Acoustic information applied to 4D environmental studies in the Baltic

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Abstract

Since 1981, acoustic information collected in the form of calibrated measurements of integrated echo energy has been applied at the Sea Fisheries Institute to observe the relationships between fish distribution and environmental factors. Data gathered in different seasons for each elementary distance unit (EDSU) at standardised depth intervals were compared to the values of selected environmental parameters measured in parallel. Acoustic, biological and hydrological data were correlated in space and transferred to the complex database, enabling 4D analysis of numerous factors characterising a wide range of fish behaviour. A number of methods and standards of comparisons are described to explain how to improve understanding of the relationship between 3D spatial environmental gradients and fish distributions. The results of various case studies, including the influence of hydrologic and seabed characterising factors, illustrate the practical application and validity of the methods. Particular attention is given to indicators of the dependence of local fish biomass density on the temperature structure in the sea.

1. Introduction

Understanding the functioning of the marine ecosystem, especially in the context of fisheries science, requires a substantial enhancement of the database describing the spatial and temporal structure of the main and critical abiotic and biotic factors in this area. Very attractive methods for surveying marine ecosystems have been based on satellite optical and infrared sensors (Yoder & Garcia-Moliner 1993), but the minimal depth penetration range resulting from the high attenuation of electromagnetic waves limited their application to surface layers only. Owing to their very low attenuation in water, sound waves present a most promising approach for complex observations of the marine ecosystem at a scale appropriate to its dimensions. In response to the gradients of physical properties (density and sound speed), acoustic waves are reflected and refracted. The application of echo sounding affords the possibility of locating areas of physical instability and of estimating their effect on the received echo. As a consequence, the distribution of received echoes characterises the qualitative and quantitative 3D components of the marine ecosystem (Clay & Medwin 1977, Holliday 1993, Sherman et al. (eds.) 1993, Orlowski 1989a,b). Echoes correspond to all types of acoustic instability in media and, in the case of the marine ecosystem, are associated with seabed, fish and plankton organisms, gas bubbles, hydrologic gradients, and many other sources. The application of different frequencies and directional characteristics of acoustic systems enable different spectra of objects to be detected (Clay & Medwin 1977, Holliday 1993, Holliday & Pieper 1995). Systematic surveys and subsequent computer processing of the data make it possible to observe important ecosystem characteristics at an appropriate spatial and temporal scale (Orlowski 1989c, 1990, 1998, Socha et al. 1996, Jech & Luo 2000, Szczucka 2000, Kemp & Meaden 2002, Massé & Gerlotto 2003, Peltonen et al. 2004). Results of interdisciplinary measurements, unified in space by the acoustic location of all elements, can be easily collected in a large database and visualised for better interpretation of the analysed processes (Orlowski 1989c, 1998, 2003a,b, Bertrand et al. 2003). The importance of such studies for fisheries is obvious (Barnes & Mann 1991, Helfman et al. 1997). These results are of fundamental significance for all marine scientists and ecologists, enabling the model's input factors to be correlated and interpreted.

This paper describes a number of case studies illustrating the practical application of acoustic information to selected elements of the Baltic Sea marine ecosystem. Examples are selected from the last two decades of the author's research work at the Sea Fisheries Institute at Gdynia: Orlowski (1989a,b,c, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003a,b, 2004, 2005), Orlowski & Kujawa (2005). That period began in 1989 with the publication by Orlowski (1989) of his Ph. D. dissertation entitled 'Application of acoustic methods for studying the distribution of fish and scattering layers in the marine environment'.

2. Material and methods

Between 1981 and 2004, research vessels of the Sea Fisheries Institute in Gdynia (r/v 'Profesor Siedlecki' and r/v 'Baltica') were used for a series of cruises to gather acoustic, biological and environmental data in the southern Baltic: three took place in summer (July 1981, August 1983, 1988), and two in spring (May 1983, May 1985). Since 1989, all cruises have taken place in autumn (October 1989, 1990, 1994–2004), in line with the ICES Baltic pelagic fish stock assessment programme. During each two-three-week-long cruise, data were gathered from an acoustic transect 1000–2000 nautical miles long. Samples were collected continuously and integrated every nautical mile, 24 h a day. The temporal distribution of samples (24 h a day) in relation to the whole period 1981–2004 was homogeneous; this constitutes a good basis for assessing the 4D characteristics of fish behaviour in the southern Baltic.

In the early eighties, an EK 38 echosounder and a QMkII echo-integrator were used for acoustic data collection. Since 1989 EK400 and a QD echo integrating system have been applied with proprietary software. In 1998 the EY500 system was introduced to comply with international standards of acoustic measurements. Both systems used the 38 kHz frequency and the same hull-mounted $7.2° \times 8.0°$ transducer. The equipment was calibrated with the aid of a standard target in Swedish fjords from 1994 to 1997 and in Norway from 1998 to 2000. The cruises in those years took place in October and lasted 2–3 weeks, affording the possibility of collecting samples over 1000–1500 nautical miles (n.m.) (approximately 450 transmissions per n.m.). To ensure a high degree of measurement comparability, the survey tracks of all cruises were located on the same grid.

