Acoustic seabed classification applied to Baltic benthic habitat studies: a new approach

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Abstract

The application of acoustic methods for the classification of bottom habitats is based mostly on the analysis of measured parameters without relating them to the bathymetric structure. Geological complexity and biological patterns are closely related to bathymetry. This paper presents a new approach to the acoustic classification of bottom habitats in that it combines the distribution of a selected acoustic parameter with its bathymetric structure. The hypothetical effective angle of a bottom echo $\Theta'/2$, corresponding to its normalised length, was the acoustic parameter applied. This parameter broadly characterises the complex acoustic reflecting and scattering properties of the seabed. Its highest values correspond to a layered bottom consisting of soft sediment. The southern Baltic area was classified by a direct comparison of two factors measured acoustically: the statistical distribution of $\Theta'/2$, and the correlated depth structure within selected standard regular geographical areas ($15'$ latitude and $30'$ longitude) which the total area was divided into. The area size was matched with the density of the measurements collected. The same factors were also estimated for the whole southern Baltic. The study was based on soundings collected on board r/v 'Baltica' during regular acoustic surveys in 1995–2003. The classification applied provides a new possibility of complex seabed identification and comparison of seabed structure dynamics, useful in benthic research and in the ecologically based administration of marine areas.

The complete text of the paper is available at http://www.iopan.gda.pl/oceanologia/

1. Introduction

Developing a basis for the responsible administration of marine ecosystems and their resources requires the application of methods supplying wider and more precise characteristics of the area, as well as cross-correlations of dynamic processes. A crucial aspect of the marine ecosystem is the bottom habitat, which plays a major role in the biological chain, strongly affecting the circulation within the local ecosystem (Barnes & Mann 1991).

The benthic habitat is formed by the seabed structure, the hydrodynamics of the water column and the amount of light penetrating from the surface. These elements, along with anthropogenic factors, exert a far-reaching influence on benthic communities (Barnes & Mann 1991, Lubniewski & Pouliquen 2004, Atallah & Smith 2005). The state of the benthic habitat is a direct reflection of the quality of the marine ecosystem. More detailed information on this subject will be found in Anderson et al. (2002), Freitas et al. (2003), Hewitt et al. (2004), Kurths et al. (2004), Orlowski (1989, 1998, 1999), Tęgowski (2005), Wienberg & Bartholoma (2005).

Acoustic methods, very effective in providing information about sea depths and the seabed, have been applied in the Baltic Sea for bottom classification since the early 1970s (Orlowski 1984, 1989, Klusek et al. 1994, Tęgowski 2005).

This paper presents a new approach to the acoustic classification of the bottom habitat in that it combines the distribution of the acoustic parameter with its bathymetric structure. It proposes as a signature of the sea bottom an acoustic parameter, referred to here simply as *theta*, which is the hypothetical effective angle of a bottom echo $\Theta'/2$ corresponding to its normalised length; it was introduced by the author in 2005 (Orlowski & Kujawa 2005). The measurements were based on acoustic bottom recordings, collected during a series of cruises (1995–2003) intended for the acoustic assessment of pelagic fish resources. The results of those surveys, together with the spatial statistical distributions of the hypothetical effective angle of a bottom echo (the $\Theta'/2$ parameter) and the bottom depth structure, were used to develop a two-parameter classification of the bottom habitat. The combination of these two latter factors for this classification is the most important innovation of the new approach. It provides a reasonable basis for classifying the properties of the individual seabed sectors and supplies a very wide range of comparisons of two ecologically important factors: seabed structure and its related bathymetry.

2. Material and methods

2.1. Acoustic transects

Systematic acoustic surveys of the Polish Exclusive Economic Zone (EEZ) started in 1989 as part of the ICES autumn international survey programme. The recording of samples 24 hours a day for each nautical mile distance unit (Elementary Standard Distance Unit – ESDU) in a computerised database began in October 1994. An EK400 echosounder and a QD echo-integrating system and purpose-designed software were used in 1994–97. In 1998 an EY500 scientific system was introduced to meet international standards of acoustic measurements and enable the research to be continued. Both systems (EK400 and EY500) were used for the calibration and acquisition of data. The minimum level of bottom detection was −60 dB (according to EY500 standards). This level gave a stable bottom echo detection throughout the research area. The bottom depth in the area did not exceed 100 m, and the circumstances surrounding the data collection process were quite convenient (see Ona & Mitson 1996). Both of these systems operated at a frequency of 38 kHz and the same hull-mounted 3 dB transducer of beam width $7.2° \times 8.0°$. Calibration was carried out by SIMRAD specialists with a standard target sphere in Swedish fjords in 1994–97 and in Norwegian fjords in 1998–2004. All the cruises took place in October; each lasted two-three weeks so that samples could be collected over distances between 1000 and 1500 nmi.

