of interest were collected during the herring abundance survey cruise in January 1996 with R/V "Johan Hjort". The region of interest is that of Vestfjord: from Barøy at 16°E to about 14°20'E, which is indicated in Fig. 1. This was surveyed by a series of parallel transects equally spaced at 4' of longitude over a 32-hour period beginning on 19 January at UTC 0114. In Fig. 1, only the parallel transects are shown; the endpieces are discarded, as is customary, in an attempt to avoid unequal weighting of the data. The radius of a circle is proportional to $s_A^{\frac{1}{2}}$, where s_A has been computed for all herring throughout the water column. The maximum s_A-value shown here is 897995 m^2/NM^2, where NM denotes nautical mile.

Interpreted data underlying Fig. 1 contain another dimension, that of depth, albeit with 10-m resolution. These are the data, arranged in transects, that are to be visualized. The form of presentation is simple when color is used to represent intensity, as in displaying S_v-based echogram values on BEI. For a black-white presentation, however, the dynamic range of the data must be respected. If reckoned from a minimum significant value of 1 m^2/NM^2, the dynamic range spans approximately six decades for the present data set. The s_A-range is accordingly divided into decades, with an increasing degree of cross-hatching applied above the minimum displayed value of 100 m^2/NM^2.

Geostatistical analysis

In order to characterize the spatial properties of the data, the variogram is computed (Matheron 1971, Cressie 1991). This is done for the values of s_A derived by integrating throughout the water column. If this is represented by the variable Z, then the variogram is defined as one-half the expectation of the difference in Z-values located at positions separated by the vector distance $\underline{h}$, applied throughout the defined region. It is convenient to normalize this by the sample variance s^2,

$$\gamma(\underline{h}) = \frac{1}{2s^2} E\{[Z(\underline{x}+\underline{h}) - Z(\underline{x})]^2\} \quad ,$$

where $\underline{x}$ represents the vector position of a measurement point in the surface plane.

