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ANALYSIS OF DIURNAL VARIABILITY OF THE BALTIC SOUND SCATTERING LAYERS

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Schools of fish, aggregations of plankton and concentrations of gas bubbles cause scattering and attenuation of sound waves. In the Baltic Sea, in some seasons and during some hours, at the thermo- and halocline depth there persist aggregations of small marine organisms registered in the range of lower ultrasound frequencies. Diurnal vertical migrations of biological objects (fish and plankton) are easily observed by echosounders. The possible reasons for this well known phenomenon are different: light changes, animal morphology, social behaviour, grazing, chasing for prey or escaping from predator. The present study aims to recognize diel and seasonal changeability of the zooplankton aggregations, to show some examples of vertical migration and to search for possible mechanisms of large differences between day and night measures of the total backscattered energy, integrated over the entire water column. In accordance with bioacoustic practice, the term *zooplankton* in this paper will be used for both zooplankton and micronekton [2].

INTRODUCTION

Intense vertical migrations of zooplankton were observed during the investigation of diurnal scattering patterns in the southern Baltic Sea in all four seasons. The fundamental characteristc feature of the Baltic scattering layers is their persistence at night and invisibility or weakening in the day time. After sunrise they either spread over the water column or rest at the halocline (salinity jump region). Generally speaking, during the warm seasons, when there is a well-defined thermocline (strong temperature gradient region), after sunset the scatterers form a well-marked subsurface layer at or above the thermocline, but this formation disappears during the day. During the cold periods of the year, when the water temperature is nearly constant, the scatterers occupy at night the whole lower part of the water column (not reaching a sea surface), whereas during the day they stay in the vicinity of the halocline.

The majority of zooplankton organisms immerses during the day in the deeper regions in order to avoid predators. At night, when the lack of visual contact makes hunting more difficult, zooplankton feel safe, moves to the surface and graze on the abundant phytoplankton, blooming in the upper layer due to photosynthesis. Complete description of the vertical migration mechanisms is more complicated and migratory habits of zooplankton are far from the full recognition.

The most intriguing fact noticed during the multihour echosounding of the Baltic Sea is an abrupt day-night difference in the backscattered energy integrated over the whole water column. It reaches the value of 20 dB and can not be explained by changes in zooplankton abundance. There exists a variety of hypotheses concerning this phenomenon. Some reasons can lie with changes of abundance and configuration of zooplankton (coherent and incoherent scattering, effects of multiple scattering). Another possible explanation is a variability of the target strength of the individual scatterer - changes of the tilt angle of the organisms relative to the acoustic beam direction or changes in swimbladder volume connected with depth and variable hydrostatic pressure.

The aim of this paper is to examine individual factors influencing the backscattering strength measured in the sea.

