ACOUSTIC STUDIES OF THE DIEL MIGRATORY BEHAVIOUR OF BALTIC FAUNA

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Marine animals, fish and zooplankton, migrate vertically in a diel cycle in search of food and to avoid predators. Their crusades are determined mainly by the light amount, but also seasonally variable hydrological conditions have a big influence on the distribution of marine fauna and their aggregative and migratory behaviour. This paper presents the results of numerous series of acoustic measurements (echosounders and ADCPs) conducted in the Baltic Sea in various seasons at different frequencies (30-300 kHz) during the last 17 years. Long-term variability of echo signal parameters on the background of other environmental factors reveals some key features of marine fauna behaviour, among them a double-cycle of diel migration, a loop shape and hysteresis of the dependence between mean gravity centre depth of the signal envelope and backscattering strength, a diel variability of the distribution of SV-values, and seriously limited vertical migration in windy time. The vertical migration velocity is determined by three methods and the results are compared.

INTRODUCTION

The area of our investigation, the Baltic Sea, is a specific basin because of its land-locked location, brackish water and small depth. It is characterised by enormous diversity of time-variable hydrological conditions.

The Baltic biodiversity is rather moderate and members of particular species are smaller than their open-sea equivalents. Although our Baltic animals are meager, which is connected with their miserable habitat, they pose a great value for us and deserve comprehensive investigation and careful treatment.

Diel Vertical Migration (DVM) is the largest animal movement on earth. Most of zooplanktonic species perform the DVM, ascending at night towards the surface to graze on phytoplankton (they are followed by fish!) and descending in the morning to the deeper water and staying there during daytime. It is a worldwide phenomenon, taking place in all oceans, seas and lakes. This behaviour seems to be the trade-off between feeding and predator avoidance. It is connected with the changes in light intensity, but its range and intensity also depend on other hydrological conditions.

Acoustic methods enable us to determine zooplankton and fish abundance, their size distribution and their behaviour – aggregation, collective movement and vertical migration [5, 6, 12]. Aggregations of the biological objects are called the Sound Scattering Layers (SSL). In the Baltic Sea they comprise fish, mainly herring, sprat and cod, and various species of zooplankton. All these organisms are subjected to the continuous stress of having to adapt to rapid changes in the temperature and salinity of the surrounding water and are exposed to highly variable environment of their every-day vertical movement.

This paper presents the variety of phenomena connected with DVM of the Baltic fauna obtained on the basis of longstanding acoustic measurements carried out in the Baltic Sea in various seasons systematically for the last 17 years.

1. EXPERIMENTAL MATERIAL

Experimental material presented in this work was collected in over 20 Baltic cruises of r/v OCEANIA in various seasons from 1991 to 2008 at different locations. Backscattered acoustic signals were recorded by 3 different echosounders: SIMRAD EK500 (120 kHz), HONEYWELL ELAC (30 kHz), BioSonics (420 kHz), 2 ADCPs: vessel-mounted (150 kHz), and bottom-moored (300 kHz), and Autonomous Hydroacoustic System (130 kHz) [10]. The measurements were carried out in stationary conditions from the anchored ship or from the bottom-moored equipment. Obtained data have been used to determine the biomass distribution as well as the field of sea currents.

Acoustic Doppler Current Profiler (ADCP) measures the water flow basing on the Doppler shift of sound scattered by the naturally floating particles, mainly zooplankton. It delivers the vertical profiles of water velocity and, as a by-product, the valuable data on the total backscattering strength of the targets enclosed in the water column [3, 7]. Echo intensity data collected by the ADCP were converted to mean volume backscattering strength *SV* measured in decibels by use of formula given by Deines [2]. Data from echosounders were converted to the form of *SV* by the adequate sonar equations [1, 12]. For each individual instrument many specific technical parameters were necessary (pulse length, transmit power, etc.). Also the attenuation coefficient, depending on frequency, temperature, salinity and depth, had to be calculated. For the low-saline Baltic its value at 10°C is enclosed in the range 0.0015÷0.04 dB/m for the frequencies from 30 to 300 kHz.

CTD profiling was conducted concurrently in order to provide hydrological background. No biological sampling was used in this analysis.