The survey tracks of all the cruises mostly followed the same grid to ensure better comparability of measurements. Because of instabilities in

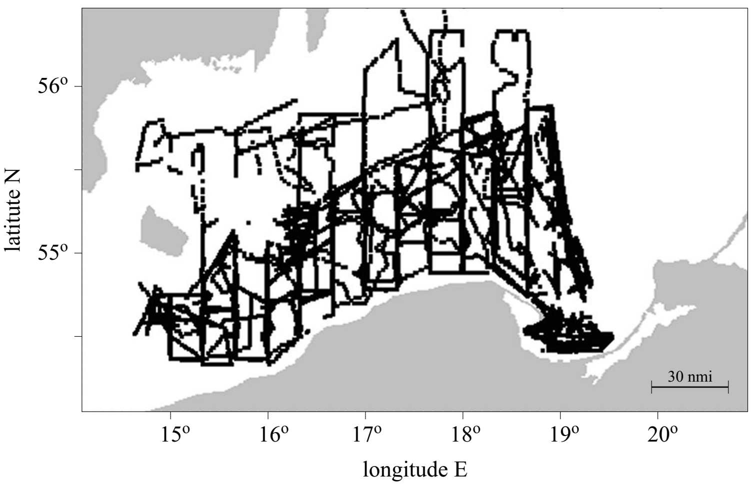

Fig. 1. Survey tracks of r/v 'Baltica' from 1995 to 2003

sampling, data from 1994 were not taken into consideration. The present study is based on data from 1995–2003. Fig. 1 shows a map of the transects from 1995 to 2003 given by the positions of the ESDU ends. The frequency, transducer (beam width $7.2° \times 8.0°$) and pulse length were the same during all the cruises. The system threshold and sensitivity were stabilised on the basis of the calibrations.

2.2. Acoustic parameters characterising the seabed

The seabed was described by two parameters collected for each nautical mile (8139 in total) – the bottom depth and the $\Theta'/2$ factor – collected during 1995–2003.

The method of estimating the $\Theta'/2$ factor was introduced by Orlowski & Kujawa (2005). Previously, the present author had utilised multiple echo measurements for evaluating the seabed (Orlowski 1984). Numerous methods based on different acoustic measurements have been developed with the aim of providing a description of seabed properties (Orlowski 1984, Anderson et al. 2002, Ellingen et al. 2002, Freitas et al. 2003, 2005, 2006, Lubniewski & Pouliquen 2004, Tęgowski 2005, Wienberg & Bartholoma 2005, Preston 2005). The main aim of the method applied here is to simplify the classification procedure, primarily by limiting the output to one-parameter values. In the other hand, the parameter selected has to be sensitive to different aspects of the bottom properties affecting the echo length, such as scattering by morphological and layered structures (Klusek et al. 1994, Ellingen et al. 2002, Freitas et al. 2002, 2003, 2005, 2006, Brown et al. 2005, Orlowski & Kujawa 2005, Preston 2005). A signal reflected from the seabed is characterised by its amplitude and its duration. The duration of a bottom echo τ_s depends on components arising from the pulse length, beam angle, bottom scattering and reflections from below the water-bottom interface (Orlowski & Kujawa 2005):

$$\tau_s = \tau_1 + \tau_2 + \tau_3 + \tau_4, \quad (1)$$

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 sounding pulse length. It has to be compensated by subtracting τ_1 from τ_s. Component τ_2 is directly associated with Lloyd's mirror effect and with the effective width of the echo-sounder transducer beam pattern. Scattering from the seabed is responsible for component τ_3, which is closely dependent on the morphological and sedimentary structure of the seabed. A rough bottom gives 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 depends quite strongly on the type of vertical geological structure of the sedimentary layers. In a situation 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. The influence of the superposition all the reflected waves is responsible for the final value of τ_4.