Between 1994 and 2004 biological samples were collected with the same pelagic trawl, on average every 37 n.m. of the transect. The fish observed during all the surveys were mostly pelagic – herring and sprat (*Clupeidae*). Hydrographic parameters (temperature (T), salinity (S), and oxygen level (O_2)) were measured with the Neil-Brown CTD system, mostly at sample haul positions, with a similar biological sampling space density. Each hydrological station was characterised by its geographical position and the values of the measured parameters at 2 m depth intervals (slices).

3. Methods and results

Fig. 1 illustrates the use acoustic measurements as a tool for the 4D correlation of biological and oceanographic data.

Owing to the limited sampling possibilities of each of the three channels shown in Fig. 1, the survey strategy had to be well matched to the

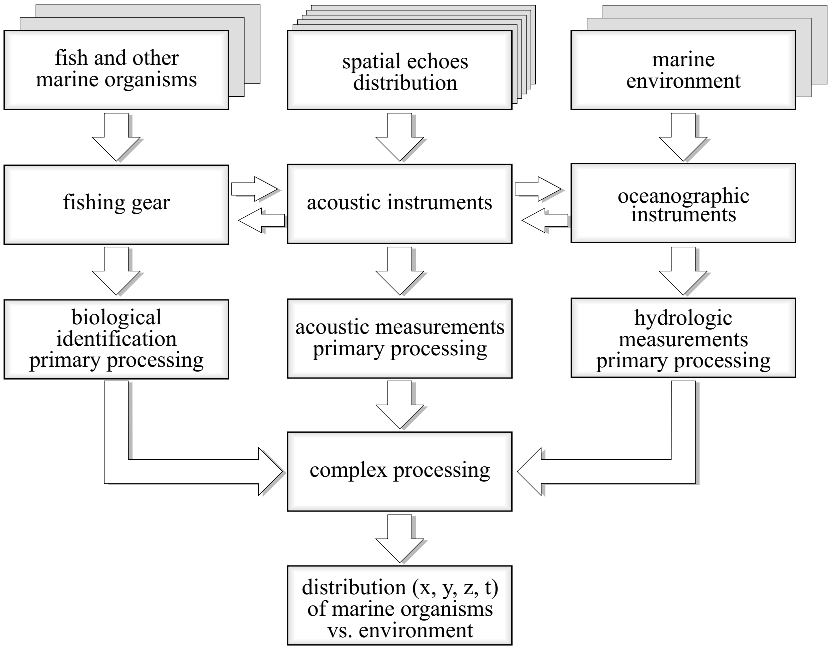

Fig. 1. Scheme showing the acoustically coordinated compilation of a common interdisciplinary database for the marine ecosystem

spatial characteristics of the surveyed area. (The geographical structure of a surveyed area has a significant influence on the strategy of its sampling.) Fig. 2 presents an example of a such strategy applied in October 2004. The sampling density is differentiated according to the methods of the research.

The distance of one nautical mile was considered to be the elementary unit (record) of the database. Each unit was characterised acoustically by the mean column backscattering strength (Svc), nautical area scattering strength (S_A) and volume backscattering strength in normalised depth layers (Orlowski 1999). For each record, the values of the remaining factors characterising the biological and hydrological parameters were estimated. By extending the record to include the depth structure of acoustic scattering Sv (z), as well as biological and hydrological components, and by introducing a time factor, a 4D database, called 4D-ABO (A-acoustics, B-biology, O-oceanography) can be produced, covering a wide range of parameters. Owing to the limited possibilities of the 2D sampling density of biological and hydrological parameters, their values per EDSU had to be estimated within certain standardised statistical areas (ICES rectangles in the Baltic). Detailed descriptions of the method of applying acoustic soundings for producing a 4D interdisciplinary database in the Baltic are given in Orlowski

