ACOUSTIC EXPERIMENT ON DIEL FISH BEHAVIOUR CYCLE PERFORMED IN THE GOTLAND DEEP

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This paper describes the results of 24 h acoustic experiment based on three-dimensional measurements of the S_v distribution of herring and sprat in the southern Baltic in October 2001. The experiment was based on a continuous (24h day) integration of fish echoes using an EY500 echo sounder from a vessel with a constant speed of 8 knots, moving along the sides of a square equal to 4 n.mi., localized inside the specified area. Duration of the experiment was limited by deterioration of the weather conditions but nearly 300 ESDU samples were collected. These are correlated with values of coincident environmental factors: time, depth, water temperature, salinity and oxygen levels; estimated on the basis of survey data. Fish behaviour vs environmental factors is described by different macrosounding visualizations, statistical, and mathematical models. The purpose of the paper is to compare results of the experiment to the average characteristics of fish behaviour in the same basin, based on autumn studies over the period 1995-2001. General analysis was provided for the selected area of the Polish EEZ (south Gotland Deep), characterized by the greatest depth movements of fish diel migration. The most significant differences were found between fish migration pattern and diel stability of the acoustic response between these situations, specially during the sunset period.

INTRODUCTION

Necessity of developing local studies of fish behaviour and its influence on acoustic response (1, 6, 9, 10, 11, 12, 13, 14, 15, 16) is cause by specific features of the Baltic ecosystem characterized by low salinities (2-20 PSU) and a two layer structure. Studies, curried out for clupeoids in the Baltic (October data over the period 1989-1999 for the Polish EEZ) within a diel cycle (13,14) have shown a possibility of determining a significant types of variability of factors observed by application of different ways of transformation of all data collected. Their analysis can be widely applied for monitoring relationships among biotic and a-biotic factors of the marine ecosystem, frequently modulated by geographical conditions.

Diel variability of the acoustic response of the fish – the basic parameter of the interest from the point of view of fish stock assessment - was identified as associated with three main elements (8, 12, 13, 14, 15):

- factors dependent directly on fish depth: pressure and temperature (physical),
- indirect physical factor (inertial changes of gas volume inside fish body).
- diel behavioural factors (migrations, tilt angle variability, regulation of gases balance due to migrations).

Studies provided in differentiated areas of the Baltic over the long-term period indicated different patterns of observed relationships, due to local diversity of the factors ranges (13, 15). It means that application of the data from many cruises together could provide a significant smoothing or neutralising each other all time dependent particular effects.

One of the ways to avoid those problems is to provide continuous observation of diel fish behaviour and correlated environmental and acoustic factors within a small section of the sea in a shorter time gate (1-2 diel cycles). Measurements have to be collected by sweeping up the section with a constant, and repeatable itinerary. Such an experiment (planned for 48 hours) was carried out during international survey of pelagic fish resources of the Baltic in October 2001. The area of the experiment was selected after an analysis of all collected data. Main criterion was based on minimising the gradients of observed parameters within the area and its surroundings, while the fish migration could be recorded parallel at the maximum range (more than 100m). Such an area, with the depth over 110 m was determined within the Polish EEZ in the south part of the Gotland Deep.

Studies were based on three-dimensional measurements of the S_v distribution representing the mixture of herring and sprat. These were correlated with values of coincident environmental factors: time, depth, water temperature, salinity and oxygen level; estimated on the basis of survey data. Fish behaviour vs environmental factors was described by different macrosounding visualizations, statistical, and mathematical models. Basic results of the experiment were not similar at all to the characteristics estimated for the whole Polish EEZ (13, 14). The main goal of the paper is to describe diel fish group behaviour in the small section of the sea investigated in 2001 (acoustic experiment) and to compare to the average characteristics over the period 1995-2001 within the whole south Gotland Deep area, containing the experiment section.

1. MATERIAL AND METHODS

Sea Fisheries Institute started to conduct systematic acoustic surveys of the southern Baltic area in 1981. Recording of samples 24-h a day, for each one nautical mile distance unit (ESDU- Elementary Survey Distance Unit) in a slice-structured database was established aboard R.V. Baltica in 1994. EK400 and a QD echo integrating system were applied with the own software. Since 1998 an EY500 have been used for acoustic surveys. 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 (6 n mi of a transect per one square n mi approximately). Survey tracks of all cruises were on the same regular grid to obtain high comparability and better splitting of measurements collected in succeeding years.