All measurements of τ_s were related to the stabilised sensitivity of the system, expressed by the calibrated S_v threshold (−64 dB was applied in this study). Different systems can be easily intercalibrated by finding the correlation between values measured for the same geographical elementary units.

The value of τ_s depends on all these components and increases with depth as a result of the spherical spreading of an acoustic wave. The application of τ_s for characterising the seabed requires its value to be normalised against depth. The value of the $\Theta'/2$ angle is defined as a one-dimensional parameter describing the complex properties of the seabed and fulfilling the condition of normalisation of τ_s against the bottom depth, expressed by t_d:

$$(\Theta'/2) = \arccos(1 + (\tau_s - \tau_1)/t_d)^{-1}, \tag{2}$$

where

$\Theta'/2$ – the *theta* parameter, characterising the acoustic seabed properties,
τ_s – superposition of all seabed echo time components,
τ_1 – a component dependent on pulse length,
t_d – the pulse travelling time (between transducer and seabed surface).

The distribution (PDF – probability density function) of $\Theta'/2$ values represents the superposition of two separate sub-types of seabed categories. When the bottom is not layered, the echo duration is related mostly to the transducer beamwidth and the scattering properties of the bottom surface 3D structure. The range of *theta* values is much narrower (13.4–26.0°), whereas the average value is the lowest (18.97°). For a layered bottom (sediment accumulation zones), the sounding pulse is reflected from beneath the surface layers; then *theta* takes an the average value of 31.57°, and lies in the 23.20–38.80° range (5–95% of the cumulative distribution of *theta*).

2.3. Method of classification

A sub-area with a higher sampling density was selected from the data collected in the southern Baltic in 1995–2003. This sub-area (Fig. 2) was

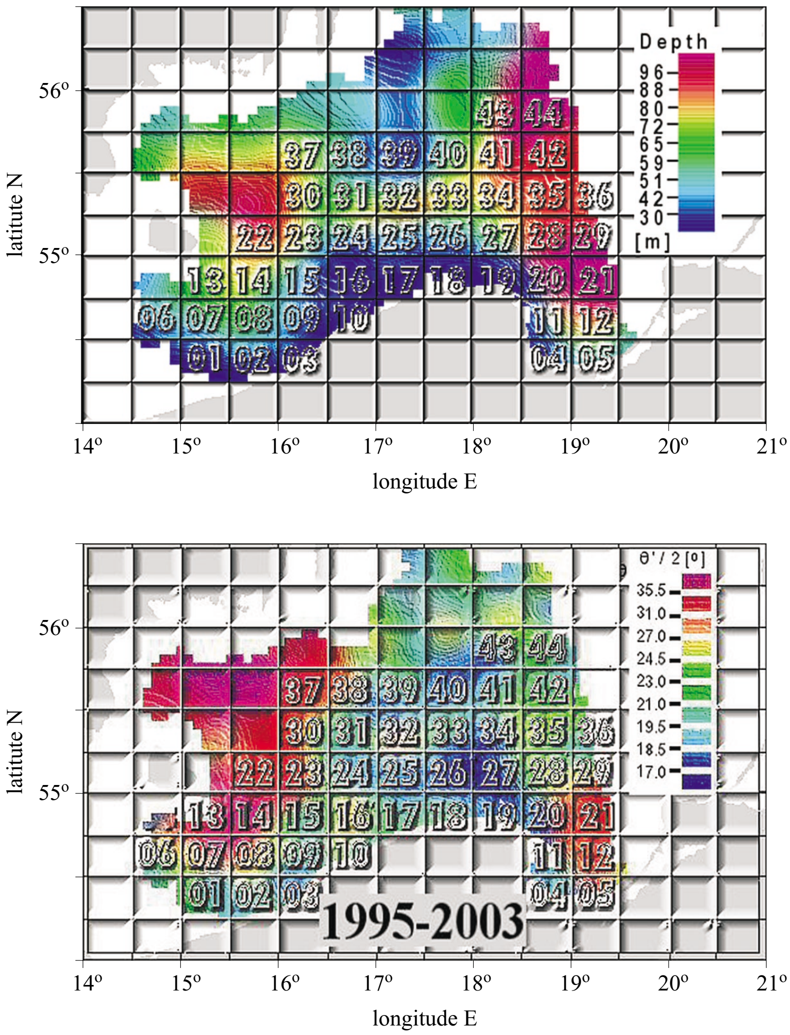

Fig. 2. Bottom depth and *theta* values calculated from the collected data. The survey area has been divided into standard rectangles 01–44. Area 00 corresponds to the entire survey area

