Papers

Acoustically measured diurnal vertical migration of fish and zooplankton in the Baltic Sea – seasonal variations

OCEANOLOGIA, 42 (1), 2000.
pp. 5–17.

KEYWORDS
Sound scattering layers
Diurnal vertical migration
Baltic Sea

Joanna Szczucka
Institute of Oceanology,
Polish Academy of Sciences,
Powstańców Warszawy 55, 81–712 Sopot, Poland; e-mail: szczucka@iopan.gda.pl

Manuscript received 25 October 1999, reviewed 21 December 1999, accepted 12 January 2000.

Abstract

Acoustic measurements were conducted at different seasons in the last five years at a fixed point of the Baltic Sea at a frequency 30 kHz concurrently with temperature and salinity sampling. Echosounding records were used to determine the seasonal and diurnal migration patterns of scattering layers in accordance with thermohaline conditions. Different seasonal patterns of nocturnal aggregations of organisms dependent on the temperature gradient in the thermocline were found. This paper illustrates the diurnal distributions of sound scattering layers and analyses the way they are linked to the physical structure of the water.

1. Introduction

Diurnal vertical migration in marine organisms is a well-known phenomenon widely documented in the literature (Everson 1982, Plueddmann & Pinkel 1989, Baussant *et al.* 1992). Though usually regulated by light, the range and speed of such migration can be limited by other factors, such as water temperature and density. While in many ocean areas the general patterns of vertical migration are predictable to some extent, in others – especially coastal regimes – the biological and physical factors affecting aggregative behaviour in fish are not well understood. In recent years, diurnal and nocturnal acoustic scattering patterns in the Baltic Sea have been studied (Orłowski 1996, Szczucka & Klusek 1996, Szczucka 1997). Acoustic methods are effective tools for the rapid, high-resolution detection of both fish and zooplankton.

Because of its shallow and brackish water, the Baltic (mean depth 52 m, maximum depth 459 m, mean salinity *ca* 7 PSU) is not a typical sea, but is a land-locked sea that can be treated as a gigantic estuary receiving water from over 200 rivers. It is a small, cold and strongly stratified basin, and its climate is shaped by strong continental influences and occasional water inflows from the North Sea (the main source of oxygen in the deeper layers). The biological balance of the Baltic is very fragile: the sea is inhabited by few endemic species, and newcomers from other basins are subjected to the continuous stress of having to adapt to an enormous diversity of time-variable hydrological conditions. It is important to note that the thermal conditions in the southern Baltic vary significantly during the year. In summer there is a 20°C difference in the vertical temperature profile down the whole water column. In spring, by contrast, this difference is no greater than 1°C and in winter it is less than 0.5°C. In autumn the summer thermocline lingers on with its steep temperature gradient and temperature difference of about 7°C.

One of the objectives of the acoustic investigation of this particular area was to determine the typical features of scattering layers in the Baltic and to compare them with the generally accepted characteristics of the World Ocean. A further aim was to understand the abiotic factors causing aggregative fish behaviour in the environment to vary in accordance with seasonally changing thermohaline conditions.

2. Experimental and data processing

The sound backscattering measurements presented here were carried out during regular cruises of r/v 'Oceania' to the Baltic Sea in different seasons during 1994–99. Station P116 ($\varphi = 54°40'$N, $\lambda = 19°20'$E; depth 90 m) was chosen as a fixed site for our research in order to eliminate spatial variability, which is impossible to distinguish from purely temporal changes. Continuous acoustic measurements were performed for over 24 hours from the anchored vessel. They provided long-term data on fish distribution and their diurnal vertical migration. An ELAC 4700 echosounder was used in tandem with an LHZ 135 transducer sounding vertically at a frequency of 30 kHz (pulse length 1 ms, trigger rate 1 s). A frequency of 3 kHz was used to sample the echo envelope, 64-ping sequences being recorded together with the time and technical settings of the echosounder (power, gain, pulse length, pulse rate, type of time varied gain – TVG). Temperature and salinity data were collected simultaneously. In accordance with the frequency used, the organisms detected by our acoustic system were fish with swimbladders. Unfortunately, particular species could not be identified as no net-trawl samples were taken during the acoustic measurements. Although the species composition could not be determined by this simple, single-frequency echosounder, it was possible to characterise some fine-scale patterns of backscattered echoes and relate them to environmental parameters.