Biological samples were collected over the period from 1995 to 2001 by the same pelagic trawl (WP 53/64x4), on average every 37 n.mi. of the transect. Fish observed during all surveys were mostly pelagic, herring and sprat (Clupeidae). 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. The area A (south Gotland Deep) taken into consideration in comparisons, and area B where 24-h experiment transect was carried out are shown in Fig. 1. Area A had superficies of approximately 4.6 thou square n mi and contained in total nearly 1 thou ESDU. Only samples in which bottom depth was exceeding 90 m were taken into consideration. Area of the experiment (B) was relatively 290 times smaller than A one and characterized by superficies of 16 square n mi and 298 n mi ESDU in total. Biological characterisation of the experiment area was based on results of one pelagic day time pelagic haul, carried out in the middle of the square (headline height 60m depth, vertical opening 20m). Weight composition of the haul was as follows: 19.5% of herring, 78.7% of sprat, and 1.8% of cod. At the same as the haul position the CTD station was made. For the period 1995-2001 in the area A composition of fish by weight was quite similar (29.2% herring, 64.4% sprat, and 6.4 % cod). In both cases sprats were predominant.

The results of echo integration for each ESDU and for each slices of depth were converted into values of normalized area backscattering coefficient (s_A), following Knudsen's formula (3):

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

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]. S_A were converted into s_v values by the formula:

$$s_v = s_{AA}\, \varepsilon^{-1}\, A(z_{i+1} - z_i)^{-1} \qquad (2.)$$

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. Day and night time index was estimated on the base of analysis of fish echo recordings.

For each ESDU basic parameters characterising fish distribution, as upper and lower fish depth limits, depth of the 'gravity centre' of s_v (z) distribution and the values of corresponding environmental factors were calculated with the use of the self prepared software. The approximate models of diel variability of parameters mentioned above were estimated on the basis of the methods described by the author (10, 11, 12, 13, 14). Visualizations (macrosounding, T-macrosounding: 9, 10, 15), significantly enhancing description of the diel behaviour of the fishes were applied.

The final description of the variability of acoustic fish response was based on 2D probability function representing the distribution of data corresponding to each ESDU against S_{vc} and time of the day classes. Distributions were found for both compared cases (A and B). Numerical models of diel variability of relative fish echoes energy (S_A/< S_A >) as well as the other daily modulated parameters were estimated by using trigonometric polynomial functions (Orlowski, 1998).