divided into 44 standard rectangles of 30′ longitude (17.2 nmi or 31.8 km) and 15′ latitude (15 nmi or 27.7 km). Each rectangle was characterised by approximately 200 ESDU units of *theta* (lower panel of Fig. 2) and depth measurements (upper panel of Fig. 2). For each rectangle two basic characteristics were found: the distribution of *theta* values and the corresponding average values of bottom depths calculated for each statistical interval of *theta*. The interval width was assumed to be 2° (*theta* is expressed in degrees).

The idea of this classification was based on the hypothesis that both parameters can express independently some features correlated with the physical, chemical and morphological conditions of the bottom habitat. In consequence, unique conditions influencing the biodiversity of the bottom habitat can be distinguished.

The parameter *theta* can be correlated with the type of bottom surface morphology (scattering properties) or layered structures beneath the bottom, reflecting the cumulative character of the seabed. The depth structure within a rectangle, correlated with *theta* values, describes other factors governing environmental properties such as light intensity, hydrostatic pressure, salinity and oxygen level. All these factors are spatially (3D) variable in the southern Baltic and are significantly correlated with sea depth and geographical position. Fig. 3 gives three examples of the characteristics of both factors. These characteristics were calculated for the whole southern Baltic (00) and for two, widely differing, rectangles – numbers 24 and 20 (see Fig. 2). The rectangles were selected randomly as examples demonstrating the basic elements of the results.

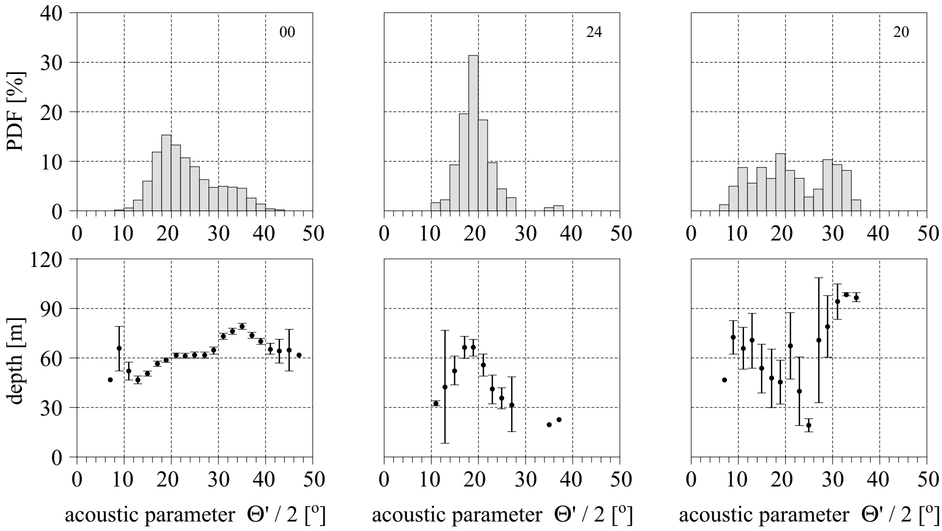

Fig. 3. Examples of probability density (PDF) distributions of *theta* and average depths for each statistical interval for the whole southern Baltic (00) and two characteristic rectangles 24 and 20 (see Fig. 2)

The Euclidean distance was applied as the measure of the variability factor of the tested aggregations (single rectangles). Its low value expresses a high similarity of the values of the parameter analysed in the pairs of rectangles, and vice versa.