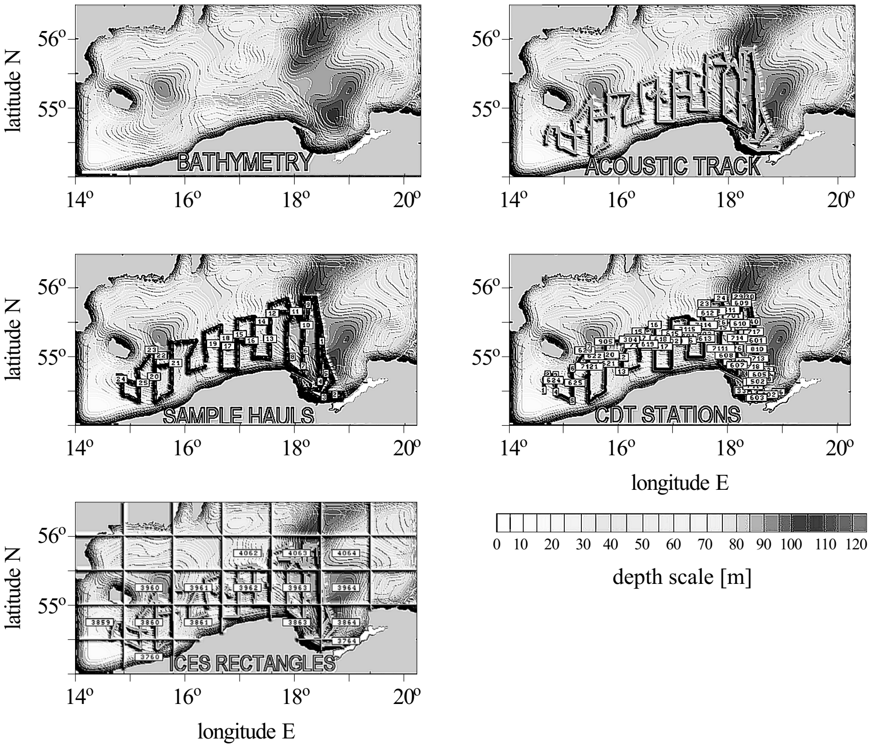

Fig. 2. Study area of r/v 'Baltica' in October 2004, sampled in the same way every year since 1981. The geographical structure of the basic components of the 4D-ABO interdisciplinary database

(1989a,c, 1990, 1997, 1998, 1999, 2000, 2001, 2003a,b, 2004) and Orlowski & Kujawa (2005).

3.1. Influence of temperature on fish distribution

Temperature is a first-order factor with respect the horizontal and vertical distribution of fish (Barnes & Mann 1991, Helfman et al. 1997). Variability of this factor is associated with the season of the year, but from the fisheries research point of view, it is most important to correlate its instability with fish distribution anomalies. In the same season (month), the temperature can vary over a very large range. Fig. 3 gives an example of such a fluctuation. The patterns in this Figure show strong fluctuations in depth structure, gradients and absolute temperatures.

The vertical distribution of fish during the day is very different from that prevailing at night (Fig. 4). This means that the hydrological variability exemplified in Fig. 3 will independently modulate the day- and nighttime

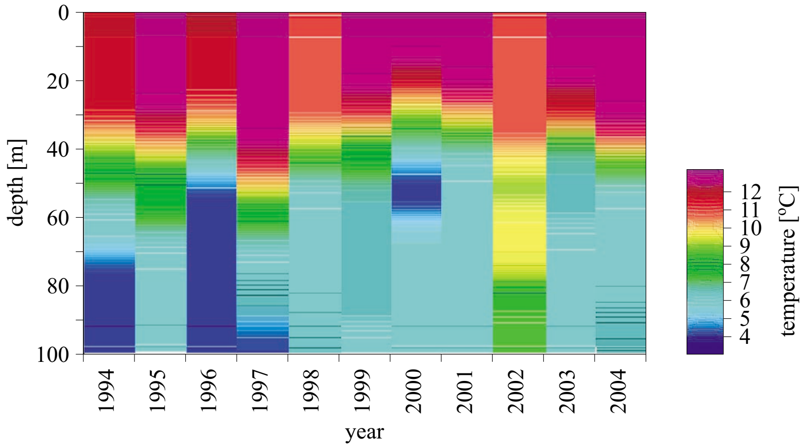

Fig. 3. Average temperature-depth structure in the southern Baltic in October 1994–2004

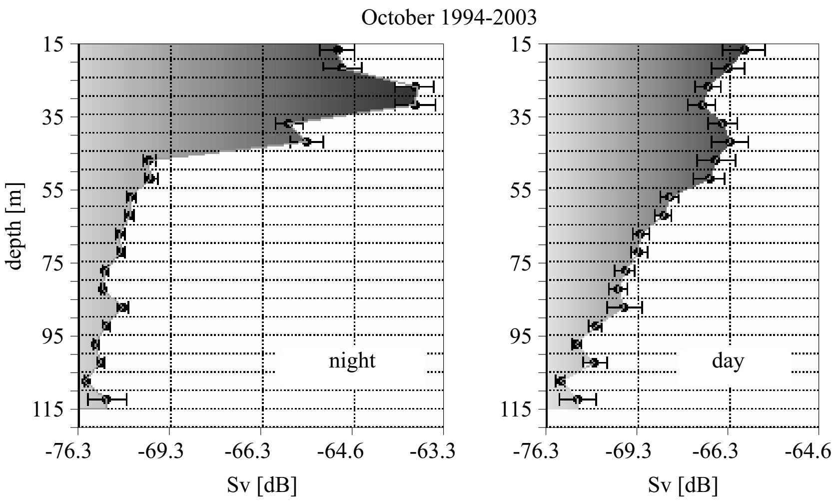

Fig. 4. Average day- and nighttime depth distribution of Sv (z) in the southern Baltic in 1994–2003