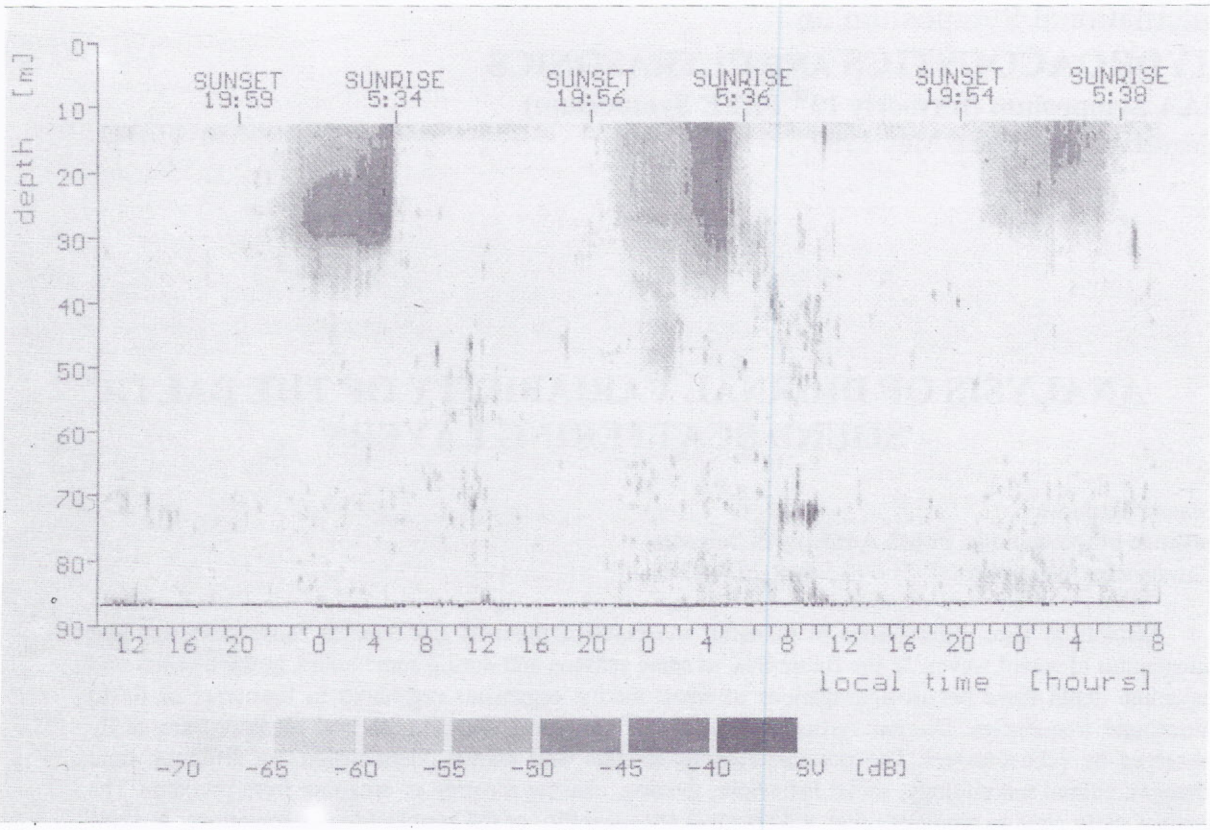

Fig.1. Condensed echogram prepared on the basis of 72-hour sounding at station P116 in August 1996 (frequency 50 kHz).