The Euclidean distance W_p between two selected rectangles 1 and 2 was calculated by the universal formula (Santini & Jain 1999):

$$W_{p1-2} = \frac{1}{n}\sqrt{\sum_{i=1}^{n}(x_{1i} - x_{2i})^2}, \tag{3}$$

where

n – number of elements of classes 1 and 2 (aggregation),
W_{p1-2} – Euclidean distance between aggregations 1 and 2,
x_{1i}, x_{2i} – elements of aggregations 1 and 2.

The analyses were carried out for the *theta* statistical distributions and average bottom depths for each class interval of *theta*. Calculations were performed for the whole southern Baltic and for each of the 44 standard rectangles. In total, 1990 combinations of pairs for each factor were calculated. The results were normalised against the average values in all 45 areas (44+1). W_p normalised values for *theta* distributions were expressed as $W_{\Theta i-j}$ and for appropriate bottom depth structures were expressed as W_{di-j}. The lengths of vectors R_{i-j}, constructed on both components ($W_{\Theta i-j}$ and W_{di-j}), were also calculated. These lengths represented the global difference between aggregations (rectangles).

Complementary elements were additionally estimated for each statistical area:

– average, standard deviation and confidence intervals, and quartiles of cumulative distribution of $W_{\Theta i-j}$ and W_{di-j}, *theta*, and bottom depth,
– average and standard deviation of R_{i-j} against the remaining rectangles.

3. Results and discussion

This paper proposes one method of acoustic seabed classification based on the statistical comparison of two parameters: the *theta* distribution and the average depths for each *theta* class. These statistical characteristics differentiate all the selected standard rectangles. Charts of both parameters are shown in Fig. 2.

The bathymetric pattern of the area (upper panel) is characterised by the existence of two principal, deep basins: the Bornholm Basin in the west, and the Gdańsk Basin in the east. These basins are connected in the deepest area by the Słupsk Furrow.

The distribution of *theta* values is shown in the lower panel of Fig. 2. The charts indicate the similarity and differences of both dynamic structures, which provides a good foundation for improving the classification range by the application of both parameters simultaneously.

Fig. 3 exemplifies the characteristics of three selected areas of the southern Baltic. The first area (00) corresponds to the whole southern Baltic, the second one (24) to the northern part of the Słupsk Bank, and the third one (20) to the western slope of the Gdańsk Deep. The characteristics represent the relation between the *theta* factor and the associated bottom depth.

Area 00 – Average $\Theta'/2 = 23.51°$, standard deviation 6.56°, range (25% –75% of the cumulative distribution) = 9.14°. The distribution of *theta* indicates the existence of two basic modes: the lower range is caused by the surface scattering by the seabed, the upper one by vertical scattering within the seabed layers. Since the average distribution of *theta* values in a rectangle is evidently differentiated, single rectangles can be distinguished on the basis of two parameters (*theta*, depth).

Area 24 – Average $\Theta'/2 = 19.51°$, standard deviation 3.73°, range (25% –75% of the cumulative distribution) = 4.01°. Only the first mode of the *theta* distribution is recorded in this rectangle. The most numerous class is very well correlated with the maximum bottom depth, whereas the lower and higher *theta* values are characteristic of shallower depths. This area is thought to be strongly influenced by the water current, which influences its narrowband characteristics.

Area 20 – Average $\Theta'/2 = 21.53°$, standard deviation 7.75°, range (25% –75% of the cumulative distribution) = 14.0°. This area is characterised by a very high dynamic range of both parameters and can be classified as a gradient zone between the dynamic, shallow, coastal waters (coastal current) and the stagnant waters of the Gdańsk Deep. The range of *theta* is very wide, with no one class being dominant. The bottom ($\Theta'/2 < 12°$) is smoothest at 50–65 m depths. At depths over 65 m the seabed has a layered structure with $\Theta'/2 > 29°$, characteristic of soft muds (Zachowicz et al. 2004) and the absence of currents (Kurths et al. 2004).