The basic quantity inferred from the echosounder data is the backscattering strength SV, a logarithmic measure of the volume backscattering coefficient Sv,

$$SV = 10 \log\, Sv. \tag{1}$$

This is the total backscattering cross-section per unit volume, composed of contributions from many types and sizes of scatterers, expressed by the integral

$$SV = \int_0^\infty \sigma(a)\, n(a)\, da, \tag{2}$$

where

σ – backscattering cross-section for a particular scatterer at a given frequency and size a,

$n(a)$ – concentration of scatterers of size a in a size scale bin da.

For different scatterer types (fish, particles, gas bubbles), the cross-section depends variously on frequency and size. Sv reflects changes in the number of scatterers as well as changes in their scattering properties.

To determine the backscattering strength SV, the sonar equation for the volume scattering was applied (Clay & Medwin 1977):

$$SV = 20 \log U_i - (SL + VR) - G - DI - 10 \log (c\tau/2), \tag{3}$$

where

U_i – voltages of consecutive samples,

SL – source level,

VR – voltage response,

G – receiver gain,

DI – directivity index.

SL, VR and DI are calibration values constant for a given echosounder. In order to compensate for the geometrical spread of the acoustic beam and absorption loss in the seawater, the standard time-varied gain

$$TVG = 20 \log\, R + 2\, \alpha\, R \tag{4}$$

was used, where R is the one-way distance, and α is the absorption coefficient expressed in dB m^{-1}.

The recorded data enabled echograms to be retrieved during data processing. The vertical profiles of backscattering strength averaged over 64 consecutive transmissions (lasting about 1 minute) could be extracted. The pulse duration $\tau = 1$ ms yielded 75-cm depth resolution ($\Delta z = c\tau/2$, $c \approx 1500$ m s^{-1} – velocity of sound in water). The final results of sound backscattering measurements are presented here in the form of transformed echograms, which show a large-scale temporal dependence of the echo energy on depth. Each vertical line in the echogram is a mean value of several minutes, averaged over hundreds of successive echoes. The colour scale represents backscattering strengths: the greater the echo intensity, the warmer the colour. Signals from less than 14–20 m depth were suppressed, as they were dominated by transducer backlobe reflections from the water surface and the ship's hull.

3. Results and discussion

The most characteristic feature of the Baltic scattering layers is their persistence at night and weakening during daylight. After sunrise they either spread over the water column or remain in the halocline, close to the bottom. On spring and autumn nights there is a uniform, dense layer of zooplankton and fish close to the sea surface down to the depth of the thermocline. Downward migration begins immediately after sunrise. With a strong thermocline, as is the case in late summer, the situation is slightly different. At night a dense, narrow layer of scatterers is present, mainly around the thermocline depth, whereas the water column above and below is almost empty. As a rule during the warm seasons, when the thermocline is well defined, the scatterers form a well-marked subsurface layer at or above the thermocline after sunset. This formation disappears during daylight. In the cold periods of the year, when the water temperature is nearly constant, the scatterers occupy the whole lower part of the water column at night, never rising to the sea surface, whereas during the day they remain in the vicinity of the halocline (Szczucka & Klusek 1996, Szczucka 1997). Two early-spring records (Figs. 1 and 2) illustrate this. The former refers to April 1997, before the water had begun to warm up and temperatures were still those of winter, *i.e.* a constant value of 3°C at all depths except the near-bottom layer (Fig. 1, right). The echogram (Fig. 1, left) looks like a typical winter chart, with animals moving up and down within a limited depth range, but never actually reaching the sea surface. The April 1994 chart (Fig. 2) depicts a totally different situation: here, the water has already started to warm up. The temperature of the subsurface layer has risen to 4.2°C and organisms have migrated from the bottom up to the topmost layers.