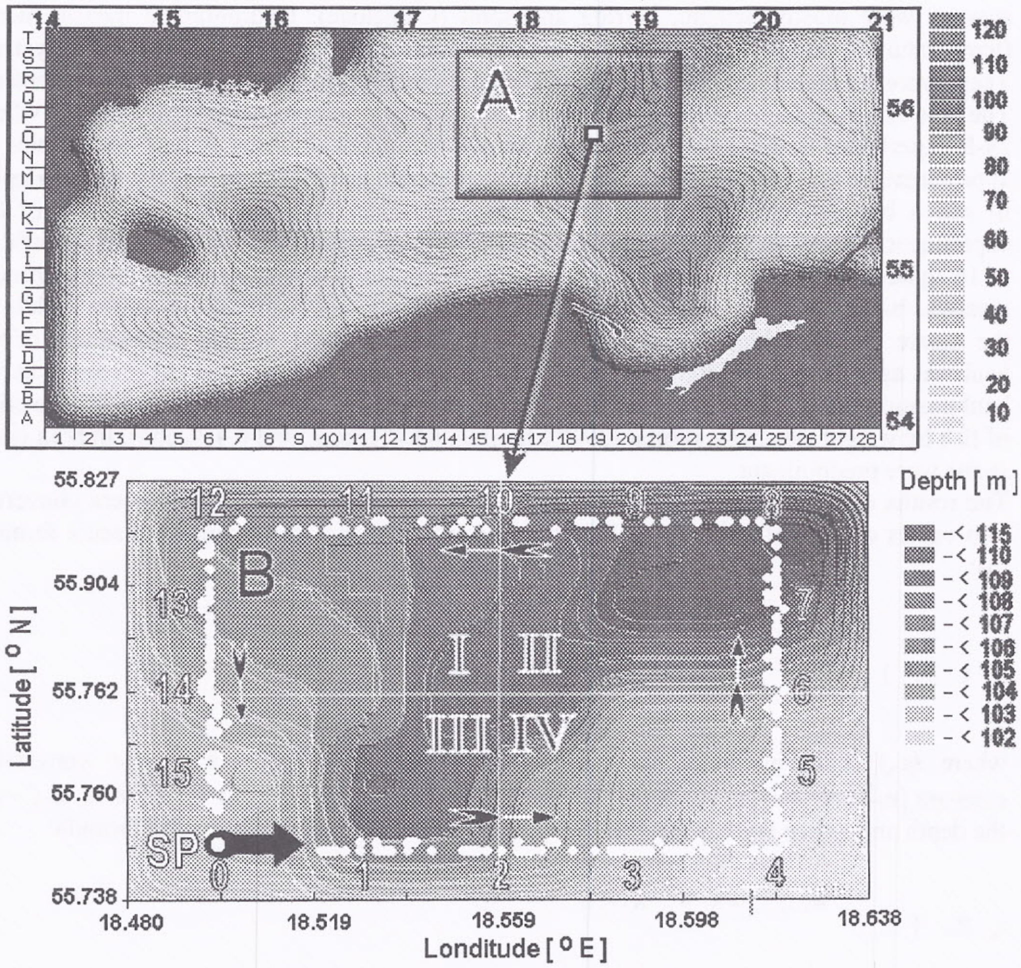

Figure 1. Areas of the southern Baltic from which data were analysed: upper panel – area A - south Gotland Deep - considered for long-term (1995-2001) comparison, lower panel – area B - where 24-h experiment in 2001 was conducted. At the lower panel are marked: starting point - SP, and by white circles - positions of the ESDU ends (related to visualization at Fig. 2A), by numbers - successive ESDU ends corresponding to the macrosounding visualization shown in Fig.B-C. Quadrants of area B are marked by Roman numerals.

2. RESULTS AND DISCUSSION

Time-space distributions of fishes within the area of the experiment (Area B) are given in Fig.2. Macrosounding visualization (9, 10) given in Fig. 2A permits to observe continuos changes of main range of fish recordings at 298 n. miles, along the sides of a square. The period of repetition (16 n mi) is clearly seen in a shape of a bottom pattern. The upper (magenta) layer, in which dots density is proportional to s_v, is closed between fish minimal depth and the depth of the 'gravity centre'. The lower layer (blue) is limited by the fish maximal depth. The distance at O_x axis corresponds to the distance between the ends of each

ESDU. Continuos line at the depth of the sea surface expresses the day time, dashed one - the night period. The pattern shows clearly vertical dynamics of fish distribution over the whole period of the experiment. During the day time the fishes are mostly concentrated between 50m and 70 m (layer of sample haul), randomly migrating towards the bottom. Possibly they are the feeding migrations, being limited in time by low oxygen level below 80 m depth (< 0.5 ml/l). Lower limits of fish distribution depth are correlated to the salinity and oxygen gradients, shown on the right of the figure. Night distribution lower limit was correlated to the temperature gradient.

T-macrosounding visualisations, expressing average fish night and day distribution calculated on the basis of a sliced structure of integration data in relation to remain parameters selected from the data base (15) are shown in Fig.2B-C. Number of mile samples was limited to 214, due to elimination of dense migrating fish schools appearing in the first 62 miles of the experiment. Each unit at the O_x axis corresponds to n mi distance, including the symmetrical stripe along the transect and contains all samples from the night (Fig.2B) or the day (Fig.2C) time. Data from transition periods between night and day were not taken into consideration. Due to conditions assumed the visualization gives more detail average distribution of fish, related to particular space elements of the experiment area B. Simple visual analysis gives a conclusion that the vertical distribution of the fishes was different for night and day time, but very uniform in the whole area B. In conclusion it gives better basis to treat results as representative for observed phenomena. Uniform character is confirmed by small differences in statistical parameters of S_A values in four quadrants I-IV of the area B (Fig. 1).: I $<S_A>=245.67$, CI=50.11; II-$<S_A>=279.41$, CI=44.98; III $<S_A>=215.71$, CI=33.30; IV: $<S_A>=239.49$, CI=33.46.