Fig. 4 compares *theta* medians and ranges corresponding to 25–75% of its cumulative distribution for each statistical rectangle. The comparison of ordered values indicates cases of similarity and differentiation among rectangles. It is easy to determine groups with similar seabed properties and rectangles of high variability characteristic of transition zones (i.e. rectangles 5, 20, 38). The trend of median variability indicates an interesting instability, observed for the determined ranges of *theta* medians. Thus, for values over 23° a sharp increase is observed. Such phenomena appear at the thresholds 28° and 32°. Taking into consideration the analysis presented in Orlowski & Kujawa (2005), these thresholds may be associated with changes in the basic seabed structure, from simple and flat to morphologically more

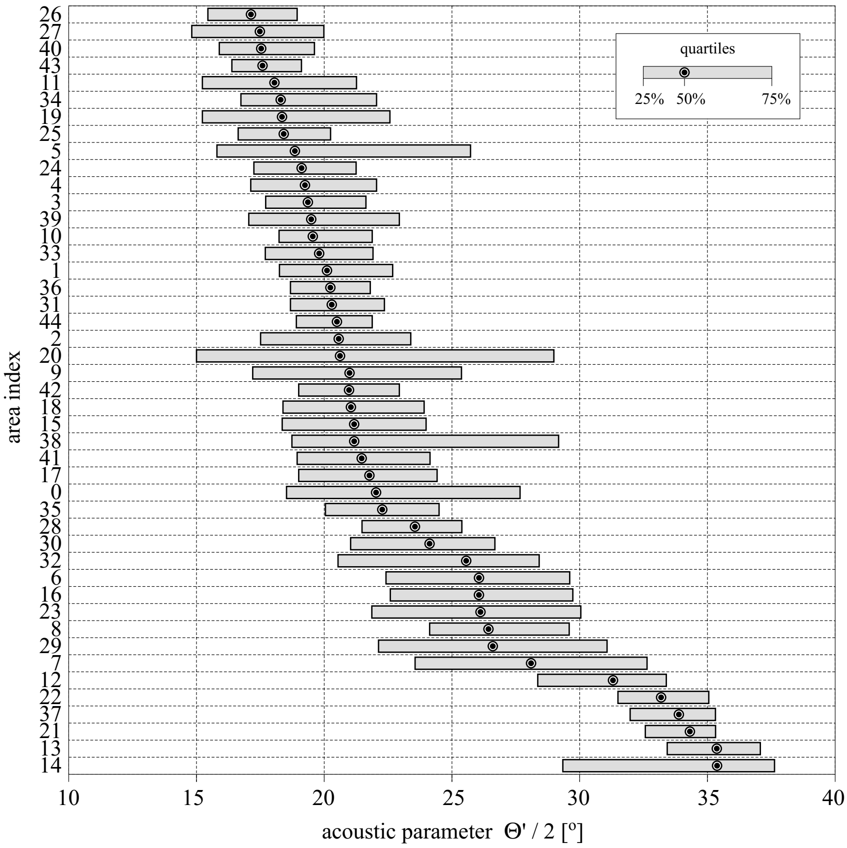

Fig. 4. Medians and quartiles of $\Theta'/2$ for each statistical rectangle (area index), ordered in relation to the median values

complicated, through partially layered, to strongly and covered with soft sediment.

As mentioned in 2.3. the seabed classification was based on the analysis of two factors: $W_{\Theta i-j}$ – expressing the normalised difference between the *theta* statistical distribution in rectangles i and j, and W_{di-j} – expressing differences in the depth structure of *theta* classes in the same rectangle. In addition, vectors R_{i-j}, constructed on components corresponding to $W_{\Theta i-j}$ and W_{di-j}, can be applied to sort the results.

Fig. 5 gives the summary distribution of factors $W_{\Theta i-j}$ and W_{di-j}. The pattern corresponds to the density of points representing pairs of similarity expressed by W_{di-j}, located on the Ox axis, and $W_{\Theta i-j}$ on the Oy axis. For the set of 44 rectangles (plus the whole area) 1990 permutations were calculated. The pattern exposes the uniform distribution of both factors within wide limits of values. The ranges for both factors are very