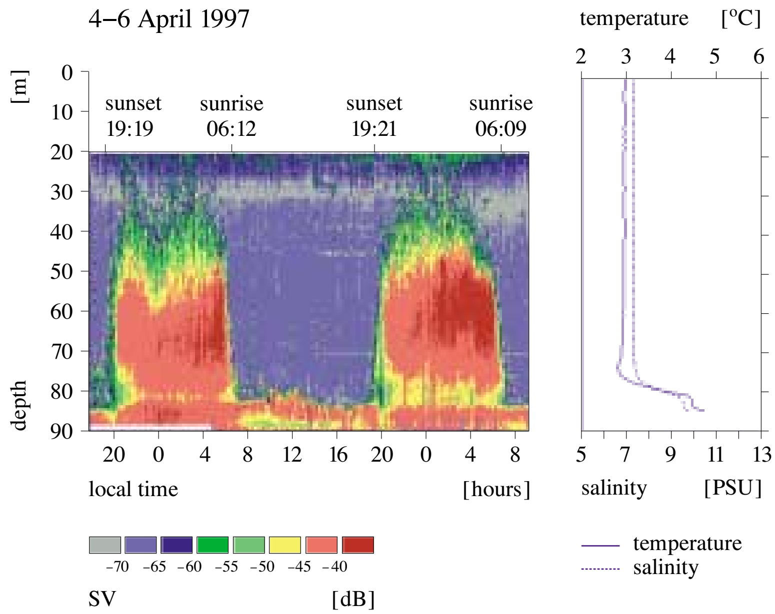

Fig. 1. Condensed echogram prepared on the basis of a 38-hour acoustic sounding (left), mean vertical profiles of temperature and salinity (right) in April 1997

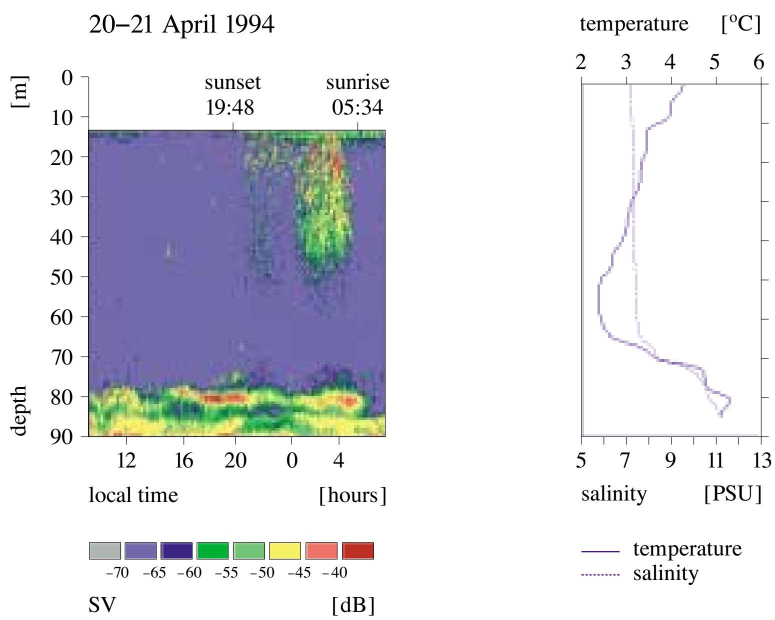

Fig. 2. Condensed echogram prepared on the basis of a 23-hour acoustic sounding (left), mean vertical profiles of temperature and salinity (right) in April 1994