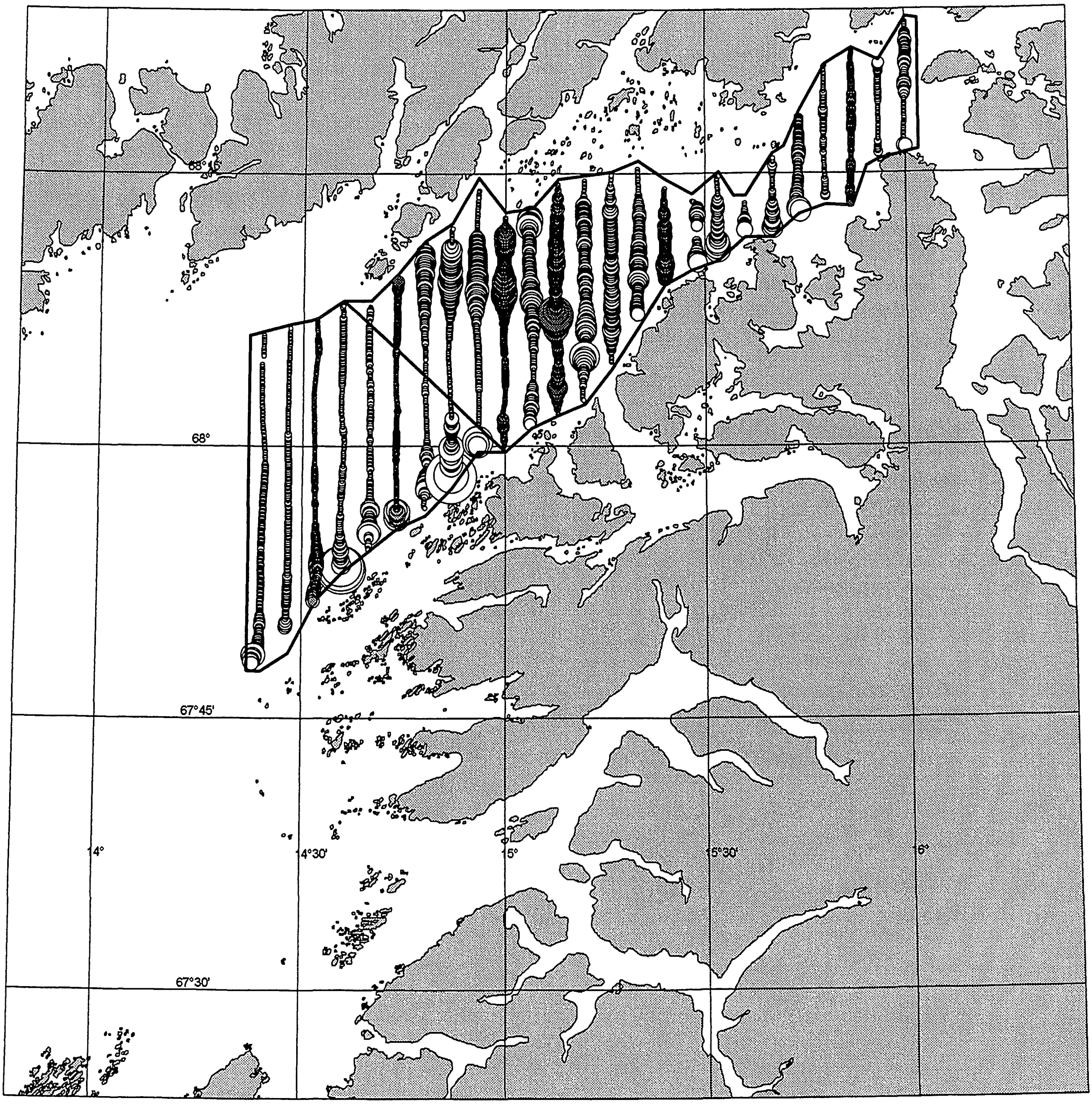

Fig. 1. Distribution map of herring in two strata of Vestfjord in January 1996. The radius of a circle is proportional to the square root of s_A after integration over the entire water column and compensation for extinction.

In general, $\gamma(\underline{h})$ is anisotropic, depending on the direction of the vector difference $\underline{h}$. Here, directional properties are ignored, and the so-called isotropic case is considered. Thus the argument $\underline{h}$ has magnitude only,

$$h = (|\underline{x}+\underline{h}|^2 - |\underline{x}|^2)^{\frac{1}{2}} \quad ,$$

which is called the distance lag.

Computation of $\gamma(h)$ is performed digitally on a finite set of points. The total range of h is necessarily subdivided into a set of finite intervals. The incremental size of this is chosen to be consistent with the block size of averaging, namely 0.2 nautical mile. For the given data set, this results in typical numbers for pairs in the same distance class of hundreds to thousands. This is a very reasonable size for ensuring stationarity in $\gamma(h)$.

For convenience, the experimental variogram is modelled. That is, a generic function is fit. For present work, a simple combination of nugget N(h) and spherical function S(h) is adequate,

$$\gamma(h) = A_N N(h) + A_S S(h) \quad ,$$

where N(h) is unity except at the origin h=0 where it vanishes, $S(h)=1.5(h/a) -0.5(h/a)^3$ for $h \leq a$ and 0 otherwise, and the amplitudes A_N and A_S are both non-negative and sum to unity.

RESULTS AND DISCUSSION

The principal visualization is shown through the sections in Fig. 2. For reference, the periods of nautical twilight are 0626-0743 and 1440-1557; civil twilight, 0743-0913 and 1310-1440; and daylight, 0913-1310 (Øi 1995). It was overcast on 19 January but mostly clear on 20 January, so there was little perceptible light outside of the period of nautical twilight on the first day, but easily perceived light during the period of astronomical twilight on the second day.

A major difference is seen between the first four sections and the last two. In fact, the sections originate in two different strata (Foote et al. 1996). These represent, respectively, the wintering region of inner Vestfjord, where mature and immature herring are mixed, at least on the large scale, and the region of active outwards migration of the mature fish. In the cited reference, the strata are identified as v42 and v44, respectively.

Visually, the herring is observed to be high in the water column at night in Section 3, deeper and vertically spread over a 200-m range during the daytime in Sections 10 and 14, with sun within about 5 deg of the horizon, and spread throughout the water column over a 300-m range during the late afternoon period of astronomical twilight in Section 16. In the