vertical fish distribution patterns. Orlowski (1999) introduced standards ($T_{F25\%}$, $T_{F50\%}$, $T_{F75\%}$, $S_{F25\%}$, $S_{F50\%}$, $S_{F75\%}$, and $O_{2F25\%}$, $O_{2F50\%}$, $O_{2F75\%}$), expressing ranges of hydrological factors associated with day- and nighttime fish distributions.

Characteristic points were associated with the cumulative empirical distribution of a given factor at the fish main depth (25%, 50%, and 75% quartiles), weighted by S_A. Fig. 5 shows the values of $T_{F25\%}$, $T_{F50\%}$, $T_{F75\%}$, $S_{F50\%}$, $S_{F25\%}$, $S_{F75\%}$, and $O_{2F25\%}$, $O_{2F50\%}$, $O_{2F75\%}$ for the years 1989–2004.

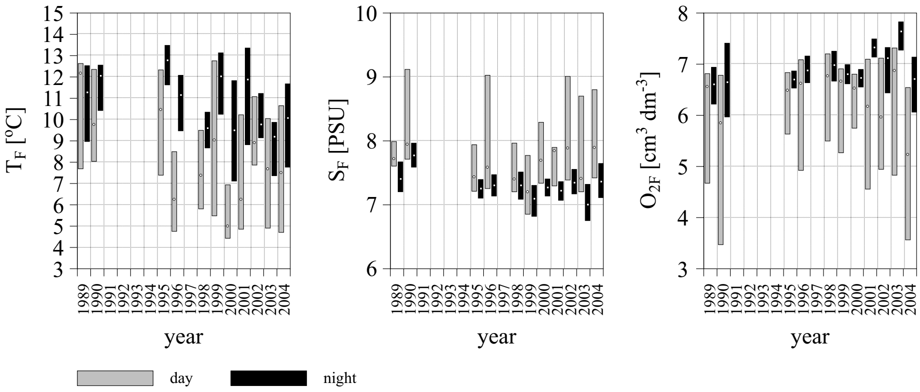

Fig. 5. Acoustically determined temperature, salinity, and oxygen level limits: $T_{F25\%}$, $T_{F50\%}$, $T_{F75\%}$, $S_{F25\%}$, $S_{F50\%}$, $S_{F75\%}$, and $O_{2F25\%}$, $O_{2F50\%}$, $O_{2F75\%}$ characterising the day- and nighttime distributions of the fish biomass in the southern Baltic in 1989–2004

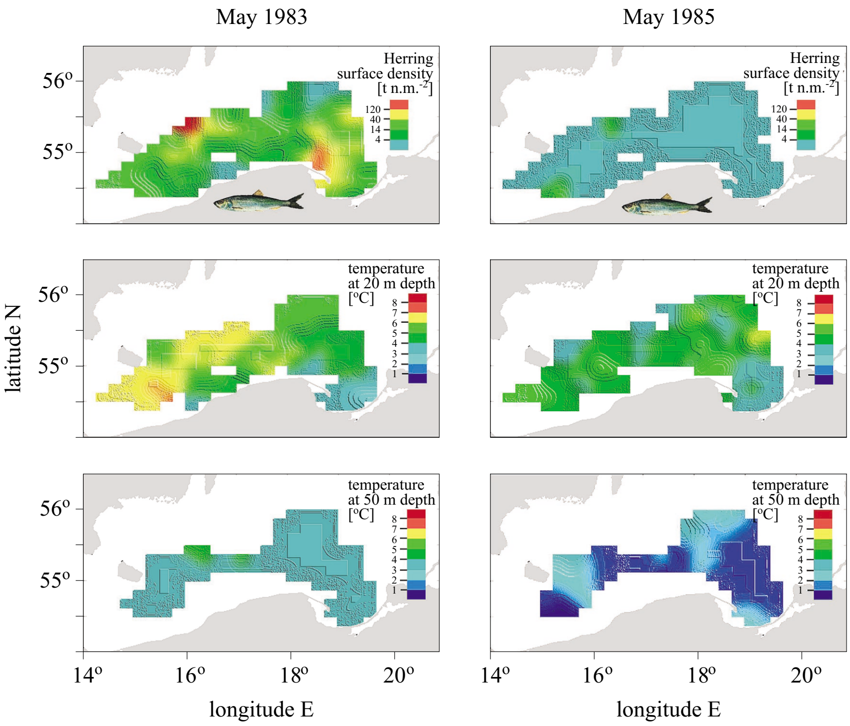

Fig. 6. Comparison of herring distribution and temperature structure in the spring seasons of 1983 and 1985

Fig. 6 illustrates an extreme effect of temperature on the herring distribution in the southern Baltic. Herring distributions were compared against temperature at characteristic daytime (50 m) and nighttime (20 m) depths. The presence of very cold waters ($< 3°C$) in 1985 dramatically reduced the biomass of herring in the Polish EEZ from 217 000 t in 1983 to 10 700 t in 1985.