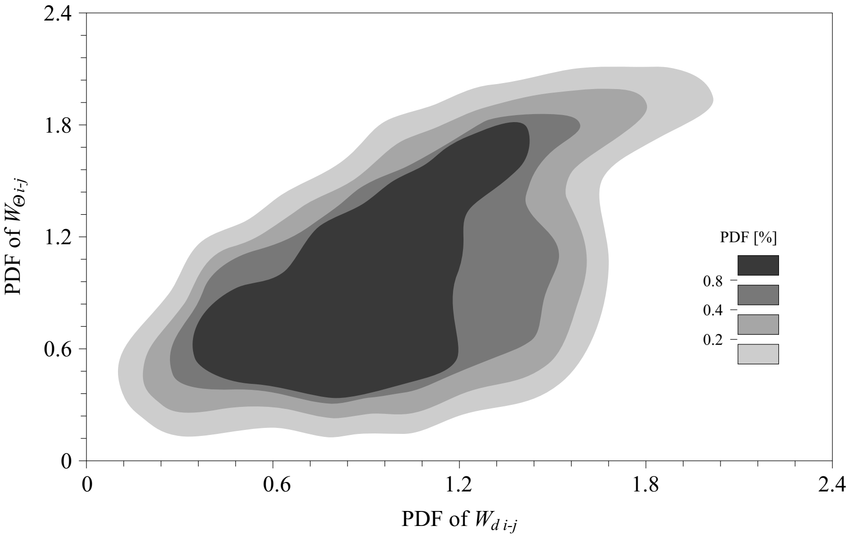

Fig. 5. Probability density distribution (PDF) of factors W_{di-j} and $W_{\Theta i-j}$ calculated for pairs characterising 44+1 statistical rectangles of the southern Baltic

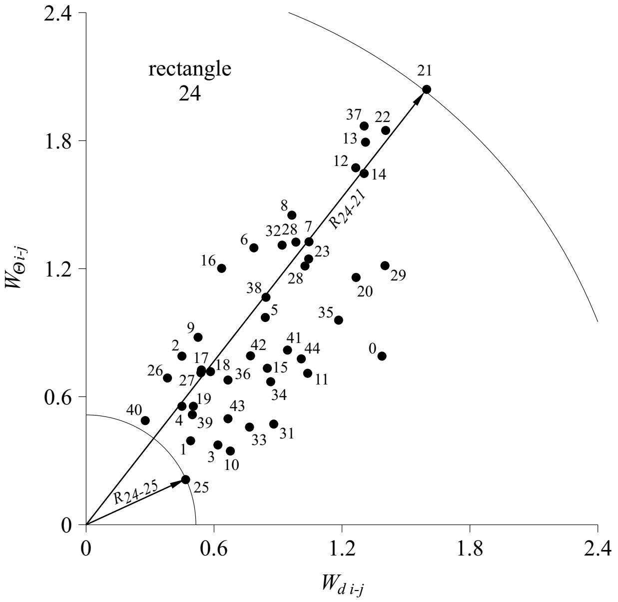

Fig. 6. Comparison of acoustic characteristics of a selected statistical rectangle (24 in this example) with all the other areas. R_{24-25} – distance between rectangle 24 and 25, R_{24-21} – distance between rectangle 24 and 21. The numbers correspond to the rectangle in compared pair. The number 0 corresponds to the entire survey area

comparable. Such a situation supplies a very good reason for applying W_{di-j} and $W_{\Theta i-j}$ to distinguish and classify all statistical rectangles. Each factor expresses a similarity in a different domain: $W_{\Theta i-j}$ estimates the distance according to the *theta* parameter, W_{di-j} compares the depth structures of *theta*. When the diagram in Fig. 5 is expressed in the form of points identifying each compared pair, we can assess in every case separately the distance to Ox (depth structure) and the distance to Oy (*theta* distribution). This enables the dominant source of the difference (*theta* or depth structure) to be evaluated. The explanation of such a categorisation is given in Fig. 6 for rectangle 24.

Rectangle 24 is also presented in detail in Fig. 3 (see also Fig. 2). The area is characterised by a narrow range of the *theta* distribution, strongly modulated with the depth structure. Two extreme cases are marked in Fig. 6: the most similar rectangle – 25 (distance R_{24-25}) and the most different rectangle – 21 (distance R_{24-21}). Among the other combinations we can easily identify a further six similar areas: 40, 1, 39, 4, 3 and 27; while areas 40, 4 and 1 are most similar in depth structure, areas 3 and 1 most resemble each other in the *theta* domain. With such an analysis we can estimate in a simple way the similarity of all standardised areas of seabed habitat and assess the role played by the two factors.

