ACOUSTIC STUDIES ON ENVIRONMENTAL PRESSURE ON 3D FISH DISTRIBUTION IN THE BALTIC

ANDRZEJ ORLOWSKI

Sea Fisheries Institute
Kołłątaja 1, 81-332 Gdynia, Poland
orlov@mir.gdynia.pl

This paper describes results of enhanced version, of the macrosounding method to integrate acoustic data with environmental and biological parameters in a time and space scale, for use in marine ecosystem analyses. Fish distributions are shown by a vari-coloured topographical space, or time based, matrix of volume back-scattering strength (s_V)*. The matrix is calculated for one or the series of surveys for each distance unit (ESDU) in standardized slices of insonified volume. Each* s_v *visualization is accompanied by a parallel cross-section of the same space unit, which provides a distribution of the selected environmental parameter measured during the same survey. Charts of such parameters are produced with the same procedures as for* s_v*. This presentation of multi-disciplinary data greatly improves recognition of time and space gradients. Analyses of data from multi-dimensional matrix calculated for individual transect improve interpretation and modeling of ecosystem characteristics. Application of the method was illustrated by examples, showing its practical use for data from 1994-2001 in the southern Baltic, collected during the autumn ICES acoustic surveys.*

INTRODUCTION

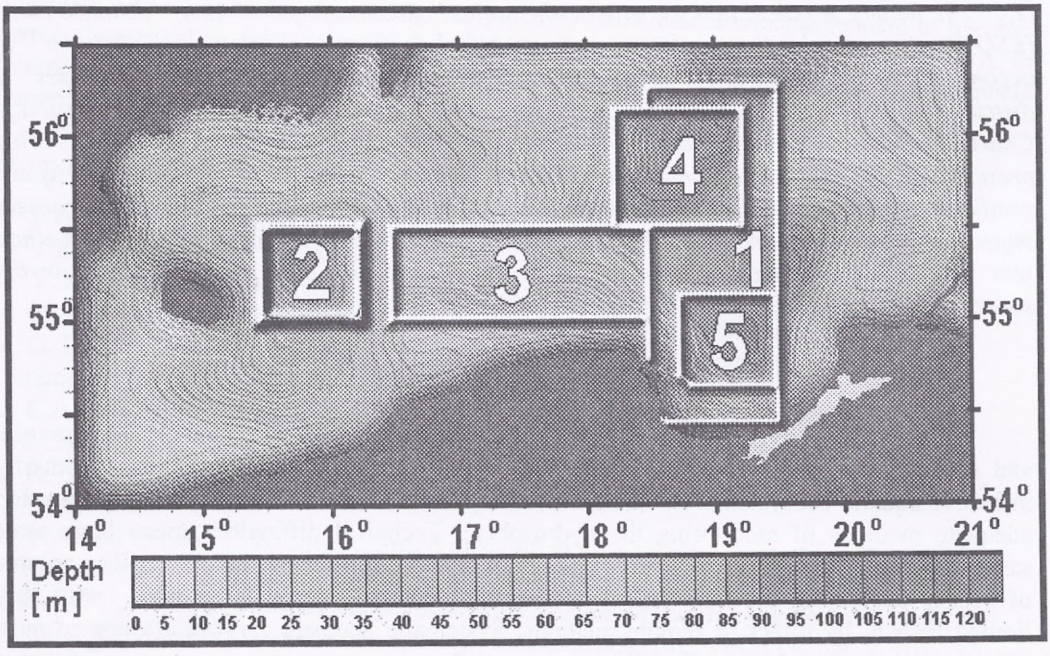
Barnes *et al.* (1991) underline the role of increasing pressure of global climate changes, and accumulated processes of contamination caused by human activity, which primarily influence aquatic ecosystems. Estimation of this phenomenon raise the necessity to develop adequate methods of monitoring the hydrosphere. Technical difficulties mean large scale satellite observations of the biosphere were limited to the surface of the oceans. The volume of oceans containing the majority of accumulated thermal energy is sampled with very limited density by direct or remote methods. Systematic acoustic surveys are one of most effective ways to produce vertical cross-sections of marine ecosystems in respect of fish and plankton aggregations. Development of visualization methods for acoustic data are widely observed in recent years (Jech, and Luo, 2000; Mayer *et al.*, 2001; Orlowski, 1990, 1998, 1999, 2000; Roman *et al.*, 2001; Socha *et al.*, 1996; Szczucka, 200. Most deal with monitoring relationships among biotic and a-biotic factors of the marine ecosystem. Some are directly intended to verify numerical models of the aquatic habitat (Horne *et al.*, 1996; Orlowski, 1998, 1999).

The paper describes studies provided by the most recent version of the macrosounding method, introduced by the author (Orlowski, 1990) and consequently modified due to increasing needs, experience, and technical advances (Orlowski, 1998, 1999, 2000).