There are many parameters useful in the analysis of the echo signals. Three of them occur to be of special interest in the investigation of scatterers configuration and variability:

- the mean backscattering strength

$$SV = 10\log\left(\sum_{i=1}^{N} Sv_i \Big/ N\right) \quad (1)$$

- the depth of the centre of gravity of the squared signal envelope

$$z_{gc} = \sum_{i=1}^{N} Sv_i z_i \Big/ \sum_{i=1}^{N} Sv_i \quad (2)$$

- the normalised moment of inertia

$$InCen = \sum_{i=1}^{N} Sv_i (z_i - z_{gc})^2 \Big/ \sum_{i=1}^{N} Sv_i \quad (3)$$

where:

N - the number of samples in the ping

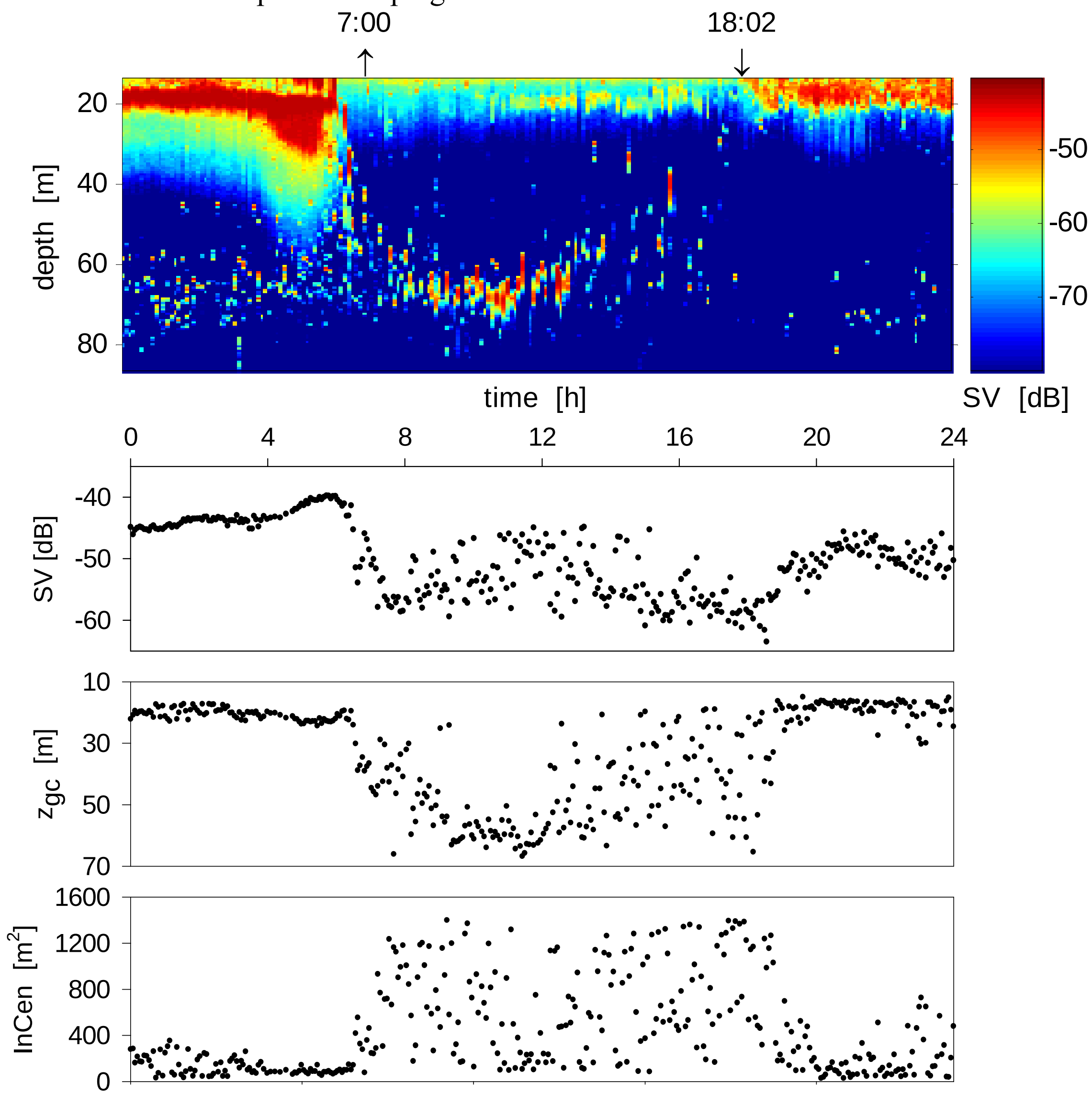

Fig.1 24-hour part of echogram taken from the 4-day series and temporal diagrams of parameters: backscattering strength, gravity centre depth and normalised moment of inertia. Moments of sunrise and sunset marked at the top of the echogram. ELAC 30 kHz, October'1999

M - the number of pings in one block

Sv_i - the mean backscattering coefficient of the i th sample averaged over M pings

$$Sv_i = \frac{1}{M}\sum_{j=1}^{M} Sv_{i,j}$$

z_i - the depth related to the i th sample

The depth of the centre of gravity well describes the movement of scatterers' aggregations as a whole. The mean backscattering strength allows for comparison of the total energy scattered in different moments of observation. The normalised moment of inertia is a measure of the dispersity of the scatterers in the water column. The value of the normalised moment of inertia is close to zero when the scatterers are concentrated in a distinct, narrow layer. On the other hand, when they are dispersed throughout the water column the moment of inertia increases. Fig.1 presents an example of the full day echogram prepared on the basis of the *SV* profiles averaged over 2 minutes together with the calculated parameters: *SV*, z_{gc} and *InCen*. All the events connected with the day-night vertical dislocation of scatterers can be easily inspected in this visualisation.