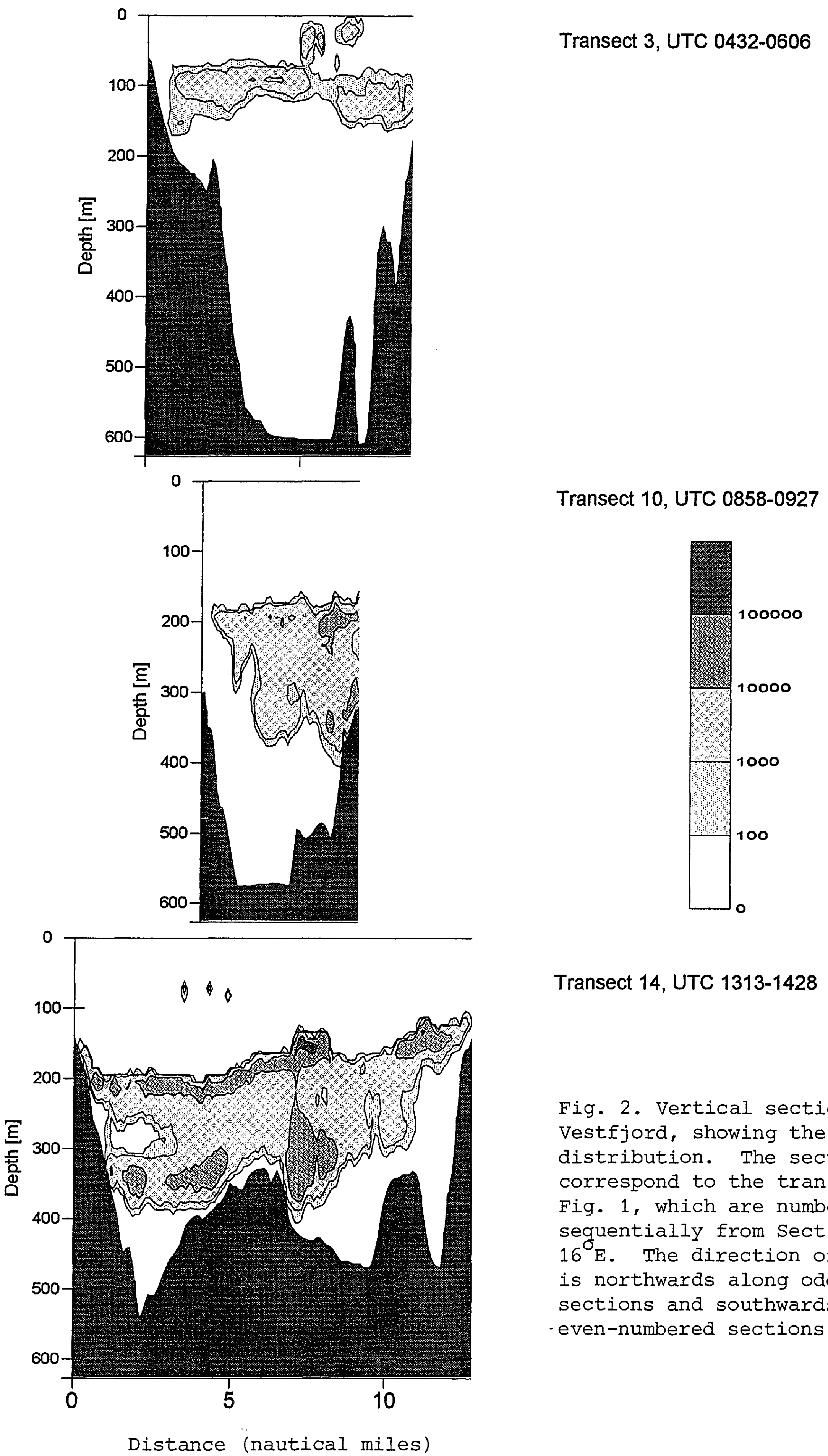

Fig. 2. Vertical sections of Vestfjord, showing the herring distribution. The sections correspond to the transects in Fig. 1, which are numbered sequentially from Section 1 at 16°E. The direction of sailing is northwards along odd-numbered sections and southwards along even-numbered sections.