Figure 3 gives the possibility of comparisons of results of the measurements and their mathematical models for both analysed cases (A and B). Diagrams are completed by Table 1. Values of four basic factors (fish depth, T, S, and O_2) were estimated at three characteristic levels: minimal, main, and maximal fish depths. Average values of all mentioned parameters within 1-h classes were applied to calculate trigonometric polynomials of 11^{th} degree. The error of approximation was very low (between 0.16 % and 4.34%). Higher degree of approximation polynomials had no positive influence on approximation error. Diagrams show confidence intervals of the average values. The highest dispersion within the intervals is observed during the transition periods, mostly correlated to sunrise and sunset periods. General dispersion is higher in the area A, which covers bigger section of the sea and which data represent long-term period, while in area B data were collected in relatively very small area over the period 1.6 day only.

Vertical distribution of fishes during the night and day was very similar in general in both areas. It is indicated by very small values of differences of average values of fish depth parameters (Table 1) and similar patterns of the models. The average fish depth during the night was i.e. 33.1∀0.8 m in the area A and 30.3∀1.6m in the area B. Values of the same parameter for the day time were: 66.7∀1.9m (A) and 67.5∀1.6m (B). Analysing the data presented in Table1 in comparison to their models - it has to be taken into consideration that transition periods were included in this case into night and day hours also.

More detail analysis of fish depths time dependence exposes more complicated character of the diel fish behaviour. Due to influence of factors producing higher dispersion in the area A it seems more reasonable to concentrate on the analysis of results collected in the experiment area B only. That assumption indicate the importance of providing such experiments, which enable to find more real picture of fish behaviour.