2. CHARACTERISTIC FEATURES OF DIEL VERTICAL MIGRATION

Diel variations of backscattering strength

Fig.1 shows very clearly that *SV* averaged over the entire water column has its maximal value at night. Just after sunrise it decreases and increaes again after sunset. This phenomenon is better visualised when *SV* values are further averaged in 1-hour intervals. Fig.2 shows two diagrams: *SV* and z_{gc} for the 88-hour series conducted in November'1997. On the background of the general regularity – the nightly increase of <*SV*> and shallowing $<z_{gc}>$ – also small peaks of these quantities were observed at noon. A 3-4 dB rise in <*SV*> and slight decrease of $<z_{gc}>$ are seen especially well. Such a "double-cycle" of diel migration has been observed in three series of measurements only. It can be interpreted as an instant mid-day increase of the scatterers activity, but the reason for it is not clear.

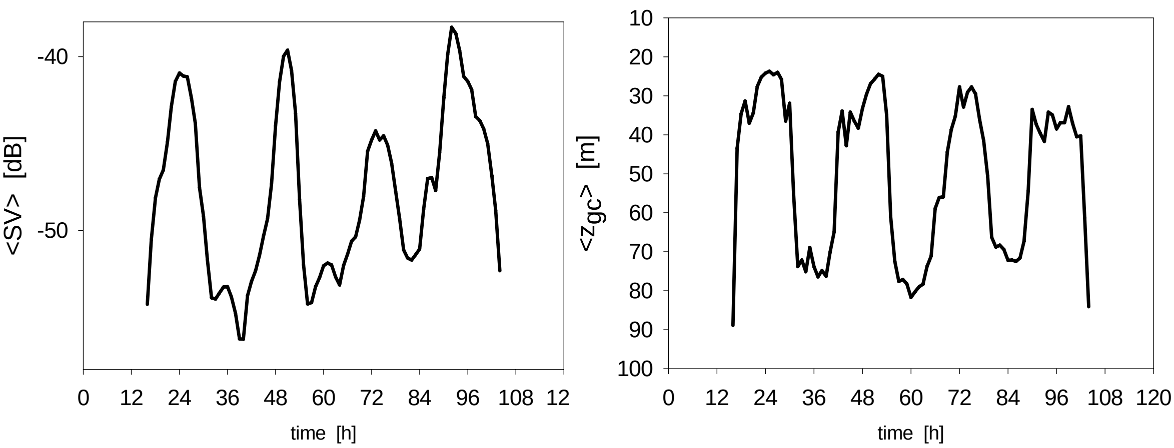

Fig.2 Multidiel variation of backscattering strength and gravity centre depth for the longest series of measurements. Values of SV and z_{gc} are averaged in 1-hour intervals. ELAC 30 kHz, November'1997

Another interesting feature of DVM is the relationship between backscattering strength and gravity centre depth (Fig.3). A majority of the nocturnal data is concentrated in the upper

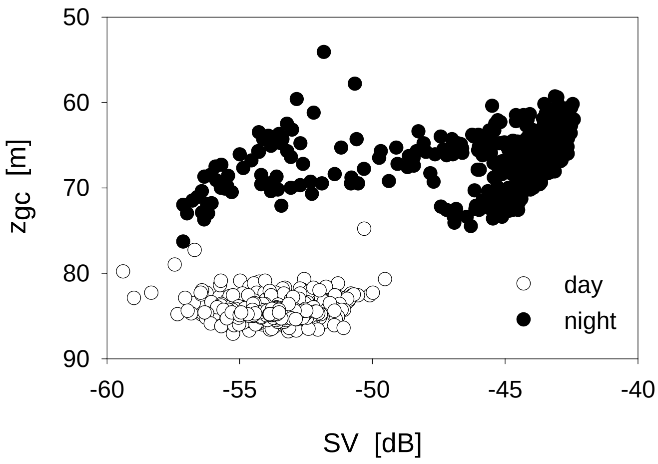

Fig.3 Gravity centre depth versus backscattering strength averaged over 64 pulses. Black circles – night values, white circles – day values. ELAC 30 kHz, April'1997

