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ENVIRONMENTAL EFFECT ON ACOUSTIC MEASUREMENTS OF BALTIC FISH

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Behaviour of fish is one of most potential sources of bias in fisheries acoustics. The paper describes methods and results of analyses of unique acoustic, hydrologic, and biologic data base collected by research vessels of Sea Fisheries Institute in the southern Baltic in the years 1989-1998. On the basis of numeric models of measurements, interactions between environmental and behavioural factors and fish acoustic response have been estimated. Significant influence of environmentally modulated fish behaviour on effective value of the acoustic back-scattering cross-section was found, described, and discussed. Results indicate a necessity of further research on fish target strength within separate periods of a diel cycle, to define more accurately biomass conversion factors or to eliminate from the surveys the periods of the day, characterized by high instability of fish acoustic properties. Models of environmental background of fish diel cycle can be also applied in wider ecological studies.

INTRODUCTION

Analyses of results of fish biomass estimations carried out by acoustic methods show that coefficients applied to convert echo-integrator output into fish biomass need to precise the correlation of fish back-scattering cross-section σ to environmental factors influencing their effective values [2, 3, 5, 9, 11, 15, 16]. Fish back-scattering cross-section σ, being also known as a target strength TS, represents the most important multiplier in such conversions. The ICES Working Group on Fisheries Acoustic Science and Technology [1] has confirmed during the meeting in St. John's in 1999 that fish behaviour is one of most potential sources of bias in fisheries acoustics and has recommended behavioural studies of σ measurement due to diel fish migration. Number of adequate studies increase year by year [3, 5, 6, 9, 11, 13, 14, 15, 16]. The problem is very complicated as the list of factors potentially influencing physiological state of fish is very large and still has not been closed . Some behavioural phenomena have been determined just by acoustical data analyses [13, 14, 15] and they vice-versa wait for studies by fish physiologists.

The paper gives basic results of studies on interaction between fish and environment which influence on effective value of the fish target strength over the 24h cycle. Unique acoustic, hydrologic and biologic data collection, characterizing fish distribution in the southern Baltic in the autumn of the years 1989-1998, was applied to formulate diel numerical models of basic relationships between fish acoustic response and correlated environmental or behavioural factors. The results are discussed in terms of the ability to specify more precisely conditions of estimation fish acoustic response to minimize the bias of fish stocks assessment.

1. MATERIALS

Data for this investigation were collected during cruises of RV "Profesor Siedlecki" and RV "Baltica", conducted in October in the southern Baltic in different weather conditions, in comparable areas in the years 1989-1998. Each cruise lasted three weeks and had a potential to collect data from approximately 1-1.5 thousand nautical miles of acoustic transect. Samples were collected continuously, every one nautical mile, 24h a day. The time distribution of samples in relation to the whole period (1989-1998) was homogeneous to give a good base on which to analyse the diel characteristics of fish echoes. Main balance of data collection is given in Table 1.

The acoustic magnitudes were collected over one mile intervals but the average for each 3-5 nautical miles (see Table 1) was taken as the most representative to minimize autocorrelation effect [12]. Calibration of acoustic system was carried out in 1989 and 1990 on the basis of intercalibration with the Swedish RV "Argos", as a part of international programme. In 1994 and 1996 calibration was carried out with a standard sphere in the fjord, near Västervik, in Sweden. High stability of the system allowed to apply the same acoustic constant in 1995 and 1997. In 1998, after a mounting of a new EY500 echo-sounder, the calibration was performed by SIMRAD in a fjord in Norway. The same hull-mounted transducer 7.2° x 8.0° was used in the studies.

Hydrologic samples were collected by Neil-Brown CTD system approximately every 35 n.mi of acoustic transect, while biological identification of fish was provided by sample trawls, with a similar frequency (Table 1). Fish observed during all surveys were mostly pelagic, herring and sprat, from the family Clupeidae (96.6% in 1989-1998). Very small percentage (3.4%) corresponded to cod.

Table 1. Overview of acoustic, hydrologic, and biologic data collected over the period 1989-1998: PS – RV "Profesor Siedlecki", average – averaging interval.