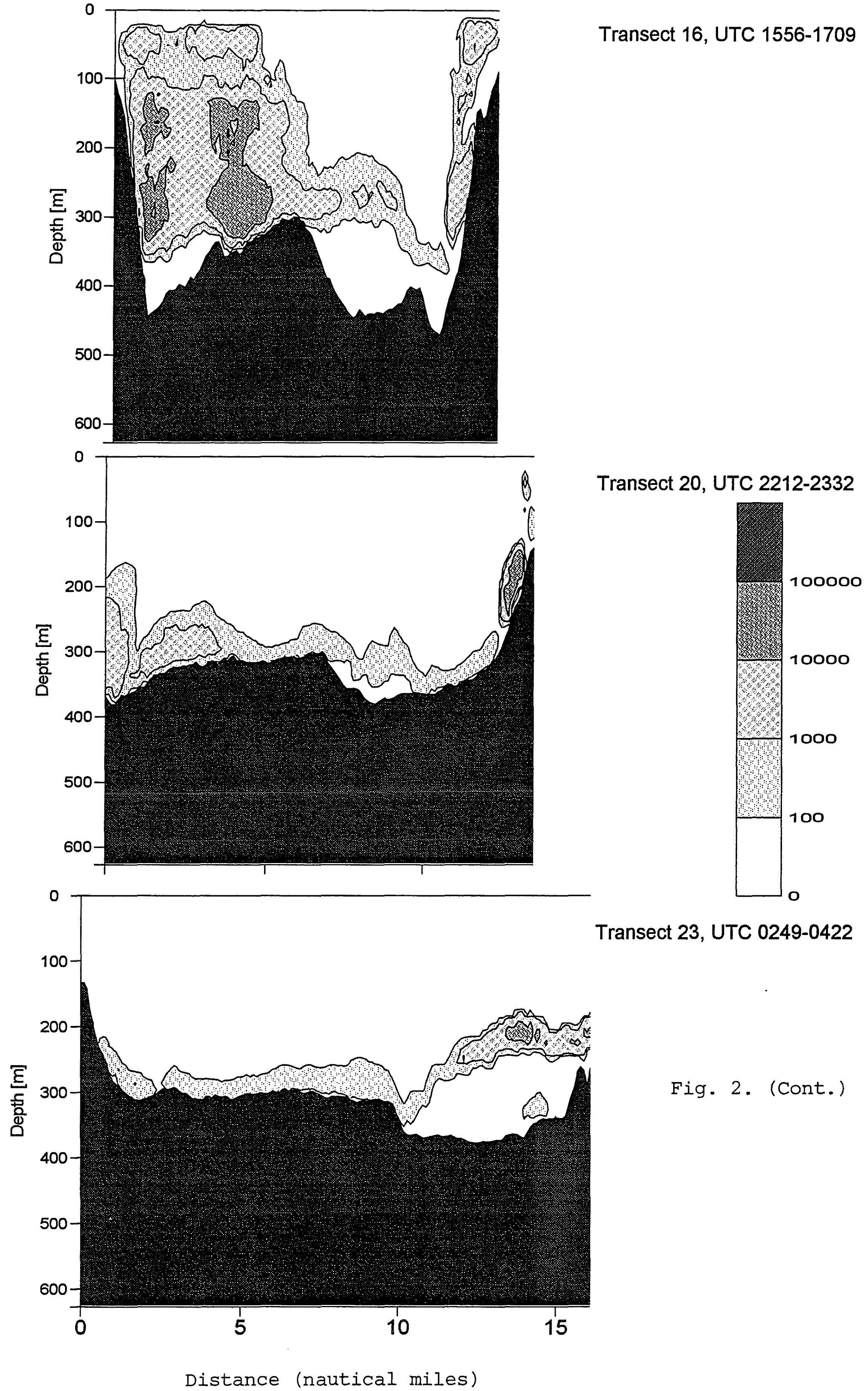
Transect 16, UTC 1556-1709
Transect 20, UTC 2212-2332
Transect 23, UTC 0249-0422
Depth [m]
0
100
200
300
400
500
600
100000
10000
1000
100
0
5
10
15
Distance (nautical miles)

Fig. 2. (Cont.)

night-time Sections 20 and 23, the herring is observed to lie mostly in a rather compact band of approximate thickness 50 m near the bottom. This must be a significant feature, which contrasts starkly with the diurnal pattern shown in Huse and Korneliussen (1995). Given that the cited study concerns wintering herring and the current study was begun after the onset of the spawning migration, a clear difference in behavior is observed across the diagonal line separating the two strata in Fig. 1.

A difference is also seen in the experimental variogram for the two strata, shown in Fig. 3. For inner Vestfjord, where mature and immature herring are both present, the range of the variogram is about 2.5 nautical miles. Beyond this distance, the variability is so great that structure, if present, is indistinguishable from noise. At the shortest distances, the variogram vanishes, showing continuity in structure on the small scale. The variogram model for the inner stratum is thus

$$\gamma_1(h) = S(h/2.5) \quad .$$

For the outer stratum, marked by migrating mature herring in the absence of immature fish, the variogram has a nugget or unresolved variability of about 50%, but a range of about 7.5 nautical miles. That is,

$$\gamma_2(h) = 0.5N(h) + 0.5S(h/7.5) \quad .$$

The two variogram models are indeed different, indicating both different degrees of continuity and different scale sizes of spatial variability. Just why the variograms differ as they do may be attributed to the mentioned difference in biological composition and behavioral states. To draw more general conclusions, however, requires a larger, more systematic study than can be supported by the limited, if highly suggestive data of this investigation.