right corner (shallow depths and big scattering strength). The daily values are more diffused in the water column and their *SV* values are lower than at night. After averaging in 1-hour intervals and over 4 consecutive days the dependence $<SV> – <z_{gc}>$ takes a shape of the loop with a characteristic hysteresis [13]. In any case $<SV>$ at any given depth is lower while the organisms move up (at twilight) than while they move down (at dawn). It can be caused by the change in fish body orientation – oblique in the evening, when they actively swim upwards, and almost horizontal in the morning, when they passively sink towards the bottom. It results in the different values of their target strength. Different intervals of z_{gc} and *SV* changeability are recorded in various seasons, however**,** they do not seem to depend on the temperature difference between day and night depth levels. They rather seem to depend generally on the food availability.

The probability density function of *SV* values calculated for different times of day is presented in Fig.4. It is evident that the shape of PDF is changing – from the small values' dominance during the day to the large values' dominance at night and some transient distribution just after sunset. The *SV* distribution moves from the positively skewed in day time to the negatively skewed in darkness. It should be emphasised that the population of animals seems to be the same at night and during the day, because the measurements are stationary. In this way the *SV* distribution is a mirror of a *TS* distribution, so the presented PDFs concern also the diel changes of target strength. Why *TS* of fish is bigger at the end of the night, when fish go down, than in the evening, when they climb up to the sea surface? There are different possible explanations: (1) their stomachs are full of food; (2) they do not actively swim with their heads down, but naturally sink in the horizontal position; (3) their swimbladders are accustomed to the lower pressure.

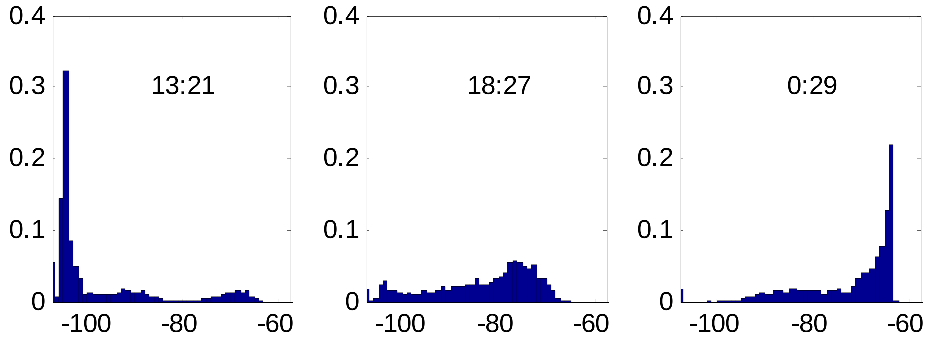

Fig.4 PDF of SV values for a daytime, twilight and nighttime. Hours of registration are marked on top of each histogram. ELAC 30 kHz, April'1997

Diel dependence between normalised moment of inertia and gravity centre depth

Spatial distribution of organisms differs from season to season. An analysis of diel dependence of normalised moment of inertia on gravity centre depth shows the reversed trends recorded in cold and warm seasons [12]. Two series of measurements have been used for comparison. In April 1997, before the water began to warm up, temperatures were still those of winter, less than 3°C to the depth of 70m. In October 1999 there were still late-summer conditions and the temperature came to 16°C close to the surface and fell to 4°C at the thermocline lying at the depth of 20m. Fig.5 compares diagrams of 1-hour means of normalised moment of inertia <*InCen*> versus depth of gravity centre <z_{gc}> calculated for these two seasons. Some characteristic features can be observed. First of all, the inclinations of both loops are opposite. In a cold season the slope of the regression line is negative (-0.25 m^{-1}) while in warm season it is positive ($+ 0.035$ m^{-1}). These coefficients differ in sign as well as in