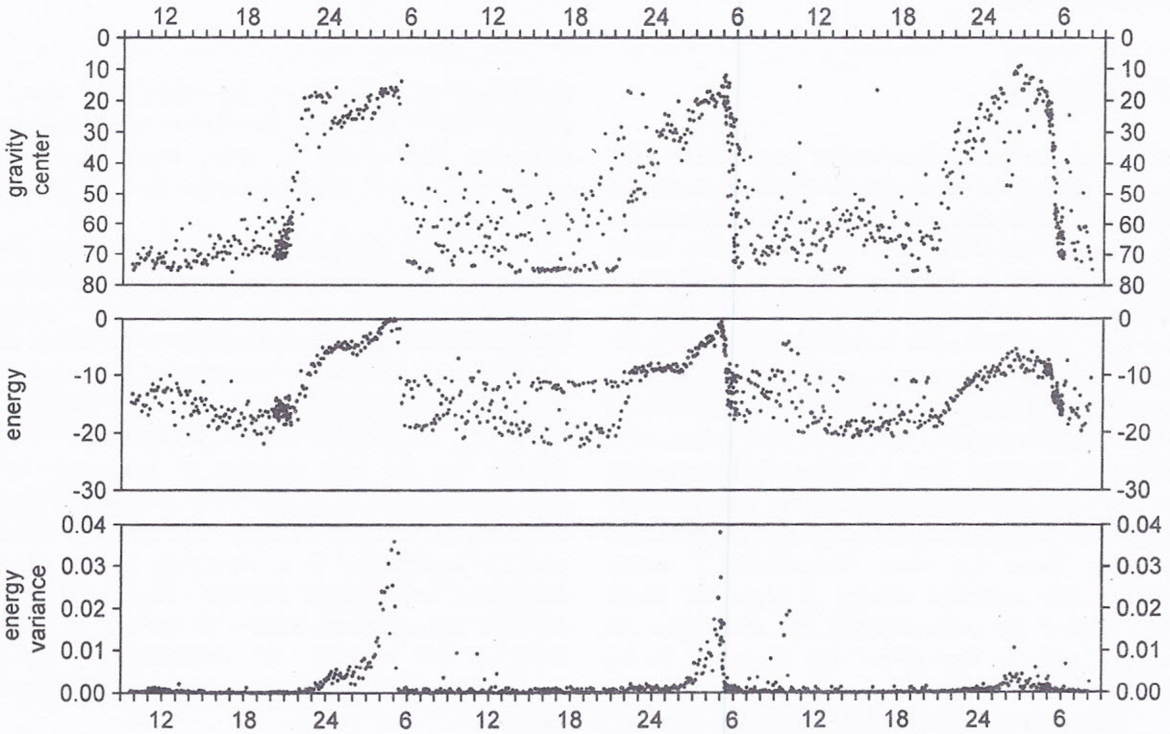

Fig.2. Time changes of the depth of the centre of gravity, the integrated energy and its variance (72-hour record from station P116, August 1996).

MEASUREMENTS AND RESULTS

The sound backscattering measurements presented here were carried out during regular cruises of r/v "Oceania" to the Baltic Sea in different seasons of the years 1991-1996. In order to eliminate the spatial variability in the plankton migration patterns we have chosen a fixed oceanografic station P116 located in the Gdańsk Deep (φ=54°40' N, λ=19°20' E). The bottom depth at that station was 90 m. The measurements were performed by means of standard echosounders working at frequencies 30, 50, 60, 120 and 210 kHz. The pulse length of 0.3-1 ms and trigger rate of 1 s were established. The echo envelope was sampled with a frequency 3-5 kHz and 64-ping sequences separated by 1-minute breaks were recorded together with the time and geographical position, and the technical settings of the echosounder (power, gain, pulse length, pulse rate, TVG). The recorded data anabled echograms to be retrieved during data processing. Simultaneous STD sampling (salinity, temperature, depth) were also done. Unfortunately, species could not be identified as no net samples were taken during the acoustic measurements.

The results of diurnal sound backscattering measurements are presented here in the form of a transformed echogram, which shows a large-scale temporal dependence of the echo energy on depth. Each vertical line in the picture is a 1-minute mean value (averaged over 64 successive echoes). The grey scale represents backscattering strength: the greater is the echo intensity, the darker is the colour. Figure 1 shows the 50 kHz condensed echogram recorded in August '96. This 3-day record shows the process of aggregation of organisms in the subsurface sea layer at night and dispersing of scattering objects over the water column after sunrise. The morning descent starts exactly at the moment of sunrise, whereas the evening movement indicates some delay related to the sunset time. Plankton begin to fall just after sunrise and after 20 minutes they form clearly seen aggregations in the vicinity of halocline (at the depth ~70 m). Figure 2 shows the temporal dependence of three parameters of the echo envelope: the depth of the gravity centre, the integrated energy and its variance. They are defined as follows:

- the depth of the centre of gravity

$$z_{gc} = \sum_{i=1}^{N} U_i^2 z_i \Big/ \sum_{i=1}^{N} U_i^2$$

- the energy backscattered by the whole water column

$$E = \sum_{i=1}^{N} U_i^2 \Big/ k_U$$

- the variance of the mean energy

$$\sigma = \sum_{j=1}^{M} U_j^4 \Big/ M - \left(\sum_{j=1}^{M} U_j^2 \Big/ M \right)^2$$

where

N - the number of samples in the ping
M - the number of pings in one block
U_i - the averaged voltage of the i th sample
U_j - the averaged voltage of the j th ping
z_i - the depth related to the i th sample
k_U - the electrical gain