No	Year	Vessel	Acoustic equipment	n.mi no	CTD no	Sample hauls	Average [n.mi]	Calibration
1.	1989	PS	EK400+QD	970	50	29	5	intercalibr.
2.	1990	PS	EK400+QD	844	46	26	4	intercalibr.
3.	1994	Baltica	EK400+QD	1088	13	29	4	Västervik
4.	1995	Baltica	EK400+QD+PC	1160	35	25	4	
5.	1996	Baltica	EK400+QD+PC	1456	51	38	4	Västervik
6.	1997	Baltica	EK400+QD+PC	534	12	14	3	
7.	1998	Baltica	EY500+PC	807	23	22	3	Horten

2. METHOD

Echo-integration was conducted in 8 independent channels and output values for each mile interval were converted into S_a values adequately to a system applied [8]. Threshold –80 dB per each ping was applied for S_v for all channels. Due to a draught of the vessel, hull reverberations and aeration zone, integration process started at 15 m depth. Eight channels were used to separate basic layers in the following order: 15-25 m, 25-35 m, 35-45 m, 45-55 m, 55-65 m, 65-75 m, 75-85 m, 85-115 m. Each channel comprised 10 m integration layer, only the last one (the deepest) comprised 30 m. Fish below 115 m depth is not usually expected in the area of reported research. Integration data were averaged (Table 1) and mean depth of fish biomass gravity centre (D_f) was calculated and verified with echograms. Values of corresponding environmental factors (T_f -temperature, S_f -salinity, and O_f -oxygen) at depth of the gravity centre were estimated only for acoustic data units (3-5 n.mi distance intervals), closest to CTD stations. Means of mentioned magnitudes for 2-h intervals were calculated for all data collected over the period 1989-1998, assuming that samples were dispersed randomly from a geographic and bathymetric point of view. Following the homogeneous time distribution of samples and taking into consideration periodical form of approximations, trigonometric polynomial functions for modeling were applied [4, 17] and approximations curves $D_f(t)$, $S_a(t)$, $T_f(t)$, $S_f(t)$, and $O_f(t)$ were calculated. Analysis of approximation errors (coefficients of random variation) were used to limit polynomials up to third degree and such functions were applied for modeling. On the basis of time dependent approximations of mentioned factors interdependence between themselves was regenerated as the main objective of the paper. Approximations of S_a were normalized in relation to the average value $<S_a>$ to make a comparability clear. Due to all assumptions previously made a variability of normalized $S_a /< S_a>$ can be interpreted as a relative variability of equivalent $<\sigma>$ or $<TS>$. Mean migration speed of fish $(V_f(t))$ was estimated as differential coefficient $dD_f(t)/dt$ to include into comparisons.

3.RESULTS

Diel variability of effective energy of fish echoes and their spatial configuration is well known and reported in many papers i.e. [2, 5, 12, 13, 15, 16]. Very illustrative picture of those phenomena is given in Fig.1., showing a diagram of 2-D probability function representing density of empirical data in relation to 1 dB (S_v) and 1h classes. Measurements represent average values of S_v in each integration channel per one n.mi distance unit. Values over the years 1994-1996 (more than 23 thousands) were taken into consideration due to availability of such type of measurements. S_v distribution was significantly modulated during 24h period in a sense of the mean value and the coefficient of dispersion. During the night, most of pelagic fish in the form of scattering layers inhabit a reduced depth range in the warmer near-surface waters, while during the daytime fish are present in a form of shoal-like concentrations within a wide depth range [15]. Basic behavioural fish reactions evidently influence the pattern of fish acoustic response.

More detail analyses of environmental effect on acoustic measurements of fish were achieved by extraction of relationships between normalized values of $S_a /< S_a>$ and basic environmental factors D_f ,T_f , S_f , and O_f. Approximation curves were calculated with a step of 0.1h. Such a solution enabled also to assess a gradient in time of visualized factor, which increase proportionally to a distance between the dots of the diagram. Final diagrams describe a diel interdependence of two variables while time, the third variable, become a parameter.