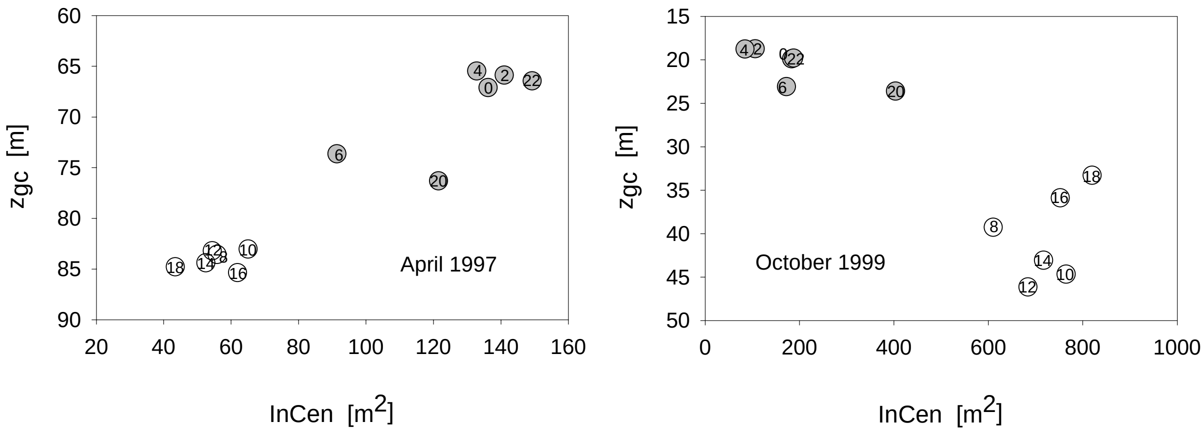

Fig.5 Relationship between the normalized moment of inertia and gravity centre depth for the cold and warm seasons. ELAC 30 kHz, April'1997 and October'1999

value. In each of the two seasons the scatteres occupy completely different depth intervals – it is 65-85 m in April and 15-45 m in October**.** Also values of <*InCen*> are substantially different: 40-140 m^2 in April and 60-840 m^2 in October. Generally, in warmer seasons the organisms prefer upper layers and seem to be much more dispersed in the whole water column than they are in winter, when they prefer the lower part of the water column.

Sunrise and sunset times

Upward and downward movement of marine fauna is synchronous with sunset and sunrise time. In order to prove it, seven series of measurements conducted in the small area within the Gdańsk Basin have been selected in order to compare the time of sunrise and sunset with the onset of migration. These measurements were carried out in different years (2003-2008) and with different tools (ADCP, SIMRAD, ELAC, BioSonics). The algorithm taken from Lorke *et al.* [4] was used to determine the moments of migration. In the nocturnal aggregation layer – bin 13 in Fig.6a – the vertically migrating organisms produce a sharp change in the *SV* values (Fig.6b) and their time derivatives possess the distinct extremes (marked by the red arrows in Fig.6c). The width of these peaks is approximately 1 hour and times corresponding to the maxima and minima were considered the moments of the evening and morning migration. All data obtained by this method seem to be well synchronised with the local times of sunrise and sunset (Fig.7). In the majority of observations the migration starts in darkness, e.g. before sunrise and after sunset. The evening events are consistently shifted by 1÷1.5 hour relative to the moment of sunset, whereas the times of the morning migration are more diverse.

Velocity of migration

The range and speed of upward and downward migration can be determined by various direct and indirect methods. Migration velocity can be determined from the trace on the echogram, from the slope of the sigmoidal or hyperbolic curve approximating the gravity centre location in the transition regions or, in the ADCP case, directly from the vertical velocities calculated from the Doppler shift of backscattered signals.

Vertically migrating group of animals causes**,** at a given time**,** the local maximum of *SV* at a given depth. The edge of the migrating aggregations of scatterers seen in the echogram can be recognised by the simple thresholding method or by the running mean method. Each of them can be used in rows to find the area of rapidly rising *SV* values. These row maxima together with the window width constitute the vertical migration path, ascending at dusk and descending at dawn (Fig.8). The inclination of the migration path can be a measure of the