A new version of the visualization, called "T-macro-sounding", fully applies a slice structure (as in tomography , reason of the letter "T" in the name of the method) of acoustic and environmental data, enabling very precise observations of details of spatial and temporal gradients, within a full range of insonified depths. Observations can be performed in a wider range of data base filtering possibilities. Additional graphical transformation of a calculated cross-section pattern by commercial software was applied to give optimal readability and the highest range of the final visualization. Separate type of visualization was applied for selected parameters of the cross-section pattern.

1. MATERIAL AND METHODS

Systematic acoustic surveys of the southern Baltic area have been conducted by Sea Fisheries Institute since 1981. Recording of samples 24-h a day, for each one nautical mile distance unit (ESDU) in a slice-structured database started aboard R.V. Baltica in 1994.



EK400 and a QD echo integrating system were applied with own software. In 1998 an EY500 scientific system was introduced to fulfil international standards of acoustic measurements, enabling research to continue. Both systems were using a frequency 38 kHz and the same hull-mounted transducer of 7.2°x8.0°. Calibration has been performed with a standard target in Swedish fjords in 1994 to 1997 and in Norway from 1998 to 2000. Cruises were carried out in October and lasted 2 to 3 weeks, giving a possibility of collecting samples over 1 to 1.5 thousands of n.mi. Survey tracks of all cruises were on the same grid to obtain high comparability of measurements.

Biological samples were collected over the period from 1994 to 2000 by the same pelagic trawl, on average every 37 n.mi. of the transect. Fish observed during all surveys were mostly pelagic, herring and sprat (*Clupeoidae*). Hydrographic measurements (temperature-T, salinity-S, and oxygen level-O_2) were made by a Neil-Brown CTD system. These were mostly at sample haul positions, with a similar biological sampling space density. Each hydrological station was characterized by its geographical position and values of measured parameters at 2m depth intervals (slices).

The results of echo integration for each ESDU were converted into values of normalized area backscattering coefficient (s_A), following Knudsen's (1990) formula :

$$(s_A)_i = \varepsilon \int_{z_i}^{z_{i+1}} s_v\ (z)\ dz \qquad (1)$$

where: $(s_A)_i$ is the integrator output [$m^2 n.mi^{-2}$] for i-slice layer , ε is the conversion constant [$m^2 nmi^{-2} sr$], s_v (z) is the volume backscattering strength [$m^{-1} sr^{-1}$], z, z_i, z_{i+1} – are the depth and i-slice layer limits [m]. Due to draught of the vessel, hull reverberations and the aeration zone, the first layer of integration had to start at 15m depth. Each ESDU unit was characterized by a series of $(s_A)_i$ values (slices), geographic position, date, time of day and sea bottom depth. s_A were converted into s_v values by the formula:

$$s_v = s_A\ A\ \varepsilon^{-1}\ A\ (z_{i+1} - z_i)^{-1} \qquad (2)$$

The process of converting acoustic and environmental data into T-macrosounding visua-lization is realized in two stages.

In the first stage, software prepared in the Sea Fisheries Institute is applied to prepare and calculate a 3D (x, y, z – coordinates) matrix of requested cross-section of the marine ecosystem for analyzed factors (s_v, T, S, and O_2). This matrix is calculated with standardized space or temporal resolution, within required limits of the selected parameters. Interpolation can be involved in the calculation process. A graphical chart in which each rectangle gets the colour corresponding to the mean value of analyzed parameter is presented as the output of this stage of the process. The scale of colours is based on a cumulative percentage of an empirical distribution of each parameter value. One colour corresponds to approximately a 10% range of the cumulative distribution.

Two basic types of cross-section are mostly taken into consideration: geographic and time related.