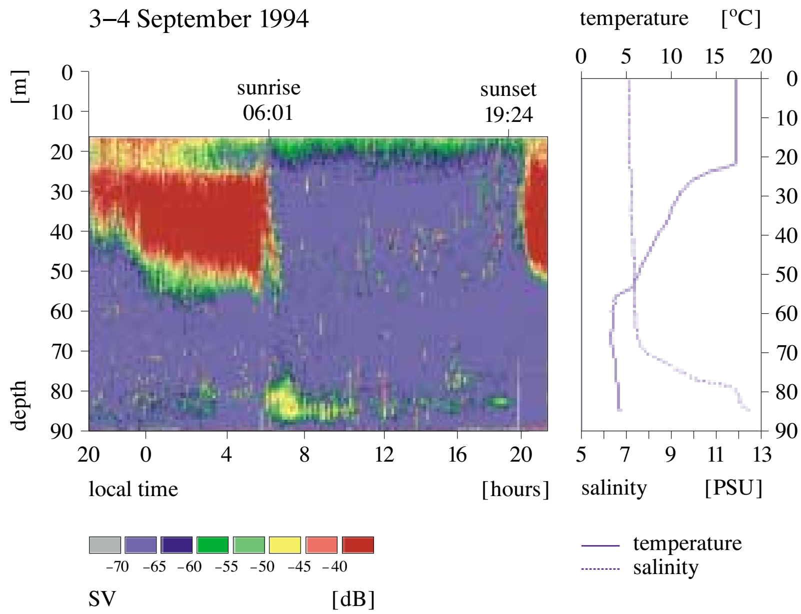

Fig. 3. Diurnal condensed echogram (left), temperature and salinity profiles taken at 20:00 (right) on 3 September 1994

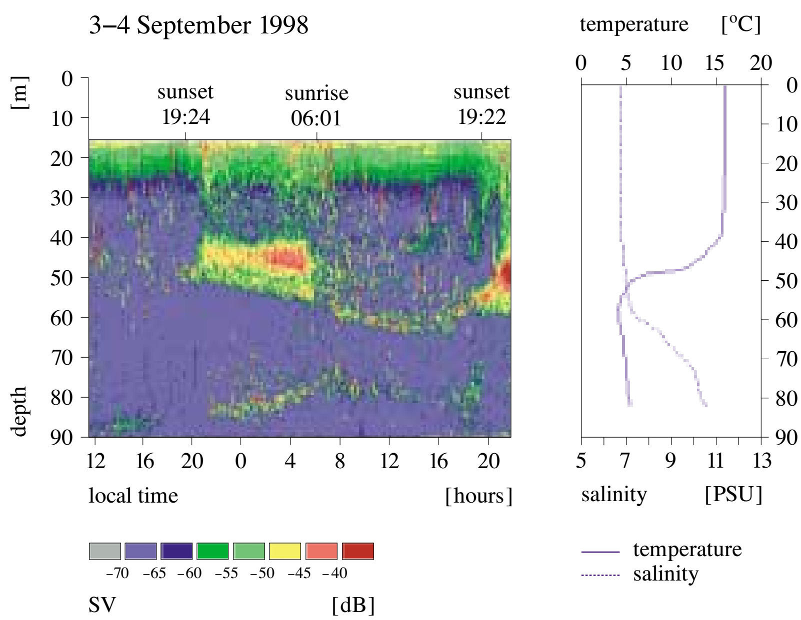

Fig. 4. Diurnal condensed echogram (left), temperature and salinity profiles taken at 20:00 (right) on 3 September 1998

Figures 3 and 4 show two September observations with different thermoclines. Fig. 3 refers to September 1994 when the thermocline spanned the depth interval 25–55 m. A very dense aggregation of fish was detected in this area at night. Another type of thermocline with a characteristic width of 48–60 m (September 1998) is shown in the right-hand part of Fig. 4: scatterers again occupy this particular layer (Fig. 4, left). Many schools of fish are observed during the day in the warm upper 60 m layer (green, yellow and red spots in the echogram). The continually falling lower boundary of the scattering aggregation in the period between 20:00 on 3 September and 16:00 on 4 September is obvious. A comparison