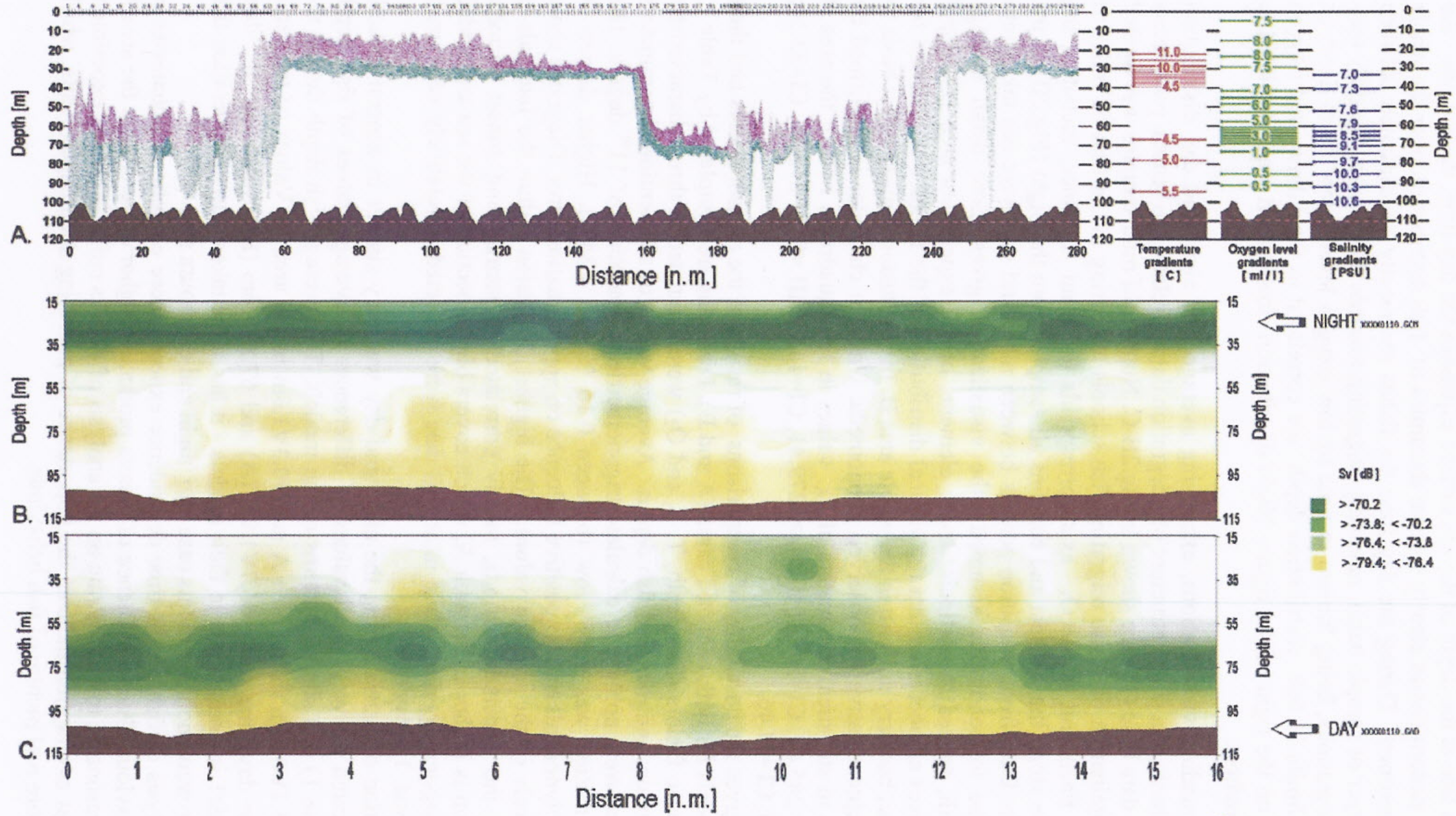

Figure 2. Visualizations of fish distribution during the experiment: A: macrosounding picture of all collected ESDU samples, completed by temperature, oxygen level and salinity isolines, expressing gradients of factors related, B: T-macrosounding expressing average fish distribution at route along sides of square (Fig. 1B. – n mi numbers) during night time, C: as mentioned, during day time.