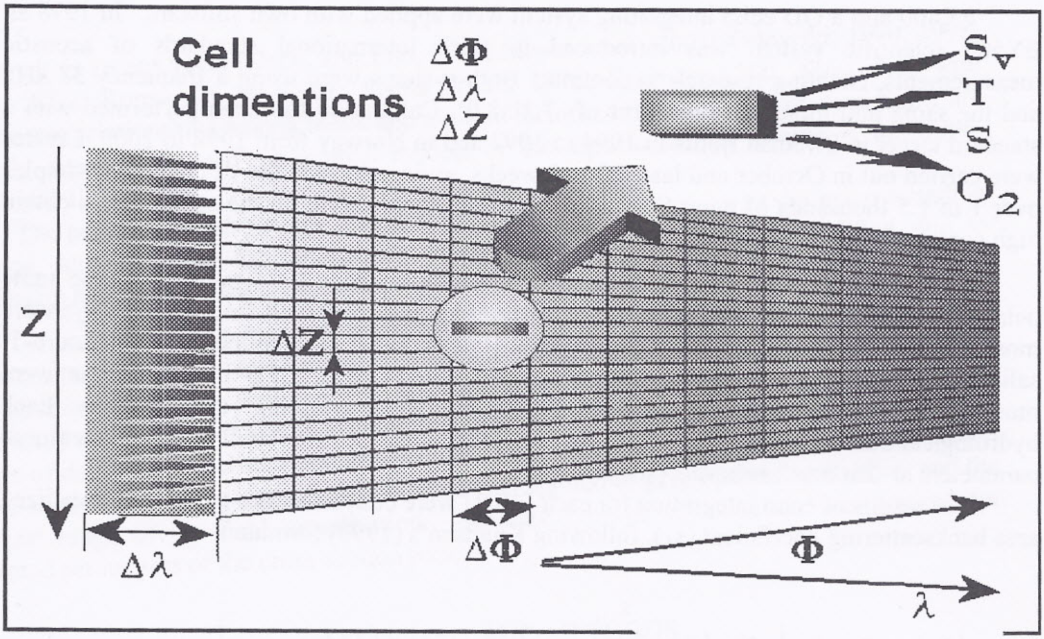


Fig.2. Diagram showing the correlation of a single cell ()N,)8) characterized by latitude and longitude (N, 8) with estimated values of the selected factor (s_v, T, S, O_2).

In the first case, O_x-axis expresses a distance along a parallel of latitude, or meridian. O_y-axis corresponds to a depth and O_z axis to s_v values. Bottom depth is taken into consideration in this process. Visualizations have to be produced separately for day and night-time as the fish distribution pattern differs significantly between those periods (Orlowski, 1999). Daytime is characterized by the presence of shoal-like concentrations within a wide depth range. During the night most pelagic fish, in the form of scattering layers, inhabit a reduced depth range in the warmer near-surface waters.

The second type of cross-section describes the 24-h variability of s_v against depth, illustrating basic characteristics of fish diel behaviour (dynamics of migration pattern) in an environmental back-ground.

Data for calculation can be filtered and up to 7 independent factors within defined ranges can be taken into consideration. As a consequence, fish distribution patterns can be observed, i.e., in different geographical transects or within the characteristic sub-areas of the ecosystem. A similar process is used in calculation of the matrix of environmental factors. Due to a lower space density of hydrological samples, an adequate matrix is calculated with lower geographical resolution. Day and night options have no sense in this case.

In the second stage a visualization produced by our software is transformed by commercial graphic software using procedures selected after a long series of trials for the optimal results. The Jasc-Software was chosen as a useful and efficient tool for this purpose. A procedure called "topography effect" was applied to convert a primary version of visualization into an enhanced multi-colour chart in which single rectangles of colour matrix elements are transformed into topographical patterns.