Changes of the location of the gravity centre (upper part of Fig.2) mirror the diurnal vertical migration effect described above. The temporal variability of the gravity center allows to estimate the speed of vertical migration of plankton. Its value is bigger at sunrise than at sunset and equals 60-90 m/h in downward direction and 25-32 m/h in upward direction. The total energy backscattered within the entire water column, displayed in the middle part of Fig.2, is evidently much higher at night than during the day and varies by 20 dB between day and night. The variance of the total ping energy (lower part of Fig.2) increases significantly during the migration periods, especially at dawn, what additionally confirms the fast changes in the zooplankton configuration.

DISCUSSION

It is very intriguing and perplexing, that the total energy backscattered within the entire water column changes significantly between day and night. It looks as if the organisms disappeared during the daytime. In the case of our measurements we always observe the morning fall of the sound scattering layers, sometimes down to the bottom, sometimes to the thermocline only (in warm months) and sometimes to the halocline. But during the standard vertically downward sounding we get no information concerning the upper subsurface layer (the upper several metres) because of the dead zone of the echosounder and the disturbances introduced by the surface reflections (some part of transmitted energy is going up despite the damping of the transducer!). So, the first question mark is: can zooplankton converge at the surface in the daytime? In order to check this possibility a short experiment in a reverse geometry was conducted. The transmitter was located at the depth ~12m in the upside down position. In such a way the whole top layer could be monitored. The experiment comprised two stages: 5-hour sounding at night and 0.5-hour at dawn. After elimination of the signals reflected from the surface itself, the backscattered energy was integrated over 12

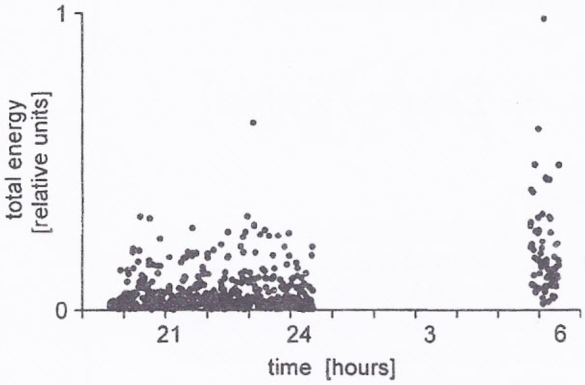

Fig.3. The averaged ping energy integrated over upper 12 m (station P116, September 1996)

metres. Comparison of this variable for different moments of sounding is shown in Fig.3. It seems that total energy backscattered in the top layer is a bit higher about 6 am than about midnight, what can mean that morning upward migration also takes place. Nonetheless, this small upward displacement of zooplankton can not explain the sudden , day-night changes of the backscattered energy integrated over the whole water column, from 12m to the bottom. These dramatic diurnal variations are an inexplainable fact registered in all seas and oceans of the world.

Assuming incoherent and single scattering, the coefficient of backscattering of sound by unit volume is

$$S_{bs} = \sum_i N_i \sigma_{bs,i}$$

where N_i describes the concentration of the i-th class scatterers and σ_{bs} their backscattering cross-section. For the water column of the thickness $[z_{min}, z_{max}]$ the backscattering coefficient is expressed as:

$$S_v = \int_{z_{min}}^{z_{max}} S_{bs}(z)\,dz$$

An amount of the backscattered energy is determined by the value of S_{bs}, which depends on the number of scatterers and their spatial configuration as well as on σ_{bs} - the scattering properties of the individuals. The last one relies on the acoustic wave frequency, the contrast of the acoustic impedances, the body size, shape and orientation. In the case of resonant swimbladder σ_{bs} is also dependent on depth (hydrostatic pressure).