A similar phenomenon (see Orlowski 2003b) was observed in autumn, when the absence of warmer water in the Polish EEZ was correlated directly with the decrease in the total biomass in the area. Fig. 7 is an illustration of that relationship. In 1989–2001 the total biomass of fish was quite strongly correlated with the temperature at the fish main depth during the daytime.

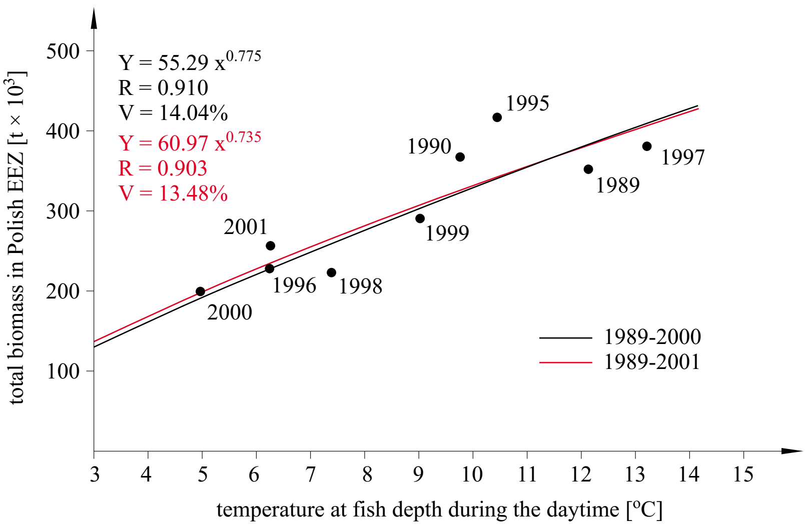

Fig. 7. Regression between temperature at the fish main depth during the day and the total biomass of fish in the Polish EEZ in 1989–2000 and 1989–2001

3.2. Characterising the diel cycle of fish

The diel cycle of fish is one of the most basic processes regulating fish biology (Helfman et al. 1997). The activity patterns of fish represent their response to an environment poorly understood by humans. As a consequence, research on characterising the diel cycle of fish can considerably enhance our knowledge of interactions between fish and the surrounding marine ecosystem. Acoustic methods are one of the most effective means of observing fish and large schools of fish, as shown by Aoki & Inagaki (1992), Castillo et al. (1996), Fréon et al. (1996), Tameshi et al. (1996), Orlowski (1997, 2000, 2001), Szczucka (2000), Pieper et al. (2001), Gauthier

& Rose (2002), Bertrand et al. (2003), Massé & Gerlotto (2003), Cassini et al. (2004), and Pelotonen et al. (2004). On the other hand, a detailed knowledge of the diel cycle of fish can reduce to an absolute minimum any errors in estimating their acoustic scattering properties. Application of the 4D-ABO database enables many single or cross-correlated characteristics of the marine ecosystem to be estimated. One of the first steps has to be a comprehensive visualisation of the cycle against the environmental background (see Fig. 8). The measurements were carried out during a two-day experiment in the south Gotland Deep, during which echo integration was provided along the sides of the square track. The process of constructing the visualisation is described in Orlowski (2003) and the experiment is described in detail in Orlowski (2005). Fig. 8 shows that a number of different phases of fish (clupeoid) behaviour can be distinguished. These phases are closely related to characteristic time and spatial limits, and each one yields a different echo pattern.