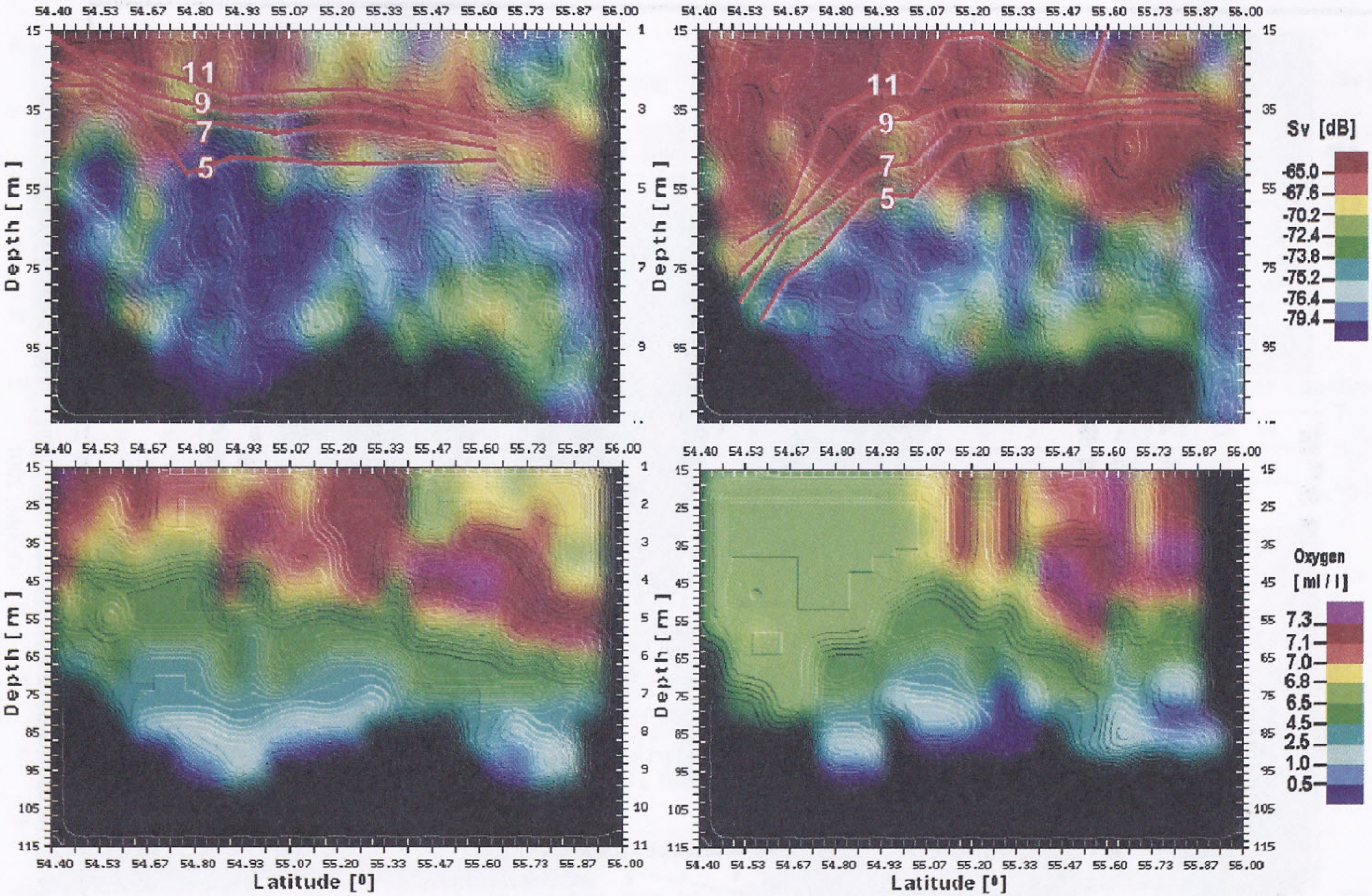


Fig.3. T-macrosounding visualizations of latitude cross-section of the Polish EEZ along 19°E, generated for cold (years 1996,1998 and 2000 together- left panel) and warm (years 1994,1995,1999 together- right panel). Night-time sv distribution is shown together with isolines of temperature in the upper part of the figure. Distribution of oxygen level pattern is shown in the lower part.