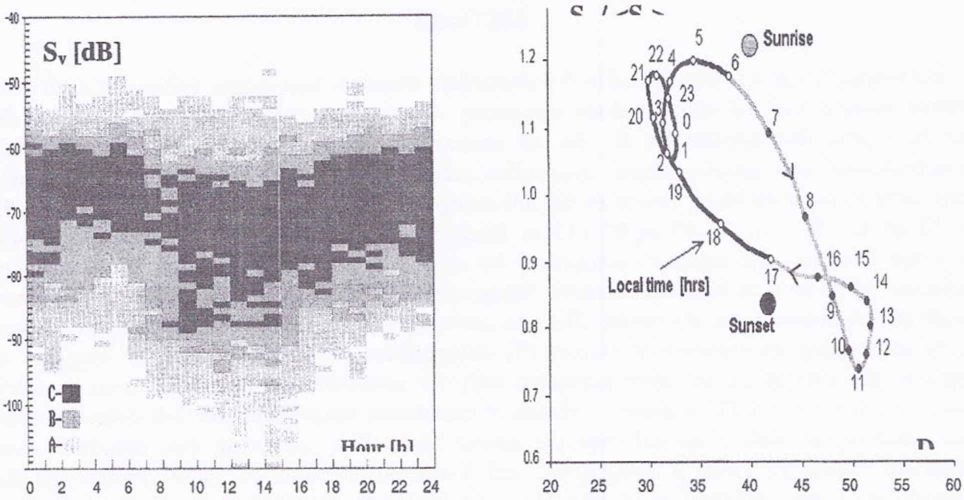

Fig. 1. Probability density function (2D) of volume back-scattering values for integration channels collected over the period 1994-1996: $0 < A < 0.005$; $0.005 \leq B < 0.0175$; $C \geq 0.0175$.

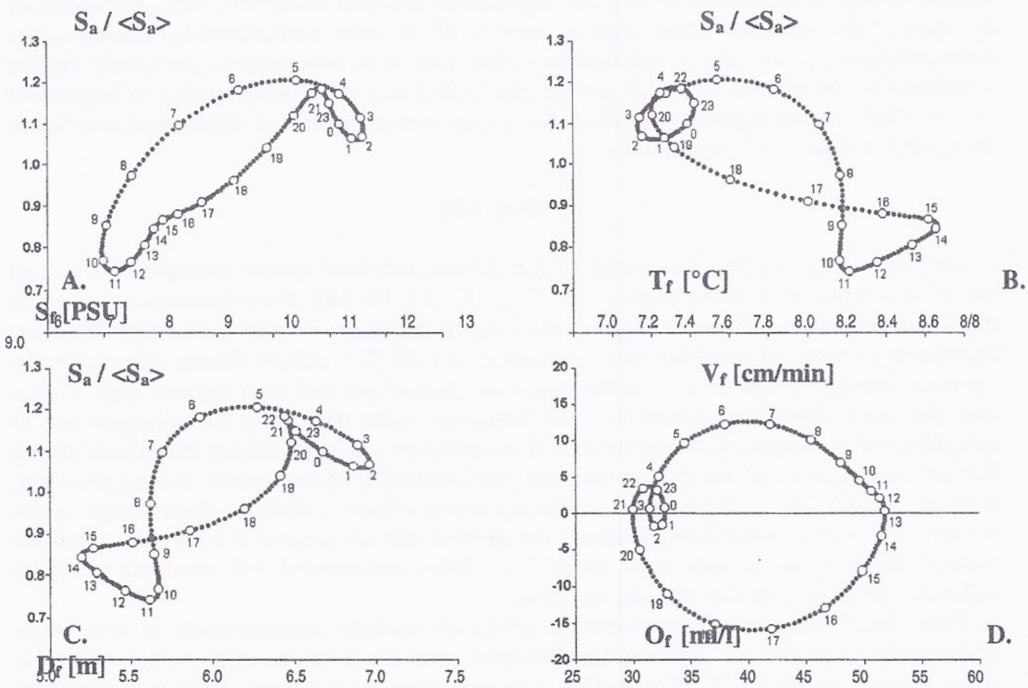

Fig. 3. Basic relationships among fish acoustic response expressed by normalized $S_a/<S_a>$ and correlated environmental factors : A. temperature, B. salinity, C. oxygen level. Diel pattern of average fish group migration velocity (+ means towards deeper water): D. All diagrams are related to a local time (hours marked by circles).