Comparison of the average distance R_{i-j} between all the statistical rectangles 1–44 indicates rectangle 9 as being the most similar to all the others, whereas rectangle 21 is the most different. Such a qualification makes it possible to identify the uniqueness (estimated in relation to the two different factors) of each geographical unit of bottom habitat.

The method and results of bottom habitat classification by two different factors, measured acoustically, appear to be a very effective tool for comparing seabed characteristics from the ecological point of view. The methods described in the literature (Orlowski 1984, Klusek et al. 1994, Anderson et al. 2002, Ellingen et al. 2002, Freitas et al. 2003, 2005, 2006, Hewitt et al. 2004, Kurths et al. 2004, Orlowski & Kujawa 2005, Tęgowski 2005, Wienberg & Bartholoma 2005) take a very long list of parameters into account. The standards of measurements vary according to how the parameters are defined. This situation can cause difficulties as regards the comparability and interpretation of the results. All of these methods take into consideration only the parameters describing the scattering properties of the seabed. A geological classification of sediments based on particle size measurements produces a scale of classification based on very discrete elements. This means that the bottom structure of the area classified is not involved in the classification process. In the method described in the present paper, one continuously variable parameter *theta* and the corresponding area depth structure are taken into consideration simultaneously, thereby enabling the bottom habitat dynamics to be monitored.

If we inspect the results of seabed classification by Uścinowicz & Zachowicz (1991) and Zachowicz et al. (2004), the geographical limits among different classes seem to be unreasonable and artificial from the ecological point of view. They reflect a philosophy of differentiating seabed classes, of treating them as discrete entities; natural processes, however, are characterised in most cases by continuity and gradients of observed factors.

Fig. 7 compares two maps of the southern Baltic. The left-hand one (Zachowicz et al. 2004) was produced by classic geological ground-truth (grabs) surveys. The basis of classification is discrete, and the visualisation of ground properties is a poor reflection of the gradients of properties. The map on the right is based on *theta* measurements. The visualisation applied is based on a scale that is statistically uniform, which means that each step (basic colour) corresponds to 10% of the cumulative distribution of the *theta* parameter (Orlowski & Kujawa 2005). As a consequence, the classification and type of visualisation (not possible on a geological scale) expresses the dynamics of the seabed in a more readable way. It is interesting to observe how the *theta* parameter clearly defines the zones of sediment accumulation (mud, $\Theta'/2 > 27°$) and the gradient zones. There is some difference in the north-eastern part of the area. It is possible that sediment accumulation conditions were not stable there. Taking into consideration both elements (the *theta* distribution and its depth structure), the classification of the bottom habitat can be significantly better matched to ecological standards, minimising the number of grab samples necessary to identify the sediment properties.

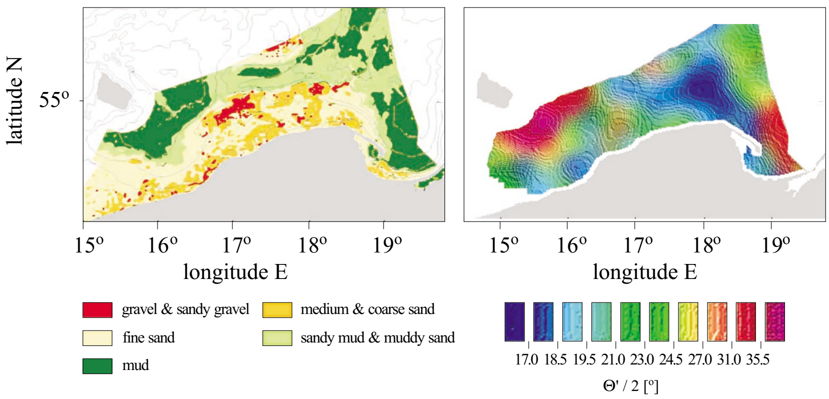

Fig. 7. Comparison of geological (grabs) and acoustic ($\Theta'/2$ measurements) classifications of the southern Baltic seabed

The novel approach to acoustic seabed classification described in this paper may reinforce the ecological foundation for differentiating significant units of a benthic habitat. The method may be useful for determining ecologically and biologically significant areas (EBSA) and may significantly improve the analysis of results in benthic research.

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