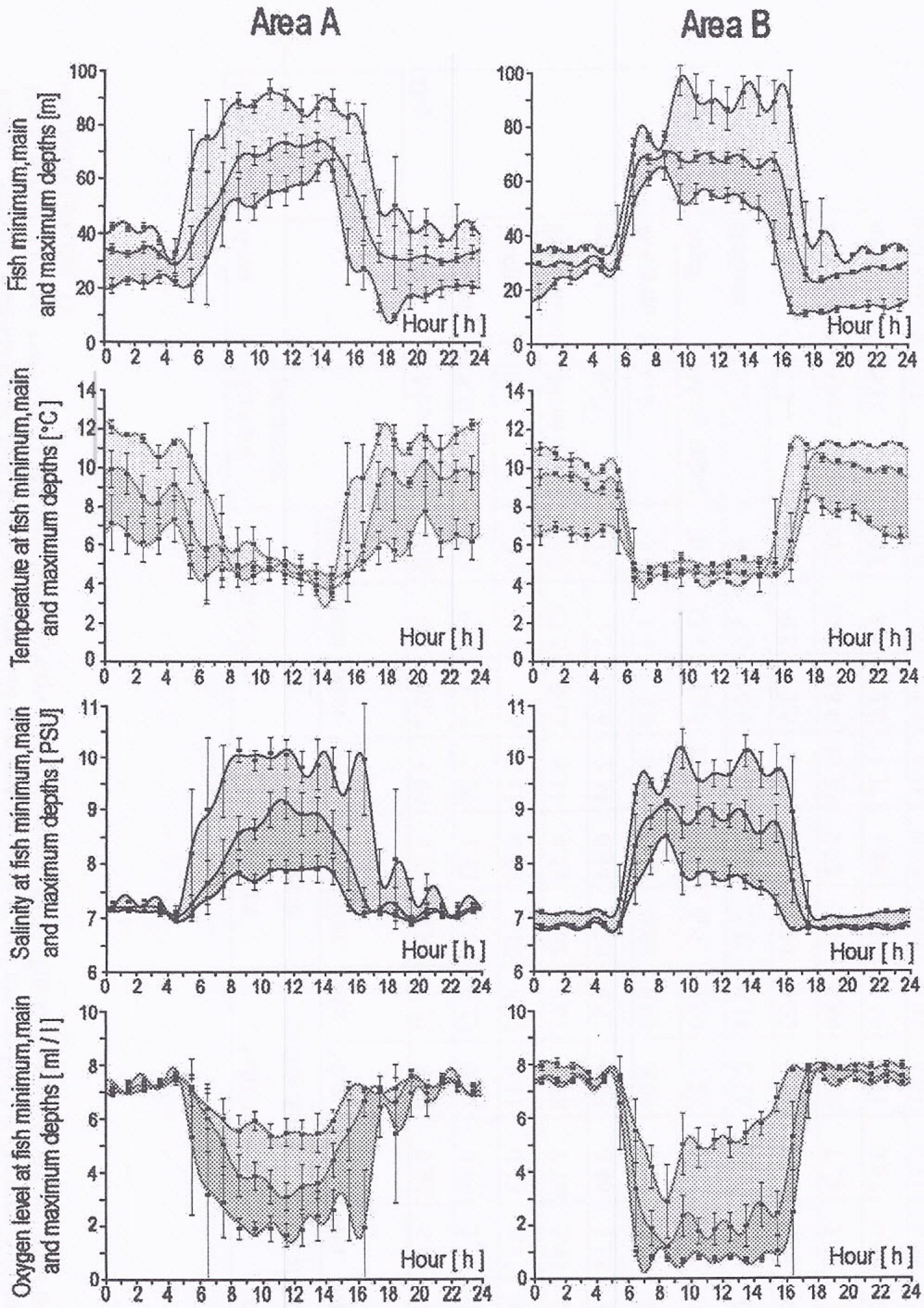

Figure 3. Approximation models of basic parameters characterizing fish diel behaviour in area A and B, expressed by trigonometric polynomials of 11[th] degree. Confidence intervals and of mean values of parameters within 1-hour classes are shown.

Table 1. Statistic parameters of fish depth and correlated temperature, salinity and oxygen level in the area A of south Gotland Deep (period: October 1995-2001) and area B of the experiment (October 2001). Transition periods are included into night and day hours (see Fig. 1).

Day/night	Area	Statistic parameter	Fish depth			Temperature at fish depth			Salinity at fish depth			Oxygen at fish depth		
			Min.	Main	Max.	Min.	Main	Max.	Min.	Main	Max.	Min.	Main	Max.
Day	South Gotland Deep – **A**	Mean value	50.6	66.7	86.7	5.96	4.75	4.87	7.73	8.60	9.86	5.86	4.18	2.22
		S.D.	19.4	15.5	12.7	3.39	1.92	0.69	0.55	0.92	0.89	1.34	1.96	1.68
		C.I.	2.4	1.9	1.6	0.42	0.24	0.10	0.07	0.11	0.13	0.17	0.24	0.24
	Experiment area 4x4 n mi- **B**	Mean value	53.3	67.5	86.8	5.11	4.56	5.08	7.67	8.78	9.76	5.43	2.24	0.79
		S.D.	13.5	7.1	13.6	2.34	0.34	0.30	0.53	0.53	0.46	1.58	1.44	0.33
		C.I.	3.0	1.6	3.0	0.39	0.06	0.06	0.09	0.09	0.10	0.26	0.24	0.07
Night	South Gotland Deep- **A**	Mean value	20.8	33.1	42.5	11.61	9.45	6.61	7.09	7.28	7.35	7.16	7.22	7.15
		S.D.	6.2	5.6	10.9	1.05	1.96	2.11	0.14	0.16	0.48	0.35	0.45	1.03
		C.I.	0.9	0.8	1.5	0.15	0.27	0.29	0.02	0.02	0.06	0.06	0.06	0.14
	Experiment area 4x4 n mi- **B**	Mean value	20.2	30.2	38.0	10.80	9.72	7.18	6.84	6.92	7.23	7.73	7.46	6.85
		S.D.	10.7	8.5	2.0	1.37	1.39	1.17	0.19	0.31	0.67	0.56	0.92	1.70
		C.I.	2.0	1.6	2.0	0.21	0.22	0.18	0.03	0.05	0.11	0.09	0.14	0.27

Starting from the moment of sunrise we observe since 0530h very synchronised migration of fishes towards higher depths. Sunrise migration from 30m up to 70m (approximate values for the fish main depth) has been observed in very narrow, 20m layer. Such a situation remains till 0900, when fish schools disperse in a double in comparison range of depths (see Fig.2). Fish sunset migration is less synchronised and starts in different moments for various fish depths. At first, migration towards the surface is appearing in the upper layers. Difference between migration starting point between upper and lower fish layer can be estimated as more that 1 hour.