In Fig. 2 is given a diagram expressing an average pattern (1989-1998) of diel cycle of variability of normalized S_a/< S_a> against mean fish depth. The factor S_a/< S_a> is replaced by relative fish cross-section $<\sigma_n>$ in further description. Consecutive hours, sunrise, and sunset moments are adequately marked. It can be considered that the cycle starts at ~0200h [15], when morning twilight begins to influence fish reactions. The moment of sunrise (~0600), the most important stimulus in the cycle, raises a strong fish reaction being expressed by vertical migration towards deeper layers. Strong decrease of $<\sigma_n>$, with maximum gradient in time, is observed during the whole period of migration while a mean fish depth is increasing from 35 m up to 50 m, close to the noon hour. The period between 0900 and 1500 is characterized by relatively stabilized value of $<\sigma_n>$ in time and minimal variability of fish mean depth. Due to observations described in [15] during the downwelling light (1500-1600) beginning of increase of S_v in upper depth layers indicates a start of fish vertical migration towards to the surface. Migration starts more visibly after the sunset (1700) and ends definitely at ~2000. Moderate increase of $<\sigma_n>$, up to the average value ~1.1 is observed during that period. No distinct signs of fish migration are observed between 1900 and 0400, besides a value of $<\sigma_n>$ fluctuates and finally increases about 20%. Systematic decrease of $<\sigma_n>$ goes together with downwards migration, which starts at 0400. Process of shifting the biomass gravity centre lasts till the moment of the highest position of the sun and it is accompanied by a relative decrease of $<\sigma_n>$ by factor 1.70.

Periodical changes of the main fish depth influence the values of other environmental factors associated with adequate water layers. Figure 3.A shows a relationship between $<\sigma_n>$ and water temperature at the main fish depth. The highest temperature corresponds to a starting point (0200) of the cycle. Increase of $<\sigma_n>$ has a place between 0200 and 0500, while no migration and no temperature changes are observed. Proportional decrease of $<\sigma_n>$ with temperature is recorded between 0500 and the noon, while the opposite phenomenon appears between the noon and 2200. In period 2200-0500 changes of $<\sigma_n>$ seem not to be correlated with temperature. A significant hysteresis between $<\sigma_n>$ values for the same T_f values during opposite migration direction is noticed.

Relationships between relative $<\sigma_n>$, salinity (Fig.3.B), and oxygen level (Fig.3.C) shows that highest changes of $<\sigma_n>$ are not directly correlated to analysed factors. The largest decrease of $<\sigma_n>$ between 0600 and 1100 (160%) corresponds to ~4% increase of salinity and oxygen level only. Analysis of a ratio between day and night average values of $<\sigma_n>$ and D_f, T_f, S_f, O_f for five differentiated areas of the southern Baltic showed a significant correlation between $<\sigma_n>$ and D_f (0.892) and $<\sigma_n>$ and T_f (0.882). Correlation coefficient between $<\sigma_n>$ and S_f was equal –0.038 and between $<\sigma_n>$ and O_f was equal 0.179.

Diel pattern of fish group migration velocity is shown in Fig. 3.D. Velocities are positive when the fish move towards deeper water. Horizontal line separates areas of different velocity sign. Circular shape of the pattern and symmetry against the position of the sun (angle) indicate that factor as the most important one influencing fish behaviour.

4. DISCUSSION

The paper points the way of extraction of environmental effect on fish acoustic response having a significant influence on the results of methods of fish stock assessment. Application of the approach described in the paper afforded possibilities to systemize a description of diel variability of fish echoes in relation to environmental factors and to compare results with other authors. Changes of the normalized effective fish cross-section $<\sigma_n>$ were mostly correlated with fish depth and associated water temperature, variable due to fish diel vertical migrations. Direct correlation of $<\sigma_n>$ to salinity and oxygen level were not noticed.

Higher values of $<\sigma_n>$ were observed during the night, when the most of fish were concentrated in upper layers (less than 55 m depth). In spite of depth, the area was characterized by highest water temperature, highest oxygen level, and lowest salinity. It means that total water density in that area was the lowest also. During the daytime the fish were dispersed in the whole range of depth, generally deeper, and $<\sigma_n>$ was significantly lower.