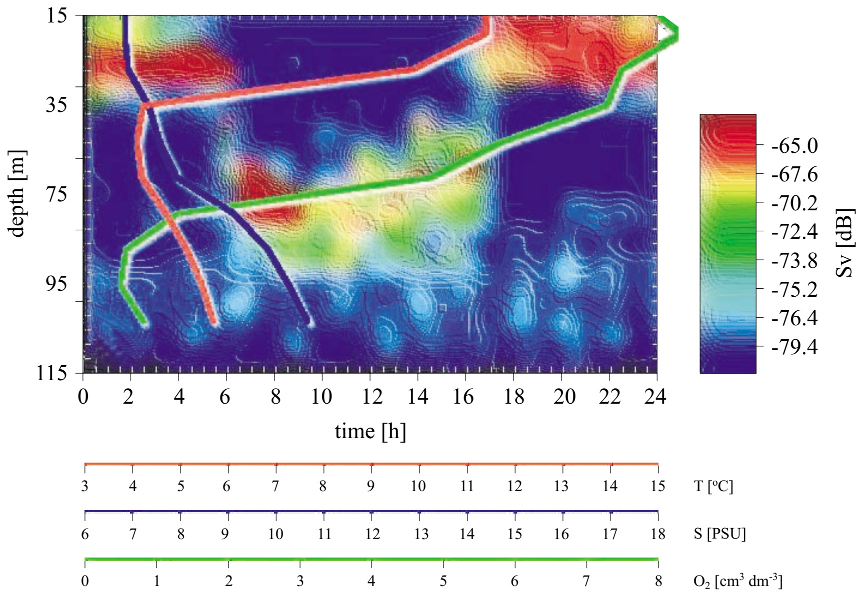

Fig. 8. TDS visualisation of diel cycle of fish distributions (Sv) in a 4 × 4 n.m. area in the south Gotland Deep in October 2001. Average temperature, salinity and oxygen level are shown in diagrammatic form

Diel cycle characteristics can be expressed by time-dependent functions describing average values of basic parameters such as depth, temperature, salinity and oxygen level, and also by the vertical migration of fish. The trigonometric polynomials suggested by Clay & Medwin (1977) are

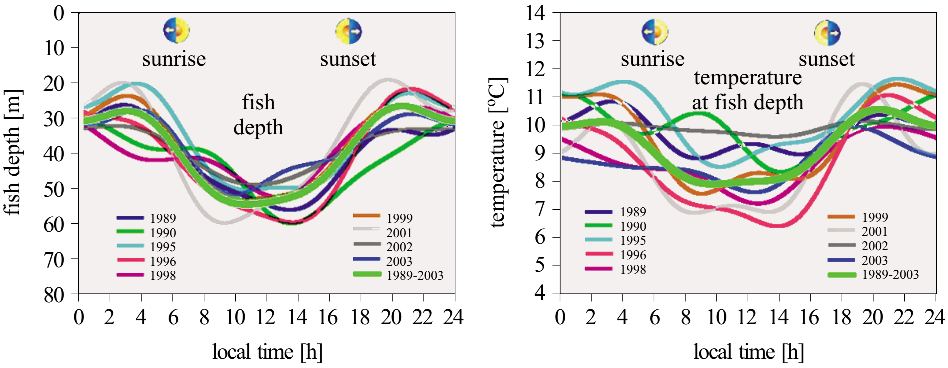

Fig. 9. Diel cycle of clupeoids approximated by curves expressing the relationship between the time of day and fish main depth (left-hand panel), and the temperature at the fish main depth (right-hand panel) for the period 1989–2003, and for each single year in that period

extremely useful for approximating these periodic relationships: Orlowski (1998) was the first to apply them for this purpose. Mathematical models of the diel variability at the fish main depth and the temperature at this depth were compiled on the basis of the 4D-ABO October database for each consecutive year from 1989 to 2003 (see Fig. 9).

The diel dependence of the fish main depth on the time of day seems quite regular over the period investigated. The pattern averaged over the period 1989–2003 has a regular, quasi-sinusoidal shape associated with the variability of the light factor (position of the sun). The time dependence of the temperature at the fish main depth (centre of gravity of the scattering strength) is strongly influenced by the vertical structure of the temperature (Fig. 9, right-hand panel) and varies significantly from year to year. It is possible to distinguish years of clearly regular differentiation between day and night, and years of minor day and night differences.

Fig. 10 shows approximate empirical relationships between the time of day and the fish main depth (left-hand panel), and the temperature at that depth (right-hand panel) in spring and summer. The patterns were calculated for the spring seasons in 1983–1985 and for the autumn seasons in 1989–2003. In spring, the vertical migrations of fish are much stronger than in summer, when the temperature at the fish main depth varies much more widely.

If the average pattern of the diel dependence of environmental factors at the fish main depth is taken to be the standard pattern, each year can be compared with reference to that standard. Fig. 11 shows such comparisons between these functions from the 1994–2004 period and from 2004.