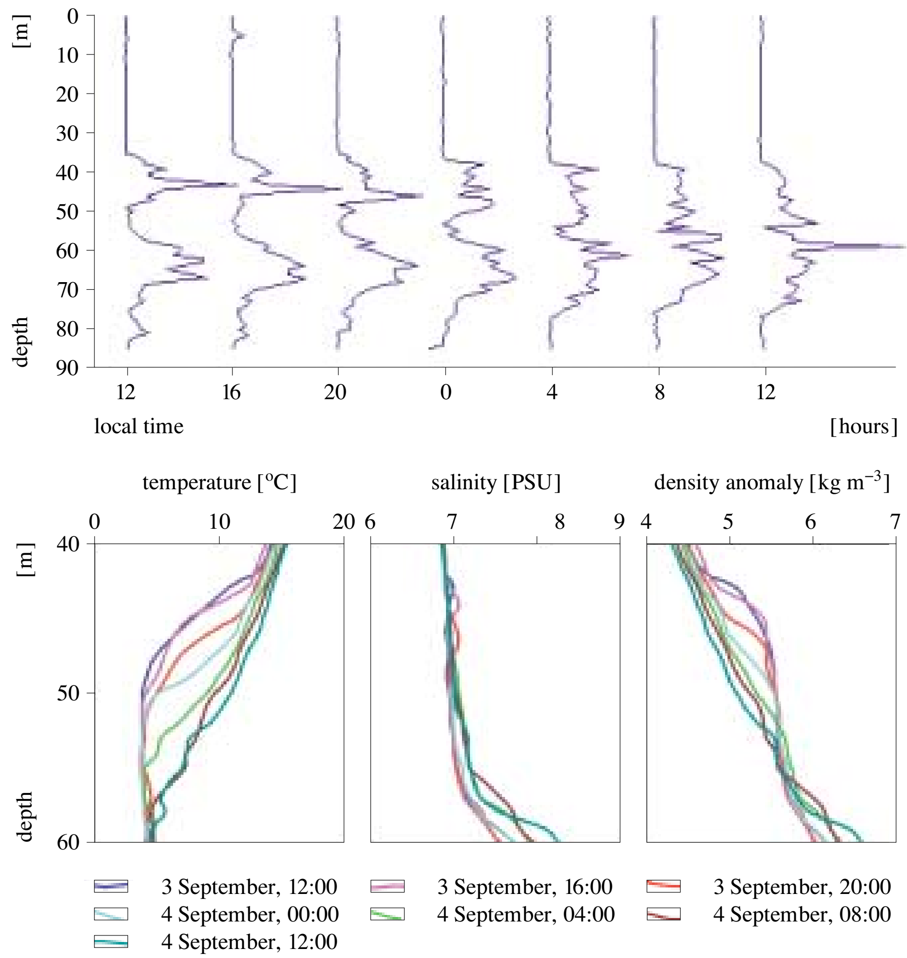

Fig. 5. Density gradient calculated for different instants of observation (upper), temporal changes in vertical profiles of temperature, salinity and density for the 40–60 m layer (lower) in September 1998

of the echogram (Fig. 4) and the density gradient curves (Fig. 5, upper part) suggests that there is a connection between the density jump region and the location of the scatterers. This density jump layer has descended by almost 10 m during 24 hours. In all probability the descent of the thermocline was caused by a mesoscale front passing through our station: a mass of warmer water succeeded a cooler one and the temperature at 50 m increased from 3.8°C at noon of 3 September to 10.8°C by noon of the next day (Fig. 5, lower part).

Figure 6 is another example of the variability of water masses, this time recorded on 4–8 November 1997. The lower part displays the calculated vertical profiles of the water density gradient, while the upper part shows the condensed echogram. The shape of the lower boundary of the scattering aggregations closely follows the shape of the maximum density gradient values. This implies that the region around the maximum density gradient constitutes the best habitat for zooplankton and, in consequence, for fish.