Use has been made of the two variogram models to perform interpolation, hence mapping, according to ordinary kriging (Matheron 1971, Cressie 1991, Foote and Stefánsson 1993). This is done for the respective strata, which are assembled in a composite plot in Fig. 4. The neighborhood used in the kriging is defined by a circle about the kriged point with radius equal to twice the range of the pertinent variogram, hence 5 and 15 nautical miles for the inner and outer fjord regions, respectively.

It may be useful to observe that the present analysis supports in detail the original stratification performed in the Vestfjord region in Fig. 1. This was done by I. Røttingen on the basis of catch data and other biological data (Foote et al. 1996). The present visualization through vertical sections in Fig. 2 and variogram analysis in Fig. 3 are unambiguously corroborative. It is to be emphasized that the basis data to Figs. 2 and 3 are the same, but the geostatistical analysis operates on s_A-values derived by integration throughout the water column, and which are displayed in Fig. 1, whereas the data presented in the sections in Fig. 2 preserve the depth information. Application of kriging in Fig. 4 has complemented the data presentation in

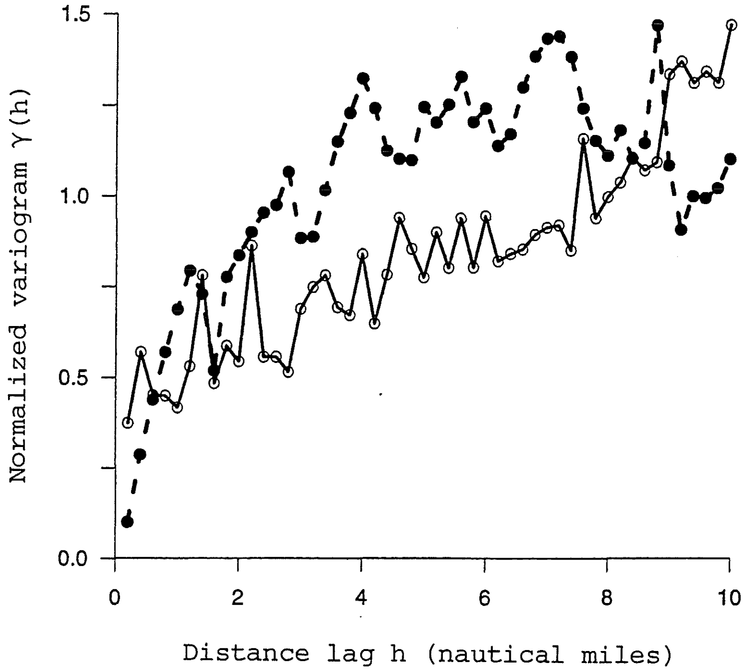

Fig. 3. Experimental variograms for the two strata indicated in Fig. 1. The variogram for s_A-values in inner Vestfjord is shown by the dashed line connecting the filled circles. That for the outer stratum is indicated by the solid line connecting the open circles.