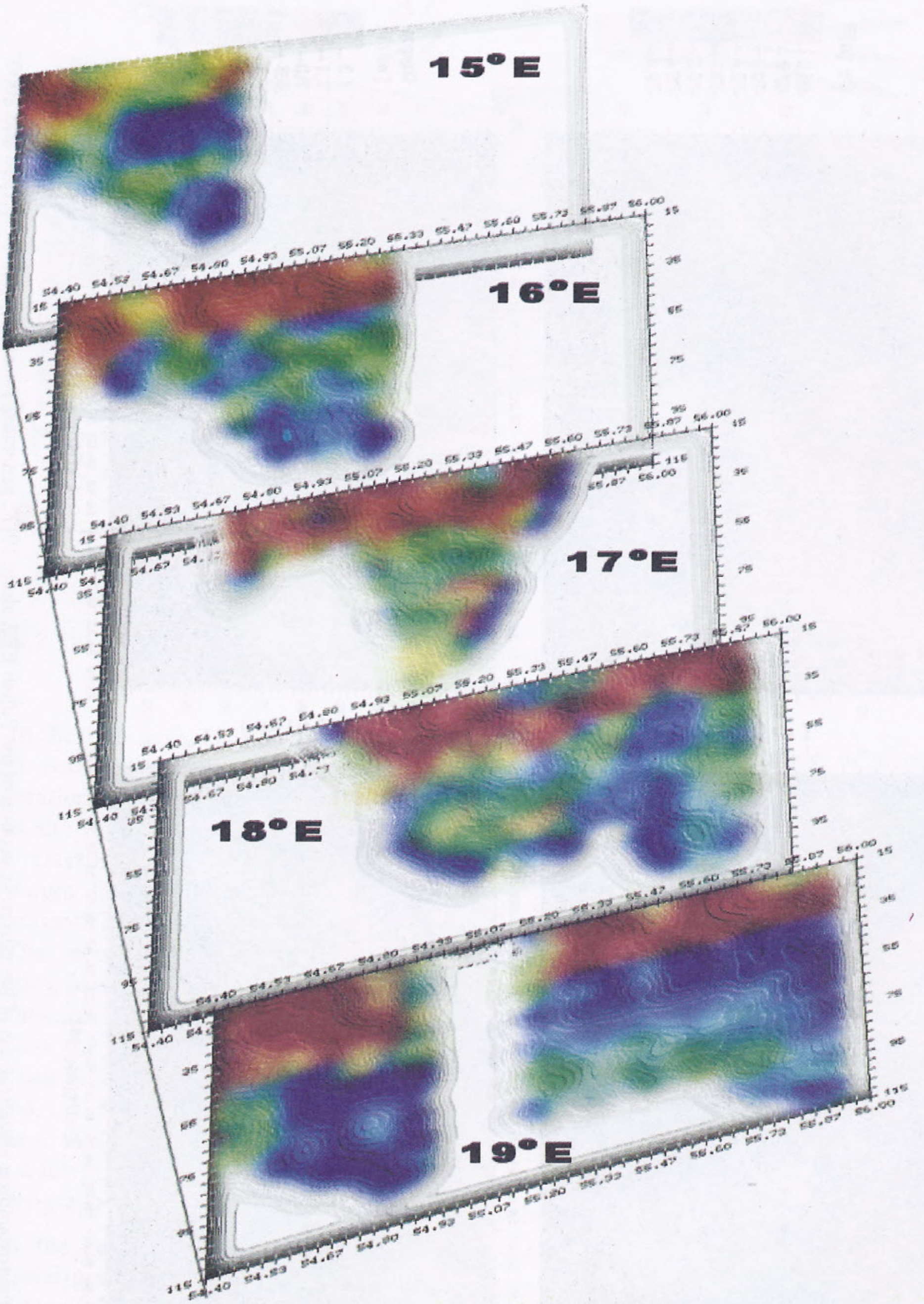


Fig.4. Quasi 3D visualization of night fish distribution within the area of the Polish EEZ in October 2001.