Distribution of the fish during the night hours is not uniform in time also. During the first period fishes are dispersed within the wider (approximately 30 m) layer. The layer of fish becomes very thin (less than 10 m) just before the migration. This phenomenon was observed clearly in the both (A and B) areas.

Time variability of temperatures at depths occupied by fishes shows unexpected patterns. During the night, when fishes are stabilized in small range of depths - adequate temperature range is the biggest (6.61-11.61°C in area A, 7.18- 10.80°C in area B). During the day time adequate range of temperatures (Table 1) is very small (4-87-5.96 °C in the area A and 5.08-5.11°C in the area B), besides of strong dispersion of fishes in a wider depths range. It is easy to identify the smallest thickness of fish layer with the vertical migration through the depths of temperature gradient.

Variability of salinity shows an opposite character against the temperature one. During the night hours salinity at fish depths varies within very small range (6.84-7.23 PSU), corresponding to the upper layer of the Baltic, traditionally divided into two different layers. During the day time fishes migrate vertically within depths characterized by wider range of salinity (7.67-9.76 PSU).

Salinity and oxygen patterns in relation to the depth are negatively correlated and it has a direct influence the oxygen patterns, presented at the lowest panel of the Fig. 3. For both mentioned factors the dispersion of day values is similar. The lowest level of the oxygen (0.79∀0.07 ml/l) during the experiment (area B) was the only parameter significantly different in comparison to the whole area A (2.22∀0.24 ml/l). As we can notice in Fig. 2A – the fishes were migrating towards the bottom (low oxygen) depths for temporary periods only.

Fish depth, salinity, and oxygen level approximations are showing the same division of the day time into two distinct sub-periods: the period between the sunrise and 1000 hour, and the period between 1000 hour and the sunset. During the first sub-period the fish is dispersed in a narrow depth layer. It can be considered that the first sub-period can be interpreted as an adaptation phase, while the second one as a phase of full fish activity.

The final analysis of fish behaviour was made in relation to factors describing acoustic properties of fish reflected signals in both terms (A and B) of studies. Basic results are shown in Figure 4. The upper panel of the figure shows diel modulation of echoes received by the echo-sounder by 2D probability function representing the distribution of empirical acoustic data (ESDU values of column scattering strength S_{vc}), separated in dB classes (against S_{vc}) and 2 h (against hour) classes. Distributions were calculated for two separate situations (area A: 1477 ESDU from the period 1995-2001 and B: 147 ESDU from 24-h period selected from experiment data). Diel modulation of the distributions is very clearly seen and it is has similar characteristic moments.

They are noticed for the sunrise, day time, sunset, and night time periods. In the case of the area A the dispersion of S_{vc} values is much wider, attaining 20 dB during the day time and 14 dB during the night time. Mean values of S_{vc} were higher at night than during the day. Some characteristic transformations of the distribution are noticed for the sunrise and sunset periods. The transformation joint with the sunrise is marked by the strongest relief. In the case B we could observe very similar phenomena, but they were much clearly marked, as the situation was observed within one 24-h period , in a small section of the sea only. The most important is to notice a similarity of the pattern of the diel variability of fish echoes, expressed by $p(S_{vc}, t)$ distribution.

In the lower part of the Fig.4 are given models of relative value of fish acoustic response