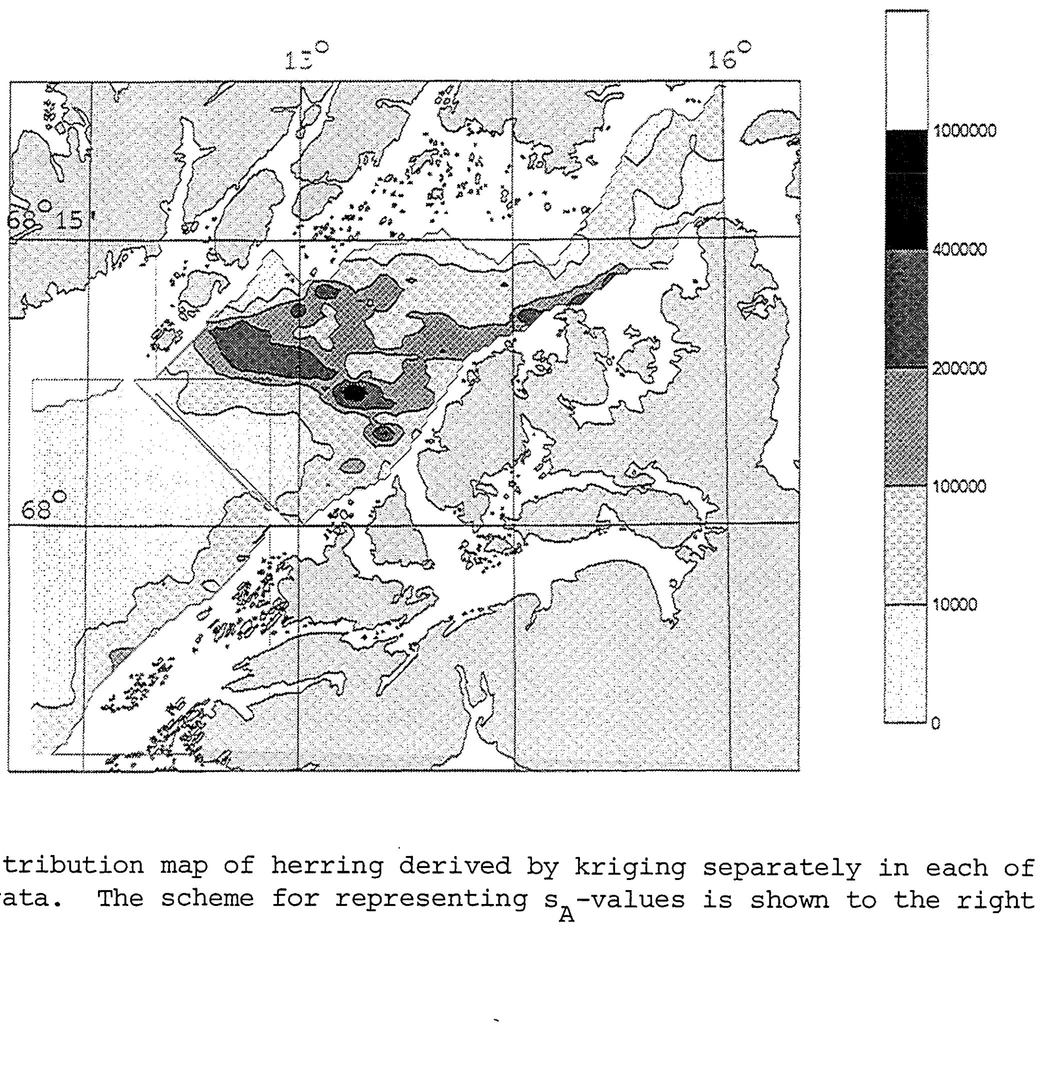

Fig. 4. Distribution map of herring derived by kriging separately in each of the two strata. The scheme for representing s_A-values is shown to the right.

Fig. 1, if still operating in the two dimensions of the surface plane.

Possible extensions of the present study may be entertained. These include (1) collection of more data to determine general geostatistical characteristics of herring in different states of wintering and spawning migration, (2) computation of two-dimensional anisotropic variograms in the surface plane, (3) computation of three-dimensional anisotropic variograms throughout the volume of interest, and (4) performance of visualization of the herring distribution by means of three-dimensional kriging. Ultimately, in a manner of speaking, the current manner of portraiture may be supplanted by a computer animation of the herring distribution.

A potentially valuable use of the geostatistical tool called the variogram is in distinguishing different kinds of behavior in the same geographical region but differentiated by depth. Integration of volume-distribution visualization software and a variogram calculation program, as in the object orientation approach to software design (Ostrowski 1996), may effect a rapid, interactive selection of strata on the basis of acoustic data alone, without the need for external catch data. While catch data are presently indispensable for the process of converting acoustic data to biological quantities, acquiring enough catch data to perform the stratification seems to be a steadily elusive goal. If the stratification could be done on another basis, such as that of the acoustic survey data, then limited catch data could be used far more rationally, as keys for biological assignment of scatterer classes rather than for the proven more complicated and cumbersome task of defining strata in the first instance.

CONCLUSIONS

The exercise of portraiture, with the support of geostatistics, is seen to give both qualitative and quantitative insight into behavioral and other biological characteristics of herring. Applications of portraiture that might be achieved through the object orientation approach to software design offer the exciting prospect of stratification on the basis of acoustic data alone.

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