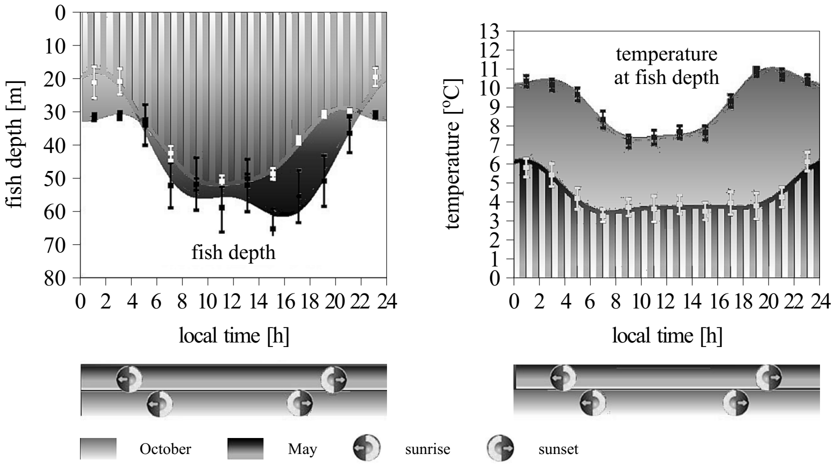

Fig. 10. Spring and summer dependence of the diel cycle of clupeoids approximated by curves expressing the relationship between the time of day and fish main depth (left-hand panel), and the temperature at the fish main depth (right-hand panel)

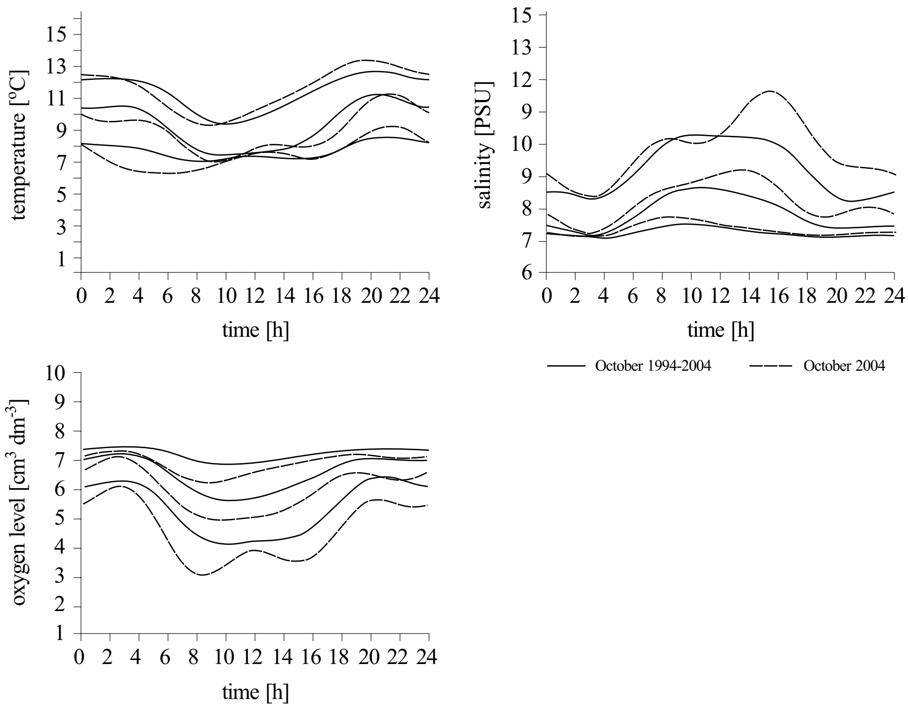

Fig. 11. Approximated curves modelling the diel dependence of temperature, salinity and oxygen levels at characteristic fish depths (upper depth limit, main depth, lower depth limit) for 1994–2004 and 2004

3.3. Characterising the relationship between the seabed and demersal fish

A new method for acoustic bottom classification was introduced by Orlowski & Kujawa (2005). Previously, this author had introduced the application of multiple echoes for evaluating the seabed. The main intention of the method presented below is to simplify the classification procedure by limiting the output to one parameter.

A signal reflected from the seabed is characterised by its amplitude and duration. The duration of the bottom echo τ_{s} is dependent on four principal components:

$$\tau_s = \tau_1 + \tau_2 + \tau_3 + \tau_4, \tag{1}$$

where
τ_{s} – superposition of all components,
τ_1 – component dependent on pulse length,
τ_2 – component dependent on beam width,
τ_3 – component dependent on scattering properties,
τ_4 – component dependent on reflections from below the bottom surface.

Component τ_1 is related to the sound pulse length. It has to be subtracted from τ_{s}. Component τ_2 is associated with Lloyd's mirror effect and with the effective width of the echosounder transducer beam pattern. Scattering from the seabed is responsible for component τ_3, which is strictly dependent on the morphological and sedimentary structure of the seabed: a rough bottom yields a much bigger value of τ_3 than a smooth one. Bottom roughness and the type of sediment and sedimentation structure are responsible for the reverberation level, which effectively prolongs the duration of this component. Component τ_4 is quite closely dependent on the vertical geological structure of the sedimentary layers. Where the seabed material is highly porous, the acoustic pulse is not reflected effectively and can propagate through deeper sediment layers, producing a series of reflections. Their superposition influences the final value of τ_4.