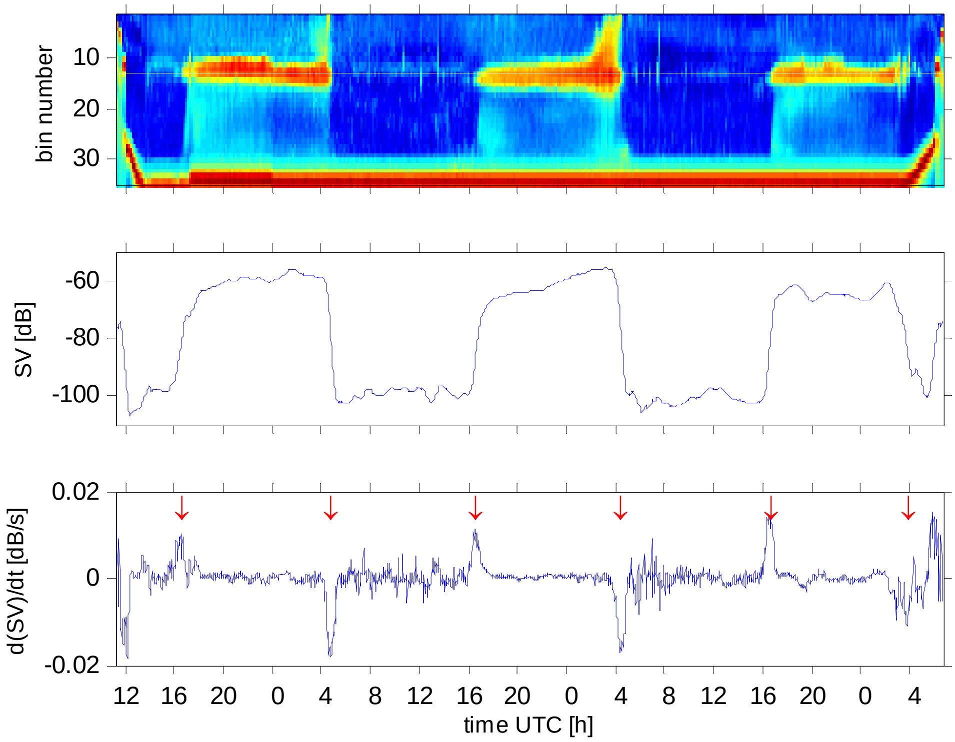

Fig.6 Echogram, backscattering strength at bin 13 (white line on the echogram) and time derivative of SV. ADCP 150 kHz, October'2006

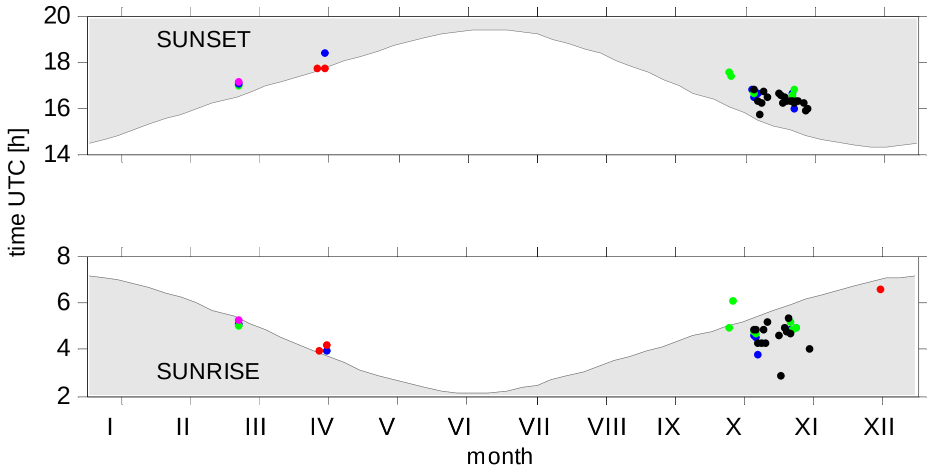

Fig.7 Diagram of sunset and sunrise time at the selected point of the Gulf of Gdańsk together with times of migration determined on the basis of different acoustic observations: ELAC 30 kHz (red), ADCP 150 kHz (blue), SIMRAD 120 kHz (green), ADCP 300 kHz (black), BioSonics 420 kHz (magenta))

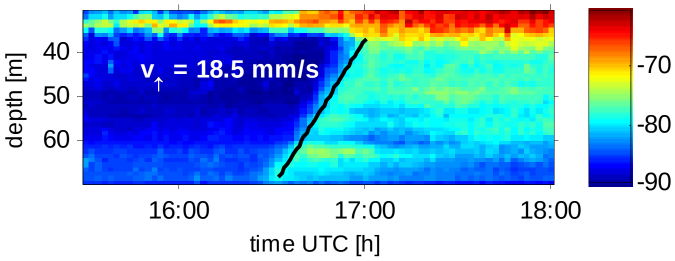

Fig.8 Migration edge on the echogram recorded at sunset. ADCP 300 kHz, October'2006. migration speed [9]

Another way of searching for the migration speed is the analysis of z_{gc}. Usually we can notice the characteristic shallowing of the depth of the centre of gravity at sunset and its sinking at sunrise (Fig.9). The 4-parameter hyperbolic curve has been used to approximate the change of the gravity centre depth:

$$y = y_0 + B\,(\tanh(x - x_0)/C) \quad (4)$$

From the slope of this curve in transition phase we can calculate the velocity of vertical migration: $v_\uparrow = 7.8$ mm s^{-1} and $v_\downarrow = -6$ mm s^{-1} [8].