In order to compare migration patterns in different seasons, it is useful to visualise the time dependence of two parameters calculated for the echo envelope: the depth of the centre of gravity and the mean backscattering strength. They are defined as follows:

- the depth of the centre of gravity

$$z_{gc} = \sum_{i=1}^{N} Sv_i \, z_i \Big/ \sum_{i=1}^{N} Sv_i \tag{5}$$

- the mean backscattering strength

$$SV = 10 \log \left(\sum_{i=1}^{N} Sv_i \Big/ N \right), \tag{6}$$

where

N – the number of samples in the ping,

M – the number of pings in one block,

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

$$Sv_i = \frac{1}{M} \sum_{j=1}^{M} Sv_{i,j}, \tag{7}$$

z_i – the depth related to the i th sample.

In each season the centre of gravity descends at dawn and ascends at dusk. This movement mirrors the downward and upward diurnal vertical migration of the sound scattering layers. At different seasons this migration starts at different times in accordance with the times of sunrise and sunset,

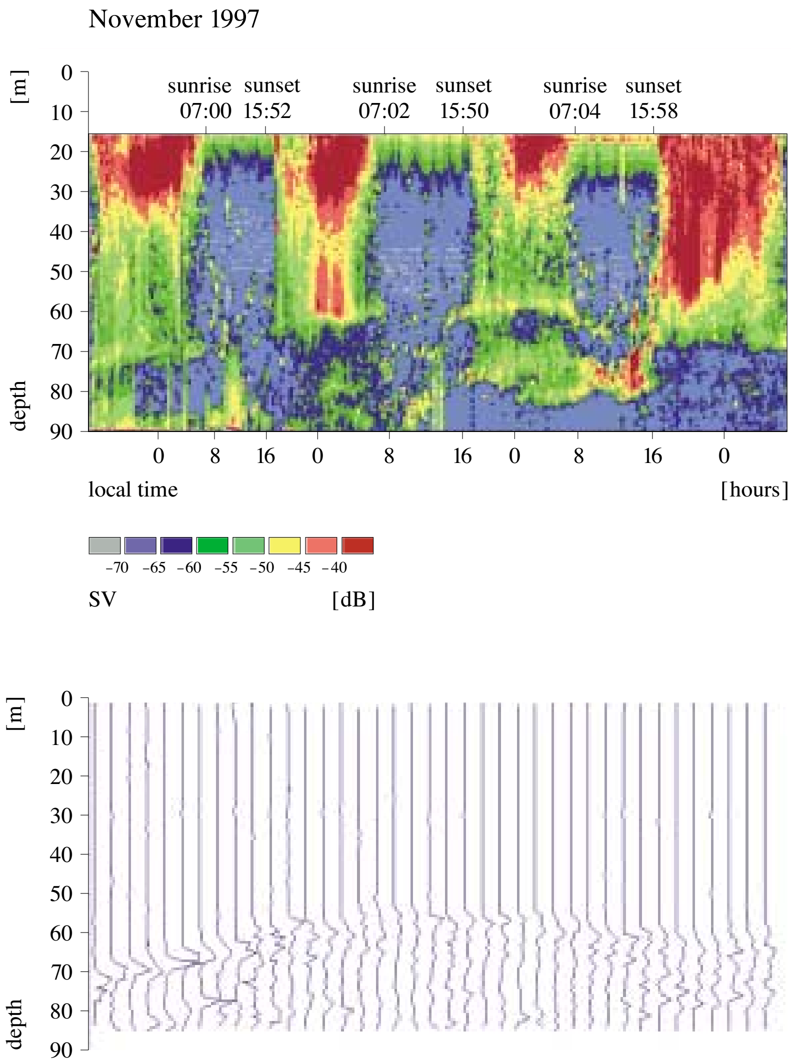

Fig. 6. 3.5 day condensed echogram (upper), vertical profiles of density gradient calculated for different instants of observation (lower) in November 1997

but migration, intensive and rather short-lived though it is, always occurs just then. Generally, the morning and evening vertical redistribution takes less than 1 hour to complete. By way of example, the temporal variability of z_{gc} recorded in April 1997 is presented in Fig. 7 (upper part). The approximate vertical migration velocities at dawn and dusk were calculated at 23 and 36 m h^{-1} respectively. Comparison of these values with those of fish in other basins (Iida *et al.* 1996) indicates that the former are rather