The parameter applied in this work is defined as the hypothetical effective angle Θ corresponding to the received seabed echo. In the case of a multilayered bottom, this interpretation of the parameter is invalid (Orlowski & Kujawa 2005). The angle is defined as:

$$\mathrm{arc}\cos(\Theta'/2) = (1 + \mathrm{c}(\tau_{\mathrm{s}} - \tau_1)/\mathrm{d})^{-1}, \tag{2}$$

where
$\Theta'/2$ – parameter characterising complex acoustic seabed properties,
τ_{s} – superposition of all seabed echo time components,
τ_1 – component dependent on pulse length,

c – sound speed,
d – bottom depth.

Comparison of the values of $\Theta'/2$ within regular statistical rectangles of the surveyed area with the percentage of fish available from the 4D-ABO database yields a relationship between these two factors. Fig. 12 presents patterns of statistical correlation between the percentages of herring, sprat and cod, and seabed classes characterised by $\Theta'/2$ intervals. The percentage of each species was calculated from the results of sample catches carried out during every cruise. The relationship is based on all the data collected from 1995 to 2003.

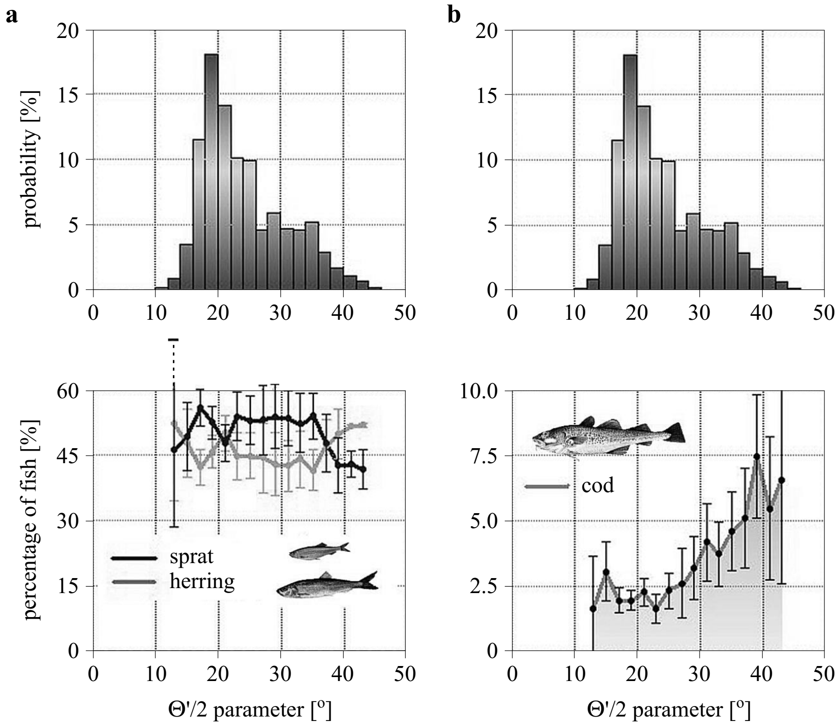

Fig. 12. Percentage of pelagic (A – herring and sprat) and bottom fish (B – cod) in the areas characterised by the $\Theta'/2$ parameter (situation between 1995 and 2003)

Evidently, the percentage of pelagic fish shows no correlation with $\Theta'/2$ values for the bottom areas. Being a typical demersal fish, cod is distinctly and strongly correlated with seabed type.

4. Conclusions

Selected examples of methods and results obtained show how the application of acoustic data can effectively improve understanding of the functioning of the marine ecosystem. The most important part of this process is to compile an acoustically coordinated, common interdisciplinary database for the marine ecosystem (4D-ABO).

The value of this database is greater when data are gathered with similar temporal and spatial strategies and technical means. Each new parameter added to the data collection considerably extends the range of possible analyses. Relations and trends between the environment and the distribution of living organisms in the 4D structure can be estimated and formulated by mathematical models for further comparisons and multi-dimensional modelling.

Analyses of case studies presenting selected applications provide a very wide range of possible characterisations of the marine ecosystem by an acoustically produced 4D database (4D-ABO) describing the distribution of living organisms, and environmental gradients and limits. In the examples discussed, the following aspects of marine ecosystem dynamics were characterised:

- the depth-related geographical structure of marine organisms;
- the annual, seasonal and diel dynamics of biological cycles in relation to environmental factors;
- environmental pressure on the horizontal distribution of fish;
- comparisons of defined standards of fish behaviour for determined periods and areas;
- the association of fish species with seabed characteristics.

Similar studies done by other authors have been cited in this paper. The application of acoustic information to describe the 4D functioning of the marine ecosystem can be significantly improved if the standards, functions and magnitudes characterising its elements can be precisely determined (normalised) and contributed to by other researchers. It goes without saying that this will significantly improve comparability and facilitate the establishment of joint databases produced in the 4D-ABO format.

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