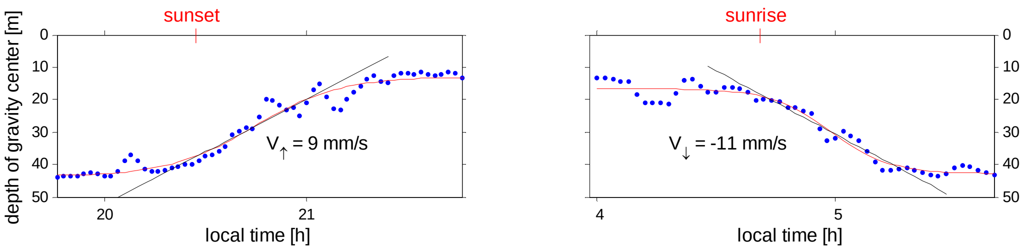

Fig.9 Gravity centre depth in transition regions approximated by the hyperbolic curve (4). ADCP 300 kHz, May'2006

ADCP gives the vertical component of water flow in a direct way. In general, this field is rather chaotic and special methods are required to deduce some useful information concerning the vertical component of the velocity vector. Normally, ADCP measures the flow speed, but during sunrise and sunset the measured speed is of migrating animals. Fig.10a displays the mean vertical velocity calculated for the depth interval spanning the area of diel migration. We can notice the clear positive peak (up to 7.8 mm s^{-1}) in this curve about 9 pm, which is strictly correlated with upward migration at sunset. The negative peak connected with downward migration is also discernible, but not so clear. Nevertheless, its value $v_\downarrow \cong -4$mm s^{-1} exceeds the noise level. Fig.10b presents two distributions of vertical velocity values calculated within the migration path. The left one, characteristic of sunset, is positively skewed, with a mean value $\langle v \rangle = 3.2$ mm/s. The right histogram (sunrise), is negatively skewed, $\langle v \rangle = -1.8$ mm/s. This is another confirmation of the fact that in the morning, after heavy meal, animals stop swimming and passively sink towards dark ocean deep [8].

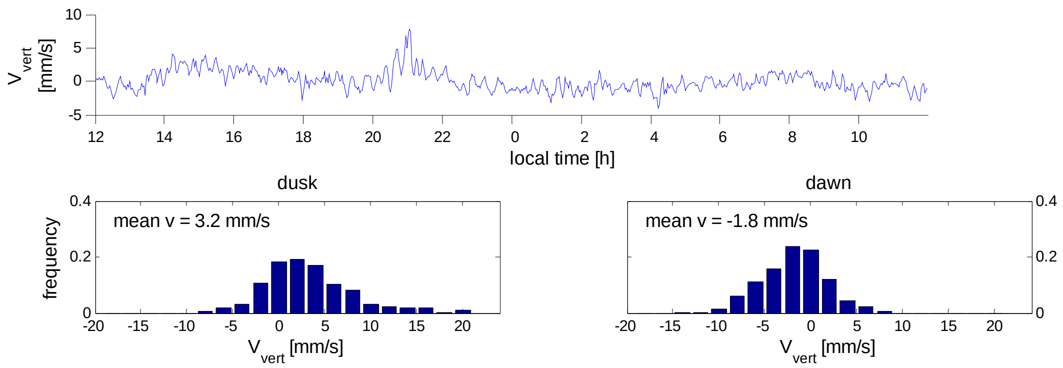

Fig.10 Vertical velocity averaged over 4 days at depth interval 13÷36 m and histograms built from 435 velocity data calculated directly by ADCP within the migration path. ADCP 300 kHz, May'2006

The vertical migration at dusk and dawn takes place with various speeds, which seems to depend on the local life space determined by the depth, temperature and oxygen content. It has been shown on the example of three different basins – The Baltic Sea, Lake Tanganyika and Lake Wdzydze [11], that the deeper the water is, the quicker is the vertical movement.

Generally, the vertical velocity calculated directly by ADCP is smaller than the estimate derived from the slope of the migration path. The uniform vertical migration of the whole populations should be discerned from the vertical movement of individuals – some of them migrate in the principal direction, some are non-migrating scatterers and others can migrate in the opposite direction. ADCP measures the average swimming behaviour of individuals.

Migration in stormy conditions.

One series of measurement conducted in the Baltic Sea by the Autonomous Hydroacoustic System shows an interesting phenomenon [14]. On the background of the normal diel vertical migration**,** some strange effects are evident. When the wind speed increased to 14 m/s and**,** due to the wave breaking**,** dense clouds of air bubbles were generated and entrained deep into the water column, the upper level (maximum depth) of nocturnal persistence of migrating animals became much lower, 30m instead of typical 10m. An illustration of this phenomenon can be the *SV* curves calculated and averaged separately for the day time and night time (Fig.11). The diurnal curves are the means over 5 hours, from 10:00 to 15:00, while the nocturnal ones are averaged over 10 hours, from 19:00 to 5:00. The transition periods, sunrise and sunset, are omitted. For the clarity of the picture the depth is limited to the upper 55m. The daily records are flat having the sharp maximum very close to the surface. The windy days, the second and the third one, are the exception when the bubbles enter the deeper layers of water column. The night charts are more diverse. During the first night the scatterers migrate upward almost to the sea surface. The third night is characterised by the distinct maximum in the layer between 20 and 40m, which is in all probability connected with the aggregation of animals not reaching the sea surface (afraid of reaching the noisy and bubbly subsurface area). The last three nights have the characteristic maxima at the 5-10m layer caused by the nocturnal clusters of vertically migrating marine fauna. The last pattern is commonly treated as a standard one.