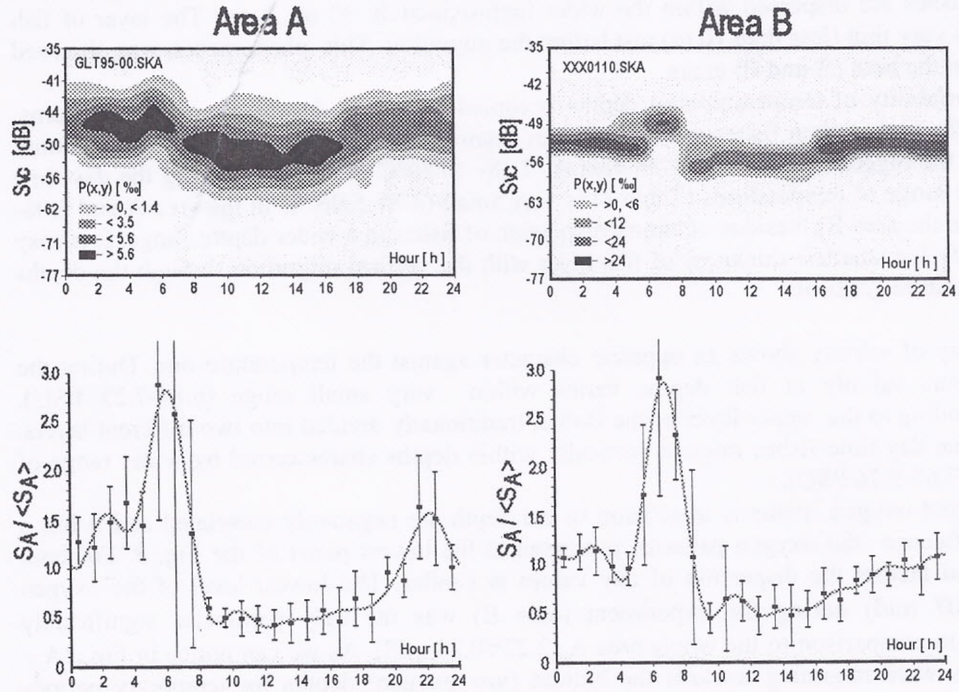

Figure 4. Characteristics of diel variability of fish reflected acoustic energy in area A and B: upper panel - 2D probability distribution of empirical values of s_{vc}, in time of a day; lower panel - approximation curves expressing trigonometric polynomials of 7th degree models of relative energy of fish echoes during a diel cycle. Confidence intervals and mean values within 1-h classes are shown

($S_A/<S_A>$), normalized to the diel mean value. Models are expressed by trigonometric polynomials of 7th degree, with approximation error equal 14.7% (area A) and 5.7% (area B). Higher degree of polynomials did not influence on decrease of the approximation error. Confidence limits of the average of $S_A/< S_A >$ values within selected time intervals are marked. Curves, calculated for different periods and areas are showing very similar form. In general they are similar to the curve presented in Orlowski, 2001 (Fig.6b), calculated on the base of all measurements made in the whole Polish EEZ in a period 1989-1999. In both case echoes are stronger during the night. Similar conclusions on increase of fish target strength during the night hours was given in (8). Due to the fact that the average depth in the Polish EEZ is approximately 67m the measurements were characterizing significantly shallower area than analysed in the studies described above. The most characteristic points of diel dynamics of acoustic response (Fig.4- lower panel) are joint with the same sunrise moment. In both cases (A and B) effective value of $S_A/<S_A>$ is increasing strongly (2-3 times) in that period. Such an increase was observed in the mentioned publication, but it was not exposed so strongly. Very significant increase of the fish echoes during the sunrise period needs to find some explanation. In (2) we can find adequate comment: "When fish descends, the volume of the gas bladder decreases due to increasing pressure, add the fish must add the gas to maintain the neutral buoyancy". We can complete the thesis: it is also necessary to avoid a danger of squeezing of the gas bladder and total lose of the buoyancy. Respecting such a simple physical relation we can interpret increase of fish acoustic response by behavioural reaction of fish, which goes ahead of the descending migration. Clupeoids as physostomes are able to more dynamic controlling their gas bladder volume. They are able even to extensive gas bubble releases, what was reported in (7). The phenomenon associated with fish vertical migration has to be present while the fish school is descending during the day hours as well.

System of methods applied in the described studies is based on self-experience and complementing the methods of visualization characterized also in (4, 5). In (5) Mayer *et al.* are presenting 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. Visualizations applied in described analysis could be useful for direct ecological studies, based on acoustic semi-tomography, or to define sub-areas where numerical models, presented in the paper can be searched or verified.

Recapitulating on examples of acoustic studies of clupeoids diel behaviour in the Baltic it can be concluded:

- combination of different methods (acoustic, environmental, biological sampling) applied parallel enhances a chance to identify and characterize important local differences in environmentally conditioned fish behaviour, estimated in long- and short-term scale,
- application a series of different macrosounding multi-disciplinary visualizations effectively complete details on fish behaviour in particular conditions,
- the highest instability of fish acoustic response was observed for the period of vertical migrations,
- detail knowledge on fish behaviour can be directly applied to estimate or to avoid errors of acoustic measurements.

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