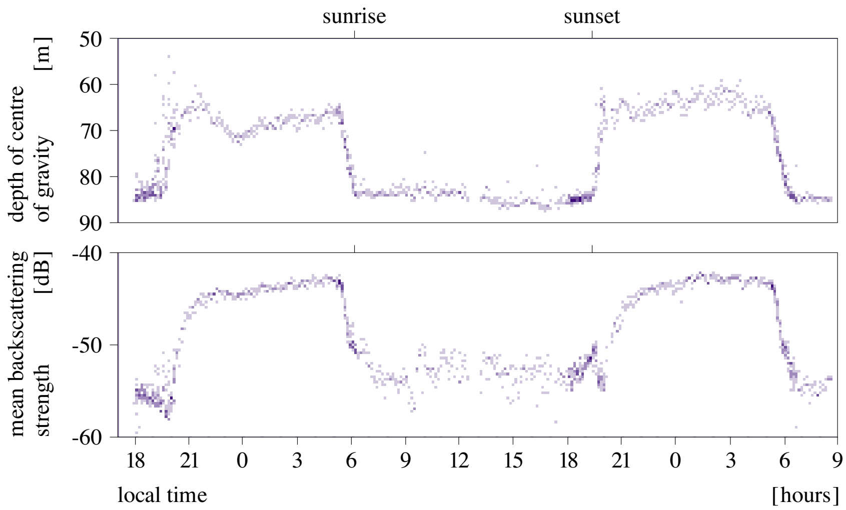

Fig. 7. Temporal variability of the depth of the centre of gravity (upper) and mean backscattering strength (lower) on April 1997

small. This could be due to the fact that vertical migration in the Baltic Sea is limited by the small living space and extremely diverse thermohaline conditions.

The amount of backscattered energy is determined from the backscattering coefficient Sv, the value of which is directly related to a combination of the number of scatterers and their individual scattering properties. Its logarithmic measure, the mean backscattering strength depicted in the lower part of Fig. 7, is evidently higher at night than during the day and varies by several dB between day and night depending on the season. The night-to-day difference in the mean SV often exceeds 20 dB. These dramatic diurnal variations may be due to a variety of factors, but multiple scattering and coherent effects in dense aggregations as well as changes in target strength seem to be the most probable reasons for the observed effect. The target strength is a logarithmic measure of the backscattering cross-section and its diurnal variation is caused by behavioural factors, mainly by the changes in the orientation of scatterers in space.

In order to compare the temporal changes in the backscattering strength, averaged over given layers and time intervals, the volume backscattering coefficient Sv was computed in non-logarithmic form and integrated vertically through 10-m-wide layers and horizontally through 1-hour time intervals. After averaging it was reversed to the logarithmic form SV. The temporal variation in mean SV for consecutive 10 m layers is presented in Fig. 8 for the April 1997 measurements. As can be seen, the night-to-day differences are very small in the upper 30 m water layer, while at depths of 50–80 m they can even reach a value of 40 dB, which is much larger than in the case of SV averaged over the whole water column. This is due to the fact that concentrations of scatterers vary within a given layer and that their scattering properties can change during the diurnal cycle. The example in Fig. 8 is not typical: it demonstrates the most intensive SV changes in the lowest sea layers. In warm seasons, however, the biggest differences in mean SV are associated with the upper sea layers, when the most intensive diurnal migration takes place.