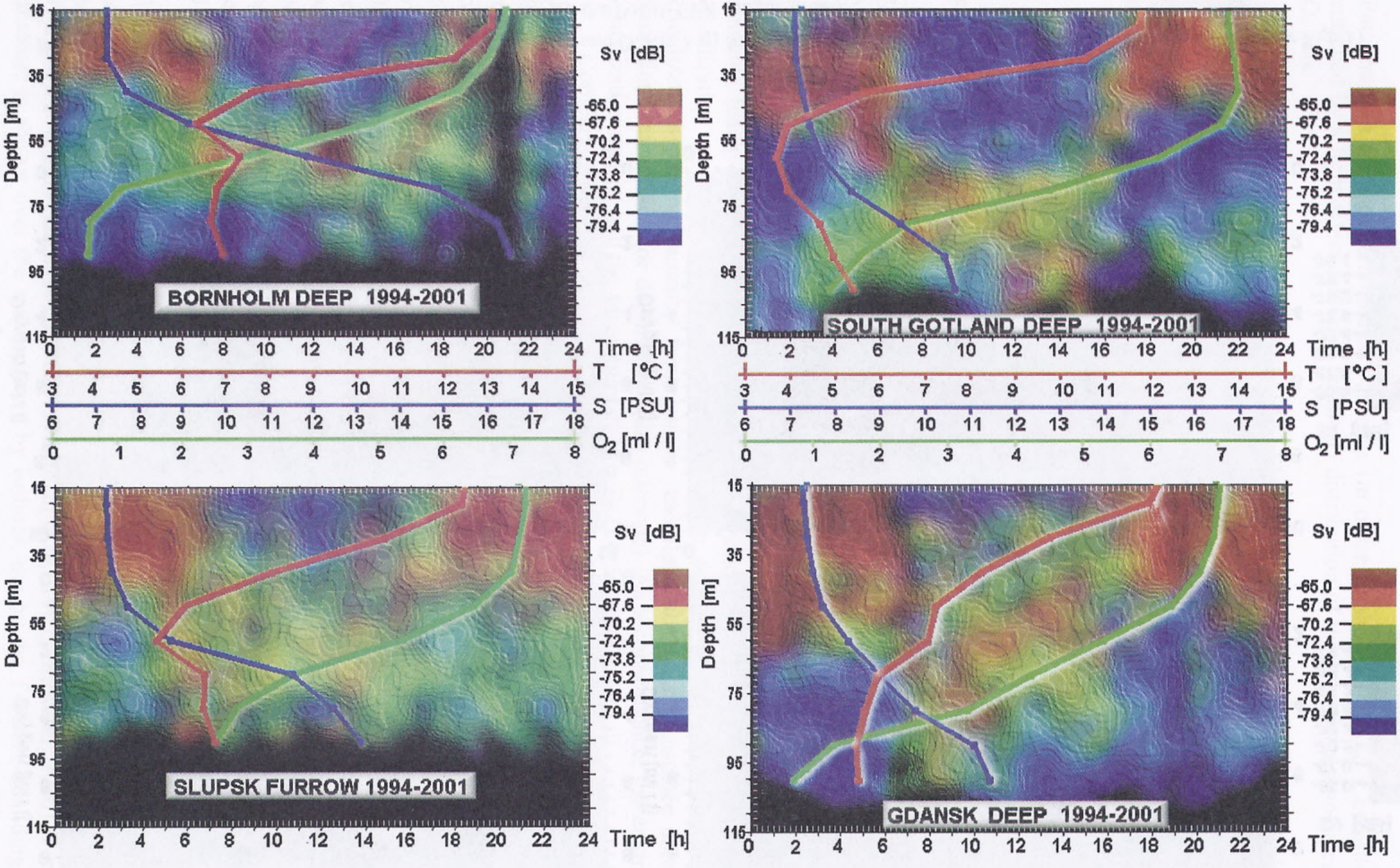


Fig.5. Diel migration patterns of fish in different sub-areas of the southern Baltic Sea estimated from the data collected over the period 1994-2001. Mean temperature (red line), salinity (blue line), and oxygen level (green line) diagrams.

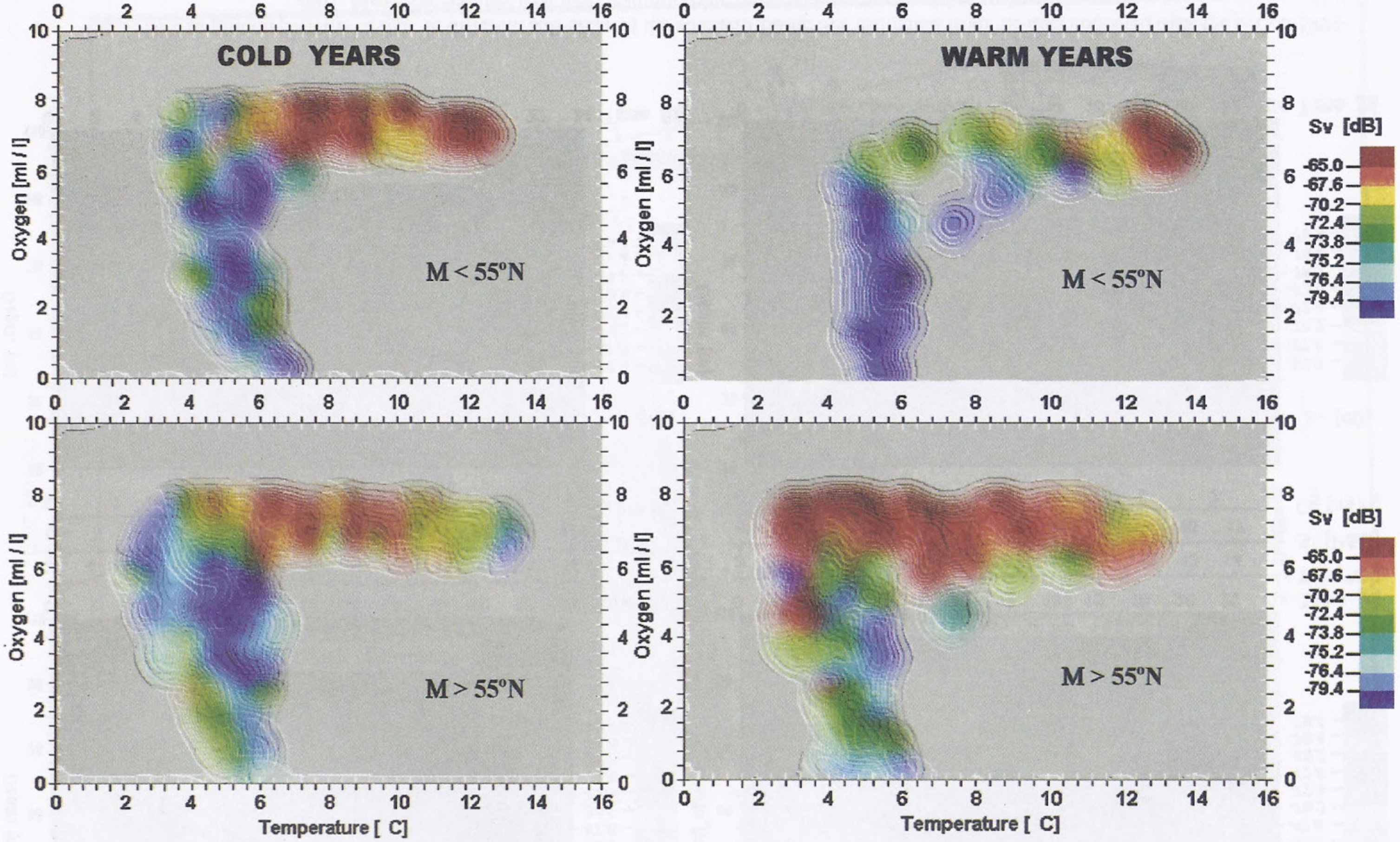


Fig.6. Comparisons of the values of sv (.ij, 8 ij), T(.ij, 8 ij), and O2(.ij, 8 ij) for the southern and northern part of the main cross-section (see Fig. 1) of the Polish EEZ (night-time).