Let us consider these factors:

Coherent effects and multiple scattering

Coherent scattering may be stronger in very dense aggregations, whereas incoherent scattering is predominant in the case of diffuse objects. In dense and ordered zooplankton aggregations the effect of coherence causes the increase of the total echo energy, as it was proved analitycally and numerically by Gorska [1] and Szczucka [9]. The analogous effect was found in fish investigations [5]. Fish gathered in schools move in polarised and synchronised way, giving stronger echoes than in diffuse state.

The multiple scattering takes place in large zooplankton concentrations causing the increase of scattered energy. Nevertheless, this phenomenon is accompanied by the rise of attenuation [9], that lowers the level of the total signal.

Tilt angle

In the case of lack of the resonant swimbladder or any free bubble attached to the scatterer, the most likely explanation of σ_{bs} changes is variable spatial orientation of the scattering body. There are many models describing the scattering process on different shapes of scatterers - a sphere [4], a prolate spheroid [3], straight or bent cylinders [7]. If we assume, for example, a model of straight cylinder, we can estimate the dependence of scattering strength on the tilt angle of the cylinder. In the case of nonisotropic scattering we have

$$\sigma_{bs}(\theta) = D^2(\theta)\sigma_{bs}(0)$$

where θ is an angle between the direction of the acoustic beam and a normal to the vertical cylinder axis. $D(\theta)$ is scattering directivity of a body, which for small θ can be described by the sinc function [8]

$$D(\theta) \approx \frac{\sin\Delta}{\Delta}, \quad \Delta = kL\sin\theta$$

L is a length of the cylinder, k is a wavenumber. Under assumption that $\Delta \ll 1$, $\theta \ll 1$, the following approximation can be used:

$$D(\theta) \approx \exp\left\{-0.2(kL)^2\theta^2\right\}$$

Figure 4 displays this function for 5 frequencies and the value L=2 cm, approximate length of prevailing species of Baltic zooplankton. It can be seen, that the change of the tilt angle in the interval 0 - 12° causes the change of the target strength from a few to tens of decibels, depending on the frequency. The higher is the frequency, the bigger is the effect.

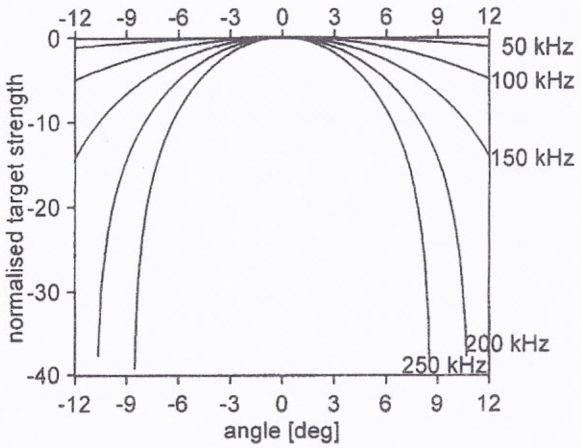

Fig.4. Directivity function 20 logD(θ) for the cylinder of the length 2 cm.

Resonant swimbladder

When the scattering layer decends, that means the depth and hydrostatic pressure increase, the bubbles included in marine organisms are compressed. This process is so slow, that it can be treated as the isothermal one and we have

$$PV = const$$

where P is a pressure and V - a volume. If the amount of gas inside the bubble does not vary, then

$$\left[\frac{a(z)}{a(z_0)}\right]^3 = \frac{P(z_0)}{P(z)}$$

where a is a bubble radius and z - a depth. It is well known, that gas bubble resonates with the incident sound and its resonant radius a_R is inversely proportional to the frequency f:

$$a_R(z) = \frac{1}{2\pi f}\sqrt{\frac{3\gamma P}{\rho}} = \frac{1}{2\pi f}\sqrt{\frac{3\gamma P_0(1+0.1z)}{\rho}}$$

where P_0 is a hydrostatic pressure at the sea level and γ is a polytropic exponent. Comparison of $a(z)$ and $a_R(z)$ allows to determine the depth z_R of the resonance of the bubble, which radius at the depth z_0 was $a(z_0)$:

$$z_R = \left[\frac{a(z_0)2\pi f}{\sqrt{\frac{3\gamma P_0}{\rho}}}\right]^{1.2} 10(1+0.1z_0)^{0.4} - 10$$