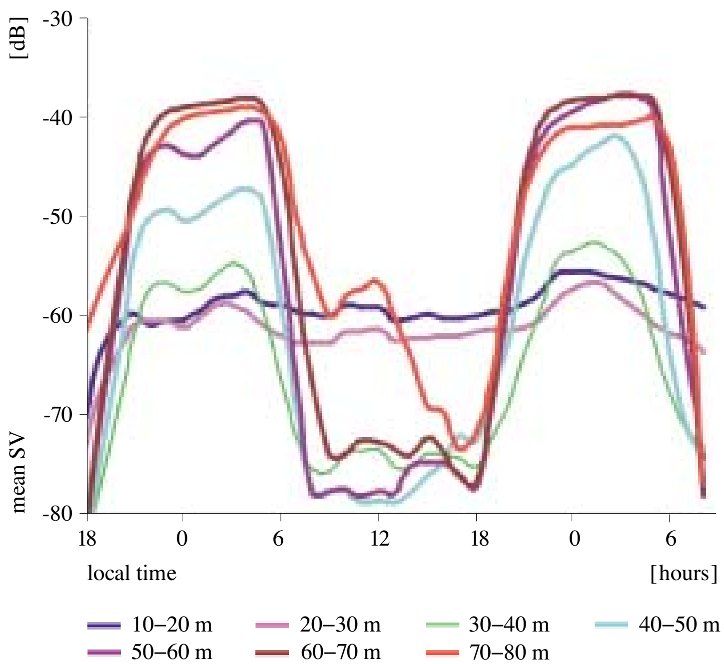

Fig. 8. Temporal changes in mean SV averaged over 10 m layers and 1 hour time intervals in April 1997

4. Conclusion

The main aim of this research was to record scattering layers in the Baltic waters in different seasons, recognise diurnal vertical migration patterns and find the relationship between the acoustically-detected fish and zooplankton layers and the structure of the thermohaline field. The depth, thickness and pattern of the sound scattering layers were studied with respect to temperature and salinity data.

In general, the results indicate that at night during the warm seasons the scatterers form a strong subsurface layer at or above the thermocline, whereas in the cold periods of the year the scatterers occupy the whole lower part of the water column, without ever reaching the sea surface. During the day they stay in the vicinity of the halocline. In the case of the variable depth of the density jump area, echo-producing patches evidently follow the evolving thermocline.

Two parameters of the echo envelope – the depth of the centre of gravity and the mean backscattering strength – were calculated and analysed for each series of measurements. Their temporal variability indicates a significant day-night redistribution of biological scatterers, which is very rapid during the transition periods. In most cases the temporal variability of the centre of gravity allows the vertical migration velocity of the animals to be estimated. The mean backscattering strength is a parameter enabling the absolute values of energy backscattered from the whole water column to be compared at different moments of observation. There are significant differences in the mean backscattering strength (up to 20 dB) between day and night. They represent the combined effects of changes in abundance and changes in target strength. Such a strong variability in the number of scatterers is unlikely, so they reflect rather a change in spatial distribution and orientation of the same animal population. The risk of systematic error in biomass estimation may therefore be incurred if the target strength is assumed constant.

References

Baussant T., Ibanez F., Dallot S., Etienne M., 1992, *Diurnal mesoscale patterns of 50 kHz scattering layers across the Ligurian Sea front (NW Mediterranean Sea)*, Oceanologica Acta, 15 (1), 3–12.

Clay C. S., Medwin H., 1977, *Acoustical oceanography*, John Wiley & Sons, New York, 544 pp.

Everson I., 1982, *Diurnal variations in mean volume backscattering strength of an Antarctic krill (Euphausia superba) patch*, J. Plankton Res., 4 (1), 155–162.

Iida K., Mukai T., Hwang D., 1996, *Relationship between acoustic backscattering strength and density of zooplankton in the sound-scattering layers*, ICES J. Mar. Sci., 53, 507–512.

Orłowski A., 1996, *Diel variations of acoustic properties of the Baltic fish*, Proceedings of the 13th Symposium on Hydroacoustics, Gdynia–Jurata, 35–48.

Plueddemann A. J., Pinkel R., 1989, *Characterization of the patterns of diel migration using a Doppler sonar*, Deep-Sea Res., 36 (4), 509–530.

Szczucka J., 1997, *Analysis of diurnal variability of the Baltic sound scattering layers*, International Symposium on Hydroacoustics and Ultrasonics, EAA Symp., Gdańsk–Jurata, 109–114.

Szczucka J., Klusek Z., 1996, *Migration patterns of acoustic scatterers in the southern Baltic Sea*, Oceanologia, 38 (1), 61–79.