Patterns in a form of interpolated terraces (in order to show x, y, and z coordinates) are enriched by a light effect, giving a quasi-3D distribution of the parameter associated with the O_z axis.

Visualizations can be realized as a systematic cross-sections of the surveyed area and thus can be ordered in space and presented as a quasi 3D characteristics.

Values of the factors measured (T, S, O_2), calculated for the same space element – cell ()N,)8), characterized by latitude and longitude (N, 8), can be easy related and compared in pairs to fish densities expressed by s_v in a similar as cross-sections visualizations.

2. RESULTS AND DISCUSSION

Examples showing a practical application of the T-macrosounding method are shown in Figure 3 –6.

In Figure 3 T-macrosounding procedure has been applied to characterize distribution of fishes along the most significant cross-section of the Polish EEZ (see Fig. 2 also – rectangle No 1). This area plays important role in a final fish biomass distribution in the southern Baltic. The profile crosses along the meridian 19°00E areas between Gdansk Bay and south Gotland Deep. The cross-section takes the form of a strip of 96 n.mi. long and one degree of longitude wide (approximately 34 n.mi.). Length of the area was divided into 48 elements (each 2. n.mi. long) and depth was divided into 25 slices of 4m each for s_v visualization matrix (1200 cells). A smaller space density of hydrologic stations caused visualizations of environmental factors to be calculated for 4 n.mi. distance units. Higher resolution was applied for depth slices (2m intervals). As a consequence, the environmental visualization matrix had the same number of cells (24x50=1200 cells).

Comparison of the mean water temperature (relatively to whole water volume within the Polish EEZ) and total biomass of fish (herring, sprat, and cod) for the autumns 1989-2000 show increasing instability of thermal conditions since 1995, and similar oscillations of fish total biomass. Distribution of observed factors are sufficient to provide analysis of data in two sections, representing warm and cold years. Separation of the years was made on a simple comparison of the values of mean temperatures of water masses in each year against the average. Mean temperature for the period 1989-2000 was 9.51°C (standard deviation 0.927°C, confidence radius 0.886°C). The years 1989, 1990, 1995, 1997, and 1999, with mean temperature exceeding 9.51°C (the average for the period 1989-2000) were considered as warm years and were recorded as one data file (warm years). Mean temperature for warm years was 10.13°C, with a standard deviation 0.291°C (confidence radius 0.610°C). The remain years 1996, 1998, and 2000 were considered as the cold ones. The mean value of temperature for cold years was 8.35°C, with a standard deviation 0.021°C (confidence radius 0.077°C).

Visualizations in the Figure 3 show the geographical structure (south-north axis) of fish distribution, expressed by s_v (z) values along the profile. The phenomenon was analyzed separately for the cold years of 1996, 1998, and 2000 and warm years, 1994, 1995, and 1999, data series. Analysis was performed for night time when fish are more stabilized by hydrological factors (Barnes *et al.*, 1991; Helfman *et al.*, 1997, Orlowski, 2000). Temperature structure is shown over the s_v (z) pattern by isolines, not by the T-macro-sounding chart, to reduce number of illustrations. It was also possible due to a simpler form of the temperature structure. T-macrosounding visualization was used to produce a more complicated oxygen level chart (Figure 3 – lower panel) and to show details of the method in full. No differences in the salinity pattern between warm and cold years were observed, which is the reason it is ignored.

Patterns of fish distribution for cold years showed significant limitation of the zone of high s_v values (s_v>-67.6dB) to areas of higher water temperature (T>7°C) but not exceeding 45m depth. The range of a more abundant layer was decreasing towards the north down to 20m, while it was double in the southern part of the profile.

However, during the warm years, higher values of s_v were found in a significantly wider range of depths from 75m on the south up to 65m on the north. The areas mentioned were very well correlated with a volume of water mass whose temperature exceeded 7°C (see temperature isolines in Fig. 3).

If we consider charts of oxygen distribution the nature of the phenomenon becomes more complicated. In this case we can easily confirm how T-macro-sounding cross-sections can clearly expose two parallel phenomena: (1) during cold years the fish distribution layer depends on water temperatures (lower depth limit), (2) the fish layer is perfectly correlated to the oxygen level range (O_2>7 ml/l).