Variability of $<\sigma_n>$ with fish main depth and adequate temperature has similar features. One of them is hysteresis. The values of $<\sigma_n>$ at the same depth and for the same temperature (Fig.2 and Fig.3A) are different (even above 20%) for different direction of fish migration. It can be expected that reasons can be associated with the temperature and water pressure. When the fishes move to warmer areas the gases come out of solution and form bubbles in the blood [7], causing evident increase of $<\sigma_n>$. This process explains also increase of $<\sigma_n>$ after a main migration period (1900-2100). Variability of $<\sigma_n>$ during the night (2100-0200), when values of all environmental factors are stabilized, can be correlated with changes of tilt angle. Observations made by the author from the RV "Profesor Siedlecki" underwater window showed that fish tilt angle is more vertical and it is rotating within some limits during that period. That period is associated with minimal fish migrations (Fig. 3.D) and can be identified as a proper night. Morning twilight reaction modify fish position into more horizontal (full activity) what reflects in higher $<\sigma_n>$.

Characteristic presented above corresponds to average pattern of analysed factors over the years 1989-1998. In particular days fish behavioural reactions are quicker and shifted +/- in time, due to cloudiness and the moon phase.

A diel cycle of environmental effect on fish behaviour shows very complicated pattern of fish acoustic response. In [7] and [18] were given detail biological descriptions of 24-hour periodicity of fish behaviour. In [2, 3, 9, 10, 11, 16] authors suggested the possible influence of swim-bladder on depth dependence of $<\sigma>$. Mukai & Iida [11] showed decreasing of $<\sigma>$ with depth for live kokanee salmon by cage experiments. They determined an empirical formula describing a reduction of fish $<\sigma>$ applying Boyle's law. Migration of fish 40 m deeper causes 1.85 times decrease of due to Mukai & Iida experiments. Similar trend was observed by Reynisson & Sigurdsson [16] for oceanic redfish. I this paper a ratio between estimated value of $<\sigma_n>$ at mean depth 30.8 m (2200h) and corresponding temperature 10.9°C and the value of this magnitude at depth 51.3 m (temperature 7.5°C) at 1200h was equal 1.55. It was showed that changes of fish depth are not fully and directly responsible for changes of $<\sigma_n>$. Increase of $<\sigma_n>$ with decrease of depth can be directly correlated with water pressure (depth factor) but hysteresis observed indicate also delayed influence of water temperature on fish physiological state and the balance of gases inside their bodies [7, 18]. That process can cause that changes of $<\sigma_n>$ observed in this paper are relatively higher. The same factors are considered as predominant in [9]. Salinity and oxygen level can be considered as less important in immediate influence on $<\sigma_n>$. They can play a significant role in the processes causing the hysteresis of described relationships.

Spatial distribution of fish and the establishment of physical and chemical boundaries characterizing fish preferences have to be considered as a very complex question, specially in relation to final effect on acoustic measurements of fish. It is impossible to define these boundaries by a single factor, but rather by accumulation of several conditions. The fish reaction can be stressed by the factor of the highest importance, but the influence of remain ones can be significant in wider time dependent scale.

Description of environmental effect on fish acoustic measurements, expressed by numerical models shows the importance and complicated character of observed interactions. Fish behaviour and related environmental factors have very significant influence on effective value of $<\sigma_n>$. In a consequence biomass conversion factor becomes not precise and result of stock assessment becomes doubtful. It must be underlined that variability observed in this paper is strongly reduced by the fact of averaging data over the period of the years 1989-1998. Variability of $<\sigma_n>$ observed in particular cruises was higher due to differences in migration and environmental factors ranges.

There are few ways to minimize environmental effect on the error of acoustic methods of stock assessment. One of them is to apply all described conclusions on fish behaviour stages and to evaluate fish target strength standards in relation to the diel variability of that magnitude. The other way is to reduce time of measuring of S_a up to determined day periods, while $<\sigma>$ can be estimated with a minimal error and minimal variance. That condition could be associated with respecting the moments of minimal horizontal migration of fish also. In the other hand the optimal season of most daily stable value of $<\sigma>$ has to be found.

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