Figure 5 presents two groups of curves: dependence of bubble size on depth in the process of compression for bubbles, which at the sea surface had the radii 40, 80, 120, 160 and 320 μm (thin curves) and dependence of resonant radius on depth for frequencies 30, 60 and 120 kHz (thick curves). We can see, that at given echosounder frequency, at different depths the different bubbles are visible (because the resonant scattering is several orders of magnitude stronger than nonresonant one). On the other hand, if the descending zooplankton aggregation is equipped with gas bubbles of similar size, it can give very strong echo at any depth, but at another depths it can be completely invisible.

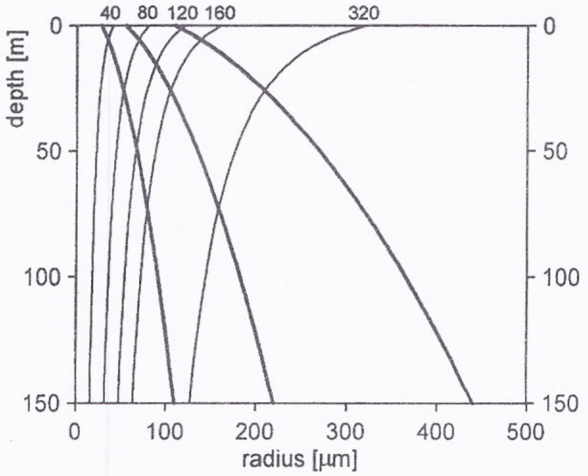

Fig.5. Compression of gas bubble with depth (thin lines) and depth dependence of resonant bubble radius (thick lines)

CONCLUDING REMARKS

Acoustic sampling allows to discern some fine-scale patterns in the marine zooplankton aggregations. Our systematic observations reveal the following features of the Baltic scattering layers:

1. The structure of the biological aggregations varies between seasons. They can be formed in different shapes and lie in different depths, depending on the hydrological conditions and the life cycles of zooplankton.
2. The vertical migration at dusk and dawn takes place with various speeds.
3. There are significant differences between day and night in the integrated backscattered energy, caused in all probability by the coherence effects and the changes in scatterers spatial orientation.

The acoustic observations of biological aggregations represent combined effects of changes in abundance and changes in target strength. Some of the factors determining backscattering strength were examined: the influence of the spacial configuration and orientation of scatterers and resonant properties of swimbladders. It seems, that among these factors, the tilt angle (spatial orientation) is the most likely explanation for the differences of the total backscattered energy. Also the density of aggregation can result in presence or absence of coherent scattering effects, what changes the level of backscattered energy. Orłowski [6] suggests the influence of moon phase on the reflecting properties of the Baltic fish. His conclusion is, that during the periods of the full and the new moon the target strength of fish is ~20% higher than in other periods. In future, this effect is to be checked in our data collection. Unfortunately, the effect of resonant bubbles or swimbladders was not observed in our experiments. Differences in acoustic images of the scattering formations observed at frequencies 60, 120 and 210 kHz suggest an absence of gas bubbles. The differences in vertical profiles of the backscattering strength for various frequencies were very small.

As a summary we can say, that changes of the tilt angle and swimbladder volume strongly influence the target strength of the individual scatterer. This fact should be taken into account in biomass assessment. Assumption of target strength value constant in time can lead to the serious errors in biomass evaluation.

Apart from many interesting conclusions, the interpretation of our acoustic images calls for more knowledge about the nature and behaviour of the sound scatterers and the interactions between physical and biological agents in the sea.

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