During warm years, layers of fish concentrations (s_v >-67.6dB) were mostly correlated to warm water masses with an exception in the northern part of the area (north to 55°30'N). At the slope of the south Gotland Deep, concentrations were strongly correlated to water characterized by a high oxygen level (O_2>7 ml/l). The area of main fish concentration (Gdansk Bay and Deep) was characterized by lower (O_2<6.8 ml/l) oxygen. This means that the temperature can be considered as a factor of the first rank in environmental pressure on fish distribution. It must also be added that the biological structure of fish is different in the south (high percentage of young fish) and the north of the profile (adult fish, high year classes).

Figure 4 shows quasi 3D T-macrosounding visualization of night-time fish distribution in October 2001, expressed by $s_v(z)$ cross-sections for consecutive parallels 15-19°E , each shifted 1° to the East. We can identify where fish are concentrated more and which areas play most important role in the scale of the whole Polish EEZ. The same visualization produced for remain environmental factors could help in finding their influence on fish distribution in particular years and seasons.

Figure 5 gives a comparisons of fish diel migrating patterns, estimated in different areas of the ecosystem, as the mean characteristic for a period 1994-2001. Areas (see Fig. 1) are differentiated by bathymetric structure into four separate sub-areas. Starting from the West (the direction of the North Sea in-flows) we have: Bornholm Deep (No 2 at Fig. 1), Slupsk Furrow (No 3), South Gotland Deep (No 4), and Gdansk Deep (No 5). T-macrosounding visualization gives a pattern of fish diel migrations, expressed by $s_v(z, t)$ for each selected sub-area. At each T-macrosounding visualization a pattern of three basic environmental factors (temperature, salinity , and oxygen level) are given by colour lines. At first we can conclude that an area in which the fish occur during the night-time is limited by a depth of the thermal gradient. The same limit, but counted from the from the other side is mostly setting the upper depth of fish concentration during the day-time. The lowest amplitude of migration is found in the Bornholm Deep, a medium in the Slupsk Furrow and the highest in the South Gotland Deep. The depth of the lowest limit of fish occurrence is correlated to the oxygen level. In practice the oxygen level 1ml/l sets a boarder of the pelagic fish zone. When the temperature gradient is not strong enough – the fish occurrence during the nigh-time is enhanced to a wider range (Gdansk Deep).

As it was mentioned, we can provide the comparison of the values of the factors measured (T, S, O_2), calculated for the same space element – cell ()N,)8), characterized by latitude and longitude (N_i, 8_j), in pairs to fish densities expressed by $(s_v)_{ij}$ in a similar as cross-sections visualizations. In Figure 6 it is provided a 3D comparison of fish distribution (s_v), and both more important factors (temperature and oxygen level). The comparison is made for the same cross-section as it was shown in Fig. 3 (No 1, in Fig. 1). The cross-section was divided into two parts: southern one (<55°N) and northern one (>55°). During the cold years, while much smaller biomass is observed in the area, southern and northern characteristics of s_v (T, O_2) are not visually differentiated. During the warm years it is notified a big difference between both sub-areas: in the southern part (upper left panel) the fish is associated with warm water only (s_v>-67.6 dB) while in the northern part the fish is appearing in a wider range of temperatures. It has to be underlined that southern concentrations are formed by a juvenile fish mostly.

Recapitulating examples given above we can conclude that application of a series of T-macro-sounding visualizations effectively enhances a chance to identify and characterize important local differences in environmentally conditioned fish behaviour. Such information is very necessary to enrich the knowledge on particular marine ecosystem elements, with additional possibility of development of short-term and long-term research. It gives the possibility of a new type of treatment of inter-disciplinary data collected during research cruises, in respect of small and large-scale analysis of the ecosystem in the context of global variability.

The solution described, complements a range of methods of visualization characterized in cited references. Horne *et al.,*(1996) applied a similar visualization technique to produce patterns of numerical density of fish and temperature distribution along single transects of Lake Erie in verification of a bio-energetic model of the aquatic habitat. Very small cells (40mx0.5m), correlated with model assumptions were used.

A similar visualization for single transects was used by Roman, *et al.,*(2001) to present research on zooplankton and salinity distribution in Chesapeake Bay (near Baltimore) carried out in 1996.

Diurnal migrations of zooplankton in the Baltic Sea were studied by a similar way by Szczucka (2000).

Mayer *et al.,*(2001) described initial studies related to the transition from single to multi-beam applications, with a task of introducing geomatics and 3D visualization software to assess fish stocks and enhance knowledge of pelagic fish schools.

All these references were dealing with a single series of measurements. The methods described in this paper is mostly intended for long-term and large scale research on fish behaviour in relation to environmental characteristics of the ecosystem, using accumulated time and space series of measurements. Suggested methodology could be useful for direct studies of structure and function of marine ecosystems, based on acoustic semi-tomography, or to define sub-areas where numerical solutions can be easier found and verified.

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