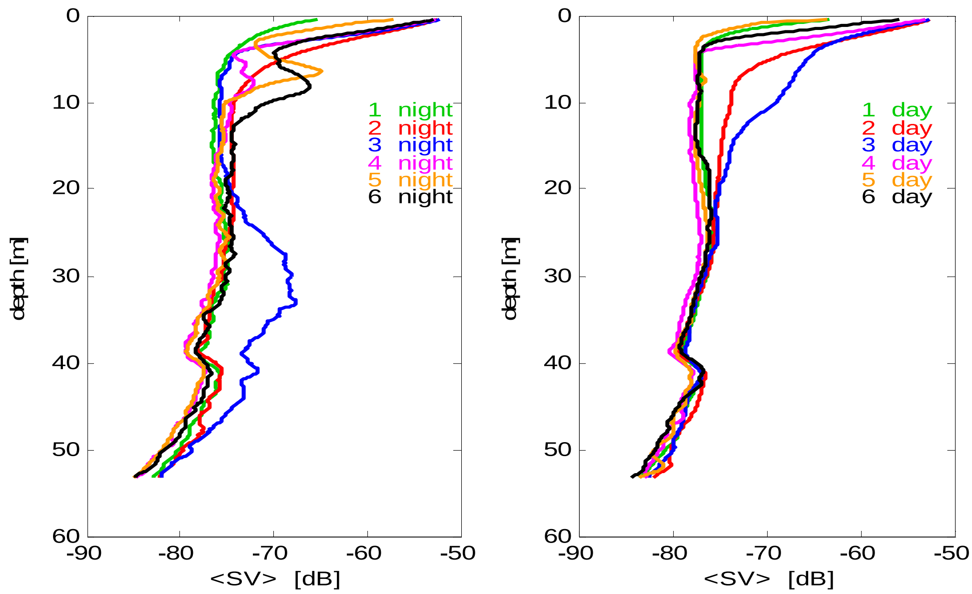

Fig.11 Mean SV profiles for 6 consecutive nights and days. Autonomous Hydroacoustic System 130 kHz, March’2002

This observation documents that fish are afraid not only of the artificial man-made noise, but also of the natural one. In stormy conditions they seem to sense some danger. The reason for this can be the wind noise or bubble songs, as well as turbulence or oxygen oversaturation.

3. CONCLUSION

The high resolution of acoustic method enables the spatiotemporal monitoring of marine organisms and correlating their behavioural features with the abiotic environmental factors. Diel vertical migration of marine fauna finds its reflection in specific parameters of the echo signal. The most important features of the diel vertical migration of the Baltic fauna are the following:

- Migration patterns change seasonally – in warm seasons the animals migrate at night to the sea surface, while in cold seasons they do not migrate so far.
- Times of the evening and morning migration are well correlated with the moments of sunset and sunrise.
- The depth of the centre of gravity in transition periods (sunrise and sunset) can be well approximated by the sigmoidal or hyperbolic curve, which can serve to determine the migration speed.
- Diel dependence between the gravity centre depth and mean backscattering strength is loop-shaped with a characteristic hysteresis.
- There is a double-cycle of diurnal migration. Except for the nocturnal peaking of the mean backscattering strength and gravity centre depth, several dB peaks of these quantities were also observed at noon. It is not easy to explain it; we can presume, however**,** that this fact could be the result of some mid-day reactivation of the animals.
- Normalised moment of inertia occurs to be a useful parameter to discern various forms of marine fauna aggregations. Its value is close to zero, when the layer is strong and narrow. When the organisms are diffused in the water column**,** its value increases.

- There are significant diel changes in *SV* distribution, which in all probability is caused by the diel changes in target strength of the same population of animals.
- During the strong wind the Baltic animals change their migratory habits and do not migrate so close to the surface as during calm weather.
- Three methods of vertical velocity calculation are used: (1) from the migration path on the echogram, (2) from the inclination of the mean gravity centre depth curve, (3) directly calculated by ADCP. Obtained values are comparable to those measured by other people in other basins.

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